CHAPTER VI
FACTORS AFFECTING TEST RESULTS

SECTION 60. GENERAL
When Wohler in 1852 started the first fatigue test, his aim was to find out how different materials responded to different ranges of stress reversal. These two factors, the material and the stress amplitude, are still the main factors in any fatigue test, although Wohler himself very soon realized that other factors, for example, the mean stress, had some influence on the result.

Since then the number of factors known to influence the behaviour of the test piece has increased manifold. It has also become apparent that minor differences in them may frequently cause considerable differences in the fatigue life. A review of the early literature discloses wide variations in results owing to lack of understanding of the important influence of many factors. This neglect is quite understandable, considering the difficulties involved first in suspecting which they are and then in discovering their quantitative effect.

It is now quite clear that in a fatigue test there is a number of extraneous factors which must be kept constant if large variations in results are to be avoided; or at least they must be known and specified if the observed results are to be interpreted properly. Their effects on the test results will be discussed in the following sections of the present chapter.


SECTION 61. MATERIAL

61.1 Composition and Heat Treatment
For many test purposes a material is sufficiently well defined by its composition and heat treatment, and for standardized materials these are most easily indicated by various symbols and abbreviations.

The composition limits of steels, standardized by the Society of Automotive Engineers and the American Iron and Steel Institute together with corresponding SAE and AISI numbers, for example, will be found in the ASM Metals Handbook, 1948 edition, pp. 307–308. General principles of heat treatment and individual specifications for different groups of steels according to the above specifications are given on pp. 607–632.

The composition of aluminium alloys, standardized in the U.S.A. with corresponding designations for trade name, ASTM number, Government number, and foreign equivalents, are presented in data sheets on pp. 810–840 of the book cited together with temperature ranges for heat treatment and the physical properties thus obtained. General principles for the heat treatment of aluminium alloys are discussed in an article on pp. 775–777 and temper designations for aluminium alloys are listed on pp. 806–809.

An index of British Standards and Aircraft Specifications for aluminium and its alloys is given in a publication by the Aluminium Development Association. Other references are to be found below.

For some test purposes a more elaborate description of the material and its properties is needed in order to distinguish between nominally identical materials and to understand the subtle but important factors of quality which cannot be explained by the composition of the material as ordinarily reported in the usual analysis.


61.2 Structure in General—Grain Size
The structure may be regarded from three levels of observation: the macroscopic, the microscopic, and the submicroscopic. The first level is characterized by visual observation, the second by the requirement of special equipment (microscopes and X-ray diffraction pattern), and the third by the statement that structural changes cannot be observed directly. For the present purpose, the microscopic level will be the only one that will be considered.

If a polished and etched surface is examined under a microscope, a network of crystal grain boundaries is observed. The size of the grains thus detected has been found to have a marked influence on the quality of the material which could not be explained by the composition alone. A measure of grain size was therefore strongly needed. The actual units employed in such estimates of grain size vary from country to country.

The most usual terms for grain size are:

(i) number of grains (n) (per mm2);
(ii) average area of grain (in mm2);
(iii) mean diameter (arithmetic or geometric) of grain;
(iv) an arbitrary number (N).

For example, the Timken, ASTM, index of grain size is defined by

\[ N = 1 + \log n/\log 2 \]

where \( n \) = number of grains per \( \text{in}^2 \) at a magnification of 100.

The number \( n \) is estimated either by counting the number of grains over a known area of image at known magnification or by matching the microscope image with charts that have standard graded patterns of an idealized hexagonal network. If the magnification is lower or higher than 100, say 100k, the index \( N \) may be computed by

\[ N = 1 + \log (nk^2)/\log 2 = 1 + \log n/\log 2 + 2 \log k/\log 2 \]
61.3 Inclusions and Inhomogeneities

The influence of inhomogeneities caused by the presence of slag, oxides, sulphides, and the like, depends more upon their shape and distribution than on their size. They must be considered in relation to their effect on the behaviour of the surrounding matrix. Stryi (1951) found, for example, that high-strength hard steels are more adversely affected by inclusions than a low-strength ductile steel. According to Grant (1950), specially treated cast iron with spheroidal graphite exhibits a fatigue strength which is definitely superior to that of the same cast iron with the same tensile strength but with the characteristic stringy dispersion of graphite flakes.

The effect of inclusions on the endurance properties of steels has been studied by several investigators, among whom may be mentioned Stewart and Williams (1948) and Ransom (1954). A comprehensive programme of fatigue tests has been carried out by Frith (1954) who aimed at establishing more definitely the influence of various metallurgical factors, including non-metallic inclusions, on the behaviour of steels in service. One result of Frith's work was that only certain types of inclusion, particularly non-deformable spherical silicates, were found to be harmful.

An unusually large test series, involving more than one thousand smooth specimens, has been carried out by Cummings, Stulen and Schulte (1953, 1956) for the purpose of clarifying how non-metallic inclusions act as microscopic stress-raisers. Some of the important results will be reported here. All the specimens were taken from a single heat of SAE 4340 aircraft quality steel, heat treated to give nominal ultimate tensile strengths 140,000, 190,000 and 260,000 lb/in². The inclusions, identified as complex manganese alumino silicate type, were essentially spherical in shape with no appreciable elongation in the longitudinal direction. The size of each inclusion from which fatigue failure has originated was measured. The geometric mean diameter, defined by multiplying the length normal to the specimen surface by the width parallel to the same surface and then taking the square root of this product, was used as a measure of the size. None of the inclusions was larger than 0.0025 in. in diameter, about half were somewhat over 0.0010 in., and the other smaller down to about 0.0004 in.

A plot of inclusion size against kilocycles to failure showed strong correlation for a set of 170 specimens of 140,000 lb/in² ultimate tensile strength, stressed at 86,000 lb/in² as estimated by the nonparametric corner test (see Section 90.8), the fatigue life increasing with decreasing diameter of inclusion. This simple correlation was not so apparent at high stress levels, at least not in the case of steel of the same quality, heat treated to 190,000 lb/in² ultimate tensile strength, probably owing to the fact that multiple nuclei appeared in increasing numbers of specimens as the stress level was increased. The average number of nuclei, being only one per rotating-beam specimen (190,000 lb/in² ultimate tensile strength) at alternating stresses from 93,000 to about 120,000 lb/in², increased gradually to 12—14 at an alternating stress of 180,000 lb/in². These nuclei of failure cracks were in all cases close to the surface, but in some cases a rather large inclusion appeared in a nucleus at a measurable distance (some thousandths of an inch) below the surface in long-lived specimens. It is possible that, at higher stress levels, other microscopic stress-raisers than inclusions might have been responsible for the fatigue failure, as suggested by Dieter and Mehl (1953). The appearance of multiple nuclei at higher stress levels has also been observed by Marco and Starkey (1954).

References: Cummings, Stulen and Schulte (1955), Dieter and Mehl (1953), Frith (1954), Grant (1950), Marco and Starkey (1954), Ransom (1954), Stewart and Williams (1948), Stulen (1951), Stulen, Cummings and Schulte (1956), Stryi (1951).

