Some Experiments on The Effect of Repeated Stresses on Materials.

Paper read by Professor F C Lea, D Sc , M Inst C E , M I Mech E , before the Institution in the Lecture Room of the Junior Institution of Engineers, 39, Victoria Street, London, S W 1, on 13th January, 1927 Dr A P Thurston, D Sc , M B E , F R Ae S , M I A E , etc (Honours Member), in the Chair

IN introducing the lecturer, Dr Thurston said Professor Lea is a distinguished engineer and professor of engineering, very well known both in aeronautics and in the world of general engineering He is a Whitworth Scholar, the first, or one of the first Doctors of Science (Engineering) in the University of London, and the author of many valuable researches During the war he was responsible for many researches of great value to the nation, not only in the design of aeroplanes as a whole, but also in construction of metal parts and fittings Professor Lea's activities have been so numerous that it is difficult to give a brief summary of his life work in a few sentences, but we may be sure of this—that the paper which he will give us to-night will add to his already great reputation, and at the same time be a most valuable contribution to our own Proceedings I now have pleasure in calling upon Professor Lea to read us his paper

Professor F C Lea A very large amount of data on the effect of repetition stresses has been gathered during the last ten years , and it can truly be said that the development of aircraft during that period and the difficulties that have had to be faced and only partly overcome have given a remarkable impetus to the study of this important subject

The time that has been available to write this paper, sandwiched as it has been with many other activities, has made it possible to refer only to certain parts of the subject, and that very incompletely The sequence will rather reveal the bigness of the subject than finality

It would take a very large proportion of the space available to refer to the published work in this and other countries, and the author does not propose, therefore, to deal with the bibliography of the subject This decision, however, seems to demand some apology to the many workers who have made contributions to the subject and particularly it would appear ungracious to Gough, Griffiths, Haigh, Hankin, Hanson, Jenkin, Mason, and others in this country, to Jasper, McAdam, Moore, and others in the U S A , not to mention workers on the continent of Europe and in Japan

During the war in co-operation with Commander Jenkin the author was led to carry out repetition stress experiments on *aluminium alloys for aircraft, including duralumin and the cast alloys for engine parts, and to consider problems that arose in connection with fractures under repeated stresses of springs, crank shafts and other engine elements

Several points arose out of those early experiments, which have been much more closely followed up by the post war work These tests have shown (1) that with certain materials the range of repetition stress did not appear to have any definite relationship with the primitive elastic limit of the material, as then defined, or to be more accurate with the primitive limit of proportionality and that specimens would resist ranges of stress much greater than the apparent proportional range for very many millions of repetitions

(2) †The number of repetitions which would be resisted by a specimen for certain ranges of stress depended upon what might be called the path of loading, or in other words the range of stress could be considerably raised by gradually raising the applied stress while the specimen was going through cycles of stress The author was able to show later that a mild steel specimen could, by gradual loading, be made to resist for 20 million repetitions, a range of stress 25 per cent greater than the range that would break it in less than 13,000 repetitions, if applied at once to the specimen

(3) That even cast alloys could be run for more than 250 million repetitions without fracture providing that the range of stress was below a certain amount Subsequent experiments have shown that very many more than 250 million repetitions can be applied

(4) Changes of form, or discontinuities of section were of some importance and that ranges of stress at such discontinuities, less than those at other more favourable parts of the specimen might cause fracture Subsequent work by Thomas and others since the war has shown that the lowering of the range is not nearly so great as would appear to be indicated by the Elastic experiments of Coker, and by the theoretical analyses of Griffiths, Southwell and Gough

(5) That the safe range of stress for a given material could not safely be implied from short runs of from 1 million to 3 million repetitions but that fractures after from 10 to 15 million repetitions probably gave the range within a very few per cent of the safe range

(6) Tests were run at speeds ranging from 1,000 to 4,000 repetitions per minute on the Wohler type of machine and these indicated that the safe range was not much affected by speeds within these limits at ordinary temperatures Subsequent work has shown that at high temperatures the rate is very important and Jenkin has shown that even at ordinary temperatures when the number of repetitions per minute is very high, or of the order of thousands per second, the range of repetition stress is higher than at the lower speeds The Wohler type of machine gives results agreeing fairly well with those from the Haigh machine, especially if the Wohler specimens are hollow

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* Materials for Aircraft Jenkin Proc Royal Aeronautical Society, 1919

† Loc Cit and Engineering, Feb , 1923

(7) Following, as it subsequently transpired, the methods used by Smith, Mason and Gough, attempts were made to draw load-strain diagrams for specimens subjected to repeated stresses These soon indicated that for normalised mild steel the load strain curves showed deviation from proportionality at stresses very close to those which would cause fracture at between 50 and 90 million repetitions, but for other materials, cold drawn steels and brasses, quenched and tempered steels and alloy steels it was very difficult to determine the fatigue range from such curves A great deal of work, to be referred to later, has been done upon this point both on the Wohler type of machine and in the beautiful machine designed by Haigh, but it can hardly be said that except for certain special materials, reliable fatigue ranges can be obtained by this method

(8) The effect of vibrations upon the fatigue range may be serious and small blows may cause fracture at comparatively low fatigue ranges It, however, transpired even with a material like duralumin, that a specimen could run at a high speed such as, for example, 4,000 revolutions per minute, with a certain amonnt of vibration and the range of repetition stress for more than 10 million repetitions would still be, say, 80 per cent of the range for the most perfect conditions

Turning for a moment from the experimental side to the practical side very many anomalous causes of fracture, viewed in the light of these experiments, have been brought to the author's notice, and no doubt such is a common experience

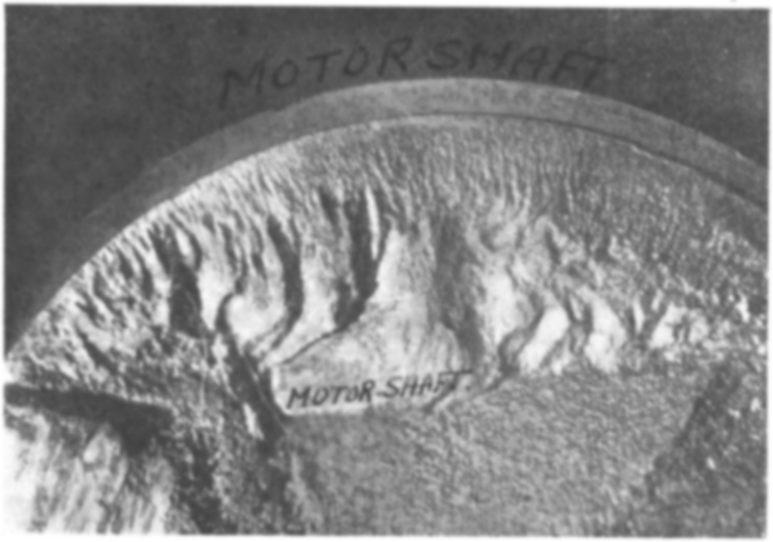

FIG 1

Fig 1 shows a fractured motor shaft which broke at the bottom of a thread The motor drove a pump from an overhanging pulley and no doubt there was some shock, during driving, in fact much more than in any of the cyclical experiments which are generally carried out or which are referred to under the headings 1 to 8 The stresses calculated by the ordinary theories of torsion and bending were very much lower than those which the results given in published data would indicate as safe ranges for this material, even allowing for the rather sharp angle at the bottom of the thread

A microscopical examination of the structure of the material, however, showed that it was " large grained " and an Izod test showed that, although the elongation per cent and tensile strength were about the same as those from another piece of mild steel of finer grain, the impact factor of the standard specimen was only 22 lb ft , as compared with 88 lb ft , for the fine grained material In the light of experiments which the author has carried out on materials of very variable Izod factors it is clear that the low impact factor would not be serious for small, up to say, one million blows, although it of course would for a large blow

Another example to which the author's attention was drawn recently is of a railway axle which was found cracked within the wheel, but it had not broken It was subsequently fractured There was evidence of fatigue failure, as shown by the smooth fracture to within 1 inch of the surface, but the axle did not actually break in service The stresses calculated in the ordinary way were again very much smaller than might have been expected to produce fracture in this steel, but the nature of the blows to which it had been subjected as it passed over rail joints, points and crossing, etc , could not be known An interesting point about the axle, however, was that careful measurement showed that there was every probability that near where the fracture started the grip of the wheel upon the axle was exceptionally tight Figs 17 and 18 show tubes that have been subjected to repetition stresses and held in collets The stresses during the test at the reduced section of the tube were in some cases 100 per cent greater than at the section where the fracture occurred The sudden discontinuity apparently was a very important contributory cause of the failure A remarkable case is referred to later in which a copper alloy specimen held in a collet, was run for 565 million repetitions at a range of stress of 10 1 tons per square inch in the reduced part of the specimen After 565 millions the load was raised so that the range of stress in the reduced section was 12 24 tons per square inch After a further 37 11 million repetitions the specimen broke just in the collet where the range of stress, as calculated from the bending moment, was only 8 tons per square inch The appearance of the fracture suggested that it had been probably cracked for quite a long time and that at the time of fracture the range of stress was no doubt much greater than 8 tons per square inch These cases, which could be supplemented by many others, are mentioned to show that the problem of repetition stresses is far more involved than a mere determination of the ranges of stress obtained from ideal laboratory conditions and that the rather abnormal conditions that may occasionally occur have an all important bearing upon the probable life of a specimen In this respect consider the following tests Specimens of mild steel were subjected to a range of repetition stress by bending The safe range of stress for more than 10 million repetitions on a bending machine was ±15 3 tons per square inch, and for more than 70 million repetitions on the Haigh machine it was ±14 5 tons per square inch A steady torsional stress of 15 32 tons per square inch was simultaneously applied with a bending stress of 15 32 tons per square inch ; this had no effect upon the life of the specimen On applying a torsional stress of 26 2 tons per square inch the safe bending range of stress was, however, reduced to ± 11 tons per square inch

Here the conditions to determine failure seemed to be controlled The torsional stress of 26 2 tons per square inch, when continuously applied, apparently produces large torsional strains which will not allow the material to heal, or in other words produces molecular cracks These cracks apparently become the centres of failure, and the range of repetition stress is correspondingly lowered The torsional stress of 15 32 tons per square inch does not produce permanent cracks, and as the applied torsional stress does not affect either the range of shear stress or the range of normal stress on any plane, it would appear that a certain range of shear stress is necessary to produce failure, but that when a crack has once been produced, the actual shear stress at the crack, due to the applied repetition stresses is greater than the apparent stress, and a smaller range of applied stress will produce fracture There has been much talk about the effect of cracks but it has not been easy to get direct evidence of their being the cause of many failures ; they have been assumed as necessary This experiment does seem to give some quantitative value to the assumption On the other hand, the applied mean stress changes the principal stresses and it may be that the failure, when the mean stress is 26 2 tons per sq inch, occurs on a plane where the maximum stress is higher than on the plane normal to the axis, but on which the range of stress is not a maximum, This has been discussed briefly by the author in a recent paper * Tests to be referred to later give evidence of progressive molecular cracks being produced by torsional repetition stresses of certain ranges

