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No. 3.—On the Effect of Time and Temperature on the Strength of Steel and Iron.

BY

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ON THE EFFECT OF TIME AND TEMPERATURE ON THE STRENGTH OF STEEL AND IRON.

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INTRODUCTION

The behaviour of iron and steel under simple stresses of various kinds has long been a subject of investigation by the Engineer, and very complete data are available for use in designing structures in metal.

When iron or steel is subjected to tensional stress sufficient to cause a permanent stretch in the material, it is well known that the ductility of the material is reduced, and that ultimately the elastic limit rises.

As a first consequence, however, the elastic limit is first of all lowered, in some cases to zero, but if the bar be left to itself the elastic limit ultimately rises to a higher value than before.

In the last few years the phenomenon has received considerable attention at the hands of Bauschinger*, Ewing† and Muir‡.

The present paper relates to a few experiments which have been made in the Testing Laboratory, McGill University, following the lines indicated by the authorities mentioned above.

I. MEASUREMENT OF SMALL STRAINS.

The measurement of the change in length of a bar, by such a small quantity as 1/50,000 inches has been rendered comparatively

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* Unwin's Testing of materials of construction.

† Ewing "On the measurement of small strains in the Testing of materials and Structures" Proc. R. S. 1895.

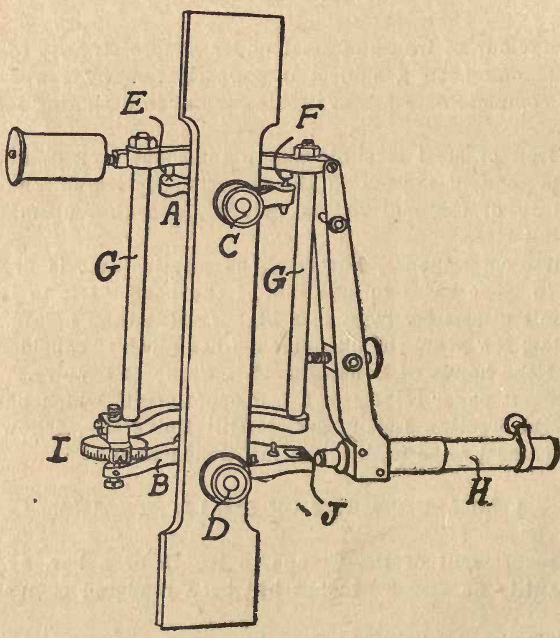
‡ Muir "On the recovery of Iron from overstrain." Phil Trans 1899.

easy by aid of extensometers devised by Bauschinger, Unwin and Ewing. The instrument mainly used in these experiments was one constructed after Professor Ewing's design, and has several novel features. It is, moreover, especially adapted for work where several settings of the instrument are necessary.

II. EWING EXTENSOMETER.

The instrument is shown in Fig 1, mounted upon a test piece, and consists of two clips, A and B, fixed upon the bar at a standard distance apart by set screws C, D. Upon the upper clip A, are two pins E, F., upon which latter the frame G is mounted. The frame carries a reading miscroscope H, and a micrometer screw I; this latter gears with a conical hole in the lower clip B, and is kept in engagement by a spring. The reading microscope is sighted upon a thick wire mounted horizontally in a plate, J and illuminated from behind by a small mirror.

Fig 1



The clips are made of gunmetal, and are formed so as to give slightly when the set screws engage the test piece, and thereby if a slight diminution of section occurs in the bar, while the test is proceeding, the screws do not become slack, and one sourse of error is thereby avoided.

The clips A and B are each centred upon the bar, and each has one degree of freedom with respect to it, viz., that of rotation about their respective set-screws, and by causing the micrometer screw I to gear with the lower clip, both degrees of freedom are removed and the apparatus becomes a rigid whole.

In setting a flat tension bar in the jaws of a testing machine, it is difficult to avoid giving it a slight twist, but by pivoting the frame G upon the upper clip in a transverse direction, a slight twist will not cause error in the readings.

The micrometer screw and observation wire are set equidistant from the set screws D upon the clip B, so that the wire can be moved up or down by turning the micrometer screw, and this movement is measured by reference to a glass scale in the eye piece of the reading microscope.

In this manner the scale is calibrated by reference to the micrometer screw, which latter has 50 threads to the inch, and the scale is so arranged that a movement of the wire through 1-50 inch corresponds to a reading of 50 scale divisions. In actual working since the micrometer screw engages the clip B, any extension between the set screws will cause the relative movement between the reading microscope and the wire to be doubled, so that the value of one scale division =1-2 x 1-00 x 1-50 = 1-5,000 inch, and as 1-10 division can be estimated, a reading of 1-50,000 on an 8 inch length can be measured.