61.4 Structural Surface Conditions Produced by Heat Treatment

The heat treatment may have the purpose of improving the structure of the material or relieving stresses after turning or polishing, but it is sometimes accompanied with the detrimental effect of decarburization. Hanks and Becker (1931) and Hanks, Becker and Mills (1935) were among the first to study this effect on the fatigue resistance of steel. They found that
the decarburized material had poorer durability at all stresses. There are many investigations which support this opinion, including those reported by Jackson and Pochapsky (1947) and by Garwood, Zurburg and Erickson (1951). There are, however, other tests which have exhibited little or no effect of decarburization (Weibull, 1952) and even a beneficial effect, as found by Gill and Goodacre (1954). Decarburized wires showed a greater fatigue strength than homogeneous wires at high stresses.

The detrimental effect of decarburization is usually eliminated by grinding and polishing. The effect of grinding on the physical properties of hardened steel has been examined by Boyer (1948).

Modern heat-treatment methods, however, have made it possible to keep the finishing to a minimum after heat treatment. In many applications, no post-heat-treatment finishing is required. In view of this trend, Robinson (1957) found it desirable to investigate the manner in which the metallurgy of the first few thousandths of an inch of material at the surface influenced the properties of the test piece. Three factors were studied, namely: (i) surface decarburization on spring steel; (ii) network carbide in a carburized case; and (iii) subsurface oxidation, often observed in the carburized case of steels treated in conventional carburizing media. One remarkable result of this investigation was that the effect of surface decarburization depends on the magnitude of the test stress. At a stress level producing failure in 50-100 kc. decarburized steel showed a superior durability. At lower stress levels near the endurance limit, surface decarburization was shown to be detrimental, and slight reduction in surface carbon content appeared to lower durability as much as severe decarburization. The effect of carburization has also been studied by Roberts and Mattson (1957) who investigated the influence of material composition, case depth and section size, tempering, refrigeration, and electro-polishing. They found that removing 0.002 in. from an as-heat-treated surface by electropolishing is tantamount to removing material that is damaging to fatigue properties.


61.5 Structural Surface Conditions Produced by Mechanical Treatment

Cold working generally improves the fatigue strength. It is not quite clear whether this effect is caused mainly by an improvement of the material owing to reduction of the crystallite size or mainly by residual stresses, but probably both effects are important.

The effect of shot-peening has been studied by Almen (1943) and also by Mattson and Coleman (1954). The beneficial effect of this surface treatment as well as such treatments as polishing, carburizing or nitriding depends, according to Almen (1950, 1951), upon the fact that the surface material is inherently weak but is improved by these treatments both by phase transformation of the material and by residual stresses. The separation of these two effects on the phenomenological scale is very difficult. Combs, Sherratt and Pope (1956) conclude that removal of material from the surface layers of a shot-peened specimen results in a variation of fatigue life at constant stress. The life increases up to a maximum value several times as great as that for a peened or an untreated polished specimen, and then decreases again to values commensurate with those of untreated polished specimens of the same diameter. Great care must be taken in establishing peening conditions since, if the material is overpeened, surface cracks will occur and some of the beneficial effects will be lost. The correct conditions vary considerably with the hardness of the material to be treated. Lessells and Brodrick (1956) found that shot-peening, if properly controlled, considerably improves the fatigue strength of subsequently damaged surfaces. These benefits were more marked as the hardness of the steel was increased. Improvements up to 110 per cent were observed.

The beneficial effect of surface-rolling on the fatigue strength of large axles has been demonstrated by Horger and Maulbetsch (1936) and Buckwalter and Horger (1937). Fatigue strength of screw threads before and after prestressing with rollers has been determined by Almen (1951) who found that the fatigue durability was greatly increased by this treatment. References: Almen (1943, 1950, 1951), Buckwalter and Horger (1937), Combs, Sherratt and Pope (1956), Hempel (1937), Horger (1935), and Maulbetsch (1936), Lessells and Brodrick (1956), Mattson and Coleman (1954).

61.6 Structural Changes relating to Size of Test Piece

The effect of size on fatigue strength is a complex problem. It frequently depends both upon structural changes in the material and upon the "statistical size effects". Only the former effect will be discussed here. The latter effect will be discussed in Section 63.1.

The best known effect of size on the strength properties of a material relates to cast iron. It is an old observation that its strength is in general much better in bars of small than of large diameter. This effect is readily explained by the difference in cooling rate. An investigation separating this effect from the statistical effect has been carried out by Meyersberg (1952) by means of different types of static tests.

In the same way, the effect of heat treatment of the material may depend on the size, and fabrication processes such as rolling and wire drawing may turn out products which differ with regard to the material owing to the dimensions.

A comprehensive survey of fatigue characteristics of large sections has been presented by Horger (1954). Investigations into the composite size effect have been performed by Horger and Maulbetsch (1936) who compared their early work on size effect in plain specimens with that reported by Peterson (1930). They found that in general the fatigue strength of 0.3-in. plain specimens is 10 to 15 per cent higher than that obtained for specimens of about 1 in. diameter. Other investigations to be mentioned are those by Buckwalter and Horger (1937), Moore and
Morkovin (1943), Morkovin and Moore (1944), Moore (1946) and Moore, Dolan and Hanley (1948). There again specimen sizes of 0.125 in. showed as much as 15 per cent higher values than 1-in. specimens in the case of some materials, while for some others the decrease was much less. Horger and Neifert (1952) found that plain specimens 6 in. in diameter had a minimum endurance limit 35 per cent lower than that found for the conventional 0.3 in. diameter plain specimen from untreated steel. No significant size effect was exhibited however, between geometrically similar fillet specimens from normalized and tempered steel 1% and 5% in. diameter for two r/f ratios. A hypothesis to explain the effects of size of specimens has been suggested by Yen (1950).

References: Buckwalter and Horger (1937), Horger (1954), Horger and Maulietsch (1936), Horger and Neifert (1952), Meyersberg (1952), Moore (1945), Moore, Dolan and Hanley (1948), Moore and Morkovin (1943), Morkovin and Moore (1944), Peterson (1930), Yen (1950).

61.7 Structural Changes caused by Preloading and Prestressing

Crystalline structure in relation to preloading was studied by Gough (1938). Structural changes in ingot iron caused by repeated plastic stressing were studied by Horger (1938). Similar studies have been made by Bollen, Head and Wood (1953). Observations on the fatigue process in pure aluminium were made by Forsyth (1952), who also compared the behaviour of cold-worked pure aluminium and age-hardening alloy (1956). He found that both materials developed soft spots under the action of fatigue stresses, the cold-rolled material by locally recrystallizing and the alloy by an over-aging process. Both of these processes are described as "shaking down" processes. Thompson (1956) has attempted to detect the beginning of a fatigue crack as early as possible, and to follow its gradual progress in copper and in nickel. This has been done by a careful and thorough microscopic examination. The interpretation of the observations is that the crack starts in a slip-band, in a single grain, at an early stage of the test. The presence of the crack produces a region of low stress on either side of itself, so that further slip is inhibited there. Near the tips of the crack, the stress is increased so that an extra dense patch of slip is produced, through which the crack propagates further. The changes in hardness during fatigue tests on copper have been examined by Davies, Mann and Kemsley (1956) and the influence of preloading and prestressing on the fatigue life by Drozd, Gerold and Schulte (1950).


61.8 Anisotropy

The importance of anisotropy as a factor influencing the fatigue strength has been recognized for a long time, and also that all real materials are anisotropic on a microscopic level of observation. For the present only macroscopic anisotropy will be considered; that is, a material may be regarded as isotropic if it has the same fatigue properties at all points and in every direction, even if it has microscopic stress raisers dispersed over the volume.

