Research and Failures of Metals in Service*

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INTRODUCTION

In common with scientific study in other fields, mechanical engineering research is often categorized as "fundamental" or "applied", although the sphere embraced by the former type is perhaps a little difficult to define. One somewhat crude way of differentiating between the two types is to estimate when the work is likely to find obvious direct application. If the answer is in ten years or more, the work is clearly fundamental; applied research, on the other hand, is always intimately associated with the current efforts of industry to provide an expanding economy with the necessities and luxuries of civilization.

One of the most direct ways in which the engineering industry creates problems for the research worker occurs when design overreaches itself, and some mechanical failure occurs. Failures of structural and machine components are, of course, of common occurrence, and existing knowledge of materials and their behaviour in service is often sufficient to explain them and provide a remedy. Occasionally, however, when the best available knowledge is brought to bear on a particular failure, some aspect of the trouble remains unexplained, and a deficiency of data is revealed; alternatively, a well known problem can be so disguised as to be not immediately recognizable. The purpose of this paper is to describe briefly some examples of mechanical breakdown of this type, and to draw attention to the programmes of research which have resulted more or less directly from them.

No mention will be made of "brittle fracture" in this paper. The conditions for fast fracture of mild steel plate have been studied intensively in many countries, and the literature of the subject is vast. These researches arose directly, of course, from the extensive damage to, and occasional loss of, ships, caused by unexpected and extensive cracking and tearing of the structure. It is now known that even in a material as ductile as mild steel, a crack will propagate at high speed when certain conditions relating to applied stress and crack length are fulfilled.

LABORATORY CONDITIONS

In the laboratory mechanical and other tests are made of materials under controlled conditions. Conditions, let it be admitted at once, that are rarely duplicated in practice. But the primary job of the research engineer is to try and understand what happens and why. To do this he must be able to separate variables and to investigate the simple case before he can begin to consider more complicated ones.

In the course of such work he may look on hundreds of fractures every year. In time he learns to associate certain features of fracture appearance with certain test environments and conditions. This is very much a matter of experience, both his own and that of other people, and a gradual and almost unnoticed absorption of knowledge. It is rarely possible to be dogmatic, for things are not always what they seem. The appearance of a ductile tension fracture is well known, and yet a fatigue specimen subjected to a comparatively few cycles of high stress may be very similar, although the operative conditions are very different. Fig. 1 shows a number of fatigue specimens, tested at a high tensile mean stress. The "cup and cone" tensile type of fracture will be noted. Again, numerous fine cracks, especially in mild steel, often regarded as indicative of corrosion fatigue may, in fact, be due to a large area of surface having been subjected to repeated high stresses in air. An example is shown in Fig. 2.

SERVICE FAILURES

A laboratory such as the National Engineering Laboratory is often consulted about failures, and such procedure is to be encouraged, for the more that are seen the more can be learnt; the greater the general store of knowledge, the greater the possibility of help being given in any particular instance. Because N.E.L. is in contact with many branches of industry, the variety is large exen if the total number is not very great.

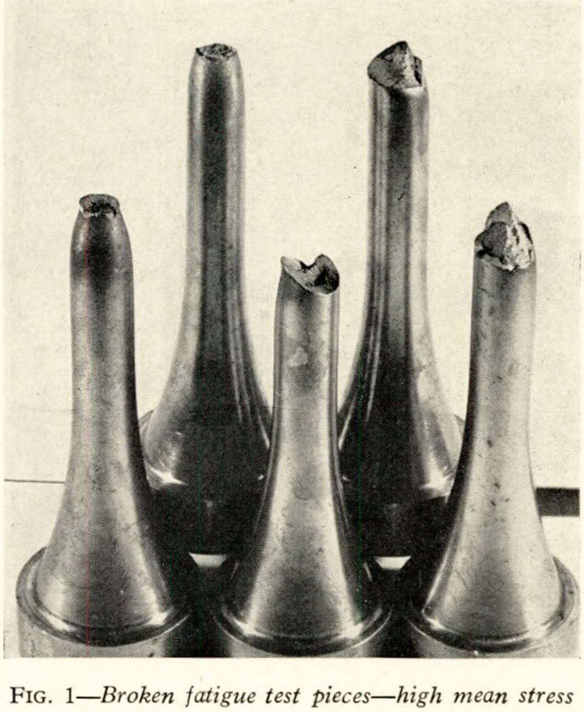

FIG. 1—*Broken fatigue test pieces—high mean stress*

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* Paper presented at a meeting of the Scottish Section of the Institute of Marine Engineers on 14th January 1959.

