THE RESISTANCE OF MATERIALS TO IMPACT.

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During the years 1904–1905 the authors were engaged in a research on the resistance of certain kinds of iron and steel to reversals of direct stress.* In these experiments the change from tension to compression was gradual, and followed an approximately simple harmonic law, special care being taken to avoid the subjection of the specimens to sudden shock, the effect of which, it was considered, would complicate the problem, and might conveniently form the subject of another research.

Since in ordinary machine practice the stresses induced in the moving parts are, in general, due to a combination of shock and gradually applied load, as might happen in the case of the crank-pins and bearings of reciprocating engines, it appeared to the authors that the determination of the relative resistances to sudden shock of the same materials as used in the previous work on gradual reversals of stress would, combined with the previous results, be of considerable value to the designer. This determination appeared to be the more urgently required, since in the opinion of engineers of such wide

* Proceedings, The Institution of Civil Engineers 1905-6, vol. clxvi, page 78.

experience as Messrs. Seaton and Jude,* the proof resilience of a material, that is, the maximum work which can be stored up per unit volume without permanently deforming it—as calculated from statical experiments—is quite unreliable as an index of "useful toughness."

A research with this object in view was accordingly commenced, and some suitable testing machines for the work were designed and made in the workshop of the department.

As in the research on alternating stresses, the testing machines were designed for the purpose of carrying out endurance tests up to one million shocks or more. Since however these machines lent themselves equally well to the fracture of specimens under comparatively few blows, the authors were led to the comparison of the results of impact tests which consisted of a large number of small blows with these consisting of a small number of heavier blows or even of a single blow to destruction.

The results of this comparison, together with the interest taken at the present time by engineers in the respective merits of impact tests by the "single-blow" and the "many-blow" methods, induced the authors to enlarge somewhat the scope of the work so as to include a study of the development of the changes in the relative shock-resisting properties of materials as the number of blows for fracture is increased. In doing this the authors have no intention of making any comparison of the *relative merits* of the two methods of test, since in their opinion such a comparison cannot be made for the following reasons:—

An impact test on any given material may be made for one of two objects.

(1) To ascertain if the material is in an abnormal or dangerous state, that is, is brittle; or

(2) To determine the resistance to shock under working conditions of the material relative to the resistance of other well-known materials.

It is obvious that the first object will primarily concern the steel maker, who will be naturally anxious not to supply the

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* "Impact Tests on the Wrought Steels of Commerce." Proceedings 1904, Part 4, page 1135.

constructor with dangerous material; and that the second will concern the engineer or designer of machinery, to whom a knowledge of the relative values of the true resilience of materials, which are otherwise constructionally satisfactory, is of considerable importance.

It is further almost obvious that the nature of any proposed impact test will depend upon which of the above objects is in view, since for the detection of brittleness, its chief characteristic, which is an absence of permanent strain on fracture under impact, will be best brought out by a test to destruction, which will involve the least amount of energy spent in elastic deformation, that is, a single-blow test. Again, for the determination of resistance to shock under approximate working conditions, the test should be one in which the energy absorbed in plastic deformation is a minimum, since such plastic deformation has little relation to its constructional value. The proper test in this case would therefore appear to be what may be called a "shock-fatigue" test, involving a large number of relatively small blows. It seems evident, therefore, that no comparison of the relative merits of two tests which reveal different properties of the material can be made, but these considerations do not seem to have been fully appreciated in previous discussions on the subject, in which there has been frequent evidence of the opinion that impact tests by the single-blow method afford all the information which the steel maker and engineer require for the selection of the material which is best suited for endurance of shock.

As the very considerable expenditure in time and trouble involved in making fatigue tests would be saved, if this assumption were true, the authors decided to make the investigation of its validity the chief feature of the present research, by selecting materials differing widely in their strength and elastic properties, and by subjecting them to a varied treatment under impact, so that a scale of "useful toughness" for the materials could be determined.

Methods of Test and Testing Machines used.—For the experiments on the bending of a notched specimen by the single-blow method, an Izod impact tester was kindly lent to the Laboratory by Messrs. Avery and Co., of Birmingham, at the request of Captain Sankey, who has shown great interest in the present work.

This machine, which has been fully described* and is well known to engineers, is shown diagrammatically in Fig. 1, in which is indicated the standard form of specimen and method of estimating the energy absorbed in fracture.

The other form of single-blow impact tester adopted was that which would produce fracture of a plain specimen by direct tension. The machine made in the workshop for this purpose is shown in

Fig. 1.
Impact Tester (Izod).

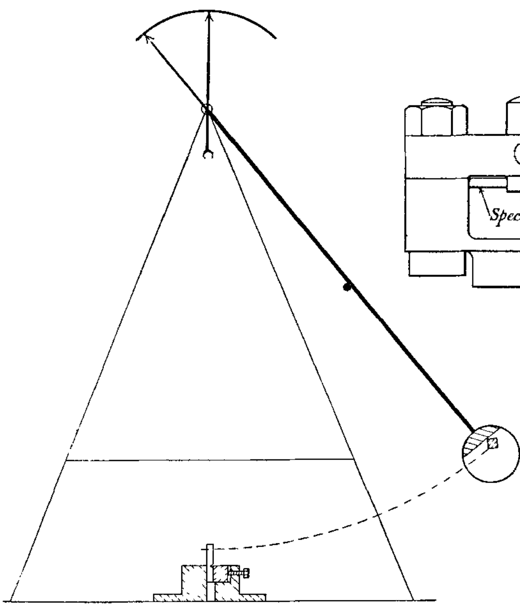


Fig. 2.
Apparatus for Static Tests.
(N. P. L. Method.)

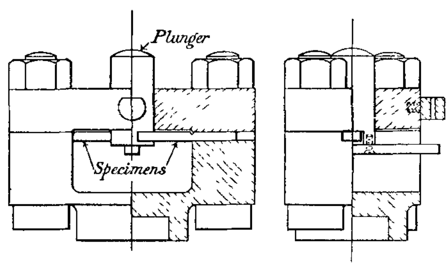


Fig. 3. The specimen is 0·25 inch diameter, 1 inch long, and has shanks at each end screwed with a half-inch Whitworth thread. In testing, the specimen is screwed into the base-plate BP, and at its other end is attached to the cross-head C. This cross-head is connected by two side-rods to a piston P, which is struck by the

* Proceedings 1904, Fig. 170, Plate 43; and "Engineering," 25 September, 1903.