Two different types of anisotropy may be distinguished: location anisotropy and direction anisotropy. The first type is represented, for example, by a material having spherical inclusions of different density in different parts of the volume. Considering the fact that the surface material is inherently weak, as pointed out by Almen (1950) and substantiated with the observation that fatigue strength is improved by cold working, shot-peening or nitriding which makes the surface more fatigue resistant, it could be postulated that all specimens have location anisotropy. This statement agrees with the observation made by Stulen (1951) that "in carefully prepared specimens, the origin of failure is almost always at a microscopic non-metallic inclusion which is open to the surface or is slightly subsurface." It may be pointed out that an experimental decision as to whether a specimen has such a surface anisotropy or not is possible by subjecting cylindrical specimens to axial load and rotating bending of the same maximum stress. If the same fatigue strength is obtained, this type of anisotropy is proved; otherwise the rotating bending will indicate a higher fatigue strength. Such a test series has been carried out by Chadwick (1954) who found a close agreement between the fatigue strength of light alloy specimens subjected to axial and rotating-bending loadings.

Direction anisotropy may, for example, appear in a material containing inclusions of stringer type. The literature on anisotropy of the static properties, giving an indication also for fatigue properties, has been reviewed in a book by Barrett (1943). In this case the material has different fatigue properties in different directions and the orientation of the specimen influences the result. A comprehensive survey of results from fatigue tests in plain bending is presented by Findley and Mathur (1955). The fatigue strength of a specimen cut perpendicular to the direction of grain may in some cases be considerably less than that of a specimen cut parallel to this direction. Reductions of up to 48 per cent have been observed (SAE 4340, steel forging).

A very high degree of anisotropy was also observed in several studies on SAE steel forgings by Ransom and Mehl (1952, 1953), on heat-treated steels by Cornelius and Krainer (1941), and on various nickel and nickel-chromium steels by Pommy and Angelle (1935-36), Junger (1930), and Mahlander (1936).

Fatigue tests on aluminium alloys by Berner and Kastron (1933) and by Martin and Shelton (1949) indicate high anisotropy, while Atchison and Johnson (1929), Morris (1946), and Templin, Howell and Hartmann (1950), studying various steels and aluminium alloys, reported very little or no evidence of anisotropy.

Findley and Mathur (1955) investigated anisotropy in fatigue under two different states of stress, bending and torsion, applied to two aluminium alloys and a steel. The fatigue strength in bending decreased as the
orientation changed from longitudinal to diagonal to transverse, whereas the fatigue strength in torsion was nearly constant for all three orientations. The authors concluded that cyclic principal shear stress is the primary cause of fatigue, but the ability of the anisotropic materials to withstand this action is affected by the magnitude and direction of the complementary normal stress acting on planes of principal shear stress, as well as by the anisotropy of the material. The bending fatigue strength in transverse and longitudinal directions was determined by von Rossum (1942).

The effect of fibre orientation in ball races and ball bearings under rolling contact has been examined by Butler, Bear and Carter (1957) and Carter (1958).


61.9 Origin

It is obvious from the above that the process of fabrication may cause considerable differences in the properties of the material in different parts of the product. For this reason it may be useful to know the origin of the specimen, i.e. from which part of the ingot, bar or sheet the specimen is taken, and the orientation in relation to the rolling direction, or whether the specimens are taken from different batches or from different manufacturers.

As an example reference is made to a comprehensive investigation made by Ineson, Clayton-Cave and Taylor (1956) to establish whether or not the fatigue properties of the rolled products of commercial steel ingots vary significantly firstly within an individual ingot, and secondly from ingot to ingot in a given cast of steel. It was concluded that small, statistically significant variations existed within an ingot, but they were not thought to be of any practical importance. The fatigue limit of the material from the top portion of one of the ingots examined was 34.9 tons/in², compared with 32.9 and 32.5 tons/in² for material from the middle and bottom portions of the same ingot. This difference was closely linked with variations in hardness and tensile properties (i.e. no significant difference in the fatigue limit, measured as a percentage of the tensile strength Sₕ, was found).


SECTION 62. TYPE OF STRESSING

62.0 General

The most general way of describing a state of fluctuating stress at a point in a solid is by a combination of a static (steady) stress tensor superimposed upon a completely reversed stress tensor, the latter satisfying the condition that each of the three principal stresses are completely reversed. The state is thus defined by six components: three principal mean stresses and three principal stress amplitudes. This pair of tensors may vary from point to point, and the fluctuating stress field distributed over the volume of the specimen is consequently defined by the distribution of this pair of tensors. This is a very abstract way of describing this type of stressing, and some of the theoretical possibilities are impossible to reproduce by known testing devices.

From a practical point of view it therefore appears more convenient to classify the various types of stressing according to the stress fields obtained by placing the specimens in machines actually used for testing purposes. This method of classification eliminates types which are of purely academic interest. Even so, each type must be defined by a state of stress and a distribution of this state, although the latter is limited to a few simple alternatives, the uniform and the linear distribution, which can be defined by a stress gradient. A steady stress, uni- or multi-axial, may then be superimposed upon these reversed stresses. By appropriate comparison of the different types of stressing, the effects of the state of stress and of the distribution can be separated. It must be pointed out, however, that due consideration must be taken of possible influences of anisotropy in the material, which have been discussed in Section 61, and of size and shape of the specimen, which will be discussed in Section 63. These factors may be of considerable importance, and if not properly considered may upset the comparison.

The simplest type of stressing is obtained by subjecting the specimen to a reversed, tension-compression load. The stress within a smooth, unnotched specimen, is then uniaxial and uniformly distributed over the volume. This type may be taken as the reference to which the other types may be compared.

The following types will now be discussed: (1) tension-compression; (2) repeated bending; (3) rotating bending; (4) torsion; (5) combined bending and torsion; (6) biaxial and triaxial stresses (other than combined bending and torsion and usually produced by subjecting tubular specimens to internal or external pressure); (7) surface-contact stresses; to which (8) failure criteria for multi-axial stresses will be added.

For each type, comments will be made on general characteristics and comparison with the preceding types, the influence of superimposed steady stresses, and different criteria.

62.1 Tension-compression

This type of stressing is characterized by a uniaxial state of stress and a uniform distribution.

The effect of a steady stress superimposed upon reversed axial load was investigated as early as 1874 by Gerber (1874), who summarized the results by introducing a diagram, now called the Gerber diagram (see Fig. 82.7), based on a parabolic relation between the stress amplitude S and the mean stress Sₘ. The quadratic term (Sₘ)² implies a symmetrical diagram. A fair amount of work has been carried out since then to determine safe ranges with various mean stresses. Some of the tests have supported Gerber's assumption (Hahn 1915, 1917) but some have led to modified diagrams as
demonstrated in Section 82.2. Reference is made to the work of J. H. Smith (1910) and Bolleńraith and Cornelius (1938). A summary of the work up to 1942 is contained in a paper by J. O. Smith (1942).

The large number of data compiled by J. O. Smith were used by Peterson (1952) who found that the $S_{n}$-$S_{m}$ diagram could be represented with good accuracy by a cubic curve for both unnotched and notched specimens. It is of particular interest that these two curves differ only by the fatigue notch factor $K_{f}$, which implies that the value of $K_{f}$ is independent of the steady stress value.

The cubic relation means an unsymmetrical diagram with an increased range on the compression side. This type of diagram is particularly marked for a material such as cast iron, as was earlier demonstrated by Pomp and Hempel (1940).

