On the Behaviour of Steel under Mechanical Stress

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Dr. Fison said he had made experiments on the electrification of flame, and found that potentials varying from + 2 volts to $-1\frac{1}{2}$ volt could be obtained in the region within and surrounding a Bunsen-flame.

Prof. S. P. Thompson commented on the contrast between Mr. Bidwell's experiments and those of Dr. Lodge on the dissipation of fogs by electricity, and also asked whether the colour of the jet depended on the length of spark produced by the machine.

Prof. Forbes thought a crucial test between the two hypotheses of Helmholtz could be obtained by trying the experiment in a germless globe.

The President said he had recently noticed that gas-flames were electrified.

Mr. Bidwell, in reply, said that since writing the paper it had occurred to him that the effect of flame upon the water-jet might possibly be due rather to the introduction of dirt into the stream than to electrification, Lord Rayleigh having observed that scattering did not occur if a little soap or milk were added to the water. He thought that the colour assumed by the electrified steam-jet appeared generally to be independent of the sparking-distance. He had not tried whether a red-hot iron produced any effect.

XLIII. *On the Behaviour of Steel under Mechanical Stress.* By C. A. CARUS-WILSON, B.A., A.M.I.C.E., Demonstrator in the Mechanical Laboratory at the Royal Indian Engineering College, Coopers Hill*.

[Plates IX.-XI.]

THE effect of uniform longitudinal stress on a steel bar is threefold :—

- (i.) The molecules are strained.
- (ii.) The elements are strained.
- (iii.) In virtue of the straining of the elements "flow" is produced.

The strain usually observed is the elongation due to flow, which may be recoverable or irrecoverable. The strains of an element can be shown to be a uniform dilatation combined

* Read December 6, 1889.

with a uniform shear about an axis parallel to that of the bar ; hence the elongation due to flow consists of a sliding combined with an increase of volume.

The state of strain of an element may be conveniently described by defining the shape, size, and orientation of the strain quadric, which is a sphere of radius $3\sqrt{\frac{k}{p}}$ combined with an hyperboloid of two sheets whose principal semi-diameter is $\sqrt{\frac{3n}{p}}$ and axis parallel to that of the bar ; where p is the intensity of longitudinal stress, n the rigidity, and k the bulk modulus.

Up to a certain stress the elastic properties of the steel are such that the strain produced is recovered when the load is removed, but at that stress the elastic resistance is overcome, and the molecules slide over one another, the strain being permanent.

This sliding beyond the limit of elastic resistance does not continue. The elastic resistance is raised by the sliding, and consequently the sliding is limited.

A stress-strain curve can be drawn which shows the increase of the limit of elastic resistance ρ with sliding ; the rate of increase of the former at any point may be measured by observing the angle which the tangent to the curve at that point makes with the axis of strain ; I will call this angle ϕ .

The initial value of ρ is often taken as an indication of the "hardness" of the steel, and when ρ is raised by permanent strain the steel is said to be "hardened" thereby. This, however, conflicts with a measure of hardness usually employed, namely the amount of permanent strain caused by performing a given amount of work on a bar.

Thus if a hard steel edge attached to a weight is allowed to fall on the surface of a steel bar, the depth of the indentation is taken as a measure of the softness of the metal.

If we draw the stress-strain curve O P for the steel under examination, the work done in producing a permanent strain O D is the area O P D. If O Q represent the stress-strain curve of a harder bar, the same amount of work, O Q C, will clearly produce less permanent strain, O C. The hardness then is evidently determined by the form of the curve ; but

this depends upon the rate of increase of ρ with permanent strain, *i. e.* upon the value of ϕ . Hence $\tan \phi$ is the true measure of the hardness; but $\tan \phi$ is not constant, it diminishes: therefore the initial value of $\tan \phi$ must be taken as the measure of hardness. It will be

seen that ρ cannot be taken as a measure of the hardness, for ρ is the same at R and P for the two bars, but the former is obviously the harder*.

We can say, then, that permanent strain raises the limit of elastic resistance, but diminishes the hardness—defined as the rate of increase of ρ with permanent strain.

I imagine it is because the harder steel has the greater value of initial ρ that ρ has been taken as a measure of the hardness.