The chief advantage of the instrument is that it can be calibrated in position, that the reading is a mean of two sides of the bar, and that it can be quickly and accurately set on the specimen.

In order to set the clip accurately upon the specimen a distance piece is provided, having V shaped recesses to receive corresponding studs on the clips, and clamps to hold the clips in place, until these latter are set on the bar.

The apparatus for applying tensional stress was a single lever Wickstead testing machine, which was capable of exerting a pull of 200,000 pounds. As the stresses used were comparatively small, the weigh lever was mounted to cause the jockey weight to travel the whole length of the weighbeam for a range of 50,000 pounds, and so render the measurement of applied stress as accurate as possible.

III.—RECOVERY OF STEEL FROM TENSIONAL OVERSTRAIN.

When a bar of iron or steel is subjected to a tensional stress sufficient to cause a permanent stretch in the material, the physical character of the bar changes, and it becomes semi-plastic, while its elastic limit generally reduces to zero, followed by recovery, which is comparatively rapid in the case of wrought iron, but less so in the case of steel.

As an example of this, the case of a mild steel bar may be taken. This bar, and others referred to later, were cut from a piece of boiler plate, and afterwards straightened and annealed. The bars were machined to a breadth of 2.07 inches, and the thickness was left untouched, the mean thickness in the present case being 0.377 inches, and the length under test 8 inches.

The Extensometer used was of the Ewing type, one division corresponding to 1-50,000 inches.

A test was first made to give the bar a permanent stretch, with the following results:—

Loads in Lbs.	Reading of Extensometer.	Difference.
0	400	
2,000	435	—35
4,000	470	—35
6,000	505	—34
8,000	539	—35
10 0	573	—34
12,000	608	—35
14,000	643	—35
16,000	679	—36
18,000	715	—36
20,000	753	—38
23,000	Went off scale. Extended length.	
24,000	8.10 inches.	
24,500	8.12 "	
25,000	8.14 "	
26,000	8.15 "	
16,500	8.155 "	
27 000	8.165 "	
0	8.15 "	

The measuring instrument was immediately re-set to the standard distance of 8 inches, and a re-test was made, rising by increments of 2,000 pounds to 24,000 pounds, and then to zero again by decrements of 2,000 pounds. The following results were obtained:—

LOAD IN POUNDS.	READING OF EXTENSOMETER.	DIFFERENCE.
0	400	
2,000	435	—35
4,000	469	—34
6,000	506	—37
8,000	543	—37
10,000	580	—37
12,000	622	—42
14,000	662	—42
16,000	704	—42
18,000	744	—40
20,000	798	—54
22,000	846	—48
24,000	897	—51
22,000	862	—35
20,000	827	—35
18,000	790	—37
16,000	748	—42
14,000	709	—39
12,000	669	—40
10,000	629	—40
8,000	588	—41
6,000	546	—42
4,000	504	—42
2,000	460	—44
0	415	—45

A comparison of the readings obtained at once shows how differently the bar behaves after the tensile overstrain. There is now no linear relation between the stress and the strain, but the latter rises irregularly as the stress increases; the differences are irregular and do not agree except accidentally with the differences obtained as the load is removed.

The bar was now laid on one side, and a gradual recovery of its elastic properties took place, which was shown by the approach to the first readings made. At the end of three hours there was a marked recovery, and the following readings were taken:—

Load, lbs.	Reading.	Difference.
0	400	
2,000	434	—34
4,000	468	—34
6,000	505	—37
8,000	542	—37
10,000	580	—38
12,000	619	—39
14,000	660	—41
16,000	700	—40
18,000	742	—42
20,000	787	—45
22,000	829	—42
24,000	875	—46
22,000	841	—34
20,000	800	—35
18,000	769	—37
16,000	731	—38
14,000	693	—38
12,000	654	—39
10,000	613	—41
8,000	573	—40
6,000	532	—41
4,000	489	—43
2,000	446	—43
0	402	—44

The tests of the bar were repeated at the end of one day, 3 days, 7 days and 28 days, and these showed a further recovery, whose rate diminished with the time, but at the end of the month the recovery was practically complete. The readings obtained are shown in the annexed table:—