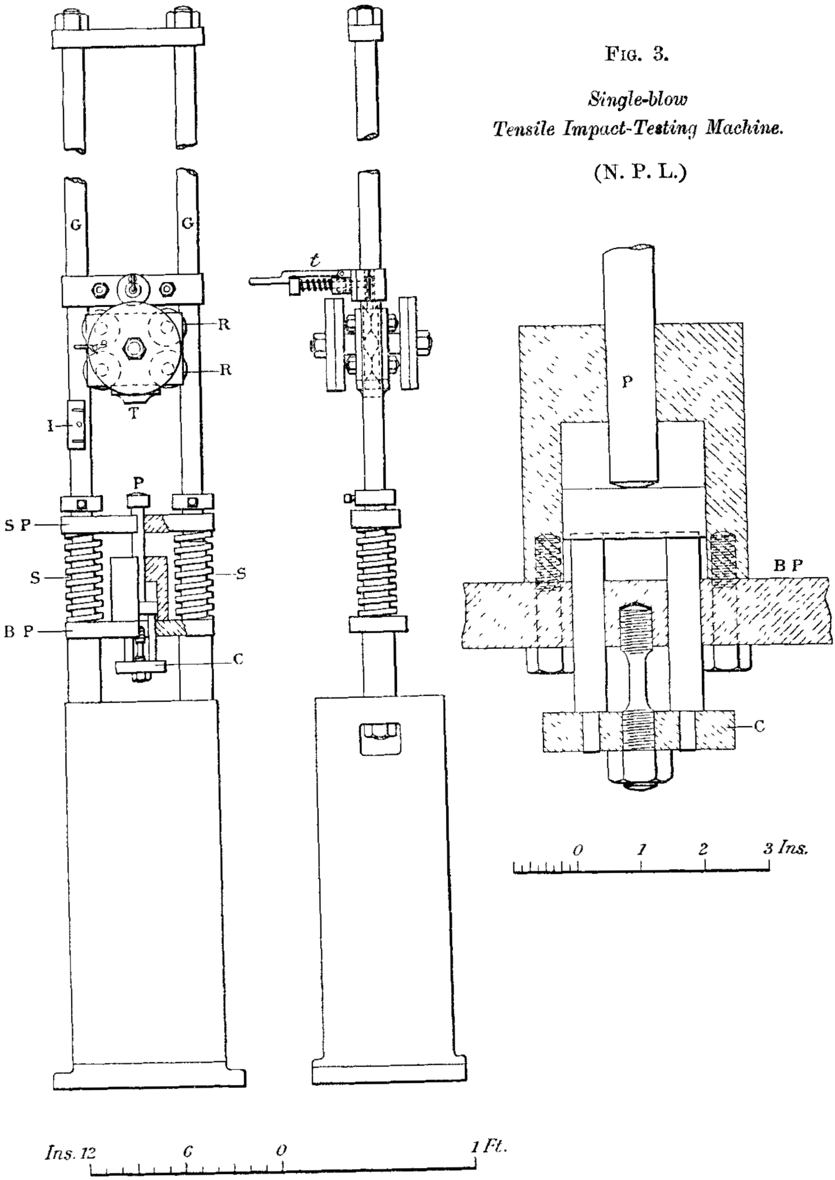


FIG. 3.

Single-blow
Tensile Impact-Testing Machine.

(N. P. L.)

falling tup T. This piston is provided with a collar at its upper end, which, after the fracture of the specimen, engages with the striking plate SP, resting on the spiral springs SS, which absorb the residual energy in the tup. This energy appears in the rebound of the tup, and is measured on a calibrated scale I. The tup is supported before the test by a movable cross-head attached to the guides G, and the release is performed by the trigger *t*. The tup is provided with four conical rollers R to reduce the friction as much as possible.

For the comparison of the energy expended in the fracture of a specimen in this machine with the work done in a static test of a precisely similar specimen, the laboratory 10-ton machine was used with a special micrometer for taking the extension.

The corresponding static test on the notched specimens used on the Izod machine was more difficult, and the arrangement finally adopted for doing this is shown in Fig. 2 (page 892).

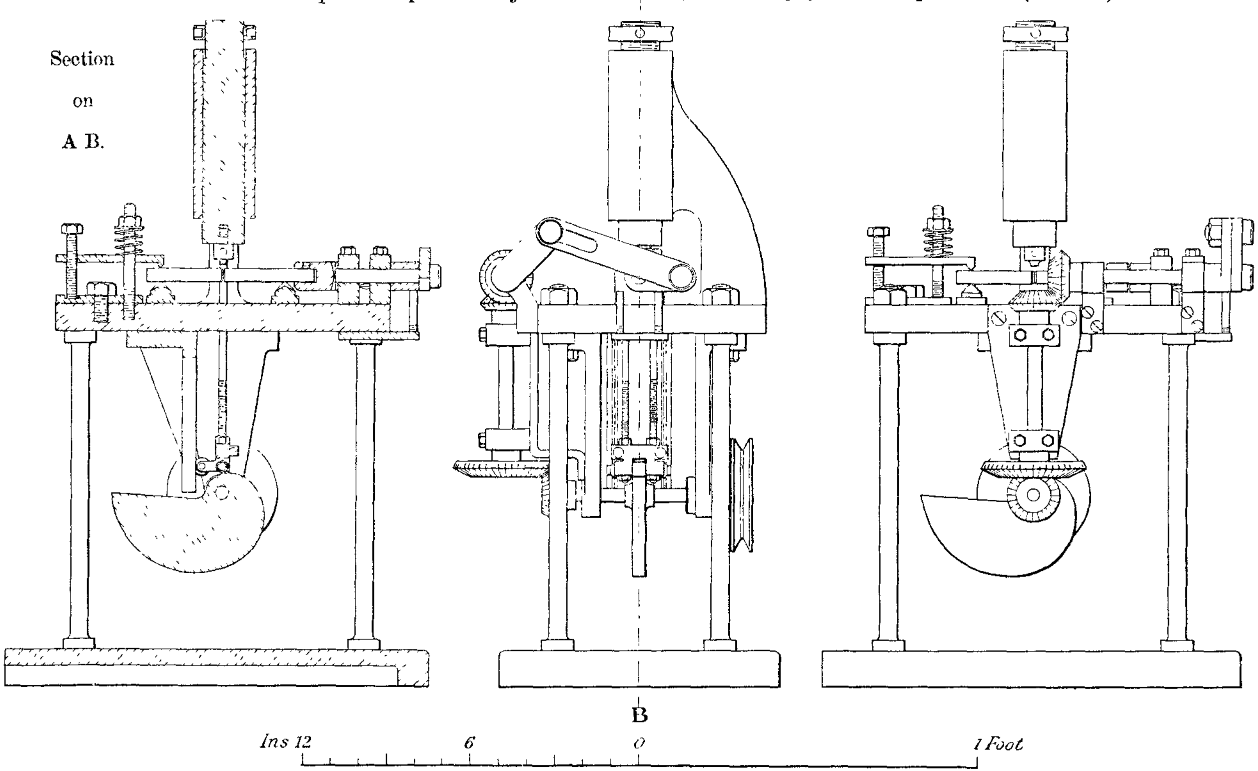
In this, two specimens are clamped in the cross-head, which is fixed to the shackles of a compression testing-machine, facing each other in such a way that the plunger bears upon both at points equal to the distance of the striking tup from the notch in the impact tester. In this way a steady downward pressure is all that is necessary to make the test, the deflections being taken by a micrometer.

Corresponding to the two machines on the single-blow method, two repeated-impact testing-machines were designed and made, one for bending-impact tests on notched specimens, and the other for direct-impact tests on plain specimens.

In the bending-impact tester, which has been fully described,* the turned specimen, 0·50 inch in diameter, with a V notch in the centre 0·40 inch in diameter at the bottom, is placed on knife-edges $4\frac{1}{2}$ inches apart and receives blows over the notch from a falling tup which strikes it alternately at each end of a diameter. To do this the specimen is reversed between successive blows by a link motion, the details of which will be clear from Fig. 4. The fall of the striking tup can be regulated from 0 to $3\frac{1}{2}$ inches

* "Engineering," 13th July 1906.

Fig. 4.—*Repeated-Impact Testing Machine* A *for Bending of Notched Specimens.* (N. P. L.)



and its weight is 4·7 lbs. On the fracture of the specimen the tup strikes a small bell-crank lever which breaks the circuit of the driving motor and thus stops the machine. A counter is attached to the machine, which registers the number of blows, so that the machine can be left without any attention except for occasional lubrication. The maximum speed attained in this form of tester was 100 blows per minute, which renders a fatigue test up to half a million blows a somewhat long process.

The manner of fracture of the specimens, whether of soft or hard material, is that a crack is developed on each side of the specimen at the bottom of the notch, the two cracks spreading inwards as the test proceeds. In the case of a light blow and many reversals these cracks will spread nearly to the centre before fracture occurs, as will be seen from the photograph in Fig. 20, Plate 29, which is from a specimen of mild steel (0·20 per cent. carbon) which broke after 50,000 blows.

