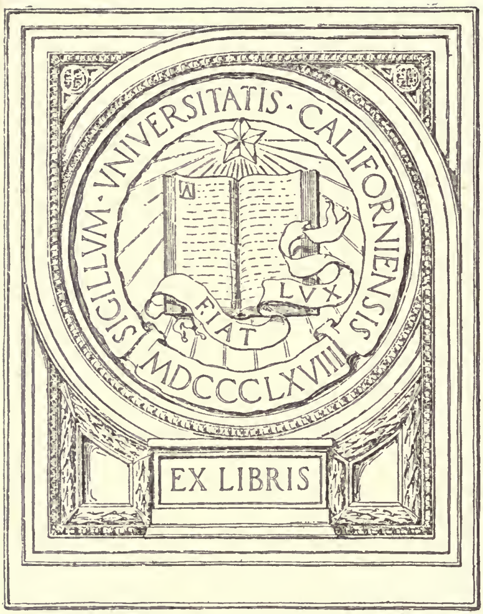
INGOTS AND INGOT MOULDS

A. W. & H. BREARLEY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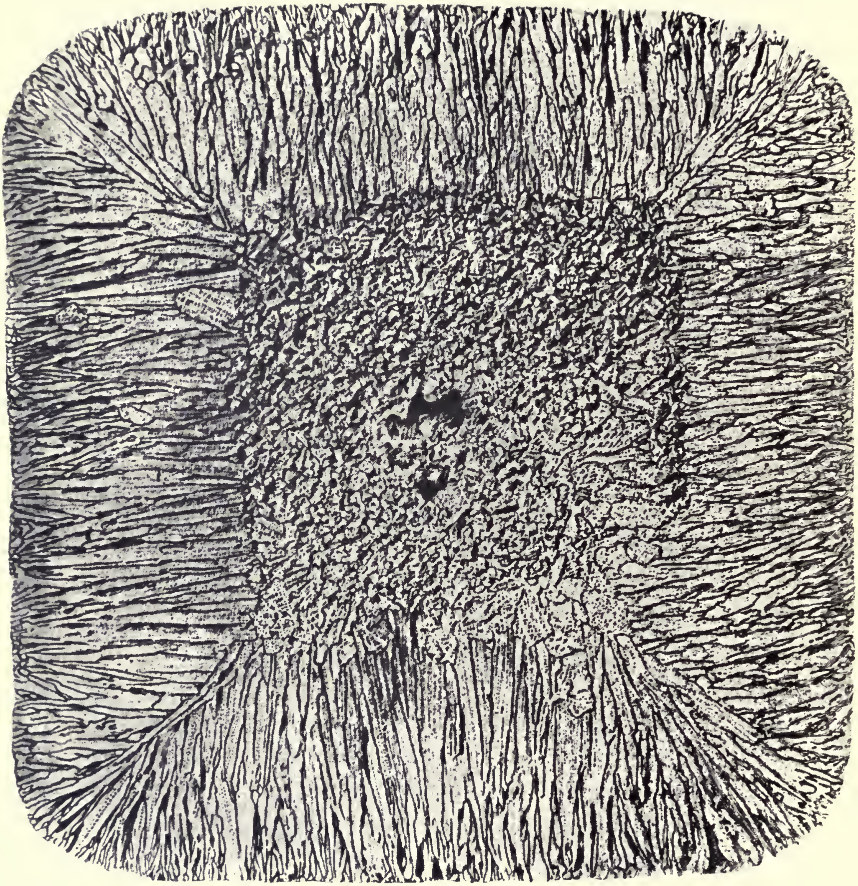

[*Frontispiece*

Chill and free crystals on etched surface of ingot (see p. 208).

INGOTS AND INGOT MOULDS

BY

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AND

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WITH ILLUSTRATIONS

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DEDICATED TO
THE WORKMEN OF
BROWN-BAYLEY'S STEEL WORKS LTD.
IN APPRECIATION OF THEIR EFFORTS
TO REACH THE IDEAL IN
ACTUAL WORK

PREFACE

The authors were induced to prepare a considerable part of this book for teaching purposes. During the few years the MS. sheets have been so used, they have been freely criticized by capable men whose business it is to make steel ingots. During the same period a number of opinions held tentatively have been confirmed by oft-repeated experiments made on a commercial scale in different steel-works; similarly, a number of opinions have not withstood criticism and further experiment, and have therefore been modified. Incidentally the authors are less confident than formerly that they are qualified to elucidate the art of ingot making. They have frequently failed to interpret observations correctly, and have also misapplied facts. They can hardly hope, therefore, that the following pages are free from error, and they offer the book only as an imperfect contribution to a difficult subject. They have tried to write plainly without being offensive, and for the sake of clearness they have sometimes assumed simplified conditions which do not occur in practice.

It has been objected to the use of stearine wax as an experimental material for indicating approximately what may occur with steel ingots, that the physical properties of the steel and wax are different, as are also the relative rôles played by radiation, conduction, convection, pressure, temperature differences, occluded gases, segregation, etc. The authors recognize that there may be something to be said for this objection, but makers of steel ingots are, on the other hand, very much impressed by the similarities in the behaviour of stearine and steel. Whilst the authors would not suggest that experience with stearine entitled a man to call himself a steel-maker, they think that those who are actually making steel ingots are not likely to go far wrong with stearine, or other low melting-point material, used as a means of illustrating and extending principles with which they are already familiar.

In making simplifying assumptions in order to arrive at general truths, the authors are following the practice of pure science. In the laboratory one may use whatever simplifications may be needed for separating out the factors of complex phenomena, but in applying ascertained truths to works practice one realizes that industrial processes start with a complexity which is always much greater than could be permitted in a laboratory experiment devised with the object of arriving at a clear answer to a simple question.

The book is intended especially for those who are interested in ingots and engaged in making them, and such persons may be expected to read it critically.

The authors are greatly indebted to their colleagues, Frank S. Nicholds and J. H. G. Monypenny, who have carefully prepared illustrations, read proofs, and compiled the index. They also appreciate very highly the kindly interest taken in their observations by Mr. Robert Armitage, who has permitted and also encouraged the authors to make large-scale experiments at Brown-Bayley's Steel-works.

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INGOTS AND INGOT MOULDS

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INTRODUCTORY NOTE

THERE is no way of studying the respective conditions favourable to the production of good and bad ingots more instructive than that of making ingots, according to well-defined variations of the processes of ingot making, and subsequently cutting or breaking them to observe their good or bad qualities. A very fine opportunity for such observations was enjoyed, at negligible cost, by the old crucible steel melter in the days when ingots were "topped" down until the pipe or other evidence of unsoundness was broken away. He knew what the conditions of casting were, he was familiar with the state of the ingot mould, he saw daily a score or two of ingots topped down to nearly half their length, and his eye was trained to note minute differences in the appearance of the fractured surfaces.

Though undoubtedly thorough, this training was a lengthy one, and the student who wants to learn a good deal about ingots from actual observation will find that, nowadays, the opportunities are scarcer than they used to be, because ingots are rarely topped; and the need to learn by some quicker method is more pressing, because as larger ingots are made the consequences of defects are more serious. To make experiments with steel is no doubt the most reliable way of learning about the changes that occur during the casting and subsequent solidifying of steel ingots; but it entails a costly plant, and molten steel is an expensive material and also dangerous when handled by any other than an experienced person. There is also no method of determining the temperature of molten steel with satisfying accuracy which could be applied to such purposes as we have in mind; and if, finally, the ingots were made in pre-determined ways the cutting or breaking of them would be difficult and costly. There is not much hope that the University student or young artisan will learn experimentally all he wants to know about the structure and mechanical properties of ingots unless he can employ some more manageable material which is broadly analogous in its behaviour to the behaviour of steel. Of the possible materials a quite close resemblance to steel is exhibited by stearine wax. With a few pounds of stearine, a pan of water, a beaker, a bunsen burner or spirit lamp, a few tin moulds, and a lot of patience, a great number of observations can be made to illustrate, extend and also in some respects to correct prevailing notions about steel ingots.

One of the objects of the following pages is to commend the use of stearine (or other low melting-point substance) for teaching purposes, and to show how it may be applied to elucidate many of the problems relating to ingots and ingot moulds. At very little expense and with perfect safety we may study the formation of pipe and secondary shrinkage cavities, the influence exerted on these by the shape and dimensions of the mould, the advantage or otherwise of feeder heads, the influence of casting temperature on the soundness and strength of the ingots, and the location and effects of segregation. If the results are cautiously interpreted stearine wax (or other low melting-point materials) may also be used to illustrate the relative advantages of the various processes suggested from time to time for casting sound ingots; and also as an aid to foundry practice, for observing the cause and effects of pulling, the value of feeder heads, and the unsoundness necessarily present in castings of certain shapes.

STEARINE.—Pure stearic acid melts at about 70° C.; but commercial stearine, which is the solid part of certain fats from which the liquid portion has been expressed, has a freezing point varying in different consignments between

50 and 54° C. It is therefore advisable to purchase at once as much stearine as will serve for the projected series of experiments and make an accurate determination once for all of its freezing point. The authors have used material which freezes sharply at 54° C., and have not observed any variation from this figure when the materials have been repeatedly remelted. An essential property of the material, when cast from a temperature of 60° C. or over, is that it shall form well-defined crystals springing from the cooling surfaces; for this purpose saponified stearine is to be recommended.

MOULDS.—These may be made from tinned sheet iron, brass, or hard-rolled copper. A very suitable size for square moulds is $1\frac{3}{8}$ inches at the top tapering out to $1\frac{5}{8}$ inches at the bottom end and 5 inches long. They should be made with a flush joint on the inside. Round and octagon moulds of similar dimensions, and flat moulds, as may be required, are made in the same way; but from time to time larger moulds may be made from plaster, sand, wood, or even millboard. For series observations the moulds should not be too large, because they would need a great deal of wax and the ingots would take a long time to cool; nor, on the other hand, too small to show clearly shrinkage and contraction cavities.

The inside of a mould may be wetted to avoid sticking, but the expedient is inadvisable if the ingot can be otherwise easily removed from the mould. A coating of French chalk may sometimes be used to prevent sticking. In very difficult cases, *i.e.* where there is no taper on the mould, the ingot may be loosened by closing the open ends and dipping the mould, for a short while only, into water at about 60° C.

MELTING.—Stearine may be melted in an ordinary laboratory beaker, or an enamelled jug, suspended or standing in a bucket or saucepanful of hot water. For melting larger quantities up to two cwts. the authors have used a gas-fired domestic copper.

An ordinary open-scale thermometer graduated in degrees centigrade may be used for measuring casting temperatures. A thermo-couple with delicate recording pyrometer adds greatly to the interest of many observations, but is a luxury which can be dispensed with.

Breaking and Cutting.—Stearine ingots can usually be split by making a sharp notch in the required direction and using either a large pocket blade or a table-knife blade as a wedge. A few sharp taps on the back edge will usually cause the cutting edge of the knife to start a deep crack. A tenon saw does very well for cutting up the ingots when a fractured surface is not required. Very thin sections can be prepared from a sawn strip by planing with a small metal-faced hand-plane. To facilitate the delicate operation of preparing transparent sections the strip of wax may be fastened on to glass with Canada balsam before planing. When planing ordinary sections a bench hook may be conveniently used, *i. e.* a strip of wood with a projection at one end to prevent it sliding over the table, and a smaller projection at the other to prevent the wax ingots from moving forward with the plane.

II

CRYSTALLINE STRUCTURE AND ITS EFFECTS

When steel or any other crystalline substance is cast into a mould the freezing commences from the inner surfaces of the mould, supposing the substance is quite fluid to begin with. Assuming the mould to be made from cast iron and its cross-section a square, then freezing in any plane occurs more rapidly at each of the four corners than elsewhere; and the crystals lying in and about the corners, in consequence of the rapid cooling, are comparatively small ones. Crystals grow also from the sides of the mould, but as their growth sideways is hindered by the adjacent crystals and their growth forward into the fluid

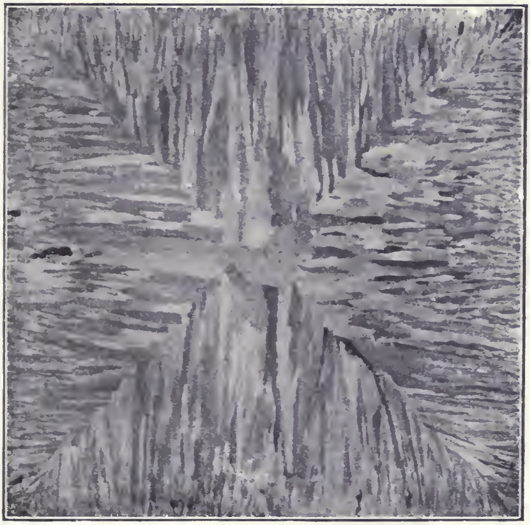

Fig. 1.—Etched section of steel ingot.

mass is less restrained, they become long and narrow in shape. The crystals growing from any one side of the ingot mould, presuming the entire mass remains fluid, meet crystals growing from the adjacent sides, and a boundary to the cooling effect of each side of the mould is visible on a polished and etched specimen, or on a fractured surface, as junction lines lying diagonally on the square. These remarks are illustrated by Fig. 1, made from a section of a chromium steel ingot.

In the same way from the bottom of the mould, which is assumed to be flat, crystals grow also upwards until they meet those crystals growing from the sides of the lower part of the mould. It is easy to realize that crystals growing thus from a surface at right angles to the rest would meet obliquely on planes which outline the form of a four-sided pyramid. In the same way the cooling effect of the atmosphere on the free upper surface would cause crystals of the same narrow kind to grow downwards until they also terminated on the surface of a four-sided pyramid, assuming, of course, that the fluid material froze quickly and was not disturbed at the upper end by shrinkage cavities or segregation effects.[1] These considerations enable us to make a sketch diagram illustrating the arrangement of crystals as seen in any longitudinal section cut parallel to a side of the mould (Fig. 2 *a*); in a cross-section cut at right angles to the axis of the ingot near the bottom (Fig. 2 *b*); and in a similar section cut nearer the middle of the ingot. The height of the pyramid at the foot of the ingot is, of course, a measure of the cooling effect of the base as compared with the sides of the mould, and this, as we shall see later, can be advantageously modified.

The diagonal lines in Figs. 1 and 2 are lines of extreme weakness; partly because they are lines of contact between crystals growing in different directions to each

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[1] For the sake of simplicity assumptions of this kind will be made from time to time without, it is hoped, misleading ourselves in any way. As Collingwood says, "Practical geometry deals with ideally perfect triangles and circles, not with crooked sticks; but it may be useful in building and engineering more than if it assumed that all wood is warped and all iron flawed."

other, and partly because they are coincident with the intersection of the plane surfaces in the ingot which at successive moments were the last to solidify. Consequently, the diagonal planes are rich in segregates and non-metallic impurities (if such, as in steel, can possibly form), they are likely to be occupied by elongated gas cavities, and are also in the position where small cavities caused by shrinkage stresses would form. The influence of segregates plus shrinkage cavities would account for a great deal of the observed weakness along the diagonal planes, and it is not possible, apart from this influence, to determine how much of the observed weakness is due only to the crystalline arrangement.

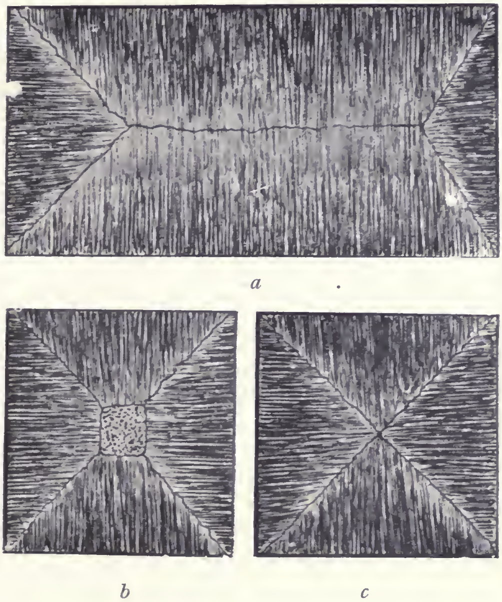

FIG. 2.—Diagram of crystal growth in ingots.

These general observations can be readily verified and illustrated by means of ingots cast from molten stearine.

> *Experiment* 1.—Cast two or three square ingots from molten stearine whose temperature is at least six or eight degrees centigrade above its freezing

point. When cold note that the ingots can be readily broken, by the hands, crosswise and exhibit an appearance on the fractured surface corresponding to Fig. 1.

Experiment 2.—Now put two notches about one inch apart, by means of a pocket knife, into the side of an ingot, at right angles to its axis, and break off the slab. Saw the slab into two halves, then, taking one of them in the hand, press the knife edge into its side in the direction of the saw cut, and note that a crack travels easily between the crystals but comes to a dead stop against the diagonal face; this face has a dull matted appearance quite unlike the ones made up of long shining crystals. Next take a similar slab and chamfer off one of the corners; into the central white line thus exposed press the edge of the knife, and note that a crack runs at once to the centre of the slab along a diagonal line. In the same way, by pressing the knife edge into the centre of one of the sides of an ingot it splits easily and exposes a fracture like Fig. *2 a*.

Experiment 3.—Break an ingot across about one inch from the bottom. Then press the edge of a knife into one of the flat sides of the piece broken off, and in doing so twist it slightly upwards. Do this on each side in turn, and repeat the operation. At first the layers broken off extend to the centre and the upper surface remains approximately flat; but after a time, if care be taken that the knife does not penetrate very far below the surface, a small peak appears in the centre, and grows larger as the layers are split off and break away when the fracture reaches the surface of the peak. Very soon the wax assumes the form shown in Fig. 3, and finally there remains a four-sided pyramid.

It may be seen from these experiments that all substances which crystallize like stearine wax—and steel is one of them—develop on cooling from the fluid state in a square mould a number of planes of weakness. An orderly arrangement of the elongated crystals enables the ingot to be split at right angles to either face of the ingot mould and either parallel to or at right angles to the axis of the ingot. In addition to this weakness there are others, more serious in their effects on material which has to be rolled or forged, which depend on the shape of the mould. In a square ingot the planes of weakness originate at the corners of the mould and divide the ingot into four triangular prisms whose bases are the sides of a quadrilateral pyramid which grows from the bottom of the mould. It would be distinctly worth while for the student to fix these facts in his mind by making a wooden model which can be taken to pieces, and on whose inner surfaces he may make a drawing of the defects which we shall find later are located there.

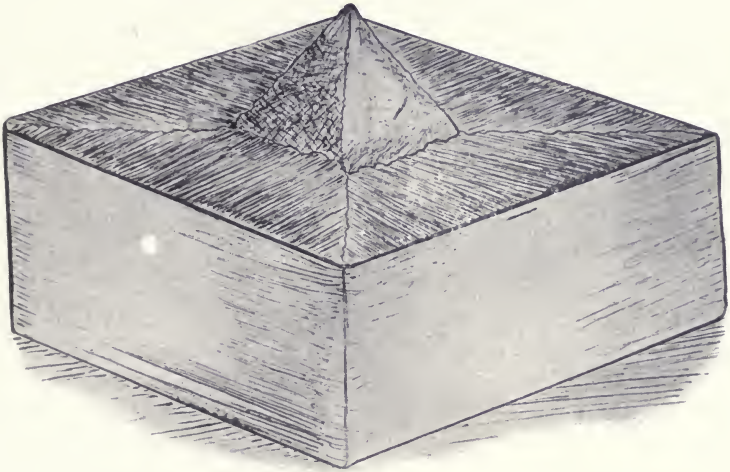

FIG. 3.—Partly exposed base pyramid in wax ingot.

In a round ingot the crystals growing from the bottom of the mould are formed into a cone, and in an octagon ingot they form an eight-sided pyramid. In each case the base pyramid is longer or shorter, depending on the cooling effect of the bottom in relation to the cooling effect of the sides; but generally the base exerts its full effect, because it remains throughout in direct contact with the freezing ingot, whereas the sides of the ingot, soon after solidifying, leave the mould and are thereby partly insulated from its cooling effect by a gaseous envelope. In many cases, however, the pyramid may be separated intact, by the method already described, and it is instructive to take ingots to pieces, as it were, in order to observe the effects of segregation and shrinkage cavities localized on their interior surfaces.

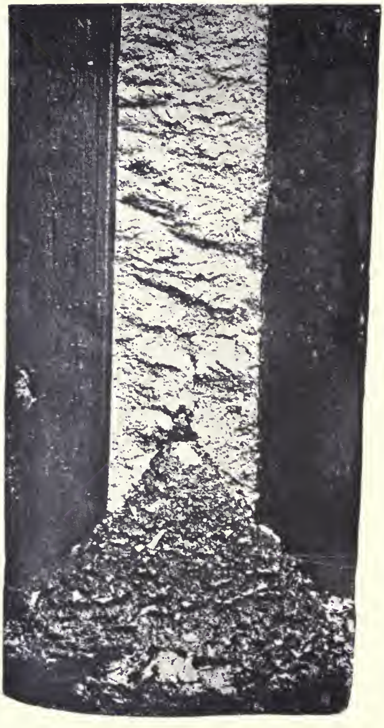

Fig. 4.—Exposed pyramid in base of steel ingot.

Those engaged in making ingots for the manufacture of ordnance are aware that for some years it was usual in many works to cut discs from the ends of ingots and after polishing to etch them. On many such discs the etching revealed a ring of white spots which were really ferrite areas segregated about slag globules. The nearer the base the disc was cut the larger the ring of white spots, which was quite natural on the assumption that the white spots represented the outline of a section cut through the base pyramid. Though the white ring appeared frequently during the few years such observations were being made, no steel-maker, within our experience, would admit that a well-formed cone, such as could be dislodged from a stearine ingot (see Fig. 3), could ever exist in a steel ingot. Eventually, however, a steel ingot weighing about eight cwts. was cast in such a way that it was held fast at each extreme end. When cooled under such conditions the ingot cracked across the weakest part, and produced the cleanly separated cone shown in Fig. 4.

The growth of elongated crystals originating at the surface of an ingot mould depends on circumstances which appear to be somewhat contradictory, *i. e.* their formation is favoured sometimes by slow cooling and sometimes by rapid cooling. So long as the fluid in the interior of the partly solidified ingot remains quite liquid the crystals already growing from the side of the mould increase in length as the temperature of the liquid about their extreme ends falls to freezing point. The act of freezing liberates heat which is either stored up in the fluid or dissipated, via the solid crystals, through the sides of the ingot mould. If the crystals are bad conductors of heat the cooling is necessarily slow whatever the properties of the ingot mould may be, and the fluid in the centre of the ingot remains clear almost to the last drop. Under these circumstances "quick" cooling is impossible, except by stirring, or otherwise by mechanical means hastening the setting, and the crystals grow with their greatest length lying between the sides and centre of the mould.

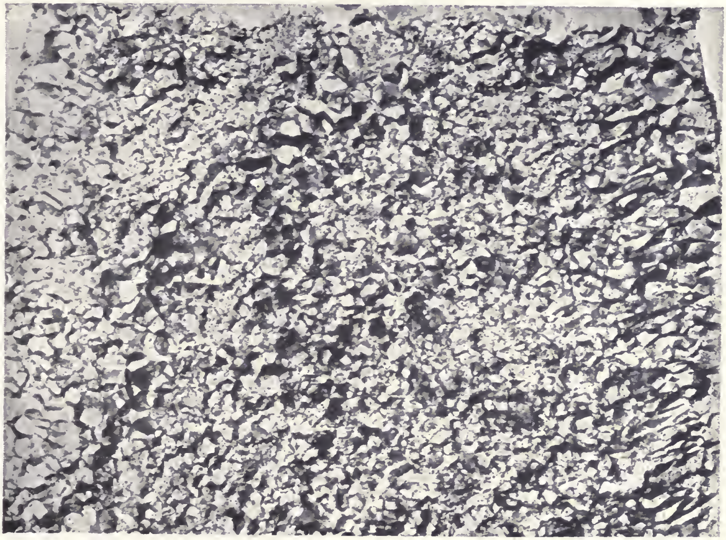

FIG. 5.—Crystals of steel formed by slow cooling.

But if the crystals themselves are good conductors of heat, then the heat liberated as they form and also heat from the fluid interior is rapidly dissipated through them.

In this way the temperature of a large volume of fluid may reach its freezing point in many places almost simultaneously before the crystals growing from the sides can extend to the centre, and thus the interior of an ingot would consist of crystals which had grown from independent centres and were developed equally in all directions.

Of crystallizable substances, therefore, which are clearly liquid when cast, those that are very poor conductors of heat will form crystals of the same kind from the surface inwards if allowed to cool undisturbed. But steel, on the other hand, which is a good conductor of heat, will form crystals of the same kind from surface to centre of the ingot only if the cooling takes place very quickly or very slowly. In the former case the crystals grow rapidly and extend themselves into the clear liquid as quickly as its temperature falls to freezing point—the result being thin crystals like those seen in Fig. 1. In the latter case, however, the cooling is so slow that, owing to its high thermal conductivity, the temperature of the fluid mass

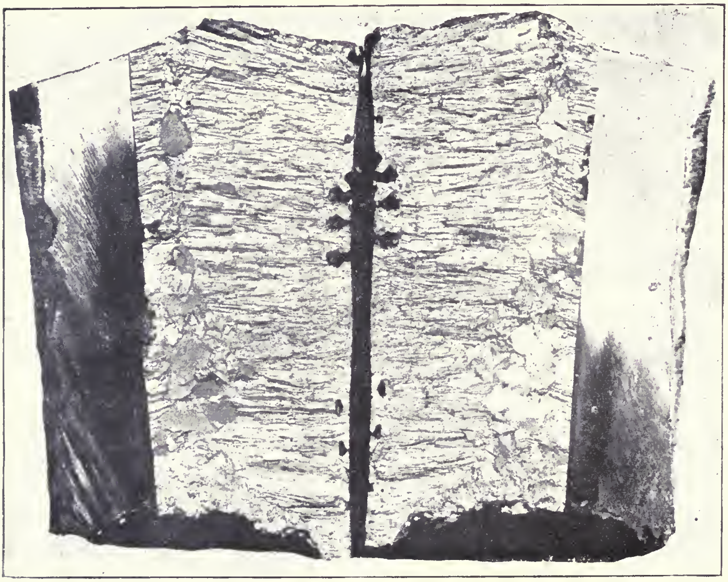

FIG. 6.—Needle and equiaxial crystals in small ingot.

is practically uniform throughout, and a crystal is as likely to start growing in one place as in another, the result being irregular and approximately equiaxial crystals like those seen in Fig. 5.

The considerations in these last two paragraphs are closely bound up with the question of casting temperatures, which will be discussed later. But meanwhile it may be said that the elongated crystals occur in steel ingots cast in chill moulds of narrow section and the equiaxial crystals in dry sand castings, and also generally in large ingots cast in chill moulds. Obviously there exists a great number of instances where both kinds of crystals occur in the same ingot, as seen in Figs. 6 and 78, the exterior crystals being needle-shaped and the interior equiaxial.

III

SHRINKAGE AND CONTRACTION CAVITIES

If we imagine an ingot mould filled with fluid material that could be cooled with perfect uniformity down to its freezing point we should find that the level of the fluid would gradually sink as the fluid cooled and shrank. If at this point the fluid were to solidify instantaneously without change of volume we should have a solid ingot. But neither stearine nor steel behave in this manner, and cavities, due both to shrinkage of the fluid and contraction of the solid material, exert a great influence on the economic production of ingots and have to be reckoned with.

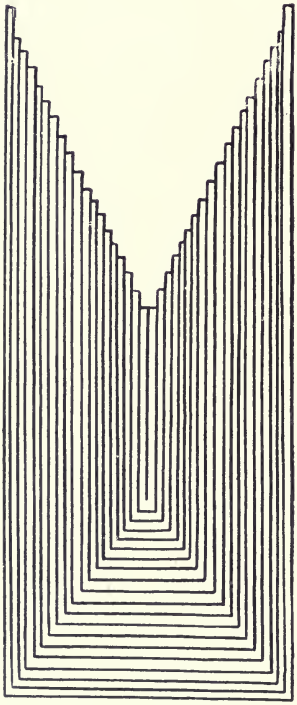

Fig. 7.—Diagram to illustrate freezing in straight moulds.

The formation of the main shrinkage cavity, which generally opens to the air and exists about the axis of the ingot, can be easily understood. It is known as a " pipe " or " piping," and is due to the gradual shrinkage during solidification of the metal in successive layers towards the inside.

An ingot just cast consists of a thin layer of solid wax (or metal) with a fluid interior whose temperature is practically the casting temperature. The outside length of the ingot has been fixed by the thin solid envelope extending downwards from the highest level of the molten wax in the mould. After a little while the solid envelope has thickened, say, by a millimetre, but before that occurs the fluid wax has cooled, and, owing to shrinkage, does not now stand at the same level. This has been represented in Fig. 7 by a step down between the first and second millimetre in thickness of the freezing envelope. This process may be thought of as repeating itself in successive and distinct stages as long as any fluid remains in the interior of the ingot, and, as a result, the central cavity or pipe would be as represented in Fig. 7. As a matter of fact, Fig. 7 does represent the general outline of all central pipes in ingots cast in moulds having parallel sides. It differs from an actual pipe only because the thickening of the solid envelope is a continuous process and not an intermittent one; and also because the contraction of the solid envelope and the cooling effect of the atmosphere on the upper surface of the ingot must also be taken into account.

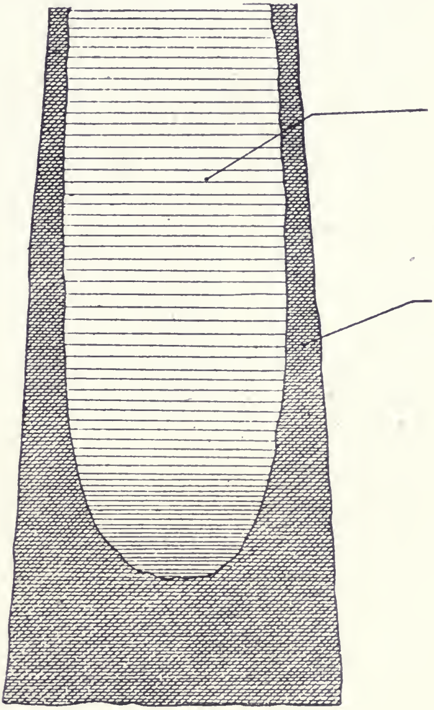

Fig. 8.—Usual representation of freezing ingot.

That the freezing of an ingot takes place by continuous thickening of the solid envelope in planes parallel to the cooling surfaces of the mould is not unanimously admitted. The illustration given by Harmet

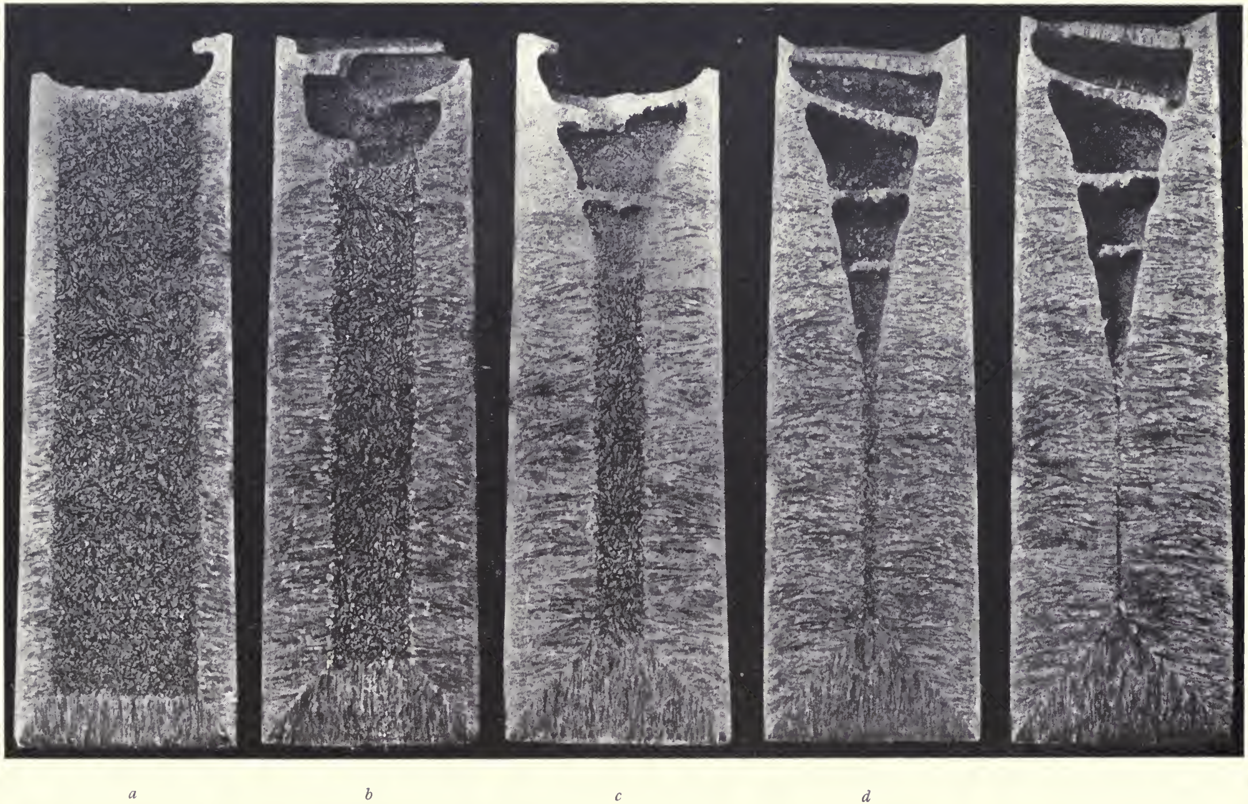

FIG. 9.—To illustrate symmetrical freezing of ingots.

(Fig. 8)[1] has been reproduced and approved as a representation of the freezing of steel ingots. It is, however, so far as the authors' observations go, a misleading representation of steel ingots and an inaccurate representation of the freezing of any crystalline substance, metallic or otherwise. A few experiments with stearine will help us to form a correct impression.

> *Experiment* 4.—Cast a series of wax ingots simultaneously from, say, 65° C. in square moulds, in all respects identical and widely spaced apart so that each cools freely. Pierce the top and invert one of them after fifteen minutes, and a further one after each additional fifteen minutes. We are then left with a series of shells of gradually increasing thickness, but in each case the shape of the cavity out of which the fluid wax has been emptied corresponds to that made by the inner surfaces of the mould.
>
> *Experiment* 5.—The same fact can be demonstrated in a more elegant manner by gradually planing down a single ingot parallel to one of its faces. After a few strokes with the plane the sectioned surface exhibits an envelope of crystals lying in the plane of the section and others lying at right angles to it. The thickness of the envelope increases as the planing proceeds just as it did when the ingot was freezing, but it remains quite symmetrical in all parts, as may be seen from the series of photographs reproduced in Fig. 9. Also it thickens parallel to the cooling surfaces and forms where the bottom and sides intersect a sharp corner and not the greatly thickened curve seen in Fig. 8.

That steel behaves in a practically similar manner is known to most furnacemen who have opportunities now and again of seeing ingots broken up that have been upset or otherwise accidentally and completely bled. By way of illustration we reproduce Fig. 10, representing a crucible steel ingot that was intentionally inverted; and

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[1] *Jour. Iron and Steel Inst.*, 1902, 11, 148.

Fig. 11, which represents one much larger ingot from a series prepared by Talbot.[1] When freezing takes place *in* the fluid mass and not by direct thickening of the walls the above conditions do not apply.

To avoid confusion we have confined our attention in Figs. 9 and 10 to the lower part of the ingots, because the cooling of the upper surfaces from the formation of an incipient pipe onwards is likely to be erratic. It is easy, however, to follow the general effects of atmospheric cooling and liquid shrinkage which mainly influence the shape and dimensions of the pipe in ingots cast from the same temperature in similar moulds.

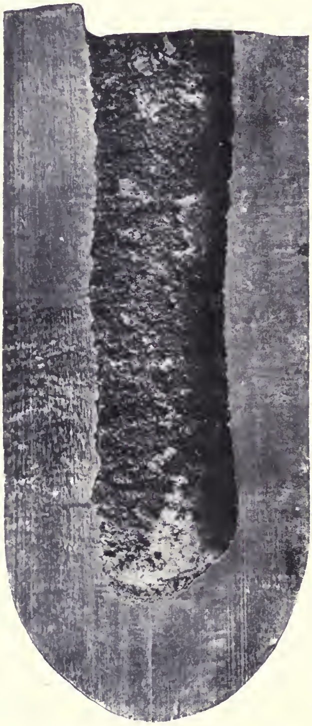

FIG. 10.—Partly fluid crucible ingot intentionally inverted.

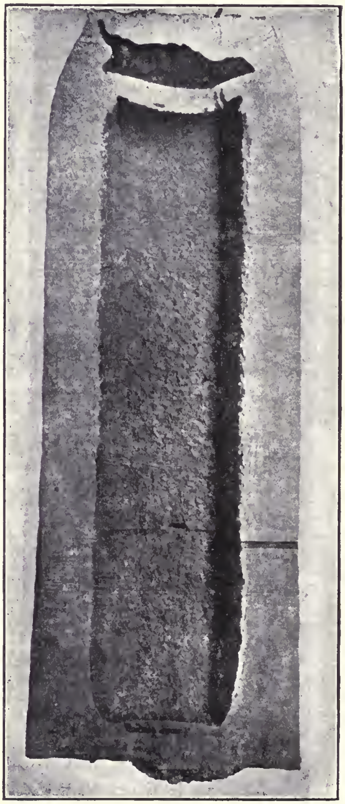

FIG. 11.—Open-hearth ingot intentionally bled.

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[1] *Jour. Iron and Steel Inst.*, 1913, 1, 30.

The upper surface of a wax ingot, immediately it has been cast into a metal mould, is convex. Shortly afterwards a film of solid wax forms on it, and then or some time earlier, depending on the casting temperature, the surface becomes concave. As the fluid wax sinks the concavity of the surface film increases; but the surface of the fluid beneath it is approximately flat, and ultimately the film and the fluid are in contact at one spot only. Meanwhile, the sinking of the fluid wax has left a cavity between its level surface and the under side of the concave film which contains little or no air. Hence a moment arrives, before the fluid loses contact with the lowest part of the film, when the pressure of the air breaks through the soft apex of the concave and causes a small bubble to push back the fluid wax and rise into the vacuous space beneath the outer edge of the film. This process is visibly in operation as long as the lowest end of the film and the fluid are in contact. When the fluid wax has sunk entirely out of contact with the film then its level surface may be regarded as the original surface of a new ingot narrowed, of course, by the thickening of the ingot walls which meanwhile has taken place.

The solidified films thus formed are sometimes spoken of as bridges,[1] and they are almost invariably perforated. The air entering through the perforation acts as a cooling medium and aids the formation of a second film on the surface of the fluid wax. This second film undergoes the same changes in shape as the one first formed, and similarly a third one and a fourth one is formed, each narrower than its predecessor, until the amount of fluid wax is exhausted. Fig. 9 shows examples of the formed bridges here described.

If it should happen that a bridge is not perforated,

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[1] Howe and Stoughton (*Amer. Inst. Min. Eng.*, April 1907) speak of these as "surface tension bridges," and ascribe their formation to the presence, in the stearine wax used, of copper oleate. But as bridges of a like kind are formed in ingots which do not contain copper oleate their explanation is not convincing. Howe and Stoughton also overlook entirely the influence of casting temperature and ascribe some effects to other causes, which, according to their photographic illustrations, are obviously due to variation in the temperatures at which the wax was cast.

as may be the case when the rate of surface cooling and the temperature of the fluid wax are favourable to the formation of films strong enough to resist the air pressure, then the fluid contents of the ingots are hermetically sealed. Under these conditions the surface of the fluid cools very slowly and may sink and become narrowed a great deal before a further bridge can form; or the bridges formed are very thin or perhaps no further bridge whatever can form before the wax is frozen entirely.

Bridges do not form by any means so readily in steel as they do in wax. The steel is stronger and a much better conductor of heat, and, consequently, when the upper surface of the molten steel freezes over it is relatively thicker and much stronger, and does not therefore become concave to anything like the same extent nor necessarily perforated; and perforation, as we have seen, is extremely favourable to the formation of a series of bridges. It is not unthinkable that bridges might form in small steel ingots, but the authors cannot recall having ever seen them; on the contrary, the setting and shrinkage of a three-inch steel ingot cast into a chill mould takes place so quickly that the upper central portion is formed into a pipe almost before its surface can stiffen into a solid layer. Bridges, however, form in large ingots and in the feeders and risers of sand castings, but the opportunities of seeing very large ingots cut up longitudinally are very rare. When bridges do occur in steel they are flatter than those seen in wax, because they are stronger and do not sag so easily, but otherwise their formation is favoured by circumstances precisely similar to those described in regard to wax ingots.

The influence exerted by size and shape of ingot mould on the position and dimensions of the pipe will be discussed later, but it is desirable at this stage to consider a feature exhibited by many ingots cast in straight-sided moulds as distinct from taper moulds used with either the narrow or wide end up.

When sufficiently removed from the cooling influence of the closed bottom and the open top of an ingot mould the freezing of any horizontal section of the fluid ingot may be regarded as due to loss of heat through the sides of the mould. When the mould has the same cross-sectional dimensions from top to bottom the crystals growing from the sides in any one plane are as likely to meet in the centre as soon as those growing in any other plane. Now, in both commercial stearine wax and in steel a plane of the material may be all but rigid, quite too rigid at the centre to flow downwards, but requiring still to contract over its entire area. The material next the ingot mould is coldest and most rigid, and if the unavoidable contraction cannot pull the flat outer surfaces inwards the assumed plane must split at the centre where the material, all but set, offers little resistance. The result is a small central cavity with no material above it fluid enough to flow downwards, and the net effect in an ingot of this kind is a number of cavities, roughly spherical in shape, lying in the axis of the ingot. For shrinkage or contraction cavities of this kind an increased length or breadth of feeder head is a doubtful remedy, as in actual practice such cavities occur always in small crucible ingots cast into straight-sided moulds and fed by steel kept fluid in a hot dozzle.

To these two kinds of cavities, viz. the pipe proper and a continuation of the pipe that exhibits itself as a kind of axial sponginess, which, when elongated, may be regarded as a secondary pipe, we must add also cavities, axial or otherwise, arising from the contraction of the hot solid ingot. Such cavities occur in wax ingots independent of their shape, and should perhaps be described as contraction rather than shrinkage cavities.