Sufficient has already been said, if such were necessary, to show the difficulty of the problem and to indicate the desirability of a closer co-operation between the metallurgist, and the experiments in the laboratory and practice, particularly in the most careful examination possible not only of the actual fractures that occur, but of the exact conditions under which they occur Were the stresses of a simple or compound character, were they applied cyclically or suddenly ? Did the fracture occur at a discontinuity of any kind ? Had it probably originated at a sharp corner or sudden change of shape and if so were these essential features of the design ? Did it probably commence at a " metallurgical " flaw, where there was segregation and then discontinuity or at a blowhole, or did it commence at a point where boundaries of " large " crystals occurred in the material and in the plane of greatest stress ? The author has examined many fractures of machine parts in which it has been alleged that the working stresses were far less than the fatigue ranges obtained either from bending or torsional tests, or combinations of the two in the laboratories and which could apparently only be explained by an assumption of stresses produced by blows or by sharp scratches, or molecular

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* Brit Assoc 1924 *Engineering*, September, 1926

cracks, or metallurgical discontinuities, far greater than the assumed working stresses and it would appear therefore that as in other engineering work, the final answer to the many problems raised can only be found in the great laboratory of experience and by co-ordination of data from practice as carefully and precisely gathered as is generally expected in laboratory work

MACHINES USED TO DETERMINE THE FATIGUE RANGES OF MATERIALS

The types of machines used on tests on fatigue are fairly well known (1) In the common type of Wohler machine a specimen is subject to a bending moment and on any section each element passes through a cycle of stress from a maximum tension to a maximum compression during each revolution, the mean stress is zero (2) In the Haigh machine the specimen is subjected to similar cycles of stress, but the mean stress may be made of any value between the limits of the machine (3) In a type of machine recently described* by the author a rotating specimen is subjected to a constant bending moment cycle together with a torque (4) In other machines and devices specimens are subjected to cyclical torsional stresses, and in (5) cyclical torsional stresses are imposed upon any desired mean stress

The results to be obtained from all these types of machines have been discussed except those from (3) and (5) by many writers, and in many papers, and time and space here will only admit of rather special reference to some of them

Testing Materials in Torsion

Several types of machines have been used for testing materials in torsion under repeated stress In the Stromeyer machine, as used by Gough and others, a forced oscillation which can be varied in amplitude, but which for any particular test may be kept constant is impressed upon a specimen which is free to oscillate and which carries a mass having a known moment of inertia about the axis of the specimen

A crank OA, Fig 2, is made to oscillate through an angle θ by the connecting rod CA The specimen S is fixed by suitable collets to a horizontal shaft which can rotate freely in suitable bearings The mass M is fixed to the shaft and can be varied If the angle θ or θ_1 is measured, the torque on the shaft can be determined

The author and Mr Frank Heywood have designed a machine, Fig 2 (see *Engineering*, June, 1926), which is a modification of the Stromeyer machine, and which can be used for testing unmachined wires as well as other types of specimens The mass M can be varied, but in addition, the head stock carrying the bearing B has a degree of freedom in the direction of the axis of the specimen, and a variable speed motor makes it possible to oscillate the crank at such a speed that if desired, there is a node in the specimen, this can be so arranged that the mass oscillates through a very small angle θ_1, which can be accurately measured by a spot of light moving over a ground glass screen

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* Brit Assoc 1926 *Engineering*, August, 1926

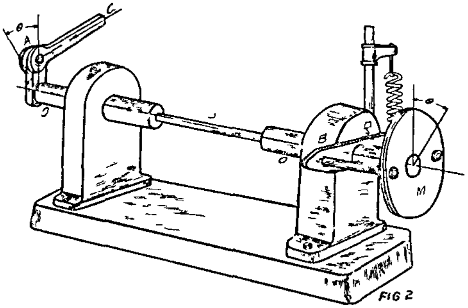

FIG 2

When the one end of the specimen is free, any mean stress desired can be impressed upon the specimen by means of a spring which, through a knife edge, pulls at an arm BD connected to the spindle 00_1 This arm oscillates through a very small angle and thus the pull in the spring only changes during a cycle by a very small amount Further the degree of freedom of B makes it possible to put any desired tension on the specimen

As an alternative the specimen can be fixed to the head stock when the node must be outside the specimen When the head stock is fixed, fractures in the case of wires, may take place in the collet By forcing a node between the collets the possibility of breaking away from the collet is increased The difficulty with any free oscillating mass machine is that when the range is above the fatigue range the angle of oscillation θ_1 alters as the test proceeds Thus the torque does not remain constant If it be assumed that the Modulus of Rigidity and the speed remain constant then the torque, or the assumed stress, can only remain constant if θ_1 remains constant, or if $\eta^2\theta_1$ remains constant, where η is the speed of the machine

The angle θ_1 can, however, be kept constant during any test by

(1) Altering the speed of the machine
(2) Altering the angular movement of the driving crank
(3) Altering the length of the specimen

The author has constructed a second machine in which the specimen at one end is fixed to a lever similar to Fig 2, but which can be so moved and fixed that any degree of initial strain, or if the Modulus of Ridigty is known, any degree of stress, can be imposed on the specimen To measure the applied torque a torque meter is placed in series with the specimen Time and space prevents further description of these machines

Both of the machines are driven by D C Motors and it is possible to alter the speed easily It is not difficult to alter the angular movement of the driving crank in the second machine, while in the machine in which a node is forced between the collets, it is easy to adjust the length of the specimen The adjustments (2) and (3) both require the machine to be stopped and this has been the weak point in torsional strain machines of the inertia type If they are left running for a time it is generally found that the angle of the oscillation of the free end has changed and an adjustment of the machine is required

In another type of torsional repetition machine, described by Moore and Jasper,* the specimen S is fixed perpendicular to a rotating axis To the specimen is connected an arm B which rotates also about the same axis , the free end of the arm rotates in a ball bearing which is attached to a spring or other loading device This has the advantage of keeping the torque practically constant during the cycle and during a test

Torsion-Strain Diagrams and the Fatigue Range

Since the angular displacements θ and θ_1, in the machines described for torsional tests are a measure of the torque and, on the assumption that the Modulus of Rigidity remains constant, they are a measure of the stress it would appear that a ready means may be available for determining a fatigue range from a torque-strain diagram This has been used by Gough and others The author finds, however, that the torque strain method, though giving an indication of the fatigue range, in certain cases requires great care and is tedious

It has been remarked that when a specimen is subjected to variable torque by means of an oscillating mass the amplitude of oscillation varies and adjustments of the machine are necessary It has been found that these adjustments are greater, the higher the range of stress applied to the specimen It might appear that the torsional rigidity of the material had altered and that the strain has consequently changed It is doubtful, however, whether the torsional rigidity does seriously change and if it did it might be expected to change quickly and after a very few cycles the change of amplitude would be seen , this is not generally the case On the other hand when the stresses are high the fatigue will progress comparatively rapidly and the outer layers of the material may, after a certain number of repetitions, become cracked Such cracks if they exist cannot generally be seen by the microscope The amplitude of the free end and the torque fall and the apparent stress at the outer layers of the specimen is diminished Fig 3 shows how the torque on a specimen may change with time, the torque being in this case proportional to $\eta^2\theta_1$ where η is the speed and θ_1 the angular twist of the oscillating mass As another illustration the following particulars of tests made for the author by

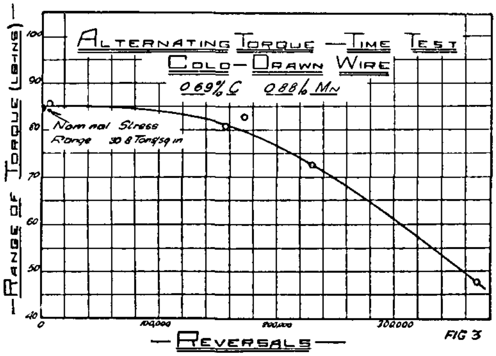

FIG 3

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* University of Illinois, Bulletin No 37, May 14th, 1923

Mr Jolley, are of interest A quenched and tempered wire was tested under torsional oscillations To keep $\eta^2\theta_1$ constant it was necessary to gradually change the length of the specimen by 0 255 inch , the original length was 2 21 inches , the range of stress was ±16 3 tons per square inch , the number of repetitions to fracture was 0 521 million A second specimen, 2 25 inches long, was subjected to a smaller torque and the length had to be changed by 0 16 inch to keep $\eta^2\theta_1$ constant , this broke after 1,062,000 oscillations , the range of stress was ±15 9 tons per square inch A third specimen, 2 26 inches long, was loaded with a torque corresponding to a range of stress of ±15 25 tons per square inch The change in θ_1 was very slight and only necessitated a change of length of 0 015 inch , the specimen withstood 29,213,000 repetitions without fracture

If the oscillations of the specimen were allowed to continue with the amplitude falling at any speed, even though the specimen broke, the fatigue range obtained would be uncertain By using these facts another method of approximating to the fatigue range is obtained

Let a specimen be run at a given speed and the amplitude noted and let it be observed whether the amplitude changes after, say, one hour If so, it is probable that the initial torque applied is greater than the safe torque Let now a lower torque be applied to a specimen and its effect noted In this way in a few hours the torque that does not change the amplitude seriously can be obtained and the fatigue range approximately obtained for certain materials This must be checked by long time runs A test of this kind has been made for a number of cold drawn and quenched and tempered wires The range of stress in two cases was indicated as approximately 30 tons per square inch and 28 tons per square inch

Table I shows the results obtained by long run tests for two cases , $\eta^2\theta_1$ was kept practically constant during the test Time and space forbids any further reference to this subject Much data has been published on tests of actual steels It can generally be said that the fatigue range in torsion for hot rolled and quenched and tempered steels from the hot rolls can be taken as about half of the range under direct repetition tests For most of the cold drawn wires tested by the author whether tested in the cold drawn condition or quenched and tempered condition the range of repetition stress is only about one-third of the ultimate tensile strength or 0 4 of the torsional strength of the material, calculated from the formula

$$f = \frac{2\,T}{\pi r^3}$$

Data from long time tests for two of these materials is shown in Table I

Alloy Steel—quenched at 850° C in oil

TABLE 1 No 1

Range of stress (*tons per sq in*)	*Reversals*	
± 16 5	1,929,900	Broke near grip
± 16 3	521,100	,,
± 15 9	1,062,400	
± 14 5	18,993,600	Not broken
± 15 25	29,213,000	,,

Tensile strength of wire 94 7 tons per square inch
Torsional strength of wire 77 1 ,, ,,

Carbon steel wire as drawn

No 2

Range of stress (*tons per sq in*)	*Reversals*	
31 00 ± 15 5	1,461,000	Broke
30 60 ± 15 3	2,795,000	,,
28‘10 ± 14 05	4,761,000	,,

Tensile strength of wire 92 7 tons per square inch
Torsional strength of wire 71 ,, ,,