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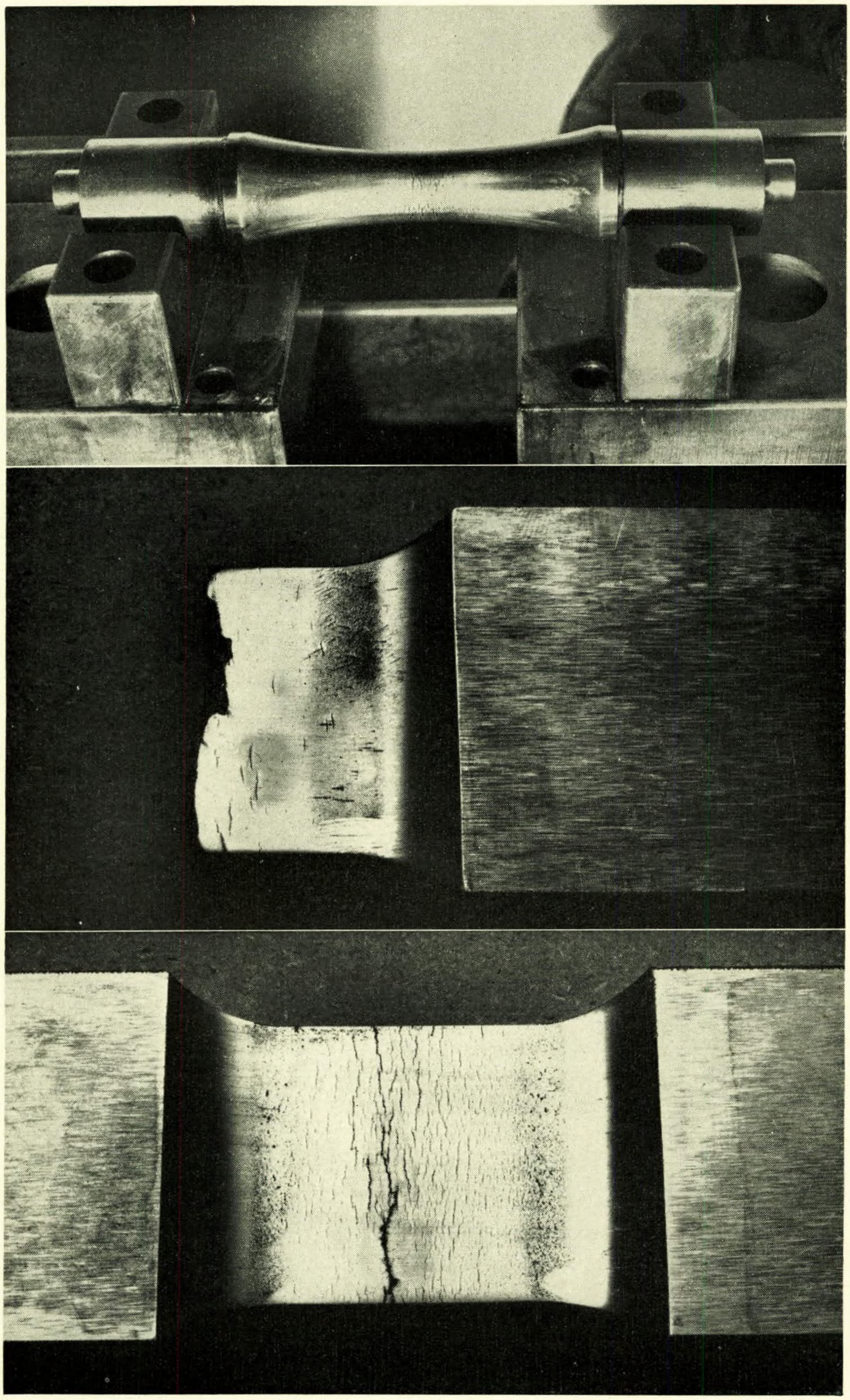


FIG. 2—*Fatigue in air—high stress level*

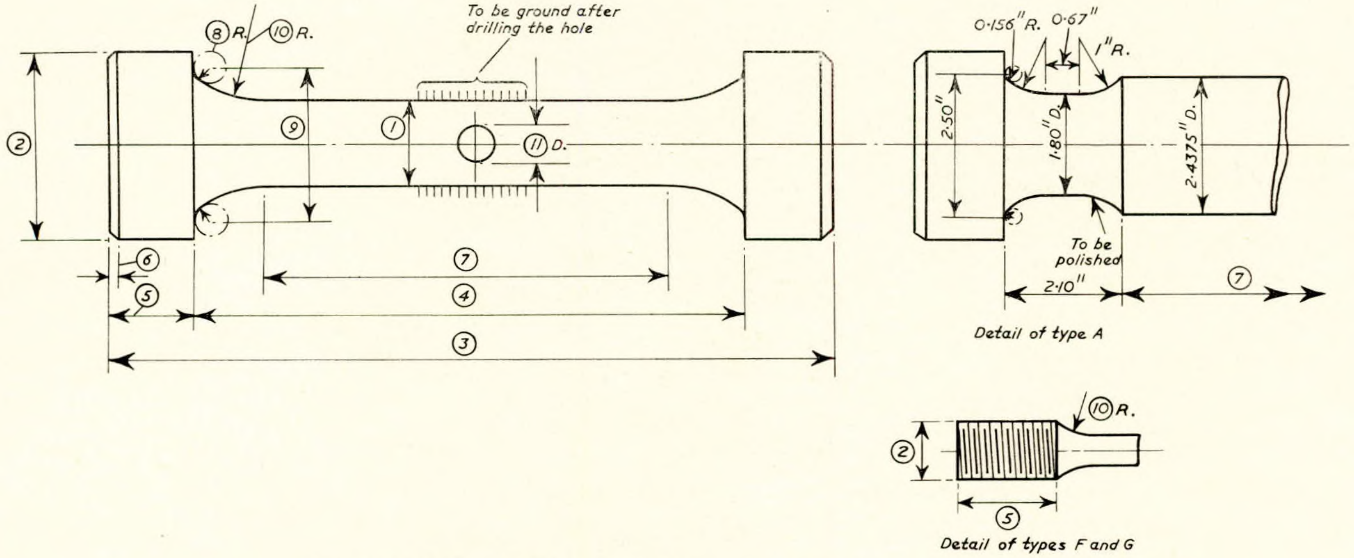


FIG. 3—*Transverse hole fatigue specimans for direct stress machines*

They have varied from clothes drier covers, 4ft. in diameter, down to pump spindles, ¼in. diameter; from leaf springs, 0·020in. thick, to flywheels, 4in. thick. But research establishments seldom see the more obvious failures such as those due simply to overloading.