If a bar of soft steel be taken and cut in four pieces; No. II. “hardened” in oil; No. III. in water [alkaline]; No. IV. in water [acid]; if each piece is now tested we shall obtain stress-strain curves as in fig. 1, Plate IX. A curve can be drawn through the points O A B C D E F, which I will call the “yield-line”; this will be the locus of all points such as A and F for pieces of the same bar “hardened” to different degrees. The points A, B, C are called the “yield-points.”

As the piece is harder the yield-point—or initial limit of elastic resistance—is higher, and the yield A F is less†.

When the yield begins it continues until ρ is raised by a given amount λ . If we could show that λ was the same for each piece, then it would follow that the yields as A F, B E, C D are direct measures of the hardness of the piece.

If there is any inequality or want of homogeneity in the bar due to unequal stresses in the manufacture, there may be

* If $\tan \phi = 0$, the bar at that point is perfectly plastic.

† Fig. 2, Plate IX. is a facsimile of an autographic diagram thus obtained: the steel bar was cut in three pieces; A was soft, B hardened in oil, and C in acid.

one plane or planes along which the limit of elastic resistance is less than along any other.

Hence when this resistance is overcome sliding will take place throughout the bar parallel to that plane or planes until the limit of resistance along that plane has been raised, by the sliding, to that of the rest of the bar, when the sliding will henceforth be uniform.

In a bar cut into pieces the required increase is the same in each piece, only in the harder bar less permanent strain is required than in the softer. Hence λ is the same in each piece and the yield is a measure of the hardness.

Steel bars and plates can be shown in which the permanent strain at the yield-point has clearly taken place as a sliding parallel to one plane only.

It would seem that there was an apparent discontinuity in the form of the stress-strain curve at the yield-point.

The question arises whether the curve may not actually be continued through a double inflexion, and be one with the rest of the curve as shown by the dotted lines, fig. 1, Plate IX.

Let us imagine a solid model made so as to represent at any point of its surface a particular condition of the bar with respect to stress, strain, and hardness. Let the curves I., II., III., IV. (fig. 1, Plate IX.) be placed parallel to one another at distances from the plane $X O Y$ proportional to the hardness which each curve represents, with their origins in the axis $O Z$ (perpendicular to $X O Y$), and let the surface of the model be made to pass evenly through all these curves and other similar curves which would be obtained at higher and lower degrees of hardness.

We see that from the curve which just passes outside the yield-line there is a part of the solid figure entirely wanting. It would seem a much more natural view to suppose that in some sense the successive curves are theoretically continuous, as shown by the dotted line above.

Such a supposition involves a state of affairs in which the limit of elastic resistance decreases as the permanent strain increases.

This would be the case if the sliding at the yield-point instead of taking place simultaneously over the whole bar parallel to one plane only took place as a strain wave passing

up or down the bar with a definite velocity without any further increase of load.

This is what actually takes place. Sliding is started at one end and takes place along a definite plane, generally at 45° to the axis; this disturbs the equilibrium of the molecules in the parallel plane next to it, and sliding is induced in this plane, so that a wave of strain passes the whole way up the bar; or sometimes starting from both ends two waves meet in the centre.

The velocity of the wave varies greatly with the quality of the steel; sometimes the wave appears to be instantaneous, sometimes so slow that it may take 30 seconds to pass up a 10-inch bar, in which case the pencil drawing the stress-strain curve is seen to follow the wave; in the former case the pencil drops as if the bar had broken.

When the wave starts from one end a plane in the centre experiences no permanent sliding until the wave has reached the plane next to it, so that while originally the resistance to sliding was greater than the stress, now it is less; in other words, permanent strain (in an adjacent plane) diminishes the resistance to permanent strain.

The most reliable stress-strain curves are those drawn by Prof. Kennedy's apparatus, and these show a rapid and irregular inflexion at the yield-point (see fig. 3, Plate IX.). In these diagrams the record of stress is unaffected by the inertia due to the load.

These stress-strain curves indicate the condition of strain in a steel bar as, by gradually increased stress, the steel is converted from an elastic solid to a viscous fluid. It is interesting to compare such curves for steel of different hardness with the stress-strain curves of a gas at different temperatures (see fig. 4, Plate IX.).