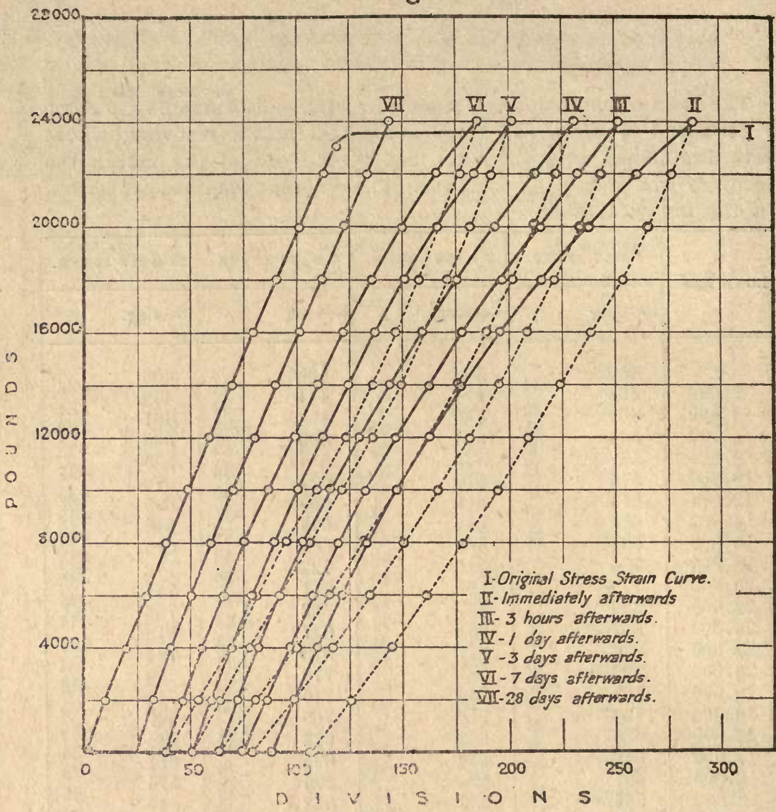
LOAD LBS.	1 DAY AFTER.		3 DAYS AFTER.		7 DAYS AFTER.		28 DAYS AFTER.	
	Reading.	Δ	Reading.	Δ	Reading.	Δ	Reading.	Δ
0	400	–34	400	–34	400	–34	400	–33
2.000	434	–35	434	–35	434	–34	433	–34
4.000	469	–35	469	–35	468	–35	467	–33
6.000	504	–35	504	–35	503	–35	500	–35
8.000	539	–37	539	–35	538	–36	535	–35
10.000	576	–38	574	–37	574	–35	570	–35
12.000	614	–40	611	–37	609	–37	605	–35
14.000	654	–41	648	–37	646	–38	640	–36
16.000	695	–41	685	–40	684	–38	676	–36
18.000	736	–43	725	–40	722	–39	712	–35
20.000	779	–43	765	–42	761	–41	747	–36
22.000	822	–45	807	–44	802	–45	783	–35
24.000	867	–35	851	–34	847	–34	818	–34
22.000	832	–35	817	–35	813	–34	784	–34
20.000	797	–35	782	–36	779	–34	750	–35
18.000	762	–38	746	–36	745	–36	715	–35
16.000	724	–38	710	–38	709	–37	680	–35
14.000	686	–38	672	–38	672	–37	645	–34
12.000	648	–41	634	–38	635	–39	611	–35
10.000	607	–41	596	–40	596	–38	576	–36
8.000	566	–41	556	–39	558	–39	540	–35
6.000	525	–42	517	–39	519	–38	505	–35
4.000	483	–42	478	–40	481	–38	470	–35
2.000	441	–43	438	–41	443	–41	435	–36
0	398		397		402		399	

In order to exhibit the changes in a manner which shows the recovery in a striking manner, the results were plotted in Fig. 2 after the manner first suggested by Prof. Ewing.* A number proportional to the load was subtracted from each reading, and the new reading obtained was plotted instead; this accentuates the differences, and as each curve is plotted from a different initial point, the recovery is exhibited in a form which can be readily followed by the eye. In the present instance 25 divisions were subtracted for each increment of 2,000 pounds.

Referring to the diagram, curve I. denotes the original stress strain curve, only part of which is shown, as the total exension Table I. is 8,250 divisions at a load of 27,000 pounds. Curve II. and the succeeding curves show the result of the overstrain. The stress-strain curve becomes a loop, and the area enclosed is a mea-

*Muir on the Recovery of Iron from Overstrain. Phil. Trans., 1899.

Fig. 2



sure of the work done on the bar by the loading and unloading, and therefore is a measure of the imperfectness of the elasticity.

The rest caused a gradual recovery of the metal, and showed itself in the gradual diminution of the enclosed area until at the end of 28 days the recovery was very nearly but not quite perfect.

SHEAR STRAIN.

The recovery of iron and steel from shear strain appears to follow the same general law as for tension. It will be sufficient to quote the case of a turned specimen of wrought iron, having a diameter of .0446 inch, and length under test of 4.00 inches. The specimen was subjected to shear by a twisting couple, and the distortion between the sections was measured by a strain measuring instrument of special design.* The bar was first subjected to torque of gradually increasing amount until the elastic limit was passed. The readings obtained were as follows, the calibration of the instrument being such that 12.8 divisions corresponded to 1 minute of arc.