An ingot which has quite set and is still hot contracts in volume on cooling; but as the outer surface of the ingot is hard and will not yield much the stress of contraction will be satisfied, wholly or partly, by the formation of internal cracks or cavities in those positions where the resistance is least. We know already that in a solid ingot there are certain planes of weakness, due to the arrangement of crystals, which converge from the corners of the mould towards the axis of the ingot. An ingot is, therefore, easily split along its axis by tensional forces acting at right angles to its length; and it is further induced to yield to such forces by the fact that the ingot is hotter in the centre and weaker also on that account. This explanation accounts equally well for axial cavities and cracks formed just before or just after complete solidification. As, however, the contraction of the hot solid wax takes place continuously in those parts of the ingot already solidified, and does not wait until the entire ingot becomes solid, so we may expect to find contraction cavities which were formed whilst the centre of the ingot was still fluid, and in that case they would not, of course, be formed at the centre.

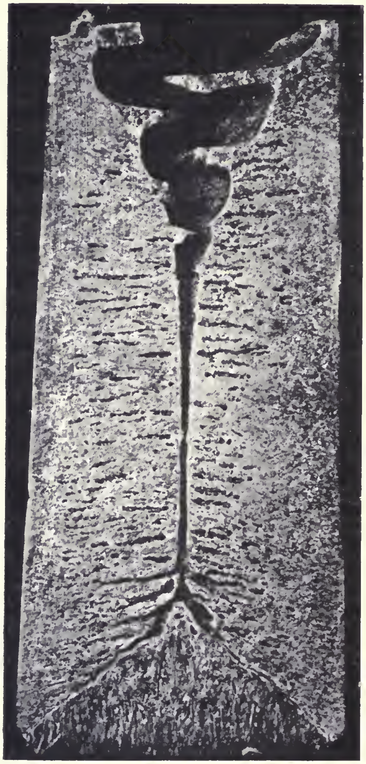

FIG. 12.—Diagonal contraction cavities.

From the moment that a solid envelope is formed about the liquid ingot the crystals growing from the sides of the mould form planes of weakness where they meet each other obliquely (see Fig. 2 *c*), and it is along these planes that contraction cavities are located. They are easily seen when a wax ingot is split diagonally along its length, and they can be reproduced photographically, as in Fig. 12, after planing the ingot down until a diagonal section is exposed. These cavities all converge to the centre of the ingot, and appear to depend on and originate from an axial cavity That they are not developed in that order, but begin to form whilst the centre of the ingot is quite fluid, may be shown by a short series of experiments with wax ingots.

Experiment 6.—Cast two or three square ingots from a temperature 15–20° C. above the freezing point of the wax. Chamfer off two opposite corners and split the ingot diagonally, after placing the cutting edge of a knife on the white line in the middle of the chamfered surface, by striking the back edge of the knife one or two sharp blows. Notice the occurrence of lateral cavities as indicated by Fig. 12.

Experiment 7.—Split a similar ingot through the centre but along a plane parallel to two opposite sides of the mould, and note small axial cavities. The lateral cavities are not visible, but their existence can be demonstrated by probing with a pin obliquely through the axial cavities. Note also that contraction cavities are visible along the faces of the base pyramid (see Fig. 33).

Experiment 8.—Cast three or four ingots in all respects like those used already in experiments Nos. 6 and 7, but pierce the upper end and pour out the fluid contents after intervals of ten, twenty and thirty minutes, counting from the time of casting. Split these ingots in turn like the previous ones, or better still saw them longitudinally near to but not quite through opposite corners, then plane the sawn surfaces, quite up to the corners, and note that the lateral cavities had begun to form whilst the centre of the ingot was still fluid.

We see, therefore, that ends of crystals pull apart as masses of them contract. It is, in fact, possible at times, by means of a good hand lens, to see in the contraction cavities sharp faces of crystals which have grown up to each other and separated later. The cavities thus formed are protected by an inner layer of unbroken wax from contact with the central fluid, and this protection is itself broken later, but meanwhile a new layer of solid wax has grown up in front of it. In this way the lateral contraction cavities are protected and extended until they reach the centre and no more fluid wax remains.

There are several reasons why contraction cavities should lie along those planes extending from the corners to the centre of a square ingot. In the first place, the planes are formed by the intersection of surfaces of the ingot which at successive moments were the last to solidify; and about the angle thus formed the contraction stresses are localized, with the consequent danger so often exhibited in the hardening of steel tools cut with sharp-cornered keyways, etc. Then any absorbed gases liberated at the moment of setting and impurities likely to segregate are also to be found in abnormal amounts along these planes. It needs, therefore, nothing but a favourable concourse of circumstances to produce large cavities or even extended cracks; and in average cases it needs very little force in addition to the ordinary contraction stresses to cause rupture (see Fig. 13).

FIG. 13.—Rupture along diagonal plane of steel ingot. × 25.

But, in addition to cavities that are obvious to the naked eye, it is not unusual in steel ingots to find cracks

FIG. 14.—Fig. 1 enlarged to show crack between crystals.

FIG. 15.—Cracked surfaces corroded by pickling.

running between the crystals at right angles to the surfaces of the ingot mould. These cracks are discoverable by direct microscopic observation, as in Fig. 14, which is an enlargement of part of Fig. 1; or indirectly by making use of a corrosion effect.

Cracks may be revealed in large numbers by immersing a disc of steel in a ten per cent. solution of hydrochloric acid. The acid attacks the metal most vigorously along the edges of any existing crack, and eventually the crack widens into a visible cavity. This effect is shown in Fig. 15, which represents a disc cut from a four-inch square ingot; it will be noted that the length of the cavities lies in the same direction as the length of the crystals between which they occur. Cavities of a similar kind which originate from segregated areas may also be developed by extended pickling; but there are decisive means of distinguishing one kind from the other, and confusion is not likely to arise if careful observation be made of the scattered distribution of the former compared with the occurrence in groups of the latter.

Fig. 16.—Radial crack in 30-ton steel billet.

Radial cracks may occur in steel ingots which do not exhibit elongated crystals on a fractured surface. When a disc cut from a large steel ingot, weighing, say, forty or sixty tons, or from a circular billet which has been forged from such an ingot, is polished and etched with a very dilute solution of nitric acid in alcohol, the intercrystalline cracks are located by the evolution of small gaseous bubbles from them. That the gaseous bubbles may escape more easily it is advisable to arrange the disc with the polished face in a vertical position and wash it over by means of a broad camel-hair brush with the etching fluid; small strings of bubbles then run with the solution down the face of the disc from one or two or maybe from a score or more cracks. Fig. 16 represents the radial kind of crack we are speaking of as it existed in a thirty-inch billet. The light-coloured spot is a miniature ghost, and

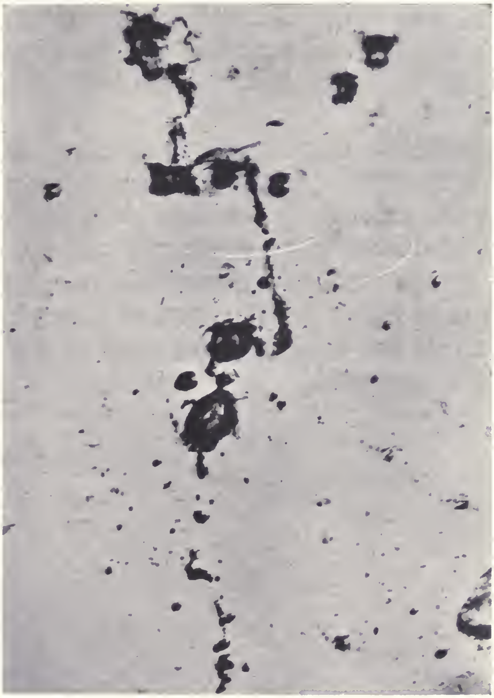

FIG. 17.—Easy passage of radial crack between slag occlusions.

when these occur in groups the crack will generally pass from one to the other (see Fig. 17) as the small slag globule or streak of slag, around which the ghost forms, has already broken the continuity of the metal. If the material in which the cracks occur is not weldable, then it is also not forgable and will crumble under the hammer. This explains why some alloy steel ingots may not be forged, whereas others of the same composition, but melted and cast under different conditions, forge fairly well. The number and magnitude of the cracks would obviously be increased if the steel had air-hardening properties.

The objectional features of contraction cracks are emphasized by segregation or slag occlusions; and these as well as the amount of hot work done in the forging determine whether or not a crack will weld up.

Radial cracks and the occurrence of many other defects in steel ingots are favoured or otherwise by the temperature of the fluid steel (or wax) at the moment it is cast into the mould.

IV

CASTING TEMPERATURES

When a crucible steel ingot breaks with a needle-like fracture resembling Fig. 2 *c* it is said to be "scorched"; and scorching is said to be due to the molten steel having "had too much fire." A furnaceman does not generally commit himself by saying whether the steel has been for too long a time in the furnace or at too high a temperature. He may not know; but he does know a scorched ingot can be broken across with remarkable ease, and that he will very likely get into trouble if he makes many such ingots. Badly scorched ingots used formerly to be broken up and remelted; under the present method of topping ingots the extent of the scorching is not so fully exposed, and many suspects are sent to the forge and mill.

Scorched ingots are objectionable only on account of their fragility due to arrangement of the crystals in definite directions and the extended contraction cavities which may arise. This is, of course, a serious objection, because unless the scorched ingot, after careful reheating, is also very carefully, and, to begin with, very gently forged, the weakness between the well-developed crystals will cause cracks to form at the corners of the forged bar. But, apart from obvious defects like this, the quality of the steel is neither better nor worse for having shown the scorched appearance in the ingot.

However intimate one's knowledge of a fluid steel may be, it is not easy to say beforehand whether an ingot produced from it will be scorched or not.[1] The determining

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[1] Before the use of aluminium as a deoxidizer became general a good crucible melter whose charges consisted mainly of Swedish iron was able to tell beforehand whether a pot of steel presented to him would produce a scorched ingot or not if cast immediately into a three-inch mould. The charge was necessarily low in manganese and had been raised well above its melting point to "kill" it; if therefore the "killing" heat had not dissipated it was very likely to make a scorched ingot.

conditions are casting temperature, rate of casting, material and mass of ingot mould and its cross-sectional area. Fluid steel cast into an ingot mould may produce an ingot scorched to the centre, whereas the same steel cast into a similar but larger mould may show little or no scorch. If the steel is cast "cold" then the smallest ingots made industrially do not show scorch; and incipient freezing is one of the points carefully watched for by the teemer before he balances the pot on his knee, and controlled by him during the act of casting.[1]

The general conditions affecting the occurrence of scorching are mentioned on p. 11. They apply both to stearine wax and to steel, and though they may not be exactly summarized in brief sentences, it may be said that if an ingot is made sufficiently large or cast slowly enough it will not be scorched whatever the casting temperature may be; also, if it be cooled slowly enough it will not be scorched whatever the size of the ingot or the casting temperature may be. And, consequently, though a high casting temperature is favourable to a scorched appearance, it may, if very high, act unfavourably by warming up the mould and thereby delaying the rate of cooling. We shall shortly see this diverse behaviour reflected in the mechanical properties of ingots cast from successively higher temperatures.

Three inches square steel ingots which are badly scorched are so tender that they are sometimes accidentally broken by loading into or unloading from a cart, whereas an ingot of the same composition when it has been cast "cold" is very difficult to break. Between these two extremes lie ingots which can be broken more or less easily for reasons due to, but not generally associated

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[1] According to Carpenter and Keeling (*Journ. Iron and Steel Inst.* 1904, 1, 224) a pure iron-carbon alloy containing ·9 per cent. carbon freezes at 1443° C., and one containing ·1 per cent. carbon at 1504° C. The milder steel can be just melted without any appreciable margin of temperature in a coke-fired crucible furnace, and in the same furnace there would be no difficulty in scorching the harder steel. It may therefore be assumed that the temperature necessary to produce scorch in a three-inch ingot made from ·9 per cent. carbon steel is considerably less than 100° C. above the melting point of the steel.

with, the temperatures at which the respective ingots were cast.

A variation in the strength of wax ingots lies broadly along the same lines. The strongest possible wax ingot is the one cast when the stearine has reached its freezing point and begun to crystallize on the surface. The ingots produced from such material do not possess the needle-like structure exhibited by Fig. 2, and they have roughened outer surfaces just like steel ingots have when the metal is cast cold. The appearance of an outer surface of a "cold cast" wax ingot is illustrated by Fig. 18.

The characteristic appearance of both the inside and outside of "cold cast" ingots is understandable after seeing a wax ingot cast into a glass mould. First as to the outside. As the wax, per assumption, has already reached its freezing temperature it solidifies immediately on contact with the bottom and sides of the mould. It freezes also over the free upper surface into a crust of crystals, and as more fluid wax is added the liquid level and solid crust rise together, the latter gradually increasing in thickness. But the crystal crust has solidified in a piece with the sides of the ingot, and as the fluid wax rises it pushes the crust upwards most effectively where it is least restricted, *i. e.* in the centre. The crust therefore becomes increasingly convex until, broken by upward pressure of the fluid wax, a new surface is formed. In the act of forming a new surface the fluid wax strikes the glass mould and is frozen before it can fill up the

FIG. 18.—Appearance of surface of "cold cast" ingot.

lowest part of the convexity, and hence the surface of the stripped ingot is a series of rings where it has been in contact with the mould and a series of depressions lying alternately between them where it has not been in contact with the mould.

Pieces of the broken crystalline crust are washed into the fluid material and form independent centres of crystallization in both wax and steel. But in steel they form also blow-holes, due to gas liberation promoted by their oxidized surfaces, and also irregular lines of weakness which may not weld up completely in the subsequent forging.

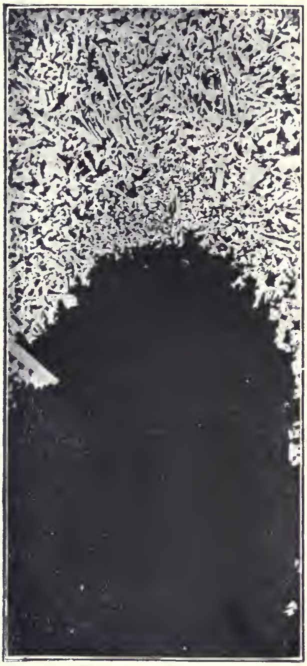

FIG. 19. — Antimony crystals floated to surface of partly solidified alloy.

The internal structure of a " cold cast " ingot is unlike that of a " hot cast " ingot, because in the former case the centres of crystallization are dispersed throughout the entire ingot instead of being confined to the inner surfaces of the mould or the solid metal envelope already formed from it. The crystals therefore do not grow in planes, as it were, but in all directions, and form spherical clusters floating in the fluid like seed pods of a dandelion floating in still air. The clusters of solid crystals are heavier than the fluid wax (or steel) and tend to sink to the bottom of the mould; if therefore any well-defined acicular crystals grow into prominence they are likely to be found in the upper part of the ingot which may have been occupied by fluid and fairly clear metal when the solidification is nearing completion.

We have said that an ingot freezes by a gradual and uniform thickening of its solid walls in planes approximately parallel to the inner surfaces of the ingot mould (see Fig. 9). But this statement applies only when the conditions are such that the interior fluid is a perfect liquid. If free crystals form in the liquid independent of the cooling effect of the mould they will rise, as in antimony-lead alloys (see Fig. 19), if they are lighter, or sink, as in wax and steel, if they are heavier than the mother liquid. In the latter case the base of the ingot will be thicker, at any moment during solidification, than can be accounted for by direct cooling effects in those positions.

The presence of separated crystals in wax ingots can be demonstrated in either of two ways. First, by sawing strips, say, from a square ingot, parallel to one of the sides and afterwards planing these as thin as possible. When held up to the light such strips are practically opaque on the edges, where the crystals lie parallel to the sawn surfaces, whilst in the centre, where the crystals lie end on, they are translucent. The opaque and the translucent parts are divided by a sharp straight line; but in the latter any irregular dark patches which may be visible are due to groups of crystals that have formed freely in the fluid and sunk to rest on the solid bottom or sides. By cutting a series of strips it is possible in this way to determine how thick the walls of the ingot had become before the fluid centre began to crystallize on its own account.

The second method consists of emptying out the fluid portion either by inverting the ingot or by passing a hot rod through the base of the ingot. By the first-named procedure the crystal groups are disturbed and are found in the split shell more on one side than the other; by the last-named procedure some of the fluid solidifies in passing through the thick cooler base of the ingot. But in either case the information sought for can be easily interpreted apart from these interferences, as may be seen by reference to Fig. 20, which represents wax ingots cast from 55° C. and bled through the top end after varying lengths of time.

If a small quantity of soluble colouring matter be added to the wax, then the crystals lying in different directions exhibit different shades of colour and can be distinguished by this means. On planing the flat surface of an ingot the crystals lying parallel and at right angles to the face are visible as in Fig. 9; but the crystals which fall later from the fluid wax on to the inner surfaces of the solidified shell take up no particular direction, and when the plane cuts through them they are at once distinguishable by their lighter colour (see Fig. 21). In this way the depth of scorch in a wax ingot can be determined without breaking it, but if it be broken subsequently it will be found that the scorched appearance extends to that point where the deposition of crystals by gravity on the inner sides of the solid shell began.

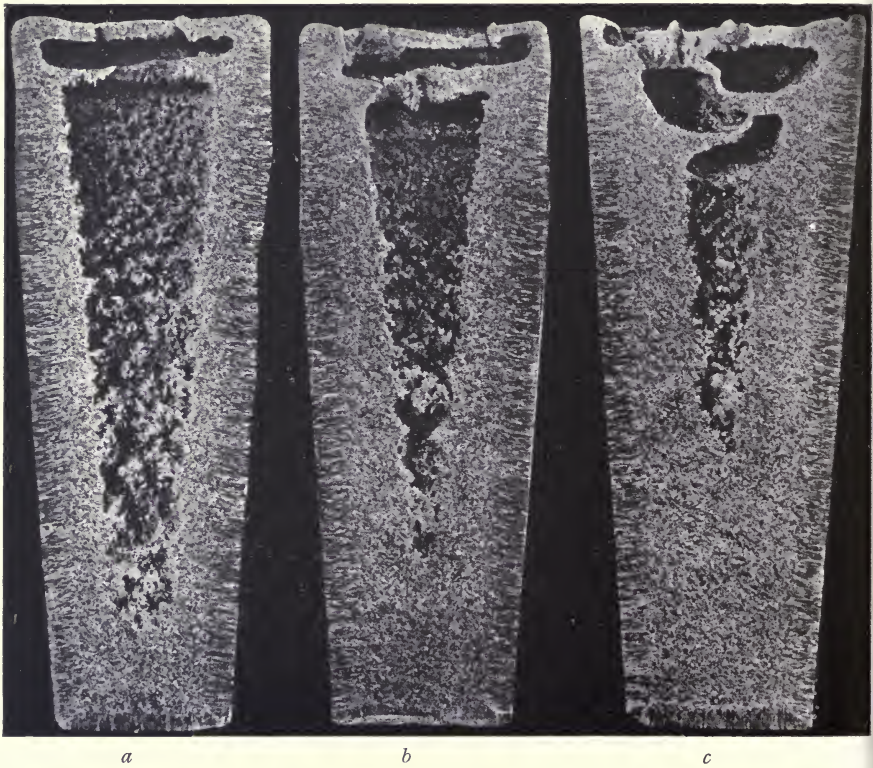
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FIG. 20.—Crystals deposited upon partly solidified ingots.

The formation of free crystals[1] in the fluid material adds considerably to the mechanical strength of an ingot by interfering with the growth of elongated crystals at right angles to the sides of the ingot mould, *i. e.* by suppressing the scorched appearance. This is apparent in wax ingots on attempting to split them diagonally, and particularly in attempting to remove the base pyramid as described on p. 8. It is apparent also in small steel ingots by the greater effort required to top them. In large steel ingots it is also apparent by the very marked difference in carbon content between the top and bottom of the ingot; in fact, it is impossible to cast a very large ingot of, say, thirty tons or over from the same ladle and maintain, apart from localized segregation, a uniform amount of carbon throughout its length. The steel-maker producing very large ingots has, therefore, to compromise between two evils, *i. e.* he may either cast hot and emphasize local segregations, shrinkage cavities and contraction cracks, or cast cold and widen the difference in composition between the top and bottom of the ingot. The crystals first formed in fluid steel contain, of course, less carbon than the remaining mother liquor, and this explains why the settling of the crystals to the bottom of the ingot widens the variation in composition.

FIG. 21.—Deposited free crystals in solid wax ingot.

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[1] Free crystals form more readily in wax which contains suspended impurities.

It has been said that the lower amount of carbon near the bottom of large ingots is caused by crystal groups growing from the solid sides being broken off and settling to the bottom; but that explanation seems hardly to account for the observed facts. Groups of crystals do undoubtedly grow from the sides near the top end of large ingots; and when the general level of the fluid metal falls, owing to shrinkage of the mass, they are left with a perfection of outline and detail which is quite beautiful (see Fig. 22). But groups of such crystals do not form in numbers large enough to account for the great weight of material deficient in carbon at the base of an ingot; and such groups of crystals could be detached from the sides on which they grow only by forces greater than can conceivably be operative inside an ingot which is allowed to cool free from outside disturbances. Moreover, if the groups of large crystals were dislodged from the upper part of the sides and fell to the bottom they could certainly not be remelted by the surrounding metal, and would, therefore, be discoverable by polishing and etching discs cut from the bottom end of the ingot. The authors cannot learn from others who have had special opportunities of making observations that such crystal forms are seen in etched discs, nor have they themselves ever seen them. It may therefore be assumed, for the time being, at any rate, that in steel ingots, as in those made from stearine, the unattached crystals formed in the liquor sink, owing to their greater density, and account for the low carbon percentage in the bottom part of large steel ingots.

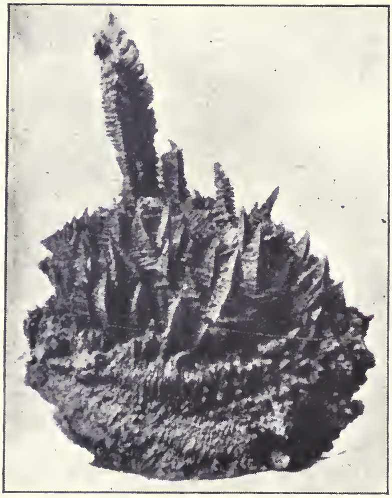

Fig. 22.—Group of mild steel crystals (Krupp).

No special effort is required to show that the general effects of a high casting temperature are harmful. We may omit for the present the smooth appearance of the outer skin of an ingot, which is important in its way, and overlook the efforts of the foundry-man to sharply reproduce the outline of an intricate pattern. An ingot is raw material for the production of forgings, and has usually to be reheated before it reaches the hammer or the rolling mill. It is advisable, therefore, that it should withstand the reheating without cracking or bursting either internally or at the external corners. A high casting temperature increases the amount of total shrinkage, and therefore lengthens or broadens the pipe; this defect can be remedied by scrapping more of the ingot. But a high casting temperature increases also the number and dimensions of contraction cavities and cracks and adds to the weakness of the ingot along the planes which lie between the corners and centre of the ingot. In fact, the white line on the chamfered corner of wax ingots, mentioned on p. 8, has its counterpart well marked even in large steel ingots. These defects are the more serious because they are mainly unsuspected until the forging comes to be machined or treated mechanically, and before then a good deal of work has been done on the ingot.

To express in definite figures the influence of varied casting temperature on the mechanical properties of steel would involve an enormous amount of labour and require great experimental skill. It would not, for example, suffice to machine test pieces out of an ingot, because the defects to be looked for would sometimes be in the test piece and at other times not; and even if it were practicable to machine always a test piece containing a typical defect it would be quite impossible to arrange for the defect to occupy the same relative position in every test piece; and therefore the tensile properties of the test pieces would vary amongst themselves without indicating any corresponding variation in the ingots from which they had been prepared.

The least objectionable form of test piece is the ingot itself. But as commercial ingots are not amenable to the requirements of testing methods and machines, and as, further, there is no handy means whereby the casting temperature of steel can be accurately measured, we are obliged to content ourselves with general statements to the effect that the casting temperature of steel may be too high or too low to produce the best results. When we remember that the correct, *i. e.* the best, casting temperature differs from one material to another, and for the same material according to the weight and dimensions of the ingots, to say nothing of foundry castings, there appears to be ample room for the exercise of the Art, as distinguished from the Science, of steel-making.

But in making wax ingots the variable conditions are controllable with that degree of accuracy which yields confirmatory results from duplicated tests. And as the behaviour of stearine wax in so many respects is comparable to the behaviour of steel, it may be possible by its aid to confirm the general statement alluded to in the preceding paragraph and also by analogies carefully drawn to add something to it.

Apparently the least troublesome way of casting a series of ingots from varying temperatures is to melt a large beakerful of wax and cast one ingot after another as its temperature falls. But the application of this method leads to very erratic results, because, in passing over the colder lip of the beaker, the wax solidifies and, in the worst cases, small pieces of the solid wax are carried forward into the ingot. These are comparatively harmless when the temperature of the cast ingot is sufficiently high to remelt them, but otherwise they cause what should be a scorched ingot to appear granular or finely crystalline on its fractured surface.

To avoid this irregularity use may be made of glass tubes, seven inches long by three-fourths of an inch in diameter, which have at each end a well-fitting perforated cork. Pieces of thin glass tubing fit into the corks, the one at the lower end being drawn out to a fairly fine point, and the one at the upper end being provided with a few inches of rubber tubing and a spring clip (see Fig. 23).

The lower drawn-out end of the glass tubing is kept at the temperature fixed for the ingot next to be cast, so that when immersed in the fluid wax the opening is not stopped up. The molten wax is drawn upwards by suction on the rubber tube until the mould is nearly full. The pinch cock is then closed, the end of the lower projection is dipped into cold water, to solidify the wax and so close the opening, the upper cork together with the rubber

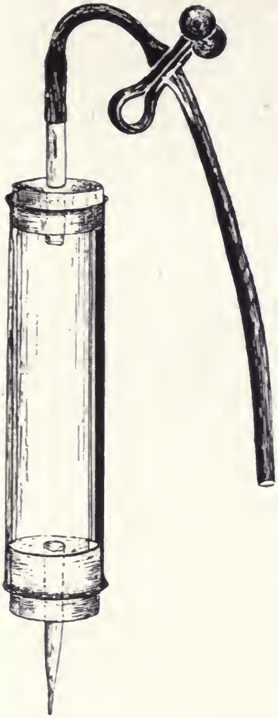

FIG. 23.—Arrangement for casting wax test ingots.

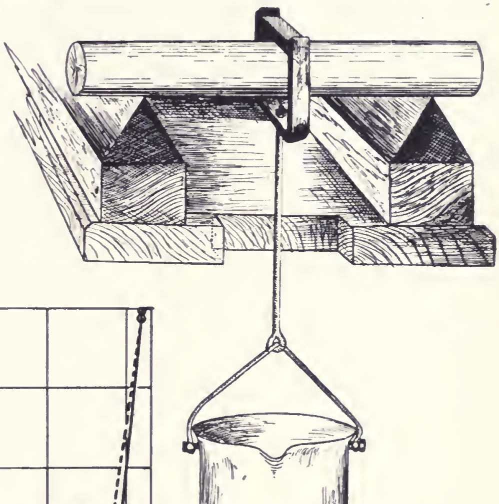

FIG. 24.—Arrangement for testing strength of wax ingots

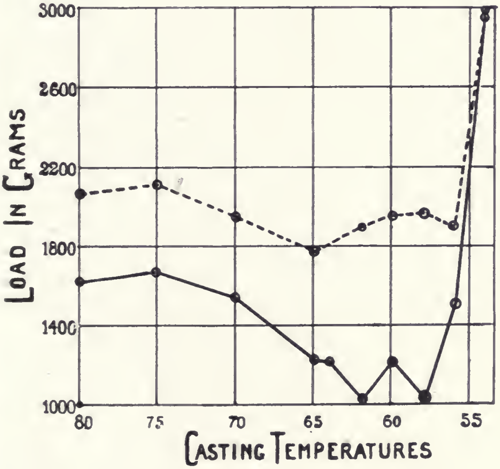

FIG. 25.—To illustrate influence of casting temperature on strength.

tubing and pinch cock are removed, and the mould is allowed to stand quietly in a vertical position until it becomes quite cold. Series of ingots are made successively in this way as the temperature of the melted wax sinks; and it is easy to arrange for the temperature to fall at the rate of, say, one degree centigrade in fifteen minutes, thus permitting duplicate or triplicate ingots to be made at each chosen temperature.

The simple piece of apparatus shown in Fig. 24 may be used to test the strength of the ingots made as described. The ingots rest on supports four inches apart, and midway between the supports a pan is hung into which mercury is allowed to flow from a graduated burette, or into which small leaden shot is poured, until the ingot breaks. The burette is then read off, or the weight of shot used is noted, in order to arrive at the breaking load in grams. As the results are merely comparative the net breaking load on the three-quarter-inch circular ingots used are given in the following table and plotted as a curve in Fig. 25.

Casting temperature.	Breaking Load in Grams.					
	1.	2.	3.	4.	5.	Average.
80° C.	1618	—	—	—	—	—
75° C.	1671	—	—	—	—	—
70° C.	1551	—	—	—	—	—
65° C.	1220	—	—	—	—	—
64° C.	1292	1155	1208	—	—	1218
62° C.	1048	1009	—	—	—	1029
60° C.	1224	1274	1168	—	—	1222
58° C.	982	1009	1088	—	—	1026
56° C.	1459	1155	1605	1830	—	1512
54° C.	2783	2995	2783	3193	3127	2938
One minute after reaching 54° C.						3250
Two minutes ,, ,, ,, ...						3224
Three ,, ,, ,, ,, ...						3021
Four ,, ,, ,, ,, ...						2995
Five ,, ,, ,, ,, ...						3101
Six ,, ,, ,, ,, ...						2929
Seven ,, ,, ,, ,, (unsound) . . .						2558

The mechanical properties of the wax ingots of this series cast from very high temperatures are erratic owing to the occurrence of visible cracks; they are therefore not of much use for comparison. The cracks, however, are most marked in those ingots cast at intermediate temperatures, and improve in this respect as the temperature rises.

The most noticeable feature in this series of results is the great increase in strength between those ingots cast respectively at 56 and 54° C., the latter being almost twice as strong, and this is confirmed by the appearance of the fractures, which show a marked difference within this short range of casting temperature. The ingots cast at 54° C. have a granular or finely crystalline structure, whilst those cast at 56° C. or over show scorch. This observation is quite in line with the behaviour of small steel ingots both as to appearance of fractured surfaces and mechanical strength.

The increase in strength when the casting temperature reaches 60° C. is also notable and not especially difficult to understand. It is to be expected that, all other conditions being equal, a rise in the casting temperature alone would cause the ingots to become gradually weaker. But a rise in casting temperature disturbs the other conditions and more especially the rate of cooling. So that an ingot cast with wax at 58° C. into a thin mould might at once have a solid envelope formed around it by the cooling action of the mould; whereas when cast from a higher temperature the heat lost in heating the mould might depress the temperature of the fluid wax to 58° C. without causing a solid envelope to form around it. The rate of cooling in the two cases would then vary, and the latter would be more or less disposed to form the stronger equiaxial crystals depending on the thermal conductivity, specific heat, and mass of the ingot mould, and on the relative thermal conductivity of the fluid and solid ingot material. It is therefore to be expected that at some temperature well above the freezing temperature the wax ingot (or steel casting) would become stronger; but the rise in strength would not occur at the same temperature of course except under identical experimental conditions.

The best-known example which may be cited to illustrate the influence of casting temperature on the strength of steel ingots is 25 per cent. nickel steel. This material when cast at the correct temperature will bear an almost unlimited amount of deformation under the hammer. Individual firms, however, have been so much bothered by cracked ingots and unsound bars that they have given up the manufacture of the material in despair. And yet the only precaution needed apart from deoxidation is to cast the fluid alloy at a temperature only just above its freezing point. Twenty-five per cent. nickel steel is usually made by the crucible process from wrought iron or steel scrap and cube nickel. Both these ingredients have a high melting point, but the freezing point, or range, of the molten alloy is comparatively low; and if the ingot is cast from the temperature needed to melt either of the ingredients it will be frightfully scorched and go to pieces under the hammer as did the specimen illustrated in Fig. 26; each crystal being so well defined that on a fractured surface they could be pulled apart from each other. When, however, the molten alloy is kept in the pot

Fig. 26.—Fracture of " hot-cast " nickel steel ingot.

until it begins to freeze on the surface, and is then cast as slowly as is consistent with the production of a good ingot, no subsequent forging troubles need be anticipated.

The authors have observed with great interest the increasing tonnage of electric furnace steel ingots. During the past ten years many such ingots have been cut up and fractured for information purposes. Many tons have been charged into open-hearth furnaces as scrap, and many hundreds of tons have been remelted as cracked billets after passing more or less successfully through the cogging operation. The greater part of such wasted material was spoiled by being cast from too high a temperature. In the crucible process or the open-hearth process the margin of temperature attainable above that needed to keep the charge fluid, and cast it, is probably not more than 100° C. But in the electric furnace, even more so than in the Bessemer converter, the temperature of the charge may be raised much beyond this margin. One of the minor worries of steel making is the occurrence of skulled ladles. A heavy skull is generally an indication that the charge has been tapped too cold or the ladle has not been properly prepared, and there is no doubt who is responsible. Such a skull being difficult to hide or get rid of advertises its existence and indicates its origin to whoever may be interested. The absence of a skull, on the other hand, is no clear indication that the steel has not been properly made and cast. If a skull does not exist it cannot bear witness, and if perchance the ingot cogs badly there is always a possibility of it having been reheated too rashly or overheated. And so it happens that electric furnace ingots, unless they are cast by a person having good judgment and confidence in his judgment, cog more wastefully than open-hearth ingots; and forgings made from them are more apt to have the characteristics of steel which has been cast too hot. For this reason amongst others the product of electric furnaces appears not to have given unqualified satisfaction to those who regarded it as a likely substitute for crucible steel. Time and experience will bring a remedy.

V

INGOT MOULDS

THE CARE OF MOULDS

No class of moulds used in the making of steel ingots receives the same careful attention as those into which crucible steel is cast; and in comparing the quality or reliability of steel made by the different processes this point and many other details of the actual casting operation are frequently overlooked. It is hoped, in this chapter, to show that however excellent the molten steel may be, the preparation of the mould and the art of casting the steel are by no means unimportant factors in the production of sound ingots.

All steel-melters like to see nice clean ingots turned out of the moulds, and this, although not of much importance when the ingots are for mild steel forgings that have to be machined, is almost imperative for ingots that are to be forged direct into finished bars. To get the nice surface usually found on crucible steel ingots the mould is rubbed with a rag, or with a piece of coke if necessary, and then coated with a fine layer of soot (reeked) or pure graphite.

The reason the inner surface of a mould is all the better for being well rubbed out and reeked is not far to seek. It is a well-known fact that when grey cast iron is heated repeatedly to redness it expands and ultimately cracks and breaks up into a friable mass. The interior part of the mould most exposed to this action becomes quickly covered by a loose scaly deposit. This deposit consists of partially oxidized iron and is kept under to an appreciable extent by reeking, but in any case diligent rubbing as well as reeking is necessary.

When high carbon steel is cast into a mould from whose surface the loose deposit has not been rubbed away, the ingot has a pitted and dirty-looking surface. This appears to be due to a reaction between the carbon of the steel and the oxidized deposit with evolution of carbon monoxide or dioxide gases, which force their way into the semi-fluid steel. It may also be observed, when hard steel is being cast into a dirty mould, that it spits around the edges as the surface of the molten metal rises in the mould, and the teemer will pour more slowly when this is noticeable, the idea being to allow the surface of the steel rising in the mould to crust over and cool; this delay certainly improves the skin of the ingot.

When mild steel is cast into equally dirty moulds the ingots produced are much smoother. This is probably due to a combination of circumstances. In the first place the amount of carbon in the steel is less and does not so readily react with the oxidizing material; and, secondly, as the molten steel freezes more quickly, any gas evolved has less time to form cavities on its surface. Groups of mild Siemens steel ingots if cast cold into bad moulds will not be pitted, but if cast hot into the same moulds they will spit and be pitted.

These considerations suggest the strongest possible reasons why the use of the split mould is advisable in the crucible furnace. They indicate also why hard ingots cast into solid moulds which are necessarily subject to less rigorous inspection and preparation, say, for example, on a Siemens furnace plant, are apt to have surface defects which are not to be explained entirely by a difference between the two methods of casting. After a mould has been used a great many times it becomes increasingly difficult to keep its surface quite clean. Fine cracks and a roughness penetrate the metal and cannot be rubbed away; perhaps the cheapest way of improving such moulds is to replace them with new ones.

The life of a mould is greatly affected by the time the hot ingot is allowed to remain in it. If stripped before becoming red hot the mould only requires wiping out with a rag and reeking again, and will thus last a long time. During one year some ordinary three-inch crucible moulds used under average conditions cost 14·6 lb. of mould per ton of steel cast into them. During the following year the wear and tear of the moulds would have been more had they been used in the same way. Special care, however, was taken to strip them always before they became red hot, and the cost in weight of mould per ton of ingots was only 10·9 lb.

These figures may be usefully compared with those for moulds of all sizes used on a crucible plant and kept under strict observance during the same two years.

Year.	Size.	Lb. of moulds per ton of ingots.
1908	3″ square	14·6
,,	All larger sizes	16·9
1909	3″ square	10·9
,,	All larger sizes	13·6

The reason the figures for all larger sizes are higher than those for the three-inch mould is that the latter cools the ingot quickly and it may soon be stripped, whereas the larger ingots may not be stripped so early and the moulds get much hotter; consequently they scale, warp and crack; and the edges of the "rabbit" crumble away sooner than in the three-inch mould.

The wear of moulds expressed in pounds per ton of ingots cast into them might have been expected to be all in favour of the larger moulds whose actual weight compared with the weight of ingot is much less. That the contrary should be the case confirms in a striking manner the advantage of keeping the moulds as cool as possible.

The loss or gain of a few pounds of cast iron is, of course, of no consequence; but the saving in clean bars free from roaks is very considerable. It is not generally possible to strip large ingots before the mould becomes red hot; but on the other hand an ingot is, in many cases, allowed to remain in the mould longer than is necessary with the idea of keeping the ingot warm. To say the least of it, this is an extravagant procedure, and very apt to lead to defects in subsequent ingots.

The sooner an ingot is stripped the better it is for the mould, as it undergoes thereby less expansion. And having been stripped the moulds are naturally all the better if they can be cooled uniformly, even if, as it appears from certain published results, for that purpose they are plunged vertically into a water tank. Though at first sight objectionable the cooling of ingot moulds by immersion in water is said to have justified the bold venture. At the works of the Witkowitz Coal and Iron Company the experiment was first made on a number of moulds with the following results:—

Weight of mould.	Not cooled.		Water cooled.	
	Number of moulds used.	Average ingots cast.	Number of moulds used.	Average ingots cast.
33 cwts.	116	45·7	153	87·5
38 ,,	170	45·8	153	91·4
42 ,,	34	46·8	52	71·4

It is a common practice to warm moulds before casting into them. This as a matter of experience has been found advantageous, but it can be carried so far that the net result is an exchange of one kind of defect for another kind of defect. If an easily fusible metal such as lead, or lead tin alloy, be poured on to a piece of smooth glass which has been well cleaned with a dry cloth, the underside of the cold metal will have a brightly-polished appearance where it has been in contact with the glass, but it will also show a number of small pinholes. If, on the other hand, the glass is warmed before casting, the metallic surface will be equally bright and also free from small cavities. The small cavities are supposed to be due to a film of moisture, which is removed by warming the glass plate. For the same reason, *i. e.* to avoid the presence of moisture, it is advisable to warm ingot moulds. But the practice, commendable enough in itself, is harmful when the minimum temperature necessary is exceeded. If the temperature of an ingot mould is 300° C. to 400° C. to begin with, it becomes red hot and deteriorates more quickly, which means generally that less satisfactory ingots are produced. The net effect on its life of heating an ingot mould is the same as decreasing its thickness.

Not alone the degree of warming, but the manner in which moulds are warmed before use is important. They are frequently placed between hot ingots, and, arbitrary as this procedure may seem, it is better in its final results than the practice of slipping the mould over a hot ingot, because in the latter case the mould is heated most on the inside, and stressed already in the same direction as it will be further stressed when the molten steel is poured into it. When the inside of a mould is red hot it expands, but cannot do so freely if at the same time the outside of the mould is not even visibly red, and consequently the inner parts are in compression and the outer parts in tension. Deformation of the ingot mould and cracks on its inner surface arise from these opposing stresses, which are called into existence every time the mould is heated and cooled.

On casting, the inside of the mould gets hotter more quickly than the outside; but after stripping the outside cools faster than the inside, particularly if the moulds stand on the floor without any possibility of the air circulating freely through them. If, further, the moulds are cooled on the outside only by a water spray, acting mostly on one side only, the conditions are still more unfavourable to the life of the mould.

The advantages of the split mould for small crucible ingots are fairly obvious. It is an easy matter to get to all parts of the mould to clean it. It is also easy to find out any defects on the surface of the mould, or such defects just under the skin as will quickly make the mould objectionable. The split mould has, however, a less obvious but still a considerable advantage to the maker of crucible ingots, which is usually overlooked.

The two halves of a split mould are held together by rings and wedges, and these have something to do with the production of good ingots. The mould resting in the teeming box (Fig. 27) is always inclined more or less from the vertical, so that the stream of metal flowing over the lip of the pot may not strike the side of the mould. Exactly how much the mould must be set out of the perpendicular depends on the degree to which the top of the pot has been turned in and the shape of the lip. As this and other minor factors may vary slightly, so also it is necessary to vary the slope of the mould. This the teemer does by raising or lowering the bottom ring, which is always brought into contact with the side of the teeming box, thus controlling the slope of the mould.

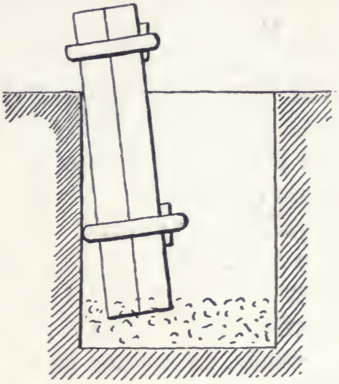

FIG. 27.—Position of crucible mould in teeming box.

The solid mould, as used on Siemens and Bessemer plants, has been tried in crucible furnaces with very little success. It is more difficult to clean, to reek and to set at the proper angle in the teeming box, consequently the ingots are not so good. In larger sizes, say six or seven inches, it is used a great deal in Germany and Austria. The ingots, however, are frequently circular in section, and are turned in the lathe to remove skin defects before being forged into bars or rolled into sheets.

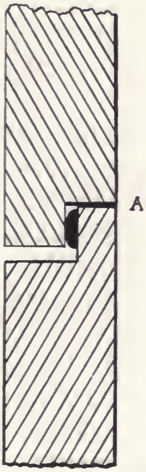

FIG. 28.—Joint in split crucible mould.