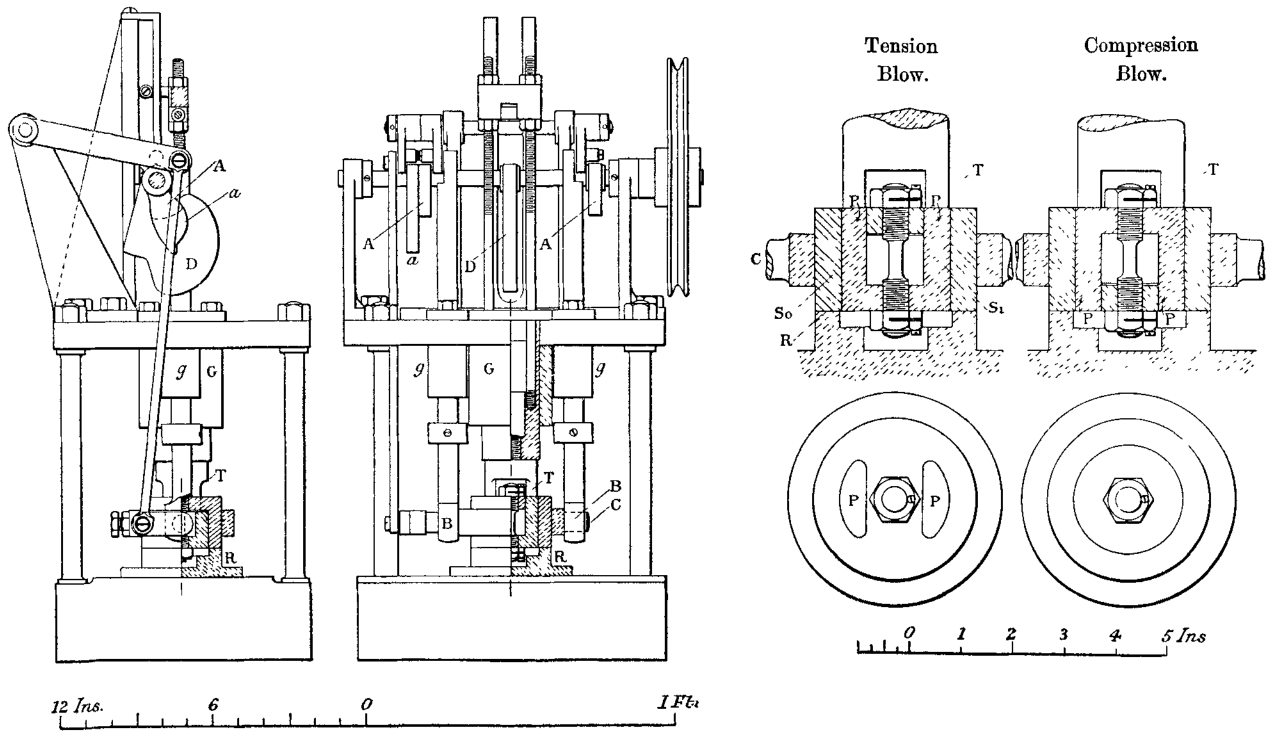
Except for tests in which the number of blows is small, that is, less than 100, there is no appreciable permanent set in the specimen until within a few blows of the ultimate fracture.

Testing Machine for Alternating Direct Impact.—In this machine the specimen is held by two concentric hard steel sleeves S_i and S_o into which it is screwed and locked as shown on the right of Fig. 5. The blow of the striking tup is always delivered on the inner sleeve, the outer one being supported on a rigid steel ring R. The change from compression to tension is effected by a rotation of the sleeves about a horizontal axis between successive blows. For the compression blow the inner sleeve is struck at that end of it which holds the specimen, and for the tension blow, at the opposite end on the two projections PP, which pass through openings in the outer sleeve.

The outer sleeve is held by the cross-head C, which is carried on the bearings BB, at the extremities of the two side rods working in the side guides *gg*.

The rotation of the cross-head and sleeves is performed in two operations. First, the cross-head is raised vertically by the two side cams AA, (which engage with rollers on the side rods) to a distance

FIG. 5.—*Impact-Testing Machine, for Alternating-Tension and -Compression.* (N. P. L.)



sufficient to enable the cross-head in its rotation to clear the ring R. Secondly, by means of another cam *a* and the system of rocking levers shown in the figure, the cross-head is rotated into its new position and then lowered on to the ring R. The initial motion of the cross-head during rotation is made as rapid as possible, so that its inertia carries it over the "dead point."

The striking tup T moving on the guide G is actuated by the centre cam D, which engages with a hard steel roller on an adjustable cross-head attached to two tail-rods on the striking tup. By this means the fall of the tup can be varied from 1 inch to 3·3 inches. To reduce the friction of the tup in the guide as much as possible, the former is machined with a broad spiral fluting to reduce the surface of contact.

The machine is driven by a $\frac{1}{6}$-H.P. motor through a reduction gear, and is provided with an automatic cut-out worked by the tup on fracture of the specimen and a counter to register the number of blows.

Materials used in the Research.—As previously stated, one of the chief objects of the present research was to predict the limiting resistance, under impact, of the materials for which the resistance to alternating stresses had already been determined. Unfortunately the amount of this available was not large, and although Sir Robert A. Hadfield very kindly procured for the Laboratory another supply of Swedish Bessemer steel of carbon content varying from 0·16 to 0·6, the strength properties of these did not precisely agree with those used previously. It was therefore decided to use the remainder of the original stock for the experiments on limiting resistance and the new material for the comparison of the one and the many-blow methods. The description, analyses, and results of the tensile tests of the materials used are given in Tables 1 and 2, and for convenience these materials will be referred to in the Paper by the numbers attached to them in the Tables.

TABLE 1.—*Analysis of Materials used.*

Test No.	Description.	Carbon.	Manganese.	Silicon.	Sulphur.	Phosphorus.
1	Swedish Charcoal Iron.	0·039	trace	trace	0·000	0·018
2	Commercial Bessemer Steel.	0·160	0·640	0·007	0·056	0·069
3	Swedish Bessemer Steel.	0·165	0·310	0·017	0·019	0·022
4	Mild Steel Boiler Plate.	0·170	0·570	0·040	0·030	0·050
5	Best English Wrought Iron.	0·195*	0·005	0·086	0·011	0·054
6	Swedish Bessemer Steel.	0·206	0·290	0·009	0·016	0·020
6A	,, ,, ,,	0·170	0·100	0·021	0·012	0·013
7	,, ,, ,,	0·270	0·250	0·027	0·012	0·023
8	,, ,, ,,	0·414	0·320	0·036	0·012	0·017
8A	,, ,, ,,	0·446	0·370	0·058	0·012	0·028
9	,, ,, ,,	0·604	0·190	0·022	0·012	0·016
9A	,, ,, ,,	0·645	0·260	0·062	0·010	0·028
10	Boiler Plate supplied by Mr. Milton.	0·311	0·415	0·018	0·033	0·020

* *See* Dr. Stanton's further Note to the Discussion (page 1021).

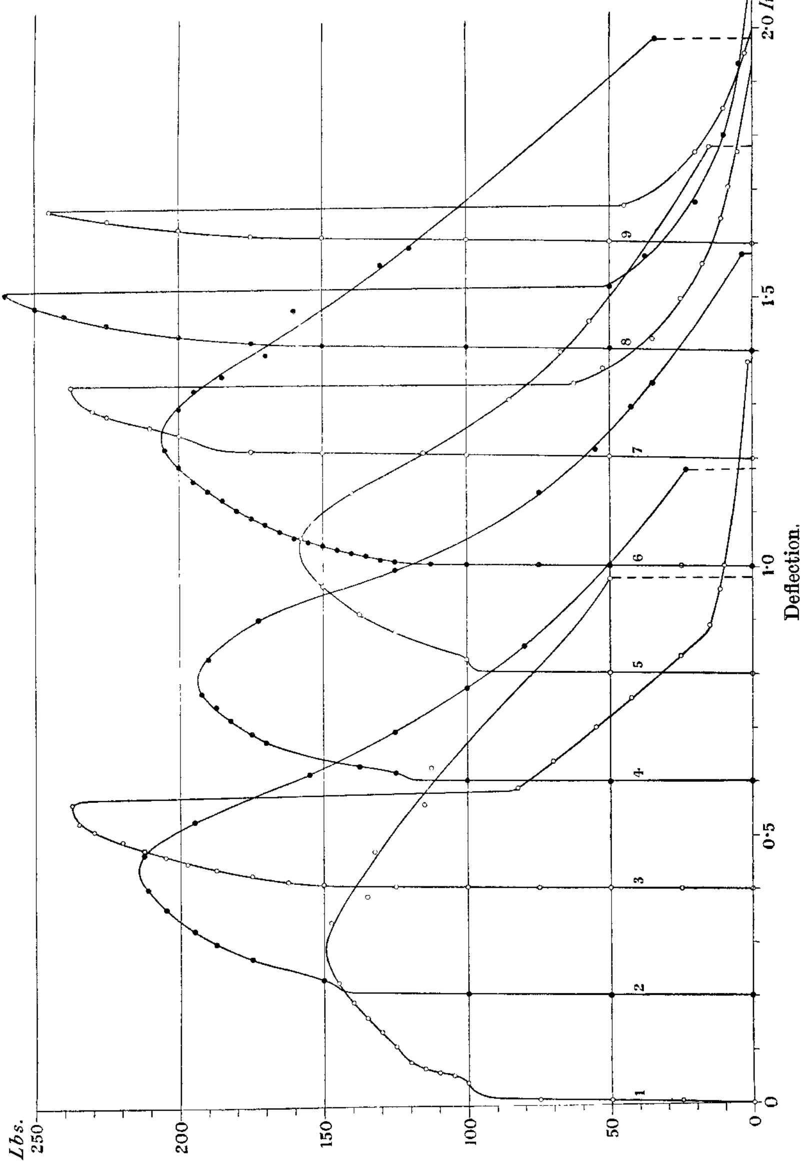
TABLE 2.