The first examination of a failure is visual. It is surprising how much can be learned about a fracture just by looking at it, especially if it is viewed from different angles and with various lighting. By mentally associating fracture appearance with those of laboratory specimens, it is frequently possible to identify conditions which caused failure, even if only in general terms. The position of crack initiation and direction of propagation also give valuable help, and then consideration of the operating conditions may show whence the dangerous stresses are arising. Occasionally the fracture appearance is characteristic of certain specific loading conditions. As an example, the typical appearance of failures of splined shafts, due to occasional high loads, superimposed on more normal stress levels, can only be reproduced in the laboratory when such high loads are present. It is a most unfortunate fact, however, that the texture of a fractured surface of "as cast" material does not, in general, indicate clearly the loading conditions.

Here it is as well to stress a point which has been frequently mentioned, but which is still not as widely appreciated as it might be. Although it seems natural to suspect the material when a failure has occurred, the majority of failures are in material of normal and satisfactory quality. Rarely

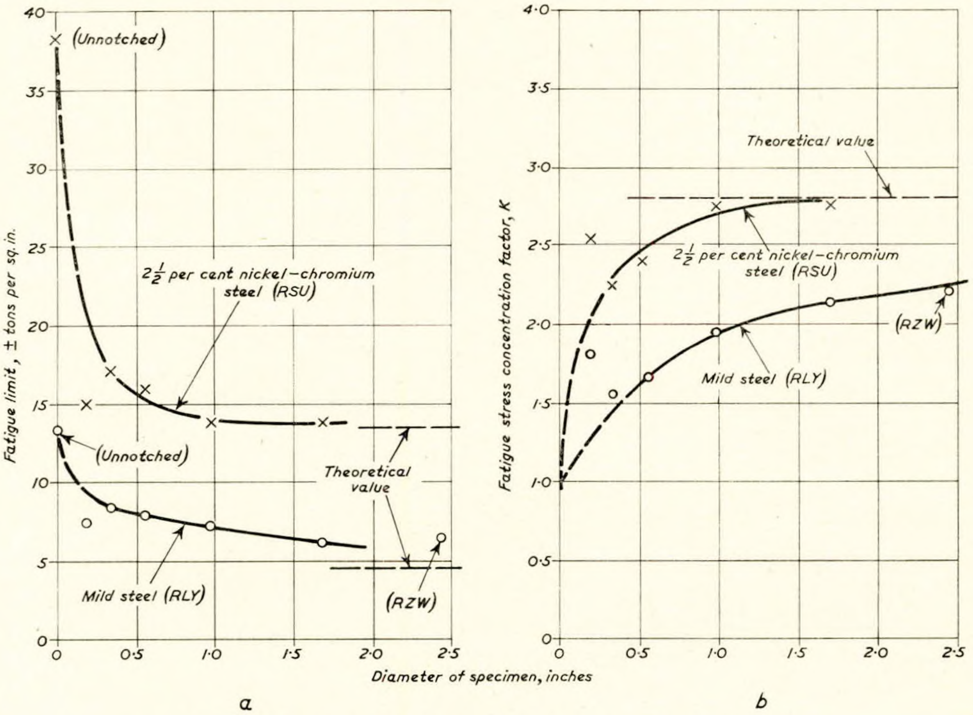


FIG. 4—*Effect of size of transversely bored specimens*
a) On the fatigue limit
b) On the fatigue strength reduction factor

is it possible to point to faulty material as the cause of failure. By far the greatest number are due to unsatisfactory design and some to faulty workmanship.

Effective design calls for a knowledge of the stress and environmental conditions under which an assembly is to operate and very often those conditions are either not known or their importance is not appreciated. Unsuspected transient stresses may be significant or the loading conditions so complex that an exact analysis is impossible; moreover, it would be idle to claim that the performance of any material is adequately known under all possible combinations of differing stress, temperature and environmental conditions.

SIZE EFFECT AND FATIGUE STRENGTH REDUCTION FACTORS

Cases have arisen in which a satisfactory design of machine had been progressively stepped up in size without any major trouble; then quite suddenly, after a further increase in size, a spate of fatigue failures developed. The same general problem has arisen in various guises and, in consequence, a number of studies of size effect have been carried out in many laboratories. At the National Physical Laboratory a series of geometrically similar test pieces of the form shown in Fig. 3, and with diameters at the centre ranging from $\frac{3}{16}$in. to $2\frac{1}{2}$in., was tested under direct-stress fatigue conditions(1,2). Because of the geometric similarity the theoretical stress concentration factor is the same for each test piece, but because of the difference in size, the stress gradient, for any given maximum stress, will be different, and this is reflected in a difference in fatigue strength.

In Fig. 4 we see these differences for the case of two steels; the theoretical stress concentration factor is 2·8. The $2\frac{1}{2}$ per cent Ni-Cr-Mo steel RSU had a tensile strength of 63 tons per sq. in. and an intrinsic fatigue strength for an unnotched test piece of ±38 tons per sq. in. The mild steel RZW had a tensile strength of 26 tons per sq. in. and a fatigue strength of ±13 tons per sq. in. On the left hand side are plotted the actual fatigue limits for the various sizes of test pieces. The smaller test pieces are stronger (in terms of stress) than the larger. On the right the same information is given in terms of the fatigue strength reduction factor; that is, the fatigue strength of the material divided by the fatigue strength of the drilled test piece.