For all sizes of ingots above eight or possibly ten inches square, the split mould becomes too cumbersome and deteriorates too rapidly by regular use; it is therefore superseded entirely in the larger sizes by the solid mould. Deterioration in split moulds occurs largely at the "rabbit," because there is proportionately less metal at that part to take up the heat of the molten steel. The joint between the two halves of the mould must be perfect, otherwise the fluid metal creeps in between them and makes a fash on the ingot. When once the joint is defective it wears very rapidly, because the edges of the junction are acted upon on both sides by the fluid steel.

It goes without saying that the two halves of the mould should be in perfect alignment at the joint. This is secured by the very simple and ingenious device represented in Fig. 28 *a* by the blackened patch. The moulds are in close contact only on the edges marked A; the other edges of the "rabbit" stand apart so that only one pair of faces require to be fitted. In order to bring these two faces into perfect alignment a couple of small pellets are cast between the "rabbit," and one or both pairs of them are filed down until the face of the two halves of the mould are in exactly the same plane. The inner part of the "rabbit" is heated disproportionately by the ingot, because it stands free from the outer part and for some inexplicable reason the inner part is generally the thinner; it ought, of course, to be made as thick as possible in order to resist the injurious effects of repeated heating and cooling.

THICK AND THIN MOULDS

As to whether the walls of an ingot mould should be relatively thick or thin is a matter about which we cannot help ourselves by observations with wax. Or, at any rate, whatever results were arrived at with wax would need more skill than is available in the authors to apply them to steel. The difficulty is twofold—steel is cast into moulds made from material (cast iron) having a lower melting point and wax into moulds having a higher melting point than the ingot material; and, secondly, steel undergoes crystalline transformations on reheating and wax does not. Any attempt, therefore, to use very thin moulds for wax leads to the formation of a slender solid wax envelope which melts almost as soon as it is formed, whilst a similar experiment with steel would result in the melting of the mould. The question of thick and thin moulds had better, therefore, be discussed as to its bearing on the quality of the steel ingot produced and the cost of the two kinds of moulds per ton of ingots made in them.

To the advocate of thin moulds one advantage may be conceded without discussion; the thin moulds being lighter are easier to shift about. When the lifting is done by hand this advantage is considerable, but when it is done by power cranes the greater weight is not of much consequence. As moulds are generally bought by weight the cost per mould of those with thin walls is naturally less, and the economy is a real one if the life of the mould is equally as good as that of the thick moulds. So far the question is simple and could be settled definitely by a departmental costs clerk.

It is claimed, however, that the thinner mould produces better ingots, *i. e.* ingots with a better outside appearance and free from the damaging effects of chilling. As to the outside appearance there may be something in the contention when ingots are cast in groups through the bottom, although the main mould factor in the production of " good-looking " ingots is the condition of the inner surface of the mould, as we have shown. The only point in dispute worth more than passing notice is whether or not the thickness of the mould has any noticeable effect on the crystalline structure, the appearance of scorch near the surface of the ingot and such properties as are consequential to these appearances.

The authors have frequently observed that steel cast into a three-inch square ingot mould would have a normal fracture, whereas metal cast afterwards from the same pot into a two-inch square mould would give a badly scorched ingot, and in both cases immediately after casting the outside of the mould was only hand-warm. Also an ingot cast into a wedge-shaped or conical mould whose walls are of equal thickness from top to bottom shows the appearance of scorch only on the thinner part of the ingot. These facts seem to indicate that the relative thickness of the mould is of some importance in the production of scorched and fragile ingots. If, however, a conical mould is made so that the thickness of its sides bears a constant ratio to its internal capacity at any part, then the ingot produced from it would also be scorched on the thinner part only. It should, however, be remembered that the narrower part of the ingot would normally be teemed faster per inch of depth than the wider part.

If the walls of an ingot mould were made so thin that they were raised immediately to a temperature not appreciably less than the freezing point of the steel and the heat was not rapidly dissipated into the atmosphere, then the ingot would not be scorched, but such conditions are commercially impracticable. So long as cast-iron moulds are in use they must be at least thick enough to take up the heat of the molten steel without being themselves raised, even on their inner surfaces, to a temperature approximately within 200–300° C. of the melting point of cast iron, *i. e.* the temperature of the mould in use should not exceed 900° C. The practical issue, therefore, narrows itself down to this—is it of advantage to the quality of an ingot, or any economy, to cast into moulds frail enough to be raised by the molten steel to 900° C., as compared with a heavier mould whose mean temperature cannot possibly exceed 600° C.?

It is clear that a cast-iron mould must be thick enough to freeze the fluid steel rising in it and reduce its temperature below that of the melting point of cast iron; the surface of the mould would otherwise melt, and the ingot would stick in the mould and pull cracks into itself. It is equally clear that the envelope of solid metal first formed must soon become thick enough to contract on to the fluid mass and leave the sides of the mould. So that whether a mould is a thick one or a thin one the actual contact of the molten steel with it is but a brief one and is followed quickly by the shrinkage of the solid envelope and the expansion of the mould, which leaves an annular space between them. At this stage the scorching of the solid part of the ingot has already occurred, if it can occur, and that obviously independent of the thickness of the mould, because whether the mould be thick or thin the outer surface of its walls will not be visibly red by the time the annular space has formed around the ingot.

The separation of an ingot from the face of a mould depends entirely on the heat taken up by the mould from the steel. Contact between the two is maintained only so long as the solidified steel shell is too weak to support the pressure of the fluid metal it contains. If separation on the same plane occurs in an irregular manner the weaker and last separated part may be torn asunder and the cold ingot would then exhibit a vertical rib which looks like a crack. A great difference in the time at which the top and bottom of an ingot separated from the sides of the mould might cause the ingot, owing to contraction in length, to hang from the plane of contact and thus cause horizontal cracks. This danger is greatest in taper moulds cast wide end up, but in every case the thickness of the walls of the mould, so far as they can be made operative, should be such as to produce as soon as possible a thick solidified shell which will separate simultaneously in the same plane.

That the appearance of scorch, if it occurs at all, is caused during the rapid formation of the outer solid envelope, which as we think is independent of the thickness of the cast-iron moulds, is illustrated by the behaviour of the compound ingots known as steel lumps. These are cast into split moulds. The steel is cast first, and then immediately one side of the mould is taken away and replaced by a similar but deeper piece, which leaves a space, between the face of the new piece and that of the hot steel ingot, into which the melted iron or dead mild steel is poured. The steel parts of such ingots, if scorched at all, are as badly scorched on the side adjacent to the iron, which was only a very short time in contact with the cold iron mould, as they are on the side left in contact with the mould.

Also if an ingot be inverted immediately after casting the hollow shell will be scorched quite independent of whether the mould was a thick or a thin one; and if the outside of the mould were in either case barely warm before the inversion took place the thickness of the solidified steel envelope would also be independent of the thickness of the mould. It may, therefore, be concluded that the thin mould does not favour the production of ingots free from scorch and the mechanical weakness associated with it.

The argument against thin moulds may be carried still further. Being thin the mould quickly gets hot and reaches a higher temperature than is possible with a thick mould. This means that it grows in size and disintegrates in the manner explained by Carpenter.[1] The inner surface especially of the mould cracks, expoliates and oxidizes, and thus produces on ingots cast subsequently the very trouble it is designed to avoid, *i. e.* dirty ingots which are apt to be mechanically weak owing to surface flaws. A mould gets hottest about one-third from the bottom and grows most at this part. The bottom part of the mould is, meanwhile, kept much cooler by the iron plate on which it stands, and being unable to follow the expansion it cracks. To strengthen the bottom by having a band cast on to it leaves a sharp angle between the unequally expanding portions; and even if the sharp angle is replaced by a large fillet the fact that the middle part grows faster than the bottom makes the mould barrel-shaped and causes trouble and expense in stripping the ingots. This trouble and expense should be debited to the thin mould when relative costs are being reckoned. To strengthen the mould by gradually thickening it up to or beyond half its length would, of course, lengthen its life; but that procedure at once makes it into a thick mould where the demands on it are greatest and abandons nearly every claim made in favour of thin moulds.

It is even doubtful whether a thin mould cools a steel ingot less rapidly than a thick one. The ingot and mould are in actual contact for a short time only; but all the heat on any plane of an ingot well removed from its top and bottom must be dissipated through the mould. In the former case the mould becomes very hot and the air moving about the outside of it may carry away the heat faster than in the latter case, where the outside of the thicker mould is at a much lower temperature. Under ordinary conditions of casting the difference is probably

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[1] *Jour. Iron and Steel Inst.*, 1909, II, 29; 1911, I, 196.

not a great one, but it is interesting to note that the last resource of the thin mould is of problematic value.

The scorching of ingots in whatever kind of chill mould they are cast occurs more frequently than is generally surmised. It may be seen more rarely in large ingots which are fractured when cold, but it is frequently, one might almost say invariably, seen in ingots which have " pulled " or been torn asunder after the steel has frozen. The torn surfaces of a hot crack in a large ingot or steel casting are seen to be made up of needle-like crystals in all respects identical with the well-known appearance of a scorched crucible steel ingot. If, however, a fresh fracture of the cold material is made in an adjacent position, it may, and generally does, happen that no trace of scorch is visible. This observation enables one to determine roughly in what range of temperature a particular crack in an ingot has occurred.

Two possible explanations may be given to account for the appearance of scorch in a hot pull and its absence from the surface of a fracture made through the cold metal. One is that during slow cooling the original crystalline structure undergoes transformations which break up the elongated (or dendritic) crystals and replaces them by the equiaxial crystals generally found in large ingots and sand castings (see Fig. 5). The authors have no evidence to offer in support of this suggestion, and are not aware whether in steel or any other metallic alloy such drastic crystalline transformations have been known to occur during cooling of the hot solid metal as distinct from the changes which undoubtedly occur during heating. The other is that elongated crystals due to the chilling effect of moulds are themselves comparatively pure, but exist in an envelope of comparatively impure material, which has consequently a lower freezing point and may, therefore, be still semi-fluid when the crystals are stressed across the direction of their length and pulled apart. A fracture made under such circumstances would naturally expose elongated crystals in the most prominent manner. When, however, the impure envelopes had themselves become solid as, *e. g.*

when a fracture is made of the cold material, there is no reason to assume that the fracture would take the same course because the impure envelopes, if they have not been dispersed by interdiffusion, may on account of their increased strength be less likely to break than other parts of the metal. We incline to this latter explanation in those cases where the possibility of reheating effects cannot be entertained.

When a scorched ingot is heated from the cold to some temperature above a certain minimum, depending on the composition of the steel, the appearance of scorch disappears or can be made to disappear by repeating the treatment presuming that no discontinuity in the metal exists. If, therefore, an ingot is cast hot into a three or four-inch square mould it will cool rapidly on the outside, take up the scorched appearance and leave the sides of the mould. During this short time the outer part of the ingot may become black hot, and afterwards, when stripped, regain heat from the much hotter interior metal. In doing so it may satisfy the conditions which are known to cause the disappearance of scorch, and thence may be deduced a very likely explanation for

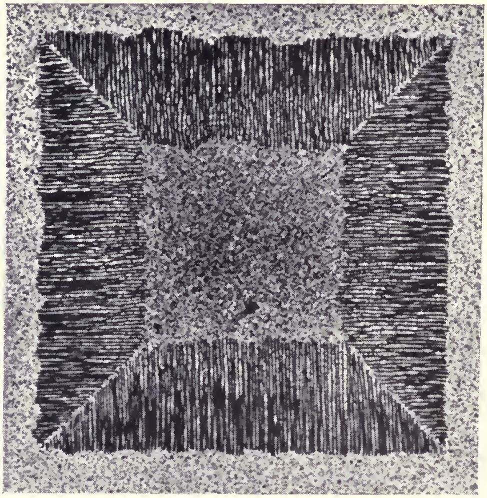

FIG. 29.—Scorch in intermediate part of ingot.

those crucible ingots which are found to be free from scorch on the outside, and may be also in the centre, whilst the intermediate material is badly scorched as indicated by Fig. 29.[1]

The outer portion of the ingot in these cases appears to have been scorched and recrystallized by reheating in the manner suggested. The central portion is free from scorch because the acute chilling effect of the mould has not reached the centre before the temperature of the fluid metal falls to the freezing point and crystallizes from innumerable centres; and the intermediate portion retains its scorched appearance because, although it may become reheated, its temperature in the first instance had not fallen low enough to enable the reheating to take place through the upper critical range (Ac_3), as is necessary in all crystal refining operations which do not involve mechanical work.

These considerations help to explain a number of everyday observations:—

1. Very small ingots may present a completely scorched structure because the chilling effect of the mould penetrates quickly to the centre of the ingot, which is not of sufficient mass to reheat the outer part to the temperature requisite for recrystallization.
2. Medium-sized ingots may be free from scorch on the outer edges and in the centre for reasons given in the last two paragraphs; and
3. Large ingots may be free from scorch on the surface because the results of the sudden chilling effect are destroyed by reheating when the temperature of the ingot begins to equalize itself.

These broad generalizations are not intended to be dogmatic; if they appear so it is on account of the necessity for clear statement of workshop observations.

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[1] When scorched ingots are stripped rapidly and thrown on a heap they are sometimes found to be free from scorch on one side, where they have been warmed up by neighbouring ingots, and quite unaffected on the other, where they have been exposed to the cooling effect of floor plates or the atmosphere.

They are made in respect to ingots of no particular size, though obviously the observations are to be made most conveniently on such ingots as may be readily broken, *i. e.* relatively small ingots.

THE TAPER OF INGOT MOULDS

A split ingot mould may have parallel sides, but the inner walls of a solid mould must be tapered, otherwise there would be endless trouble in the stripping operation. Most ingots are cast with the narrow end of the taper mould upwards,[1] as this enables the mould to be lifted off whilst the interior of the ingot is still fluid. This practice is economical both as to ingot moulds, which last longer because they are not made unnecessarily hot, and in the further costs of working the ingots if they are kept hot in soaking pits until they are ready for rolling. The following remarks, however, apply only to such ingots as are allowed to go cold under normal conditions and are made solely in the interest of sound ingots without any regard to particular workshop conditions, big outputs or apparent economies.

If it be assumed that a taper ingot mould with the narrow end upwards is filled with fluid metal at a uniform temperature, the act of setting may be represented by a series of equidistant lines drawn on a longitudinal section of the mould parallel to its inner surface, as in Fig. 30 A; each line being made shorter than its predecessor to account for the continuous shrinkage (see p. 15.). The point at which a pair of these lines meet within the mould may be taken as indicating that in the horizontal plane passing through it the metal has solidified completely. The cavity above the point of intersection is a pipe pure and simple, and may be distinguished as "primary" pipe. But there still remains a triangle marked K, which, according to our assumption, contains fluid metal and is hermetically sealed. This fluid in due course will also shrink and freeze and contract, but there is no

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[1] This was quite true when written four or five years ago. During the past two years inverted moulds have been widely adopted.

possibility of the cavities thus formed being fed, and there is formed thus a more or less discontinuous extension of the pipe, which may be called "secondary" pipe.

On representing in the same manner the freezing of metal cast into a taper mould with the wide end up, but with shorter steps down because the shrinking fluid is falling from a wider into a narrower part, we arrive at Fig. 30 B. Here, also, the lines intersect and represent similarly that the material lying below the point of intersection has become solid. There is also a triangular residue of fluid metal, but in this latter case the triangle is inverted and the metal within it will freeze earliest at the lowest point, any shrinkage being meanwhile fed from above, leaving, finally, a hollow shrinkage cavity in the axis and at the upper end of the ingot. It is not possible in this kind of ingot to have a secondary pipe.

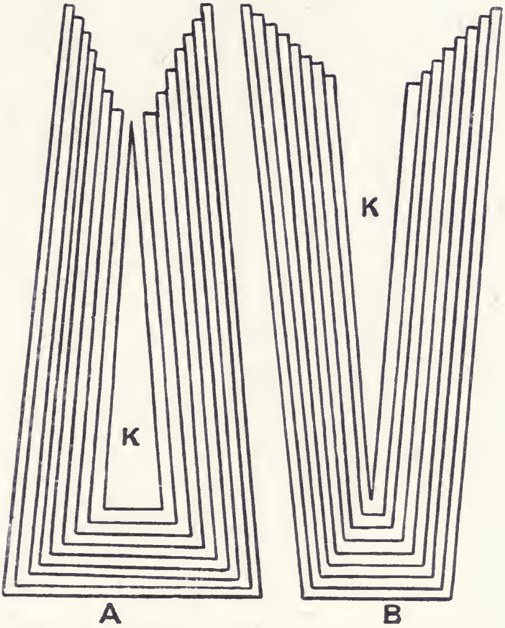

FIG. 30.—To illustrate freezing in taper mould.

The assumptions on which Fig. 30 is based take into account neither the speed at which the ingot is cast nor the cooling effect of the air on its upper surface.

Ingots are not made by filling moulds at the greatest speed, or when they are the ingots are inferior ones. It may take anything from one-half to fifteen minutes to cast an ingot (depending on its size, the kind of steel from which it is made and the temperature of the molten steel), and during that time the lower parts of the ingot become solid and the upper part of the ingot mould gets heated before the fluid metal reaches it.

Fig. 31.—Section of small steel ingots cast narrow and wide end up.

The cooling effect of the air forms a cover of greater or less thickness over the top end of the pipe. In large ingots the thickness of this cover may be several inches; in small ingots it may not persist at all; but in either case the atmospheric cooling thickens also the metal about the upper part of the pipe. If, however, the influence of these variations be added to the hypothetical case represented by Fig. 30 it will not be modified out of all recognition, as may be seen by comparing the assumed forms with those of two actual steel ingots reproduced in Fig. 31.

Nothing can be done to prevent the shrinking of fluid steel as it passes from the liquid to the solid state; and the only means of providing against the inconvenience of it is to arrange for fluid metal to be kept at a higher level ready and able to flow into what otherwise would be a shrinkage cavity. This means that an ingot must always solidify from the bottom upwards, which it does naturally when cast into a taper mould with the wide end up; or in general terms the metal in any plane must solidify earlier than the metal in any higher plane if extended shrinkage cavities are to be avoided.

Many attempts have been made to force this essential condition on to ingots cast in taper moulds with the narrow end upwards; but few of them are really successful and some are entirely impracticable. This subject will be fully dealt with in subsequent chapters, but reference may be made here to the oldest of all such methods, *i. e.* feeding the ingot with hot metal and keeping it open, *i. e.* breaking the bridges, by moving an iron rod up and down the centre of it. Whether such a method could be successful would depend on the vigour of the movement and the temperature of the feeding metal. However it may act for cast iron, it is considered now to be an obsolete method for steel ingots.

The fluid ingot cast with the wide end up shortens less rapidly than one cast with the narrow end up, and it is therefore more likely that the upper crust of frozen metal will resist the pressure of the atmosphere when the fluid underneath ceases to support it. This to some, not very great, extent will help to keep the upper and interior parts of the steel fluid; it is more valuable, however, because it may prevent oxidation of the interior of the pipe and thus facilitate its welding when it comes later to be rolled or forged. It may also be observed that the pipe in the one case takes the form of a long pointed cavity, and in the other a short cavity with a rounded end (Fig. 31). Apart from the relative volumes of material thus made unsound, and likely to be scrapped, the former, occurring in ingots cast with the narrow end up, is more likely to cause ingots to clink in the reheating furnace. These are all points of minor importance in themselves, but experience shows that they lead sometimes to grave consequences, and it is therefore worth while to note that in these minor respects the soundness and reliability of the ingot is improved by casting with the wide end up.

The pipe in a series of wax or steel ingots made in moulds of a gradually decreasing taper undergoes a continuous change as the taper decreases until the sides of the mould become parallel; after that a very slight taper upwards alters the character of the pipe altogether —it becomes shorter and more rounded at its lower end, and secondary pipe occurs only under abnormal circumstances. When the side of the mould are parallel the ingots exhibit special features, which have been dealt with on p. 20. One or two other effects arising from the use of straight-sided moulds may be glanced at for the sake of their bearing on the production and properties of tool steels.

Until about twenty years ago most small tool-steel ingots were cast into straight-sided moulds which were in halves and held together by rings and wedges. The extent to which the primary pipe extended in the smaller of such ingots was very well known. Every melter was aware that a well-piped ingot was practically free from blowholes, that the pipe was larger when the metal was cast hot than when it was cast cold, and that a hard steel piped more than a mild one. These and many correlated observations about which there has been a good deal of aimless discussion were every day disclosed to the minds of men specially gifted in respect to detailed observations, and impressed on them by the payment of a premium on the weight of pipeless, *i. e.* topped, ingots.

Ingots are still cast into moulds with parallel sides, but they are dozzled, and it is generally believed that the ingots so produced are quite sound. The " dozzle " is a fire-clay sleeve which is made white hot and dropped on to the ingot immediately it has been cast; it is then filled up with molten steel, which remains fluid longer than any other part of the ingot and feeds downwards into such cavities as it may have access to.

When the head of a dozzled ingot is broken or cut across it is found to be quite sound. But the lower parts of the ingot are not sound, and out of six ingots made by different melters in two factories not one, on splitting them longitudinally, was found to be free from axial cavities. After what has been said on p. 20 the cause of such unsoundness is not far to seek, and a photographic reproduction of two of the ingots, Fig. 31*a*, may be left to speak for themselves, whilst we turn our attention to defects in forged or rolled bars arising from them.

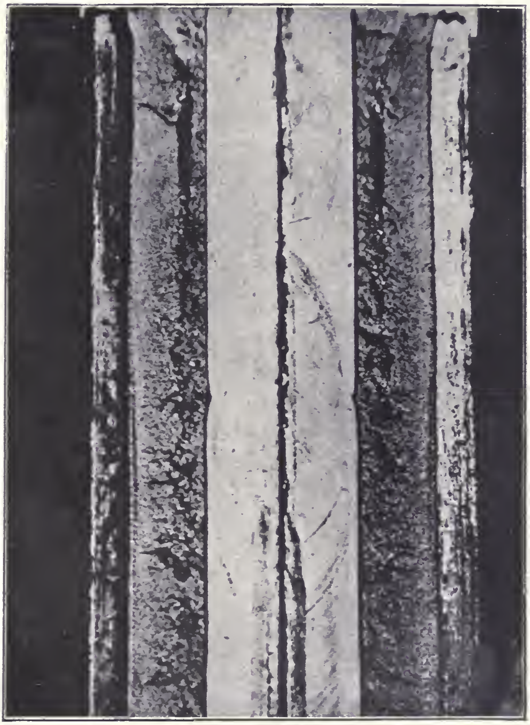

FIG. 31*a*.—Cavities below dozzle in crucible ingots.

The disadvantage of a shrinkage cavity whose surface has been oxidized by exposure to the atmosphere is recognized, no matter in what kind of steel it occurs; but it is widely believed that other kinds of shrinkage cavities will weld up without the steel being any the worse. Such a view is not quite in harmony with actual experience, and it may be said that the question is not, and cannot be, quite settled as has been inferred[1] by boring holes into ingots or cogged bars, and then, after sealing hermetically, observing their behaviour on forging.

A hole made with a drill is smooth and perfectly clean. The interior of an unoxidized shrinkage cavity is uneven, and its walls are often lined with small crystallites which make sharp angles with each other and form very favourable starting-places for internal clinks when the ingot is reheated too rashly. On the surface of such cavities one may sometimes find a fine coating of alumina, which has been floated there on the decreasing mass of mother liquor and left high and dry as the last of the fluid falls to a lower level. It appears to be on this account that blisters raised on thin sheets during hot rolling are occasionally found to be coated on their inner surfaces by a layer of alumina of a pale yellow colour. This also has something to do with the lamination of saws and other articles, either during stamping or in the subsequent hardening operation.

The central and unoxidized shrinkage cavities lying in parallel-sided ingots below the feeder head were at one time, during the progress of setting, filled with liquid steel, which fed the crystallites of purer metal growing from the walls of the cavity. But whilst the fluid metal sank downwards the crystallites remained; and when the ingot becomes a billet or bar that part of it formed by the free-standing crystallites is purer, *i. e.* contains less carbon and other segregating elements, than the surrounding material. This means, of course, that some part of the bar or bars will have a soft centre and cause disappointment if made into chisels or drills, or if made into accurately drilled objects such as rifle barrels. This kind of defect is most clearly visible to the naked eye in the fracture of steels containing between ·9 and 1·1 per cent. of carbon, but it can also be detected in lower or higher carbon steels by polishing and etching. The position of a soft centre in a steel bar is the same as that

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[1] Stead, *Jour. Iron and Steel Inst.*, 1911, 1, 54.

of a hard centre, and the one may occur not far behind the other. Fig. 32 is a photograph of a bar which has been split longitudinally in order to disclose the soft centre.

The harder the steel the more important it becomes that the ingot should be free from these axial cavities; and that not only because the danger of clinking is greater and the chances of welding up the cavities are less, but because the harder material at forging or rolling temperatures is less ductile and under distortion the cavities may actually extend. This observation is notably verified by the behaviour of high-speed steel, and on that account ingots of high-speed steel ought always to be cast in taper moulds with the wide end up and fed by means of a white-hot sleeve or dozzle. The neglect of

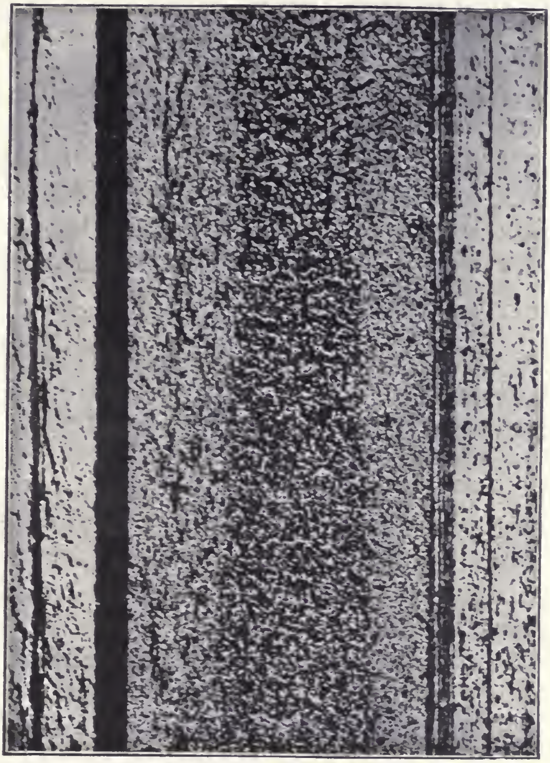

FIG. 32.—Soft centre in cogged bar.

this precaution is one of the contributory causes to which the well-known splitting along their length of high-speed steel tools may be ascribed.

To revert again to the taper mould used wide end up. There are some serious drawbacks to its universal use, the chief being the extra trouble entailed in stripping the ingots. It is necessary either to use movable bottoms and push the ingot so far out of the mould that it can be gripped by suitable tackle, or to insert a hook into the ingot head before the metal solidifies and thereby remove the ingot direct, or to up-end the mould after the ingot has solidified, or to use split moulds. The latter method is too slow and requires more floor space than is usually available in an open-hearth or Bessemer steel-making plant, but it is the usual practice in crucible steel-making plants; the three former methods will be discussed later.

Whatever advantage there may be in thickening the lower part of an ingot mould with the idea of increasing the rate of freezing, is attained in the usual type of taper mould used for making crucible ingots. The moulds are tapered on the inside only; the outer sides of the mould are straight, and it might be assumed that owing to the inside taper the ingot would remain in actual contact with the sides of the mould and transmit heat to a decreasing extent from the base upwards, thus assisting the order of freezing most favourable to the production of sound and short-piped ingots. It is, however, at least doubtful whether this occurs, because as the smaller and bottom part of the ingot cools in any case most rapidly it would leave the sides of the mould and cause the ingot to hang from the top, which being cast last and having a larger cross-section cools and contracts more slowly. This would cause the ingots to "pull," and transverse cracks would commonly occur unless the ingot in all stages of its setting was strong enough to support its own weight.

As a matter of experience pulling does not occur in crucible ingots cast into moulds with a taper of one inch to the foot. And even when the bottom of the ingot mould gets worn into uneven depressions, as it does by the falling of the molten steel on to it, there is still no pulling, although the ingot sticks to the bottom of the mould; it should, however, be said that when sticking is to be feared the bottom rings are always knocked off as soon as the mould is lifted out of the teeming box. The rounded bottom of an ingot cast into an old mould into which depressions have been formed by the falling stream of molten steel is almost invariably pulled, whatever the shape of the mould may be. The ingot contracts transversely as well as longitudinally, and as the metal in two widely spaced depressions resists this contraction a pull is inevitable. Whenever the rounded bottom end of a crucible ingot shows the protrusions which indicate the extent of wear of the bottom of the mould, then careful examination discloses, at some point between the protrusions, a small crack, which widens out subsequently and appears as a split end on a cogged bar or billet.

The inverted taper mould is not generally used for ingots whose wide end is less than four and a half inches across; the reason being that, with the usual taper, the narrower end becomes too small to be struck directly by the molten stream without fear of its having previously impinged on the side of the mould. When a stream of molten steel strikes the side of the mould the ingots are said to be "catched." A catched ingot is regarded as objectionable, because it scars the surface of the ingot and may lead either to a lamination, akin to a lap, or a roak on the surface of the bar. On the surface of very hard steel, notably on self-hard steel ingots, a catch may lead to deep transverse cracks in the forged bar.

In many cases part of the fluid steel which strikes the side of the ingot mould adheres to it, and is not only solidified but comparatively cold before the steel rising in the mould reaches up to and covers it. The cold strip of steel then adheres and becomes part of the ingot, and may be regarded as an inlaid strip of metal whose inner surface is more or less in contact with the ingot. The strip, however, never remelts, and its temperature does not become equal to that part of the ingot in which it lies. As, therefore, the ingot shortens in length by contraction, the strip, unless it contracted at the same rate, which owing to variation in temperature it does not, will locally resist the ingot's contraction, and small cracks in the ingot may be formed underneath or about the strip. What happens is really a pull on a small scale, but the hardly discernible cracks on the ingot develop into obvious cracks in the bar forged from it.

It may also be observed that the material immediately beneath a catch is spongy. The sponginess is caused by oxidation of the surface of the strip of steel before the metal rising in the ingot mould covers it. The oxide film reacts with the carbon of the fluid metal as soon as the two come into contact, and small quantities of carbon monoxide or dioxide gases are liberated just as though that part of the ingot mould were rusted (see p. 44).

It has been repeatedly suggested in these pages that, apart from primary pipe, an ingot must be solid when cast into a taper mould with the wide end up, or when by any other means the fluid steel is induced to freeze from the bottom upwards. So far as the occurrence of shrinkage cavities are concerned this statement appears to be correct, nor have we ever seen a sectioned steel ingot which contravened it. The statement cannot, however, be extended to cover the occurrence of such contraction cavities as are illustrated by Fig. 12.

The two wax ingots reproduced in Fig. 33 will help to make our meaning clear. They were cast at the same time and in similar round moulds, but one of them from a very much higher temperature than the other. In the fluid state the two ingots were of equal length; when cold the hot-cast one, on the left-hand side, was noticeably shorter and also more crystalline. The cavity in the lower half of this ingot is not pipe in the sense that it is due to liquid shrinkage; it is due to contraction of the hot solid wax, and has occurred in the position indicated because the outer portion of the ingot was too rigid to yield to the inner contractile forces; and the axial material was fragile both on account of its higher temperature and the lack of cohesion between the ends of the large and well-defined crystals. It will be noticed that the cavity broadens out downwards and extends part of the way along the exterior of the base cone.

The ingots in Fig. 33 have not a great taper, and it might be assumed that, after all, the freezing not having taken place in the expected order from the bottom upwards, the lower cavity was an extension of the pipe. In order to allay this suspicion further ingots of the same kind were cast and others also into ingot moulds having a greater taper, and one of the latter sectioned down the centre showed the same general characteristics.

FIG. 33.—Relative shrinkage and contraction in hot- and cold-cast ingots.

A further comparison between the ingots in Fig. 33 confirms some statements about bridges made on p. 19. It will be observed that several bridges occur in the hot-cast ingot, and they are relatively thin. They are thin because the hotter wax sinks more rapidly away from them, and they are several in number because in each case the bridge breaks and admits air to the fluid beneath it. The cold-cast ingot, on the other hand, has formed a thick upper crust, partly because the fluid wax was colder, and partly because it shrunk away more slowly. Also this upper crust was not perforated and therefore no second bridges formed, though the cavity has narrowed in an irregular manner due to the precipitation of free crystals from the liquid wax.

The authors have seen once only anything approaching an axial contraction cavity in the lower part of taper steel ingots cast wide end up, and in that instance the ingots were cast extremely hot; so hot, in fact, that the ingot moulds were badly cut by the stream of molten steel, and there was a possibility that the ingots had stuck in places to the sides of the mould, which would, of course, increase enormously the contractile forces. But though such cavities may not actually form in steel, owing to its superior strength and ductility as compared with stearine wax, there can be no doubt that the contractile stresses tend to split ingots in the centre. And when the tendency is increased by the sudden expansion of the outer part of the ingot, which follows on its being charged into a hot reheating furnace, the core may crack—owing less to the negligence of the fireman than to the carelessness of the ingot-maker.

It has been asked when and by whom the practice of casting taper ingots wide end up was introduced. The authors are not able to answer that question, although it is quite certain that the procedure had been in use on a commercial scale long before it was adopted as a common practice by the crucible steel-makers of Sheffield. Such moulds were in use as early as 1881 at Landore for round ingots which were to be rolled into tin-plate bars. The moulds for making 7-cwt. ingots were eight and a half to nine inches wide at the top and seven inches at the bottom, *i.e.* they were roughly the shape of a flower pot, and were provided with trunnions so that the ingots could be stripped by turning the moulds over. The Swedish steel-makers have also for many years cast their ingots wide end up, and this practice has undoubtedly had a very favourable influence on the reputation of Swedish bar steel for general reliability and soundness.

THE SHAPE OF MOULDS

The authors do not propose to lecture engineers on the design of ingot moulds. They desire only to point out certain defects in ingots which have been observed to arise directly from the shape of the mould as distinct from the dimensions of its parts. And here again, as in all general matters relating to ingots, the most helpful experience is to be obtained from a crucible steel-making plant where small ingots can be easily, and are frequently, broken up.

Some special forms of moulds once prevalent appear now to have disappeared entirely; such are the wortle and the cross-cut (or bug) mould. The former (Fig. 34) was used for casting wire drawers plates to the shape in which they would ultimately be used. The better kind of drawing plate now in use is comparatively small and made from high-chromium steel, which is found to be much more durable than the old kind of plate containing frequently over two per cent. of carbon. In the cross-cut mould long ingots necked in from two to five places were cast, and after breaking off at the neck the separate pieces were rolled into blanks for cross-cut saws.

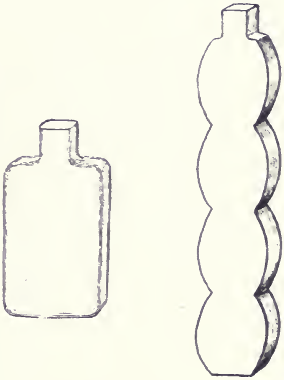

FIG. 34.—Wortle and cross-cut ingot moulds.

Both kinds of ingots would be unsound, and in the latter case perfect sheets or blanks would be obtainable only if the shrinkage cavity in each piece happened to weld up. Moulds of this kind belong to that period when manufacturing profits in the steel trade were able to withstand avoidable waste, and when it was considered heresy to cut ingots up to look for the hidden defects. Even now some steel-makers, at all costs of logical violence, manage to retain the belief that they can cast sound ingots in moulds of a prevailing but none the less objectionable kind; objectionable, that is, if soundness is of first-rate importance.

One of the most astonishing features in the development of ingot making is the use, over an extended period, of such shapes of ingot moulds as cannot possibly enable a sound ingot to be produced. And yet the faculty for minute observation and comparison amongst the steelmakers of two generations ago was proverbial! They knew how to distinguish one degree of hardness from another amongst their own ingots with a nicety that could not be bettered by the analyst. For half a century or more they observed and turned to good account minute differences which the younger generation, relying on the resources of chemistry and physics, will never see. They knew, of course, that such ingots as were broken up from time to time exhibited defects quite different from and in addition to those suspected; but explanations were not wanting, and with a faith that would do credit to a religious zealot they believed the unbroken ingots to be perfect.

If to their undoubted faculty for minute observation there had been added the stimulus of imagination! If the young men amongst them, as is a young man's privilege, could have seen visions and dreamed of any possible improvement the crucible ingots made by our fathers would have been cast in inverted taper moulds and dozzled. But, as is always the case when a handicraft is followed and extended entirely according to commercial experience, the older members of the craft were its seers and high-priests, and the young mind strove to emulate but was not encouraged to criticize them. The most obvious evidence was available, as it now appears, that the long parallel-sided ingot could not be sound; but the "elders" said the axial cavities and sponginess were due to hot casting, and the novice admired their wisdom and held his tongue. How true it is both of observers and commentators that "Unless you are very careful you will find what you are looking for."

FLAT MOULDS.—Sheets for saws and many other purposes are frequently rolled from flat ingots. This is the very worst form of ingot so far as the wasteful effects of piping are concerned. The pipe extends laterally right to the ridge of the conical wedge growing from the narrow side of the mould, and in its widest part is generally remote from the narrow side of the mould a distance equal only to about half the ingot's thickness. This is illustrated by the photograph of two sections of a wax ingot reproduced in Fig. 35.

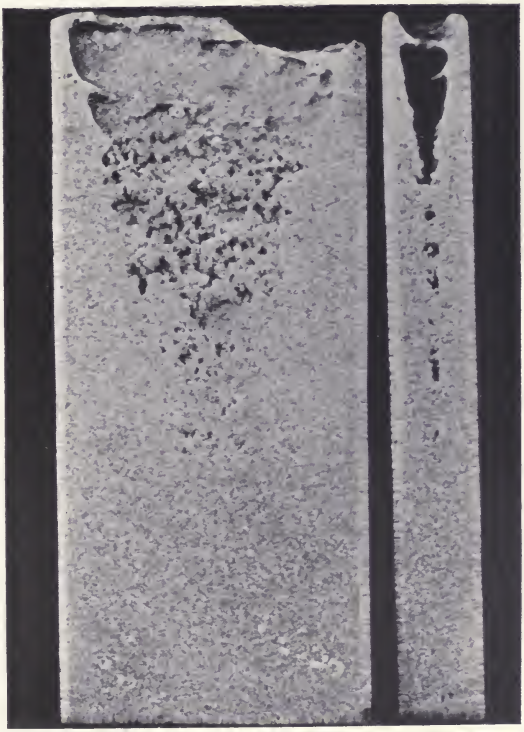

FIG. 35.—Sections of flat ingot.

The surface of the pipe in a flat ingot has a much greater area than the pipe in a square ingot of equal weight; and, unless the pipe is unoxidized and welds up, the area of faulty sheet metal produced from it will be greater. This can be easily demonstrated by cutting a piece of clay or plasticene of square section down the centre and laying it in a piece of similar material of different colour. In a similar way a piece of coloured plasticence of the shape and relative dimensions of the pipe is laid between two sections representing a flat ingot, and the two model ingots are then rolled out on a pasteboard. On cutting up the rolled sheets across the direction of the pipe the comparative amounts of sound material will be strikingly evident. This experiment can also be made with steel ingots by first allowing them to solidify in the mould and then, whilst still hot, pouring molten copper into the shrinkage cavity.

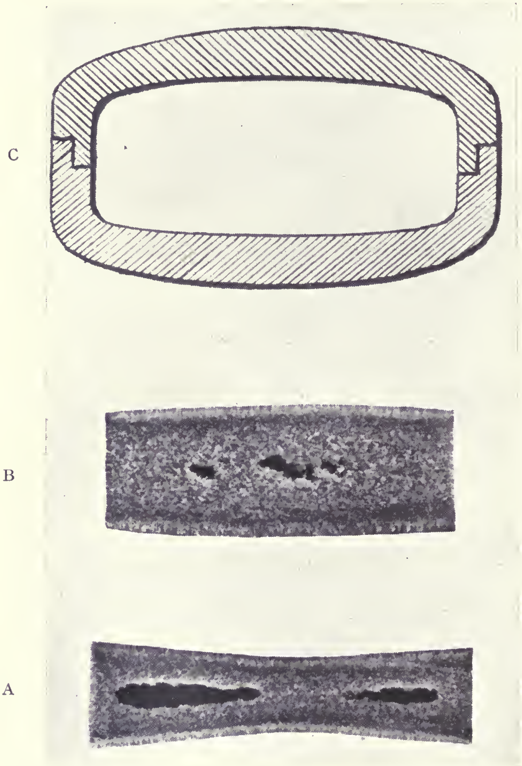

Fig. 36.—Sections of flat ingot and mould.

The flat sides of cast-iron moulds sometimes warp inwards, and are assisted in doing so, in split moulds, by the driving in of the wedge which, with the rings, hold the two halves of the mould together. This causes the pipe to divide in the lower part of the ingot, as indicated at A in Fig. 36. In order to avoid this the ingot should be made convex on its broad side, as indicated at B in Fig. 36. Also, in order to protect the mould from rapid deterioration, it should be thickened, as at C in Fig. 36, where the heat given out by the ingot is greatest.

FIG. 37.—Planes of weakness in flat ingots.

The contraction cavities in flat ingots which are slightly convex on the broad side do not occur in the centre of the ingot as an apparent extension of the primary or secondary pipe, but they occur, as indicated in Fig. 37, at the apex and along the sides of the rectangular pyramids whose bases are the narrow sides and bottom of the ingot mould. These cavities are readily discoverable in wax ingots by the methods of breaking, cutting and planing already described.

ROUND MOULDS.—Amongst a number of reasons why ingots should be made round special prominence has been given to the fact that the area of their surfaces is less in proportion to the mass of metal they contain than can possibly be obtained in any other form of ingot. This can be an advantage only if the ingots contain surface defects; and even then, as the area of two forgings in any comparative case will be the same, any particular defect in the round ingot will be spread out more than would an identical surface defect in an octagon, square, or flat ingot. It is true that defects in hot round ingots can be gouged out more easily than similar defects on a flat surface; also that the first deformation of a round ingot under a hammer or press causes a good deal of scale to loosen and fall off, thus lessening the fear of reheating scale being hammered into the surface; but the combined advantage is at any rate not a great one, and is offset by some disadvantages.

Round ingots are very apt to crack both internally and externally. The suggestion that external cracks are due to expansion of the fluid steel as it solidifies is not supported either by actual observation or reasonable inference. Steel does not expand on solidifying, otherwise there would be no difficulty in casting ingots free from pipe, and cracked ingots of all shapes would be very common. Such cracks as do form on the outside of round ingots certainly appear to be due to pressure exerted from the inside, which, if uniformly distributed, would be greater per square inch of the surface in round ingots than in those of any other shape.

