A REDETERMINATION OF THE ELASTIC MODULUS OF ALUMINIUM.

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The modulus of elasticity of aluminium was determined by two distinct methods, viz., by the bending of a rod when supported upon knife edges at the two ends and weighted in the middle, and by the stretch of a wire, when weights are suspended at one end and the other end fixed. The bend in the first case and the stretch in the second were both measured by screw micrometers, one reading to $\frac{1}{1000}$ mm. and capable of eye estimation to $\frac{1}{10000}$ mm. and a second reading directly to $\frac{1}{10000}$ of an inch.

The apparatus employed for the bending experiments consisted of a bronze clamp sliding upon a massive steel tube, down the middle of which a straight line was drawn to indicate the centre of the apparatus. The bronze clamp carried the micrometer and held it rigidly in position. Two steel knife edges were then set upon two firm supports, carried upon a brickwork column, exactly one metre apart, the metre being measured by a Whitworth standard metre, each knife edge situated exactly half a metre from the centre line of the tube bearing the micrometer clamp. The two supports and knife edges were exactly level. The aluminium bar was carefully straightened and laid on the knife edges. Exactly in the centre a knife edge carrying a scale pan was placed. The casing of the knife edge also carried a point for making contact with the micrometer. In order to tell when contact was made, the bar and micrometer were placed in series with a couple of Leclanché cells and an electric bell. As soon as contact between the micrometer and point on scale pan suspension was made, the ringing of the bell indicated the closing of the circuit. In this way it was found possible to make series of experiments showing excellent agreement for similar materials. The total deflection varied from about 2 to 12 mm., according to the diameter of the bar under test, but as a rule averaged 2-5 mm., it being important to keep the deflection small in proportion to the length of the bar and to avoid a permanent deformation.

The determination of the elastic modulus by the stretch of a wire was effected by hanging a length of 4-5 metres of wire from a solid support carried on the wall and measuring the increase in length caused by loading the end. The measuring apparatus consisted of a block of teak, which was bronze faced and fitted with a sliding centre, to which the wire under test was clamped and which carried the scale pan for the weights. The block was carried by two exactly similar aluminium wires to that under test, one on either side of the test wire. The fixed portion of the block carried a micrometer and the slider a pointer for making contact, the contact being indicated by a battery and bell, as in the bending experiments. The whole apparatus was kept in a perfectly vertical position by counterpoise weights on

each side. The general arrangements of the two pieces of apparatus are shown in Fig. 1, A and B.

A series of preliminary experiments showed that the results of the bending tests could be reproduced to within 1-2 per cent. without difficulty when repeated upon the same sample. This involved a reading which varied only in the second decimal place. A large number of experiments were made upon different material and it was found that definite differences existed, due most probably to differences in the amount of work done upon the metal. It was further found that the values obtained for the modulus of elasticity of

FIG. 1.

aluminium by the two methods were in good general agreement. The experiments and the results obtained will now be discussed.

SERIES I.

Bending Experiments.

The aluminium bars used in this series of determinations consisted of metal of not less than 99.25 per cent. purity. The analysis of an average sample gave :

					Per cent.
Silicon ...	...	...	...	...	0.35
Iron ...	...	...	...	...	0.28
Copper ...	...	...	...	...	trace
Aluminium ...	...	...	...	...	99.37
					<hr/> 100.00

The bars used were :

Square bars,	0.375 in. sq.
Rectangular bars,	0.800 × 0.436 in.
Rectangular bars,	0.876 × 0.312 in.
Round bars,	0.25 in. diameter.
Round bars,	0.375 in. diameter.
Round bars,	0.625 in. diameter.
Semicircular bars,	0.500 × 0.250 in.