The full effect of the hole is apparent with the Ni-Cr steel by the time the specimen diameter has reached $1\frac{1}{2}$in. The mild steel is still a long way off it at $2\frac{1}{2}$in. but the curve is still rising, and at a diameter of about 5in. the full effect would be felt. It can be seen that although it may not be economic to design small parts making full theoretical allowance for stress concentrations, to design large parts on the basis of results of tests on small test pieces may well lead to trouble.

CRACK INITIATION AND PROPAGATION

The effects of changes of section on stress distribution have been known for many years, and the work of Coker and Filon(3) on photoelasticity provided a most valuable tool in the study of notch effects. Fractures originating from notches or other changes of section are commonplace; moreover, occasionally the nominal stresses are low and a crack has progressed very slowly, sometimes taking many millions of cycles to travel completely across a section. In addition, inspection of components in service often reveals cracks which have formed, propagated a short distance, and then ceased to grow.

Until comparatively recently it was considered reasonable to regard a crack as the extreme form of a sharp notch and as such the strength reduction effect associated with it should be very high; it might therefore be expected that a crack should always progress rapidly even under low stresses.

A number of current researches(4, 5, 6) are throwing some light on this matter. It is now known that a crack is not necessarily the extreme case of a stress raiser under fatigue conditions as it would seem at first sight to be. In Fig. 5 and Table I are shown the results of fatigue tests on specimens with varying severity of notch. Although a crack may have a very high theoretical stress concentration factor it will be seen that less sharp notches can have a greater effect in lowering the fatigue strength. In Fig. 5 the area to the right of the peak in the curve is marked "non-propagating cracks". Laboratory work has shown that with a sufficiently sharp notch and appropriate stress conditions it is possible to initiate a crack in a test piece and yet to be quite sure that the crack will not propagate to failure, unless the applied stress range is increased. Studies of the conditions under which cracks propagate naturally follow, and recent work suggests that two critical stress levels must be considered in relation to fatigue fracture:

a) The stress necessary to initiate a crack, taking into consideration any stress raiser present.
b) The stress necessary to propagate the crack once it has been formed.

This is shown diagrammatically in Fig. 6, from which it can be seen that if the stress concentration is sufficiently great the stress to initiate may be less than the stress to propagate, with the result that a crack can start but not grow beyond a limited size. Hence, it is now not surprising to find that components

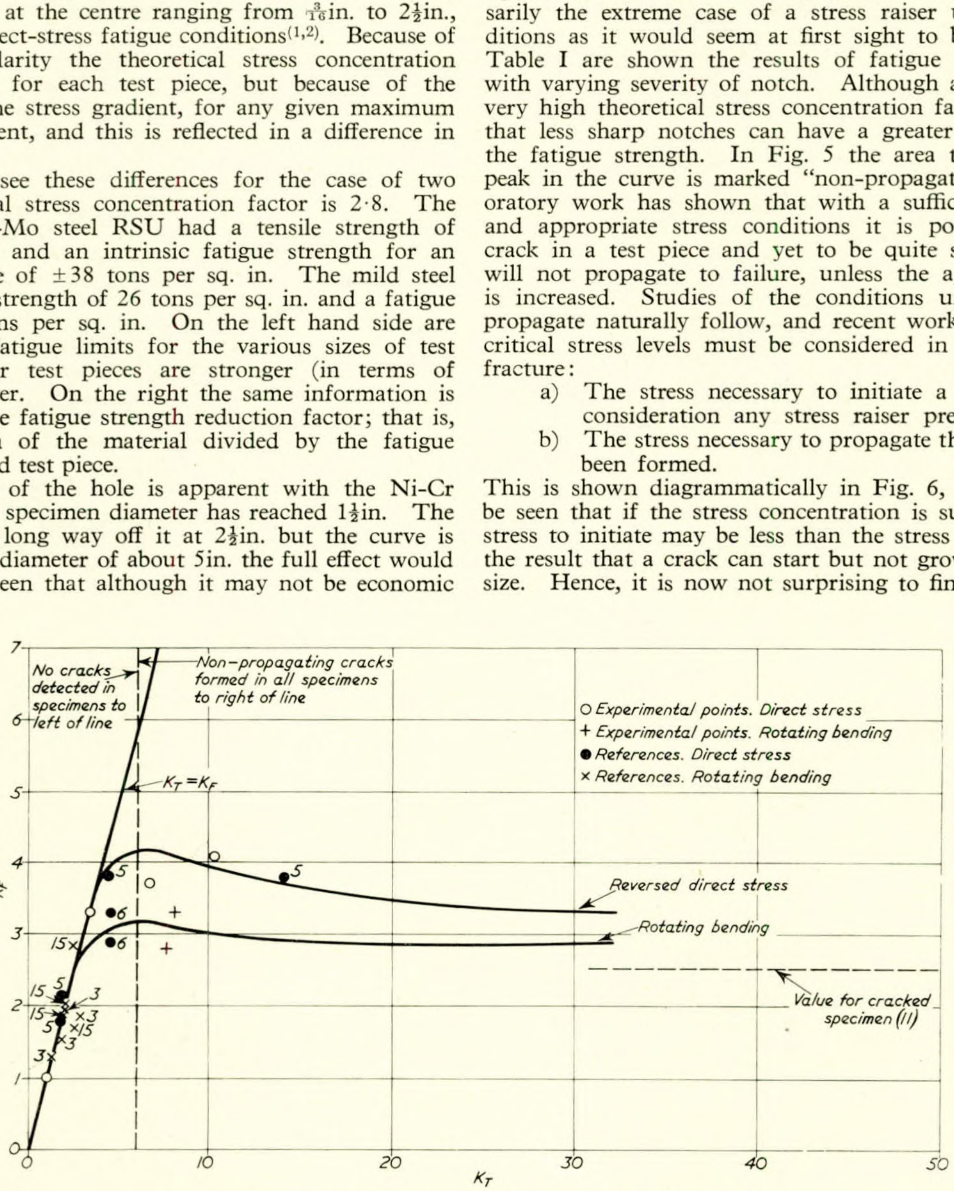
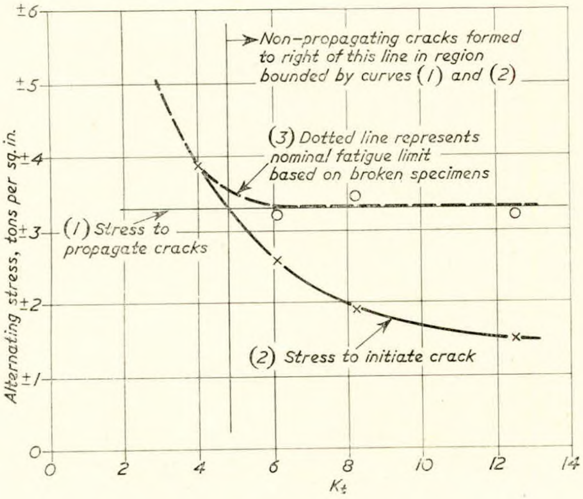