Pressure exerted from within on the surface of an ingot may arise from either of two causes, *i.e.* that due to the weight of the liquid after the outside of the ingot has solidified and left the mould, and that due to the expansion of the hotter interior of the solidified ingot when the steel passes through the pearlite change point, *i.e.* in ordinary steel at about 700° C. The former kind of crack would be encouraged by casting the metal hot and quickly, and the latter by any condition which caused the outside of the ingot to cool very rapidly. An examination of the cracked surface formed in the earlier instance would certainly show scorch; those formed at the later stage might or might not, depending on such circumstances as are discussed on p. 57.

Harmet pressed ingots furnish good examples of cracked ingots due to expansion of the interior portion of solidified material. They are sometimes cast round, and are kept in contact with the interior surface of the water-cooled mould whilst under compression. To avoid the tendency to crack, which is thus increased, it is necessary after stripping to equalize their temperature by cooling them in some kind of soaking pit or charging them directly into a slowly fired reheating furnace.

Internal cracks are apt to occur in round ingots either after stripping or during reheating for the same reason that round bars of tool steel sometimes split up the centre on hardening and tempering. The outside of a large ingot is rigid long before the interior of it ceases to contract; if, therefore, the outside by added warmth (in the reheating furnace) or by heat diffused from the inside is caused to expand, it increases the tension at the centre and may pull it apart, and that occurs most easily, of course, through the bottom of irregular and sharp-angled cavities.

The danger of internal flaws, either actual or potential, is always greatest in complete round sections. In the first place, because the stresses are symmetrical and all converge on the centre; and in the second place, because (on reheating) the heat is equally distributed and the expansion, therefore, is comparatively large before any portion of the rigid surface is hot enough to become plastic. The corners of a square bar quickly attain the temperature of a reheating furnace and may yield to internal stresses before the surface expansion produces rupture; moreover, under like conditions the middle part of flat surfaces can yield better than any part of a circular section. Rectangular pieces are less apt than squares to break in this manner, even if they are very thick, and never if they are thin, unless the steel is defective.

It has been found possible to make large round ingots in cast-iron moulds lined with steel-moulders' composition or ganister; and large ingots made from crucible steel for guns and marine shafts were formerly cast in that manner. The refractory lining of the mould decreases the rate of cooling enormously and minimizes to a considerable extent the danger of hot casting. The solidified outer shell forms more slowly, or in the case of very hot casts might even form in places and melt again as it does in an ordinary casting ladle. There is, therefore, not anything like the same tendency to scorch in the outer envelope, and after leaving the sides of the mould it is better able to withstand the internal fluid pressure which, in turn, is also less. The temperature of the ingot is also more uniform throughout, and consequently there need be less fear of external cracks, owing to equalization of inner and outer temperatures.

But with all these advantages no steel-maker would venture to cast very large ingots of round section in loam-lined moulds. Partly because the cost of preparing the mould and cooling and stripping the ingot is prohibitive, and partly because, owing to the slower rate of cooling, the effects of segregation are more marked. And whilst the segregates are tolerable and comparatively harmless in a straight shaft they are highly objectionable in a gun tube, a turbine drum, or any other object which in use is stressed transversely.

A compromise between a chill and a loam-lined mould may be secured by arranging long bars of square iron vertically on the inside face of the moulds and filling the gaps between them with refractory material. The steel then freezes first against the iron bars, but cannot contract from them because they are disconnected. The ingot leaves the surface of the mould when the parts facing the refractory strips become strong enough to resist the liquid pressure. The preparation of such moulds is also a costly matter.

The idea that because a round forging is required it should be advisable to make it from a round ingot ought not to be encouraged. To elongate a round ingot by rolling it under the blows of a hammer is one of the surest ways of causing it to crack in the centre. So that whether the ingot is cast round or not, if the full benefit of forging is to be obtained it must be made and kept approximately rectangular until it has been reduced to something like the required size. Neglect of this precaution is responsible for such defects as are illustrated by Fig. 38, representing bars which have been purposely reduced in this undesirable way from a sound bar of larger section. The same objection to working a round ingot does not apply, of course, to hollow forgings worked on a mandrill.

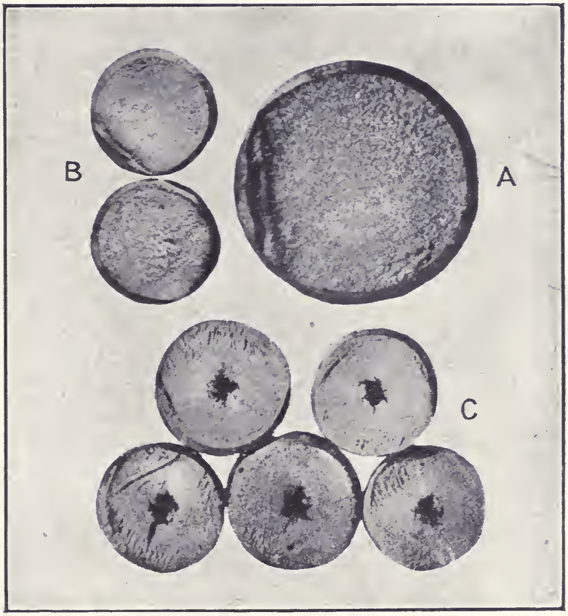

FIG. 38.—A. Original bar. B. Properly forged bar. C. Improperly forged bar.

The danger of cracking in round ingots increases with the hardness of the steel, and it is quite impossible to make very large and sound ingots of high-speed or air-hardening steel in chill moulds. The danger, however, decreases with the diameter of the ingot, other things being equal, and it is therefore practicable to cast round ingots of air-hardening steel up to six, eight, or even ten inches in diameter.

In Germany and Austria, and also to a lesser extent in England, high-class steel ingots are made in circular moulds so that before they are forged surface defects may be removed by turning. This plan, properly carried out, seems to be an economical one.

In certain kinds of sheet steel, steel for calico-printers, rollers, drop stampings, and in all kinds of intensive air-hardening steel, the condition of the surface of the ingot is responsible for many defects which often spoil the forged article entirely. On this account the most carefully cast ingots may require chipping, and, after cogging, may even be pickled in order to discover further defects requiring to be ground or chipped out.

In spite of so much trouble the final machining, or some subsequent operation, may disclose further faults which have originated from surface defects, *i. e.* one can never be certain that every kind of surface defect has been chipped out. A certain amount of security can be obtained by leaving a large margin to be machined away from the forging; this, however, increases the cost of both material and labour and is not an absolute safeguard.

Ingots made in circular moulds, after softening if necessary, can conveniently be turned. The results of the method as worked on the Continent appear to be quite satisfactory and actually cheaper than the usual methods of chipping and pickling. A method involving only one handling of the material would appear on the face of it to be economical. If unavoidable defects of a serious kind occur it is also an advantage to reject the material before much money has been spent on it. It is also undesirable, apart from any question of cost, that material should be found to contain defects after it has been delivered, as this gives rise to mistrust, claims for compensation, useless freights, and various kinds of unproductive expense.

There are also circumstances in which the ingot may or must be at once rolled to finished dimensions, and in these cases the importance of faultless surfaces cannot be overrated. A number of German firms making tool steel from electric furnace plants find it indispensable to cast round ingots and turn them, as it is not possible to cast ingots from a ladle with the care and success of the competent melter who pours the stream of molten steel over the lip of the pot when and how he pleases. Round ingots, therefore, of moderate size, say, from two to ten cwts., are likely to be cast in larger rather than in smaller numbers.

It should, however, be noted that the machining of an ingot free from surface defects is no guarantee that the bars or forgings made therefrom will be quite satisfactory. If the ingot is " tender," owing to having been cast hot, for example, it may develop cracks during rolling or forging and thus defeat the object of machining. For this reason, amongst others, it may be found more economical to cogg a square ingot into a round bloom before machining and then work the machined blooms into the finished form. Such blooms may be depended upon to produce bars or forgings free from surface defects, except laps or similar blemishes directly due to careless workmanship.

OCTAGON MOULDS.—The flat ingot is the safest shape, from a geometrical point of view, that can be cast, because its broader flat sides will accommodate themselves to pressure from within or without. Next in order of safety comes the square ingot, which is more convenient than the flat one for making into any kind of bar and most kinds of forgings; it is also easier by simple means to make a square ingot sound. The square ingot is the kind generally made, but as to its properties, as determined by its shape, there is nothing to add which has not been already suggested, at least, in the earlier chapters.

Polygonal moulds with convex inner faces, used only for large ingots required in the manufacture of gun tubes, marine shafts, tyres, etc., are said to have been introduced by T. E. Vickers about 1880. The prevailing forms are octagon and hexagon, and the correct curvature of the inside faces is reputed to be equal to that of the circle which circumscribes them. The octagon mould is an attempt to preserve the advantages and reject the disadvantages of the round ingot. Probably any ingot of symmetrical form which could preserve its symmetry and modify its size after the outer shell of solidified steel contracted from the ingot mould would be an improvement on the round ingot as far as cracked surfaces are concerned. The convexity of the inner surfaces of the octagon mould increases the cooling effect of the mould, but at the same time it increases in due proportion the sharpness of the angle between one face and another.

The sharpness of the angle between the curved faces of an octagon mould is a source of danger. The upper surface of the rising steel freezes immediately in those parts, and in doing so is apt to occlude oxidized metal and slag floating on the fluid metal. Such occlusions lead readily to cracks on their own account, one of which, at low magnification, may be illustrated by Fig. 13.

The bane of octagon moulds is the longitudinal crack down one or more of the corners, which cracks, so far as the authors' experience goes, have always the scorched structure and appear to be due rather to something in the nature of a pull than to pressure arising within the ingot. By greatly increasing the convexity of the inside faces of the mould it becomes easy to realize that the corners of the ingot would quickly become rigid, and bind on the faces of the mould when a certain amount of lateral contraction had taken place. Whether or not the ingot would thus be caused to crack depends on how far it stood free of the mould and how much the lateral contraction amounted to. If the binding on to the mould occurred before the contraction was about over the ingot would certainly crack longitudinally; and if it occurred early in the process of setting the crack would locate itself near the corner.

It would seem, apart from scorching and the planes of weakness arising therefrom, that corner cracks might originate in something like the manner just indicated. It is, at least, desirable in octagon moulds to flatten the ends of the curve in addition to rounding the corners so as to provide for unavoidable variations in casting temperature, which have perhaps not been taken into account in working out strict geometrical relationships between the curvature of interior faces of the mould and the circle circumscribing them. Above all things, the steel-maker who talks about the working of processes, should know that to some extent the processes work him and he must respond accordingly if he would be successful.

A very plausible case for the admitted superiority of hexagon or octagon moulds with curved faces over those with straight faces has been stated by Reusch.[1] He says, “A mould having straight sides as in Fig. 39 A will deform as indicated in Fig. 39 B after an ingot has been cast into it. The mould will then be in contact with the ingot only at the corners marked *a*1, *a*2, *a*3, *a*4, *a*5, and *a*6, whilst in the positions marked A1, A2, A3, A4, A5, and A6, a free space will form between the contracting ingot and the expanding mould which is sufficiently great to give opportunity to the ferrostatic pressure of the fluid metal to burst through. This tendency to break is also favoured by the fact that at position A the shell of solidified metal is thinner than elsewhere. When, however, the inner surfaces of the mould are made convex both the expansion of the mould and the contraction of the ingot are more uniform, because that portion of the ingot from which most heat has to be conducted is in contact with the thickest part of the mould.”

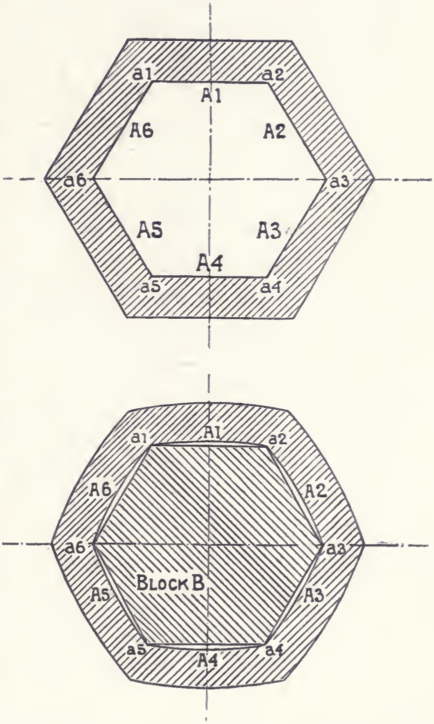

Fig. 39.—Assumed distortion of hexagon moulds.

Mould Bottoms.—In considering the general properties

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[1] *Stahl und Eisen*, 1903, 375.

of ingots it was assumed that the bottoms of the moulds were flat; this, however, is by no means always the case, nor is it the most desirable form. The height of the pyramid in the bottom of the ingot (see Fig. 2) is greater or less according to the cooling effect exerted by the plate on which the open mould stands. It is less, therefore, when the mould stands on a slab of firebrick than when it stands on a cast-iron plate. But it is possible to decrease the height of the pyramid in other ways; *e. g.* by dishing the bottom of the mould.

An ingot made with a convex or approximately semicircular base also contains a pyramid; but the growth of the crystals forming it takes place as usual at right angles to the inside face of the mould bottom, and the effect of this is to throw the apex of the pyramid nearer the bottom of the ingot. That is to say, less material would have to be discarded if it were thought desirable, as might be the case, to get rid of the segregates accumulating on the face of the pyramid. There need also be less anxiety, when the ingot has a curved base, that the pyramid will be forced out, or slipping occur along its faces, during forging. This danger is non-existent in any case in mild steel, but by no means so in very hard steels, such as high-speed tool steel, which are less plastic and less weldable at forging heats.

Ingots are generally made with rounded bottoms, for a more obvious reason. In crucible practice the bottom of the mould is always semi-circular or parabolic, in order that the first impact of the molten metal may not scatter and spoil the lower part of the ingot; and also to aid the formation as early as possible of a pool of fluid steel into which the remainder may be quietly poured.

In large top-cast ingots the bottoms are made round for the same reason. This requires, of course, that each size of ingot mould must stand on a bottom specially designed for it, and thus arrangements for casting become more precise and less convenient. To provide otherwise for the rapid formation of a well of liquid steel into which the stream can fall the bottom plate is sometimes cast with a recess into which a fireclay vessel, shaped like a shallow flower-pot, is placed. The nozzle of the casting ladle is opened directly over this refractory dish, and the scattering of the metal is thus minimized. Two such dishes are occasionally fitted into the base plate of large, flat ingot moulds that are to be filled from two separate ladles, but the practice is not a commendable one, as it introduces the danger of pulling in the bottom part of the ingot lying between the two fireclay dishes. The same danger arises whenever the flat or rounded bottom of an ingot mould gets cut, with two or more widely-spaced cavities, by the falling stream, and to avoid such cavities it is the practice in some works to lay wood shavings, cotton waste, or even a thin sheet of steel, on the bottom of the mould.

But even when a refractory dish is used it is better to arrange for the bottom of the mould to slope towards its upper edge rather than to leave it flat; the reason being that the cooling from the flat-bottomed mould is always favourable to pulls. This may be illustrated by referring to the crucible ingot mentioned on p. 67. In the first place a rounded bottom is not so likely to receive widely-spaced depressions as a flat one, because the full force of the vertical stream can be exerted over only a comparatively small area. Also in the flat-bottomed ingot, a pull once started finds an easy path through the vertically disposed crystals, whereas in a round-bottomed ingot a vertical crack cannot proceed very far without having to break across a crystal, and the worst that can happen is for the crack to get diverted sideways and break off the bottom end of the ingot.

When a stream of steel with the ladle-pressure behind it falls from a nozzle to the bottom of a long ingot mould the first few hundredweights of it solidify at once, and for some time the metal scatters as solidified particles or swirls violently as a pasty mass along the bottom and sides of the mould. A fireclay dish minimizes, but does not altogether prevent this. The metal which solidifies or scatters becomes oxidized on the surface and thus introduces into the fluid metal which surrounds, and may or may not remelt it, a certain amount of iron oxide which acts in the ingot mould like the charged iron oxide (ore) does in the open-hearth furnace, and produces both oxidized forms of silicon, manganese and iron as slag enclosures, and oxidized forms of carbon as gas bubbles. Much of the slag, and some of the gas also, is trapped by the rapid solidification of the surrounding metal. But the latter has greater bulk and less weight in its favour and rises upwards. Here and there, however, a gas bubble is imprisoned in the act of rising, and being held on its underside assumes the shape of an inverted pear. Fig. 40 represents the size and shape of gas cavities found at the lower end of large ingots.

FIG. 40.—Gas cavities at base of large ingot.

FIG. 41.—Structure of material about bright cavities × 16.

Many of the gas cavities are quite clean and metallic on their inner surfaces; these possibly weld up during subsequent working and exercise very little influence on the properties of the finished forging. Some of the cavities, however, are oxidized on their inner surfaces, owing to occluded air, and these may not weld up, but increase the reedy or streaked appearance, due jointly to the occluded slag and these unwelded cavities, seen on the fractured surfaces of broken transverse tensile test pieces. The appearance of the steel adjacent to the surface of the "bright" and "oxidized" cavities, as exposed by polishing and etching, is very different. In the former case (Fig. 41) the normal structure of the steel extends to the surface, whereas in the latter case the surface of the cavity is surrounded by carbonless metal (Fig. 42).

FIG. 42.—Structure of material about oxidized cavities × 16.

Few steel-makers would care to commit themselves to a definite opinion as to whether slag is or is not soluble in molten steel. It has been argued, however, that slag is not soluble in steel, otherwise it would be found, as is not always the case, in lesser quantity in the lower than in the upper portion of an ingot, because the former solidifies more quickly and is therefore a part less favourable to the separation of slag or any other dissolved component. This line of reasoning neglects altogether the fact that the bottom part of an ingot, and especially the bottom part of a long ingot, contains an increased amount of slag, owing to the casting conditions, as noted in the preceding paragraph, being different as between the lower and upper portions.

If, however, a stream of fluid steel be allowed to fall into a mould without scattering, or if the scattered particles re-dissolve whilst the surrounding metal is sufficiently fluid to allow the reaction products to coalesce and move upwards, then the lower part of the solidified metal is freer from slag streaks than the upper part.

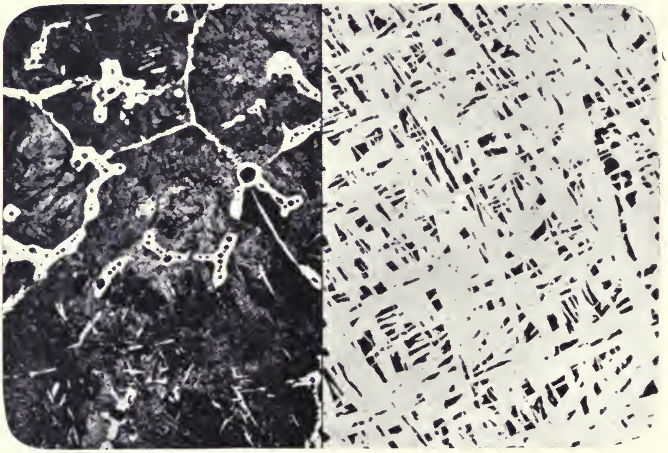

FIG. 43.—Top and bottom sections of frozen ladle metal × 10.

This observation may be made on any large sand casting or on a cast of steel that, through some mishap, has been allowed to set in the ladle. The appearance of sections cut from the top and bottom parts of a block of steel frozen in a ladle is reproduced in Fig. 43. Slag globules are absent from one and very evident in the other, but they have very little bearing on the question as to whether slag is soluble in steel which will have to be settled by quite different methods.

COST AND DURABILITY OF MOULDS

The cost of ingot moulds is a very important item of expense in a large steel plant, but economy may easily overreach itself and lose in the form of defective steel twice or three times as much as is saved in moulds. A mould should obviously be discarded immediately it causes objectionable defects on the ingot's surface. This rule, however, would discard ingot moulds in one shop which would be usable in another, and it is mainly on this account that the maker of high-class alloy steel may be satisfied with an average mould life of fifty heats, whereas the maker of mild steels expects a hundred heats.

The life of an ingot mould cannot be predicted, but it depends chiefly on design, chemical composition, mould-makers' skill and shop practice.

There should be no sharp angles about an ingot mould either on the inside or outside. Probably more moulds are rejected on account of corner cracks than for all other reasons put together. This is particularly noticeable in moulds which are repeatedly filled to within two or three inches of the top. The cracks occur partly because the top of the mould is least pure and contains larger plates of graphite which make it more fragile, but generally because the unfilled part of the mould is very highly stressed by the expansive forces in the lower and much hotter parts of the mould. The life of an ingot mould is noticeably greater if a super-imposed header is used so that the fluid steel fills the mould entirely.

For lifting purposes recesses cast into the side of the mould may be quite as convenient as lugs. It is a simple matter to design recesses with well-rounded corners, but it is not an easy matter to get the iron-founder to reproduce them in the mould. Lugs which form part of the upper end of the mould are better than wrought-iron lifting pieces cast into the sides of the mould, as these are apt to be broken or driven inwards when a sticking ingot is being bumped out. A lug on each side of a square mould is better than lugs cast on two opposite sides only, as the stresses at the top end of the mould are thereby more evenly distributed.

The greatest thickness of metal should be arranged where the greatest amount of heat has to be dispersed, *i. e.* in the centre of the flat side of the mould, and if the moulds are being used for bottom casting they may with advantage be made thicker at the lower end than is necessary when used for top casting.

Ingot moulds are generally made from hematite iron. Iron-founders say that it is the best material for the purpose. Steel-makers are said to prefer it because the worn-out moulds may be charged into the furnace instead of pig iron, thus saving about half the original cost of the mould. The best and most economical practice could be arrived at experimentally, but results connecting the life of the mould with its chemical composition either do not exist or are jealously guarded as a trade secret. It is very certain that so far as variations permissible in hematite iron go the chemical composition of a mould is not a reliable index of its durability. The following are analyses of fourteen-inch square moulds, which have done well.

No. of Heats.	Chemical analysis.					
	Si.	Mn.	S.	P.	Combined Carbon.	Graphite.
142	1·89	·63	·056	·038	·55	3·24
88	1·63	·55	·143	·035	·36	3·10
90	1·54	·64	·054	·093	·73	2·81
130	3·34	1·54	·047	·051	·05	3·40
93	2·0	·72	·074	·046	·69	2·65

But it is only fair to say that moulds of a similar composition and identical in every other visible respect have been known to do very badly.

Strangely enough, iron-founders who think that nothing but hematite iron will make a good mould for open hearth or Bessemer practice will maintain that hematite is only second rate for crucible moulds. Some crucible moulds made by such a founder contained :—Combined carbon ·05; graphite 2·43; silicon 1·65; manganese ·53; sulphur ·137; phosphorus ·279. They had been made from a mixture of hematite and another iron. They were really excellent moulds, but as they could not be replaced from the same source others were ordered similar in composition from a neighbouring foundry (in Russia) and actually contained :—Combined carbon ·46; graphite 2·59; silicon 1·8; manganese ·41; sulphur ·110; phosphorus ·343. These moulds were quite as good as the first lot imported from Sheffield, although they contained no hematite iron. Considering the large tonnage of iron made into ingot moulds and the saving which an improved durability of twenty per cent. would ensure, it would seem that this branch of iron-founding might be profitably investigated.

The weight of moulds per ton of ingots varies in crucible practice from ten to twenty pounds and in open-hearth practice from twenty to fifty pounds (excluding very large moulds). This means that open-hearth moulds weighing from one to two tons would have a life varying from 120 down to 50 heats. Attempts have been made from time to time to use steel moulds, but the authors have had no experience with them. Such published information as is available is of a most contradictory kind. On the one hand, they are said to lose their shape early and crack apparently without reason, and, on the other, they are said to be as good as new after doing hundreds of heats. Thiele[1] fixes the average life of steel moulds at 250 casts, Amende[2] at 300 casts. Both these writers describe the manufacture of the moulds, and one of them quotes an instance of 704 ingots having been cast from the same mould. To those founders who believe that what has once been done can be done again this mould may be quoted as a worthy example.

The skill of the founder is one of the most important variables influencing the life of ingot moulds. From records, extending over a few years, of moulds made from identical patterns by six different founders we observe no difference in the average chemical composition, but a very wide difference in the durability of the moulds. One kind is uniformly good, one is uniformly bad, one is uniformly moderate, another is very bad and then becomes quite good and improves beyond all its competitors. By giving the same attention to defective

[1] *Stahl und Eisen*, 1911, 1285.
[2] *Ibid.*, 1913, 491 and 1637.

moulds as is given to defective ingots the net improvement will be found to be very considerable. Moulds having a short life are found to be scabbed or pitted and are discarded because they produce rough ingots; others have one or more receding places on the inner surface and are knocked to pieces in the stripping process; others have been cast too hot, and being too weak to resist the unavoidable stress due to heating and cooling will crack at the corners. By insistence on a well-fettled mould and the absence of black lead smear or any other coating on the inside of the mould one may by careful inspection discover every ill except that due to hot casting, and this in the aggregate is the chief variable in the life of cast-iron moulds.

In most large steel-works an intelligent investigation and supervision of ingot moulds would be handsomely remunerative, not only so far as direct saving is concerned, but also in respect to improved design, fewer types, and great uniformity in important details such as taper, lugs, etc. Amongst similar moulds in the same works which have been designed by iron-founder, steelmaker or works engineer, tapers varying from 2 to 10 per cent. have been known. Sticking ingots which have to be bumped out shorten the life of a mould, firstly, because the stripping is delayed, and, secondly, because the bumping operation may start cracks. The storing of moulds is another particular in which the life of moulds is effected by shop practice; the loss on this item alone through general neglect leading to rusty moulds and bad ingots is generally sufficient to pay the cost of supervision; and in this respect, as in many others, highly intelligent supervision which can exercise a broad influence and express considered opinions is cheapest.

VI

METHODS OF CASTING

Methods of casting ingots divide themselves into two groups, top casting and bottom casting.

The former method is invariably used in making ingots sufficiently large to take the entire contents of a casting ladle, and the latter is usually used when the contents of a ladle has to be distributed amongst a large number of moulds. Each method has its own advantages, and both may be so carelessly operated that the best of fluid steel becomes thereby inferior. The amount of attention and thoughtful care devoted to arrangements for casting is as good an index as any other of the reliability of a firm's steel, and many of the curious variations in the behaviour of ingots made in adjacent steel-works may be traced to causes more frequently allied with the casting than the actual melting of the steel or the choice of raw materials.

Every increase in the size of furnaces—except with tilting furnaces—and necessarily also in the size of the casting ladles, adds to the difficulty of making perfect ingots. The use of electric furnaces for the manufacture of tool steel may be cited as an extreme illustration of this statement. As fluid metal, electric furnace steels may be almost everything that can be desired. They may be of any desired composition, extremely low in undesirable constituents, such as sulphur and phosphorus, of any desired temperature so as to obtain perfect fluidity of the most refractory of added alloys, held for any length of time to allow non-metallics to separate, and all under the best conditions, in a non-oxidizing atmosphere. In these respects they rival and possibly surpass crucible steel.

But as ingots electric furnace steel leaves something to be desired when compared with crucible steel ingots; they have not the same smooth surface, and are neither as sound nor as free from non-metallic impurities. The reason for these differences lies not, as has been inferred, in the comparative newness of electric steel-making processes, nor in the circumstance that the earlier operations were carried out by electricians who were not also steel-makers, but in the fact that the one kind is cast with personal care when and at what rate a skilful melter pleases, and the other is cast under those restrictions associated with the casting of metal either through the bottom or over the lip of a ladle. These circumstances help to justify the belief that the highest quality of tool steel can be made as cheaply by the old pot process as by the electric furnace process, if due allowance is made for unsound ingot material and scrap steel in bar form.

This is no doubt an exaggerated instance, but it is obvious, as the metal in the casting ladle increases in bulk, that either the casting period or the speed of casting must be increased, and both these alternatives have objectionable features when results are judged by the perfection of ingots made rather than by their cost of production per ton. It is equally obvious that an increase in the size of the nozzle from, say twenty to fifty millimetres during the casting of a fifty-ton charge cannot be unimportant. It may therefore be predicted that except for very large ingots required to make a single forging and for mild structural steels called for at cheap rates, the fixed melting furnaces, out of regard for the production of reliable ingots, will continue to be of moderate size.

TOP CASTING

Attention has already been directed to one of the objectionable features of top casting, *i.e.* the scattering of liquid and pasty metal on the bottom of the mould (p. 85). The sides of the mould may also get splashed either by metal rebounding from the partly formed ingot or through defects in the nozzle, which cause the stream of metal to spray outwards. If a splash sticks to the side of the mould it causes blow-holes to form under the skin of the ingot, as described on p. 68, and if it detaches itself and falls into the liquid mass it also causes gases to be evolved, which may or may not escape. Of the two evils the lesser is that the splashed metal should fall into the main body of the ingot, as there is at least the possibility of it remelting and doing no great harm; whereas when it adheres to the mould it will certainly form blow-holes in an undesirable place, and may also cause the ingot to pull itself into a crack. For these reasons a patch of splashed metal should be detached from the ingot mould, if possible, with a pointed rod. And similarly it is better to clear away any accumulation of cold metal from about the nozzle, though it falls into the ingot, than allow it to interfere with the smooth running of the stream.

Attempts have been made to avoid splashing or the consequences arising from it, but the suggested remedies have not materialized in general practice. One of them is to lower a truncated cone made of sheet iron into the ingot mould by means of cables passing over a pulley. The cone is caused to rise at the same rate as the metal, and when it arrives at the top of the ingot mould it is either withdrawn or allowed to rest on the top of the ingot. The interior of the cone is found to be encrusted with splashes of various sizes, mostly of circular shape and many of them hollow. An examination of ingots cast with the cone at the Obouchoff Works in Petrograd showed them to be free from ordinary surface blow-holes.

A second suggestion is to extend the nozzle of the ladle by attaching an iron pipe lined with firebrick to the underside of it, so that to begin with the open end of the extension would not be far removed from the bottom of the mould. As casting proceeds the ladle is raised at such a rate that the discharge end almost, but not quite, touches the surface of the fluid mass. It is easy to foresee objections to each of these proposals, and the authors are not aware that the second suggestion has ever been tried in actual practice.[1] If, however, it were found to be not entirely impracticable it possesses the advantage of avoiding splashing, and would avoid also surface oxidation of the fluid stream as it falls from the ladle into the mould.

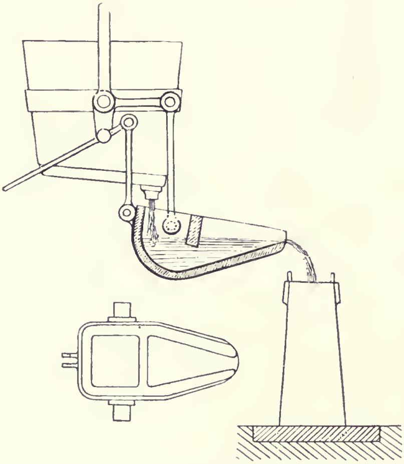

FIG. 44.—Arrangement to avoid splashing. (Harbord.)

Other devices to minimize splashing aim at lessening or getting rid altogether of the nozzle pressure due to the head of metal in the ladle. The arrangement in Fig. 44, reproduced from Harbord and Hall's *Metallurgy of Steel*, travels with the ladle from one mould to another. The arrangement in Fig. 45 is a fixture used in casting Harmet ingots. So far as the defects of splashing are concerned these devices appear to be all to the good. Experience, however, has decided otherwise for reasons not confined entirely to the inconveniences in handling.

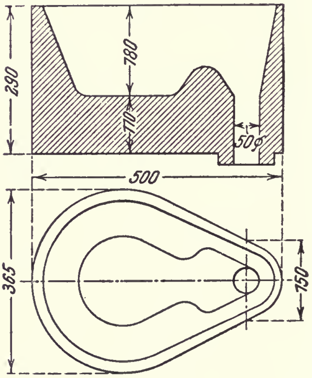

FIG. 45.—Arrangement to avoid ladle pressure.

There is no point in getting rid of splashing if the defects arising from it are caused to arise in other ways. A glance at Fig. 44 suggests at once the difficulty of directing and keeping the stream near the axis

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[1] Casting through a trumpet or guit pipe supported on the top of the mould or attached to the mould, but with an air space between it and the ladle, has been tried without any great success. But such an arrangement violates the necessary conditions, first because the nozzle opening is less than the diameter of the bottom end of a trumpet pipe, and the steel is thus caused to scatter at the lower end; and, secondly, it acts as a kind of air-pump and aggravates one of the evils to be avoided.

of the mould, as the operator cannot see into the mould, and is partly dependent for any adjustment required on a second person, *i. e.* the crane-driver. And to allow the stream to catch the side of the mould would be worse than the splashing. The same objection does not apply to the device in Fig. 45, as it may be fixed with the outlet in any desired position with respect to the interior of the mould.

Splashing is most objectionable in long narrow moulds; but whether there are splashes or not it is important that the metal should have behind it sufficient pressure to deliver an unbroken column of fluid steel. Water running from the domestic tap will fall a certain distance and then break up into drops which knock against each other and spread. The length of the smooth and unbroken water column depends on its thickness and rate of motion, and if the issuing orifice is circular the distance the water can fall before breaking up under the influence of surface tension is calculable. When the issuing orifice is oval a water column pulsates with the long axis of the oval now in one position and now in a position at right angles to the former one, and it appears to break up earlier than a circular column delivering the same volume of liquid.

These considerations apply to the arrangements in both Fig. 44 and Fig. 45. In the former the stream is a flat one, and it is a matter of chance whether it reaches the bottom part of the mould unbroken; in the latter case it depends mainly on making the outlet narrow enough and keeping the trough full of metal. But in either case, even if the spraying does not occur, a greater surface of fluid metal becomes exposed to the oxidizing influence of the atmosphere.

Oxidation of the fluid steel after it has received its "finishings" and left the furnace is harmful, but by any practicable means of casting is unavoidable. That such oxidation occurs is quite evident from the red fumes of ferric oxide[1] arising as the steel runs into the ladle and

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[1] The fumes cut off the light or heat rays from optical forms of pyrometers used to measure the temperature of molten steel as it runs from the furnace; they are less abundant around cold heats, which accounts for the fact that temperatures measured pyrometrically make no appeal to the furnaceman, whose experience they contradict.

from the envelope of blue carbon monoxide flame around the stream as its runs from the ladle into the ingot mould. These sources of oxidation, as well as the remnant of that which ought to have taken place in the furnace after the " finishings " were added, increase the amount of occluded slag globules, and they ought not to be further increased in amount by the use of intermediate ladles and troughs without ample compensation in other ways.

Oxidized forms of steel float on the surface of the metal rising in the mould as a crust of greater or less thickness. The absence of a crusted surface does not mean necessarily that no oxidation has taken place. It may be that the temperature of the steel is high enough to keep the oxides molten; they or their effects will appear sure enough if the ingot happens to be worked up and tested minutely and severely.

When, however, a crust does form, as it always will on certain kinds of steel, notably chromium steels, then one of the advantages of top casting is that, on large ingots, the crust can be watched and made least harmful. The crust is hardest and thickest near the surface of the mould; it cannot form in the centre or at that point disturbed by the falling stream. It becomes convex owing to its varying strength and the pressure of the rising fluid beneath it. If not loosened from the sides of the mould and permitted to ride easily on the surface, the rising metal will crack it, thrust it back towards the side of the mould and submerge it. Where the crust is strongest there also the steel is coldest, and when, through chance or negligence, part of the crust sticks in the pasty steel and becomes submerged by hotter metal, a magnificent gas cavity may form immediately underneath or perhaps an inch below the surface of the ingot. The harm this can do and the difficulty there may be in tracing backwards the consequent defects in fine sheets and rods is obvious.

A layer of boiled tar on the inside of moulds keeps the crusted edges " wick," as the furnacemen say, and to some extent prevents the crust from sticking to the sides of the mould. The effect of tarring is by no means the same thing as that of the spitting which takes place when hard steel is cast into bad moulds (p. 45), because in the former case the gas evolution takes place at a lower temperature and nearer the extreme surface of the rising metal. Hence, as might be expected, the tarring of small three-inch crucible moulds is unsatisfactory in its results, because the steel rises quickly and covers the tar before the volatile matter has been driven from it. If a mould is too hot when the tar is laid on the heat chars it, *i. e.* drives the volatile matter off, and lessens its value as a remedy for sticking crusts.

An ingot cast over the lip either of a crucible or the end of a trough, as in Fig. 44, is found to be dirtier on the side lying at the back of the stream than on any other of the remaining three sides, owing, it may be supposed, to the surface of the fluid steel being least disturbed and accumulating, by a sort of backwash, an undue amount of oxidized material in that position. Even if the stream is pitched in the centre, the metal on the foreside is kept livelier than that at the back; but the ingot, if cracked at all, is most likely to be cracked on the side facing the incoming stream, due, of course, to the fact that it becomes hotter and remains hot for a longer time than either of the remaining three sides.

Verbal instructions as to the speed at which an ingot should be poured cannot be of great value. The slower the pouring the less obviously the volume of shrinkage cavity, but the greater the chances of getting the nozzle frozen up or of forming congealed metal about it to interfere with the smooth delivery of the metal. Even a crucible charge cannot be cast at arbitrary speeds; if it is cold (or if graphite crucibles are used, the lips of which are better conductors of heat than those of clay pots), then it must be poured more quickly in order to avoid what the workmen call a dirty lip.

It requires considerable judgment to select the right size of nozzle for casting high-quality steel, and very large ladles are often provided with two nozzles, either of which can be chosen for use when the man in charge knows more about the steel to be cast than he can be certain of when the ladle is being got ready. To choose a nozzle "big enough" may be permissible on tonnage plants, but it is not regarded as a favourable excuse for cracks and other defects in high-carbon and alloy-steel ingots. A hot heat cast through a large nozzle will surely lead to trouble whether opened wide or restricted by lowering the stopper rod. In the latter case the nozzle does not fill completely and the fluid metal spatters; or the stopper end may be pulled off by the hot metal rushing past it, and then the passage of the ladle to the next mould is of the nature of a firework display. However much one may read about the chemistry of steel-making, studies in the actual casting of steel can be carried on only in the shops, and there even according to no pre-arranged plan or curriculum.

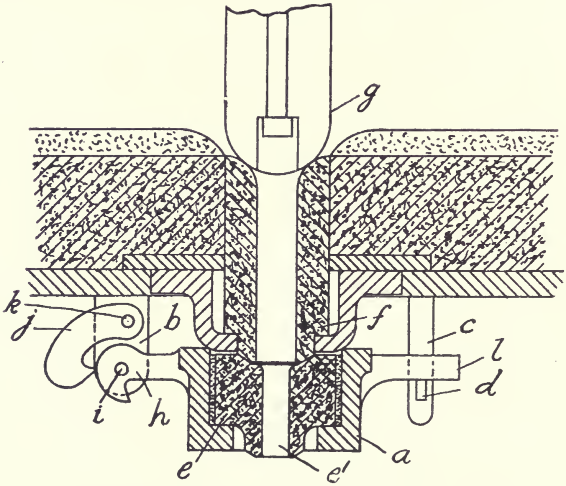

FIG. 46.—Section of Batty's secondary nozzle.

A very excellent nozzle arrangement has been evolved by Fred Batty, who for many years has attempted the thankless work of choosing ladle nozzles which would not conflict with any one of several unknown variables. Batty's arrangement, which is illustrated in Fig. 46, can be applied to existing ladles without interfering with nozzles and stoppers already in use. It consists of a supplementary or secondary nozzle box secured to the ladle bottom. It may be secured in position by studs and cotters placed at convenient distances apart, or as shown on the accompanying drawing, it may be hinged to a depending bracket *b*, on one side, and supported at the other by a bolt *c* and cotter *d*, or a movable catch may be employed, the whole being so arranged that, by knocking out the cotter or turning the catch on one side, this secondary nozzle box *a* will swing down and hang clear of the discharge orifice of the primary nozzle. This secondary nozzle box *a* is recessed to receive a smaller fireclay nozzle *e*, which is so shaped as to fit close up to the end and orifice of the primary nozzle *f*, and is provided with a smaller orifice e^1, of any desired size less than the orifice in the primary nozzle *f*; so that when the supplementary box *a* and nozzle *e* have been secured in position, and the stopper *g* is raised to allow of the flow of molten metal through the primary orifice *f*, the flow is partially arrested and reduced by the secondary nozzle *e* for a desired period until the full flow is required, immediately upon which the cotter or catch *d* is knocked away and the supplementary box *a*, with its nozzle *e*, swings clear or is otherwise moved out of the way, so that the full discharge from the primary nozzle may be continued until its stopper is closed.

This invention of Batty's is not nearly so widely known and used as it deserves to be. Its great advantage is that the size of the casting nozzle can be changed between any two ingots or groups of ingots; so that when top casting if the first ingot has been poured too quickly the nozzle can be changed. It is also possible by means of this device to run always with the nozzle full open, and thus the wear on the stopper end is to a great extent avoided, and there is very much less danger of the stopper end being pulled off. Also a full nozzle is indispensable to a smooth delivery, and with little or no spluttering and spreading of molten metal it is easier to produce nice ingots.

If a large-sized primary nozzle has been used, the Batty device on a ladle gives one almost every advantage to be derived from multi-nozzle ladles at a much less cost and with less attendant labour and danger. If the secondary nozzle is running too slowly it can be replaced with a larger one up to the size of the primary nozzle; and if it is running too fast an alteration can be made the other way about.

We do not know whether the Batty nozzle has been used much for bottom casting clusters of ingots through a central runner, but, as a smooth stream of metal delivered straight down the central guit is preferable, for several reasons, to a spreading stream washing over the upper lining of the central guit, it may be recommended for that purpose.

The use of magnesite nozzles has been strongly recommended, notably by Williamson, for casting top-run ingots. They are supposed to obviate most of the troubles connected with the rate of teeming, mainly because they preserve their original size from start to finish. It seems doubtful, however, whether a constant nozzle aperture is really an advantage. If a full aperture is desirable to avoid pulling off the stopper end, then a constant teeming speed can be secured only with a nozzle whose aperture increases gradually to correspond with the decreasing ladle pressure. A clay nozzle which will open out at the proper rate appears to be ideal. It may, of course, open out too much, and then there is no remedy except casting the ingot too fast or closing down the stopper, and thereby risking splashed ingots and loss of the stopper end.

But consider the magnesite nozzle which does not wear larger: it is necessary, as with the clay nozzle, to choose the right size to begin with. Suppose, now, the size chosen is correct and the first ingot cast is satisfactory. As the nozzle aperture is unchanged the second ingot will be cast at a slower rate, and the third ingot at a slower rate still. So that the variation in casting speed between the first and subsequent ingots may be much greater when using a magnesite nozzle which does not wear than when using a clay nozzle which does wear. The latter may not wear at the required rate, but such increase in the aperture as does occur is likely to be more approximately correct than no wear at all.