Tensile Tests of Materials Used.

Test No.	Tons per square inch.		Elongation on 2 inches.
	Yield-Point.	Maximum Load.	Per cent.
1	14·46	19·60	48·0
2	24·10	30·10	37·0
3	26·80	31·30	27·0
4	16·12	28·56	30·0
5	17·44	22·80	41·0
6	21·80	27·50	38·5
6A	23·78	28·53	32·0
7	30·55	37·00	28·0
8	31·90	41·10	24·5
8A	28·05	43·75	24·5
9	31·40	44·20	22 0
9A	29·10	47·60	20·5
10	16·35	31·00	34·0

FIG. 6.

Load-Deflection Diagrams, Static Tests on Notched Specimens.



Results of the Experiments.

Single-Blow Method.—Sets of specimens were prepared from the materials described above and tested in the Izod machine and the single-blow tensile impact tester. Exactly similar sets of specimens were then subjected to the static test in bending and direct tension, and the work done in fracture carefully estimated in each case, Fig. 6.

The results are stated in Table 3 (page 903), and for the purpose of comparison are also shown graphically in Figs. 7 and 8, in which the values of the energy are plotted on a carbon base.

Comparison of Impact and Static Tests. (Single-blow Method.)

Fig. 7.

Bending Notched Specimens.

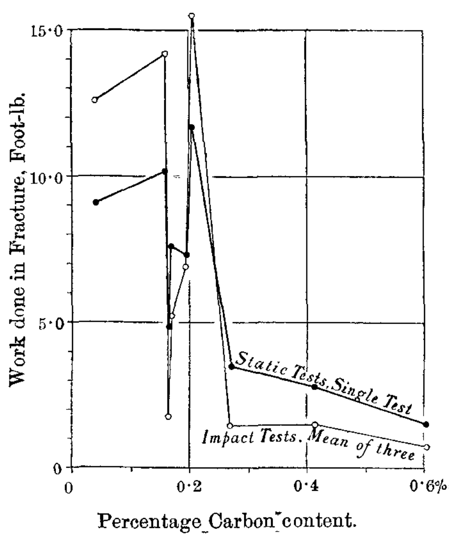
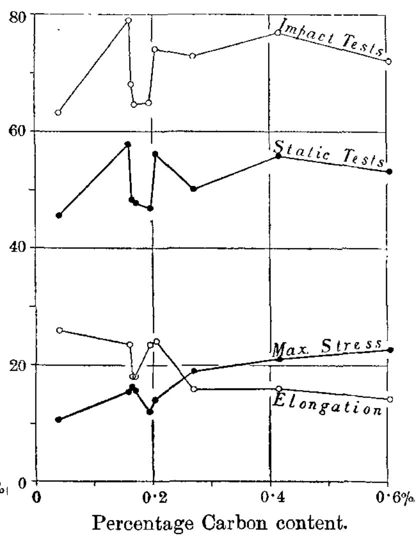


Fig. 8.

Tension Tests on Plain Specimens.



It will be noticed that, in the case of the tensile tests, the values of the energy absorbed in impact are well above the corresponding values of the work done in the static test. This is due to the loss of energy at the surfaces through which the force of the blow is transmitted and which was practically unavoidable, in order to secure the tensile effect of a blow. The most important feature of the curves is the remarkable similarity which is seen to exist between the impact test and the static test, both for the direct tensile tests on plain specimens and for the bending tests on notched specimens.

The static tests on the notched specimens presented so many difficulties that a marked agreement was hardly to be expected, especially in the cases of the low-resistance specimens; but the chief characteristics of the impact curves are reproduced so faithfully in the static-test curves, that there seems no reason to doubt that more refined methods of observation would yield results which would make the curves identical for the moderate velocities of impact here used.

The conclusion which the authors arrive at from these tests is that there is no source of weakness brought out by single-blow impact tests on plain or notched specimens which is not revealed by a careful static test.

This is in accordance with the results of the previous experiments of Professor Hatt,* of Purdue University and of Mons. Pierre Breuil,† of the Conservatoire des Arts et Métiers, Paris.

TABLE 3.

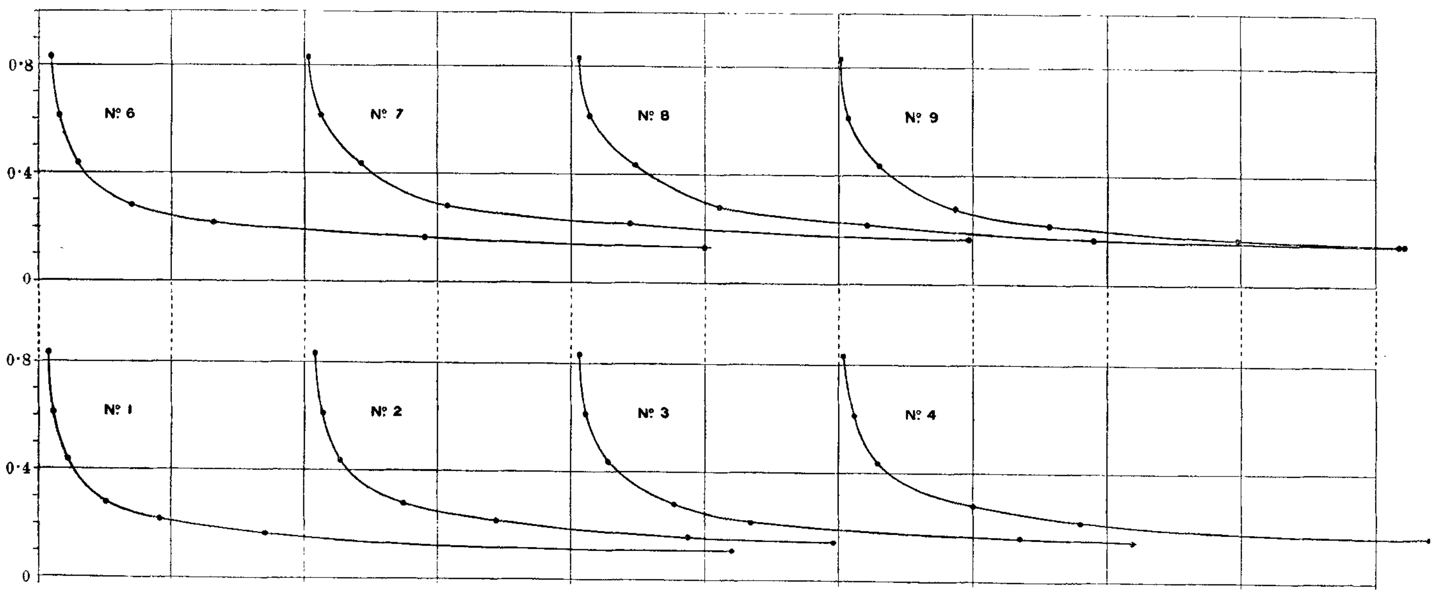
Single-Blow Method.				
Bending of Notched Specimens.			Tension of Plain Specimens.	
Material.	Energy absorbed in Impact. (Izod Test.)	Work done in Static Test.	Energy absorbed in Impact.	Work done in Static Test.
	Ft.-lb.	Ft.-lb.	Ft.-lb.	Ft.-lb.
1	12·6	9·1	63·2	45·6
2	14·2	10·2	79·0	57·9
3	1·8	4·8	68·1	48·3
4	5·2	7·6	64·7	47·8
5	6·9	7·3	64·9	46·9
6	15·5	11·7	74·1	56·2
7	1·4	3·5	72·9	50·2
8	1·5	2·8	76·9	55·8
9	0·8	1·5	72·1	53·4

* "Tensile Impact Tests of Metals." Proceedings, American Society for Testing Materials. Vol. 4. 1904.

† Journal, Iron and Steel Institute. Supplement to vol. LXV, 1904.

FIG. 9.