FIG. 5—*Relation between K_T and K_F for mild steel*

TABLE I.—FATIGUE LIMITS AND STRENGTH REDUCTION FACTORS.

Material	Mild steel		Nickel chromium steel		Aluminium alloy	
Type of specimen	Fatigue limit, tons/sq. in.	Strength reduction factor	Fatigue limit, tons/sq. in.	Strength reduction factor	Fatigue limit, tons/sq. in.	Strength reduction factor
Unnotched						
Rotating beam	±17·5	—	±36·5	—	±9·8	—
Direct stress	±14	—		—		—
*Vee notch						
Rotating beam	±4·25	4·1	±6·2†	5·8	±2·8	3·5
Direct stress	±3·9	3·6	±4·5	8·1	±2·5	3·9
Crack						
Rotating beam	±5·5	3·2	±13	2·8	±6	1·6
Direct stress		2·6				

*55 deg. Vee, 0·2 in. deep, 0·002 in. root radius.
†Root radius of 0·004 in.
±Endurance limit at 50·10⁶ cycles.



1) Stress to propagate crack
2) Stress to initiate crack
3) Dotted line represents nominal fatigue limit based on broken specimens

FIG. 6—*Fatigue strength and K_t for zero mean load*

which have given many years of satisfactory service may on examination prove to be cracked and apparently to have been cracked for some considerable time.

On the other hand, fractures are encountered in which the stressing conditions appear superficially to satisfy all the requirements for the formation of non-propagating cracks. The continued study of crack behaviour, however, has shown that mean stress can have a most significant effect. In mild steel sheet a crack will grow, albeit very slowly, under a stress range of $\pm\frac{1}{4}$ ton per sq. in. if a tensile mean stress of a few tons per sq. in. is superimposed. A practical case of some importance is that where bosses or rings are shrunk on to a shaft, as shown diagrammatically in Fig. 7. Although severe stress concentrations may arise from the geometry of the assembly, it might be thought that minute cracks, formed under very low operating stresses, would not propagate. It is reasonable, however, to postulate that the shrinking-on of the two rings induces tensile stresses in the surface between them; hence, even with very small service stresses, if the geometrical stress concentration effects are sufficient to initiate a crack, the shrink-fit conditions might well result in continuous crack propagation.

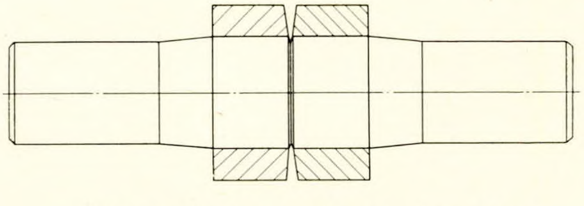


FIG. 7—*Specimen with shrunk-on rings*

In this connexion, laboratory tests have shown that an alloy steel shaft may have a bending fatigue strength of ±37 tons per sq. in. when unnotched, reduced to about ±5 tons per sq. in. with a sharp notch, but further reduced to less than ±3 tons per sq. in. when the notch is between two shrunk-on rings.

FRETTING

Difficulties arising from the mechanical interaction between two closely fitting metal surfaces which are subject to repeated small relative movement have created problems for designs for many decades. Fretting corrosion such as occurs between the plates of vehicle leaf springs can lead to a variety of troubles according to the site of the damage. Bearing housings may become worn and suffer loss of fit, or a shaft oscillated in a bush which would be quite adequate for unidirectional rotation may seize after a very short life. The most widely publicized case of damage due to fretting corrosion is that concerning the shipment of cars by rail in the U.S.A. Whilst standing on chocks in the moving freight wagons, the races in the wheel bearings were subjected to minute oscillations, with the result that, at the end of the journey, the tracks of the bearings were heavily pitted, and the bearings had to be renewed. Though not exactly a "failure in service", this and similar costly experiences have influenced some of the studies of fretting corrosion which have been made in comparatively recent years.

The first systematic study of the fretting process was made by Tomlinson, Gough and Thorpe at the N.P.L. in the 1930's(7), and among the numerous recent researches an extensive investigation using more modern techniques of analysis has been carried out over the last few years in the Lubrication Division of the N.E.L. The broad outline of the mechanism by which it occurs is now fairly well known.