Direct and Torsional Experiments at Variable Mean Torque

Experiments carried out on steel springs loaded at given mean stresses and strained through a constant amplitude at constant speed show that the range of stress can be represented very approximately by a formula

$$S_r = A - B\,S_m$$

where S_m is the mean stress and S_r the range

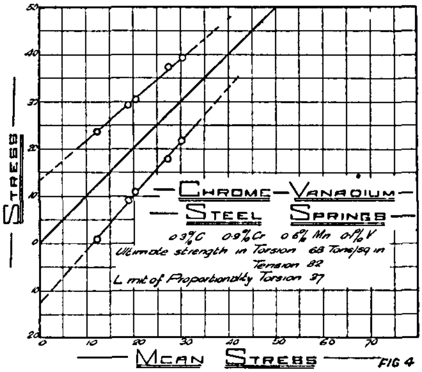
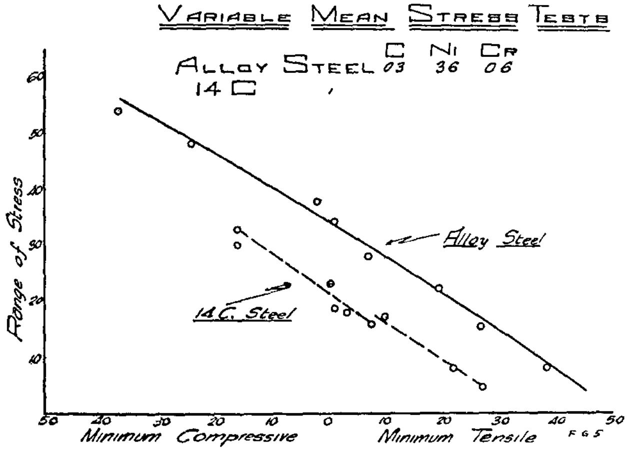


FIG 4

Fig 4 shows the type of curves obtained by plotting mean stress against maximum and minimum stress, or the ordinate between the curves gives the range of stress, for steel wires tested in torsion at variable mean torque

In the Haigh Machines it is possible to carry out direct stress tests at variable mean stresses



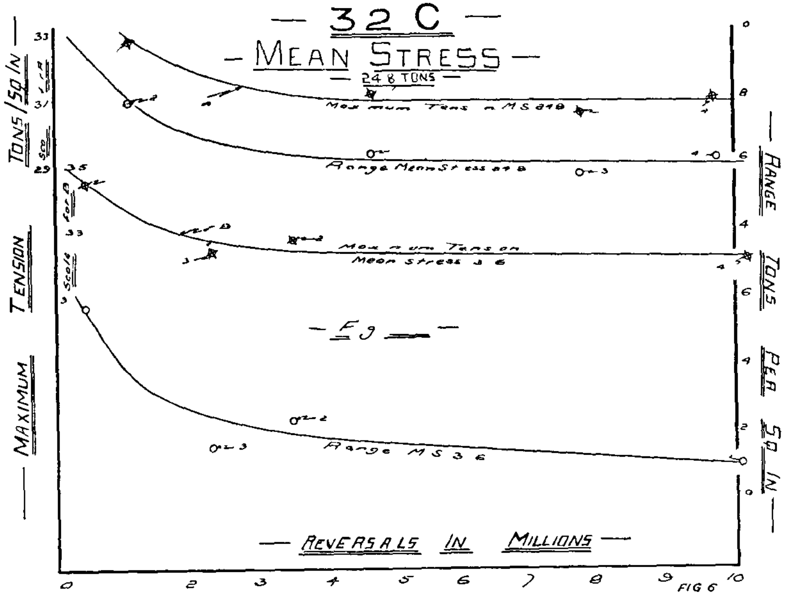


Fig 5 shows, by plotting range of stress against minimum stress, the results obtained from a 0 14 C normalised steel and from an alloy steel of the composition shown Fig 6 shows the type of stress-reversals curve obtained at variable mean stresses For the alloy steel the range is well represented by a formula of the type

$$S_r = A - B\, S_m$$

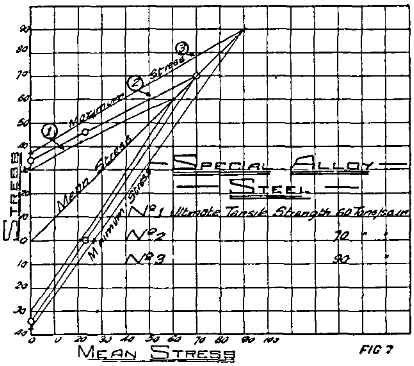


FIG 7

Fig 7 shows the results obtained from a special 3 per cent Ni, 1 per cent Cr steel quenched and tempered to give various ultimate stresses The cusp points of the curves 1, 2 and 3 show the tensile strengths and two points on each curve at zero mean stress and at zero minimum stress were obtained by long time runs Fig 8 shows hardnesses, the Izod factor and the ratio of the total range of stress for zero mean stress to the ultimate tensile strength obtained from the same steel

Aluminum Alloys

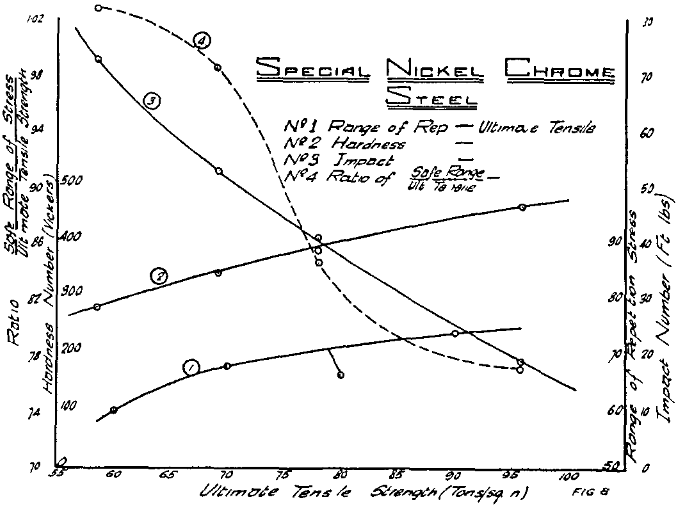
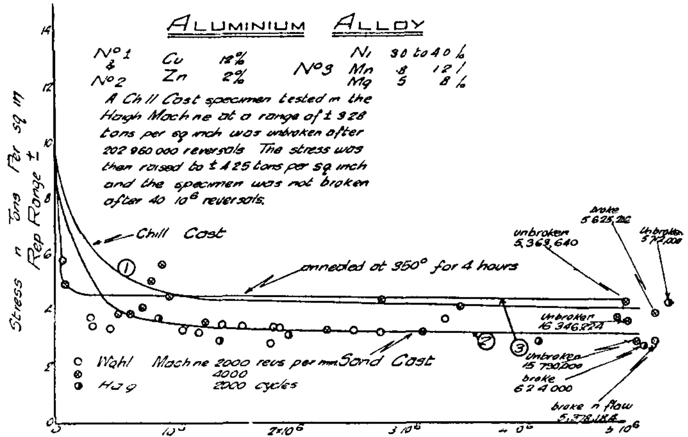


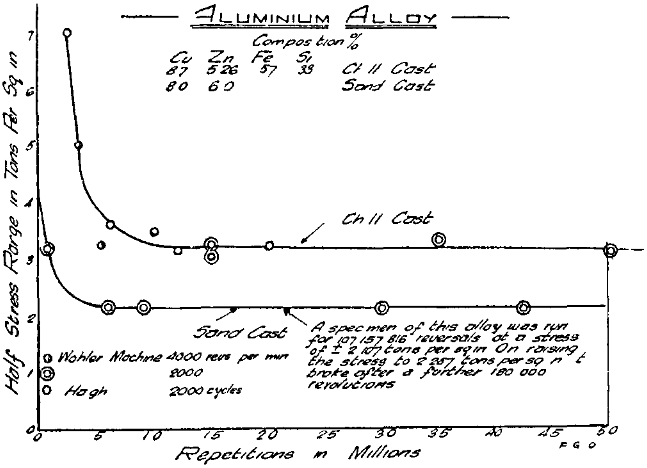
FIG 8

Aluminium alloys are so largely used in aeronautical work that reference to their behaviour under repeated stresses should be made The following tests were carried out in the Haigh and Wohler types of machines Duralumin tested from the bar made to the usual specification gave, in the Wohler machine, a range of repetition stress for 50 million repetitions of about $\frac{2}{3}$rds of its breaking load

Specimens broken four years after being made showed a slightly lower fatigue range than those tested at an early date after manufacture For hundreds of millions of repetitions the fatigue range is not much less than for 50 million repetitions, although doubt has been expressed as to whether Duralumin and other aluminium alloys have a real fatigue limit It is perhaps hardly necessary to discuss whether an infinite number of repetitions at a very low stress would break the specimen The evidence clearly shows that the fatigue range for 100,000,000 million repetitions is not much greater than for 250,000,000 repetitions



F G 9



F G 0

Figs 9 and 10 show results obtained from certain aluminium alloys The points on the curves were obtained from various machines during a period of from 3 to 4 years All the specimens were cast together and some of the tests were made shortly after casting The general results snow that for these alloys there is practically no change observable in more than three years It should be stated however, that the specimens were carefully kept in a laboratory cupboard where the amount of corrosion was certainly very small It is of interest to note that aluminium alloys when under repeated stress tests show indications of slight corrosions, especially in the neighbourhood of small blow holes The rapid load-strain method of obtaining fatigue, referred to later, could not be used with confidence for these alloys

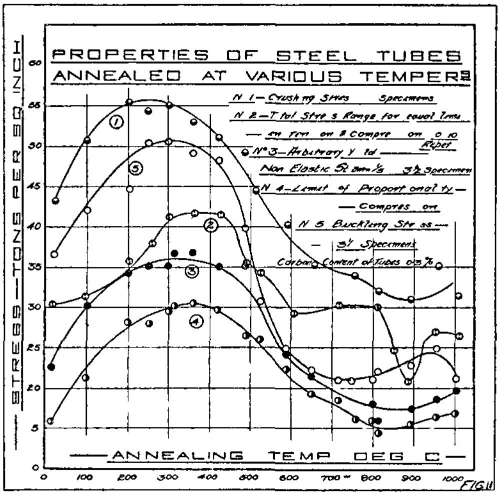


FIG 11

Experiments on Steel Tubes

Cold drawn steel tubes are used very considerably in aircraft, and their properties have been examined by the author and others The author has shown* that heat treatment of cold worked steel tubes affects their properties Fig 11 shows the effect of heat treatment on the elastic and other properties of Swedish 0 35 carbon steel tubes The tubes were drawn from hollow blooms 1 772 inches diameter and 0 159 inches thick They were given five passes through the dies In the last pass the tubes were sunk only The final outside diameter was 1 0015 inches and the thickness 0 0556 inches

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* Materials for Aircraft Jenkins

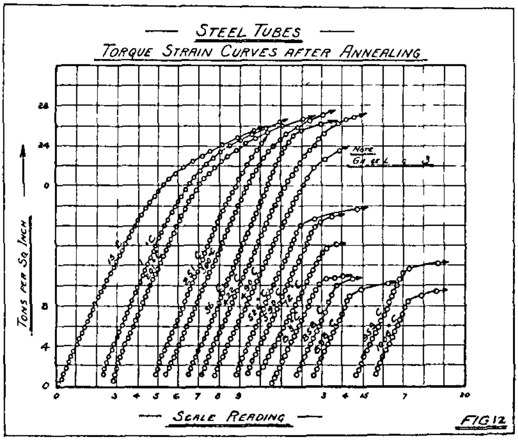

FIG 12

The Limit of Proportionality, in compression, is raised considerably by the heat treatment and it might be thought that there would be a corresponding raising of the fatigue range Fig 12 shows torsion-strain curves taken from exactly similar tubes The Limit of Proportionality after heat treatment at 360° C (23 5 tons per square inch) is 100 per cent higher than that of the cold drawn tube After normalising at 898° C the Limit of Proportionality is about 15 tons per square inch for the compression tests and 9 tons per square inch for the torsion tests