We have the effect of increased $\left\{ \begin{array}{l} \text{hardness} \\ \text{temperature} \end{array} \right\}$ doing away with the discontinuity at the $\left\{ \begin{array}{l} \text{yield} \\ \text{boiling} \end{array} \right\}$ line. Also the strong probability that in both cases the apparent discontinuity is really a double inflexion due to a change taking place piecemeal throughout the substance, and inconceivable if the substance be supposed homogeneous (*cf.* Prof. J. Thomson, Proc. Roy. Soc. 1871, no. 130).

[The stress-strain curves shown in the diagram are from Dr. Andrews's paper (Phil. Trans. vol. clix. 1869, p. 575).]

Thus far the strains considered have been those due to relative displacements of the molecules, but it is impossible to conceive that this can take place without the molecules themselves being strained, *i. e.* without a displacement of the atoms.

Such a displacement of atoms, if permanent, would alter the chemical and physical condition of the iron. Hence we must look to the straining of the atoms to account for the change that takes place when a bar is permanently strained, *i. e.* to account for the increase in the value of ρ with permanent strain.

Osmond has proved almost beyond a doubt that the so-called "hardness" of steel is due essentially to the existence of an allotropic modification of iron; that the molecules of iron may be either (α) soft, or (β) hard. (Cf. Osmond's *Etudes Métallurgiques*, Paris, Dunod, 1888.)

Hence the change induced in steel by permanent strain must be due to a permanent straining of the atoms in the molecule.

We should then expect to find evidence of a straining of an entirely different order and nature to that due to a molecular disturbance. Such evidence is forthcoming.

It has long been known that if a steel bar lying in a magnetic field of limited intensity be subjected to tension in the direction of the magnetizing force, the magnetization of the bar will be increased.

I have made a series of experiments on this subject, and find that the intensity of magnetization increases regularly with the load up to the yield-point.

The following experiments were made:—

The bar to be tested was turned in the lathe, and a screw cut on each end; it was placed vertically in the testing-machine; to each end was screwed a nut, the top one (A) of gun-metal, the lower one (B) of steel (see fig. 1, Plate X.). The former was of gun-metal so as to remove the free upper extremity of the bar as far as possible from the neighbourhood of large masses of magnetic material. These nuts rest on steel collars, C C, which have conical surfaces to fit into conical holes in the main shackles, D D, of the testing-machine. The bearing of the nuts on the collars is spherical, so as to

allow of a free movement of the specimen, and to ensure a direct pull. A short distance above the upper end of the bar a small magnet, E, is hung by a silk fibre, the suspension of which is rigidly attached to the upper shackle, so that any small motion of the latter involves the same motion of the needle; a silvered mirror is attached to the needle, which reflects a beam of light from a lamp, F, onto a horizontal scale, G; H is a controlling-magnet.

A small displacement is given to the magnet (i.) when there is no load on the bar, and the time of 20 complete oscillations observed; (ii.) the same with a small load on; (iii.) the load is then removed, and the time of 20 oscillations again observed. The results are recorded in the accompanying Table.

Experiment I.—Bar of soft steel, never loaded before: cross sectional area 0.306 square inch, 19.5 inches long; elongations measured on 10'' by a vernier and microscope reading to thousandths of an inch.

An automatic stress-strain diagram was taken (see curve A, Plate X.). The time of 20 oscillations of the needle was first observed with the bar out—102.6 seconds. From this was deduced x^2 , the square of the number of oscillations per minute, and this was deducted from N^2 , the same when the bar was in place. The results are plotted on fig. 1, Plate XI., as two curves, the upper one, A_1 , being the curve of temporarily-induced magnetism, with load on, and the lower one, A_2 , that of permanent magnetism, with load off. The arrow shows the yield-point. The two curves cross one another twice, and coincide in a third point. The third curve, A_3 , is the curve of extensions from the second column of the Table, 186 times full size. Curve A_4 is the curve of permanent set, same scale as A_3 . This bar was broken. The last observation was after the fracture.