*Coker " on Instruments for Measuring Small Torsional Strains." Phil. Mag., 1899

Torque inch lbs.	Reading.	Diff.	Torque inch lbs.	Reading.	Diff.
0	0				
		—302			
75	302			1489	
		—303	360		—81
150	605			1568	
		—303	375		—79
225	908			1666	
		—304	390		—98
00	1212			1808	
		—63	495		—142
315	1275			2038	
		—64	420		—230
330	1339			2548	
		—69	435		—510
345	1408			Specimen twisted through. 4°	
		—81	450		
360	1489				

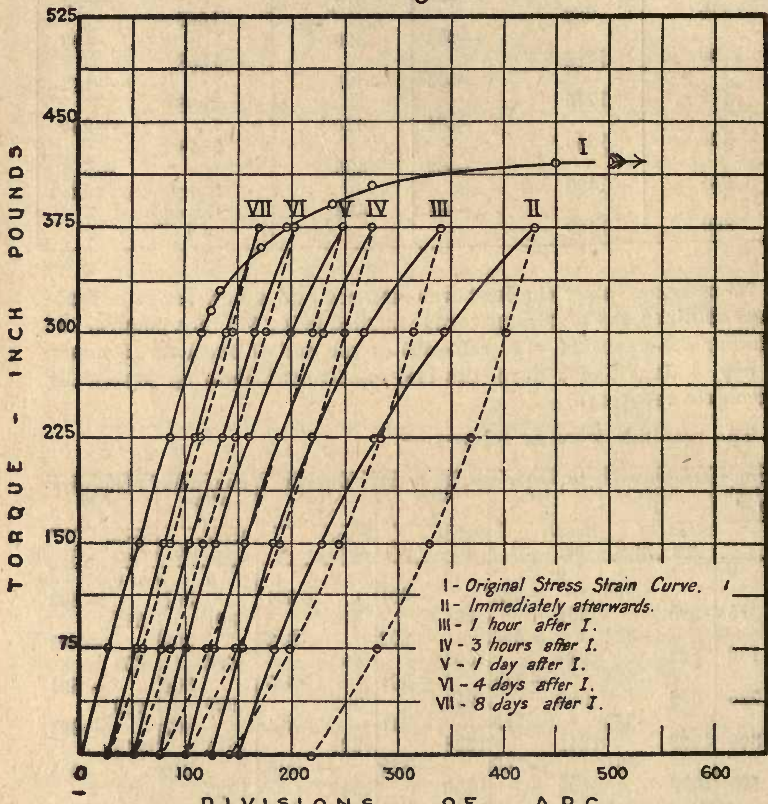
Immediately after the load was released and a new series of readings obtained, the maximum torque applied being 375 inch pounds, and similar observations were recorded at the end of one hour, 3 hours, 1 day, 4 days and 8 days, the last experiment showing practically complete recovery.

The readings were as follows:—

Torque inch lbs.	Immediately after I		One hour a ter I		Three hours after I		One day after I		Four days after I		Eight days after I	
	Reading.	Δ	Reading.	Δ	Reading.	Δ	Reading.	Δ	Reading.	Δ	Reading.	Δ
0	0		0		0		0		0		0	
		—305		—304		—301		—301		301		—302
75	305		304		301		301		301		302	
		—324		—306		—303		—302		303		—303
150	629		610		604		603		604		605	
		—324		—312		—307		—305		304		—304
225	953		922		911		908		908		909	
		—339		—319		—317		—314		307		—303
300	1292		1241		1228		1222		1215		1212	
		—361		—349		—322		—316		310		—305
375	1653		1590		1550		1546		1525		1517	
		—3 3		—301		—301		—302		302		—301
300	1350		1289		1249		1244		1223		1216	
		—305		—307		—304		—303		303		—302
225	1045		982		945		941		920		14	
		—315		—312		—309		—307		306		303
150	730		7 0		636		634		614		611	
		—325		—324		—316		—314		307		304
75	405		346		320		320		307		307	
		—338		—332		321		319		308		306
0	67		14		—1		+1		—1		1	

The readings obtained are given in the above table, and are plotted on Fig. 3, after deducting 275 divisions for each increment or decrement of 75 inch pounds of torque. The rapid recovery of wrought iron is well shown by the looped stress-strain curves II. to VII, and the rapid diminution of hysteresis in one hour after the overstrain is very marked.