Repetition Tests

The repetition tests were carried out in a simple bending machine driven by a $\frac{1}{2}$-h p motor at 2,000 revolutions per minute The loading could be gradually applied through a lever system by allowing water to run into the tank

Fig 13 shows the special arrangement for holding the tubes There is a mirror at the extreme end by means of which load-strain diagrams were taken The plottings of the results are of interest

CANTILEVER TUBE TESTING SYSTEM

SCALE FULL SIZE

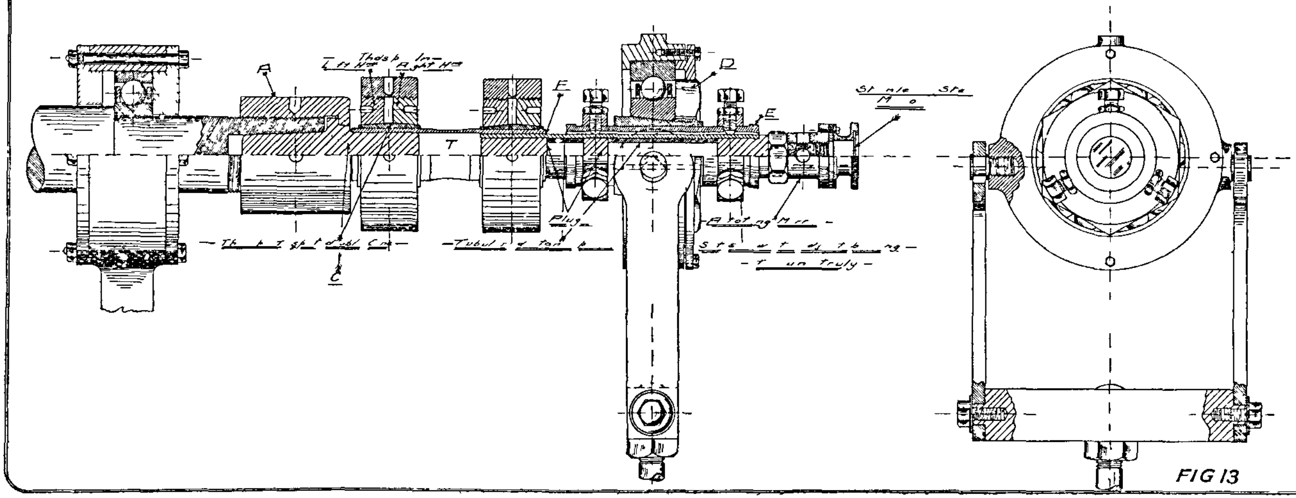

FIG 13

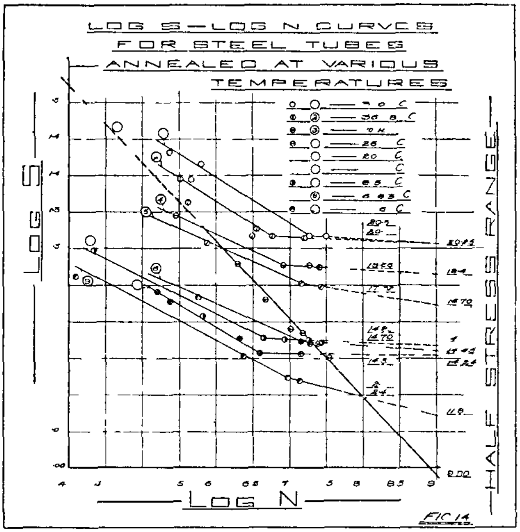

FIG 14

Fig 14 shows typical logarithmic plottings of range of stress against the number of repetitions for the untempered tubes

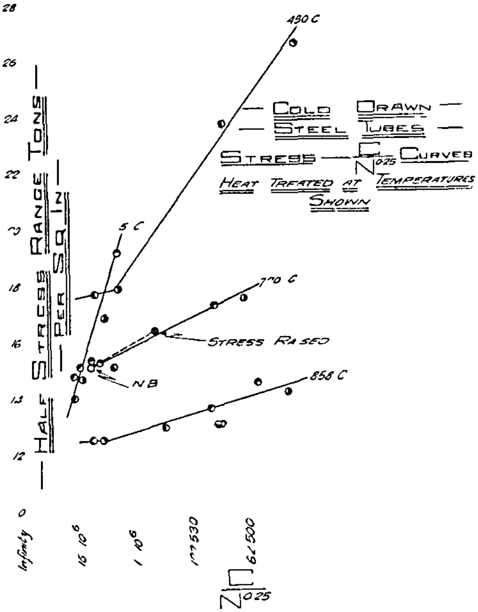

Fig 15 shows typical results plotted with stress as ordinates and $C/N^{\frac{1}{4}}$ as abcissae It will be seen that up to 35 million repetitions the log curve for cold drawn tubes not heat treated is continually falling For 16 million repetitions the range of stress is about ± 15 tons per square inch After heat treatment at 490° C the curve, Fig 15, falls rapidly and then changes direction , the range of repetition stress for 16 million repetitions is about ± 17 5 tons per square inch Log plottings show the same result and the change of direction more clearly After heat treatment the logarithmic curves except No 3, Fig 14, show a distinct change in direction After heat treatment at any temperature between 300° C and 450° C the range of repetition stress for 16 million repetitions was greater than ± 20 tons per square inch so that the raising of the elastic properties by haet treatment clearly raises the fatique range Further, the plottings of the tests of the untreated cold drawn tubes suggest that the range is continually falling and no real fatigue limit is indicated within the limits of the tests, whereas after heat treatment the log stress curve indicates change in direction after less than 10 million repetitions In Fig 11 are shown the ranges of stress for 10 million repetitions plotted against temperature of heat treatment after cold rolling The maximum range of repeated stress occurs after heat treatment at temperatures between 300° C and 400° C and agrees approximately with the heat treatment that will give maximum strength and Limit of Proportionality The half stress range is, however, below the apparent Limit of Proportionality

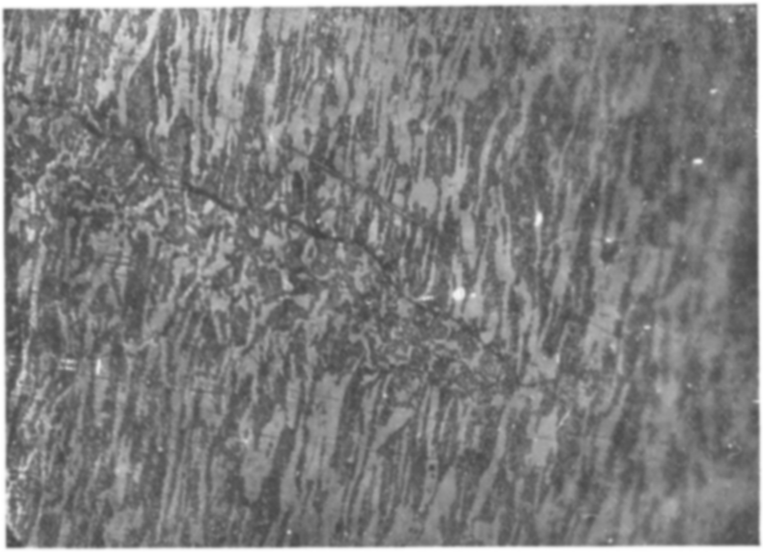

FIG 16 HEAT TREATED 360° MAGNIFICATION 360 DIAMS

Fig 16 shows a microphotograph of the steel after heat treatment at 360° C and also shows the crack developed by the repeated stresses Microphotographs after heat treatment at 858° C showed that all traces of the distorted ferrite and pearlite had been removed, and after this heat treatment the material showed the maximum ductility in compression and in torsion and the range of repetition stress was much less than after heat treatment at from 300° C to 400° C

A number of tubes were captured in the cracked condition before final fracture and it was possible to examine these under the microscope Fig 16 shows a tube heat treated at 360° C It was thought that the difference of crystalline condition might indicate different types of fracture but a careful examination of the material in the neighbourhood of the cracks shows that in most cases the cracks passed through the ferrite and pearlite indiscriminately whatever the heat treatment although there was some indication in places that in the case of tubes that had not been heat treated after being cold worked the crack tended to follow the ferrite boundaries It was not possible to say where the cracks commenced Fig 17 shows a specimen which failed under compression, the walls collapsing and spinning a rib on the tube The author had not previously seen this type of failure under repeated stress It is of interest rather than significant

FIG 17 TUBE THAT FAILED IN COMPRESSION

A number of tubes cracked at the edge of the collet holding the tube, although the stress was very much less than at the reduced section of the tube Fig 18 shows photographs of cracks which occurred at the edge of the collet In the case of the tube heat treated at 360° C the apparent stress at the crack was about ± 10 22 tons per square inch The actual fatigue range after heat treatment at this temperature is ± 21 tons per square inch and the fracture therefore shows in a very marked way the effect of a sudden discontinuity

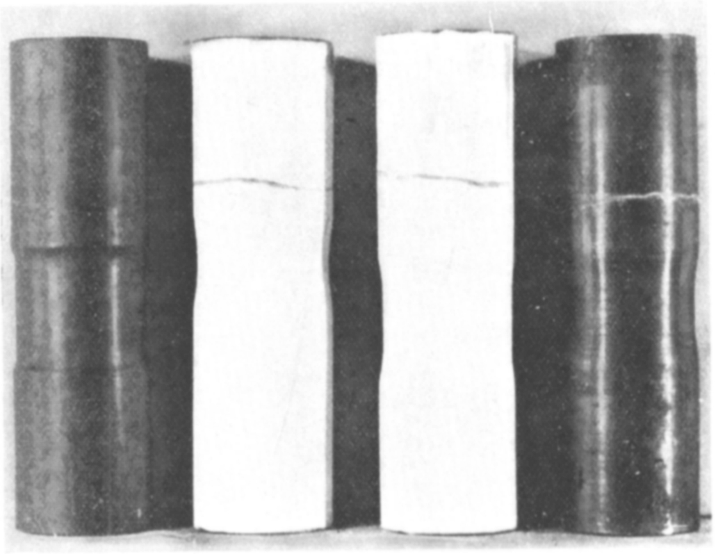

FIG 18 TEST SPECIMENS THAT CRACKED AT THE END OF THE COLLET

The tests clearly indicate that heat treating cold drawn steel tubes at a temperature of 300° C to 400° C not only increases the static properties but also raises the fatigue range for a very large number of repetitions of stress They also show that if due to brazing the temperature is raised beyond 500° C the fatigue range may be very considerably reduced and the fractures that occured in the collets, at comparatively low stress ranges, show how harmful sudden changes of section due to sockets or plugging of tubes may be

Rapid Methods of Determining the Fatigue Range

Reference has already been made to rapid methods of determining fatigue range in torsion A good deal of work has been done in connection with the Wohler bending test, one method is illustrated here from the steel tube experiments,