The bars were as straight as possible; at least two measurements were taken, at opposite sides of the bar, so as to eliminate any residual curvature which might vitiate the results. Successive measurements with the same bar showed that the results could be reproduced to within 1-2 per cent. and frequently exact agreement between the two series was obtained. In order to avoid the effect of sudden strain, the load was put on gradually, the total load being put on in about ten steps and the deflection observed at each increment of load, an interval of three minutes being allowed between each increase of load. The results were calculated from the deflection produced by the total load, the load always being kept below that required to produce a permanent deformation.

When l is the distance between the two knife edges, a the height, and b the width of the bar, all expressed in millimetres, w the load in kilograms which produces a deflection d , then the elastic modulus is given by the formula—

$$E = \frac{1}{4} \frac{l^3 \times w}{a^3 b \times d}$$

for a rectangular bar. This becomes—

$$E = \frac{1}{4} \frac{l^3 \times w}{a^4 d}$$

for a square bar, and—

$$E = \frac{1}{12} \frac{l^3 \times w}{\pi r^4 \times d}$$

for a circular bar.

The results for a semicircular bar were obtained by aid of the formula—

$$E = \frac{1}{48} \frac{l^3 \times w}{I d}$$

where I is the moment of inertia, and for a semicircular section this is equal to—

$$I = \frac{\pi r^4}{2} \left(\frac{1}{4} - \left(\frac{4}{3\pi} \right)^2 \right)$$

and when this is reduced, by substituting the values for π , the formula becomes—

$$I = 0.1106 r^4$$

whence—

$$E = \frac{1}{48} \frac{l^3 \times w}{0.1106 r^4 d}$$

The results obtained were :

Diameters.	No. of Experiments.	Highest E. Kg/mm ² .	Lowest E. Kg/mm ² .	Mean E. Kg/mm ² .
Square, 0.375 in.	12	6,929	6,779	6,841
Round, 0.250 in.	8	7,055	6,890	6,955
Round, 0.375 in.	14	7,133	6,848	6,973
Round, 0.624 in.	8	7,006	6,921	6,972

The rectangular bars gave different results when the bending took place along the short or long diameter, the differences between the two series being greater than the experimental error; repeated measurements on the same bar and along the same diameter did not differ by more than 1 per cent., and as a rule the difference was very much smaller than 1 per cent. The results for the two directions were :

	No. of Experiments.	Highest E.	Lowest E.	Mean E.
Short diameter	13	6,906	6,755	6,850
Long diameter	18	6,780	6,347	6,574

The semicircular bars gave the highest values of all, but were perfectly consistent in each series on the same bar. Two determinations were made upon each bar, one with the diameter of the semicircle resting upon the knife edges, the second with the circumference opposite to the diameter.

The values obtained for the modulus of elasticity from these experiments were :

	No. of Experiments.	Highest E.	Lowest E.	Mean E.
Semicircular bars	12	7,337	7,103	7,217

The semicircular bars appeared to have been somewhat overworked, and the tensile strength was not so great as might have been anticipated. The density of the $\frac{3}{8}$ -in. round and square and the $\frac{1}{2}$ -in. semicircular shows a variation with the elasticity, and is shown in the following table :—

Bar	ld_4 .	Mean E.
$\frac{3}{8}$ in. Square	2.7039 ± 0.0001	6,841
$\frac{3}{8}$ in. Round	2.7052 ± 0.0001	6,973
0.5 in. Semicircular	2.7095 ± 0.0001	7,217

The tensile strengths of these bars were determined, but, as already stated above, the semicircular bars had a lower tensile strength than would have been anticipated; but this may be accounted for by the fact that the grips used were not suitable for a satisfactory determination. The overworked state of the semicircular bars was shown by the fracture after breaking in the tensile machine and also by the microstructure.

The general mean of the results on the bars, excluding the two abnormal results, viz., for the rectangular bar along the long axis and for the semicircular bars, is—

$$E = 6,918 \text{ kg. per sq. mm.}$$

or—

$$E = 4,393 \text{ tons per sq. inch.}$$

SERIES II.

Stretch of Wire.