In order to make some allowance for decreasing ladle pressure magnesite nozzles are made with a top part of fireclay having a smaller aperture than the lower magnesite part. The wear-resisting properties of the magnesite are not serviceable in this combination until the clay has worn down to the same size aperture as the magnesite.

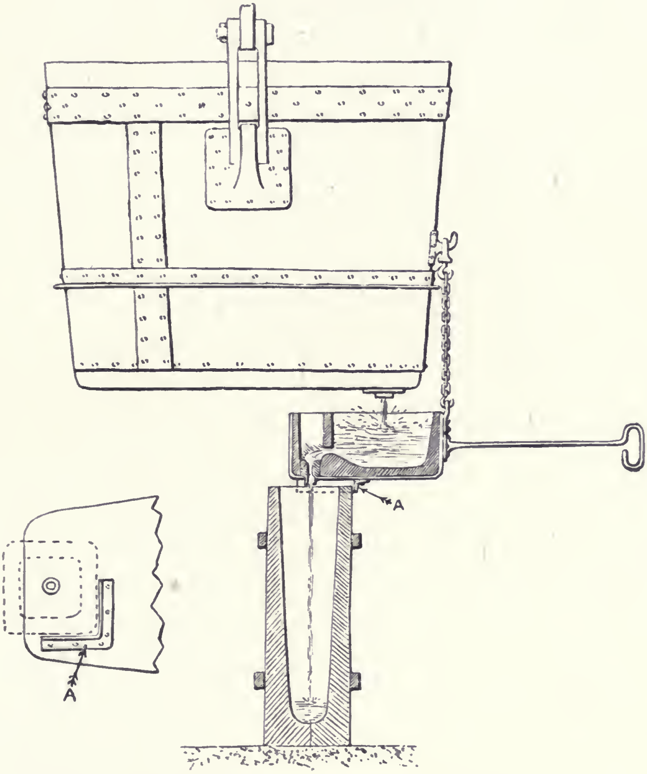

FIG. 47.—Arrangement for casting small ingots from ladle.

The latter then maintains its size to the end. If, however, it is desirable to use a nozzle which wears during the casting of the earlier ingots it would seem advisable also to have a nozzle which keeps on wearing as the ladle pressure gets less.

The arrangement shown in Fig. 47 was devised by the authors for casting small ingots of about two cwts. into split crucible moulds, from a ladle containing between two and three tons of steel. It is not possible to cast hard steel ingots of this size direct from the ladle for the following reasons :—

1. The nozzle pressure is too great.
2. The ingot moulds fill too quickly.
3. There is some difficulty in closing the nozzle after delivering only a small quantity of metal.
4. Spraying from a defective nozzle is fatal in narrow ingot moulds.
5. A ladle is too unwieldy to cast from without catching the ingots.

The arrangement consists of a trough suspended by a chain from the side of the ladle, so that the small ingots required and larger ingots cast direct from the ladle could be made in succession from the same heat. Any slag on the surface of the metal it contains is held back by a bridge at the fore end of the trough through which clean metal runs, and thence from a half-inch nozzle into the mould. To ensure that the stream falls down the centre of the mould a piece of angle iron A is riveted to the bottom of the trough and engages with two adjacent sides of the mould; this can be made adjustable to suit moulds of different sizes. The trough makes it a matter of comparative indifference whether the ladle nozzle drips or not. Its movement is controlled by the projecting handle, the *modus operandi* being as follows :—

The moulds, cleaned and reeked, are arranged in a row. The first ingot having been cast the ladle is shut off and the trough is simultaneously tilted backwards. The ingot is immediately provided with a white-hot brick-head (dozzle), which is at once filled from the trough. The second ingot is cast in the same way, and so on, no time being lost in moving and adjusting the ladle from one position to the other, as the trough is movable on its own account, and its nozzle is centred automatically on jamming the angle iron against the sides of the mould. Everything depends on careful preparation and the operations being carried out speedily, and on this account it is a great convenience to have the moulds mounted close together on a car instead of in rows on the floor.

Tun Dishes.—It is maintained, and very reasonably, that improved results are obtained from top-poured ingots if the steel is cast through a secondary ladle or tun-dish instead of directly into the ingot mould. A tun-dish may contain one or more nozzles, according to the weight of material or the number of ingots requiring to be cast. Defects arising from ladle pressure and hot casting are considerably lessened by the use of tun-dishes, and according to Kilby[1] the percentage of ingots suffering from cracks whilst being rolled or forged is reduced to a minimum if this method is thoroughly carried out. Some firms have been highly successful in the use of tun-dishes; others are less satisfied. Failure is usually invited by expecting to do too much at once, and overlooking the value of preliminary training of the workmen. The general principles of tun-dishing and suggested pieces of apparatus for the job are reproduced from Kilby's paper in Figs. 48 and 49.

BOTTOM CASTING

Bottom casting of groups of ingots is an indispensable device when large volumes of steel have to be cast into comparatively small ingots; but, as with every other convenience, something has to be paid for it, and that something is not comprised entirely in the runner scrap and extra labour involved in stripping the ingots and breaking off the steel runners. A general opinion is that sounder ingots are obtained by using closed-top moulds and casting from the bottom; and if the comparison intended is with top-cast taper ingots made in moulds with the narrow end up, it is undoubtedly justified by experience.

Individual steel-makers are to be found who contend that bottom-cast ingots can be made perfectly sound by using a long trumpet and feeding it with hot metal. This, on the face of it, is highly improbable, however long the trumpet is made, as the steel in some part of the

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[1] *Journ. Iron and Steel Inst.*, 1916, II, 193.

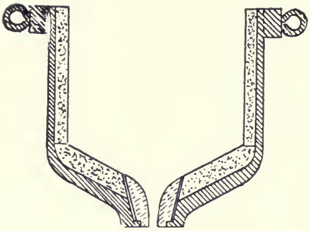

FIG. 48*a*.—Type of "tun dish." Single nozzle.

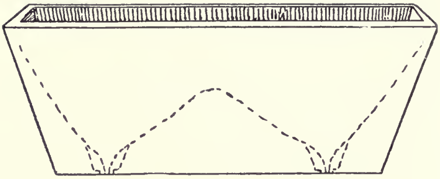

FIG. 48*b*.—Type of "tun dish." Two nozzles.

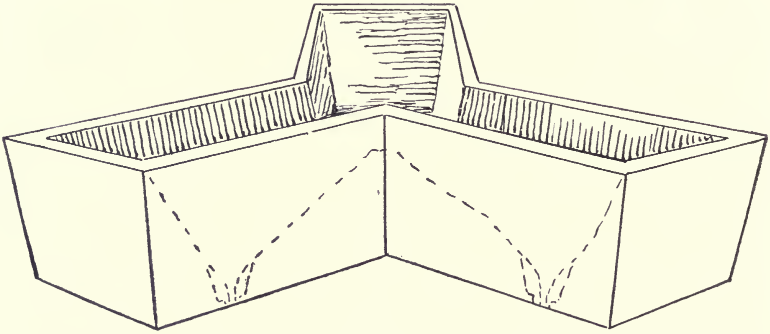

FIG. 48*c*.—Type of "tun dish." Three nozzles.

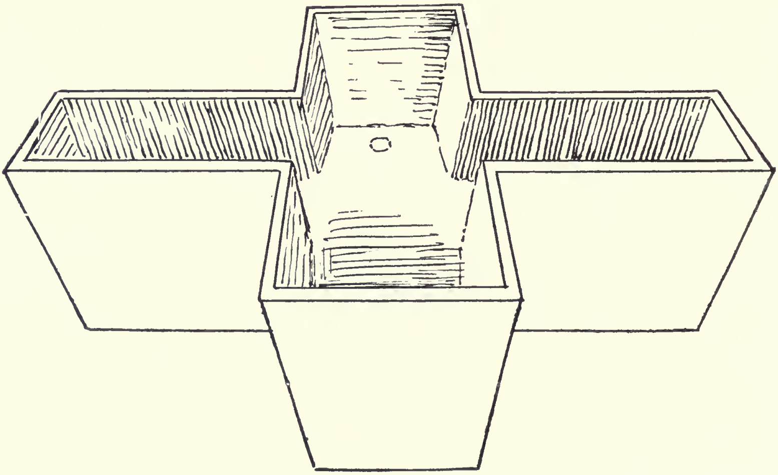

FIG. 48*d*.—Type of "tun dish." Four nozzles.

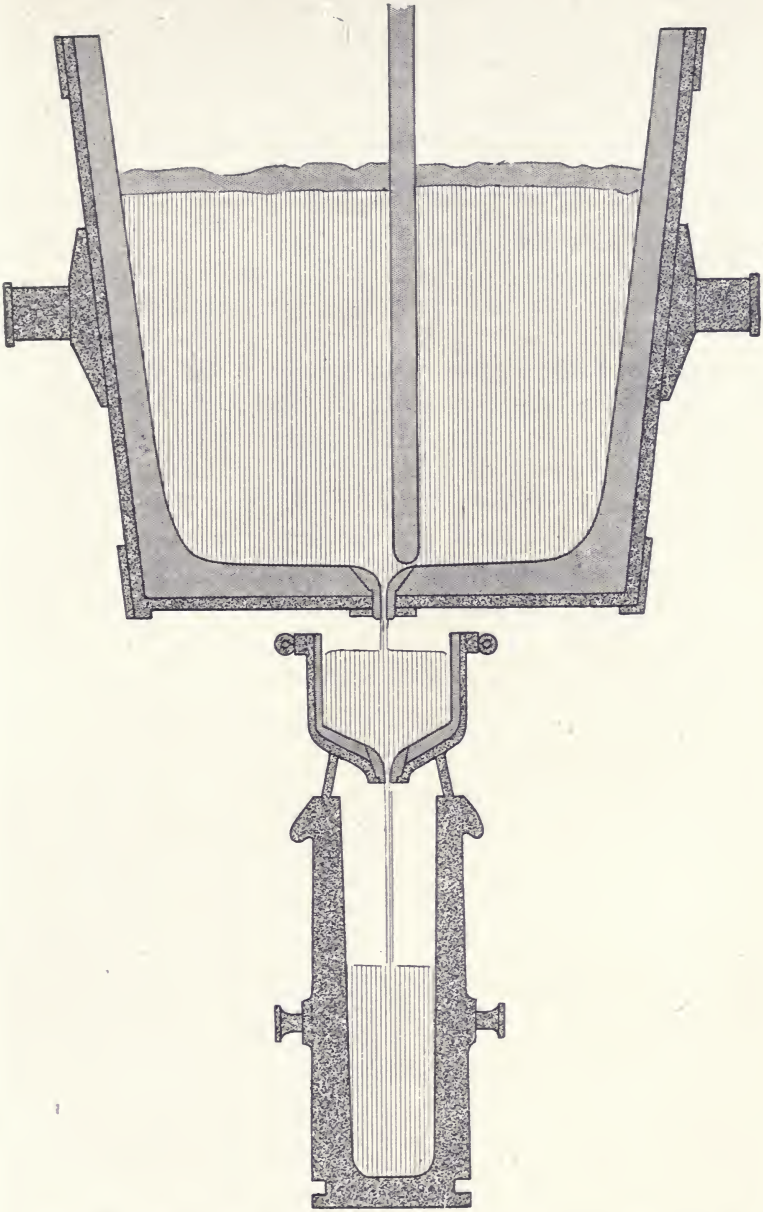

FIG. 49.—Ladle, etc., showing mode of casting. Dish may be on mould or attached to ladle.

runner bricks will certainly freeze across before the interior of the ingot has solidified and thus hermetically seal up the ingot against further feeding. As to volume of shrinkage cavity, there is not a great deal to choose between a bottom-cast and top-cast ingot which have been poured at the same rate; the advantage enjoyed by the former is that its cavities are more likely to be sealed from atmospheric oxidation.

Many people are misled as to the soundness of an ingot cast into a closed-top mould by the fact that, on keeping a good head of metal in the central guit (trumpet), the upper end of the ingot may solidify to a considerable thickness before feeding becomes impossible and shrinkage cavities begin to form. Such an ingot when rolled and cropped or broken will produce one or two perfectly sound billets, and, by arguing (falsely in this case) that the most unsound material is always to be found at the upper end, they may convince both themselves and others that the material is free from pipe. Thus self-interest or the demand for cheap material bars the way to further inquiry, though one, of course, is compelled to admit that for certain purposes—hollow drills, and waggon springs, for example—an ingot may be none the worse for being piped. The manner in which the deception referred to may arise has been discussed and illustrated by J. N. Kilby.[1]

If the feeding of a bottom-cast ingot through the trumpet be left out of account, and we imagine the mould to have been instantly filled with fluid metal, then it does not matter whether the filling took place from the top or the bottom. The position and size of the shrinkage cavity would be the same in either case, except that with a closed-top mould an upper crust of solidified metal would form, and there would be small chances of bridges forming beneath it. The first advantage, then, of bottom-cast ingots is that shrinkage cavities are more likely to be clean and to weld up.

The metal rises in the mould more slowly on bottom casting both on account of the mass of grouped ingots and also because each mould is filled against the pressure

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[1] *Journ. Iron and Steel Institute*, 1917, 1, 73.

of the column of metal in it. The steel freezes through contact with the mould whilst it is being cast, and at the end of the casting period the solid shell would be thicker, if bled, than the shell of a top-cast ingot of the same size. This is all to the good so far as volume of shrinkage is concerned. Moreover, the ingot may be fed under pressure by metal from the trumpet so long as the runner bricks remain open, and this again lessens the volume of shrinkage cavity.

As steel rises slowly in the mould, beyond the disturbing influence of the incoming stream, it heats up the sides of the mould and becomes itself colder. So that when the mould is full and the trumpet pressure can avail nothing, the freezing of the ingot is completed downwards from the narrower top end containing colder metal to the wider bottom end containing hotter metal. The slower rate at which grouped ingots are cast is an advantage only so long as the rate of casting is not too slow. Under normal circumstances the rate will be determined by the number of moulds to be filled through one runner, their cross-sectional area, the height of the trumpet, the amount of metal coming through the ladle nozzle, and the area of the passages in the runner bricks. To these must be added the temperature of the steel and its freezing point.

The clean skin expected on ingots cast from the bottom is not always realized. When cast too slowly the ingots are folded on the surface as indicated in Fig. 18, and when steel is run down the trumpet too quickly to begin with, it rises like a fountain through the bottom and splashes the sides of the mould. When cast at average speed the metal runs rather sluggishly to begin with along the cold runner bricks, and when first sighted at the bottom of the mould appears as a nodule of pasty metal. By pressure from the increasing head of fluid in the trumpet pipe the nodule is forced out of the hole and the metal enters more or less quietly. It flows over and sets against the bottom plate and the lower part of the mould, and is never remelted from this position by the large volume of fluid steel entering the mould later. If the cast is a hot one the shell first formed at the base of the ingot will not become thicker than one inch by the time the group of moulds is filled. If a single mould were inverted immediately after casting, a section cut when cold through the head would disclose a cavity roughly hexagonal in shape. Fig. 50 shows the head of a bottom-cast ingot treated in this way; the top metal about the upper part of the cavity is that which first enters the mould and freezes at its base.

FIG. 50.—Section through head of inverted ingot.

The steel having once properly entered the moulds feeds quietly into them. Later, however, a head of metal must form in the trumpet to overcome the fluid pressure inside the mould and break through any crust forming on the upper surface of the ingots. The heavy fluid thus pressed through a circular opening is expected to travel up the axis of the ingot mould and diffuse itself into the surrounding metal as it rises; there is reason, however, to believe that it often acts otherwise. The thickness of the usual runner brick where the vertical opening is made is approximately half an inch. Even if the opening were made and set mathematically true the stream would not make headway vertically through the moving mass of metal; it would be diverted first to one side and then the other by uncontrollable incidents.

But runner bricks are made and laid in the casting plate by human agencies; and sometimes the opening is sloped and sometimes it is chipped or has a fash on one side. Either incident will cause the metal delivered under pressure to rotate vertically, and that part of the mould in direct line with the sloped opening in the runner bricks will be washed by the incoming steel and may have a cavity melted out of it. This is represented diagrammatically in Fig. 51.

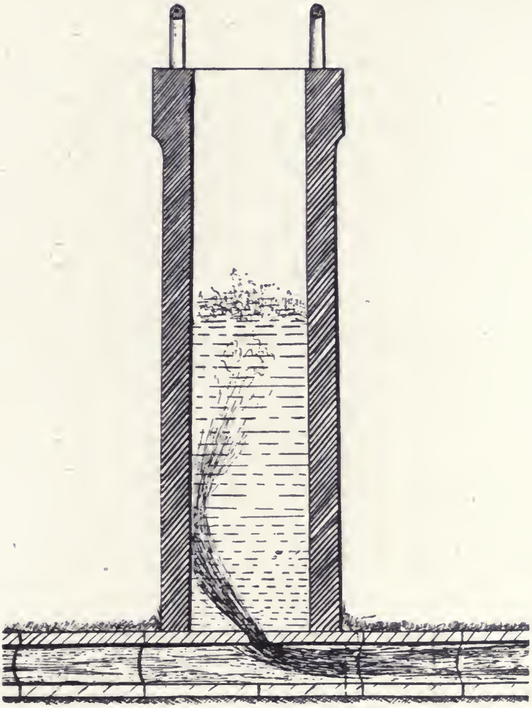

FIG. 51.—Effect of sloped opening in runner brick.

The mould is attacked in this manner at varying heights, sometimes as much as sixteen inches from its base. As the opening lies, or should lie, centrally under the mould the steel-maker may hesitate to believe that the cavity, when disclosed, can have arisen from any defect in the casting arrangement. It is much easier for him to think that the mould as delivered by the iron-founder contained such a defect more or less consciously concealed; and the view seems to be justified by the fact that troubles of this kind arise more frequently in new than in old moulds. The reason, however, for this apparent justification, apart from the fact that new moulds are more carefully scrutinized, lies in a difference between new and old moulds, the inner surfaces of the latter being protected to some extent by the deposit of oxidized metal which thickens on them by use.

Deflection of hot metal to one side of the mould favours the formation of cracked ingots. This remark ought to be decorated like a recurring decimal when applied to the casting of hard steel ingots. If the runner brick does not open in the axis of the mould the incoming stream cannot possibly form an ingot whose temperature is uniform, and the chances of the surface of the mould being cut are increased. If the mould rests cornerwise on the runner brick so that the stream of metal before entering the mould runs along a diagonal of the ingot, which owing to bad design of the bottom plate or considerations of space may occur, then the corner of the ingot to which the moving stream is directed is very apt to crack; and if not cracked on that corner the ingot will certainly not be cracked on any other. In such cases cracks are to be found only in the lower parts of the ingot; higher up the force of the stream is dissipated as the head of metal increases.

The practice of using a large ingot mould through which a number of small ones arranged about it could be filled and fed, sometimes referred to as the Hen and Chickens method of casting, appears to have become obsolete. The wear on the large mould, owing to the unusual quantity of metal passed into it, was very great, and if the smaller ones were fed effectively, then obviously the large ingot would mostly be unsound on the inside and unsightly on the outside. Harbord and Hall (p. 37) refer to an American method, designed to avoid runner scrap, in which the bottom runner is replaced by a horizontal ingot, the vertical moulds being separated from the horizontal one by perforated bricks, one inch thick, let into the bottom casting plate. The horizontal ingots are said to be perfectly sound, but if that statement is correct, then the vertical ingots must contain cavities of considerable size.

Moreover, a brick bottom instead of the usual cast-iron plate is not a good thing for the moulds used in group casting. At a certain continental works it was the custom to use a bottom plate lined with loose bricks, so that runner bricks could be laid as required instead of having to be laid, as is the usual practice, into grooves cast for the purpose in the iron plate.[1] The lower part of a mould is always rapidly deteriorated by the large amount of hot steel passed through it, but bricks take up much less heat than an iron plate, and the bottom of a mould gets hotter and crumbles more quickly when it rests on them. The danger of a break-out is also greater.

Another continental practice rarely seen in England is the use of compound moulds; that is to say, moulds with partitions cast across the centre, dividing them into two or four separate moulds. The life of such moulds cannot be very long, and the economy of using them is not a striking one. The inner walls get much hotter than the outer, and the pipe is deflected towards the hottest side of the ingot; also dirty ingots are caused by the rapid deterioration of the partition walls. As the centre piece is heated more than any other part it grows more, and a mould which originally stood firm on its four outer walls soon begins to rock on the elongated centre piece, and has then either to be rejected or put right again by planing.

Anything interfering with a firm broad contact between the mould and casting plate may lead to a break-out. The

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[1] The use of hollow iron blocks instead of firebricks is not uncommon.

fluid metal may also find its way between runner bricks when the joint happens to fall betwixt two moulds, or if too much cement has been used in the joints, or the bricks are not properly in alignment. Break-outs also occur at the bottom of the trumpet pipe, which is generally made too narrow and light at its base end. The suggestion contained in Fig. 52 for avoiding such accidents is made by Kowarsh and acts very well. It consists of a centre brick recessed in the middle which stands about an inch above the casting plate. Its projecting parts fit into a corresponding recess in the heavy cast-iron sleeve of the trumpet pipe, and the two halves of the sleeve are held together either by lugs and cotters or by a wrought-iron ring only, as shown in the sketch. It is equally efficient to drop a wide ring over the central guit pipe and fill in the space between it and the guit pipe with ganister; or a thick flange may be cast on the bottom guit broad enough to extend nearly to the outside of the surrounding ingot moulds and cover up and strengthen any joint in the canal bricks.

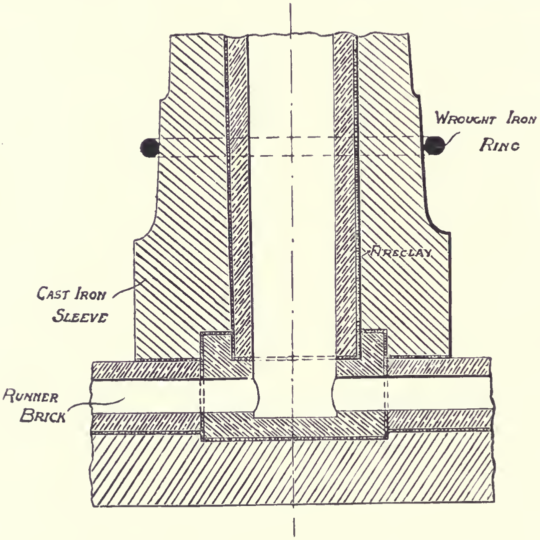

Fig. 52.—Improved form of central guit.

Ingots cast in the same group should rise to the same height in their respective moulds, otherwise a higher may feed a lower one and become itself hollow. It is therefore essential that the trumpet pressure should be sufficiently great to overcome any incidental obstruction, and that the runner bricks should have a uniform bore, offer no impediment, and be set evenly end to end. It damages a mould to have short ingots cast into it, as only part of the mould gets heated up and expanded. For this reason spare metal insufficient to make a complete ingot should be run into an old mould; firstly, because it is of lesser consequence if it is damaged, and secondly, because, having already been in use, it will not be so much deformed by partial heating as a new one.

As it is impracticable, if not impossible, to keep closed-top moulds in condition with anything like the perfection attained with split crucible moulds, defects arising from worn and oxidized surfaces must be expected. That moulds should be rejected when they can no longer be made to form clean ingots is obvious; but there is no uniform standard of cleanness by which ingots are to be judged, and some firms, perhaps justifiably, keep the moulds in use until they fall to pieces or an ingot sticks in them and can only be got out by breaking the mould. Much depends on the kind of steel being cast, and though moulds would nowhere be kept in use when they cause more trouble than they are worth, the trouble arising from them cannot, unfortunately, always be brought sharply to the notice of the individual responsible for their continued use.

Bottom casting wears out more moulds per ton of ingots than top casting, so far as temperature effects pure and simple are concerned. In the latter case the moulds are filled rapidly one after the other, and there is no essential reason why they should be arranged close together; in the former case the moulds are filled more slowly, and therefore exposed for a longer time to notable variations in temperature in their different parts. Also in the lower part of a bottom-cast mould the stream of hot metal is entering continuously and giving up part of its heat, whereas the upper end of the mould receives only the partially cooled steel; thus the conditions favourable to durability, *i. e.* uniform heating and cooling of the moulds, are in no wise attainable.

When ingot moulds are packed together on a casting plate one or more of their sides, exposed to heat radiated from other moulds, becomes hotter than the rest. The moulds should, therefore, be turned occasionally through an angle of 90°, so that each side of the mould in turn may receive the unfavourable treatment. This variation in temperature is generally without noticeable influence on the ingots, probably because group-cast ingots are too small and practically set before it becomes serious. It is, however, an approximation to the conditions prevailing in the compound mould, which does cause deflection of the pipe. A deflected pipe in a wax ingot cast under these conditions is shown in Fig. 53.

FIG. 53.—Deflected pipe due to unequal cooling.

FEEDER HEADS

A taper wax ingot cast wide end up can easily be fed with hot wax at such a rate that the level surface of the molten centre is preserved, and the resulting ingot so far as shrinkage cavities are concerned will be a sound one. Something like this method is adopted in casting certain non-ferrous alloys, *e. g.* nickel silver, whereby much waste is caused in the subsequent cold-rolling, stamping and pressing. Such ingots have been derisively referred to as "slop ingots."

Immediately an ingot is cast the fluid metal oxidizes at its upper surfaces, and a thin layer of oxidized metal forms the surface of the concave depression caused by shrinkage. If this depression is filled up a second one forms, and a third one, and so on until the ingot has solidified and its upper surface remains flat. When nickel silver ingots made in this way in flat moulds are cut transversely or longitudinally they appear to be quite sound. But the cut surfaces are not really as flawless as they appear to be, because the soft metal deforms under the cutting tool and small cavities are concealed. If the surface is milled with a fine cut, small pin-holes become here and there visible, just as they do in steel ingots and castings which are said to be spongy. When looking for sponginess in the centre of an ingot it is generally better to break it, after planing the necessary grooves for wedges, than to make a rough cut through it, because the act of breaking may cause the surfaces of small cavities to pull apart. The only way, however, to prove the absence of sponginess is to take a fine cut over the exposed surface and etch it with dilute acid, or pickle it.

A nickel silver ingot, for example, cast in the manner described yields instructive information after pickling. The photograph reproduced in Fig. 54, taken from a longitudinal section of such an ingot, shows clearly what appear to be the curved surfaces of contact between the shrinkage depressions and the fresh metal poured into them.

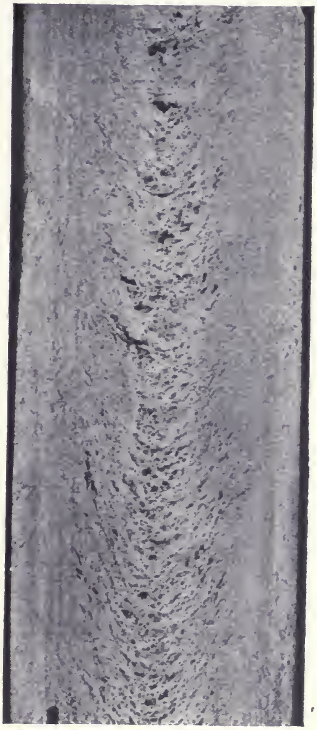
FIG. 54.—Shrinkage depressions in German silver ingot.

Although no steel-maker would think of casting "slop ingots" it is by no means certain that crucible ingots do not suffer sometimes, in a minor degree, from a similar defect. A small amount of time is always occupied in placing the heated dozzle in position and filling it; and during this time the upper surface of the ingot, according to its size, may have formed an oxidized crust, which is destroyed in the centre only when the hot metal is poured on to it. Workmen have been known to scatter sand on the surface of a tool-steel ingot before placing the dozzle on it, in order to strengthen the upper crust and prevent the dozzle sinking into the fluid ingot. It is believed, of course, that the sand rises at once through the dozzle after it has been filled up, and it might be difficult to prove that it does not, but a little exercise of the imagination raises disquieting doubts.

No ingot metal is so sensitive to defects as high-speed tool steel; the history of its development shows this quite clearly. It was possible, to begin with, to make turning tools from it but not milling cutters or twist drills, although the composition of high-speed steel then prevalent (1900–1902) was more favourable from a melter's point of view, *i. e.* was more fusible, than it became subsequently. Greater experience overcame the melting troubles, and the use of taper moulds wide end up improved the soundness of the ingots, but the need for certain precautions in forging the ingots still persists. One of these precautions is as follows:—

Unless the dozzle metal and the top end of the ingot is cut off before forging is proceeded with a conical piece attached to the dozzle metal is apt to be forced out, and the end of the ingot must then be cut off well behind the cavity left in it in order to avoid its extension into the billet or bar. For some time the authors thought that the core thrust out by the blows of the hammer was related to the crust formed on the upper surface of the ingot before the dozzle could be got ready and filled up. And though it still seems a likely contributory cause it is not a complete explanation, because if a hot dozzle prepared beforehand is thrust overhead into the upper part of the molten ingot immediately it is cast, with the idea of avoiding altogether an intervening layer of crusted metal, a cone is still apt to be forced out, partly at least, on forging.

The forcing out of the cone is undoubtedly caused by some influence brought into operation by the hot dozzle. Immediately under its lower end the plane of crystals arising from the cooling effect of the mould would be shortened. In the next lower plane the effect of the dozzle is less, and becomes still less in each succeeding lower layer until its effect ceases. A hollow cone would thus form, due to the combined cooling effect of the mould and the heating effect of the dozzle, and it is along the surface of such a hypothetical cone that the steel ruptures on forging. In actual practice the cone is not, of course, allowed to become hollow, but is fed by fluid steel added later from the crucible; but when added such steel is colder than the steel originally cast, and would tend therefore to form "free" crystals on its own account rather than extend the horizontal crystals which are growing under the chilling effect of the mould. If the formation of the hollow cone and the filling of the cone with free crystals are visualized as separate occurrences the rupture along a conical surface causes no surprise, but as they occur for the most part simultaneously and only more or less completely one feels the need of further experimental evidence before a convincing explanation can be given.

No feeder head whatever its length or cross-sectional area enables a long parallel-sided ingot weighing, say, not more than ten cwts. to be produced free from axial shrinkage cavities; with a taper ingot cast narrow end up the possibility is still more remote. The same remark applies to sand castings, and engineers would do well to take note of it when designing long parts which are specified to be free from blemishes and cavities. The metal in the lower part of the feeder head and for some distance below it may be perfectly sound, but a few hours spent occasionally at a tup where rejected castings are being broken up will seriously disturb the comfortable belief that soundness in the head is a guarantee for the condition of the lower parts. The case of small crucible ingots was dealt with on p. 62, and it only remains to say that when straight-sided ingots of high-speed steel are in question, a small cavity may extend as cracks with disagreeable consequences, akin to that illustrated by Fig. 55.

Apart from its low capacity for absorbing and conducting heat the value of a feeder head depends on its diameter, in relation to that of the ingot, and its temperature. Those used on crucible ingots are considerably less in diameter than the ingot itself, and to get any advantage from them they must be made very hot. A careful melter would sooner leave an ingot without a dozzle than use a cold one, because he knows that it would only exaggerate or conceal the defect it is intended to obviate. If the metal in the dozzle freezes across before the ingot is set it fails of its purpose. The interior diameter of the dozzle generally used on a three-inch ingot is about one and a half inches, *i. e.* it has an area of about one and three-quarters square inches, whereas the ingot has an area of nine square inches, but the dozzle is quite effective if made very hot.

Fig. 55.—Cracked centre in bar steel arising from axial cavity in ingot.

Feeder heads for large ingots are generally made with an internal diameter equal to that of the top part of the ingot mould. If they are fitted to the mould it is not possible to reheat them, and their efficiency depends on the low heat-conductivity of firebrick, or whatever other material they are made from, as compared with cast iron. Some moulds are narrowed at the top end in order to provide a broad face on which the feeder head rests. This is very bad practice, as the steel freezes first across the narrowed part, and the head, no matter what its length may be, is next to useless; it is something like strangling a man before inviting him to a feast. A very long head made with the idea of compressing the ingot metal seems also to be without reasonable basis, as compression is not required whilst the metal is fluid and the feeder head cannot compress after a layer beneath it has frozen across. It is not so much the weight of the feeder head that matters, but the certainty that the fluid metal it contains shall have an unrestricted passage to that part of the ingot where it is required.

An ingot can be properly fed only when it is cast in a taper mould with the wide end up, or when by some other means it is caused to freeze from the bottom upwards. If this condition has been complied with, then the unfed cavity is comparatively small. It is also near the top of the ingot and only a small head of the right kind, *i. e.* one that keeps its contained metal fluid until after the ingot has set, is required. Here again the practice of crucible steel-makers suggests the ideal conditions and opposes the belief that a long head is necessary. Where a long narrow head forms a useful gripping place for the forge tackle, as it does on certain kinds of large ingots, there is nothing to be said against it, but it should not be claimed that its length and weight greatly increases its value as a feeder.

To the question of how much taper a mould should have to enable a sound ingot to be produced in it one might give the non-committal reply—as much as is necessary to cause freezing to take place from the bottom upwards. The actual amount will depend on conditions other than the shape of the mould. If the mould is filled quickly with steel at a practically uniform temperature a taper of a quarter of an inch per foot is sufficient; but if it is filled slowly from the bottom, then the variation in temperature between top and bottom of the fluid ingot acts unfavourably and the taper of the mould may need to be greater. The variables are so numerous that the easiest and safest way of arriving at their net effect is to cut up a few ingots which have been cast in the same moulds under widely diverse conditions. Also to warm moulds before use they are sometimes placed on hot ingots, or a fire is made about their base, and the lower parts of them get hotter than the upper parts; the taper chosen must have a margin sufficient to overcome incidental differences of this kind.

In order further to increase the fluidity of steel in a feeder head a layer of charcoal is sometimes spread over the surface. The burning charcoal maintains the temperature and also preserves the upper layer of metal in the fluid state longer than would otherwise be the case, but at the same time it carburizes it, as may be seen from the crucible dozzle metal depicted in Fig. 56. So long as the metal settles evenly in the dozzle only the upper part of it, which is subsequently scrapped, becomes carburized, and no possible objection to the practice can be raised. If, however, the carburized metal should chance to feed into the ingot itself, then the remedy in its ultimate consequences may be worse than the disease.

The ingot-making process recommended by Sir Robert Hadfield[1] comprises the use of an inverted taper mould and a super-imposed loam head. After casting, a layer of fusible slag and then a layer of charcoal are added, and the charcoal is kept aglow by a gentle air blast. The use of charcoal and an air blast are the novel features of this process, and they are also the only features of questionable value. The interposed layer of slag insulates the upper surface of the fluid steel from direct contact with the charcoal. But as the level of the fluid steel falls it leaves a shell of hot steel of greater or

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[1] *Journ. Iron and Steel Inst.*, 1912, II, 11.

less thickness on the sides of the loam head; and shortly after feeding starts the incandescent charcoal is in contact with this hot steel. Urged by the air blast the charcoal carburizes and then melts the walls of the cavity in which it is contained, and the molten carburized metal trickles through the liquid slag and contaminates the upper part of the ingot. Evidence of this contamination is faithfully recorded in the analyses quoted in Hadfield's paper, and it would seem to be advisable to omit the charcoal or the blast, or both; in which case the slag layer may be replaced by any kind of dry warm non-conducting material, as, for example, a thick layer of the dry dirt which occurs plentifully in and about casting pits.

FIG. 56.—Carburizing effect of charcoal in dozzle.

A feeder head should preferably rest on the ingot, so that it can move with it as the ingot contracts; a ring of asbestos being interposed between the ingot and the lower part of the hot dozzle to prevent the latter sinking in the fluid steel. If a brick head is fitted into the upper part of the mould it should be made flush with the inner surface, or project slightly beyond it. Anything like a ledge over which the fluid metal can run must be avoided, as otherwise the ledge holds the ingot, and, if it happens to be stuck in the bottom, will crack it. This applies particularly to top-cast ingots; those cast from the bottom are usually so hot and tender at the lower end when the ingot shortens itself that they pull away from the runner brick. A feeder head will at times be slipped into the top of the mould and held there by wooden wedges; the fact that under these conditions the wedges, though charred, may restrain the shortening of the ingot and crack it shows how fragile is the hot metal.

VII

SOUND INGOTS

One speaks of sound ingots in a comparative sense. Absolute soundness is never attained, but imperfections which give rise to no blemishes or defects in the intermediate or final stages of manufacture are disregarded; and if they are also equally unobjectionable in the use of the article they are commercially negligible. It may happen, however, that apparent trifles arising in the course of manufacture grow into serious defects or causes of defects in service, and to trace their origin and fix the responsibility becomes a lengthy and delicate matter. If, therefore, an ingot works up into apparently faultless plates and bars and general forgings it does not follow that the ingot was a sound one, but only that any unsoundness present was of small obvious consequence.

Thousands of tons of ingots known definitely to be unsound in the absolute sense are rolled into girders, plates, rails and other forms, and appear to yield no worse service on that account. Some of a similar kind break and involve loss of life and other misfortunes as a set-off to the lower costs of manufacture arising from the use of material which is thought to be good enough but not so good as it could possibly be made. In producing steel at what is called " the market price " these " insignificant " defects in ingots are made as harmless as possible. In respect to piping and shrinkage cavities, this is accomplished by cropping the top end of an ingot, or by avoiding oxidation of the surfaces of the cavities in order to increase their chances of welding up. To a certain extent this aim is secured by bottom casting, but direct attempts to secure its success have been made in other ways.

Hinsdale and others have suggested that the ingot mould, mounted on trunnions, should be inverted soon after it had been filled. This is to be done after placing a block of cast iron in the top of the mould to solidify the metal. In this way the shrinkage cavities are formed inside the ingot, oxidation of the walls of the cavities is obviated, and the ingots are said to roll or hammer into perfectly sound billets. Another proposal is that the partly set ingot, after the top has been artificially cooled, should be laid down horizontally. The effect of these procedures on the position of the shrinkage cavities is shown in Fig. 57 and Fig. 58 respectively.

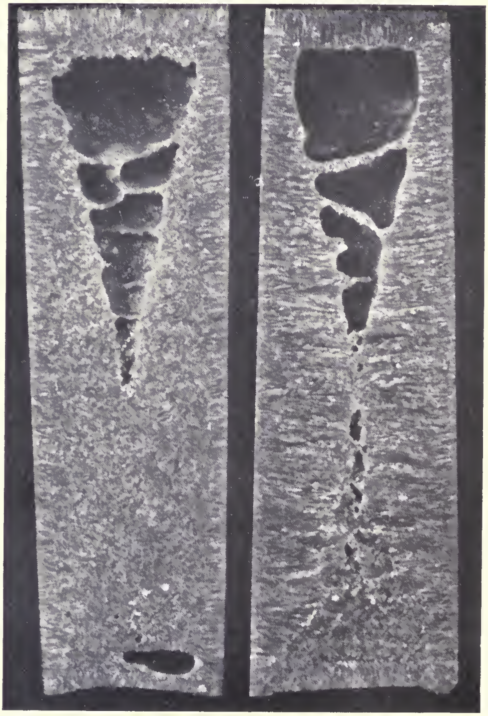

Fig. 57.—Ingots inverted whilst partly fluid.

The methods of producing sound ingots, as distinct from those methods which aim only at moving the shrinkage cavity into a less harmful position, and seeking thereby a security which is often misleading, may be divided into two groups.

1. Those using mechanical means to exert pressure on the outside of the partly set ingot, with the object of closing up the cavity or preventing its formation, and

2. Those depending on the natural properties of the metal modified by the shape of the mould and the condition of the feeder head.

Of the first group the most widely known is that suggested by Harmet. The Harmet method is generally described as a wire-drawing process; it is really not a drawing process at all, but a pushing process, and it acts as most other mechanical processes do, by crushing the outside of the ingot, and thus causing the fluid interior to rise upwards.

Ingots which are to be Harmet-pressed are cast into taper moulds whose inner surfaces are parallel for a short distance at the bottom end.[1] After casting, the ingots are pressed from the bottom upwards, and, being thus gradually reduced in diameter and thickened in the wall, the surface of the fluid interior, by a suitable pressure effect, would be kept coincident with the upper end of the ingot.

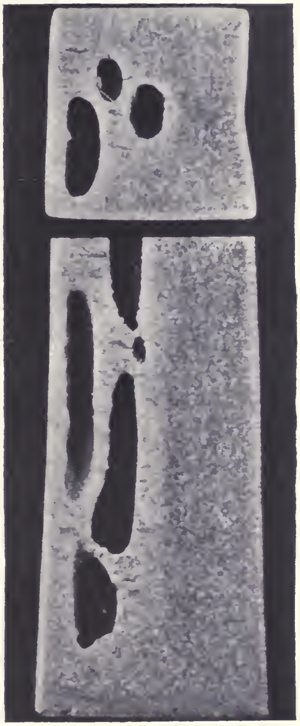

FIG. 58.—Ingot laid horizontal whilst partly fluid.

Of the cracks arising from contraction of the hot solid metal and its intercrystalline weakness we are already

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[1] Harmet (*Journ. Iron and Steel Inst.*, 1902, II, 146). The reader is assumed to have some practical acquaintance with ingot-making processes, and there is no need to present details which have previously been described in technical journals; it will suffice to discuss the principle of the methods, and leave mechanical details of plant to be looked up elsewhere by those who propose to use them.

aware, and there can be no doubt that an operation which reduces the diameter of an ingot during solidification and cooling and assists by pressure from without the contractile forces acting from within will increase the material soundness of an ingot. It attempts by the method of prevention what subsequent forging attempts to do by the method of cure.

In presenting his paper to the Iron and Steel Institute, Harmet, who underrates the value of feeder heads, draws a most dismal picture of ingots which have been left to cool undisturbed in the mould; "the whole mass is seamed with cracks, torn by internal stresses, cleft by crystallization and made irregular by liquation." If ingots were quite as bad as they are here made out to be, good forgings would be scarce; and castings, however thorough their subsequent heat treatment, would be nearly useless. Whereas we know that large sand castings, which cool more slowly than any ingot, and are therefore made up of more massive crystals, can be transformed by heat-treatment alone, excluding any form of mechanical work, into material which is not disgraced when compared with forged steel. Still, we had better admit that self-cooled ingots may be as Harmet states, since our object is to consider his process as a means of obviating the defects.

Harmet ingots are put under pressure as soon as possible after being cast. The solidified shell, having already left the inner surface of the mould, is forced back into contact with it, and a stream of water runs over the outside of the mould, or rather over a series of strengthening steel rings which have been shrunk on to it. At this stage the ingot mould may be pictured as being very hot on the inside and relatively very cold on the outside; a state of things very unfavourable to the durability of cast-iron ingot moulds.

The pressure to begin with is not a great one, because the solidified shell is both hot and slender, and it is necessary only that the contained fluid should be kept level with the top of the ingot. More pressure would simply force the fluid metal over the top of the ingot and form a bun-shaped head of waste material; this can be seen more or less on many pressed ingots.