However, one of the more insidious effects of fretting is its apparent influence in precipitating fatigue failure. Some service fatigue failures show unmistakable evidence that the origin of the crack was in a region where fretting corrosion has occurred. In a number of these cases, the available evidence regarding working loads suggests that fretting corrosion may result in phenomenally large strength reduction factors. It is ironical that the best quantitative estimates of the equivalent notch effects which may be ascribed to fretting have usually been obtained from laboratory fatigue tests where unwanted failures have occurred, for example, in specimen grips. Thus, even in research studies, fretting has been a thorn in the flesh for many a year—it is treated in some detail in a paper of 1911(8).

One of the puzzling features of fretting corrosion troubles is that many examples can be quoted where, although catastrophic failure has occurred under given conditions, an apparent repeat of those conditions can produce very similar fretting, but no failure.

Pin joints are well known forms of connexion. One particular joint (not a vital one) in an aircraft was found to be failing after a very short life, and routine replacement after a hundred or two hundred hours flying time was practised. Laboratory tests(9) showed the fatigue strength of the joint to be less than one-twentieth of the intrinsic fatigue strength of the minimum cross section. The adoption of interference-fit pins, instead of push-fit ones, increased the strength by a factor about 8. In all of the samples, fretting occurred between the pin and the hole, and it may be significant that increasing the degree of interference fit reduced the fretting as well as (in general) increasing the fatigue strength. It may, of course, be noted at this point that the interference fit superimposes a new system of stresses upon the complicated system represented by a loaded sliding-fit pin in a hole, and the improvement in strength may stem entirely from more favourable contact stresses at the interface. Conversely, in the worst cases of fatigue influenced by fretting, there is no case as yet proved against corrosion as an agent in initiating failure.

In the course of these pin joint tests, several "accidental" failures were experienced of the type illustrated in Fig. 8. Before development of failure at the hole, the steel fork made contact with the aluminium alloy tongue and initiated a fracture away from the hole; in some cases, the fracture passed through the full section of the tongue. With a uniform stress system the section would almost certainly have been able to sustain repetition of a range of load fifteen to twenty times that which actually caused failure. As a result of these experiences, in addition to its known importance to the aircraft industry, a study of fretting in relation to fatigue failure which is currently being pursued at N.E.L.(10, 11) has been concentrated primarily on an aluminium alloy. This research is by no means the first in this particular field, but the methods employed have opened up several promising lines of enquiry.

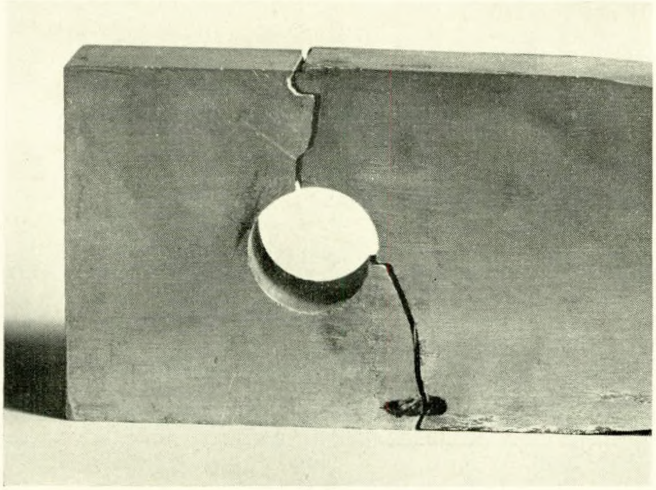


FIG. 8—*Pinjoint specimen fractured from a fretting mark*

By employing as the fretting device a bridge spanning a length of the test piece, which then frets by reason of the alternating strain in that length, it has been possible to vary the mechanical conditions of the fretting system, e.g. contact pressure, range of relative surface movement, and even the direction of this movement by invoking lateral contraction of the test piece under tension. Results obtained so far have shown that, under a fairly high tensile mean stress, the permissible range of applied stress can be reduced to about one-sixth of the range for a specimen not fretted. Under the particular contact pressure employed for most of the work, the damaging influence has been found to be comparatively small if the range of fretting movement is very small, but to increase sharply as this range of movement is increased up to about three to four ten-thousandths of an inch. Thereafter, with further increase in range of movement up to about 0·0015in., the high "equivalent notch" value is maintained, though there is much evidence to suggest that with little further increase in fretting slip the fatigue range would be greatly increased.

Understandably, variation of contact pressure reveals no simple consistent trends—probably owing to the severe perturbations of the stress system which the higher contact pressures must induce.

By interrupting fretting tests and removing the clamps at various stages, a critical stage in the damage process has been demonstrated. If fretting is allowed to persist for more than about one-fifth of the life, the endurance is about equal to what it would be if the fretting were continued to fracture, though discernible fatigue cracks may not be present at the time of removal of the fretting device. On the other hand, earlier removal of the clamps will result in a life more or less equal to that for a test piece tested at the same stress without fretting. Though visible surface damage has been caused, its influence on fatigue strength is negligible.

One attractive feature of the method being employed is that it is entirely self-contained and it has been found possible to enclose the specimen and the fretting device completely for the purpose of controlling the test environment.

A few tests have already been made in vacuo. These accord with similar physical studies of fretting in showing that surface damage may be increased by excluding oxygen, though corrosion as such is suppressed. The increase in fatigue life found under one particular set of fretting conditions was not entirely expected. The further tests which are proposed utilizing this apparatus may provide some useful pointers to new methods of alleviating the worst effects of fretting.