Fig. 3

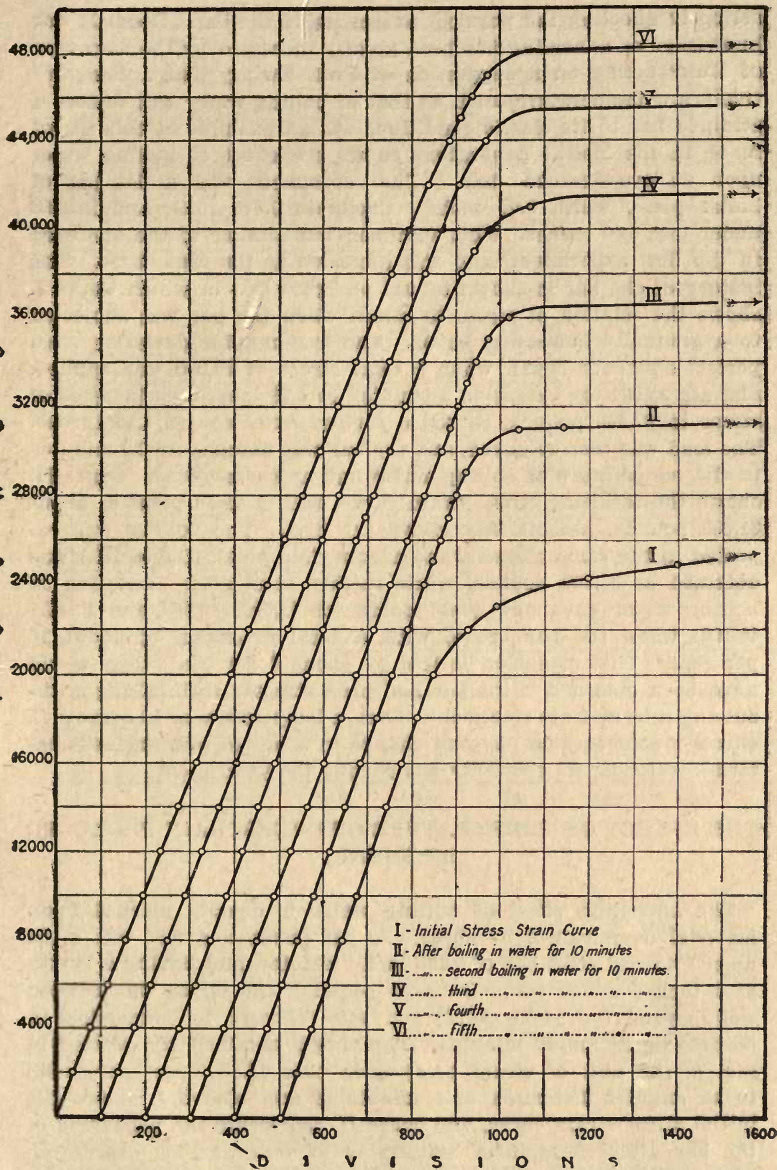


(Calibration of instrument - 1 minute of arc = 12·85 divisions)

THE INFLUENCE OF TEMPERATURE UPON THE RECOVERY FROM OVERSTRAIN.

It is well known that if a bar of iron or steel be stressed beyond the elastic limit in tension, it will regain its elastic properties if raised to a dull red heat and allowed to cool slowly in air or in lime, and this process may be repeated again and again without

Fig. 4


48,000
44,000
40,000
36,000
32000
28000
24000
20000
16000
12000
8000
4000
POUNDS
200
400
600
800
1000
1200
1400
1600
DIVISIONS
VI
V
IV
III
II
I
I - Initial Stress Strain Curve
II - After boiling in water for 10 minutes
III - ...... second boiling in water for 10 minutes.
IV ...... third ......
V ...... fourth ......
VI ...... fifth ......