Bending-Impact Tests, Comparison of Results for varying Number of Blows.



Distance between vertical lines represents 10,000 Blows.

Many-Blow Method.

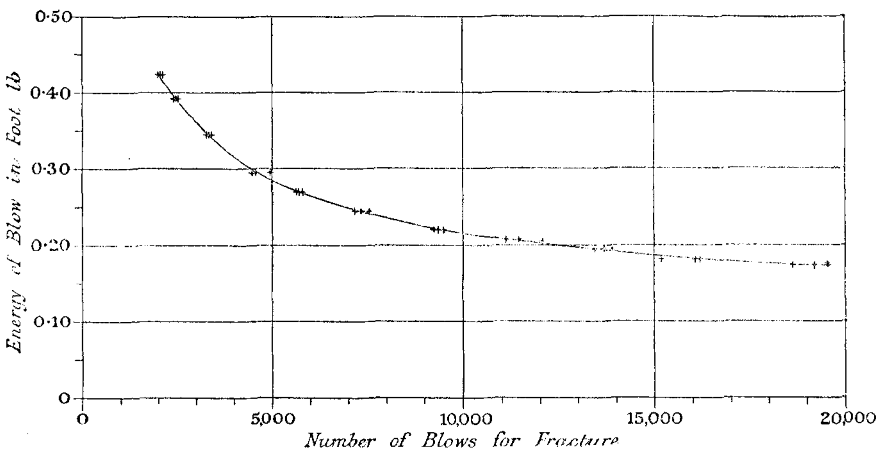
(1) *Bending-Impact Tests on notched specimens.*

(*a*) *Comparison of Results for varying Number of Blows.*—For this purpose sets of seven specimens were prepared from each of the materials, and were tested in the Repeated-Bending Impact Tester. The variation in the number of blows for fracture was made by varying the fall of the tup, whose weight was kept constant for this set of observations.

Fig. 10.

Bending-Impact Tests on Notched Specimens all prepared from one Bar of Mild Steel.

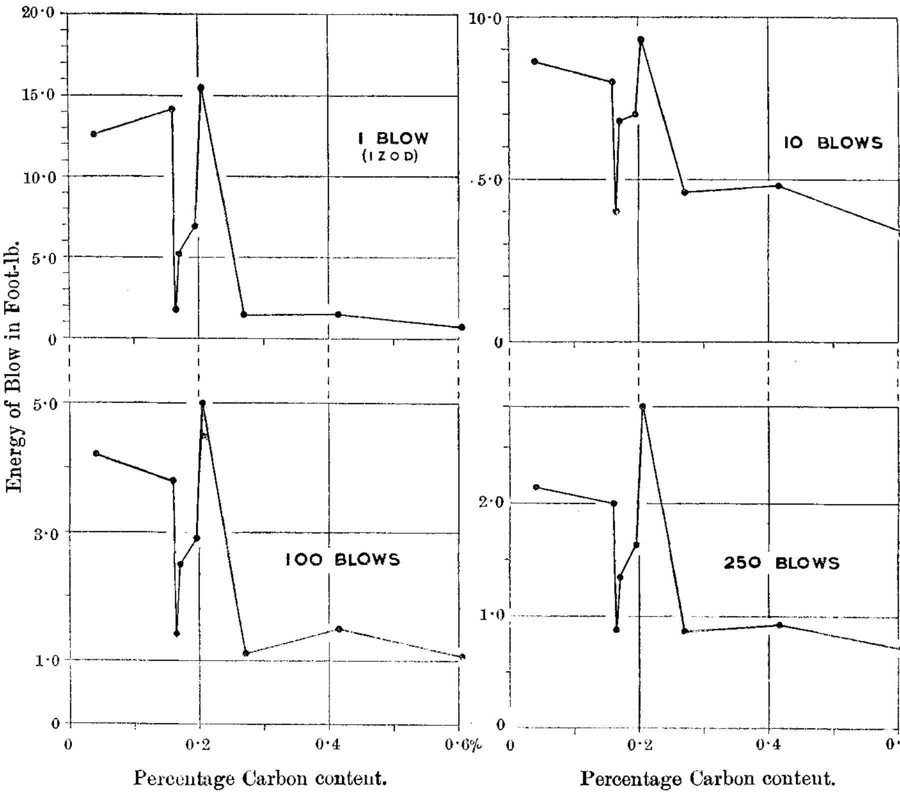
3 Tests at each setting of tup.



The results are plotted in Fig. 9, which shows the curves, co-ordinating height of fall of tup, and number of blows for fracture for each material. The remarkable uniformity of the results will be evident from the distribution of the dots about the curves of mean position, and throughout the work it was found that these tests could be repeated with only small deviations in the number of blows per fracture, which rarely exceeded 3 per cent. This is in marked contrast to results obtained in previous experiments in which the reversal was not performed mechanically. A further proof of the uniformity of the results obtained by this method is shown in Fig. 10 (page 905), in which are plotted the results of the tests on 30 specimens all cut from the same bar of ordinary mild steel. Three specimens were tested at each setting of the tup, and in only

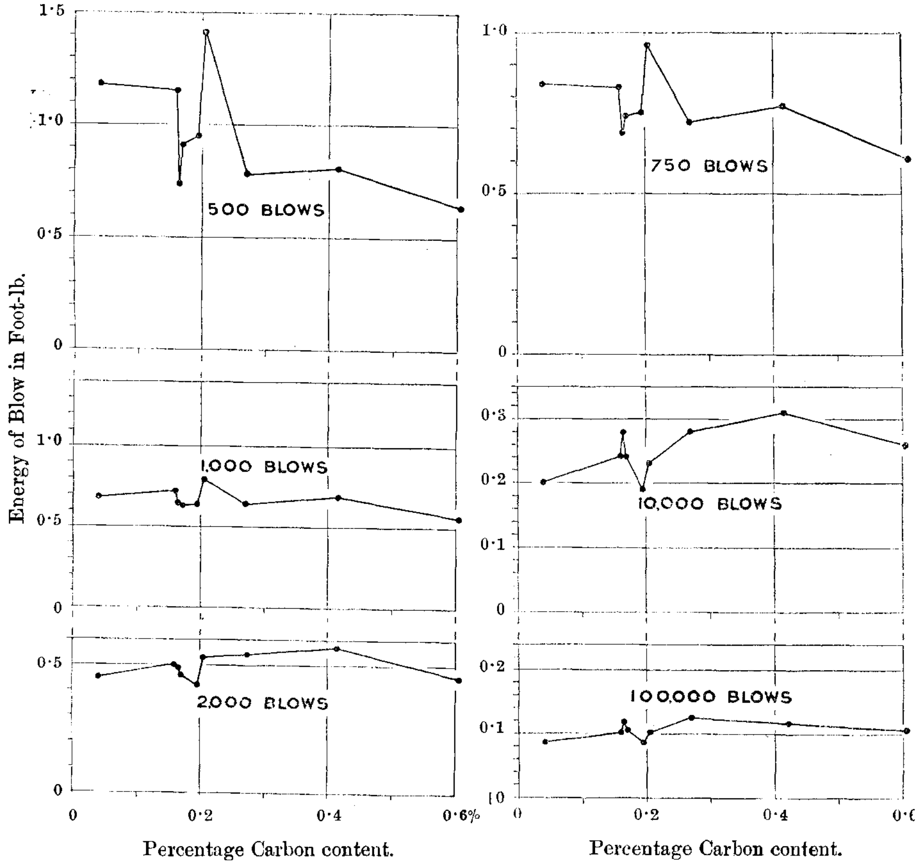
FIG. 11 *(continued on opposite page)*.

Bending-Impact Tests on Notched Specimens.



one case did the number of blows for fracture differ from the mean of the three tests by more than 3 per cent. As the curves in Fig. 9 are not very suitable for comparison with each other, a graphic method has been adopted by means of which the relative energies of the blows required to fracture the materials after a given number of blows is clearly indicated. For this purpose the number of blows for fracture after 10, 100, 250, 500, 750, 1,000, 10,000 and 100,000 blows respectively has been scaled

FIG. 11 *(concluded from opposite page).*
Bending-Impact Tests on Notched Specimens.



off from the curves in Fig. 9, and for each of these cases a curve co-ordinating energy of blow and carbon content has been plotted.

These curves, together with the one showing the results obtained by the one-blow method in the Izod Tester, are given in Fig. 11.