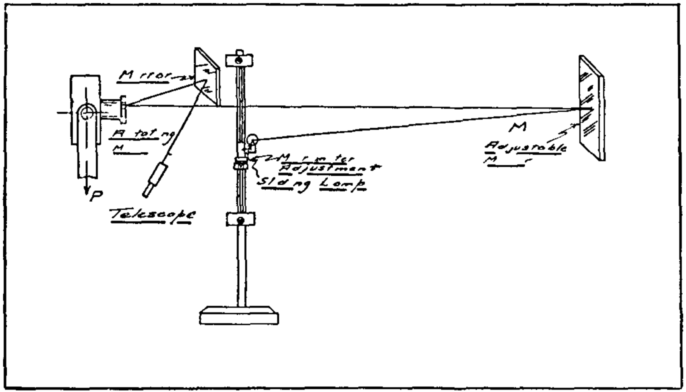

FIG 19

WOHLER MACHINE —Fig 13 shows the mirror on the end of the rotating tube specimen and the shackles used for gradually loading the specimen The optical arrangements are shown in Fig 19 A similar arrangement and the same machine have been used for determining load strain curves from a considerable number of materials

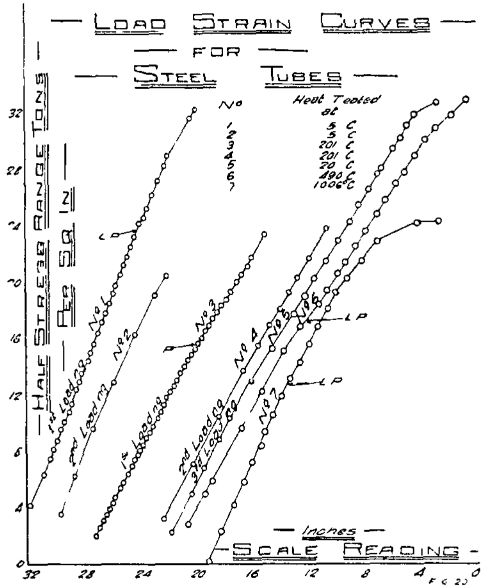

FIG 20

The optical base used was very long and departures from proportionality should be fairly readily detected The types of diagrams obtained are shown in Fig 20 Curves No 1 and 2 show the load strain diagrams obtained from an untreated cold drawn steel tube The fatigue range as determined by long time runs was ± 15 tons per square inch for 16 million reversals The load strain diagram indicates ± 23 8 tons per square inch On re-loading the specimen, however, the Limit of Proportionality was lower than on the first loading, but it was again difficult to locate the value with any accuracy Curves 3, 4 and 5 show three load strain diagrams taken consecutively from a steel tube heat treated at 201° C The initial Limit of Proportionality is at a stress from about 15 6 tons to 18 tons per square inch The stress range for 10 million repetitions, as obtained by long runs was ± 18 tons per square inch It will be seen that on the second loading the load strain diagram is nearly straight up to ± 23 5 tons per square inch Curve No 6 shows the Limit of Proportionality for a tube heat treated at 490° C to be about 17 2 tons per square inch, but it may be much higher The fatigue range for 10 million repetitions was ± 21 tons per square inch Curve No 7 shows the load strain curve obtained after heating the tube well above the normalising temperature The Limit of Proportionality in this case is from 12 to 14 tons per square inch, and the total range obtained from long time runs was ± 13 2 tons per square inch for more than 20 million repetitions It has been previously shown that for mild steel normalised the load strain method gives, when used with care, the safe range with a fair degree of accuracy, but for these heat treated tubes it was difficult to obtain reliable results

The method has been used for various kinds of materials and tested by long time runs It cannot be said that for materials in general the load strain method on the Wohler machine gives accurate indications of the fatigue range except for normalised mild steel

HAIGH MACHINE —To determine the load strain diagrams as given by the Haigh machine two methods, using the ordinary type of extensometer, have been used (1) A spot of light was focussed upon the mirror of the extensometer and reflected into a long camera with a ground glass screen on which the length of the band could be measured for various loadings (2) The arrangement of Fig 19 was adapted to the Haigh machine and extensometer The Mirror M was placed 18 feet from the extensometer The lamp A was moved until the top of the spot of light coincided with the cross hair of the telescope and then the lamp was moved until the cross hair coincided with the bottom of the band of light The movement of the lamp was a measure of the total strain produced A diamond rocker with a mirror attached has also been used

The slide shows curves obtained for mean stresses not zero When a specimen is loaded with a mean stress f_m and a range $\pm f$ is added the maximum stress is $f_m + f$ and this may be much higher than the yield point of the material, without fracture of the specimen, providing the range f does not exceed a particular value When taking load strain curves, the mean stress having been applied by straining the springs of the Haigh machine, about 4,000 cycles were run at each increment of stress to bring the material, if possible, into a constant cyclical condition Curves Nos 1 and 2 of the slide show the maximum stress and range of stress respectively plotted against strain for 0 14 C steel at a mean stress of 12 tons per square inch

It is difficult to determine the exact point when the curves depart from proportionality, but it is at about 18 to 20 tons per square inch maximum stress corresponding to a range of stress of about 16 tons per square inch The actual range of stress for a mean stress of 12 tons per square inch was, as obtained from the plottings of long time tests, about 16 5 tons per square inch Curves 3-6 were obtained from an alloy steel at a mean stress of 30 tons per square inch The load was increased until it corresponded to 54 5 tons per square inch, at which it broke

A specimen of this material ran at 30 tons per square inch mean stress and range of 23 56 tons per square inch corresponding to a maximum stress of 41 78 tons per square inch for nearly 10 million repetitions, so that the maximum stress of 44 8 tons per square inch indicated as the Limit of Proportionality is rather higher than the safe range The determination of these load strain curves is not easy and requires the undivided attention of a skilful observer The machine when running long time tests can generally be left without attention, and it will be seen that it is doubtful whether the results obtained from a single load strain curve can be relied upon to indicate the safe range for any given mean stress It is worth while, however, to determine the load strain curves in order to give a clue as to the possible safe range and then to run several specimens at ranges approximating to the indication of the load strain curve

Fatigue range by Measuring the Rise of Temperature

Tests have been carried out by many investigators to determine the range of stress at which there was a very definite indication of a rise of temperature The Haigh machine lends itself to this type of experiment and following Haigh we have over a number of years carried out experiments on a number of materials Spurts of heat are by no means a criterion that the fatigue range has been reached except in the case of certain materials Very perceptible heating may take place and the material then settles down to a cyclical condition and may run millions of repetitions without failure With normalised mild steel the thermo-couple can give a fairly accurate indication of the probable fatigue range for equal plus and minus stresses On the torsional machines a specimen may become quite hot and then cool and unless the torque is adjusted it will run for a very considerable time—probably indenifitely

Mode of Fracture and Change of the Fatigue Range

The work of Taylor* and Elam and Gough, Hanson and Wright,** on single crystals seems to indicate quite clearly that tensile or compressive stresses, whether applied statically or by repeated stresses cause slip on certain planes within the crystal and it has been shown quite clearly that when materials consisting of crystal aggregates are subjected to repetition stresses, slip bands, similar to those in the

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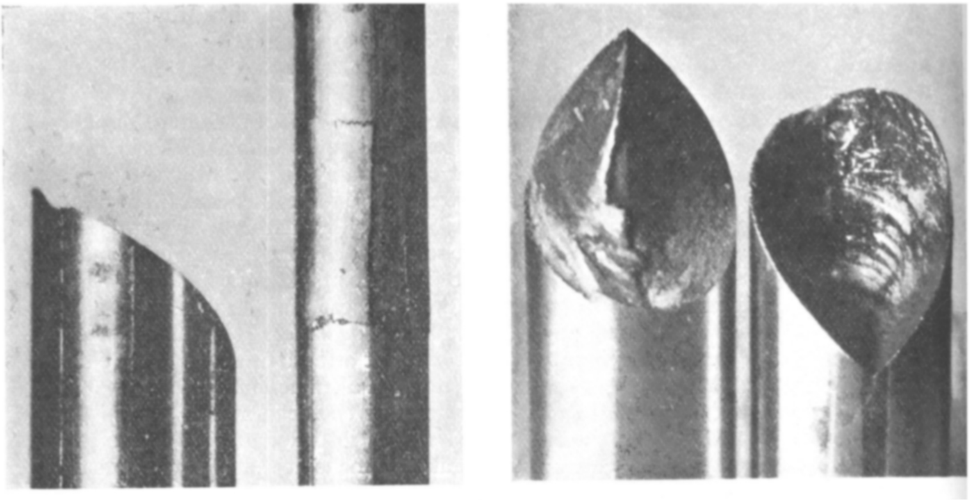
* Roy Soc Proc A Vol 102 Roy Soc Proc A Vol 112

** Phil Trans *See* A Vol 226

See Southwell and Gough, Phil Trans 1926



No 1 No 2 No 1

FIG 21 TORSIONAL FATIGUE FRACTURES OF WIRES

single crystal, occur in the material and it is generally thought that failures are due to shear stresses causing slips Such slips can occur, however, without subsequent failure Again many failures occur which make it difficult to see how shear stresses have been the cause of failure A small hole in a specimen, subjected to torsion only, will generally cause fracture on planes at 45 degree to the specimen Southwell has dealt with this problem and shown that if elastic conditions obtain a concentration of stress 2 7 time the mean stress occurs at the hole No 1, Fig 21, shows a fracture of a Chrome-Vanadium quenched and tempered wire The fracture in this case was produced by reversed torsional stresses which apparently commenced at the entrance to the collet and at a point where the fine tooth of the collet had slightly marked the specimen The range of shear stress was only a little less than that which causes fracture quite away from the collet and the fracture is clearly in the direction of 45 degree to the axis on one side of the specimen and perpendicular to the axis at the other side There seems every indication that the fracture commenced at the collet, *i e*, on planes at 45 degrees to the axis of the specimen and may have been partly due to a concentration of stress caused by the collet and the indentation No 2, Fig 21, shows quite a different fracture in which there is clearly failure by shear, simultaneously along planes parallel with the axis and perpendicular to it, specimens have been obtained with the crack parallel to the axis only Similar fractures to No 1, Fig 21, have been produced in specimens containing small holes and in quenched and tempered helical springs The plane of fracture in these cases is apparently the plane of maximum normal stress range and the fracture obtained from repeated bend tests and also in the Haigh machine, both for brittle and plastic materials is nearly always on the planes of maximum normal stress range If then the fracture is really a shear fracture it must mean that the slips take place on planes inclined to the planes on which maximum normal stress range occurs but that the slips are so small that the inclined planes are not observable even under the microscope That the slips are very small is shown by the fact that fracture can occur in specimens subjected to normal stress ranges without any measurable elongation and when stressed in torsion without any perceptible twist, or in other words the slips causing final fracture occur only in a few molecules It is possible, however, for visible slip to occur without fracture This has been shown clearly in tests from the Haigh machine and from tests and on helical springs subjected to a given range of torque, or shear stress in one direction , the springs correspond to torque specimens many inches in length In such tests creep takes place, but if the specimen is not going to break it may finally cease creeping