STRESS HISTORY EFFECTS

As already mentioned, the service loading of machine elements is very rarely of a uniform character. Loading cycles vary, occasionally in a predictable manner, more often in a random manner. Marine engines are rather an exception in this case, where a very large proportion of their working lives are spent operating at a more or less steady stress range. But a lorry travelling along a road, an aeroplane in flight, or a bridge, are in a different category. With an aircraft, some of the loadings and their sequence may be predictable, e.g. ground run, taxi, take off, but the sequence of airborne stresses is not so predictable. From many measurements of aircraft something is now known about the magnitude and frequency of occurrence of flight loads, but their distribution, in time and order, is inevitably of a random nature.

The effect of variable loading on fatigue strength of metals is something about which little as yet is known, and is a major gap in our knowledge of mechanical properties of materials. The magnitude of the problem can be seen at a glance. It is rarely economic to design, for example, a transport vehicle or bridge, such that any stress applied to it throughout its projected life, even if of rare occurrence, is below the fatigue strength of the assembly. Once this is agreed, then the design becomes one for limited life, and some knowledge of the effect of occasional stresses above the fatigue limit is required. But, for any given material, the number of possible combinations of stresses and endurances are infinite, and it has already been shown that the order in which different stress values are applied can be of paramount importance. No reasonably large scale attack on this problem has yet been made, but at this very moment a committee of the Organisation for European Economic Co-operation is formulating a programme whereby the testing of several thousand test pieces of each of two or three materials will be shared amongst several countries. The programme, in brief, is to determine the S/N curve for the material, select specific stress levels and endurances, and to carry out damage treatments involving all possible combinations of these stresses and endurances. The residual S/N curves, obtained from unbroken test pieces, will be used for assessment of fatigue damage. It is hoped that an attack on this scale will yield generally useful results; hitherto only comparatively small investigations of limited scope have been carried out.

CORROSION FATIGUE

This is a phenomenon that requires no introduction to marine engineers who often have to contend with a very corrosive environment. With a combination of fatigue stresses and corrosion attack, cracks may start and spread much more rapidly and at lower stresses than they would in the absence of corrosion. Research has shown that it may be impossible to obtain an unlimited life with certain combinations of material and corrodent, no matter how low the applied stress. If the corrosion products are soft and can be washed away, or brittle so that the applied strain cracks them, then the coating of corrosion products will be continually broken and further corrosion occurs. If the corrosion forms a tough adherent coating, then it is possible for corrosion to be so retarded that a reasonable range of stress can be withstood.

The major difficulty in linking research with service failures due to corrosion fatigue is that of exactly duplicating service corrosion conditions in laboratory tests; small changes in conditions can, in some cases, result in a large difference in behaviour. An example is shown in Fig. 9 which shows the results of corrosion fatigue tests of a 0·3 per cent carbon steel in an environment of salt spray. In the lower curve the spray was arranged to impinge directly on the test piece, while in the case of the upper curve the nozzle was lowered so that direct impingement did not occur, but the test piece remained in a salty mist. The general effect of palliative measures, e.g. various coatings, can be explored by laboratory experiment, but direct application of the results of such experiments to design problems is rarely possible.

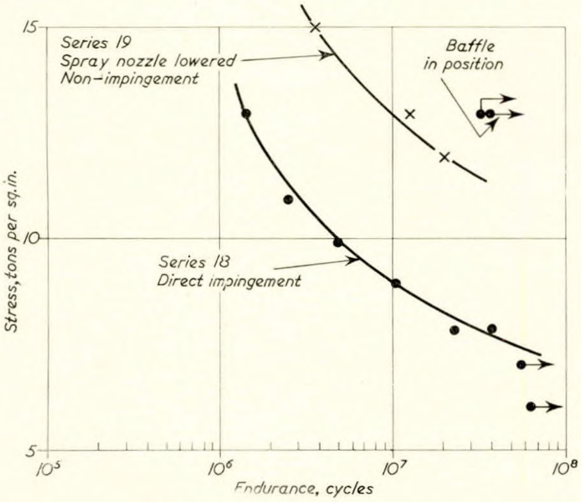


FIG. 9—*Rotating bending fatigue tests on 0·3 per cent carbon steel (uncoated). Tests in salt spray*

FAILURES AT HIGH TEMPERATURES

The mechanism of failure of engineering components which operate at high temperatures tends to be more complex to analyse than that of failures at atmospheric temperatures, since, in addition to the raised temperature influencing the conventional properties, other effects are introduced. Thus creep, which usually is negligible at room temperature, may become predominant, and the medium (even a gaseous atmosphere) in which the component operates, may contribute to the failure. There is also the probability of prolonged soaking at high temperature permanently altering the structure of the material, e.g. the type, form, distribution of certain phases, may be progressively altered during the life of the component with resultant changes in mechanical properties. These changes may contribute to failure at high temperatures or may alter the room temperature properties of the component in ways which may make failure more likely under special conditions on return to room temperature. It will be convenient to discuss failures of high temperature materials under six general headings:

a) *Creep and rupture*
b) *Mechanical fatigue*
c) *Thermal shock and fatigue*
d) *Surface attack*
e) *Structural instability*
f) *Embrittlement*

Failure of high temperature materials may be due primarily to any one of these causes, but often several of these effects contribute to failure.

a) Creep and rupture

It is convenient to distinguish between creep failures and rupture failures by defining the former as failures due to slow deformation and the latter as failure due to cracking under creep conditions. An example of the former is the deformation of pipe flanges leading to leakage in steam lines; the great deal of experimental work on model flanges, and the analytical work, done by the Pipe Flanges Research Committee(12) are evidence of how complex deformation of engineering components may be at high temperature. An example of failure by rupture occurred in the gas turbine engine when there were numerous instances of cracking in blade root fixings; in addition to extensive rupture tests on model blade root assemblies (see Report of Disc Panel Sub-Committee(13)), analytical and photoelastic determinations of stress concentrations were used to investigate the stress conditions causing failure, and in extreme cases, loss of a complete blade from its root fixing.