Fewer tests have been reported in which the mean stress of the cycle was compressive, but the results of such tests have been reviewed by Newmark, Mosborg, Munse and Elling (1951), by Grover, Bishop and Jackson (1951a,b,c) and by Wallgren (1953).

Experiments covering a very wide range has been performed by Findley (1954). Axial-load fatigue tests at mean stresses from 40,000 lb/in$^2$ in tension to not less than 135,000 lb/in$^2$ in compression on SAE 4340 steel specimens resulted in the conclusion that the fatigue strength decreased slightly as the mean stress was changed from compression to tension. At high compressive mean stress the fatigue strength increased substantially. Fatigue cracks, which were initiated at the surface and progressed to a certain depth and stopped there, have been observed.

Two other recent investigations will be mentioned. The first one by O'Connor and Morrison (1956) was conducted at mean stresses of such magnitudes that the upper stress exceeded the lower static yield both in tension and compression, the material being an alloy steel with an ultimate tensile strength of 55 tons/in$^2$. The $S_{n}$-$S_{m}$ diagram was composed of three straight lines with marked discontinuities at the compressive yield, at the tensile yield, and at the ultimate stress. No evident reason was found to draw the curve other than straight.

The second investigation, carried out by Woodward, Gunn and Forrest (1956) establishes the diagrams of seven different aluminium alloys representing a range of materials used for stressed parts in structural engineering, marine engineering, and aircraft construction. The results fall into two groups: one group, comprising NS 41 H and all the heat-treatable alloys except a sample of DTD 363 A, is typified by a curve lying between the Goodman and Gerber lines (see Section 82); the other group, comprising the soft aluminium-magnesium alloys and one sample of DTD 363 A, gave results lying below the Goodman line. The diagrams are convex upwards, which is the orthodox shape. There is only one concave diagram (DTD 363 A); it is suggested that this may be due to the presence of micro-constituents acting as inherent stress raisers. If this hypothesis is accepted, the similarity between this diagram and those for notched specimens is understandable.

It appears to be generally accepted that there is a reduction in the fatigue strength with increasing mean tensile stress, but there is some divergence as to the explanation of this observation. Gough and Clenshaw (1951) suggest that the decrease may be due to damage caused to the crystal structure of the material by deformation produced by the maximum stress, and that the effect of mean stress, as such, is negligible. On the other hand, Findley (1954) is of the opinion that resistance to fatigue is influenced by the magnitude and sign of the complementary normal stress across the planes stressed in shear, the resistance to fatigue being reduced by tensile and increased by compressive stresses. This effect of the normal stress has frequently been assumed to be linear [Stulen and Cummings (1954)], but Findley, Coleman and Hanley (1956) have concluded on the basis of tests on SAE 4340 steel at a Rockwell hardness of C-25 that there is a likelihood that the influence of the normal stress on the shear plane is non-linear.


62.2 Repeated Bending

The state of stress is the same as that obtained by axial load but the stress distribution is different. If these two types of stressing are compared on the basis of the maximum stress in the specimen, it is generally found that the fatigue strength is higher in bending than under axial load. Two explanations of this observation have been proposed; the first is the statistical concept (Weibull, 1939a,b) which will be discussed more thoroughly in Sections 63.1 and 63.2; the second postulates that the stress gradient is responsible for the improvement in endurance. The results of bending tests on specimens of different diameters led Siebel and Pfender (1947) to introduce the "relative stress gradient" defined by $(1/n) d\sigma/dx$ where $d\sigma/dx$ is the stress gradient. Varying this factor from 0-3 to 2-0 mm$^{-1}$, it was found that the fatigue strength remains nearly constant with variations of its value when it is above 1-0 mm$^{-1}$. A physical interpretation of the influence of the stress gradient has been suggested by Forrest (1953) on the basis of a block theory. This theory supposes that fatigue failure occurs, not when the maximum stress in a specimen reaches a critical value, but when the average stress over a block of finite size reaches such a value. Thus, where a steep stress gradient exists, a higher nominal strength would be obtained than with a shallow, or non-existent gradient. This theory will also be discussed in Section 63.

The effect of superimposed static bending on the endurance limit in bending of SAE 1020 steel is illustrated by a remarkable curve in the discussion of a paper by Findley (1954). The endurance did not decrease more than 3 per cent when a steady bending stress as high as 24,000 lb/in$^2$ was applied.
62.3 Rotating Bending

This state of stress is the same as in the two preceding types but the stress distribution is different. Since most fatigue failures start at the surface or slightly below (Stulen, 1951), little difference between rotating-beam and axial tests should be expected. In general, the axial load gives somewhat lower fatigue strengths than the rotating-beam test using solid specimens, but comparable data are obtained if thin-walled tubular specimens are used.

Reference is made to an investigation by Woodward, Gunn and Forrest (1956) in which results obtained from axial-load tests and rotating-cantilever tests on the same samples were compared. With the exception of one material all the axial test results are within 5 per cent of the rotating beam figures. Chadwick (1954) has found similar close agreement.

Fatigue characteristics of rotating-beam and rectangular cantilever specimens of steel and aluminium alloys have been compared by Fuller and Oberg (1947).

Usually the plain-bending test is reported to give results in reasonable agreement with the rotating-beam test. It must, however, be pointed out that due regard to the influence of the shape of the specimen is not always taken when comparing the effect of the two types of stressing. From a statistical point of view a definite difference is to be expected.

The rotating-beam test is a very easy one and much used for determining the fatigue properties of stress cyclically reversed; but it is not well fitted for application of steady stresses to the specimen. Moore and Jasper (1923) solved the problem in an interesting way. The mean stress was applied by means of a helical tension spring, acting along the axis of the specimen, while the applied range of stress were due to dead weight loading. In this way, they studied the influence of mean stresses on nickel steel and carbon steel specimens.

References: Chadwick (1954), Fuller and Oberg (1947), Moore and Jasper (1923), Stulen (1951), Woodward, Gunn and Forrest (1956).

62.4 Torsion

The torsion test provides the easiest way of producing a biaxial state of stress. The stress distribution is identical with that obtained in a rotating-beam test, and for this reason the comparison between the results from these two types of test offers an excellent way of studying the influence of the normal complementary stress on a critical shear plane, provided due consideration is taken to possible direction anisotropy in the material. This precaution has frequently been overlooked.
affected by even a small mean stress, and decreases linearly with increase in mean stress.

A considerable effect of large hydrostatic pressures on the torsional fatigue strength of an alloy steel is reported by Crossland (1956). The semi-range of torsion was raised from 19-2 tons/in² under atmospheric pressure to 25-4 tons/in² at 20 tons/in² pressure, provided that the specimen surface was protected by some impervious layer from the pressure oil, which had a deleterious effect if the fluid was in direct contact with the surface of the specimen.


62.5 Combined Bending and Torsion

The majority of combined fatigue stress tests reported have been made by subjecting a specimen of circular cross-section to combined bending and torsion. The range of biaxial principal stress ratios is then limited to values lying between 0 and —1.0, i.e., to combinations of biaxial stresses of opposite signs.