Experiment II.—Bar of soft steel never loaded before: cross-sectional area 0.308 square inch, 19 inches long; diagram measures elongations of 10''; square of number of oscillations per minute with bar out 121; ditto, bar in, no load on, 1849. The results are plotted as a curve in fig. 2, Plate XI. The arrow shows the yield-point. The observations at this point were taken after the set. The stress-strain diagram is shown at B, Plate X. This bar was broken.

Experiment III.—Wrought-iron bar never loaded before : cross-sectional area 0.203 square inch. The extensions on the diagram, C, Plate X., are on a length of six inches. The results are recorded in the Table, and plotted on fig. 5, Plate IX., the ordinates here representing simply the square of the number of oscillations per minute. The arrow shows the yield-point. The curves intersect twice. This bar was not broken.

The circles show the loads at which observations were made.

From the curves on Plates IX. and XI., it is evident that the magnetic induction is increased in a regular way by increased stress, and that the effect is largely permanent ; a point is reached, before the yield-point, where the effect produced is wholly permanent. The two curves continue side by side up to the yield-point, when the large permanent set which then takes place completely upsets the former condition of the bar, as might have been expected. The temporary effect is roughly proportional to the elastic extension below the yield-point.

The conclusions to which I am drawn by these experiments are :—

(i.) Mechanical straining produces an “atomic disturbance” in a bar which increases regularly with the stress.

(ii.) For small stresses the disturbance is only partly permanent, but as the yield-point is neared it becomes wholly permanent.

(iii.) The magnetic properties of a loaded bar are in general different from those of the same bar unloaded, but there is a certain stress or range of stresses over which the bar has the same magnetic properties whether the load be on or off.

In Experiment I. the range of stress referred to in (iii.) is about 15 to 22 tons per square inch, the latter being the yield-point ; and in Experiment III. it is about 10 to 15 tons per square inch, the latter being the yield-point. In Experiment II. the critical stress appears to coincide very nearly with the stress at the yield-point.

It is interesting to compare these results with those obtained by Joule. In his ‘Scientific Papers,’ pp. 253–256, Joule shows that an iron or steel bar elongates on being magnetized, but that if the bar is strained, the effect is reduced until, at a certain load, no effect is observed, and if the load be further

increased, magnetization produces a shortening of the bar. These experiments were made with soft iron and steel wires.

Joule's experiments show that magnetization produces a minute elongation of a bar, those quoted above show that mechanical stress increases the magnetization of a bar, *i. e.* mechanical stress produces a change similar to that produced by magnetization. It would seem, then, that Joule's critical point of no elongation (+ or -) must be reached when the molecular elongation produced by the mechanical stress is the same as that which would be produced independently by a certain given intensity of magnetization. For at that point, the molecular elongation having already been produced by mechanical stress, the effect of the given magnetization would be nil, *i. e.* there would be no further elongation (+ or -). Now, taking an intensity of magnetization, denoted by 5 in Joule's experiments, we see that this produces an elongation in a 12 inch length of soft iron wire (0.25 in. diam.) of $\frac{4}{150,000}$ in.; assuming Young's modulus for the iron at 13×10^8 tons per square inch, the mechanical stress required to produce this elongation would be about 0.03 ton per square inch.

According to Joule's experiments the critical stress is at about 6 tons per square inch, *i. e.* in order to produce this molecular elongation by mechanical means we require an elongation of the bar 200 times as great as that which accompanies the same effect produced by magnetization.

We are thus dealing with two distinct kinds of elongations—firstly, that produced by a relative motion of the molecules; and secondly, that produced by a straining of the molecules themselves.

It is clear that if the atomic displacement should be permanent, there would be a permanent change in the physical and chemical properties of the iron; and as there certainly is a change produced by permanent set, it is highly probable that we must look to such a straining of the molecule to account for it.

Thus, taken in conjunction with Osmond's experiments, those quoted above would seem to show that the increase in the value of the limit of elastic resistance with permanent strain is due to a permanent straining of the individual molecules.

Experiment I.—Steel Bar.