The second method used for determining the elastic modulus was to measure the stretch of a wire under a load which was gradually increased, but always kept far below that necessary to cause a permanent elongation. The wires used were all carefully selected, as uniform as possible in gauge, and free from bends and kinks. Before a set of measurements was made, the wires were fixed in position, and a weight was hung on one end which was sufficient to pull the wire perfectly straight. This was necessary in order to counteract the slight curvature caused by winding up on the block during drawing. In other cases the wires were previously straightened in a straightening machine and then suspended.

It was found that the measurements could be reproduced on the same wire to within about 2 per cent., if sufficient time were allowed to elapse between each series of measurements. If measurements were made on the same wire in rapid succession, each series was invariably higher than the preceding series, due to the after-effects of the stretch, which required a fair interval of time to regain its original length. As a rule the wire was allowed to stand for several hours before the experiments were repeated. The length of the wire used was about 4,500 mm., and the stretch between 2.5 and 4.5 mm., and the readings of the elongation were reproduced to within 2 per cent. in repeated series of measurements. From a very large number of experiments it was found impossible to reproduce the elongations more accurately than this, although, in some cases, it happened that an almost exact agreement was obtained. The diameter of the wires tested ranged from 1.692 mm. to 1.858 mm., and were drawn both upon the rapid working tandem machines through successive dies and also upon a wire-drawing block, at a much slower rate of drawing. The results of the experiments were calculated by the formula—

$$E = \frac{l \times w}{\pi r^2 \times d}$$

where d is the elongation of the wire, l the length and r the radius, all expressed in millimetres; w is the weight in kilograms, producing the elongation d .

The results are given in the following table :

Diameter of Wire in mm.	No. of Experiments.	Highest E.	Lowest E.	Mean E in Kg. per mm ² .
1.692	14	7,343	6,705	7,000
1.829	12	7,109	6,702	6,945
1.831	9	7,008	6,723	6,870
1.858	12	6,831	6,651	6,754

The general mean of these results is

$$E = 6,892 \text{ kg. per sq. mm.}$$

or—

$$E = 4,376 \text{ tons per sq. inch.}$$

Metal which has been overworked gives a modulus considerably higher than the above general mean. A sample of wire, 0.4266 mm. in diameter, was overdrawn to such an extent that it was impossible to bend it at right angles without fracturing. Three determinations of the modulus of elasticity upon this sample gave as a mean—

$$E = 7,323 \text{ kg. per sq. mm.}$$

The general mean of all the results obtained both by the bending and elongation experiments described under Series I and II, but excluding the abnormal results before mentioned, is—

$$E = 6,905 \text{ kg. per sq. mm.}$$

or—

$$E = 4,384.7 \text{ tons per sq. inch.}$$

The experiments were made at an average room-temperature of about 17° C.

These results are somewhat lower than the results of Slotte, Katzenelsohn, and G. S. Meyer, recorded in Landolt and Börnstein's Tables,* but they represent results obtained with technical material and of a high degree of purity. The presence of an increased amount of iron, silicon, or copper would cause a considerable rise in the elastic modulus. The redetermination of the elastic modulus of aluminium was undertaken with a view to determining the comparative uniformity of the worked material regularly manufactured, and upon the whole the results show a striking agreement by both the methods of determination. The higher values are probably due to overwork and fatigue and do not represent a desirable condition for the technical metal. The passage of aluminium into the vitreous or amorphous state under the influence of work has been pointed out in a previous paper,† and that in the vitreous state the metal should possess a higher elastic modulus is to be expected.

* Landolt and Börnstein, *Physikalisch-Chemische Tabellen*, 3rd edition, p. 43, ff.

† These *Transactions*, vii., 1911, p. 221.

ELASTIC MODULUS OF ALUMINIUM

161

The further investigation of the changes is now under consideration, with a view to determining the energy of the transformation—

and it is hoped to communicate these results to this Society in the near future.

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