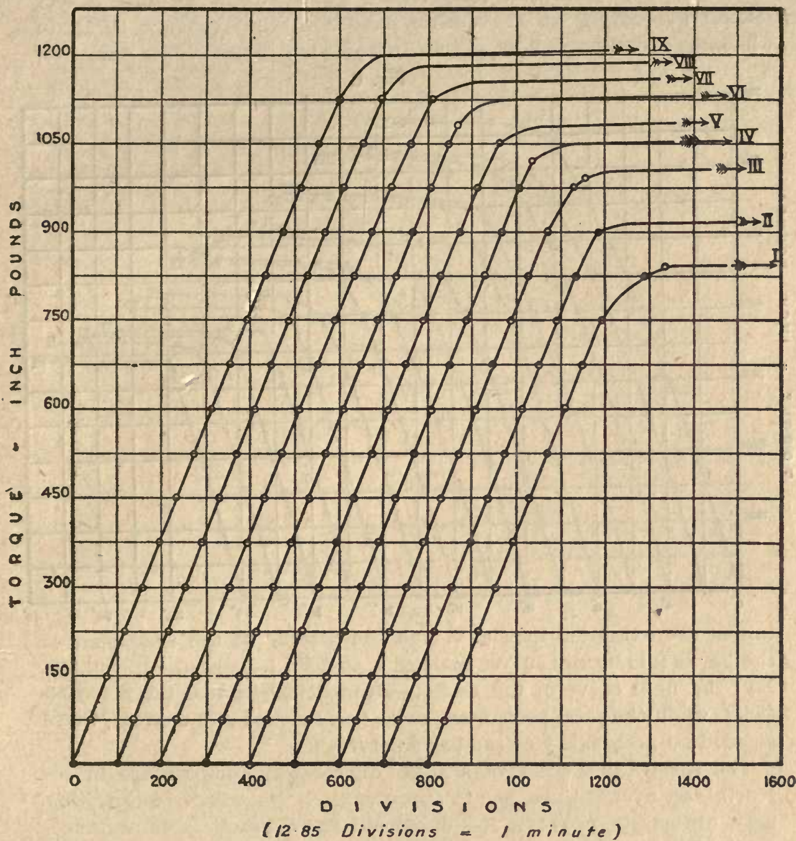
seriously affecting the physical properties of the bar. Recently our knowledge of annealing has been greatly increased by the discovery of Muir* acting on a suggestion of Prof. Ewing, that a comparatively low temperature, such as that of boiling water will restore a strained bar to its elastic condition. As an example of this a test made in the McGill Laboratory shows the effect of boiling water upon an overstrained bar. The specimen was a flat bar of boiler plate, width 2.07 inches, thickness 0.375 inch, and length under test 8.00 inches. This specimen was similar to the one used in the first experiment, and was annealed at the same time. The history of the bar is shown by aid of figure IV., in which Curve I. shows the relation of stress to strain when the bar was subjected to a gradually increasing stress. The first notable deviation from perfect elasticity began when a total stress of 20,000 was applied, and ata 25,000 the extension amounted to 8.13 inches, an increase of stress to 27,000 pounds, caused a further extension to 8.15 inches. The load was then removed, and the bar was exposed for 10 minutes to the temperature of boiling water and again re-tested. Curve II. shows the resulting stress-strain curve, with a yield point at about 31,000 pounds, considerably above the first. The boiling was repeated in the same manner, and a new yield point (Curve III.) was obtained at 36,500 pounds, while further tests after annealing in boiling water gave new yield points at 41,500, 45,600 and finally 48,100, when the bar broke, with a total extension of about 15 per cent. This extension is less by about 6 per cent. than would have been obtained if the bar had been stressed to breaking without any intermediate treatment. Even a temperature of 50 degrees C. effects a considerable physical change in a bar of overstrained material, restoring its elasticity and raising the yield point.

THE EFFECT OF TEMPERATURE ON OVERSTRAIN PRODUCED BY SHEAR.

The annealing effect of boiling water is equally marked upon material overstrained by shear. As an example, a test was made upon a turned steel bar of 0.425 inch diameter, and having a length of 4 inches under test. On each occasion the stress was carried well beyond the yield point, and was followed by immersion in boiling water for 10 minutes. The curves obtained are plotted in Fig. 5, the unit of strain being such that 12.85 units correspond to an angular distortion of 1 minute of arc. Curve I. shows the initial stress-strain curve, and curve II. represents the behaviour of the bar after 10 minutes' immersion in water at 100 degrees C. The remaining curves III. to IX. show the relation of stress to

* Muir loc. cit.

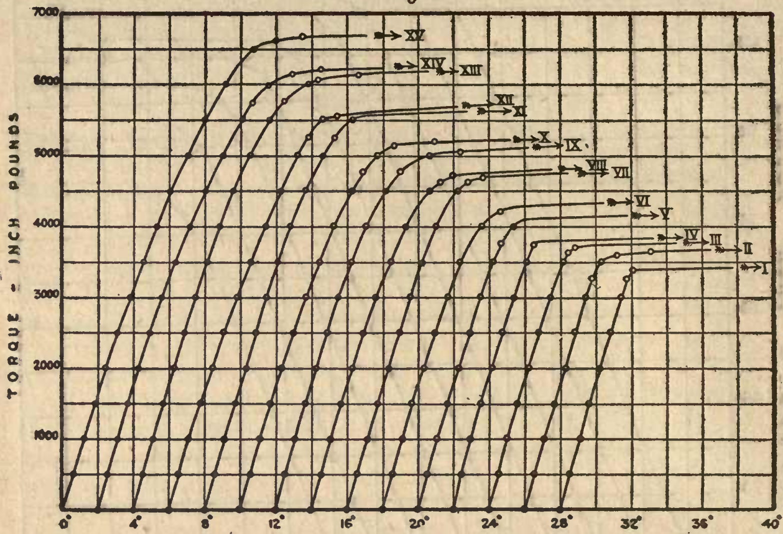
Fig. 5



strain after each subsequent annealing in boiling water. After each stress and subsequent heating, the recovery was practically complete, and the yield point rose after each annealing. At the end of 9 separate twists the bar exhibited no change externally.