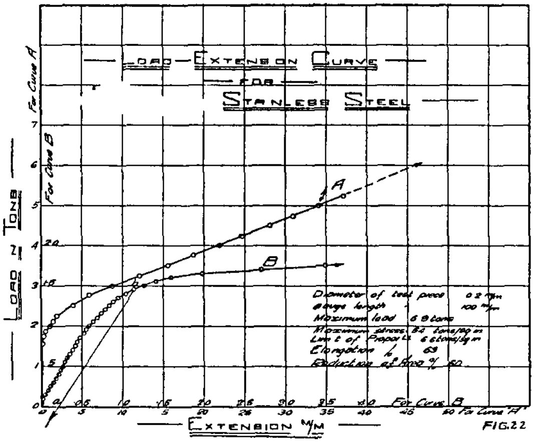


FIG. 22

Specimens subjected to equal tensile and compressive stresses in the Haigh machine may elongate under test, but if they do so except by very small amounts they will generally break The following tests, Table II, from a piece of non-corroding steel are of interest Fig 22 shows load strain diagrams for this material Its ultimate strength was 54 1 tons per square inch , the Limit of Proportionality was only 6 6 tons per square inch

TABLE II

No	*Stress Range (tons per sq in)*	*Haigh Machine Number of Cycles*	*Remarks*
1	± 15	8,200	Broke Specimen elongated very perceptibly and became very hot
2	± 12 5	19,600	Ditto A match could easily be lighted by touching the specimen
3	± 11	11,094,100	Not broken Specimen elongated in the night 0 01 in and stopped the machine
3	± 11	13,589,000	Broken
4	± 10 75 +	32,950,000	Not broken Specimen elongated and stopped the machine
5	± 11 5	98,800	Not broken

This stress was raised to ± 12 5 tons per square inch and it ran 7,058,000 repetitions without fracture

It is of interest to compare the results in the Haigh machine with those obtained from the Wohler machine These tests were carried out before those in the Haigh machine, and it was at first thought that the fatigue range, as in other plastic steels, would be about equal to the breaking strength and a specimen was loaded to a range of stress equal to the ultimate stress The preliminary results are shown in the following table —

TABLE III

Test No	*Diameter*	*Range of Stress (tons per sq in)*	*Number of Cycles*	*Remarks*
1	0 333	—	—	Test piece bent when loaded to a stress of ± 27 5 tons per sq in
2	0 2784	± 11 5	1,658,000	Broke
3	0 337	± 11	51,998,000	Not broken

The range from this does not differ very much from that obtained from the Haigh machine The hardness of the specimen that broke at ± 11 5 tons per square inch in the Wohler machine was taken along its length and varied as follows

Hardness near the end	168
Hardness within $\frac{1}{8}$-in of fracture in parallel portion	189

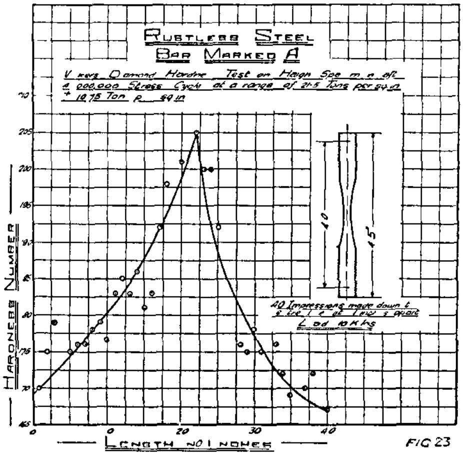


FIG 23

It was thought that this material should show in a very marked way the effect of gradually loading the specimen The specimen No 5 from the Haigh table, which at 38 million repetitions had a range of ± 10 75 tons per square inch without fracture, was loaded so that the stress was ± 12 5 tons per square inch At this stress the specimen withstood 7,050,000 further repetitions without fracture It was then cut parallel to the axis and hardnesses taken every 1/10 inch along its length These are shown plotted in Fig 23 It will be seen that in the neighbourhood of the smallest diameter, although the specimen only elonaged 1/100 inch during the test, the hardness has been raised to 205 from 164 at the ends of the specimen The specimen heated up several times during the test at ± 10 75 tons per square inch and adjustment had to be made An exactly similar specimen stressed to ± 12 5 tons per square inch at first loading became so hot that a match lighted when it touched the specimen and it broke after 19,600 repetitions Loading the specimen with a range of ± 10 75 tons per square inch for 32 million repetitions evidently strain hardened the material and raised the range of stress as shown

That this material is very susceptible to strain hardness due to repetition stresses is shown by further tests on the Wohler machine

Two test specimens, Nos 4 and 5, were made shorter than specimens, Nos 1 2 and 3, and larger in diameter, though they had a parallel test portion of 0 18 inch

All the specimens from Tables 3 and 4 were cut from the same bar

With short stiff specimen, even though the outer fibres are loaded to a larger stress, it might be expected with such a plastic material that as the bending is small only a thin layer would be over strained and under the repeated stresses it would be possible for this to come to a stronger configuration

The stress on specimen No 5 was gradually increased until it reached ± 16 6 tons per square inch The specimen was apparently running quite steadily and truly in the machine The load was then raised so that the stress was ±20 1 tons per square inch After a very few revolutions the specimen became hot and then quite unstable and the machine was stopped Hardnesses were then taken along the specimen as follows —

Length of specimen

Hardnesses from one end to the other 196, 167, 167, 217, 172, 165, 183

The hardness of 217 was taken on the parallel portion 0 18 inch long

It will be seen that the hardness is very considerably increased and that the gradual hardening has evidently raised the fatigue range

Referring again to the load-strain diagram, Fig 22, it appears that the degree to which the elastic range of this material can be raised depends entirely upon the degree of strain produced during the consecutive cycles

It is also of interest to note that since elongation can take place in the Haigh machine when the specimen is subjected to equal plus and minus stresses at the rate of 2,000 cycles per minute slip can take place on certain planes more easily when there is a tensile normal stress than when there is a compressive normal stress

TABLE IV

Test No	*Diameter inches*	*Range of Stress (tons per sq in)*	*Number of Cycles*	*Remarks*
4	0 3746	± 12 5	53,450,000	Stable
5	0 3744	± 14 87	28,191,900	Stable
5	0 3744	± 16 60	3,160,000	Would have apparently run on for a very long time
5	0 3744	±20 10	—	Specimen bent badly and was very unstable
6	0 3770	± 7 32	3,500	
		± 8 90	1,700	
		± 8 70	3,100	
		± 12 17	2,400	
		± 12 88	6,000	
		± 16 35	11,700	
		± 15 8	Very unsteady, would have broken quickly	

From an examination of Fig 22 and the results given in Table II, it is clear that the safe range of repetition stress has no relationship with the Primitive Elastic Limit, or Limit of Proportionality, neither is the ratio of the Fatigue range to the Ultimate tensile strength anything like that generally found for steels

A load strain diagram for arsenical copper at ordinary temperatures showed that the Limit of Proportionality was less than 3 tons per square inch, while the breaking stress was 14 8 tons per square inch

A specimen was loaded in the Wohler machine to ± 5 15 tons per square inch and broke after 79 6 million reversals A further specimen was loaded to ± 5 125 tons per square inch and after 560 583 million reversals of stress was not broken The stress range was then raised to 12 24 tons per square inch, and it broke after a further 37 111 millions, but not at the reduced section As already stated, it broke in the collet where the nominal stress was only 8 tons per square inch

The maximum range of stress was more than twice the Limit of Proportionality, but the apparent range at the fracture was clearly much less than the maximum range It would appear that a crack must have slowly developed at the collet due to concentration and that then the material was gradually strain hardened in a remarkable manner by very small movements

Hardness tests on the specimen showed rather remarkable results Across the unbroken end of the specimen the mean hardness number was 70 In the diminished portion of the test piece subjected to the stress of ± 5 125 and then to ± 6 12 tons per square inch the hardness (mean of three) was 74 Across the diameter near to the collet where the very slow fracture had taken place the mean of four hardnesses was 91 8 It could hardly be that this hardness was in the initial material and the increase appears to have been due to local strain hardening during the very long runs If the results from the stainless steel had not been obtained it might have been thought that the extra hardness had not been brought about in this way

The long run at 10 15 tons per square inch total range appears to have raised the fatigue range and the stress range is clearly very much greater than the range of Primitive Proportionality

In the Haigh machine the results given in Table V were obtained

TABLE V

Repeated Stress Tests in Haigh Machine

Tensile test of material (Arsenical Copper)

Breaking strength	14 8 tons per square inch
Elongation per cent	59 on 2 inches
Reduction of area	63 5 per cent

Limit of Proportionality less than 3 tons per square inch

Specimen	*Range of Stress (tons per sq in)*	*Cycles in millions*	
1	± 5 5	3 0	Broke
2	± 5 25	15 5	Broke
3	± 5 125	17 8	Broke
4	± 5 00	49 4	Broke
5	± 5 25	9 0	Broke
6	± 5 06	116	Not broken
7	± 6 1	0 726	Broken

The Fatigue range from these tests is clearly about 10 12 tons per square inch at zero mean stress That the stress range, of this very plastic materials appeared to be affected by gradually increasing the load during cycles of stress for the Wohler test is further shown in the following table The table also shows, results from the Haigh machine, on the effect of gradually raising the load One specimen was loaded in the Haigh machine so that the stress was 10 12 tons per square inch and another in the Wohler machine so that the stress was 10 0 tons per square inch The loads were then increased as follows —

HAIGH MACHINE						
Range of stress	10 12	10 3	10 55	10 75	11	11 25
Cycles in millions	116 06	5 280	2 682	2 682	2 682	0 447
Total cycles	121 34	124 022	126 704	129 386	129 833	Broke

WOHLER MACHINE						
Range of stress	10	10 5	11 05	11 6	12 1	13 5
Cycles in millions	37 851	3 584	3 496	3 534	6 59	3 52
Total cycles	37 851	41 435	44 931	48 465	55 055	58 575
Range of stress	14 2	15 25	16 3			
Cycles in millions	3 41	3 69	0 0943			
Total cycles	61 985	65 675	65 769	Broke		

In the Haigh Machine the gradual raising of the stress has not seriously raised the fatigue range, but in the Wohler specimen it appears to have done so in a more marked manner The stainless steel which had an elongation per cent similar to this material and a low Limit of Proportionality behaved similarly The explanation appears to be that the Haigh test piece is stressed practically uniformly, whereas the Wohler test piece, subjected to bending, has the maximum stress only at the outer fibres A very thin layer of the Wohler specimen may be strained plastically and be cold worked to a very small extent, while the remainder of the section of the specimen may be elastically stressed In the Haigh test piece all the section will be equally strained and there is not the same opportunity for some of the fibres to be brought to a new and stronger configuration while the remainder of the material is being strained elastically But, as shown above, when the stress is very near to that which causes fairly quick failure it may be raised considerably, even in the Haigh meachine These experiments, and others, lend support to the theory of St Venant that a material only really fails when the relative movement of the molecules to each other exceeds some defined amount, or, in other words, that the degree of strain has to be considered in relationship to the failure of materials rather than the stress This seems to be further confirmed by the results generally of repeated stress experiments

Whatever the form of the load strain diagram, whether it has a high Limit of Proportionality compared to the breaking strength as in normalised mild steel, or alloy steels heat treated at certain temperatures, or whether they are of a form similar to that of Fig 22, or with a very low Limit of Proportionality frequently found in alloy steels heat treated in certain ways, the fatigue range appears to depend upon a certain strain produced beyond that which brings the material into a uniform condition, which appears to be the same thing as saying that if complete cycles of stress are taken the material after a certain number of cycles gives hysteresis loops that do not increase in area