The ingots are necessarily cast in taper moulds narrow end up, and, on this account, apart from the greater water-cooling effect at the top end of the mould, the ingot becomes quite solid first at its upper end. Moreover, as the pressure increases, the head of the ingot is being continuously pushed into the previously unoccupied and colder part of the mould; this also causes more rapid chilling of the upper part, and ultimately the top of the ingot closes completely.

By this time the solidified shell will have thickened considerably and have become also much colder and harder. On this account the efficiency of any press must be limited by the dimensions of the ingot and also by the kind of steel of which an ingot is made. The obvious conclusion, therefore, is that very large ingots of mild steel and quite moderate-sized ingots of special alloy steels, which strongly resist deformation at red heat, could not be made solid by any practicable amount of pressure applied uniformly over the outside surface.

But if we avoid limiting conditions and follow the fate of an ingot whose dimensions and composition bring it within the specified compass of a press, we have at some stage in the process to deal with a taper circular block, as may be assumed, of steel, solid on the outside and closed at each end, whose central portions are still fluid. We have to inquire whether it is possible by any attainable deformation akin to wire drawing, which preserves the same symmetrical shape, to make the block quite solid.

If a piece of thick-walled capillary glass tubing is made hot and drawn out to many times its original length, the hole in it gets finer, but does not disappear entirely. If after the top of a Harmet ingot has solidified the pressure were withdrawn the still fluid portion of the ingot would shrink in setting and leave a cavity. No subsequent extension of the circular ingot by drawing, keeping it strictly circular the whole time, would suppress the cavity, and it would occupy finally about the same relative space that it occupied initially. And it would not appear to make much difference whether the entire shrinkage is supposed to have occurred beforehand, or whether it takes place whilst the ingot is in the act of being extended. In either case the size of the cavity would be the same, though its position and shape may alter.

But if, on the other hand, a hollow cylinder of metal were compressed and prevented at the same time from lengthening or spreading outwards, then the hollow space would become relatively less and might close up entirely. This is the basis on which the Whitworth process may claim to reduce the shrinkage cavity of an ingot, and it plays also the main part in the success of the Harmet process, though in the latter the pressure appears to be applied more effectively.

The resistance to the upward movement of a Harmet ingot depends on the weight of the ingot and the magnitude of the effort required to force it into a narrower section. The former is a constant and may be neglected. The latter is an increasing force; but even when the force is small it serves its purpose, because the parallel part of the very hot ingot is easily forced into the tapered part of the mould.

When, however, the walls of the ingot have thickened, and particularly when the top of the ingot has closed entirely, the pressure required to force the ingot bodily up the mould is enormous, and this causes the walls of the ingot to thicken. If it were not so, if the solid mass at the head of the ingot were soft and plastic, it could be reduced in diameter only at the same rate at which it became extended, and this by reference to common experience with viscid glass and drawn wire is seen to be not a very excellent method for closing central cavities.

The success of the Harmet press and its limitations appear to be determined by the same circumstances, viz. the resistance which the ingot offers, particularly when closed at the top, to being pushed up the mould. The effect of this resistance is direct compression of the solid walls of the ingot, which, if effective, causes them to thicken and the fluid interior to rise. The ingot is virtually "jumped," as the blacksmiths say, which may or may not be a desirable operation to perform on a hollow cylinder of semi-solid steel.

Unless we have overlooked some essential factor, it appears that the Harmet process attains very little, except a mechanical advantage by its wire-drawing features, and almost everything in the final and most important stages by such means as were previously used by Whitworth, *i. e.* compression of the ingot as a whole and solidification of it more or less by causing the solid walls to thicken under pressure. Whether such a process can produce a solid ingot depends on the size and composition of the ingot and the power of the press; and, without expressing an opinion on the relative merits of the two systems, it may be said that Harmet has applied his process with apparent success to smaller ingots, whereas Whitworth has been concerned with larger ingots, which either process may improve but which neither can make completely sound.

The behaviour of a Harmet press can be illustrated very well by stearine ingots. The authors have used a circular steel mould with water-cooled walls a quarter of an inch thick. After casting the ingots from a temperature of one or two degrees above the freezing point of the wax they were submitted to pressure by means of an adapted Brinell ball-testing machine. The observations thus made were as follows:—

1. The top of the ingot could not be kept open. Movement of the ingot through its own length up the mould did not make it solid. In the final stages about 300 kilogrammes was needed to press the ingot through the mould.

2. When the movement of the ingot was artificially restrained and the pressure increased finally to 500 kilogrammes the fluid pressure thrust out the top cone, which can be seen in Fig. 59.

3. When displacement of the top cone was prevented by suitable means and the pressure was kept

at 500 kilogrammes until all the wax had solidified the ingot was still not solid.

4. When the pressure was increased to 1000 kilogrammes the ingot was quite solid; but the same result was obtained without pushing the ingot through the mould at all, *i. e.* the advantage arose from the pressure and not from the wire-drawing effect.

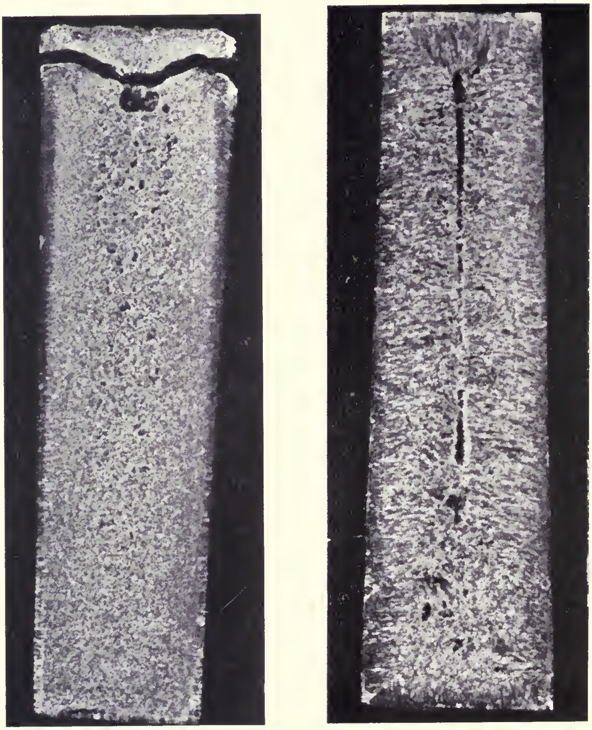
a b

Fig. 59.—Harmet wax ingot showing top cone.

5. In addition to displacement of the top cone there was also a tendency to dislodge the bottom cone. This is illustrated by Fig. 60. There was also a tendency to form cleavage planes at right angles to the axis of the ingot and the direction of pressure.

It may be that these experiments with wax ingots are not of much account so far as their bearing on steel ingots is concerned. But transverse cracks in Harmet-pressed steel ingots are not unknown, and "absolute solidity of ingot without cleavage planes" is a claim for the Harmet process which might well be qualified. The top and bottom parts of a Harmet-pressed steel ingot are sound, but the larger ingots, or those made from alloy steels, where soundness is of greater consequence, frequently contain a wider or narrower shrinkage cavity, as shown in Fig. 61. That such cavities are not due to contraction after the pressure has been released is clear from the presence on their inner surfaces of well-defined dendritic crystals.

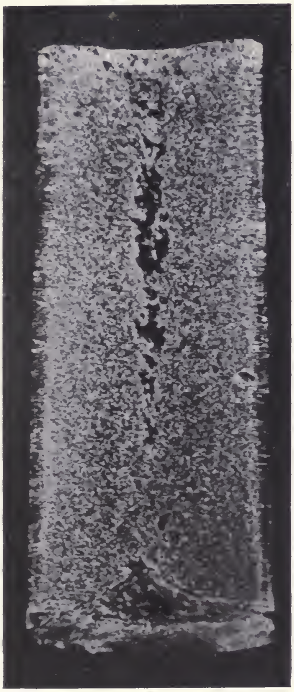

FIG. 60.—Displaced bottom cone in Harmet wax ingot.

FIG. 61.—Shrinkage cavity in Harmet steel ingot.

Reference has already been made to a tendency to form surface cracks, which Harmet-pressed ingots might be expected to exhibit. In this respect they are like all other ingots that suffer from variations in temperature, owing to their shape and size, except that the variation is a greater one. But, unlike other ingots, they have been partly forged, and have therefore not the same extreme intercrystalline weakness.

Such published and private information as is available about forged objects will hardly sustain the claim that the Harmet ingot gains any great ultimate advantage from the work put on to it in the press. As an ingot its structure is finer, as may be seen by a comparison of Fig. 62 with the usual structure of large steel ingots; but this advantage is lost almost entirely after the ingot has been reheated, and either not forged at all or cogged into billet form. The structure of the outer parts of a Harmet ingot gets coarser and that of an ordinary ingot gets finer during the reheating operation, and both are then fairly well typified by Fig. 63.

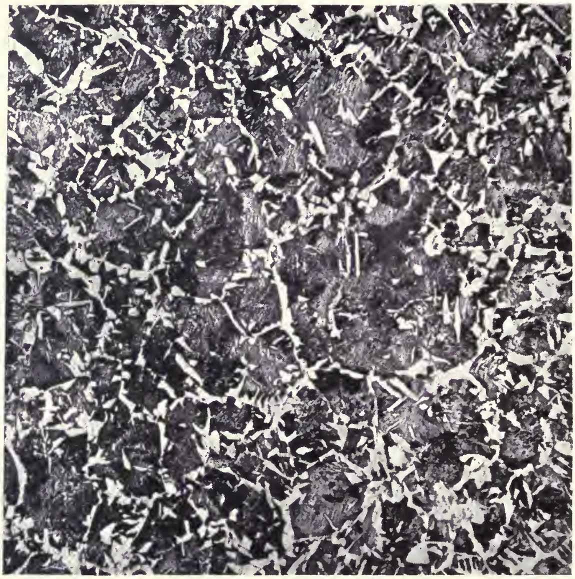

FIG. 62.—Harmet ingot structure × 25.

There is also not a great deal to choose between the solid part of a self-cooled and a pressed ingot so far as segregation is concerned. If points of this kind could be settled by selected microphotographs and sulphur prints, there is abundant evidence to show that pressed ingots of any kind may be badly segregated. Whether the segregates are more or less harmful depends mainly on the forms into which the ingots are worked. If Harmet ingots fall short of perfection, as they undoubtedly do, they are at least an approximation to it, and are so much an improvement on ordinary ingots cast narrow end up for certain articles of manufacture as to leave a margin of economic advantage, but the margin was never a great one.

FIG. 63.—Re-heated ingot or billet structure × 25.

The Illingworth process as improved by Robinson and Rodger[1] may be regarded as a typical example of the processes in which ingots are pressed horizontally without removing them from the mould. The principle of these processes is that, after casting, the split moulds are opened, and either packing pieces are removed from between their edges or a convex liner or plate is slipped between the mould and the ingot.[2] In either case, in endeavouring to bring the edges of the mould together, the solid shell around the partially fluid ingot has its two broad sides pressed inwards.

The ingot alters its shape during compression, and there is no difficulty in producing sound ingots, providing sufficient pressure is applied in the right place, and the top of the ingot is kept open. Robinson and Rodger, realizing the importance of keeping the top open, use a fireclay head for that purpose, and have the satisfaction of squeezing from the top of the ingot the last-fluid part of the metal as an enriched segregate. As the ingots are pressed in groups it is desirable to cast them simultaneously, which may be done either through the bottom in the usual way, or from the top by means of a trough. The patentees give no details of their method of top-casting by means of a trough, which is regrettable, as the operation is generally thought to be a tricky one—quite simple in principle, but very apt to go wrong in practice.

The moulds must be made heavy and strong to resist the pressure; they are consequently expensive. They must be split moulds, and therefore inconvenient to handle in large numbers. These are not very serious objections when crucible steel ingots are being made, but there is, on the other hand, no great difficulty in casting sound crucible steel ingots, as almost every condition of casting is under complete control. It was reported in 1906 that the process had been in operation for two years at Messrs. Jessops, Brightside Works, and that over two hundred ingots had been cast from the same moulds.

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[1] *Jour. Iron and Steel Inst.*, 1906, I, 28.

[2] Howe, *Ibid.*, 1902, II, 210.

The authors have had an opportunity of casting stearine ingots, using a model of the Robinson and Rodger's patented apparatus. Pipeless ingots could be made with it more successfully than with the Harmet-press model, but in every case the ingots were cracked transversely or up the corners. Steel is, of course, much stronger than stearine wax and more plastic in the hot solid state, but the behaviour of stearine may be taken as a timely indication that steel ingots should not be cast unduly hot nor be otherwise made mechanically weak. A non-crystalline wax, such as paraffin, could be made into sound ingots without cracking under pressure.

The reader may observe that we have referred repeatedly to the casting and soundness of crucible ingots as models of how an ingot should be made. One of the authors endeavoured by mechanical means (British Patent 5954, 1912) to apply conditions of crucible ingot making to electric furnace, or small open-hearth plant, practice. The procedure was as follows:—

In the bottom of each of a series of moulds arranged for bottom casting in the usual way, a fireclay sleeve or dozzle is placed, so that the fluid metal on entering the mould makes each dozzle very hot. If when the moulds are filled the entire casting plate, to which the moulds are attached, is inverted, then each ingot has the advantage of solidifying in a taper mould with the wide end uppermost. And, in addition, each ingot is provided with an automatically heated dozzle filled with fluid metal, which can feed downwards under the most favourable conditions so as to eliminate shrinkage cavities.

In the construction illustrated in Figs. 64 and 65 a casting plate A, provided with trunnions, A1, is mounted on standards B, which are disposed on either side of the pit C. The casting plate carries the central guit D, which communicates by means of runner brick conduits E with the base of each of the moulds F, six of which are shown in the illustration. The moulds are secured in place on the casting plate by means of T bolts and cotters G and G1. A circular hole E1 in the runner brick is central with each mould, and above each aperture is placed an annular slab or disc of firebrick H1, the aperture of which corresponds with the hole E1. Resting on the slab H1 so as to extend a short distance upwards from the base of each mould is a short sleeve or dozzle, the taper of the mould and the dozzle maintaining the latter in place after the moulds have been inverted. The disc H1 and the dozzle may be conveniently made in one piece.

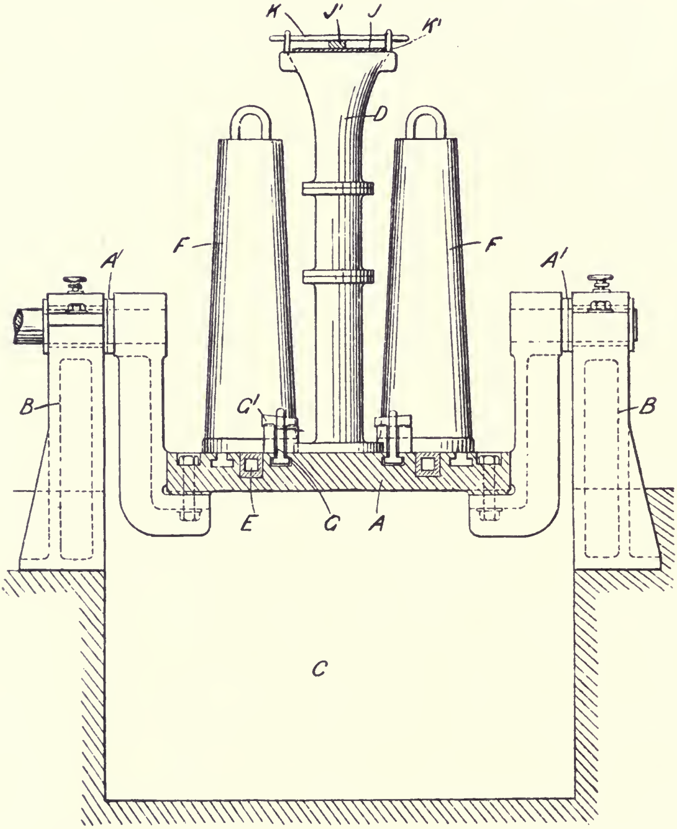

FIG. 64.—General arrangement for inverting cast ingots.

The moulds are filled in the usual way through the trumpet, the open end of which is then covered with sand and closed by means of an iron plate J, held in place by a wedge J1, which passes under a locking bar K, mounted in lugs, K1, formed on the trumpet. At this stage the entire casting plate, together with moulds secured thereto, is rotated by means of a motor-driven shaft and suitable gearing, so that the moulds are inverted.

When the molten metal is poured through the trumpet it rises through the dozzles H, and in doing so raises them to redness. When, therefore, the moulds are inverted in the manner described the most recently introduced metal is brought to the top of each mould, so that each ingot solidifies in the taper mould with its wide end uppermost, the metal in the wide upper end being maintained in a molten state by the heated dozzle until the shrinkage in the ingot has ceased. What cavity there is is confined to the dozzle.

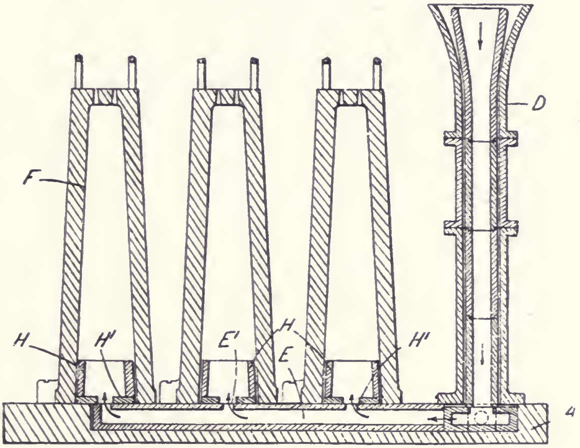

FIG. 65.—Section through guit and moulds of Fig. 64.

This brief description of the inverted casting process or "Joy-wheel," as it has been called, shows that the device combines the advantages of a wide-top conical ingot effectively dozzled together with all the advantages of bottom casting, and without any danger of cutting the moulds. The mould cannot be cut during casting no matter how the stream of fluid steel flows into it, because it is protected by the dozzle. The casting plate also does not come into contact with the hot metal, and, consequently, both mould and plate are kept in good condition longer than is possible under the usual conditions of bottom casting, and this more than compensates for the slight extra cost of the moulds and plate.

It is essential that the trumpet should be placed at one end of the plate, so that on inverting it follows the moulds and does not precede them; otherwise any mishap to the trumpet would give the steel a chance to run back from the moulds. When the machine is operated correctly most of the fluid metal from the runner bricks flows into the mould; when the fluid metal is very hot no metal whatever is left in the runner bricks.

It was not claimed that this process minimized segregation in steel ingots to any appreciable extent except in so far as it avoided "piping" segregation. The inverting of the mould after setting has commenced cannot, however, be entirely without influence. What segregation does occur will, of course, be localized in the top central position of the ingot, but sulphur prints have not disclosed any notable amount in the comparatively pure steels to which the process has been applied. In one instance the polished surface of a split ingot was etched with Heyn's reagent in order to discover any phosphide segregation. The pattern disclosed by this very delicate reagent is reproduced, from a wash drawing, in Fig. 66. No segregation in nine-inch ingots was discoverable by analysis.

Fig. 66.—Section of sound ingot etched with Heyn's reagent.

From knowledge within their own experience and arising from opportunities of inspecting the experimental results of other observers, the authors are disposed to believe that the production of pipeless ingots in the future will be probably confined to processes depending on the natural properties of fluid steel as modified by the shape of the mould and the conditions of the feeder head. Whether the ingots should be top-cast or bottom-cast will depend on shop conditions and the size of the ingots made.

We are indebted to Mr. Benjamin Talbot for an opportunity of examining longitudinal sections of three- to five-ton ingots, cast in brick-head moulds, which disposed of certain preconceived notions as to the possibility of making practically sound ingots by casting narrow end up. The taper of the moulds, however, was very slight, and it is extremely doubtful whether Mr. Talbot's procedure could be followed on plants which were not provided with a stripping machine, and even with this aid many of the ingots were not easily stripped.

In all top-cast ingots the fluid occupying the lower part of the mould is colder at the moment casting is finished than is the metal occupying the upper part of the mould, and this, to a certain extent depending on the dimensions of the ingot and the speed of casting, favours the soundness of ingots independently of the direction of taper of the mould. Also the quantitative effect of a taper of, say, one inch to the foot is not the same on the freezing of a large as a small ingot. In a small crucible mould, for example, the area of transverse sections a foot apart might be in the proportion of 4^2 to 5^2, and in a larger ingot in the proportion of 20^2 to 21^2; but in the latter case the speed of casting would naturally be more favourable to the production of sound ingots than in the former if both were top cast. For these and similar reasons it is not permissible to apply rigidly the results of observations made on small ingots with ample taper to much larger ingots cast with so small a taper that they can be stripped only with a machine. Much variation of opinion and a great deal of the recent controversy about sound ingots arise from neglect of this important difference. The difference, however, is one of detail, not one of principle, and the inverted mould is undoubtedly the safest means of securing freezing of the ingot from the bottom upwards, whatever may be the size of the ingot.

In the regular production of large numbers of ingots weighing, say, up to three tons the authors prefer to bottom cast in inverted moulds provided with superimposed feeder heads. The arrangement of the mould over the runner bricks is indicated in Fig. 67. The special features are a solid bottom mould provided, as shown, with a small taper fireclay sleeve. This ensures the formation and feeding of the ingot by a stream of fluid steel entering on and passing up the axis of the mould. The fireclay sleeve is also long enough to give direction to the incoming fluid, and both damaged ingot moulds, as illustrated by Fig. 51, and longitudinal cracks in ingots are practically eliminated.

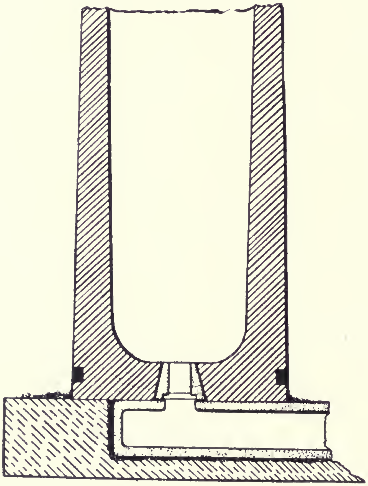

FIG. 67.—Detail of mould for bottom casting.

The feeder head has the form of a truncated pyramid (Fig. 68). It is made from cast iron and lined with a mixture of clay and sand, or clay and ganister. The lining is about three-fourths of an inch thick, and is held in position by studs on the inside and holes in the walls of the iron casting. The inside of the lining is made smooth and uniform in size by a wooden pattern, which is forced home whilst the refractory mass is still soft. The lip on the under side of the head just slips into the upper end of the mould, and the joint is made tight by clay and ganister which has been smeared over it. The intention of this lip is to ensure that the head is truly in alignment over the mould, and, on stripping, the head can only be removed by a direct lift which helps to preserve the lining. The lining, if the mixture contains the right amount of rather fusible clay, becomes glazed on the inside, and is not disturbed by stripping, but will serve, with minor repairs, for ten to twelve heats. The bead at the upper end of the head serves also to regulate the thickness of the lining, and preserves it from damage after the head has been placed in position on the mould.

After the pit has been set, and shortly before tapping the furnace, any pieces of ganister or clay or bits of lining from the head are removed by inserting a two-inch pipe connected to a powerful exhaust jet into each mould separately. The amount of dirt removed in this way by suction, even when every precaution has been taken to keep the moulds clean, is considerable, and the appearance of the bottom and sides of the ingot is greatly improved. The authors are disposed to think that what are popularly known as sand streaks, generally ascribed to wash and erosion on the runner bricks, and thought to be inseparable from bottom casting, are mainly due to avoidable dirt which could be removed by vacuum cleaning.

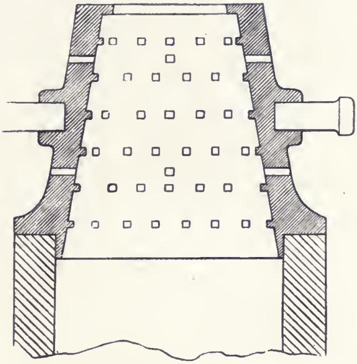

Fig. 68.—Superimposed feeder head.

As soon as fluid steel appears in the bottom of the mould an ounce or two of ground pitch is thrown on to it, thus causing the mould to be filled with a dense cloud of finely-divided carbon, which coats the inside of the mould and serves the same purpose as a thin layer of boiled tar and oil with greater ease and less interference with the thoroughness of the vacuum cleaning. There is no invariable rule governing the speed of casting which can be applied to all classes of steel, but the teemer endeavours to fill the moulds at a rate which permits the rising surface to show a very thin cover of freezing metal. Much slower speeds will cause ingots to be lapped, which may give rise to subcutaneous blow-holes, and much faster speeds will cause the ingots to scorch and make them apt to crack. Ingots made as here described are quite sound after discarding the head, which weighs approximately ten per cent. of the weight on a fourteen-inch ingot. A sulphur print made from such a head, after sectioning vertically, is shown in Fig. 69.

Fig. 69.—Sulphur print of ingot head.

When steel is cast on the cold side, as certain kinds should be to facilitate cogging in the forge or mill without cracking, the crust of crystals which forms on the upper surface of the fluid steel may be broken and thrown back on to the sides of the mould, or pieces thereof may be washed into the ingot and form blow-holes or other sources of weakness. In the ordinary form of mould this frozen surface is being pushed, as the steel rises, into a constantly decreasing area, and it must ultimately break up or allow the steel to flow over it. In the inverted mould, on the other hand, the frozen crust is rising always into a large area, which keeps its edges free and permits it to grow without becoming thicker and stronger; consequently, there is less danger of the crust being broken, and it is possible to produce groups of ingots at a lower casting temperature. This is an important advantage of the inverted mould apart from its effect on shrinkage cavities.

FIG. 70.—Split head to show effect of lifting hoops.

The increased difficulty of stripping ingots cast wide end up has brought into use a few devices to facilitate stripping. One of these consists of a mould with a loose bottom, which can be pushed up with the ingot. Others consist of various devices cast on to the mould in order that it may more easily be handled and inverted so as to tip the ingot out. One of the simplest means of stripping such ingots, providing they are not too large, is to push a hoop made from five-eighths or three-quarter inch steel into the top of the liquid head, by which the ingot can be lifted directly out of the mould. The objection to hoops is that they chill part of the steel in the head which is intended to feed the ingot; the objection is, however, entirely theoretical. The head in Fig. 70, made rather smaller than usual, was split open in order to determine whether the use of hoops on certain types of ingots were permissible, and it is clear from this illustration that they are not practically detrimental. If the hoops are made from square bars the number of the cast and the number of the ingot in the cast can be stamped on them before the ingots are teemed.

VIII

BLOW-HOLES

When the Sheffield cutler takes up a table-knife to read the inscription on the blade, as he has a habit of doing, and remarks that the blade has been made from shear steel, he accepts as evidence the unavoidable presence of seams, due to long drawn-out slag streaks, in the steel made from cemented bar iron which has not been subsequently melted. He may, however, be mistaken, because seams having a similar appearance on the surface of a ground blade might be due to badly welded blow-holes occurring in the ingot. Such ingots were purposely made many years ago, but whether with intention to deceive or with the idea of improving the cutting edge, as the slag streaks are supposed to, we do not know. Such ingots were known by the workmen as "fly-away" ingots because they emitted a stream of sparks on teeming and were also very light compared with other ingots of the same size. They were made by melting wrought iron with charcoal and casting it, without killing, as soon as it was melted. This is one of the very few instances in which blow-holes are useful or at least not detrimental.

We have found it possible to reproduce most types of blow-holes in stearine ingots by saturating the molten wax with sulphur dioxide gas or with a mixture of acetylene and coal gas. As the wax freezes the dissolved gases are evolved and cause the liquid portions of the ingot, when the top is kept open, to rise in or overrun the mould in a very realistic manner. And similarly by freezing the top of the wax ingot or closing the top of the mould the formation of blow-holes can be limited. On remelting the blown wax it can be recast into solid ingots which pipe in the usual manner. The photographs in Fig. 71, made from sectioned wax ingots, serve almost as representations of the "fly-away" ingots referred to, or as representations of the pipeless dead mild ingots which are rolled into common sheets.

The gas given off from a fluid steel ingot consists chiefly of carbon monoxide which is thought to be the product of the reaction $FeO(MnO) + C = Fe(Mn) + CO$. If the evolved gases are small in volume or are not trapped by the freezing metal then the unfed ingot would pipe in the usual way; but if the gases are evolved continuously, the shrinkage is more than counterbalanced by the volume of blow-holes and the ingot head will be convex instead of being concave. The usual precaution

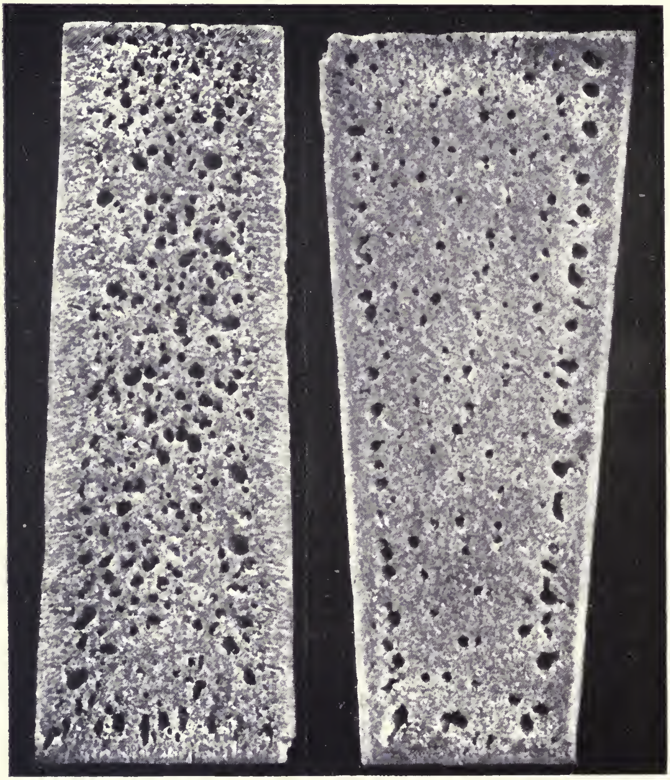

FIG. 71.—Blown wax ingots.

in casting very mild ingots is to continue feeding the ingot through the central guit for a while and then to put top plates on the ingot moulds and cotter them down.

For steels which are expected to be wild, top-casting is not popular as the tendency to evolve gas is aggravated by the oxidation of the steel, which scatters first on the bottom of the mould in the manner described in relation to Fig. 40.

Owing also, it is said, to the evolution of gas the shell of a wild ingot when bled is thinner than the shell of a quiet ingot cast and bled under the same conditions; the reason affirmed being that in the former case the solidified shell is continuously washed by the hot interior metal. Reasonable as this conclusion may appear, it is not completely logical, because of the two fluid ingots each is supposed to contain the same amount of heat, and the one therefore which has the thinner shell and hotter metal in contact with it will lose heat at the greater rate, and hence there must come a time, before the ingots are completely frozen, when the solid walls of the wild ingot are thicker than those of the quiet ingot.

In attempting to illustrate the comparative behaviour of wild and quiet ingots cast with stearine at the same temperature (55° C.), we find, in the pair of ingots bled, after ten minutes (Fig. 72) that the wild ingot B has hardly begun to deposit free crystals, whereas the quiet ingot A has deposited them quite freely from the colder layer near the solid shell. In the pair of ingots bled after thirty minutes the walls of the wild one D are notably thinner than the walls of the quiet ingot C. But in the pair bled after sixty minutes the walls of the wild ingot F are distinctly thicker when compared with those of the quiet ingot E.

The appearance of the free crystals attached to the interior walls of, say, C and D is different. It may also be observed that the upper end of ingot F is substantially solid and not bridged like ingot E. Probably both these variations arise, because in the wild ingot bubbles of gas attached to the free crystals would have the effect of floating them into erratic lodgments on the one hand,

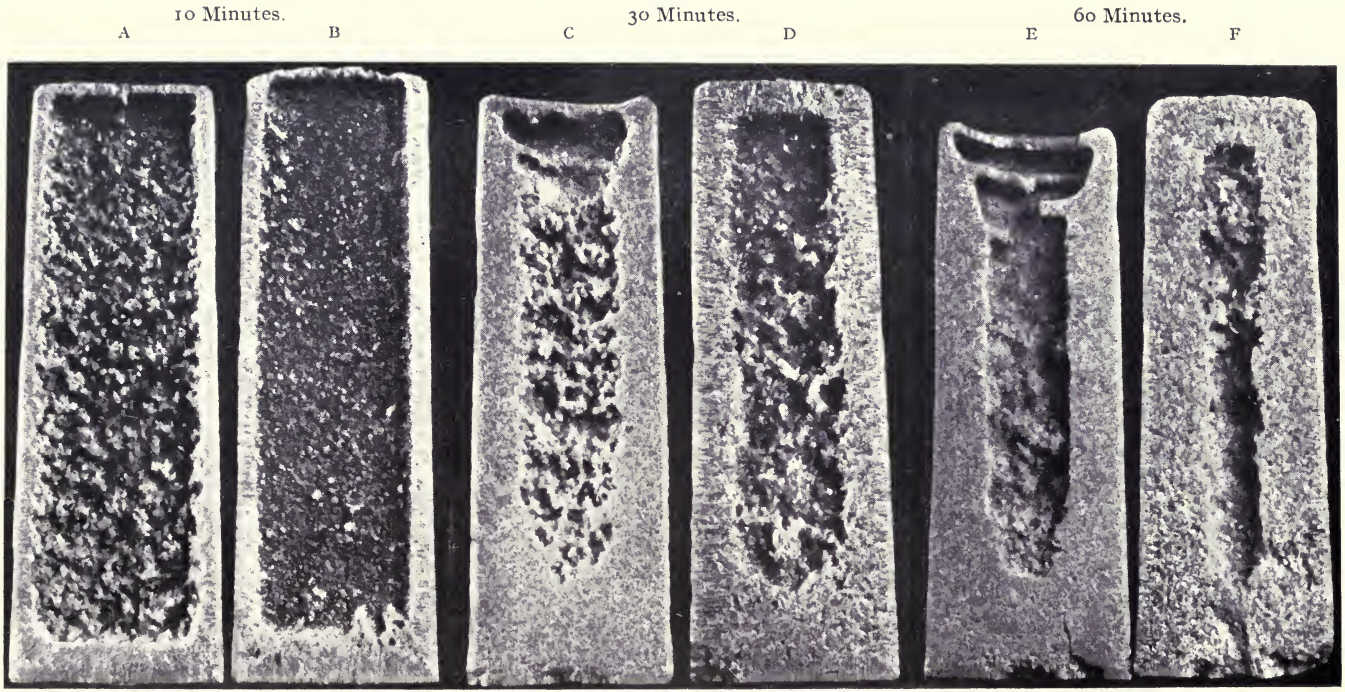

FIG. 72.—Relative rate of freezing of "wild" and sound wax ingots.

and keeping the hottest of the molten liquor pressed against the closed ingot top. When a wild stearine ingot is cast a few degrees above its freezing point, the top end of the ingot, presuming it has not been kept open, is occupied by a well-defined cone, as it should be, of course, if the hot clear wax had been kept continuously in contact with it.

Cavities or blow-holes in the interior of an ingot may arise from part of a runner brick or pieces from the oxidized surface of an ingot mould getting entangled in the steel, or they may arise from air carried into a mould by the stream issuing from the ladle, and on this account cut nozzles or a spreading stream arising from any other cause are objectionable. The manner in which air may be carried into an ingot by a broken or distorted stream, whether in bottom- or top-casting, may be illustrated by pouring a stream of water suitably disturbed into a piece of glass apparatus arranged to simulate an ingot mould with guit attachments.

When steel is cast very cold, even if it has no tendency to be wild, blow-holes are formed just under the skin. These arise from the thick crust of frozen and partially oxidized steel which is being continually pushed against the sides of the mould and submerged in the molten metal.

Blow-holes, similarly situated just below the surface, may occur in ingots cast cold or hot if they have been top cast. During top-casting the movement of the metal causes it to rise on the sides of the mould above the level to which the fluid would attain if it were lying quietly. If the teeming be stopped for a moment one observes a thin fringe of steel which has solidified instantly against the side of the mould, indicating roughly the height to which the turbulent liquid rises above the normal level. This fringe solidifies and oxidizes either simultaneously or in rapid succession, and as the ingot metal proper rises over it the usual reaction between iron oxide and fluid steel produces gas to form the subcutaneous blow-holes.

One may read this story in a favourable ingot specimen after etching, or in a sulphur print if the steel is high in sulphur. In the sulphur print reproduced in Fig. 73 the rapidly frozen skin is so finely crystalline as to appear amorphous, and the dark patches near the inner edge of the rapidly frozen skin represent the blow-holes.

Blow-holes arising as described from the turbulent movement in the mould due to top-casting are found to be empty when the ingot has been cast on the cold side, and frequently filled with segregates when the ingot has been cast on the hot side. The ingot represented by the sulphur print, Fig. 73, was cast on the hot side, as is clear from the extent to which the chill crystals penetrate. The dark patches near the edges are caused by the segregates which have been squeezed from between the elongated chill crystals into the blow-hole cavity. On the whole the blow-hole segregate is as harmful as the blow-hole cavity. Either may produce seamy bars or cause apparently sound billets to split when they are up-ended in drop-stamping operations. Blow-hole segregation just under the skin, though prevalent, will be quite unobservable on a transverse sur-

Fig. 73.—Sulphur print of top-poured ingot.

face as ordinarily machined or as machined and polished in the unetched state. It is, however, distinctly revealed by a sulphur print, of which a good example, made from an alloy steel bar, is reproduced in Fig. 74. When subcutaneous blow-hole segregates attain a size which is distinctly visible in forgings they are called ghosts.

Steel which is not in the least wild may produce very badly blown ingots if cast into rusty moulds. A cross-section of a nickel-chrome steel ingot prepared intentionally under unfavourable conditions is reproduced in Fig. 75; the remainder of the cast was quite satisfactorily made into aero crank-shafts. The arrangement of the cavities normal to the cooling surfaces is very noticeable, the more so as the steel was not cast hot and did not show scorch in the sound ingots.

FIG. 74.—Ghosts under skin of round bar.

As a general rule a scorched ingot does not contain dispersed blow-holes. It may show cavities in the centre of the ingot, particularly if cast narrow-end up, which are not pipe. This is not surprising, as the evolution and escape of gas in a hot-cast scorched ingot takes place practically unhindered by any irregular deposit of free crystals. So far as small crucible ingots are concerned, a scorched ingot is found to be always free from blow-holes, which may be due to the manner in which a scorched ingot freezes, but may also be explained equally well by the fact that scorched crucible ingots have undoubtedly been killed and are usually high in silicon.

The panacea for wild steel is aluminium, which is now so extensively applied that its use may well be thought indispensable. It is, however, but an indifferent substitute for good melting and not by any means so harmless in its effects on the properties of high-class steel as is fondly imagined, though it may be less harmful than roaks and seams arising from blown ingots.

FIG. 75.—Blow-holes caused by rusty moulds.

On two or three occasions we have been able to collect from ingot cavities a fine white powder which was distinctly crystalline and consisted mainly of alumina. The composition of two samples analysed in 1908 and 1914 were as follows:—

	1908.	1914.
Alumina	83·0	73·1
Silica	10·4	3·0
Ferric Oxide	nil	19·5
Ferrous Oxide	2·4	1·2
Manganous Oxide	4·0	2·6
Lime	nil	·6

The use of aluminium is less objectionable than its abuse. Its addition to steel has become a habit; and a reagent which should be applied as a remedy is made freely available to workmen who cannot be expected to discriminate between its good and bad effects. When steel has left the furnace the aluminium, if added at all, should be used in the ladle. Its use in the ingot mould is highly objectionable, though the objection is less forcible if the fluid steel has risen into the head before aluminium is added. The difficulty is to ensure that the workman who may apply it to the head of an ingot does not drop it into the half-filled mould.

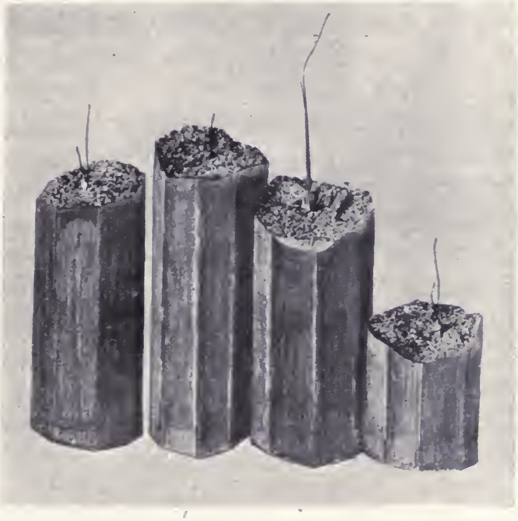

FIG. 76.—Alloy of aluminium in core of chisel steel.

We do not intend to convey the impression that the addition of aluminium to the head of an ingot is a commendable practice. On the contrary, by giving the ingot head every appearance of solidity it may suggest that the ingot is solid when such is really not the case. During the inspection of topped crucible ingots the examiner in spite of a solid-looking fracture is led occasionally to suspect, when he handles the ingot, that it is rather light for its size, and on breaking a piece from the bottom end of the ingot he rarely fails to find that the ingot is blown.

An ingot which is solid at the top and blown below may be worth more than an ingot which is blown throughout, but the danger lies in such ingots being accepted without suspicion and without any attempt being made to remove the cause of the trouble which has been so skilfully cloaked.

Instead of adding aluminium to the top of the ingot crucible steel melters occasionally add small pieces of aluminium to the few pounds of steel which have been reserved in the pot for filling up the dozzle. This also produces an ingot which on topping appears to be sound, but it may be very much otherwise, and the practice is not commendable. It may seem rather surprising that such faked ingots can frequently be detected by an experienced examiner, especially as the weight of the ingots he is examining may vary from forty to seventy pounds, but the statement is only made in relation to an examiner who is picking up his own ingots. The examiner who has the ingots picked up for him by a labourer will never detect defects of this kind.

A very unusual effect of aluminium is illustrated by Fig. 76. Some octagon bars of chisel steel on breaking into short lengths were found to contain a fine wire-like core of the following composition: Iron 87·0; Aluminium 9·2, Alumina 3·3 per cent.

IX

SEGREGATION

The first small crystal formed on cooling a molten metal, which is not a pure metal, has not the same composition as the fluid surrounding it. This is true of all crystallizable mixtures, metallic or otherwise. The laws governing the composition of crystals formed at different stages during the setting or freezing are expounded, as equilibrium diagrams, in books on metallography. We may, however, understand the broad effect of these laws without going into details if we are convinced, as any doubter may be by experimenting with a weak brine solution, that the first portion to solidify is never identical, and may be quite different in composition to the fluid in which it forms.