A test of a steel bar was also carried out for me by Messrs. Blanchard, Clement and Gagnon, Fourth Year students in the Civil Engineering Department. A turned steel bar of similar quality to the previous one was chosen, having a diameter of 0.757 inch, and a length under test of 8.00 inches. The strain measuring instrument was a simple graduated circle divided to 15 minutes, and readings could be estimated to 1 minute of arc. Each separate application of twisting moment was carried beyond the yield point, and was followed by immersion in water at 50 degrees C. for 15 minutes. Even this low temperature was sufficient to cause a very effective recovery to the elastic condition, the recovery being in all cases accompanied by a rise in the yield point. The data ob-

Fig. 6



tained are exhibited in Fig. 6, and the history of the treatment of the bar is told by the curves marked I. to XV., I. being the initial and XV. the final curve of the series. Even at the end of the fifteenth twist, when the total permanent twist had reached .270 degrees, there seemed no probability of the bar fracturing.

The remarkable effect of a slight increase in temperature in restoring an overstrained bar to approximately its primitive condition may ultimately prove to be of considerable practical importance, as it affords a means of annealing, which, although not as perfect as that accomplished by the blacksmith, has the advantage that polished surfaces of iron and steel retain their polish and are not distorted by the process. In bridge structures and the like, exposed to repeated stresses and corresponding fatigue of the metal, the suggestion that this fatigue may be partially counterbalanced by the heat of a summer's day may not be so improbable as it at first sight seems to be.

THE EFFECT OF LOW TEMPERATURE UPON THE RECOVERY FROM OVERSTRAIN.

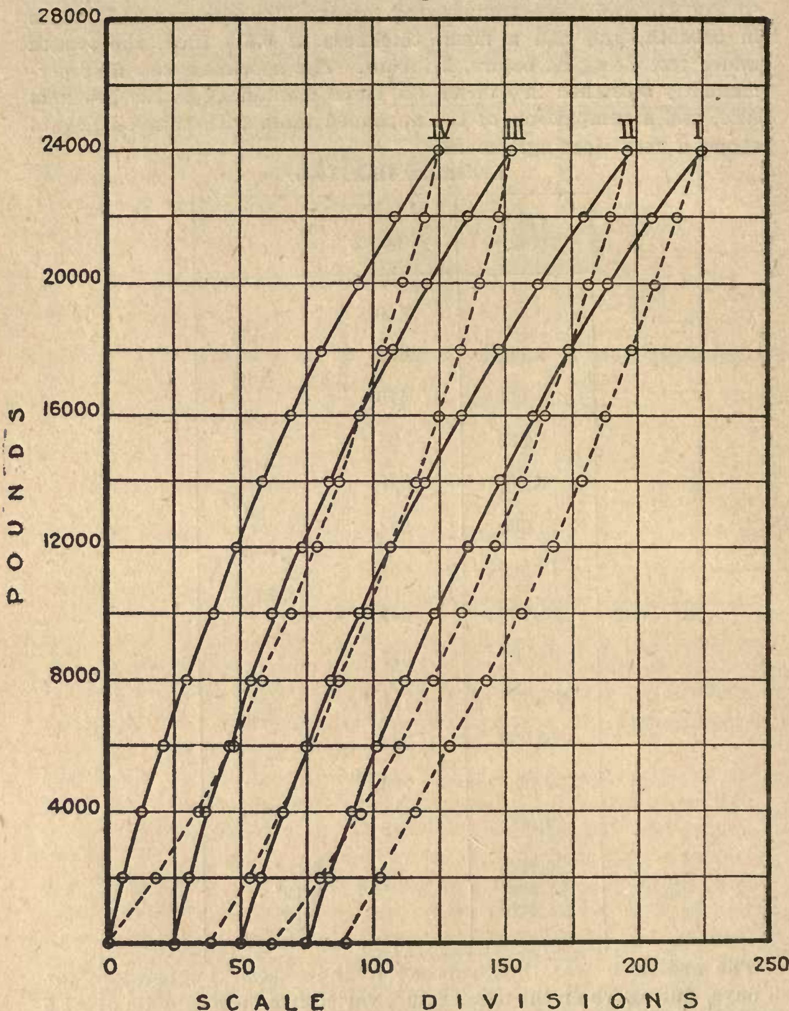
It is interesting to determine what action low temperature, such as that afforded by a Canadian winter, has upon the behaviour of steel after overstrain, and in order to contrast this with recovery at the temperature of the Laboratory, viz., about 68 degrees Fahr., a specimen was taken similar to the one described with reference to Fig. II. and the accompanying tables. The bar was 2.07 inches in breadth, and had a mean thickness of 0.378 inch, the length under test being as before, 8 inches. The specimen was first permanently stretched in exactly the same manner as in the previous case, and a comparison of the appended table with that on page 4 shows a very close agreement.