Load.	Micrometer.	Time in seconds of 20 vibrations.	$\frac{N^2 - x^2}{10}$	Load.	Micrometer.	Time in seconds of 20 vibrations.	$\frac{N^2 - x^2}{10}$
0.0	1.417	24.9	218	0.0	1.418	18.9	389
0.1	1.417	24.85	219	5.4	1.457	18.7	398
0.2	1.417	25.0	217	0.0	1.418	18.7	398
0.4	1.418	24.8	221	0.0	1.418	18.65	400†
0.0	1.417	24.85	219	5.6	1.458	18.65	400
0.6	1.420	24.75	221	0.0	1.418	18.6	403
0.8	1.420	24.6	224	5.8	1.463	18.7	398
1.0	1.422	24.55	225	0.0	1.420	18.5	407
0.0	1.417	24.9	219	6.0	1.465	18.3	416
1.2	1.424	24.1	234	0.0	1.420	18.5	407
1.4	1.425	23.7	243	6.2	1.465	18.35	414
1.6	1.426	23.35	250	0.0	1.420	18.4	412
1.8	1.427	22.4	273	6.4	1.467	18.2	421
2.0	1.428	21.8	289	0.0	1.421	18.55	405
0.0	1.417	22.6	268	6.6	1.469	18.3	416
0.0	1.417	22.5	271*	0.0	1.421	18.3	416
2.2	1.430	20.9	316	6.8	1.470	18.0	431
2.4	1.431	20.55	327	0.0	1.421	18.6	403
2.6	1.433	20.4	332	7.0 §			
2.8	1.434	20.3	336	0.0	1.455	18.8	394
3.0	1.436	19.85	352	7.0 §			
0.0	1.417	20.7	322	0.0	1.507	19.2	377
0.0	1.417	20.75	321 *	7.0 §			
3.2	1.437	19.6	361	0.0	1.538	19.4	369
3.4	1.438	19.5	365	0.0	1.538	19.5	365 †
3.6	1.439	19.65	359	7.7	2.095	17.95	433
3.8	1.440	19.6	361	0.0	2.036	25.35	210
4.0	1.442	19.45	367	8.0	2.178	16.5	515
0.0	1.417	20.05	344	0.0	2.112	25.05	216
0.0	1.417	19.9	350 *	8.3	2.323	16.8	497
4.2	1.444	19.1	381	0.0	2.248	25.45	209
0.0	1.417	19.75	355	8.6	2.455	16.65	506
4.4	1.446	19.15	379	0.0	2.374	25.7	204
0.0	1.417	19.45	367	9.0	2.692	17.05	482
4.6	1.451	19.1	381	0.0	2.616	26.4	193
0.0	1.418	19.5	365	9.3	2.981	16.8	497
4.8	1.452	18.8	394	0.0	2.893	26.35	194
0.0	1.418	18.9	389	10.0		17.4	462
0.0	1.418	18.9	389 †	0.0		27.5	177
5.0	1.453	18.85	391	10.5		17.35	465
0.0	1.418	19.05	383	0.0		28.0	170
5.2	1.455	18.65	400	10.87		18.1	426

* After 10".

† After 5".

‡ After 17 hours.

§ Load removed after small permanent set.

|| After fracture.

Experiment III.—Wrought-iron Bar.

Load in tons.	<i>n</i> . Time in seconds of 20 vibrations.	$n^{-2} \cdot 10^5$.	Load in tons.	<i>n</i> . Time in seconds of 20 vibrations.	$n^{-2} \cdot 10^5$.
0·0	17·25	336	0·0	13·2	574
0·5	16·8	354	2·7	13·25	570
0·0	17·1	342	0·0	12·85	606
0·0	16·9	350*	3·0	13·0	592
0·7	15·25	430	0·0	13·3	565
1·0	14·05	507	3·12	12·75	615†
0·0	14·7	463	0·0	14·85	453
1·3	13·05	587	3·4	12·75	615
1·6	13·15	578	0·0	15·2	433
0·0	13·5	549	3·8	12·85	606
2·0	12·95	596	4·2	13·55	545
0·0	12·95	596	0·0	16·25	379
2·2	13·1	583	4·4	13·55	545
0·0	13·4	557	0·0	15·95	393
2·4	12·8	610			

* After one hour.

† After the permanent set.