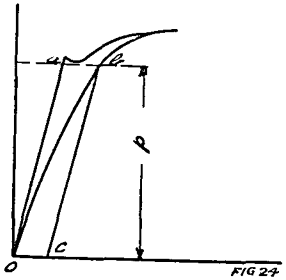


FIG 24

A material may have a load strain diagram *Oa* or *Ob* Fig 24 If it is stressed with a repeated stress it will be found that the material in either state may have a range of repetition stress equal to ± p, say The strains produced by cycles of stress are not sufficient to cause fracture even though there have been clearly certain movements in order to bring the material into a cyclical condition represented by *bc* If the range of stress ± p_2 originally applied is higher than ± p the specimen will probably break after a certain number of repetitions of the stress If up

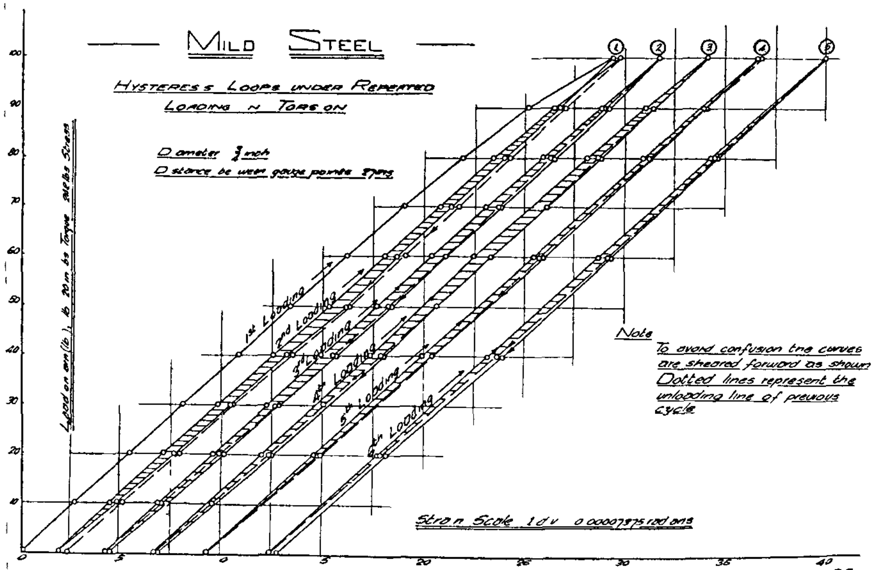


FIG 25

to a certain stress $\pm p_1$ the rate of increment of strain of part of the material, as in the Wohler test pieces, is very small for n cycles the material may heal whereas a test piece loaded with the stress $\pm p_2$, and producing strains of comparatively large magnitude will probably break* the specimen after a comparatively few repetitions

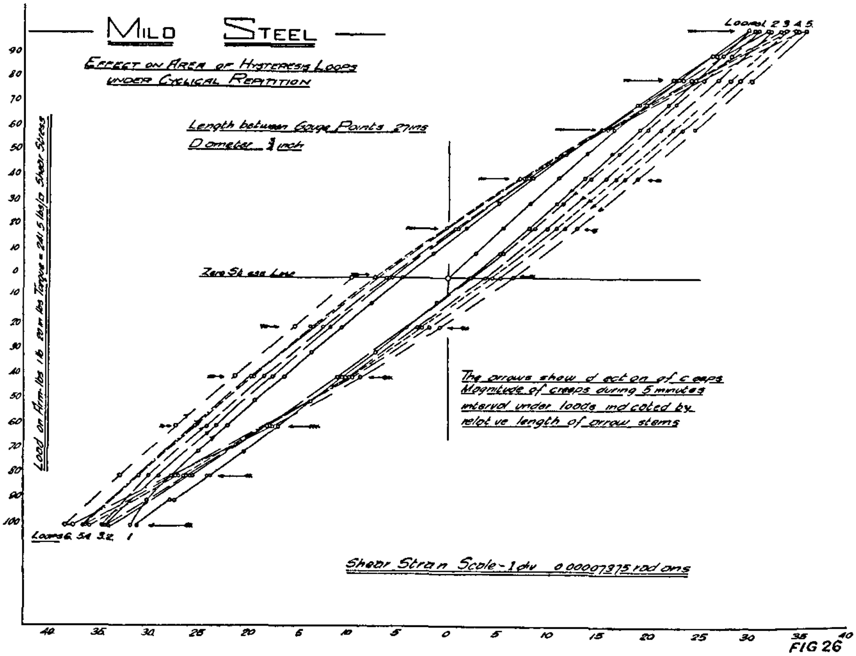
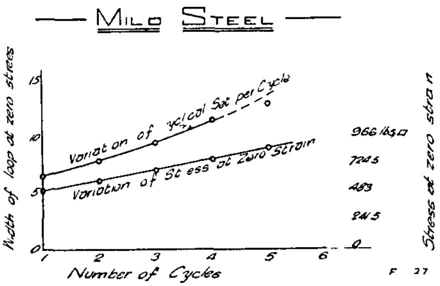


FIG 26



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* Lea Engineering Feb , 1923

Figs 25 and 26 are interesting as illustrating what probably takes place when a material is stressed in torsion Fig 25 shows hysteresis loops taken from a mild steel specimen 27 inches long, the range of stress being from 0 to 10 4 tons per square inch The strains are measured with great precision The hysteresis loops are diminishing Fig 26 shows hysteresis loops taken from the same specimen, but with a range of stress of ± 10 4 tons per square inch, which is the range of stress that will break the specimen The areas are increasing and as will be seen there is negative creep during the cycles Some molecules have slipped and are partly brought back as the stress is diminished or reversed Fig 27 shows the variation of cyclical set per cycle at zero torque or zero nominal stress and also the torque or nominal stress at zero strain taken from Fig 26 It will be seen that both increase with the number of cycles

The Rate of Application of the Load

The author regrets that he is not able to include in this paper anything, except a passing reference, of the considerable amount of work done on the effect of holes, grooves and threads cut in specimens subjected to pure bending and also to the bending and torsion combined, or on the effect of small blows The nature of the stresses produced by blows are only the same as those produced by cyclical loadings, but under the very rapid rate at which the stress accumulate from zero to a maximum the behaviour of the material is no doubt different Professor Bertram Hopkinson, whose name can always be mentioned with reverence in this Society, showed a good many years ago that a piece of wire under a very rapidly applied load was practically " elastic " to the breaking point A cyclically applied load in the ordinary machine is applied in something of the order of 1/50th to 1/100th of a second, while the time taken for the stress in a beam, as in the Stanton Machine, to reach the maximum stress is probably of the order of 1/500th or less of a second The plastic properties of materials have, therefore, not time to operate and redistribution and " healing " in the neighbourhood of sharp curves, corners and discontinuities cannot readily take place The " concentrations " of stress, therefore, under blows are more likely to agree with those indicated by the Elastic theory and confirmed by the experiments of Coker On the other hand, when there are no rapid discontinuities it would appear from the author's work at high temperatures that a viscosity term must be included in the strength of the material, and it would appear to be stronger the higher the ratio of application At ordinary temperatures the effect of rate will probably only become important when the time of a cycle is less than 1/1000th of a second Experiments have been carried out in the author's laboratory on the effects of small blows repeated many millions of times, and it is now quite clear that the curves of fall plotted against blows is of almost exactly the same shape as the well known stress repetition curves and there is just as much certainty that there is a limiting blow for any defined number of repetitions as there is a limiting stress for any defined number of cycles

Furthermore, there is distinct evidence that the stress produced by a given fall, as calculated on the elastic theory, for 10,000,000 repetitions, say, must be of the same order on an ungrooved specimen, as the range of cyclical stress that will break the specimen If during the cyclical application time is a factor in the problem and concentrations at discontinuities takes place in accordance with an elastic rather than a plastic theory then the effect of discontinuities of any kind will be much more serious under a blow than during a cyclical application, and the experiments seem in some measure to confirm this view, but not wholly The matter is of such interest, however, as to be pursued

If a beam or cantilever is struck a blow of kinetic energy U per unit volume of the beam or cantilever, then the stress produced is

$$p = \sqrt{24\ \mathrm{E\,U}}$$

In the neighbourhood of a small hole the stress concentration, accordins with the elastic theory would be from 2 7 to 3, and taking the concentration figureg of Griffiths (British Association, 1921) the stresses in certain cases would be higher than this value, whereas under cyclical variations the experiments on plastic materials show that the concentrations are not of this order It would be interesting for Professor Jenkin, in his elegant machine, for testing specimens at several thousands of cycles per second, to test the theory here advanced Specimens without sudden discontinuities in Jenkin's machine should give higher results than a comparatively slow running cyclical machine, but for specimens with small holes drilled in them or specimens with key beds and screw threads cut along them, failure should take place at an apparently much less stress than in the case of the more perfect specimen

Single crystals behave in a plastic manner at quite low stresses, and it would appear that rate of loading would probably have a considerable effect on the fatigue range In Jenkin's machine the fatigue range for single crystals—if it could be found possible to use them, there seems considerable doubt as to that possibility—ought to be much higher than in the Haigh machine for a well finished specimen, but if the crystals were grooved or badly scratched, then the fatigue range should be less

CONCLUSION

The conclusion can be drawn that for all practical purposes most materials have a real fatigue range In the case of the carbon steels and the alloy steels generally used for many parts of aeroplane engines when heat treated so as to give varying ultimate stresses, the total fatigue range for equal and opposite stress varies from 0 8 to 1 times the breaking strength, but for other materials it may be less than one half the breaking stress Assumptions made as to the behaviour of certain types of materials from the results of others without actual experiments may be dangerous

The range of stress S_r for any material depends upon the mean stress S_m and for certain steels the range of stress both for bending and torsion can be expressed as $S_r = A - B\ S_m$, A and B being constants

The curves of range with variable mean stress for materials such as mild steel more nearly approximate to the Gerber's parabola except near to the zero mean stress when, as indicated by Bairstow, the range remains constant for a certain variation of the mean stress

When there is a steadily applied stress of one particular kind, as for example a torsional stress, the safe range of stress under bending stress may be unaffected, providing the steadily applied stress does not exceed some specified amount

The factor of safety when materials are subjected to cyclical stresses should be considered in relationship to the mean stress and the range of stress This has long been pointed out

Rapid methods of determining fatigue range, by optical means or thermocouples, in the hands of careful experimenters may be reliable, but they can hardly be taken as convincing evidence without further tests

Pin holes, sharp corners and key ways on shafts, rapid changes of shape in metal spars and other elements, particularly those which may be subjected to blows or vibrations should be carefully avoided Materials should be as homogeneous as possible In this connection it would appear that rapid discontinuities either mechanical or metallurgical which give opportunities for stress concentration on a finite length in any plane should be avoided , large grained structure of metals gives opportunities of stress concentration far greater than a small grained material with crystalline growth well distributed in all directions

Cold worked materials like carbon steel tubes—and brass tubes—have their fatigue ranges increased by heat treatment

Raising the breaking strength of certain alloy steels by quenching from above the change point and tempering at various temperatures will increase the fatigue range, but the ratio of fatigue range to ultimate stress may diminish

The key to the failure of materials under repeated stress has not yet been found, but no problem in the materials of Engineering is more pressing for solution, and can have more interest or economic importance This paper has been rather rapidly compiled and has only attempted to put forward certain empirical results and theories, to lead to a discussion and in the hope that those who are connected with aircraft, in which the problem is of supreme importance, will contribute something to its solution

DISCUSSION

Mr H T COLLINS (University College) It is generally accepted that the ways of pioneers are always difficult, and one rarely finds two men to agree with him At the same time, though, I suppose we have listened to-night to a lecture which in three or four hundred years' time will be read as an early treatise on the subject of repeated stresses on materials , nevertheless, it will even then call for admiration at the amount of work done and ground covered by Professor Lea, as sketched out in his paper this evening

There are two points I would like to raise Firstly, is the method adopted for calculating the stresses due to bending in a cantilever, the usual elastic theory of bending based on the assumptions therein made, and neglecting inertia effects of rotation ? Has the deflection of the specimen as a cantilever under a static or rotating load of the same order, been found to be the same ? If so, it would seem reasonable to assume the apparent bending stress as the same as that calculated statically

Secondly, with reference to recent X-ray work done on space lattice, has the employment of short wave-lengths comparable with inter-molecular spacing produced any interpretation of the appearance of " slip bands " on the surface ? Has Professor Lea made any attempt to photograph by some such means, small areas of surface which have been submitted to fatigue stresses ?