On examination it will be seen that the characteristics of the curve for the one-blow method are practically the same as those obtained in the many-blow method when the number of blows for fracture is not considerable, as has been previously pointed out by Mr. Izod.* Thus the curves for 1, 10, 100, 250, 500 and 750 blows agree in giving a relatively high value of resistance for No. 6 material, and a relatively low value for No. 3 material. As, however, the number of blows for fracture increases, the elastic resistances, which was inappreciable in resisting a heavy blow, become more and more apparent, as is seen in the increased resistance of the higher carbon steels. This factor grows in importance, until at 10,000 blows the characteristics of the one-blow curve are practically reversed, a peak in one curve corresponding to a depression in the other.

(*b*) *The Limiting Resistances of the Materials.*—It was hoped that, by increasing the number of blows for fracture in this way, it would be possible to arrive at a limiting blow under which the material would not develop a crack, but it was found that even after a million blows this limiting resistance was not nearly reached. This experience seems to be in agreement with that of Wöhler in the similar case of the fatigue of bars under alternating bending stresses, and to be in contrast to the case of direct alternating stresses on which the limiting resistance is reached in about one million reversals. Another method of predicting the limiting resistance was therefore adopted. This consisted of subjecting the specimen to a fairly large number of blows—420,000—after which a section was made across the notch on the plane of bending, which was polished and etched and then examined to see if a crack had commenced. If so, its depth was measured and another specimen of the same material tested for 420,000 blows with a slightly less fall of tup, and was then cut up and examined microscopically. In this way, by making a sufficient number of tests, a curve co-ordinating depth of crack and fall of tup could be plotted, and as the least fall observed corresponded to a depth of crack of approximately four-thousandths of an inch in depth, only a slight

* Proceedings, 1904, Part 4, page 1213.

extension of the curve was necessary to predict the limiting fall for no crack. Owing to the length of time required for this part of the work, these limits were only attained for four materials, which were specially chosen because their limiting ranges of stress were known from the authors' previous experiments on alternating stresses, which enabled a calculation to be made of their respective proof resiliencies. The curves for these materials are shown in Fig. 12 (page 910), from which the limiting values of the energy may be scaled off. Now, the theoretical proof resilience or maximum work per unit volume which can be stored up in any material under direct or bending stresses within the elastic limit is proportional to

$$\frac{f^2}{E}$$

where f is the real elastic limit of the material;
E is Young's Modulus of Elasticity.

From the known values of f and E, derived from the authors' previous experiments, the values of the proof resiliences of the four materials chosen—which were a wrought-iron and steels of 0·2, 0·4 and 0·6 per cent. carbon content—are respectively as:—

1 : 0·92 : 2·5 : 2·7.

The limiting values of the energy of blow scaled off from the curves in Fig. 12 are as:—

1 : 0·92 : 1·3 : 1·5,

being 0·026, 0·024, 0·033, 0·038 foot-lb. respectively.

It will be noticed that, although the experimental resiliences increase in the same order as the theoretical ones, the ratio of the highest to the least of these quantities is considerably greater theoretically than that found by experiment. The authors think it possible that this discrepancy is due to the extreme difficulty in detecting a crack which has only extended two or three thousandths of an inch into the specimen, which was a difficulty in distinguishing between a crack and a boundary between crystalline grains.

2. *Direct Impact-Tests on plain turned specimens.*

(*a*) *Comparison of the Resistances.*—Owing to the relatively slow speed of the direct-impact tester, it was not found practicable to

FIG. 12.

Prediction of Limiting Resistance during Bending-Impact Tests.

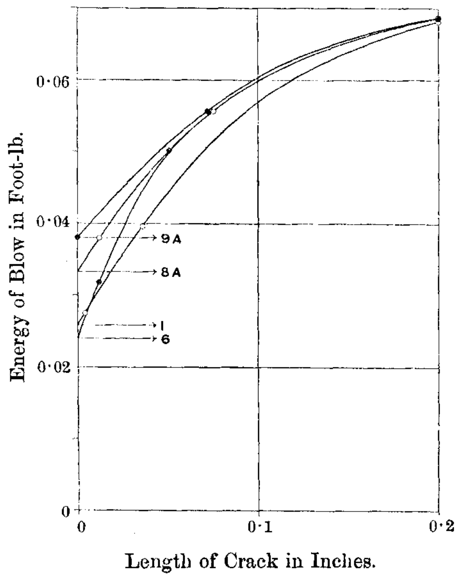
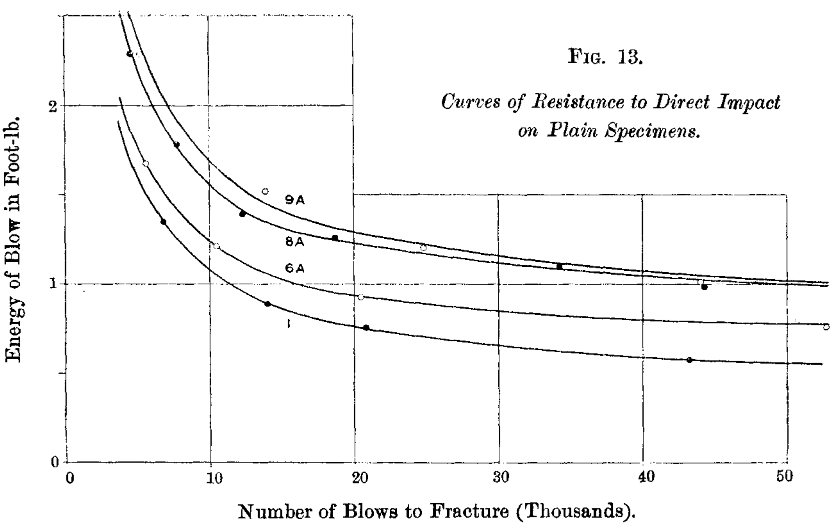


FIG. 13.

Curves of Resistance to Direct Impact on Plain Specimens.



carry out endurance tests with a greater number of blows than 50,000. Tests within this limit have been made on the same materials as those chosen for the prediction of the limiting resistance in the repeated-bending impact tester, that is, a wrought-iron and three Swedish Bessemer steels of 0·2, 0·4, and 0·6 carbon content.

The curves co-ordinating energy of fall of striking tup and number of reversals for fracture are shown in Fig. 13. The general features of these curves are similar to those obtained from the same materials under gradually applied alternating stresses, and the resistances increase in the same order. From a study of these curves there does not seem any reason for doubting that the limiting resistances are in agreement with those found from the bending impact tests on notched specimens.

(*b*) *The Changes in the Microstructure of Materials due to Impact.*—The changes which occur in the crystalline structure of strained materials have already been studied in various researches, since their original investigation by Ewing and Rosenhain. In the present work the observations made by the authors on materials subject to direct alternating stresses have been extended to the case of materials subject to repeated tension and compression due to impact. Although the microscopic study of lines of fracture due to impact has received considerable attention,* the development of slip lines due to repeated impact has not been previously investigated, so far as the authors are aware.

The specimens were of the same dimensions as the standard form for the direct impact tester, Fig. 5 (page 897), except that they were slightly tapered towards the centre in order to localize the strained region as much as possible. A narrow flat was then made on the surface parallel to the axis. This surface was polished and etched and subjected to alternate blows in tension and compression in the machine, being periodically removed for microscopical examination. The first material used was Swedish iron which had been heated to

* Proceedings, 1904, Part 4, page 1135.

1,000° C. (1,832° F.), and then cooled slowly. Figs. 14, 15, and 16, Plate 29, show three photographs of the surface of a specimen of this material, taken at intervals during the progress of a test. In Fig. 14 a set of slip lines running diagonally across the crystal have developed after 8,400 blows, half in tension and half in compression. In Fig. 15, which is a photograph taken after 12,000 blows, a second set of slip lines are seen to have developed approximately at right angles to the first, and in Fig. 16 is seen a still further development of these lines after 29,000 blows. The specimen eventually broke outside the field photographed. Fig. 17 shows a photograph of a specimen of 0·6 per cent. carbon steel which has been heated to 1,000° C. and slowly cooled, and tested as in the previous cases. It will be seen that the line of development of the crack unmistakably takes a path through the ferrite of the section, whereas in Fig. 18 the crack passes chiefly through the pearlite. As was pointed out in the Paper on alternating stresses, the surface does not definitely indicate which of the two constituents is chiefly concerned in the fracture of the material, although the greatest number of observations seem to point to the ferrite as the weak constituent.