Most of the available experimental data on the fatigue strengths of materials for combined stresses have been obtained for completely reversed stresses, using solid round specimens subjected to fluctuating bending and torsion. Such tests have been conducted by Nishinara and Kawamoto (1940), Cornelius (1941), Frith (1948), Gough (1950, 1951), Gough and Clenshaw (1951), Gough, Pollard and Clenshaw (1951), Hanley and Dolan (1951), Sawert (1943) varied the shape of the specimen and obtained in this way different ratios of biaxial completely reversed stresses.

Some tests have been conducted on cylindrical specimens subjected to combined reversed torsion and reversed bending with superimposed static torsion and static bending, or by a combination of static torsion and reversed bending. Tests of this type have been carried out by Sauer (1940), Puchner (1948, 1951) and Findley (1956).


62.6 Biaxial and Triaxial Stresses

A much wider range of biaxial principal stress ratios is obtainable by means of thin-walled tubular specimens subjected to internal fluctuating pressure than by a combination of bending and torsion, where the ratio is limited to values lying between 0 and —1.0. Tests of this type have been carried out by several investigators, as mentioned in the list of references.

If the ratio of the external to internal diameter of the tubular specimen is increased, it is possible to obtain triaxial states of stress. As pointed out by Parry (1956), a thick cylinder subjected to internal pressure when supporting its own end load can be considered as subject to a uniform triaxial tensile stress acting throughout the wall thickness with a superimposed shear stress which varies from a minimum at the outside to a maximum at the bore. The ratio of the triaxial tension to the shear stress changes with the ratio of the external to the internal diameters of the cylinder. In a bar subjected to repeated torsion, the shear stress is unaccompanied by triaxial stress. Comparison between the results of these two types of test thus offers the possibility of investigating the influence, if any, of an added triaxial tension.

The development of such a testing machine and preliminary results are described in a paper by Morrison, Crossland and Parry (1956) and further results of fatigue under triaxial stress in the paper by Parry (1956). The tests reported are not conclusive but only exploratory, and the work is being continued.


62.7 Surface-contact Stresses

When two elastic bodies are pressed against each other very high stresses result, even for small loads. The stress distribution is complicated even if the simple case of two spheres is considered. The principal stress component, acting in the direction of the line of symmetry joining the centres of curvature of the spheres, reaches a maximum value at the surface of the material. This value is generally referred to as the maximum Hertzian pressure, but as all three principal stresses are compressive this is not the danger point. There are, however, two other points of interest. In either sphere the maximum shear stress occurs on the line of symmetry, but at a certain depth below the contact surface; and also at the boundary of the contact area there is a maximum tensile stress acting in a radial direction, accompanied by an equal compressive stress in the tangential direction. Consequently, a shear exists at this point with a magnitude equal to either of the direct stresses.

The examination of the fatigue damaging effect of such a stress field is of great practical importance in connexion with ball-bearing and gear designs. Even if a very large amount of work has been carried out to determine the fatigue behaviour of actual machine parts, very few tests of a basic nature in this respect have been reported. Quite recently a study of the fatigue of curved surfaces in contact under repeated load has been performed by Kennedy (1956). The cyclic loading was introduced between two ball-bearing balls by means of a crank consisting of a double eccentric connected to a rotating shaft and a spring. The test pieces were regularly inspected by means of an ultrasonic method of crack detection. From the tests on balls of
two different hardnesses it was concluded that the maximum subsurface shearing stress did not play a significant part in the destruction of the contact surface; but the marked damage sustained at or near the contact boundary indicated that the material is subjected to conditions in this region which are more critical. This result agrees, in fact, with static tests where the crack always starts at or near the contact boundary.

Fatigue failures under rolling-contact conditions have been studied by Butler, Bear and Carter (1957) and by Carter (1958), using a rig consisting of two balls driven at high speed on the inner surface of a cylinder race by an air jet. The ball loading resulted from centrifugal forces of the balls.

The process of initiation and growth of pittings on the surfaces of gear teeth has been studied among others by Hoshino (1956) who concluded that the pitting phenomenon is not a simple compressive fatigue failure, but a failure of surface layers deformed plastically by shearing stresses caused by frictional forces of sliding combined with compressive stresses due to contact pressure. Fine cracks have been observed to emanate along the flows of metal. A theoretical discussion of pitting failures is given by Beeching and Nickolls (1948).

References: Beeching and Nickolls (1948), Hoshino (1956), Kennedy (1956).

62.8 Failure Criteria for Multi-axial Stresses

Many attempts have been made to apply the theories for yielding under combined static stresses to fatigue failures. Such theories are based on principal stress, strain or shear stresses, total strain energy and distortion energy criteria. None has, however, been completely successful, and the reason appears to be due to the influence of anisotropy and the state of stress. The interpretation of experimental results has frequently been hampered by neglect of the effect of size and shape of the test pieces. Another reason may be sought in the fact that the relation between fatigue strength corresponding to different states of stress depends upon the fatigue life preassigned as already mentioned above.

Most of the theories proposed have been applicable to combinations of bending and torsion only, but in recent years more general theories have been suggested.

One of the earliest of the first type seems to be the ellipse quadrant expression, Gough (1949). In a recent investigation by Crossland (1956) it was found that on the basis of this hypothesis all the experimental results on alloy steel specimens subjected to torsion and very high hydrostatic pressures could be correlated, provided allowance for anisotropy was made. In several papers by Findley and co-workers existing theories were corrected by introducing a suitable concentration factor in the torsional stress term of the principal shear stress theory, thus reducing six of the theories to the same form as that proposed by Gough. The equations developed are in good agreement with data on ductile metals. Other modifications reduced the principal stress theory to a parabolic form, which is in good agreement with data on cast iron and notched ductile metals.


63.0 General

The factors relating to the test piece which have an influence on the test result may be classified as follows: (1) size; (2) shape; (3) stress concentrations; (4) surface condition; (5) residual stresses. The effects of these factors on the fatigue properties of the test piece, illustrated by results from experimental investigations, and also proposed explanations and theories, will now be discussed and commented upon.

63.1 Size

It has been known for a long time that dimensions have a definite influence on the static strength of the test piece and that the strength, in general, decreases with increasing size. Several investigators have presented evidence that this rule also applies to the fatigue strength, among whom may be mentioned Peterson (1930), Fallahari, Buchholtz and Schulz (1933), and Leitner and Mailänder (1938).

Test pieces with very large sections have been tested by Horger and Neuerk (1939, 1952) and by Horger (1954) who found that 6 to 7 in. shafts have a fatigue strength in bending which is 25 to 50 per cent lower than that of 0.3 in. specimens. Differences in surface finish and slight corrosion make it questionable whether this effect is entirely due to size. Other factors which may mask this effect and produce misleading results are anisotropy of the material and unintentional stress raisers varying with the size of the specimen.
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It is possible to eliminate all such irrelevant factors by testing specimens of different lengths, provided that the anisotropy and the surface finish do not change with the length, e.g. by cutting the specimens at random from a long wire. Such a test was carried out by Weibull (1946; 1949, pp. 33–35). Specimens with gauge lengths of 25 and 50 mm were subjected to rotating bending in a wire testing machine. The stress amplitude was 31.6 kg/mm², which resulted in 18 failures out of 26 long specimens but only 10 out of 26 short specimens. The distributions of fatigue life for the two sizes were in very good agreement with the expectation from the statistical theory.

Rotating-beam tests with various sizes of specimen have been conducted by Moore and Morkovin (1943), Moore (1945), Siebel and Pønder (1947), and Dolan and Hanley (1948). Torsional tests have been carried out by Dorey (1948) and Dorey and Smedley (1956). They found by means of large steel shafts of 3, 5½ and 9½ in. diameter that size effect is a real phenomenon. The combined effect of size and stress concentration due to various diameters of fillet could be represented by one simple expression.