An example which may easily be reproduced is illustrated in Fig. 19. On allowing a mixture containing eighty per cent. lead and twenty per cent. antimony to cool slowly the crystals first formed consist of pure antimony, and, as these have a specific gravity of about 6·5, whereas the mother liquor has a specific gravity of about 10·5, they float readily to the upper surface of the molten mixture and can be skimmed off. If, however, they are left undisturbed a prepared section of the specimen ingot shows clearly what they are and how they were formed.[1]

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[1] Lead antimony alloys have been recommended as suitable experimental material for the student to use who wishes to study the influence exerted on the physical and structural properties of one substance by admixture with another, and who is more apt to learn by actual experiment than from books and photographs. The really essential apparatus for making synthetic lead antimony alloys can be made very simply and homely. An ordinary "churchwarden" clay pipe serves very well as a crucible. The stem is stopped up with clay or a small piece of wet asbestos mill-board. The weighed amounts of antimony and lead are charged into the bowl and the top is closed in with a piece of wetted asbestos paper. The pipe is then heated, say, in the kitchen fire, and subsequently allowed to cool at any desired rate. Cutting sections is very easy work, and a polisher can be easily improvized from a treadle sewing-machine or otherwise.

The progress of events in a metal mixer follow almost on the same lines as the lead-antimony alloys. In each case the separation of a substance notably different in composition to the mother liquor (segregation) occurs because the fluid does not freeze at a sharply defined temperature, but, on the contrary, through a great temperature interval during which the material is partly solid and partly fluid.

In the metal mixer iron-manganese compounds rich in sulphur, but freezing at a high temperature, form before the purer cast iron begins to solidify, and being lighter than the mother liquor rise to the surface. Having risen to the surface the sulphur compounds are oxidized by the air, thus giving rise to the strong smell of sulphur dioxide observable near mixers containing low-grade iron. From one-half to two-thirds of the sulphur present in pig iron may be eliminated in the form of an iron-manganese sulphide scum which rises to the surface as the temperature sinks.

Segregation in steel is never so complete that the segregates can be skimmed off the molten metal, or even be cut out of the solid ingot, for the simple reason that the harmful segregates are the last to freeze and not the first, and hence, whilst tending to occupy certain predictable positions, they are driven and trapped diversely according to size of ingot, casting temperature, wildness and composition of steel, etc. To these variables must be added all the complexities arising from diffusion, convection currents due to differences of temperature, and cementation effects occurring in the solid part and between the solid and liquid parts of the ingot. To realize a complete picture of what occurs inside an ingot requires imagination of a high order, and to frame an acceptable picture in words is beyond our skill. By considering seriatim the separate influences, which really operate simultaneously, the effort may be less hopeless, but it must be left to the reader to combine in due proportions the influences which are likely to have produced any given result.

A. If we imagine that an ingot, with perfect liquid diffusion but without commotion, solidifies simply by periodic thickening of the shell first formed, then each succeeding layer would be richer in carbon (neglecting all other segregating elements) and the central axis of the ingot, however low in carbon the molten steel may have been, would be practically pig iron.

B. If we imagine molten steel as in A to have been cast into a highly refractory and non-conducting mould so that its temperature as a whole remained nearly uniform and was only very slowly reduced, then the bottom of the ingot would be almost pure iron and each superior layer would be richer in carbon up to the top layer, which would be practically cast iron (see Fig. 43).

C. If in paragraph A we assume a very low rate of liquid diffusion and a flat thermal gradient between the centre and outside of the ingot, then at any moment the layer of fluid steel against the solid envelope might be so much richer in carbon than the next interior layer that this second layer would freeze earlier than the first, and this operation repeating itself would produce an ingot which on a longitudinal section was striped with segregated bands.

These three pictures, A, B and C, are impracticable extremes, but they may serve as frames wherein to trace the effect of other influences; at any rate they emphasize the fact that forces are operating which tend to locate the segregates towards the top, towards the centre and in annular rings between the centre and outside of an ingot. They suggest also that the remainder of an ingot can never be made entirely homogeneous by trepanning the core and cutting off the head.

If a bar of mild steel (or iron) is brought intimately into contact with a bar of high carbon steel at high temperatures the former becomes carburized and duly increases in weight. The carburization of the mild steel takes place the more rapidly the higher the temperature, and it takes place very rapidly indeed when the mild steel bar is immersed in molten high carbon steel. This rapid inter-diffusion of carbon between two solids or a solid in contact with a more highly carburized liquid steel is the most potent influence modifying the extreme conditions assumed in the preceding paragraphs A, B and C.

It is a matter of common experience that wrought-iron rods used for poking castings so as to keep the head open are gradually melted away at the lower end, although the temperature of the fluid metal is lower than the melting temperature of wrought iron. This is made possible by the solid rod becoming carburized by the liquid to such an extent that the melting point of the rod is depressed below the temperature of the surrounding liquid. The cementation of a mild steel rod by immersion in molten cast iron or high carbon steel might be noted by those interested in theories of case-hardening as an example of carburization occurring apparently without the mediation of gases. Owing to the rapid action of the carburizer single crystals may be observed one-half of which is unaltered whilst the other half is entirely pearlitic; such an example is reproduced in Fig. 77. When a piece of mild steel rod is immersed in molten high carbon steel

FIG. 77.—Inner edge of carburized envelope of mild steel.

containing also large amounts of sulphur and phosphorus the rod is carburized to a much greater extent proportionately than it is sulphurized or phosphorized. That is to say, the sulphur and phosphorus diffuse much less freely than the carbon.

The forces tending to drive the more fusible and highly carburized liquors towards the centre and top of an ingot are modified by the manner in which the crystals comprising the solid ingot are formed. If an ingot can be made to consist entirely of long narrow crystals as indicated in Fig. 1, the segregates will take up a notable position in the centre of the ingot. But, on the other hand, they will tend rather to accumulate at the upper end of the ingot if free crystals, being encouraged to form, fall towards the bottom of the mould.

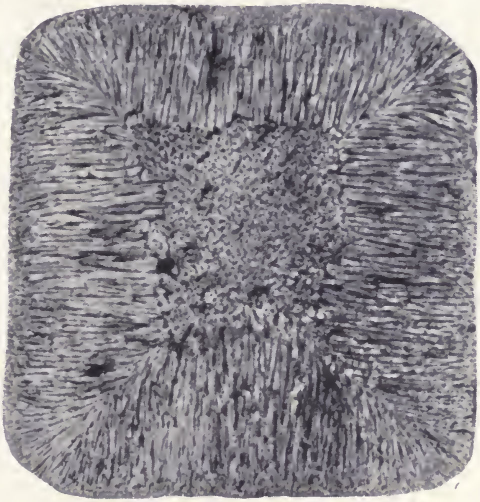

FIG. 78.—Chill and free crystals in fractured ingot.

As a general rule ingots do not consist solely either of chill crystals or free crystals but of both kinds, the former occupying the outer and the latter the inner parts of the ingot as indicated in Fig. 78. These two kinds of crystals behave differently in relation to the more fusible mother liquor in contact with them and out of which they have grown. The chill crystals which extend inwards from the solidified shell form a compact mass. They grow into close contact with each other, and as they cool and contract the less pure and fluid envelope is expressed from between their faces. The liquor thus ejected may move towards the surface of the ingot if cavities are there to receive it as suggested by Figs. 73 and 74, or it moves inwards and diffuses more or less completely with the fluid mass of interior metal.

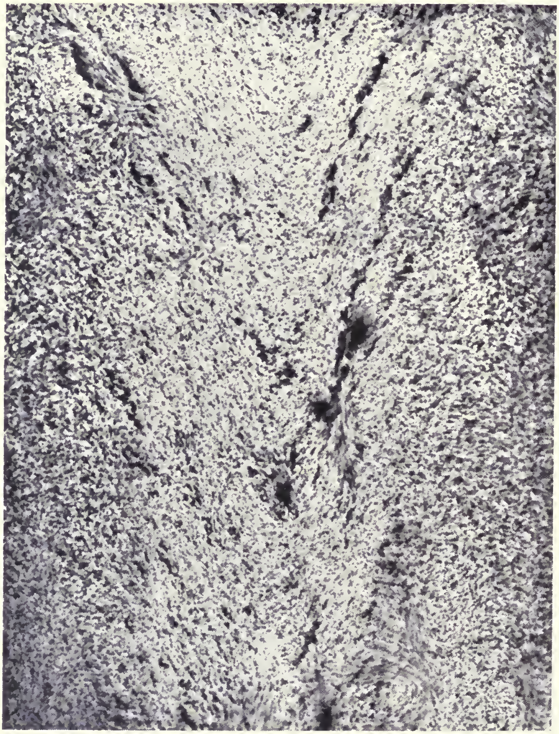

FIG. 79.—Sulphide lines in core of ingot.

In the solidification of every normal ingot, however, there arrives a time when the temperature of the fluid interior mass or considerable portions of it falls so low that free crystals form and sink towards the bottom or adhere to the inner surface of the solid walls. Such crystals lie loosely together like thistle-down and allow the liquid metal to pass between them; they do not exert a contractile pressure on each other, and do not therefore drive the more fusible liquor in definite directions as the chill crystals do.

As the free crystals fall towards the base of the ingot (and thus by the way promote solidification from the bottom upwards) the more fusible mother liquor rises. But it tends also to move downwards continuously because the material below it is shrinking and contracting. Ultimately, however, the very fusible liquid remnant which fills up the spaces between loosely adhering free crystals is small in volume, and rich in carbon and other segregates. This small volume of impure metal moves downwards as best it may, following up shrinkage and contraction as long as it is hot enough or impure enough to keep fluid. The last kick, so to speak, of the liquid metal is an effort to feed into contraction cavities, and that effort is marked at the centre of a sulphur print of a sectioned ingot as a series of V-shaped sulphide lines: see Fig. 79. Along these lines very minute cavities may often be found. These V sulphide lines, as might be expected, are not so well marked either in the lower part of a sectioned ingot or in the upper part just below the feeder head.

Talbot has shown [1] and before him Neu,[2] that when the sides of a partially solidified ingot are squeezed together to form a rough bloom, the cross-section of the bloom shows purer material in the centre and outside than on a median area. A method of producing sound ingots has been based by Talbot on this operation which he seeks to carry out after ingots have been kept for a definite period in soaking pits. That the process will be a commercial success is doubtful, but it is interesting at present in so far as the treatment of the Talbot ingots prior to squeezing is favourable to the formation of free crystals and the squeezing operation itself drives the impure fusible liquor in such directions as are open.

A sulphur print made from the cross-section of a Talbot billet is reproduced in Fig 80. This illustration suggests that the free crystals which were lying in the impure mother liquor have been squeezed together, and

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[1] *Jour. Iron and Steel Inst.*, 1913, No. 1.

[2] *Stahl and Eisen*, 1912, pp. 397 and 1363.

the more fusible liquor has travelled between them as far as possible towards the outside of the ingot, and become frozen there. It might have a fairly easy path through the free crystals whether they were lying loosely in the liquor or adhering to the sides of the massive shell, but it would be hindered as soon as it came against the compact mass of chill crystals. In sulphur prints of some Talbot ingots which the authors have examined the segregate may be observed in one or two places penetrating to the outside of the billet. This is no doubt due to the ingot having cracked during or prior to the squeezing operation, thus leaving an easy path along which the fusible segregate might travel under pressure. If it were thought desirable to move the segregate in a Talbot ingot towards the centre it could be done by increasing the chilling effect of the mould and raising the casting temperature; *i. e.* by increasing the thickness of the solid shell before the fluid it contained had reached a temperature at which crystals began to form freely within it. In the opinion of Prof. Howe, which he kindly communicated to the authors, the segregated band along the edge of the free crystals results from the porosity which during rolling arises in these layers, because they have neither the ductility

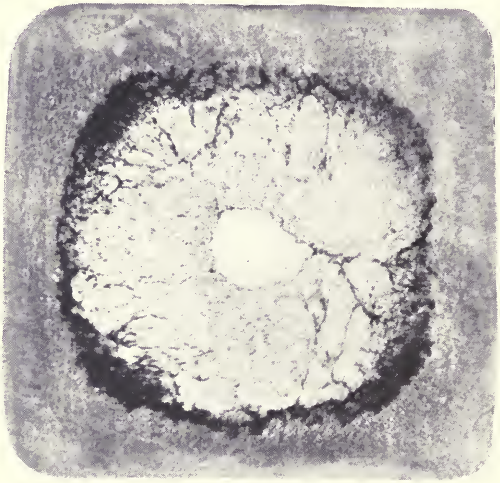

Fig. 80.—Sulphur print of Talbot billet—transverse section.

of the solid walls nor the fluidity of the still only slightly solidified central parts. These layers correspond to those which pull in the solidification of ill-designed castings, and in rolling they break up into a porous mass which, like so much blotting-paper, soaks up the impure fluid portion.

During the quiet freezing of an ingot the wall of compact chill crystals drives before it as it thickens a fluid envelope of impure metal. This envelope is relatively impure because it is the residue of the liquid from which a purer solid has just formed, and its temperature corresponds to the freezing point of the newly-born crystals. The immediate tendency of the impure envelope is to diffuse into the hotter metal nearer the centre so long as both remain quite liquid. When this interior liquid or portions of it reaches the upper limit of its freezing temperature the more flocculent kind of crystal begins to form and adhere to the compact walls, and thus restrains somewhat the free movement of the liquid segregate which at that moment occupies the same position. Unless we are prepared to assume a somewhat violent movement of the interior liquid, as in the case of a wild ingot, it must happen that the segregated fluid becomes more or less imprisoned and solidified where the two kinds of crystals meet, and as a matter of fact it is from that position inwards that ghosts are found. As a natural sequence one would expect to find the lower part of an ingot, which receives most of the deposited free crystals, to be either altogether or relatively free from ghosts. Also it might be predicted that a line drawn on a longitudinal section parallel to the side of an ingot would cut simultaneously the outer ends of a number of ghost lines.

As might be expected, the troubles arising from segregates of this kind are very marked in large ingots. Makers of gun tubes and other large hollow forgings, which are closely inspected, have all had ample experience, and many of them have thought, vainly, that some member of their staff was personally responsible. Ghosts, however, will persist, in spite of specifications to the contrary, just so long as steel is a complex substance which freezes over a considerable range of temperature, and an early recognition of this fact would avoid much misunderstanding.

We are indebted to Sir William Beardmore for an opportunity of examining the sulphur print which is reproduced on a diminished scale in Fig. 81. This print shows clearly the segregates known as ghosts which arise at the interior face of chill crystals in very large ingots. Whether the ghosts referred to do originate as here described can only be finally settled by a careful examination of large ingots which have been cast under known conditions. As opportunities of sectioning very large ingots for experimental purposes are rare and costly we venture to put on record a few correlated observations in support of the conclusions at which we have arrived.

> A. In a large ingot cast in a loam mould the ghosts were found to be distributed almost to its edge, and it was not possible from any part of the forged gun tube to secure test pieces which would pass inspection. This condition arose obviously from the fact that circumstances were unfavourable to the formation of chill crystals.
>
> B. As a result of extensive experiment it has been affirmed that much better results are obtained, *i. e.* there is less trouble with transverse test pieces cut from a gun forging when the casting temperature is high. This arises from the fact that a high casting temperature is favourable to the growth of chill crystals and hence forces the ghosts nearer to the centre, but it may arise also because non-metallic impurities, not strictly due to segregation, have a better chance of escaping to the centre and top of the ingot when the casting temperature is high.

We are permitted by Mr. Ashdown to refer to a direct experiment on this subject. He prepared a longitudinal section through a large ingot which was cast partly in an iron mould and partly in a loam mould. The result is shown very clearly in Fig. 82. Mr. Ashdown has allowed us to examine also the results of many large-

Fig. 81.—Sulphur print of large ingot, showing ghosts.

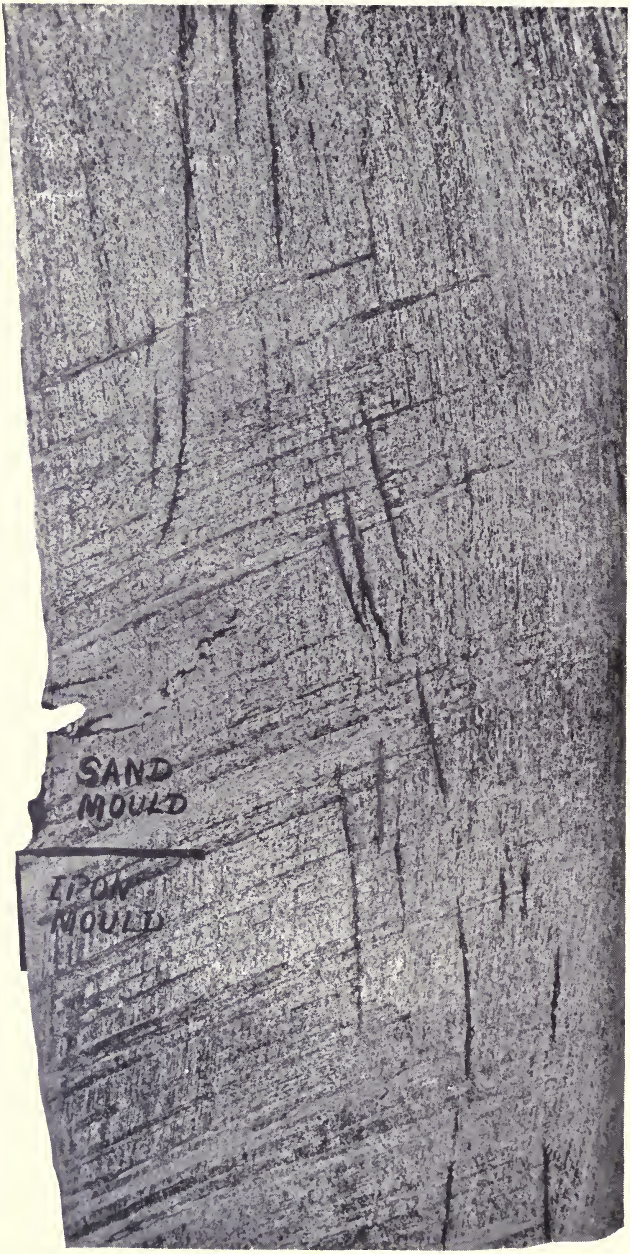

Fig. 82.—Ghosts in large ingot (Ashdown).

scale experiments along similar lines, and we were gratified to find them in agreement with our own observations and deduced conclusions.[1]

The fluid segregates in wild steel are distributed in an irregular and unpredictable manner owing to the erratic movement of the evolved gases. They tend naturally to lodge in such blow-holes as may be accessible, and under the contraction stresses of the cooling ingot they may actually be forced into blow-holes. It is, therefore, not uncommon to find the ends of lenticular blow-holes nearest

FIG. 83.—Sulphide segregation in pipe of ingot.

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[1] It should be said that the maker of gun tubes first trepans a core from the centre of the ingot or from the centre of a large billet made from the ingot. He does not care very much whether the discarded core contains ghosts or not, but it is very important commercially to have no ghosts, or as few as possible, on that part of the ingot which will lie ultimately near the bore of the gun.

the centre of an ingot filled with segregates. A small blow-hole may be entirely filled with segregates, this giving rise to what is known as "spot" segregation. This kind of segregation is said to be prevented by the use of aluminium, but the aluminium acts only indirectly by deoxidizing the dissolved substances which promote the evolution of gas; it has otherwise no great influence either on the amount or position of segregates in a sound ingot made from properly killed steel.

Fig. 84.—Crystalline growth in spoon-test sample.

When an ingot, not provided with a feeder head, is allowed to pipe, the material on and about the surface of the pipe is usually rich in sulphur and other migratory elements. A portion of a sulphur print showing roughly the extent of this segregation is reproduced in Fig. 83. It does not follow that every shrinkage cavity is lined with low melting-point segregate; it may be quite otherwise, as has been stated in relation to Fig. 32. But the primary pipe whose surfaces from the top downwards are formed from, or have been in contact successively with, the impure upper layer of molten steel which is gradually sinking must be contaminated. Whether such a pipe will weld up or not during the cogging operation will depend to a considerable extent on the percentage of sulphur in the contact surfaces. Whether, also, such steel is suitable for certain purposes may depend much more on the extent of the segregation on and about the pipe than on the average amount of sulphur in the ingot. Whence it may be concluded that a specified maximum amount of sulphur, apart from a knowledge of how the ingots will be made, is not necessarily a guarantee that red shortness or other troubles due to sulphur will be avoided.

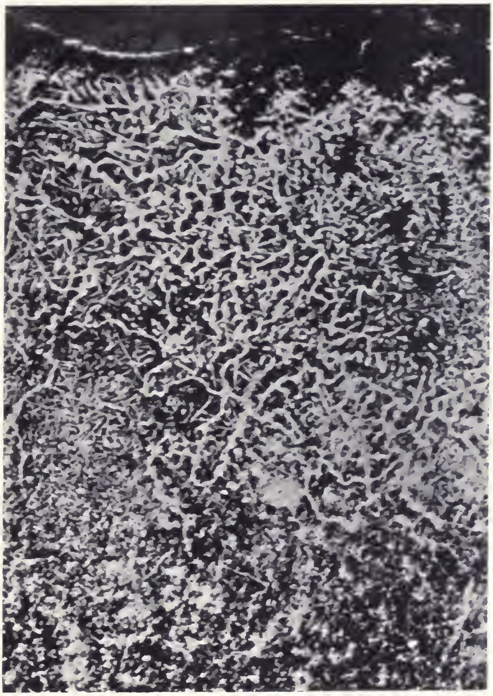

FIG. 85.—Carbide segregation in spoon-test sample.

One of the minor ills of segregation which affects the steel-maker rather than the steel-user is the occurrence of hard spots and patches in spoon tests which have been taken under a thick layer of slag. Small as such samples are, they develop under favourable conditions a magnificent crystalline structure, of which an example is reproduced in Fig. 84. In the part last to freeze the carbon may be as much as one and a half per cent., although the average carbon is only about one per cent. Fig. 85, reproduced from a spoon test shows that on taking drillings for colour carbons it would have been a safe practice to reject those taken from near the surface, or safer still to discount the spoon test in favour of a chilled-test sample in which segregation effects are suppressed by rapid cooling. For a similar reason any drillings for analysis taken from runner scrap are likely to give unreliable information.

X

SLAG OCCLUSIONS

The presence of slag in cemented or puddled steel was one of the reasons why Huntsman found such material unsatisfactory for clock springs; and whether he knew it or not the effect of remelting cemented bar was to remove such slag occlusions almost entirely. It is still a great virtue of crucible steel that it contains less occluded slag than steel made by any other process.

Less than twenty years ago it was generally believed that the existence of slag in steel was confined to such visible particles as had accidentally escaped restraint during casting and risen to the top of the ingot or been trapped against the side of the cold mould. In such cases it could be removed at will. That all kinds of steel contained slag in a much finer state of division disseminated with some degree of uniformity in ingots was an idea resisted and, finally, accepted with great reluctance by the steel-maker. The great importance of slag inclusions was also not appreciated by early workers in metallography, either because such workers were not in intimate contact with the production and testing of commercial steels, or because their own specimens were prepared under ideal conditions in very small quantities. We do not know that any particular individual claims to have been the first to discover slag as a normal component of cast steel, but it has a very much more important influence on the physical properties of steel than some other constituents the discovery of which is a contested honour.

As an illustration of the unwillingness to recognize the presence of slag occlusions and their influence on the properties of steel, one may quote an expression which has attained a certain degree of currency in metallurgical papers and text-books—viz. that nickel steel has a reedy structure. This disparaging remark is not especially true of nickel steels as compared with other steels, but it has become associated with nickel steel because that material more than any other was submitted to transverse testing, and was much tougher than other steel which had been tested transversely. To-day, at any rate, the slag streak of visible dimensions cannot be disposed of or excused by calling it a "sand crack," and it is being rapidly realized that slag is a normal and partially unavoidable constituent of steel, more important in its effects than slight variations in chemical composition or heat treatment.

Under the general term of "slag" the authors desire to include all non-metallic occlusions, such as sulphide of manganese, which are products of reactions taking place within the fluid or solid steel. There are, of course, slag globules in ingots which are nothing more than admixed furnace slag, fused runner brick or vitrified ganister, but the origin of these requires no explanation, and their unwelcome occurrence may be minimized by ordinary care and attention.

When cast steel was made by the crucible process only it was a matter of common knowledge amongst steel-makers that a charge of converted bar iron or bar iron and charcoal could not be made into a solid ingot if the pot was teemed as soon as the charge was melted. It was necessary to continue the heating, and, indeed, increase the temperature as far as possible, in order to "kill" the steel. During the killing operation the very high temperature is said to have promoted a reaction, between the steel and the clay crucible, which reduced silica from the walls of the pot into the steel, there to exist as silicon. The amount of silicon thus reduced into the steel is influenced also by the presence of coke dust in the clay mixture, and it may be taken as a general rule, other conditions being the same, that the higher the amount of carbon in the clay mixture the larger will be the amount of silicon in the steel. Fig. 86 is an expression of this rule, so far as graphite crucibles are concerned, which has been plotted from observations made by Thallner, an observant steel-maker whose conclusions are usually reliable, and it explains why Continental tool steels, which are invariably made in graphite crucibles, are higher in silicon—up to ·35 per cent.—than Sheffield tool steels, which are made in clay crucibles. The silicon thus laboriously introduced was the active killing reagent; so that, instead of the reaction $FeO + C = CO + Fe$, which produced gas and took place in the ingot mould, there was substituted $2FeO + Si = SiO_2 + Fe$, a reaction which produced a solid substance and took place in the crucible where the non-metallic product had an opportunity, whether fluxed or not, of separating itself from the steel. If the charge of crucible steel consisted of scrap only it could, when melted, be cast into a fairly sound ingot without killing, and, for this reason, the melter preferred to have as much scrap in the charge as he could get.

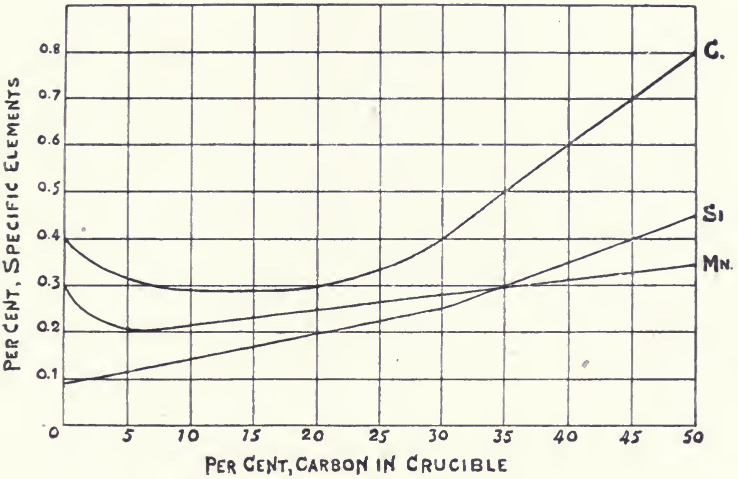

FIG. 86.—Influence of graphite crucible on composition of charge.

About thirty years ago the practice of adding aluminium to tool steels was introduced, and it was then found that the killing fire was no longer necessary. A small piece of aluminium weighing only a fraction of an ounce, and known in the trade as a "pill," was added either just before "pulling out" or after the pot had been brought up to the teeming box. The most fiery pot would be quietened with a pill without any apparent harm being done, and with a saving of that amount of coke which had previously been used for the killing fire. But it happened now and again that a yellowish-white stain appeared near the top of an ingot, or within the dozzle, which was found to be alumina, and was thought to be due, therefore, to the pill added just before teeming, or to a pill dropped into the dozzle; though no reputable steel-melter would condone this latter practice, or admit that his ingots ever required such drastic treatment.

It is clear from these observations that the pill reacted with some oxygen compound dissolved in the steel and became itself oxidized to alumina. As, however, the pill would diffuse rapidly through the fluid steel, so the products of its reaction with the oxygen compounds were also diffused in the finest possible state of division. This is the origin of what the maker of high-class cutlery calls "spotty steel." When a surgical instrument or some other tool-steel object is highly polished an appearance of fine dust under the polish, as it were, may become visible. Before the use of aluminium as a deoxidizer was known, *i. e.* when steel was killed in the old-fashioned way, this dusty appearance on polished surfaces was very rare, whereas since its use became general most makers of special cutlery steels have had material rejected on account of it. The dusty appearance is caused by small particles of alumina, which have arisen from oxidation of the aluminium added to promote soundness in the ingot.

Where only a small amount of aluminium has been used, and the steel-melting operation has been carried out with care in other respects, the alumina is in an extremely fine state of division, as seen in Fig. 87, and practically harmless so far as the mechanical properties of soft steel are concerned. In larger ingots, however, and from injudicious use of the "pill," these particles segregate into colonies of appreciable size (Fig. 88), and may lead to cracks in hardened tools, though the direct cause of such cracks may be traceable only with difficulty, or not at all, to this source. In lower-quality steels, made by the open-hearth or Bessemer process and cast into larger ingots, the particles of alumina suspended in the fluid steel would make their way towards the centre and top of an ingot, or line the lower end of a pipe or the interior of a cavity, and prevent effective welding during the subsequent hammering and rolling operations.

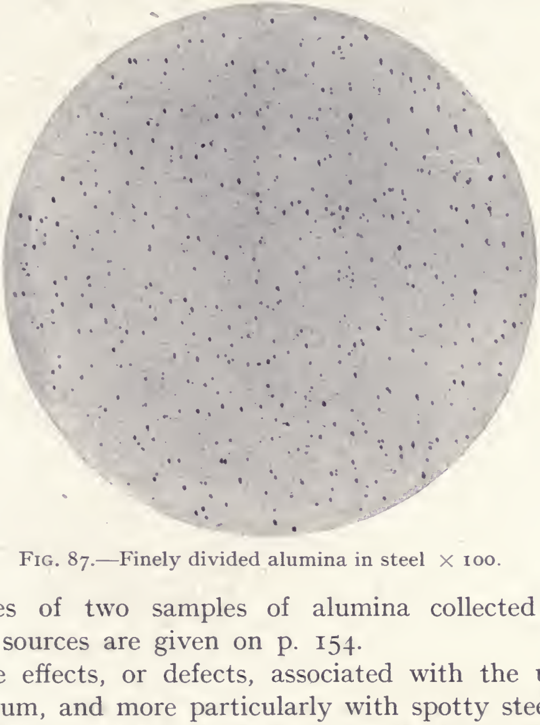

FIG. 87.—Finely divided alumina in steel × 100.

Analyses of two samples of alumina collected from similar sources are given on p. 154.

These effects, or defects, associated with the use of aluminium, and more particularly with spotty steel, are referred to in order to emphasize the fact that when a deoxidant is used which yields a refractory oxide, that oxide, according to the efficiency of its action, is disseminated in the first instance as invisibly small particles throughout the mass of fluid steel. These, according to the time which elapses before the metal solidifies, segregate into visible particles, as exemplified in Fig. 87, or into dangerously large patches, as in Fig. 88, or into still more objectionable forms. And it should be remembered that in high-quality steel used for certain purposes these defects arose into prominence when the use of aluminium was adopted, and can be modified or avoided by reverting again to the old-fashioned practice, which does not involve the use of aluminium.

So far we are on tolerably safe ground and supported by observations which have been repeated over and over again. It should be possible by analogous reasoning to understand fairly well why other non-metallic impurities occur in steel tapped in large masses from open-hearth and Bessemer furnaces.

Fig. 88.—Aggregated alumina in cutlery steel × 100.

In the open-hearth furnace the molten charge is oxidized by the addition of iron oxide; in the Bessemer by the compressed air, which may be brought to act directly or by the intermediate formation of iron oxide. In either case the product of the reaction between the added oxide and the silicon (manganese) is an iron (manganese) silicate, which is disseminated in the first place in a very fine state of division, like the alumina, throughout the reacting mass. In due course most of the very fine particles (possibly colloids) aggregate into globules, which obey the ordinary laws of buoyancy and rise to the surface. The mass of molten metal lying in a furnace may be visualized at any moment as containing particles of slag varying in size down to extremely small or colloidal forms. If the reaction could be terminated, this non-metallic product might be got rid of by allowing the fluid metal to remain quiescent in the furnace for a sufficient length of time. This may not be impossible, but it is not practicable under prevailing conditions of steel-making.

On the addition of " finishings " in the form of ferro-manganese and ferro-silicon a greater or less part of them is lost, *i. e.* utilized in reversing the oxidizing reaction, which also produces a non-metallic product similar to the iron manganese silicate, but richer in manganese. This reaction may not be absolutely completed, and the products of the reaction have certainly not had time to separate from the molten steel before it is tapped.

Let us admit, however, that the steel as tapped is free from non-metallic products, which in practice is by no means the case. On passing into the ladle and again on passing from the ladle to the ingot mould the steel falls through the air, *i. e.* we have the conditions of a Bessemer converter on a modified scale in an inverted order, the metal running through the air instead of having the air blown through it. The unavoidable result is oxidation of carbon, which can be observed as a carbon monoxide flame around the stream, and oxidation of iron, manganese, and silicon, which produce a silicate slag.

In no case is the fluid steel in an ingot mould free from non-metallics. Their amount may be relatively small, depending obviously on the extent to which the slag-producing reactions have been completed in the furnace, and on the quiescent period allowed both in the furnace and ladle for the reaction product to coalesce and rise to the surface. But, however perfect the conditions may be up to the moment when the stopper is opened in the ladle, those oxidation products formed during teeming must separate themselves out in the ingot mould.

There are two ways in which " teeming " slag may be dealt with. First by avoiding its formation as far as possible. This can only be done by shielding the stream from contact with the air. When only one or two large ingots are being made, this may be practicable by attaching a prolong to the nozzle, which reaches at successive moments to just above or just below the rising surface of the ingot; by casting in a vacuum, or by casting through an inert atmosphere. All these methods have been tried with inconclusive results. Apart from special precautions of this kind, every care should be taken to avoid spreading streams due to cut or badly-fitting nozzles. In top-casting, a bad stream may double or treble the area of molten surface in contact with the air, and in bottom-casting, a bad stream may convert the central guit into a kind of air injector. A few experiments made with a stream of water running into a glass vessel will demonstrate how widely the area of contact between the fluid and the oxidizing atmosphere may vary, and also the extent to which different kinds of streams may carry air into the fluid metal.

The second way of dealing with teeming slag is to delay the freezing of the ingot in order to give the slag particles a better opportunity of rising to the surface. This is usually done by casting the steel at a higher temperature than would otherwise be thought necessary. Mr. McCance says: " To give the slag particles time to rise to the surface after they have been cast, that is, at least those particles which have been trapped in the steel during the boiling period and have not been removed, the casting temperature of the steel should be high, so as to allow as long a time as possible to elapse before the steel sets."[1] We do not consider this a satisfactory practice for general purposes, as it is likely to lead to

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[1] *West of Scotland Institute*, 1917, p. 66.

greater troubles than it obviates. Moreover, it transfers to the ingot mould a steel-making operation which ought to be conducted in the furnace and completed as far as practicable before the first ounce of steel leaves the ladle. To cast hot may be useful in making large ingots intended for special purposes, where the object is rather to drive non-metallics into parts of the ingot where they will be harmless than to separate them from the ingot altogether.

Slag particles formed in the molten steel and trapped in the frozen ingot have not the same composition as the furnace slag. On casting very large ingots from two or more ladles simultaneously the steel is released from the ladle into a brick- or ganister-lined trough, which conveys it to the ingot mould. Small globules of molten slag may be observed rising to and flattening themselves against the surface of the stream. Analyses of trough slags are appended and compared with the analyses of samples of slags taken from the furnace launder on tapping the same heats.

	Furnace Launder.		Trough.	
	A.	B.	A.	B.
Silica	52·4	58·8	38·9	43·3
Alumina	2·0	·3	13·2	1·7
Ferrous Oxide	23·3	14·5	9·1	5·6
Manganous Oxide	8·1	16·5	36·8	41·6
Lime	13·6	3·4	1·2	trace

The notable amount of alumina in the trough slag is due to the aluminium added during tapping, the very large increase in the amount of manganous oxide comes from the finishings, and the presence of lime in the trough slag, A, shows that it consisted partly of furnace slag, and was not purely a product of reaction taking place in the ladle after the steel had left the furnace.

On cutting open large ingots or castings there may be found in cavities, which are generally near that part of the ingot last molten, one or more globules of slag varying in size from a pea to a hazel-nut. They are generally imperfect amber-coloured spheres, and appear to have grown by the segregation of semi-fluid particles. The following are analyses of globules found in large ingots varying in weight from fifty tons downwards. The steel had in each case been treated with aluminium.

	A.	B.	C.	D.
Silica	41·2	52·8	28·8	42·9
Alumina	28·6	27·8	37·5	6·3
Ferrous Oxide	trace	·14	—	1·0
Manganous Oxide	27·0	18·4	29·2	47·0
Lime	nil	nil	—	1·3

When aluminium has not been used slag globules found under similar circumstances contain no alumina but considerable amounts of ferrous oxide. Two specimens analysed by Jäger gave—

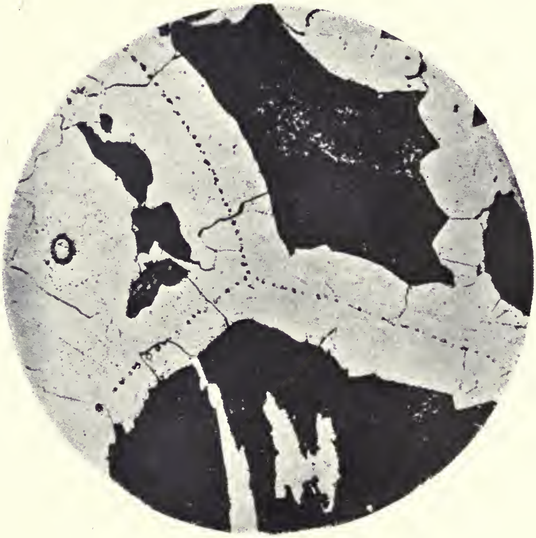


Fig. 89.—Slag particles between primary crystals.

Silica	36·75	37·70
Ferrous Oxide	18·27	18·36
Manganous Oxide	45·9	43·4

From these analyses it may be concluded that the slag particles found in steel are not necessarily particles of furnace slag, and, further, their composition varies with the kind of deoxidizing alloy added to the molten steel.

The distribution of slag particles, like the movement of segregates, cannot be defined exactly beforehand. They tend to move with the fusible segregates, and are therefore located in more than average quantities between the branching dendrites. We do not know whether slag is soluble in steel, but the particles which trouble the steel-maker have every appearance of having had a separate existence before the steel surrounding them became solid. They appear in certain cases to have been pushed outwards with the fusible residue from growing dendrites until they fall on the junction between primary crystals, and in that position they gather about them as the temperature falls an envelope of free ferrite. This is clearly illustrated by Fig. 89, and even Fig. 90, which shows in the dark junction line between the crystals growing from separate centres a fine white thread of ferrite.

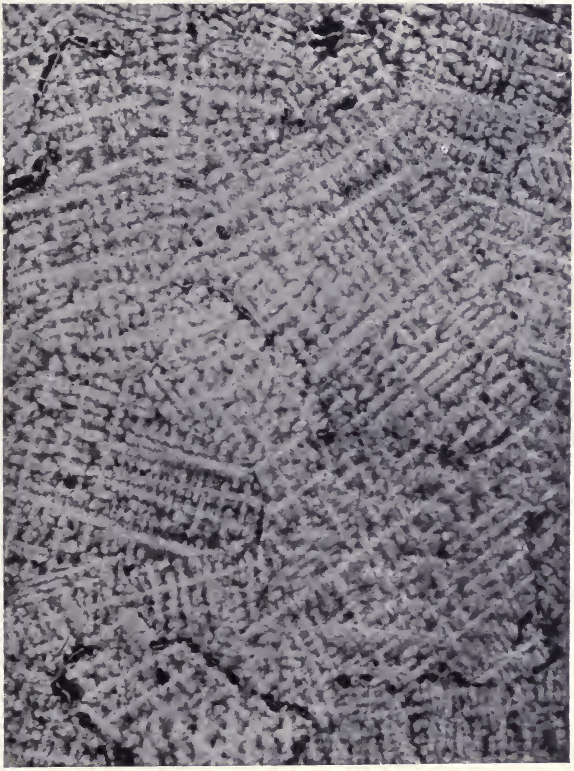


FIG. 90.—Ferrite envelopes about primary crystals.

Slag particles which individually are too small to seriously effect the mechanical properties of steel seem to have a very powerful effect on the structure of forgings and heat-treated castings. The structure seen in Fig. 90 is very proper in an ingot, but it is not a welcome appearance in a forging, as both the reheating and mechanical work are supposed to break down these elementary crystalline forms. Why they sometimes persist is a difficult question to answer, but they are most persistent in those casts of steel which have been worked and tapped under a strongly oxidizing slag and cast from a high temperature. This means, in effect, that such steels are disposed to form slag whilst in the ingot mould and also to form well-defined crystals to the boundaries of which the slag particles are driven.

FIG. 91.—Dendrites in forged piston rod.

There is reproduced in Fig. 91, at a magnification of four diameters only, the structure of a high carbon nickel-chromium steel forging. This dendritic pattern persisted in a more or less distorted form no matter how much work was put on to the steel. About the outline of each dendrite small non-metallic particles had arranged themselves. These are too small to be visible in the photo, but their relationship to the dendritic outlines can be exhibited in the following manner. On etching the polished section with a very dilute and slightly acid solution of ferric chloride circular areas about the slag particles are darkened. This darkened area is a hundred times greater in diameter than the enclosed slag particle, as may be seen by reference to Fig. 92. The darkened areas join up, as it were, one slag particle with another and produce a pattern practically identical with Fig. 91.

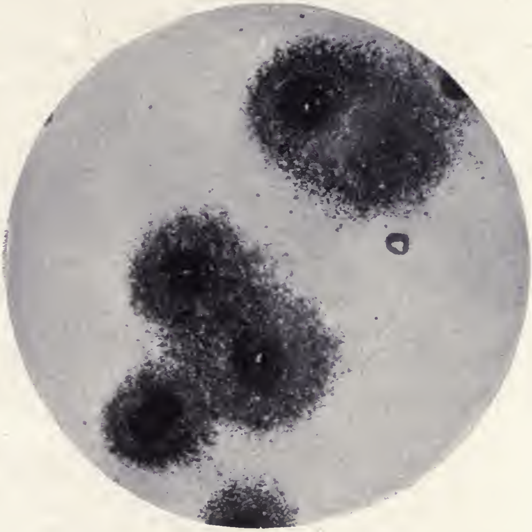


FIG. 92.—Dark etching halo around slag enclosure.