December 15th, 1900.

Load, pounds.	Reading.	Δ
0	400	
		– 34
2,000	434	
		—36
4,000	470	
		—36
6,000	506	
		—35
8,000	541	
		—33
10,000	574	
		—34
12,000	608	
		—34
14,000	642	
		—35
16,000	677	
		—34
18,000	711	
		—33
20,000	744	
		—42
22,000	786	
		—82
24,000	868	
26,000		8.08″
27,000		8.12″
27,500		8.16″
0		8.155″

The specimen was then exposed to the outside temperature for 3 days, during which the temperature varied from a minimum of —2.5 degrees Fahr. to a maximum of 11.2 degrees Fahr., and it was then subjected to a cycle of stress ranging from zero to 24,000 pounds. The results are recorded in Fig. VII., Curve I., and a comparison with Fig. II shows it to have a fair agreement with Curve III. of that figure. The bar was again exposed to the outside temperature, which had a mean value during the next four days of 18.52 degrees Fahr., a minimum value of —2.5 Fahr., and a maximum value of 31.72

Fig. 7



degrees Fahr. A second test, on December 18th, showed very little change in the condition of the bar, as will be seen by comparing the figures in Table III. with those previously obtained, and the bar was therefore given a long rest through the remainder of December and the whole of January. The mean temperature for the remaining days of December was 25.64 degrees Fahr., the highest 39 degrees Fahr., and lowest 0.6 degree

Fahr. During January the mean temperature was 12.75 degrees Fahr., the lowest temperature recorded being —16.7 degrees Fahr., and the highest 39.6 degrees Fahr. The bar was tested again on February 1st, see Table III. and Curve III., Fig. VII., and, as will be seen, it exhibited some slight indications of recovery, but very small in comparison with the recovery which would have been effected by the ordinary indoor temperature. A final test was made on Feb. 26th, the mean temperature during the interval being 12.46 degrees Fahr., with a minimum of —4.0 degrees Fahr., and a maximum of 28.4 degrees Fahr. The recovery during this period was practically nil. It appears, therefore, that low temperatures tend to retard the recovery of steel, which has been subjected to overstrain in quite a marked degree.

TABLE III.

Load Lbs.	Dec. 18, 1900. I.		Dec. 22nd. II.		Feb'y 1st. III.		Feb'y 26th. IV.	
	Reading.	Δ	Reading.	Δ	Reading.	Δ	Reading.	Δ
0	400	–34	400	–34	400	–32	400	–31
2,000	434	–35	434	–33	432	–32	431	–32
4,000	469	–33	467	–34	464	–34	463	–33
6,000	502	–36	502	–34	498	–33	496	–34
8,000	538	–35	536	–35	531	–31	530	–34
10,000	573	–38	571	–36	562	–37	564	–34
12,000	611	–37	607	–38	599	–34	598	–34
14,000	648	–37	645	–38	633	–37	633	–38
16,000	685	–39	683	–39	670	–38	671	–35
18,000	724	–39	722	–40	708	–38	706	–38
20,000	763	–42	762	–42	746	–39	744	–39
22,000	805	–44	804	–43	785	–43	783	–42
24,000	849	–33	847	–32	828	–31	825	–31
22,000	816	–34	815	–32	797	–32	794	–32
20,000	782	–33	783	–33	765	–32	762	–33
18,000	749	–36	750	–34	733	–34	729	–33
16,000	713	–34	716	–34	699	–32	696	–33
14,000	679	–37	682	–36	667	–35	663	–34
12,000	642	–37	646	–38	632	–33	629	–35
10,000	605	–38	608	–35	599	–38	594	–36
8,000	567	–38	573	–38	561	–34	558	–36
6,000	529	–38	535	–39	527	–36	522	–37
4,000	491	–38	496	–40	491	–37	475	–35
2,000	453	–39	456	–42	454	–41	440	–37
0	414		412		413		403	

In conclusion, the author desires to thank Professor Bovey, Past-President of the Institution, who placed the Testing Laboratory of McGill University at his disposal; Prof. McLeod, Secretary of the Society, who kindly supplied the information regarding the temperature variations from the McGil Observatory records, and Messrs. Blanchard, Clement and Gagnon, who made all the observations recorded on Fig. 6.