Unnotched and notched specimens of various sizes from two types of steel, one mild steel (25 tons/in²) and one nickel-chromium steel (65 tons/in²), were subjected to axial loading as recorded in a paper by Phillips and Heywood (1951). Fatigue strengths were ascertained for specimens of diameters in the range from 0.19 to 2.4 in. No intrinsic size effect with the plain specimens was observed, however. The specimens which were notched by a transverse hole and which were geometrically similar, showed a fatigue strength declining from 8.4 to 6.1 tons/in² when the diameter was increased from 0.33 to 1.7 in. for mild steel. A similar size effect was found with the notched alloy steel specimens. Fatigue limits of 17.1 and 13.9 tons/in² respectively were obtained for these two sizes of specimen. Among others, contributions to the study of size effect are reported in papers by Lehr and Rüep (1944) and by Helme (1950).

The explanation of size effect has been approached from two different viewpoints. According to the first concept it is assumed that fatigue failures originate at local inhomogeneities (inclusions or the like) which are statistically distributed over the volume of the specimen. Each such nucleus has its individual endurance limit, no failure being started from it if the nominal stress is below this value. The probability of encountering a nucleus of a certain severity increases with the volume. This concept, initially intended as an explanation of size effects in brittle materials (Weibull, 1939a,b) subjected to static strength ($N = 0$), is directly applicable to the fatigue strength (but not to the fatigue life) at an arbitrarily assigned life $N$. For some materials at least this concept is a realistic one, which has been mathematically treated by McClintock (1955). It is supported by several observations, as pointed out, for example, by Stulen (1951), who states that the material examined indicates that “the origin of failure is almost always at a microscopic non-metallic inclusion which is open to the surface or is slightly subsurface.” Investigations by Epremian and Mehl (1952) and Cummins, Stulen and Schulte (1955) confirm this statement. From the above-mentioned remark by Stulen it follows that in many, if not all, cases the surface and not the volume is the appropriate “size”.

The other approach to the size-effect problem takes into consideration the structure of the material, in particular the grain size. This quantity is a relevant factor when the stress distribution is non-uniform, and will therefore be discussed in connexion with the influence of stress distribution.

From the preceding it is safe to conclude that the size effect exists, but that it is not easily established, the reason for this being the many irrelevant factors which mask the result by simulating the proper size effect. There is, however, another reason of even greater significance, and that is that the laws of size effect must be quite different for the pre-crack and for the post-crack stages of the fatigue process. In a study of crack initiation and propagation in flat specimens notched by a central hole, size effect was found (Weibull, 1956a) on geometrically similar specimens only in the pre-crack stage; but the propagation time of the crack was independent of the size of the specimen. The relevant size in this case is the diameter of the hole (or perhaps, more exactly, the circumference). This conclusion is supported by observations made by Phillips and Fenner (1951) who found that little or no reduction in fatigue strength is produced by drilling a very small hole in a large flat specimen subjected to reversed axial load. The fatigue limits of 9½ in. panels with 9½ in. diameter holes and 9 in. panels with 9½ in. diameter holes were substantially the same as those of the corresponding undrilled panels.

References: Dolan and Hanley (1948), Dorey (1948), Dorey and Smedley (1956), Fallhaber, Buchholtz and Schulz (1933), Helme (1950), Horger (1954), Horger and Neifert (1939, 1952), Lehr and Mailänder (1938), Lehr and Rüep (1944), McClintock (1955), Moore (1945), Moore and Morkovin (1943), Peterson (1930, 1949), Phillips and Heywood (1951), Phillips and Fenner (1951), Siebel and Pønder (1947), Weibull (1939a,b; 1946; 1949; 1956a).

63.2 Shape

The influence of shape on the fatigue strength of a specimen has been proved by many investigators. Different factors in connexion with this problem have been discussed by Cazaud (1950).

A comparison of the endurance limits of cylindrical and of torus-shaped specimens of equal minimum diameter, axially loaded, has been made by Cazaud (1952), who found 17.6 kg/mm² for cylindrical and 21.2 kg/mm² for torus-shaped specimens at a frequency of 2475 c/min. Corresponding values were 19.4 and 21.9 kg/mm² respectively for a frequency of 9500 c/min. This result has been verified by Roš and Eichinger (1950). For cylindrical specimens from two different steels they found an endurance limit of 30.6 and 40.2 kg/mm² respectively, compared with the values 33.5 and 42.1 kg/mm² for corresponding torus-shaped specimens.

This result agrees with the statistical theory because the highly stressed volume is smaller in the torus-shaped than in the cylindrical specimens due to the fact that the cross-section of the former increases gradually with the
distance from the centre of the specimen. Consequently, the nominal stress for off-centre fractures is less than that at the centre section. This particular property of this type of specimen is of interest because the distribution of the location of failure has a definite relation to the scatter in fatigue life, as pointed out by McClintock (1955a,b; 1956) who gives a formula affording a check on whether or not there are present any extraneous variables affecting the scatter in fatigue life other than local variations within the various specimens. This relation between scatter in life and scatter in position of failure has been verified by the use of data from Fluck (1951).

The effect of specimen shape on the resistance of metals to combined alternating stress has been studied by Gough and Pollard (1956). Repeated stress diagrams of round and flat steel bars, T-beams, and wires have been presented by Hempel (1957).

Tests were made by Roos, Lemmon and Ransom (1949) on flat and round specimens of an SAE 4340 steel in pure reversed plane bending and on round specimens acting as rotating beams. Data show that a higher endurance limit is obtained in plain bending than in rotating-beam tests; and in round specimens subjected to plain bending than in flat specimens similarly tested. Similar results were obtained by Oseberg and Rooney (1949a,b) with reversed bending for cantilever round section, simple rotating-beam, cantilever square section, cantilever constant strength, and cantilever rectangular section. According to investigations by Dolan, McComb and Craig (1950), the flexural fatigue strengths of specimens from two types of steel were found to be, in order of decreasing endurance limits for both steels: round, diamond, modified diamond, and square. The fatigue properties of Z-section test pieces machined from an aluminium extrusion conforming to DTD 364 B have been determined by Forrest, Gunn and Woodward (1953).

The tendency of all these results reported is in agreement with the statistical theory of stressed volume effect, but various factors, thoroughly discussed by Dolan, McComb and Craig (1950), has certainly contributed to this result.

References: Cazaud (1950, 1952), Dolan (1951), Dolan, McComb and Craig (1950), Fluck (1951), Forrest, Gunn and Woodward (1953), Gough and Pollard (1956), Hempel (1957), McClintock (1955a,b; 1956), Oseberg and Rooney (1949a,b), Roos, Lemmon and Ransom (1949), Rose and Eichinger (1950), Weibull (1939a,b).

63.3 Stress Concentrations

According to the statistical theory of strength, a non-uniform stress distribution is equivalent to a uniform distribution of the same maximum stress acting on a reduced volume. This implies that the probability of failure is less in a given volume subjected to a non-uniform stress field than to a uniform distribution of the same maximum stress.