As an old student of Professor Lea's, and one who has often sat under him at lectures, I should like to register my cordial appreciation of and thanks for the lecture he has given us this evening

Dr J V Howard (City and Guilds Engineering College) I should like to be allowed to add my quota of admiration of the enormous amount of laborious experimental work, the results of which are summarised in the paper In the concluding paragraph it is stated that the key to the failure of materials under repeated stress as not yet been found Professor Lea has gone a long way to supply that key, but we have his word that it is still wanting Of the various factors involved, two appear to be the most important

The first is the element of time Professor Lea mentioned that for stress repetitions of less than 1,000 per minute, the results are independent of the speed Taken in conjunction with the interesting experiment on repeated stress on steel at high temperatures, this leads to the inference that there is a speed beyond which the strain in the material fails to respond to the stress

The second factor is suggested by the statement in the paper that micrographical examination of fatigue fractures yields negative results Possibly some light might be thrown on the mode of fracture under repeated stress by a fuller knowledge than is at present available of any variation or distortion of the space lattice under such conditions For the moment this is, perhaps, more in the region of physical speculation , and, pending a pronouncement by the pure scientists, Professor Lea has attacked the problem from the point of view of the practical engineer, and has established a number of experimental facts which must be carefully studied by engineers concerned with the problem of stress repetition

Mr Duncan (Blackburn Aeroplane Co) I should like to add my thanks to Professor Lea for his lecture, and also ask a question in regard to the test on the material (one of the new stainless steels), in which there was a small extension I should particularly like to know whether that test was for an equal variation of tensile and compressive stress , also I wonder if it is possible to say whether the tension or the compression was put on first

Further, has Professor Lea made tests of this material on his torsion machine, and if so, has he again observed an extension of the specimen ?

I suggest that the discussion should be turned to some practical points in connection with aircraft, dealing with the subject of materials, although they might not at first appear to be connected with repetition stresses

With regard to streamline wires, these have failed in service, due to vibration These wires, as most people know, are swaged down, and the fracture usually occurs at the end of the swage It does not appear that that would be a point of maximum stress, and I should like to have Professor Lea's opinion as to why the fracture should be at that point

With regard to designing aircraft by the use of maximum load factors, which really amount to a factor of safety of approximately two during evolutions in the air, perhaps a little more severe than in normal flying, it is usual for us to calculate all our tension members to the maximum load factor, by using the ultimate tensile strength of the material, *e g* , for lugs

Now taking the fatigue stress of the material as being about one-half the ultimate, we are, in the end, therefore, roughly designing our lugs to the fatigue range of the material , I should like to know what Professor Lea thinks, and in particular, whether he considers it quite safe for us to continue to design lugs on the ultimate strength, or whether we ought to design on the yield of the material

Professor WITCHELL (City and Guilds Engineering College) I have come to hear the results of Professor Lea's latest researches into the Effect of Repeated Stresses on Materials, and I was thinking while Professor Lea was talking, that we ought to be thankful, not only for the energy and skill with which these researches are conducted, but also for the very interesting way in which the results are presented

There is one point that has often occurred to me In the materials tested there is proportionality between load and extension up to a certain limit, and this limit as Professor Lea has shown, may be considerably varied according to the treatment the metal has received After this limit is passed and the straight line relationship no longer holds, hysteresis loops are developed under repeated range of stress Can Professor Lea say whether an hysteresis loop is a necessity if the straight line relationship ceases, and does he know of any material for which the relation between load and extension is not linear, and which yet does not give hysteresis loops under repeated stress ?

Dr SMITH (City and Guilds Engineering College) I should like to congratulate Professor Lea on the marvellous amount of work in the paper He has covered such a large field that it seems I should have spent as much time and then got only one small corner

With regard to the safe limit of proportionality, in most cases this is lower than the safe repetition stress, and therefore it seems to me quite a safe thing for engineers to obtain and put in their specifications

With regard to loops, these seem to be obtained by repeating the loads slowly I wonder if Professor Lea can tell us if he could get the same effect if he got that load in much the same speed as if he were carrying out experiments

With regard to slip, I have tried to find out what the meaning of the loop is, and I have come to the conclusion that the load area could be used as a measure of the amount of recoverable slip which certain materials would give I mean that in loading material in tension you may be somewhat lighter than loading in extension You get a loop, and it is quite obvious that where this loop comes together at the bottom it always comes back to the same point, so that there a part of the slip you have is recoverable It seems to me a very important quality of the material if it can only be measured I wish this could be collated with the question of fatigue stresses

Mr BRAMSON I am no less appalled than the previous speakers by contemplating the enormous amount of work that is represented by this paper On such a subject I cannot contribute anything instructive to the discussion, so I will merely ask questions

Professor Lea mentioned that from a philosophical point of view it is difficult to conceive of a fracture occurring otherwise than by a slip I am not quite sure that I can follow him there Presumably the materials hang together because there is some sort of attraction between the molecules The whole question is extremely curious, and involves in the last instance an examination of the actual shape of the molecules Do materials hang together because of the actual shape of the molecules ? If so, a fracture means something different from what we suppose, and it seems to me that the fracture may not occur through the molecules separating I do not suppose anyone thinks that any molecules at the point of fracture are themselves fractured, because that would seem to indicate that the chemical construction would be changed

Can Professor Lea tell us what in actual practice is the number of repetitions of stress without fracture that is considered to indicate that the stress has been below a set limit ?

The CHAIRMAN (Dr THURSTON) The discussion has shown how greatly this masterly paper has been appreciated I read it through with great interest before the meeting, and even if I wished to criticise, I cannot see that there is anything that calls for criticism Professor Lea has given us a clear insight into many problems previously obscure, particularly the problem of cold working and heat treatment over ranges of 360 deg to about 460 deg cent He has shown the hardening up of materials which takes place, and pointed out that the problem is still open to a vast amount of research if full information is to be obtained to enable us to fathom the bottom of every problem which we can come across in the course of our daily work

One speaker referred to the construction of matter I myself am looking to the electro-magnetic theory of the construction of matter to solve many problems, and also to the use of X-rays to develop the theory of metal crystallography It would appear that there is a large field for experiment in these directions

PROFESSOR LEA'S REPLY TO THE DISCUSSION

I must first thank the speakers for their very kind response and remarks It is a very interesting subject and a very big one

Mr Collins raised an important point If we have a material in the Wohler machine being subjected to bending, and are quite sure that under the dynamic conditions the stresses are the same as they would be under ordinary conditions, we can then calculate the stresses, using the elastic theory

It is a matter of some difficulty, but if you take the machine and load it and use our optical methods for reading the strains in the specimen, it is found that the strains produced statically only differ in a slight degree from the strains produced while the specimens are revolving, so that the answer is in the affirmative within reasonable approximations , the errors certainly are not very great I do not think there is so much danger of error in bending as in torsion

Several speakers have referred to X-ray analysis Mr Bramson's question is relative to this subject Taylor and Elam have been examining the actual distribution of the molecules in the space lattice of aluminium and of iron before and after straining

Apparently, from their work on aluminium, strain does not change the space lattice Slips take place on certain definite crystal planes When an iron crystal is distorted in tension, slip does not take place along a definite plane, but the distortion may be likened to a bundle of rods which stick to each other in groups and slide on one another

Gough Hanson and Wright have shown that under repeated stresses that produce measurable strain the slips in aluminium crystals take place parallel to certain crystallographic planes

If, however, failure under repeated stresses is purely a matter of space lattice, why in certain circumstances do you get fractures taking place at apparently very much less stress than those we get in our machines ? A knowledge of the space lattice and its distortion apparently cannot answer that question If you have a sharp corner and a break, the fundamental failure whatever it may be in the space lattice does not apparently solve the problem That is one of the points I want to make—that the fundamental construction of the crystals (the space lattice of which we know in certain cases) establishes the fact that within that space lattice a slip takes place on certain definite planes, but that does not give us the final solution of our problem

We have another problem , the physicists will have to give us the final solution as to how a material really fails under stress, but even that will not probably finally solve the problem for the engineer, because he will still be up against the difficulty as to what stresses he will get with certain loadings and forms of elements

Replying to Mr Howard regarding the time factor, that is important, but I do not think it is as important as it might seem on the surface

Replying to Mr Duncan , he asked whether extension took place when the specimen was subjected to tension and compression ? The answer is, Yes The specimen referred to in the paper after 10,000,000 repetitions, elongated just enough to stop the machine , the movement was just enough for that to happen , we then adjusted the machine, and it continued to resist the stresses without further measureable extension I do not think the elongation took place on the first loading up, as the time is so rapid I think that when put on very quickly the material behaves practically elastically to quite high stresses Hopkinson showed a good many years ago that this was possible

Mr Duncan also asked what would happen if we put the specimen wholly in tension In a paper read at Toronto on the effect of repetition of stresses at high temperatures, we showed that, provided the stress was all in tension, the stress could be taken practically up to the breaking point of the material, and repeated millions of times Under these high tensile repeated stresses, the material crept, but provided that the stress was kept within a certain range, the creep would cease

Replying to Mr Duncan's question about streamline wires, I do not know much about that particular problem, but I think streamline wires do fail under vibration stresses We do not know what stresses are set up by vibration Where the wires change section there is probably concentration of stress, and fractures would occur at these sections

Professor Witchell asked about the limit of proportionality and hysteresis loops

I have never found a piece of material that gives a straight line if the test is made accurately enough Some of our experiments were made in a cellar where there was no vibration, the same cellar in which Professor Poynting measured the density of the earth Apparently, therefore, one does get perfect hysteresis loops Provided the stress is below a certain range, they always close and do not increase in area In connection with the work of Dr Howard and Dr Smith on hysteresis loops, I think that they do not take the time factor sufficiently into consideration

Professor Witchell asked whether it was necessary to get a straight line in order to avoid hysteresis Our work on torsion showed clearly that with ordinary instruments the stress strain diagram was apparently a straight line, but with more precise measurements, hysteresis loops were obtained One has to be careful in this matter as the time factor has to be taken into account

Mr Bramson's question as to " the number of repetitions of stress," etc , is best answered by reference to the curves given in the paper If a specimen resists ten million repetitions, the range of stress is not very different from what may reasonably be called the fatigue limit

The meeting was brought to a close with very hearty votes of thanks to Professor Lea for his valuable paper, and to Dr Thurston for presiding