b) Mechanical fatigue

The most notable example of failure due to mechanical fatigue at high temperature is probably cracking of gas turbine blades, due to gas bending stresses and vibration, although the steady stress due to centrifugal loading makes the system one of combined creep and fatigue. In this connexion much work has been done by Tapsell(14) on the effect of frequency, which has been found to be specially important in fatigue at high temperature.

c) Thermal shock and thermal fatigue

These terms have come into common usage, although failure is caused by mechanical stress just as in (b), the difference being that in the present instance the stresses are induced by thermal gradients within material instead of resulting from externally applied forces. Failure from thermal shock has delayed the use of cermets in gas turbine nozzles and blades, since these materials are usually very susceptible to the rapid thermal changes which may occur in gas turbines. The term "thermal shock" is usually restricted to brittle cracking resulting from one or a relatively few but severe thermal cycles, whereas "thermal fatigue" describes cracking under a considerable number of more moderate thermal cycles. Instances are not infrequent in steam power plant and gas turbine components; the subject has been reviewed and experimental techniques used to investigate it described by Coffin(15).

d) Surface attack

The most common form of this is oxidation in air but many other atmospheres lead also to surface corrosion. The more serious forms cause intergranular penetration and cracks which are progressively opened by the stresses present in the material. Examples of failure, primarily due to surface attack, range from excessive loss of metal due to uniform scaling of carbon steels during prolonged heating above, perhaps, 500 deg. C. (932 deg. F.), to severe intergranular attack of highly-alloyed high temperature materials in gas turbines by vanadium pentoxide derived from the fuel; the latter subject has recently been reviewed by Sachs(16).

e) Structural instability

This is not strictly a different type of failure from those dealt with in (a)-(d), but may be a prime cause of failure in types (a), (b) and (d); it is listed separately to emphasize its importance in certain instances. A notable example is the occurrence of cracking in ½ per cent molybdenum steam pipes due to spheroidization and, ultimately, graphitization of the carbides. The phenomenon and its cause have been discussed by G. V. Smith(17). It should be emphasized, however, that not all structural changes occurring under creep conditions are deleterious—on the contrary, many of the most important creep resisting alloys derive their continued strength at high temperatures from gradual structural changes occurring throughout the life of the component. The subject is a complex one but its importance may be gauged from the fact that a considerable part of a recent Conference on Precipitation Process in Steel, held at Sheffield University, was devoted to discussion of these changes in high temperature steels.

f) Embrittlement

Again, this is strictly to be included in type (e), but it is convenient to list it separately to illustrate certain features of some high temperature materials which may lead to failure in special circumstances. The embrittling process, which occurs in prolonged soaking at high temperature, may cause brittleness either at high temperature or at atmospheric temperature. An example of the former is the marked reduction of rupture ductility shown by certain austenitic steels at long testing times; this is generally regarded as due to precipitation of carbides or a very brittle phase, called sigma phase, at the grain boundaries.

On the other hand, embrittlement may be apparent, not at high temperature, but on return to atmospheric temperature after prolonged soaking at high temperature. A recent example of this phenomenon occurred in the application of titanium alloys to gas turbine compressor blades and discs. This effect was most conveniently demonstrated in the laboratory by notched tensile tests at room temperature and the prime cause is now believed to be precipitation of a titanium hydride during prolonged exposure to high temperature. This has resulted in a limit being placed on the permissible hydrogen content of commercial titanium alloys.

This brief discussion of failures of high temperature components may help to illustrate the complexity of the phenomena operative at high temperature and the diversity of laboratory work required to elucidate them.

METHODS OF IMPROVING STRENGTH

Some years ago, an American motor manufacturer, as a result of repeated failures of his vehicles' springs, was comparing the behaviour of springs supplied by different works. One supplier's springs gave consistently longer service life than the others. The only difference that could be found in the method of manufacture was that he cleaned the furnace scale off the wire with a jet of sand or abrasive. Thus was founded shot peening. Research workers eventually produced the information on which today's production process of shot peening highly stressed parts is based.

Shot peening improves the fatigue strength by work hardening the surface layers and inducing favourable internal stresses, and since fatigue failure usually starts at the surface an improvement in strength at the surface can often go a long way to raising the fatigue strength of the entire part. Similar considerations apply to surface rolling, which has been very successfully applied to many products. The fatigue strength of a screw thread can be increased by as much as 100 per cent by cold rolling; the rolling of fillets has led to very useful increases in strength of automobile crankshafts without increasing the overall size.

Much has been written about the other common methods of increasing surface strength, *viz.* case hardening, nitriding, flame hardening, and it seems that no important development in this field is likely to occur in the near future.

GENERAL REMARKS

Failures in service occur at the present time more frequently than is strictly necessary. Also, there is no doubt that some failures will continue to occur and so give rise to applied researches of the kind touched on above.

Efficient design demands that less and less use be made of "factors of safety" to take account of lack of knowledge, but designers will still not be able to determine the precise patterns of stress, temperature and environmental conditions to which machine and structural components are to be subjected. Even if this could be done, the reaction of any given material to that pattern of conditions will remain an unknown quantity at least for a very long time.

ACKNOWLEDGEMENTS

This paper is published by permission of the Director of the National Engineering Laboratory. The authors acknowledge the assistance of their colleagues, whose work has been freely drawn upon.

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