A non-uniform stress distribution in a specimen may be produced either as a consequence of the type of stressing, bending or torsion, and by intentional notches and fillets, or by unintentional stress raisers such as scratches and inclusions. Unintentional stress concentrations may also be caused by too small a radius of the fillet between the grip end and the gauge length of a specimen. In any case, the theoretical stress-concentration factor $K_t$ determined by the theory of elasticity with simplifying assumptions of isotropy, which is defined as the ratio of the peak local stress to the nominal stress at the section, might be expected to reduce the fatigue strength in proportion to its value, but in reality it is always found to be less severe than theory predicts. For this reason a correction term, the fatigue notch factor $K_n$, has been introduced. It is defined by

$$K_n = (\text{fatigue strength of a plain specimen})/(\text{fatigue strength of the notched specimen})$$

both strengths taken at the same number of cycles. In general $K_n$ tends to increase with $K_t$, but the scatter is very large which indicates that there are other factors of influence. As a result of rotating cantilever tests on 24S-T specimens with V-notches producing a value of $K_t$ varying from 1 to 10, Mann (1953) found that the expression

$$K_n = K_t (1 - 0.09K_t)$$

fitted the observations. This equation implies the existence of a maximum stress reduction, the value in this case being $K_n = 3.2$ corresponding to a notch having a value of $K_t = 5.8$. It has been suggested by Neuber (1946) that a more plausible factor for stress concentration is obtained by the factor $K_N$ defined by

$$K_N = (K_t - 1)/[1 + (A/R)^b]$$

where $A$ is a material constant having the dimension of length and $R$ is the radius of the notch root. Kuhn and Hardrath (1952) have evaluated the Neuber constant $A$ for a large number of fatigue tests on steel specimens, and they have found that the fatigue factor at the endurance limit can be estimated for steels with reasonable accuracy, assuming the constant $A$ to be a non-linear function of the tensile strength of the steel. The value of $A$ is represented by a graph in the paper cited.

This method does not take into account the size effect. An expression which includes the effect of size as well as that of stress concentration is proposed by Dorey and Smitsley (1956). Summarizing the results from torsional fatigue tests on solid forged steel shafts up to 9 in. diameter with fillets of varying radius, it was found that the torsional fatigue strength $\sigma_T$ could, with good accuracy, be expressed as

$$\sigma_T = a - bD + c\sqrt{r}$$

where $D$ is the diameter of the shaft, $r$ is the root radius and $a$, $b$, $c$ are material constants. It is of interest to note that there is a limiting fatigue strength no matter how sharp the fillet radius, i.e. in spite of a theoretically infinite stress.

Instead of using the statistical approach, the other concept is that the stress gradient is the relevant quantity when correlating data on stress-concentration specimens. This suggestion has been made by Honka and
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MAULBERTSCH (1936). If the stress field is concentrated in a small volume it seems plausible that the grain size of the actual material must be considered.

By a combination of the grain size and the stress gradient divided by the endurance limit of the material, Peterson (1938) arrived at a criterion for notch-sensitivity. By plotting the data from a large number of tests he found a relation between the notch-sensitivity index \((K_t - 1)/(K_r - 1)\) and the relative decrement in stress across one grain.

Observing that the stress gradients for stress raisers such as fillets, grooves and holes were approximately proportional to \(1/r\), where \(r\) is the root radius, Peterson (1954) modified his method by using \(r\) as a measure of the gradient and plotting against the notch-sensitivity index which is given the slightly modified form \((K_t - 1)/(K_r - 1)\), where \(K_t\) is the theoretical shear energy concentration factor.

Reference is made to a critical review of the criteria for notch-sensitivity by Yen and Dolan (1952).

The preceding formulae are limited to stresses in the elastic range. An extension to the plastic range for a circular hole in an infinite plate has been presented by Stowell (1950). In order to determine the stress concentration factors in both the elastic and the plastic ranges, Hardrath and Ohman (1951) tested sheet specimens containing various notches and fillets. It was found that stress concentration factors decreased as the stresses at the critical points entered the plastic range in accordance with a generalization of the Stowell relation.

A stress raiser of particular interest is the fatigue crack. It is obvious that the theoretical stress concentration of a crack is extremely high, and for this reason it was generally believed that the fatigue crack should produce the highest stress concentration possible within a material. There is evidence that this assumption is not correct. Bennett (1946) found that cracks of 12–17 per cent of the original area had a strength reduction factor of about 2 only, and for specimens cracked 50 per cent of the original area the fatigue strength was greater than in proportion to this value. This result is confirmed by Pope and Barson (1956) who state that the strength-reduction factor for a quenching crack was found to be 1–78 relative to an “as-heat-treated” specimen. Frost and Phillips (1956) have also determined the fatigue strength of specimens containing cracks. They report that the strength-reduction factor of a crack is independent of its size, the size of specimen, formation conditions, and type of loading, when the stress is completely reversed; and also that cracks have lower fatigue-strength reduction factor than mechanically formed sharp V-notches. This statement is confirmed by the results of static tests on specimens containing fatigue cracks which have been carried out by McEvily, Illg and Hardrath (1956), by Illg and McEvily (1951) and by Weibull (1956a).

References: Bennett (1946), Bunyan and Attila (1953), Cox (1956), Dorey and Smedley (1956), Forrest (1956a), Frost and Phillips (1956), Grover (1956), Horger and Neifert (1952), Illg and McEvily (1951), Kuhn and Hardrath (1952), Lehmer and Mailander (1938), McEvily, Illg and Hardrath (1956), Neuber (1946, 1958), Peterson (1938, 1945), Petersen (1946, 1958), Hiš (1955) and plotting it against the notch-sensitivity index which is given the slightly modified form \((K_t - 1)/(K_r - 1)\), where \(K_t\) is the theoretical shear energy concentration factor. Reference is made to a critical review of the criteria for notch-sensitivity by Yen and Dolan (1952).

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FACTORS AFFECTING TEST RESULTS

PHILLIPS and FENNER (1951), POPE and BARSON (1956), UZH (1956), WEIBULL (1939b, 1956a), YEN and DOLAN (1952).

63.4 Surface Condition

The effect of the surface condition on fatigue strength in relation to different methods of preparing the specimen depends upon three factors: stress concentrations due to surface roughness, scratches and the like; changes in the structure of surface layers; and residual stresses. The effects on fatigue strength of these factors are not easily separated and therefore laws of general validity covering different materials and modes of stressing are not available, in spite of the fact that this problem has been the subject of extensive investigations as indicated by the bibliography. There is a further difficulty arising out of the fact that the merit of a given procedure for finishing the specimen cannot be defined by a single figure, because the shape and the slope of the \(S-N\) curve depends on the fineness of the finish and in many cases two different finishes will result in intersecting \(S-N\) curves. Consequently the appraisal is entirely dependent upon which part of the field is made the basis of the comparison.

This statement will be illustrated by data from an extensive investigation by Mann (1950) who tested more than 350 specimens in rotating bending using nine different finishes: two turned, four ground, and three hand polished. It was found that at \(10^6\) cycles a 220 grit circumferential hand polish gave the highest fatigue strength \((23,000 \text{ lb/}in^2)\), whereas longitudinal grinding to 40 silicon carbide and coarse turned gave the lowest value \((19,000 \text{ lb/}in^2)\). If, however, the comparison is made at \(10^8\) cycles the order will be completely changed, and the best method will be 400 grit longitudinal polish. These data have also been evaluated by Weibull (1958a) and the result that grinding to 60 grit silicon carbide gave the highest endurance limit and 400 grit longitudinal grinding the lowest one. Mann has also compared the actual and percentage scatter in strength for the different finishes at \(10^5\), \(10^6\), \(10^7\) and \(10^8\) cycles. The order differs for each life and also from the order obtained by Weibull, using the variance in fatigue strength as a measure of the scatter. It is obvious that a definite appraisal of a finishing procedure requires the complete \(P-S-N\) diagram (see Section 81).