In each of the preceding cases the repolishing and re-etching of the specimen would have removed all trace of the strain, as the lines had not developed into definite cracks. When, however, a specimen was broken by a sharp blow, a series of lines, or rather narrow bands, appeared which had quite different characteristics. Fig. 19 shows a photograph of these bands in a sample of Swedish iron. The specimen was notched and then fractured by a hammer blow. One piece was then polished and etched with the result shown. The main series of bands runs across the photograph from left to right in parallel lines. Traces of two other sets are also visible, one approximately at right angles to the first and the other inclined at about 30° from left to right. Many of these will be seen to consist of double lines, and under high magnification show as narrow bands. The bands are not visible before etching, and are not eliminated by repolishing and re-etching, this distinguishing them from "slip lines."

These bands have been described by Messrs. Osmond, Frémont and Cartaud,* under the name of "Neumann" lines, and are evidently intimately connected with the crystalline structure, and are probably due to molecular changes along cleavage planes throughout the whole crystal. These lines do not seem to have been found except when the specimen has been fractured under impact, with rupture in a very small number of blows.

On the other hand, when failure occurred under fatigue, the cracks resulted from the development of the "slip lines," and the process was the same under impact as under gradually applied alternating stress.

The Effect of the Dimensions of the Specimen.—In the discussion on Messrs. Seaton and Jude's Paper, the great desirability of discovering an impact test, the results of which should be independent of the dimensions of the specimen, was pointed out by several speakers.

As the results on the standard form of specimen in the bending-impact machine could be repeated with considerable accuracy, the authors made a series of experiments to determine to what extent these results could be repeated on specimens of different sizes.

From some preliminary experiments it was found that the number of blows for fracture with a given fall of tup—

(1) was practically independent of the sharpness of the V notch, when the number of repetitions of the blow for fracture was large;

(2) depended on the ratio of the diameter at the bottom of the notch to that of the body of the specimen;

(3) depended on the distance between the knife-edges.

The effect of the notch was observed by testing two similar specimens of the same material, one having a very sharp notch and the other a rounded one, when it was found that the number of blows for fracture was practically the same for each when the total number of blows was about 10,000.

For the second and most important determination three forms of specimen were used, each having the same span and diameter

* Revue de Métallurgie, January 1904.

at the bottom (0·40 inch) of the notch, the body diameters being :—

0·706 inch, 0·50 inch, and 0·40 inch.

From observations made on these it was found that the respective energies of the blows to break them after 10,000 blows were :—

0·175, 0·275, and 0·55 foot-pound ;

so that, per cubic inch of the material, and for the above number of blows, the specimen reduced in diameter to the value at the bottom of the notch is nine times stronger than the one with the largest diameter.

Further, as was to be expected, the resistance of the specimens diminished as the distance between the knife-edges increased.

These observations appeared to indicate that, to obtain the same results from specimens of varying size, they should be geometrically similar in form.

To test this conclusion, a series of experiments have been made on sets of specimens in which the ratio of the linear dimensions to those of the standard form was

$$1 : \sqrt{2}$$

and in order to make the conditions as dynamically similar as possible, the weight of the tup was reduced to the ratio

$$1 : 2\sqrt{2}$$

so that with the same height of fall, or velocity of striking, the energy of the tup per cubic inch of the specimen was the same as in the tests on the standard form. The results in tests of over 3,000 blows show that the resistance of the smaller specimens is somewhat higher than that of the standard form, but it is probable that, with the more refined experiments now in progress, the agreement will be found to be very close.

The Many-Blow Method applied to Brittle or Faulty Materials.—Although the investigation of the failure of faulty or brittle material under impact forms no part of the present work, this question is of such fundamental importance in impact testing that the authors have considered that the results of the methods here described on one or two typical cases of abnormal material would be of interest. For this purpose a sample of presumably faulty material has been kindly given to the Laboratory by Mr. J. T. Milton. This was a piece of boiler-plate 1 inch thick cut from a single-ended boiler 11 feet 6 inches diameter, 13 feet long, which, on being prepared for a test of 300 lbs. per square inch to meet the rules of Lloyd's Register, gave out by rupturing nearly from end to end at a pressure of 270 lbs. per square inch.* For the tests on a brittle material the authors produced some specimens by hammering some ordinary mild steel bar at a low red heat initially until nearly cold, in the manner described by Mr. Ridsdale in his Paper on the production of brittleness in soft steel.† This hammered steel had somewhat remarkable qualities, as the mechanical work put on it raised its maximum stress from 27·3 tons per square inch to 46·0 tons per square inch, and its elastic limit in tension from 18·0 to 26·0 tons per square inch. Its resistance to impact by the single-blow method when notched was exceedingly low, showing a crystalline fracture throughout, but it could be bent cold and doubled over on itself without showing the least signs of fracture.

Tests on notched specimens of these materials were made in the bending-impact tester, and the results are shown in the curves of Fig. 21 (page 916), together with the curves given by samples cut from an ordinary piece of boiler-plate for comparison.

It will be seen that the brittle specimens, although having a very low endurance for comparatively heavy blows, have remarkable endurance for lighter blows, being considerably tougher under this action than the untreated material from which they were prepared.

This characteristic is not evident in the tests of the faulty boiler plate, as the curve for it lies everywhere well below that of ordinary plate. The difference is also well marked in tests made on the two plates in the Izod tester, in which the work absorbed by the faulty plate specimens varied from 2 to 3 foot-pounds, whereas that absorbed by the ordinary plate was from 5 to 6 foot-pounds.

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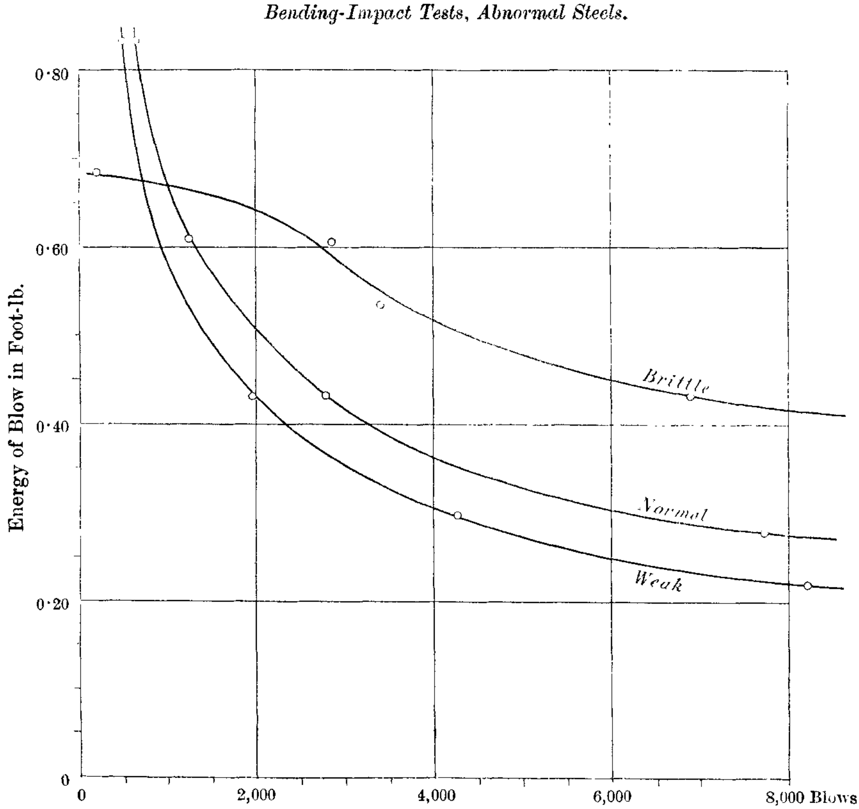
* Full details of this plate are given in a Paper by Mr. Milton at The Institution of Naval Architects. 1905, vol. XLVII, Part 2, page 358.

† Journal, Iron and Steel Institute, 1898, vol. I, page 220.

The marked feature of this piece of boiler-plate seems to be the very low value of the elastic limit when taken by a very sensitive extensometer. Using a Marten's Mirror Extensometer, the elastic limit of the faulty plate was found to be 8·8 tons per square inch.

FIG. 21.

Bending-Impact Tests, Abnormal Steels.