The proof that persistent dendritic structures in forgings are due to non-metallic particles and these in turn are due to strongly oxidizing furnace conditions and high casting temperatures is general rather than particular, and much additional work requires to be done under controlled experimental conditions. There can, however, be no doubt that slag exerts a selective action and forms nuclei around which separate micro-constituents, appearing in the solid steel, tend to segregate. The authors were led to this conclusion in 1909, and have since seen no reason to reject it, though there are doubtless other causes favourable to the aggregation of particular micro-constituents in definite forms and places.

A direct experiment on this point was made by drilling three small holes in a billet, placing a quantity of hammer scale, open-hearth slag and pure silica sand respectively in the holes, then driving a well-fitting plug of the same kind of steel into the holes, rivetting over and fusing the heads, and finally heating the billet and rolling it into a bar. When the part containing the hammer scale was sectioned nothing was found save a large patch of ferrite due obviously to the decarburizing action of the scale. The ferrite border about the open-hearth slag is very distinct (Fig. 93), which may be partly due to a decarburizing action; but the ferrite border about the silica sand (Fig. 94) is also unquestionable.

FIG. 93.—Ferrite envelope around slag enclosure.

The most objectionable tendency of slag occlusions is to break the continuity of the metal, and they are undesirable in that respect in forged steel whether the size of the occlusions be great or small. Steel-makers do not contend that for general purposes the presence of slag is helpful, but they are justified in suggesting that it should be regarded as an unavoidable constituent. Some steel-makers unfortunately do not realize that the presence of slag is unavoidable. Even so well-informed a metallurgist as Dr. Arnold makes a distinction between silicate slag inclusions and sulphide of manganese inclusions; he says, "broadly speaking, slag was avoidable but it was a variable, but the sulphide of manganese inclusion was unavoidable; it must be present in all steels. That was a point from a practical steel-maker's point of view which should be pointed out to engineers in the interests of steel-makers."

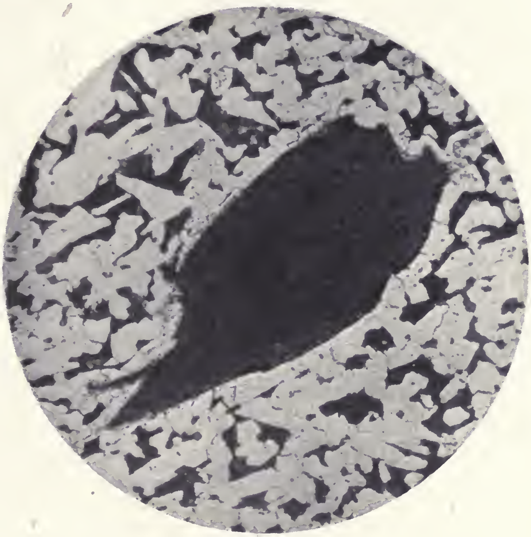


FIG. 94.—Ferrite envelope around silica sand.

As a commonplace matter of fact, it might be said that commercial steel is never quite free either from sulphide of manganese or slag. But presuming sulphur could be entirely eliminated the steel might be expected to be free from sulphide of manganese, whereas masses of slag-free steel would only be possible if certain reactions could be completed within the furnace and the fluid metal could be screened during casting from oxidizing influences. The authors do not pretend to decide which of these two metallurgical feats is the more difficult, but they are disposed to believe that if one could be done the other would not be impossible.

XI

INFLUENCE OF INGOT DEFECTS ON FORGED STEEL

A PROBLEM in geometry may be worked out on the assumption that AB is a straight line, and the same result may be reached whether AB is really a straight line or not. And in engineering calculations it may be assumed that all wood and metal is as ideally perfect as triangles or circles; but when the intended structure or machine is completed, its usefulness and length of life will depend on the margin of safety which has been provided to cover possible deviations from the ideal.

The margin or factor of safety may be regarded as a measure of our caution, or incapacity, or ignorance; and whilst no one would argue that it may be reduced to unity, many will at once admit that if the factor varies from two to ten, then either the test results used in calculations are obtained by inefficient methods, or interpreted by incomplete knowledge, or the structural material in question is not reliably uniform.

All forms of chemical and mechanical testing applied to steel are based on the assumption that the sample or test piece is representative of the bulk. This is never strictly true, and it may be grossly untrue. The inspecting engineer who proceeds on the assumption that steel is chemically and physically homogeneous will meet with disappointment, and the steel-maker who affirms that his craft is a perfect art based on a perfected science is misleading himself whoever else he may convince. The first object produced, namely, an ingot, is never perfect, and the purpose of this chapter is to consider how certain groups of imperfections in ingots affect the properties of forged steels.

Axial Shrinkage Cavities and Segregation

The influence of the central shrinkage cavity or pipe in an ingot will depend to some extent on the degree to which it has welded, but even if the weld is complete the central part of the billet or forged bar is never the same as it would have been had the pipe not been allowed to form; but whether it matters or not will depend on the purposes for which the material will be used. In the manufacture, for example, of hollow forgings like gun tubes, turbine drums, and air vessels, the core of the ingot is trepanned out and it does matter whether the ingot is piped or not, presuming that the piped centre has not led to clinking. In the manufacture of tyres, also, a small pipe is no detriment, presuming that it is entirely removed with the piece punched out of the centre of the circular block. The same remark applies to ball races, milling cutters, hollow drills and other tools from which the piped portion, whether welded or not, is discarded.

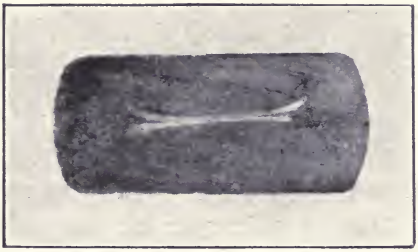


Fig. 95.—Hard centre in bar of chisel steel.

If, however, the piped material remains in finished objects such as turning tools, drills, circular saws, rifle-barrel blanks, crankshafts, hardened balls, and so on, then it may be fatal; or it may be comparatively harmless, as in shafts, straight axles, rails, girders and laminated springs.

A bar of chisel steel which is much harder in the centre like Fig. 95, whether the abnormal hardness be due directly to segregation or indirectly to pipe, will readily splinter at the cutting edge when put into service. In the form of a twist drill the material would be apt to crack up the flute. In circular saws the teeth split or laminate at directly opposite edges of the saw, although they are perfectly sound elsewhere. In multiple-throw crank-shafts small cracks appear on the journals and pins. In rifle barrels the boring tool either comes to a dead stop or runs out of truth.

The harmfulness of pipe and axial segregate are very pronounced in rifle-barrel blanks apart from any effect they may have on the useful life of the barrel. The boring and rifling are delicate operations. Unless each portion of the end of the boring bit is cutting material of the same kind the hole becomes eccentric. The barrel blanks cannot be successfully drilled unless they have been made from pipeless ingots, as the interior of a pipe is always lined more or less with segregated material. If the segregate were larger than the end of the boring tool the hole made might be concentric, but even so there is no guarantee that a pipe or a segregate existing in the geometric centre of an ingot will occupy the same relative position in a forged or rolled bar made from it. As a matter of fact a circular bar forced longitudinally through the centre of a large bloom was found to be neither circular nor central after the bloom had been worked down into round bars. Any object, therefore, such as a rifle barrel, along which a fine hole must be drilled, would present unusual difficulty if the drill were cutting a hard and a softer material simultaneously in the same plane. An etched section of a rifle barrel showing a hard eccentric core is reproduced in Fig. 96.

The amount of sulphur in the worst parts of an axial segregate may be ten times greater than the average sulphur content of the steel; and for some purposes it is preferable by far to use steel made from sound ingots having a higher sulphur content than steel made from piped ingots with an average lower sulphur content. In the axial segregate high sulphur is associated with high phosphorus and high carbon. The sulphur exists mainly as a non-metallic occlusion, and this together with the associated embrittling elements is not favourable to welding and easy working at high temperatures, or to a ready flow of the material under stress at low temperatures. It is no exaggeration to say that the standing question between the steel-maker and the forge, of whether a bar is piped or has been "crushed" will be a bone of contention as long as ingots containing either primary or secondary pipe continue to be made.

FIG. 96.—Eccentric segregate in rifle-barrel blank.

Cuppy wire is perhaps one of the best illustrations of the effect of axial segregation and pipe on cold-worked material. Wire which is apparently sound will sometimes show on a longitudinal section a series of well-developed internal fractures which open up to the surface under bending stresses. It may be possible to produce cuppy fractures in faultless material by using badly designed dies and heavy draughts; and it may be that one drawer would produce cuppy wire, whereas another drawer would produce sound wire from the same material.

But under similar working conditions the wire rod, which has been made from a piped ingot and has an axial segregate, is more likely to pull apart in the centre as it passes the drawing die, because the harder high sulphur-phosphorus core cannot extend at the same rate as the softer exterior portions. This trouble is by no means confined to wire. We have observed it in bars up to two inches in diameter, and it is seen in Fig. 97 in a small screw made from cold-drawn nickel steel. As pipe does not extend along the entire length of ingots, and as the segregates are not distributed uniformly about the surface of pipe, cuppy wire might be expected to appear here and there only in a consignment of steel. This and the variables in draw-bench practice are quite sufficient to account for the occasional epidemics of trouble. To argue that because some rods are satisfactory, all rods being from the same cast should therefore be equally satisfactory, is not valid unless the material has been made from sound ingots.

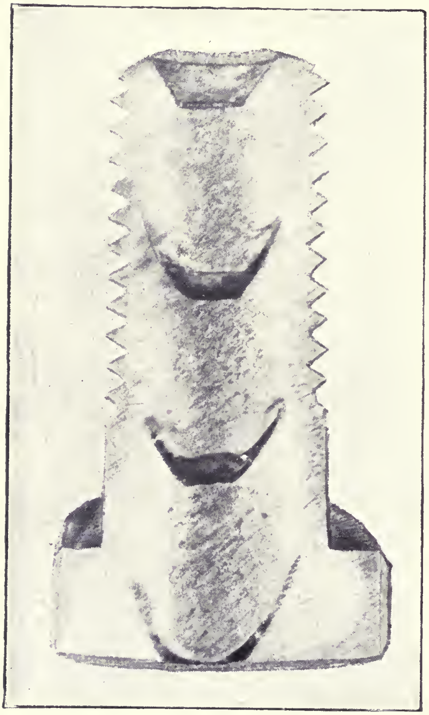


Fig. 97.—Cupped fracture in cold-drawn rod.

Every forgeman and smith is supposed to know that when a round bar needs to be tapered or reduced in diameter it should be flattened and worked down to approximately the right size in the form of a square; and then, but not before, made into an octagon by knocking in the corners and finally rounded. If the bar were kept round from start to finish it would be likely to split in the centre as seen in Fig. 98. The general impression and the inference to be drawn from Fig. 98, is that to work a hot round bar down to a smaller section whilst it is being simultaneously revolved on its own axis must inevitably produce split centres. This, however, is not correct. There certainly is a tendency at all times for the bar to split, and it will no doubt actually do so if the working is sufficiently drastic and prolonged, because the simultaneous revolution and elongation of the bar produces a transverse shearing moment through its centre. But whether it will occur or not in an operation carried out always in the same way depends on the properties of the steel, and experience shows that it occurs invariably with some bars but not with others made from the same ingot.

Fig. 98.—Split centres in round bars.

The authors have used a method which secures the simultaneous revolving and extension of bars, under well-defined conditions, as a means of comparing the strength of the central axis of ingots cast under different conditions. The ingots were rolled into bars, and these were cut into lengths for testing purposes. From the usual form of ingot cast narrow end up only those bars corresponding to the lower third would stand the test without splitting. When cast into an inverted mould about three-fourths of the ingot would produce bars capable of withstanding the test; but if cast very hot even the inverted ingot would not make satisfactory bars.

Some tests were made on bars prepared as follows:

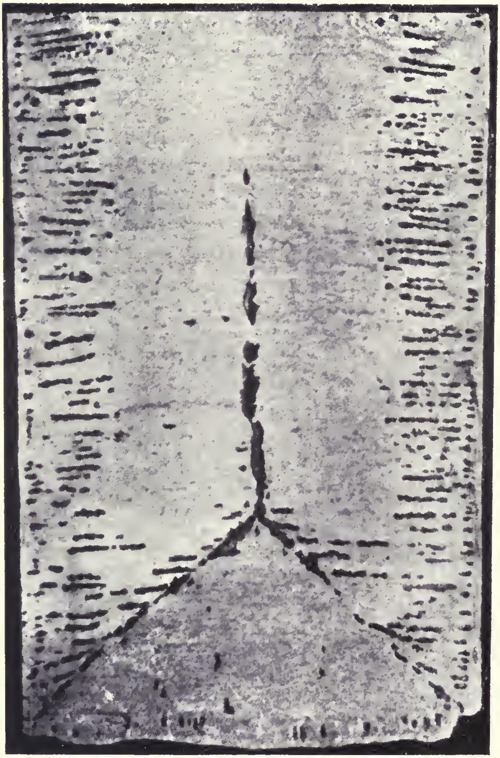


Fig. 99.—Ingot section, showing cavities on base pyramid.

The ingot was cogged into a slab, this was sawn longitudinally down the centre, and each half was rolled into test bars. In these tests the axis of the bar would not correspond either with the axis of the ingot or any plane of weakness existing in the ingot, and it is notable that out of three hundred tests not a single piece disclosed a split centre. As the demands made on the steel-maker become more and more exacting it will no doubt be realized that no ingot is perfect, and the bisecting of ingots, or slabs made from them, longitudinally so as to throw the suspect core into the discard or the machine waste, which is already an old though rare operation, will be largely practised.

The basal pyramid is very sharply defined in ingots which have been cast hot. At the surface of the pyramid there may exist either contraction cavities or blow-holes. A section of an alloy steel ingot which possessed every possible ingot defect except pipe, and amongst them a well-defined basal pyramid, is shown in Fig. 99. During forging the base pyramid would not weld to its adjacent surface or it would weld imperfectly, and thus give rise in fractured bars to separated cores like those pictured in Fig. 100. A similar defect in rolled bars may also arise from the V-shaped segregate (see Fig. 79), when owing to hot casting it exists in an exaggerated form. The authors have seen only one example of this kind of defect occurring in ordinary carbon steel forgings, but it fre-

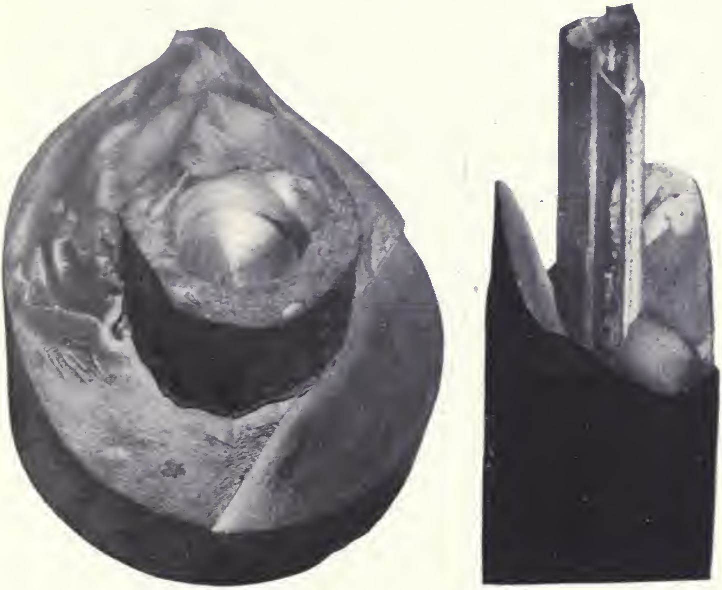


Fig. 100.—Separated cores in forged bars.

quently occurs in self-hardening steel, notably in high-speed steel. The core is so distinct from the rest of the bar that it is easy to believe it has originated from a separate piece of steel accidentally dropped into the fluid ingot. This belief, though very occasionally confirmed, may be negatived by making comparative analyses of the core and the bar in which it lies.

Instances of trouble arising from pipe and axial segregation in ingots might be quoted at almost any length, but it must suffice to state the case very broadly, leaving those concerned to work out the details of examples in which they are interested. The number of instances in which piped material remaining in the finished objects is advantageous or unobjectionable are naturally very small. It may seem indiscreet to suggest that an obvious ingot defect might ultimately be no detriment, but it may be true of ingots in particular as of steel in general, that one cannot say whether they are good or bad except in relation to the use which will be made of them. And a generation which was taught to admire slag streaks in cutlery blades and fibre in wrought iron may be expected to give fair consideration to anything which can be said in favour of piped ingots, though it may hesitate naturally to agree that the discarded top end may serve a purpose quite as usefully as the sounder bottom end of an ingot. The example which may perhaps be quoted with least offence is laminated springs.

Laminated springs are separate flat bars arranged, after cambering, in an orderly manner. In use they are stressed by a force tending to break them transversely. A spring of the same shape made from a single piece of steel would be less safe (and otherwise undesirable), because a crack started on either face would quickly extend through the entire spring, whereas, in a laminated spring, a crack through one plate disables that plate only. This advantage for the laminated spring would be unanimously admitted. Apply now the same reasoning to two single spring plates rolled respectively from the piped and unpiped portion of the same ingot. On attempting to break the notched plates it is found that the piped bar offers much greater resistance, because it is already laminated along the partly welded pipe, and one would therefore be disposed to conclude that spring bars made from the upper part of a piped ingot were as good for their purpose as those made from the lower part of the same ingot.

Without claiming to speak for spring manufacturers reference may be made to the frequent occasions when spring-makers look approvingly on what they call good fibre in a fracture which is nothing but more or less minute laminations due to partially welded pipe, slag occlusion or gas cavities. In Fig. 101 there is reproduced from a noted spring-maker's catalogue a picture of a fractured spring bar which is thought to be ideal because it shows laminations due to pipe and allied causes.

Fig. 101.—Fibre in spring steel bar.

Axles, like springs, are stressed transversely and can be broken with greater or less ease, depending on the effort required to extend a crack, already started on one surface, to the opposite side. Anything in its path which brings the crack to a full stop will increase the difficulty of extending it across the axle, because the crack will either be deflected from its direct course or it must await a favourable opportunity to start again, and either alternative will consume more energy than would be required to break a bar of similar material, which is in all respects sound and homogeneous.

The manner in which laminations or small cracks or slag occlusions, lying at right angles to the direction of a crack, retard the propagation of the crack, may be illustrated by a sheet of notepaper which has been streaked along its length with the point of a sharp knife and notched on the upper edge. When the paper is taken with the thumb and finger on either side of the notch, and an effort is made to tear it across, the tear will branch off at right angles along the first deeply-streaked line, and must follow a very irregular line before reaching the opposite edge of the notepaper. On looking on to the torn surface of the paper one sees hills and dales, as it were, between the laminations, which are but simplified and magnified images of the grey fibrous fracture so much beloved in wrought iron, and so much over-praised in case-hardened mild steels. It may therefore be thought, without pursuing the subject further, that in such objects as laminated springs and straight axles, that are stressed only in a direction transversely to their length, such blemishes as laminations, slag streaks and partly welded pipe are comparatively harmless.

SLAG STREAKS, ETC.

The fibrous appearance of a fractured surface of iron or steel is due to the fact that the cohesion between the crystals has been stronger than the crystals themselves, and under the effort to separate them, say, by tensile stress, the crystals have distorted and elongated and present ultimately a mass of rugged broken ends of a grey colour.

The appearance of fibre is heightened and may be entirely due to the presence of slag streaks. It happens occasionally that the fractured ends of a broken tensile test piece have a dark grey fibrous centre, but are crystalline on the outside. In such cases it may be observed that the centre appears dark only when the fracture is observed along the axis of the test piece. If viewed obliquely the centre appears as white, or whiter than the surrounding material. On closer examination the central part of the fractured surface seems to have been formed by a sliding action parallel to the axis of the test piece along lines of weakness due either to slag or imperfectly welded porosity or both. This type of fracture may be represented diagrammatically as in Fig. 102, as an example of the influence exerted by

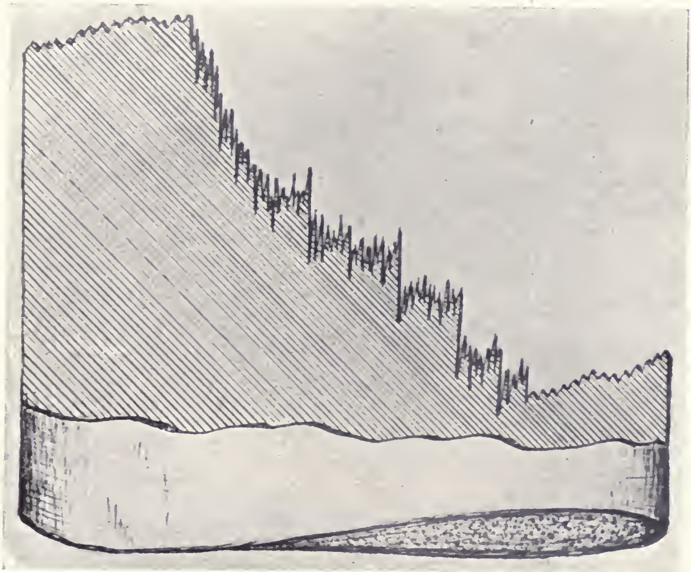


FIG. 102.—Appearance of fibre due to slag.

slag under stresses acting parallel to the length of the streak.

The extent to which slag streaks influence the behaviour of material under stress depends on the direction in which the stress is applied in relation to the direction in which the slag streaks lie. In the ingot the slag exists mainly as globules, and in billets or bars it is drawn out into threads. These non-metallic threads have the power of attracting to themselves the free ferrite as it falls out of the solution, just as threads suspended in syrup act as nuclei for the clusters of crystals known as sugar candy. On the left hand of Fig. 103 may be seen an unetched specimen of electric furnace steel unusually rich in slag, and on the right-hand side the same material in the etched condition showing clearly the ferrite envelopes gathered about the elongated slag. It needs no great stretch of imagination to realize that it would not be a matter of indifference whether the material were stressed along the page or across it.

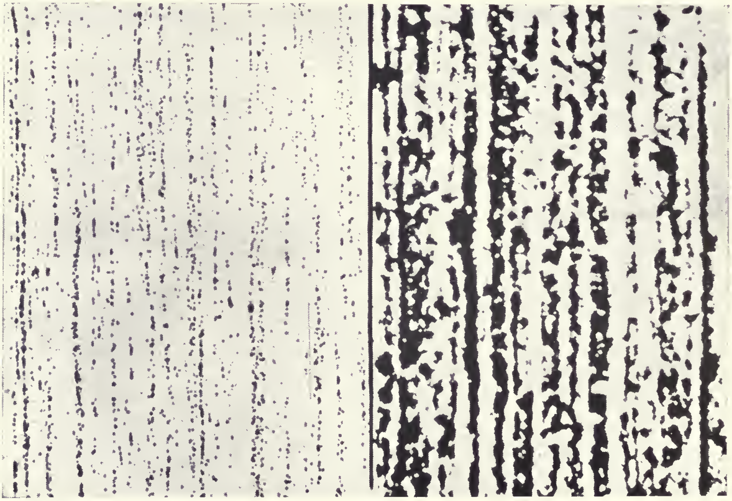


Fig. 103.—Slag chains and ferrite bands.

A cast of steel containing three per cent. of nickel was made in a Bessemer converter. One of the ingots was rolled into a slab. This slab was cut longitudinally down the centre and duplicate test bars were taken from corresponding positions of each half. The test bars were cut parallel to the direction of rolling and also at varying inclinations, including one at right angles to the direction of rolling. The test bars were each oil-hardened at 830° C. and tempered at 650° C. before being machined into the usual form of test piece. The test results are tabulated below :—

Direction of Test.	Yield Point.	Max. Stress.	Per cent.		Impact foot lbs.
			Elong.	Contr.	
Parallel	43·9	51·6	23·5	60·7	62. 69. 64
	—	50·0	23·5	61·0	63. 61.
20°	42·3	51·2	23·0	59·2	68. 62. 62
	41·9	51·2	23·0	59·0	63. 61. 66
40°	43·4	50·9	23·5	58·2	44. 35. 40
	43·9	50·9	24·0	58·5	41. 51. 37
60°	43·3	51·01	17·5	28·3	25. 29. 27
	44·5	51·2	15·5	27·9	23. 21. 25
80°	43·75	51·5	15·5	26·1	16. 19. 17
	45·9	51·6	14·5	25·2	19. 18. 19
90°	43·75	50·41	18·5	32·2	18. 19. 19
	45·6	51·4	15·5	25·5	17. 18. 16

and plotted in diagrammatic form in Fig. 104.

The maximum stress of the material is seen to be nearly constant, whether the test piece is cut parallel to or at right angles to the direction of rolling. This is always the case, providing a premature break does not occur owing to an unusually large slag streak or lamination happening to fall on or near the surface of the test piece. Both elongation and reduction of area show a marked falling off when the slag streaks lie at an angle exceeding forty degrees to the pulling force. The impact figure in particular is greatly influenced by the direction of the slag streak in relation to the direction of the blow. Generally speaking the average impact figures obtained from pieces cut parallel and at right angles to the direction of forging may be taken as a good indication of the comparative amount and distribution of slag streaks. The fractured test pieces sketched at the foot of Fig. 104

are quite characteristic of the appearance of broken surfaces as modified by the direction of the fibre.

The effort required to force a crack across a bar of streaky iron or steel is greater than the effort required to fracture material of a similar kind which is free from slag streaks or seams, because the crack is deflected from its path, more or less, on reaching a slag streak. When the bar has been only slightly bent the bending force is no longer acting strictly parallel to the direction of the crack. This means that part of the bending effort tends to direct the crack, via slag streaks, parallel to the length of the bar, and so much effort is entirely lost so far as the original purpose of breaking the bar across is concerned.

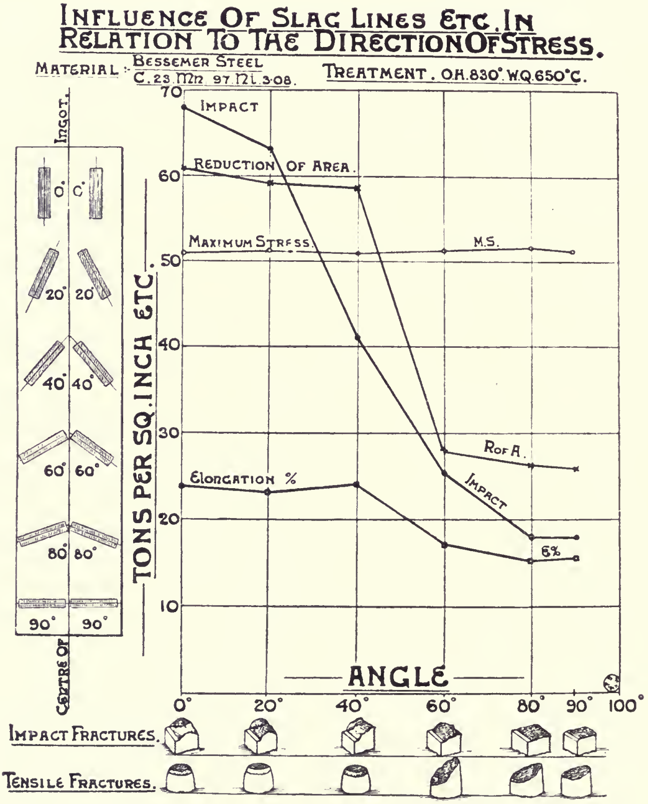


FIG. 104.—Influence of slag on tensile properties.

Moreover, before that portion of the crack under consideration can continue along the intended path, *i. e.* across the bar, it has to make a fresh start and must distort the material in its immediate neighbourhood until a new crack is formed. As a matter of experience it is known to be more difficult to distort soft material into an initial crack than it is to continue a crack already started. It may, therefore, be concluded that the occurrence of streaks and seams in a bar increases the effort required to propagate a crack across it, and it may be frankly admitted that from this point of view the seams and streaks may be of value. But it also must be realized and admitted with equal frankness that to crack the bar along the direction of rolling would be proportionately easy.

The mean of the average impact figures obtained from test pieces cut longitudinally and transversely gives the figure which one might expect to obtain if steel were free from slag and segregates and also physically homogeneous. This figure is quite hypothetical and it would be difficult to establish it experimentally, but it represents the lowest figure obtainable on longitudinal test pieces and the highest figure obtainable on transverse test pieces.

The following are a few typical figures obtained from varied material when stressed by shock across and along the direction of rolling. The tests were made in triplicate.

Kind of Steel.	Impact Figures in foot lbs.	
	Longitudinal.	Transverse.
Nickel-chrome steel	81. 84. 83	30. 25. 35
Nickel steel	56. 61. 58	17. 21. 24
Finished wagon spring	36. 35. 39	8. 7. 9
Titanium steel	25. 26. 27	6. 5. 5
Case-hardening steel	98.104.106	32. 43. 37

In commercial steels, having a tensile strength of, say, less than sixty tons, the longitudinal figures are approximately three times greater than the transverse figures. If less than twice as great the steel-maker may compliment himself on having made a clean cast of steel; if four times as great or more the steel may be regarded as a speciality, but whether especially bad or especially good will depend on the purpose to which it is applied. Fig. 105 represents the fractured surface of a tool to which such a steel has been misapplied. As a die used for forming rivet heads the material would obviously be stressed at right angles to the length of the bar from which it was made, and in that direction it is extremely weak, purely on account of what may be called its fibrous structure.

Material of the kind represented by Fig. 105 may be considered in relation to the various methods of making articles such as blanks for gears, and milling cutters. These may be produced by machining directly from a round bar, in which case every tooth will be stressed in service, in a direction least favourable to its durability, *i. e.* the fibre lies parallel to the axis of the gear. The blanks may also be made, and are made in large quantities, by cutting a suitable length from a flat bar, and after removing the corners rounding it into a disc. This method produces a gear or cutter with teeth in one position having a maximum resistance and teeth in another position at right angles thereto having a minimum resistance. A third method of making blanks is to take a bar of much smaller diameter than the desired gear and flatten it to the desired thickness. This produces a gear

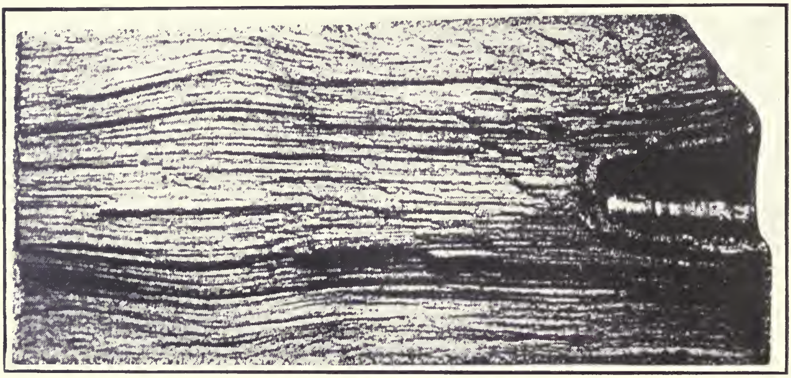
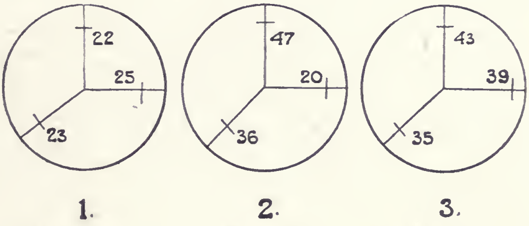


FIG. 105.—Fracture due to fibre.

whose teeth are more uniformly strong, and it is undoubtedly the best method of the three. The figures inscribed on the attached diagrams (Fig. 106) are mean impact figures obtained from test pieces cut from different parts of gear blanks made as indicated.

It is true that Method 3 is, of all forging processes, the one most likely to exaggerate surface defects in steel bars. Surface roaks open out into cracks under this treatment, and material like that represented in Fig. 74 would undoubtedly produce blanks having very ragged edges. Alloy steels and materials generally which do not readily weld are not suitable for "up-ended" forging operations unless the bars or the blooms from which they were rolled have been previously rough-turned or otherwise freed from surface defects.



Method 1. Method 2. Method 3.

FIG. 106.—Relative strength of gear teeth.

A piece of steel in a brittle condition, due either to previous hardening or to inter-crystalline weakness, does not exhibit a fibrous shock fracture even though it may contain more than the normal amount of occluded slag. This fact is illustrated by every-day experience with case-hardened bars which break with a smooth straight fracture through the hardened case, both in longitudinal and transverse tests, however much fibre they may show in the softer core (see Fig. 107). Even a badly-welded pipe may escape notice in a bar which when broken is in the hardened condition. When, however, the bar cannot be broken without being greatly distorted the more weakly cohering surfaces give way, the closed-up pipe opens out again, and the separate threads of slag give rise to minute laminations.

If therefore it is desired to emphasize the fibrous appearance of a fracture made parallel to the direction of forging and to compare such appearances in like bars of similar material, the most striking results would be obtained from bars which had been previously hardened and then tempered at as high a temperature as is practicable short of actual re-hardening. Very few samples of steel, when submitted to this test in the form of flat bars, will fail to show fibre, and when carried out under comparative conditions it is perhaps as good an indication as any other of the relative freedom of steel from occluded slag.

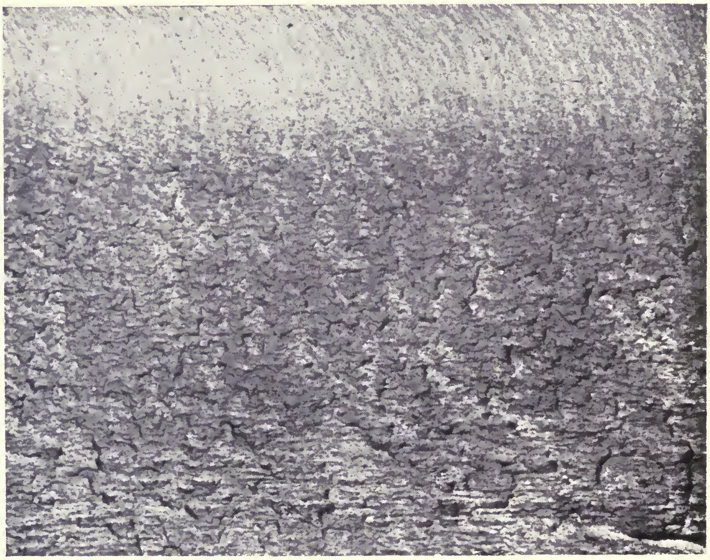


FIG. 107.—Evidence of slag in fracture of hard and soft steel.

But an approximate indication of the relative amount and distribution of slag and a determination of its concrete effect are very different inquiries. The most which can be truthfully said of a transverse tensile test is that it is a very doubtful means of determining whether material in bulk is suitable or not for a particular purpose. Forgings and castings of very great value in the aggregate are scrapped yearly because a slag streak or globule of unusual size happens to occupy a particular place in the machined test piece. If it should happen to fall well inside the test piece the test result will be satisfactory, but if it falls on the surface the test piece will break before the specified elongation per cent. has been registered. As far, however, as the forging or casting itself is concerned it is neither better nor worse for the accidental occurrence of the disturbing slag enclosure on the surface of the parallel length of the test piece.

It follows from the above and is moreover literally true that the longer the parallel length of a test piece the greater the danger of premature rupture due to occluded slag. Very few forgings or castings could meet prevailing specifications if the stipulated length of test piece were equal to the thickness of the forging, because somewhere in such a length a slag cluster would almost invariably occur. A transverse fracture made on a test piece of considerable area, an etching test, a series of impact tests, or some similar test showing not only the nature but the extent of the presumed defects, would be more informative than many test pieces cut from an infected area and subject to the pure chance of avoiding the location of a slag enclosure on their outer surfaces.

CRYSTAL ARRANGEMENT

As early as 1775 it was known that crystallites similar to those pictured in Fig. 90 might occur in metals. One hundred years later Tschernoff proved that steel ingots were composed of such crystallites. The beautiful specimens found by Tschernoff in ingot cavities have been repeatedly reproduced, and are universally admired by students of metallurgy; but that such specimens are only large-scale types of crystals occurring million-fold in every ingot made has not been clearly realized by steelmakers. If steel were a perfectly homogeneous substance the existence of crystallites could not be easily demonstrated. As, however, during growth, the impurities are rejected and accumulate in the parts which freeze later, it is quite simple by almost any form of etching to reveal the outline of the primary crystallites. All one needs to produce a metallic picture which is both beautiful and instructive is a slice from an ingot and a supply of dilute hydrochloric or sulphuric acid. After the one has been immersed in the other for a shorter or longer time depending on circumstances, the smooth steel surface becomes corroded. The steel is literally unmade, at leisure, and subject to close observation, in the reverse order to that in which it was formed. The section reproduced in Fig. 108 (frontispiece) and the fractured

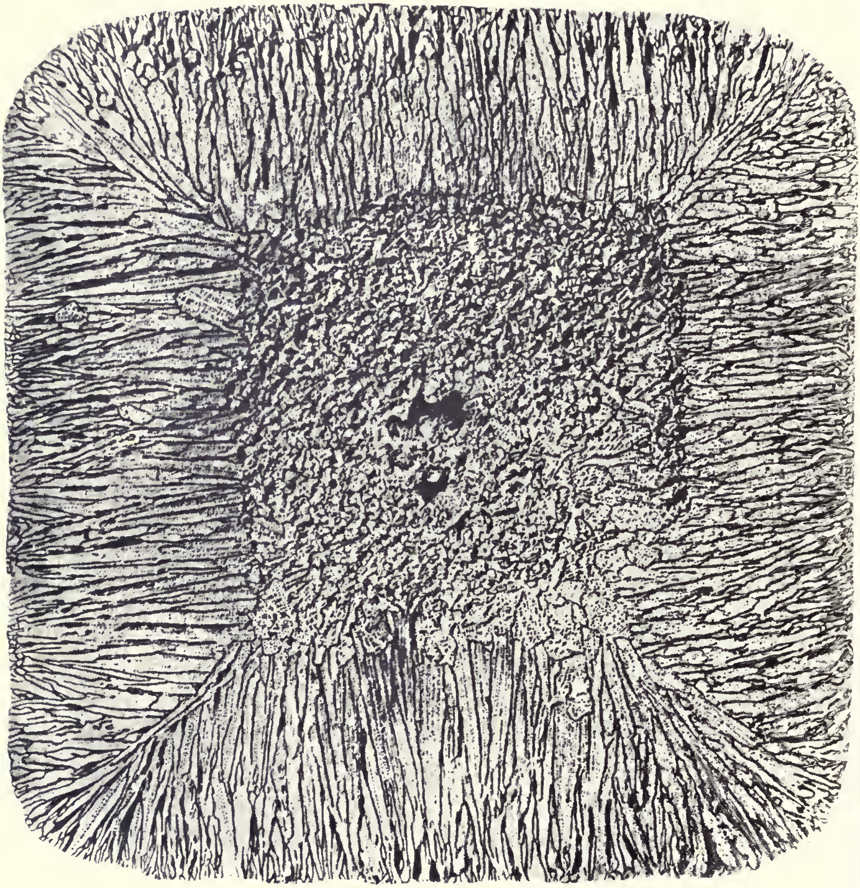


FIG. 108.—Chill and free crystals on etched surface of ingot.

surface shown in Fig. 78 are both made from the same ingot.

The properties of an ingot made from any given volume of liquid steel will depend greatly on the kind of crystals of which it is composed, and these properties persist more or less into whatever forms the ingots may be forged.

The well-defined diagonal planes of weakness passing through the corner of a hot-cast ingot are especially apt to be troublesome in octagon ingots used either for hollow forgings or tyres. In sliced tyre blocks the corners may crack during punching operations, but in any number of blocks cut from the same ingot all are not equally disposed to crack. On closer examination it is usually found that the weaker blocks come from the part of the ingot which has been cast at the greatest speed, *i. e.* those blocks in which chill crystals are most pronounced.

Unless care is taken to avoid hot casting, and the consequent formation of well-defined chill crystals, a very large proportion of ingots crack on the surface before they are sent to the mill or forge. This may be demonstrated by taking sulphur prints either from a planed surface or from a longitudinal section of the ingot. During the rolling operation the cracks open at an early stage into transverse gaps, which by degrees are transformed into longitudinal seams. Such seams are an everlasting source of trouble to the drop stamper, because although they are not easily distinguishable from a roak they are far more dangerous. A roak arising merely from a blemished surface of an ingot can, when seen, be chipped out; but a seam due originally to a transverse crack between chill crystals is not easily chipped out. The more the crack extends inwards the finer it becomes, and he is a very skilful chipper who knows for certain that the seam has been entirely removed. Many such seams are not entirely removed, according to the testimony of stampers who affirm that defects in stampings are often found in places corresponding to the chipped part of the billet.

When the chill crystals extend to the centre of an ingot, as they may do in small ingots, it is more than likely that the ingot will break up in the cogging roll. Any dispute as to whether the ingot has been burnt in the reheating furnace can generally be settled by examining the remains. If the ingot was faulty the cracks will be on every side and corner of the ingot and the fracture will have the well-known scorched appearance. If the cracks are confined to one side or two corners and the fracture is quite normal, then the mill furnaceman may be suspected. A good example of a scorched ingot which fell to pieces on cogging is reproduced in Fig. 26.

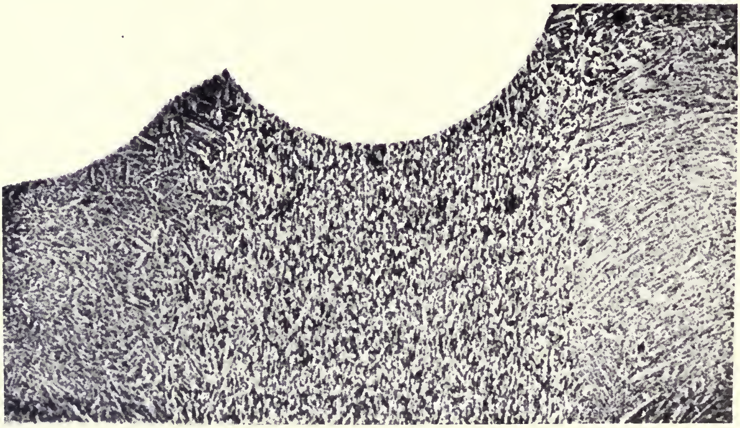


Fig. 109.—Etched section of crankshaft web showing chill and free crystals.

But, apart from cracks due to the arrangement of chill crystals in an orderly manner unfavourable to the resistance of stress, a distinction between chill and free crystals is occasionally observable in forgings. Even in the largest forgings, say, a marine shaft made from a sixty-ton octagon ingot, one may sometimes see an eight-sided figure on an etched or rusted transverse section. And, similarly, on hammered bars made from small square crucible ingots a more or less deformed image of the ingot structure is occasionally visible. The most perfect example known to the authors was found in a dismantled crankshaft of an aero-engine. A photograph of an etched section made at right angles to the line of the shaft is reproduced in Fig. 109. The distinction between the chill and free crystals could hardly have been more perfect in the ingot itself.

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