General Conclusions.—The general results of the experiments described in this Paper prove, in the opinion of the authors, that for the detection of two important faults in materials, that is, brittleness and low elastic resistance, two distinct tests are necessary, according as a weakness in plastic resistance or in elastic resistance is to be revealed. The distinction between the tests to be applied will be appreciated from the consideration that for the former case an expenditure of energy is necessary, which is approximately three hundred times greater than that required for the latter.

The authors are of opinion that conclusive evidence has been shown that materials which are strong under alternating stresses are in general strong under those shocks which are likely to be put upon them in ordinary machine practice, and not weaker as seems to be commonly supposed.*

As regards the general methods of impact testing, the bending test on a notched bar seems to be the most searching and the easiest to be made. As the detection of brittleness in steel is of supreme importance, the one-blow method would be naturally the one most used, but for the study of the constructional value of a material its resistance to impact should be investigated, not at one point of the curve, but throughout a considerable range. To do this some form of impact tester should be used in which the energy of the blow can be varied, and the specimen rotated mechanically. By a series of tests under varying strengths of blow, valuable information can be obtained and the results correlated to those given by other methods.

As an example of this, the case of two copper-aluminium alloys which formed part of a series in Messrs. Carpenter and Edwards' Report to this Institution in January 1907, may be taken. The two chosen are those containing 9·9 per cent. and 7·4 per cent. of aluminium respectively.

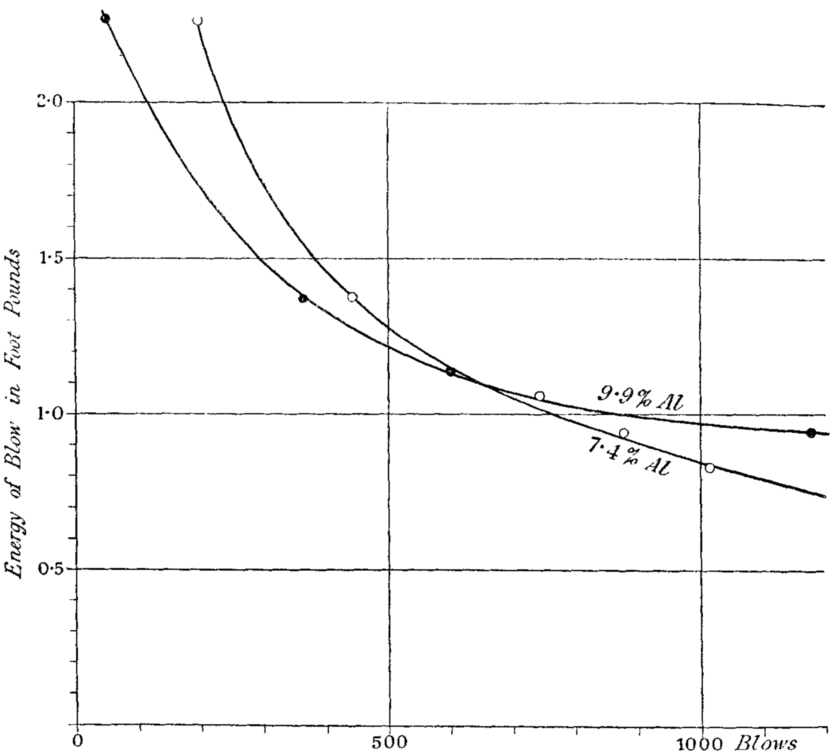
Specimens of these were tested in the bending-impact tester, and the results are given in the curves of Fig. 22 (page 918). On examination, it will be seen that these curves give practically all the information on the relative resistances to shock and alternating stress of those two materials which were given in the Paper. Thus the upper limits of the curves tend to the relative values given by the Izod test, the lower limits to those given by the alternating direct-stress

* Proceedings, 1904, Part 4, page 1135.

testing machine, and further the relative values of the number of shocks for fracture with a blow of 2·0 foot-pounds agree with those determined by Professor Arnold in his alternating-bending machine. Again, it was found that the limiting resistance of the 9·9 per cent. aluminium alloy, as determined in the bending-impact tester, was

FIG. 22.

Bending-Impact Tests, Copper-Aluminium Alloys.



approximately $2\frac{1}{2}$ times greater than that of a similar specimen of 0·4 per cent. carbon steel. Now the limiting values of the stress in alternating tension and compression for these two materials have been found to be approximately the same, so that the difference in impact resistance must be sought for in the respective values of the modulus of elasticity. These were found to be :—

0·4 per cent. carbon steel	.	30,000,000 lbs. per square inch.
9·9 „ „ aluminium alloy	.	13,500,000 „ „ „ „

The ratio of which is 2·2, so that the ratio of the impact resistances is approximately that of the respective values of

$$\frac{f^2}{E}$$

where f is the limiting stress and E the values of the modulus of elasticity.

This agreement between relative values of impact resistance and relative values of the proof resilience, as given by

$$\frac{1}{2}\frac{f^2}{E} \text{ per unit volume,}$$

has been so marked in all these experiments that the authors cannot agree with Messrs. Seaton and Jude's conclusion that the "common interpretation of resilience has failed in its practical application," but, on the contrary, believe it to be the best guide for the designer in the use of normal materials, of which the real elastic limits are known.

The experiments further showed that steel was a much more homogeneous material than it had been recently suspected to be, because, if this had not been the case, it would have been impossible to repeat so accurately the bending-impact tests on a notched bar which were admittedly the most crucial mechanical tests of want of homogeneity.

In conclusion, the authors beg to thank the Director of the Laboratory for the facilities he has afforded for carrying out the work, and the interest he has shown in the progress of the research.

The Paper is illustrated by Plate 29, 15 Figs. in the letterpress, and Tables 1 to 3.

[*The Discussion on this Paper was combined with that on Mr. Harbord's Paper, and commences on page* 974.]

Fig. 14. *After 8,400 Blows.*

Fig. 15. *After 12,000 Blows.*

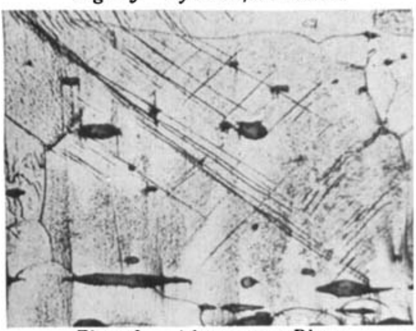


Fig. 16. *After 29,000 Blows.*

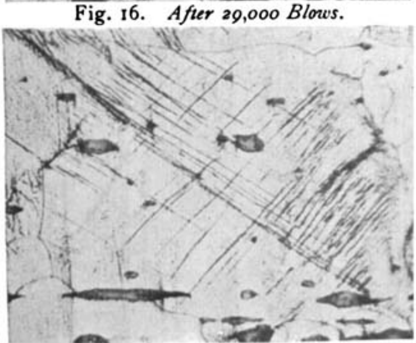


Fig. 17. *After 5,000 Blows.*

Fig. 18. *After 19.000 Blows.*

Fig. 19. *Swedish Iron, Fractured at 1 Blow.*

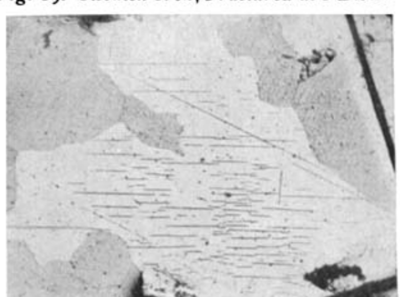
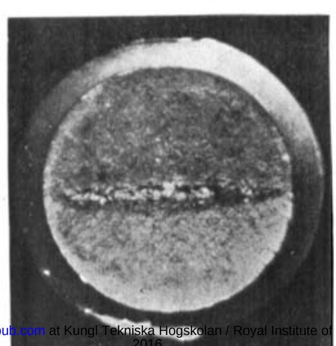


Fig. 20. *Mild Steel* (0·20 % *C*) *after* 50,000 *Blows.*



Figs. 14, 15 and 16.
Swedish Iron, heated to 1,000°C. (1,832° F.) and slowly cooled.

Figs. 17 *and* 18.
0·6 % Carbon Steel, heated to 1,000°C. and slowly cooled.

Magnification.
Figs. 14 *to* 18. = *100 diams.*

Fig. 19. = *33 diams.*

Fig. 20. = *3 diams.*