The effects of machining, grinding, and polishing are reported in several papers listed below.

The influence of the various procedures on the fatigue properties may be summarized as follows.

Polishing is favourable not only because it provides a surface free from scratches but also because of compressive residual stresses produced in the surface layers. This is confirmed by the observation that a reduction of the endurance limit results if the residual stresses in the polished specimen are released, for example, by heat treatment. Some influence of the polishing direction has also been observed.

The effect of grinding is twofold: (i) notch effects due to grinding marks and (ii) detrimental or beneficial effects due to residual stresses. Poor
Residual tensile stresses are produced in the grinding direction while the residual stresses in the perpendicular direction are mainly compressive. By choosing a suitable grinding fluid, only beneficial compressive stresses in the surface may be produced.

The effect of turning depends upon cutting speed and depth of cut. For the best fatigue conditions there exists an optimum speed which depends on the tool and the material. The beneficial effect of work-hardening in the surface material increases to a certain extent with the depth of cut.

The effect of scratches on the fatigue strength of steel has been examined by Thomas (1923), and of unintentional stress raisers such as scratches, longitudinal cracks, discontinuities in hand forging and in sand casting on structural components from aluminum alloys by Hartmann (1956). The surface preparation of electropolishing is described by Faust (1948).

Extensive reviews of the influence of surface conditions on the fatigue properties are given by Horger and Neifert (1941), Love (1952) (including 157 references on various surface treatments), Manley and Dolan (1954), and Nelson (1957).


63.5 Residual Stresses

Residual stresses in specimens are caused by mechanical fabrication processes such as turning, grinding, shot-peening, surface-rolling and by heat treatment, flame-cutting, etc. It is now generally accepted that the macro residual stresses measured, for example, by dissection methods or X-ray techniques, are additive with stresses resulting from external loads. For this reason residual stresses may be either beneficial or detrimental.

The measurement of residual stresses is rather difficult. Two different methods have been developed. The oldest one is a destructive method, based on the removal of part of the specimen and measuring the resulting strain in two directions. The second method is the X-ray diffraction method. Thanks to a co-operative work within Division 4 of the Iron and Steel Committee of the Society of Automotive Engineers, New York, different methods have been thoroughly appraised. Residual stress distributions have been determined on six standard specimens by twenty different research laboratories using five different methods of analysis.

These methods were: (i) Sachs' boring and turning method, developed by Sachs (1939); a numerical example of this method is given by Hanslip (1952); (ii) layer removal method, described by Letner (1953) and Leeser and Daane (1954); (iii) beam dissection method, described in detail by
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A review of residual stresses, their measurement and their effect on structural parts, is given by Sachs (1947) and a bibliography on residual stress by Huang (1954).

The present status of our knowledge in this field is summarized by Mattson (1956) as follows. Best prediction can be made of residual stresses from mechanical treatments such as shot-peening and surface rolling. Stresses due to heat-treatment are still not predictable in practice. Information of grinding stresses reveals almost unbelievable high stress magnitudes and gradients. Stresses due to surface cold-working vary in magnitude with material and in depth with severity of surface working.

Another process by which the surface layer of the specimen is affected is by flame-cutting. The fatigue strength of such specimens from bright and black mild steel has been determined by Köhnick (1955a, b).


SECTION 64. TESTING MACHINE

64.0 General

It is a well-known fact that the results of tests which are supposed to be conducted identically may be quite different. There are many causes of this deplorable fact, some of which are attributable to the testing machine, and will be discussed in the present section.

The desired fluctuation of stress and strain in a given specimen can be produced by means of two basically different types of loading, namely, by applying either a constant amplitude of force or a constant amplitude of displacement. The different effect of these types will first be discussed. Other factors are the individual property of the machine due to its design and the speed actually used.

Even if two machines are of the same design and are run with the same speed, they may give different results because of differences between the nominal and the actual load. This error can be stated and eliminated by a proper calibration of the machine.

All these factors contribute to different behaviour of even similar machines. The variations thus obtained will be discussed and some data will be presented.

64.1 Type of Loading

If the specimen responded to the applied stresses as a perfectly elastic body, there would, of course, be no difference between the two types of loading: but this condition is never fulfilled for loads above the endurance limit, because the first stage of the fatigue damage consists of the development of submicroscopic slip bands within the individual grains, followed by the formation of fine cracks.

It is obvious that the stiffness of the specimen is gradually changed by these occurrences which start at an early stage, and that the specimens will act differently under the two types of loading.

Internal friction and the propagation of cracks in the material may sometimes cause a temperature rise in the specimen sufficiently high to change the modulus of elasticity, with an effect equivalent to that produced by numerous small fatigue cracks. This precludes the correlation of the results of the two types by means of a stress-strain curve determined on an undamaged specimen.

This different behaviour is reflected in the different shape of the strain-against-endurance curve and the conventional $S-N$ curve. The former appears to be characterized by a break which does not exist in the conventional $S-N$ curve. As an illustrative example reference is made to a study by Torrey and Gohn (1956) on phosphor bronze strips subjected to reversed bending with constant amplitude of deflexion. A similar knee is found at a somewhat lower value of $N$ in strain-against-endurance curves established by Low (1956) for many different materials subjected to reversed bending. As a third example, an investigation by Corten and Sinclair (1955) is mentioned, where steel wires, acting as deflected rotating struts, indicate the same break at about the same number of cycles as in the first example mentioned.

It seems safe to say that a conversion from displacement levels to stress levels will be very dubious, and that a correlation between the results from tests based on the two types of load is impossible. It seems plausible that an equal endurance limit will be obtained, but this question is not definitely answered.


64.2 Design of Testing Machine

There are many minor details of the machine which may contribute to a change in the results. One of these is the grip which, due to misalignment, may cause unintentional bending moments in axial-load machines or prevent the specimen from running true in a rotating-beam machine.

Vibrations may sometimes give trouble. If the machine is not sufficiently rigid, resonant vibrations may be generated. They are of particular influence if the specimen is caused to vibrate in a transverse direction, and premature failure may occur at some definite stress levels.

Fretting corrosion may occur in some machines at the joints at the ends of the specimen, and fracture may result at the joint. The same result may be obtained by clamping effects.

Constant checking of the testing machine is therefore required, comparing with previous data and with other machines of the same type and design.

64.3 Speed

The fatigue strengths of metallic materials are usually found to be independent of speed up to 10,000 rev/min, while above this value an increase with increasing testing speed has been observed. It is, however, to be noted that in many cases the speed effect has been determined by comparing results from different types of machine and different specimens. It is therefore not impossible that extraneous factors might have masked real speed effects actually existing.

Among investigations carried out under uniform conditions may be mentioned KROUSE (1934), OBERG and JOHNSON (1937) and ROOS, LEMMON and RANSOM (1949).

Another experiment is reported by MANN (1954) who found that the effect of rate of cycling on the fatigue properties of 24S-T aluminium alloy is insignificant at low stresses, whereas at higher stresses there is a range of testing speeds (for this material between 200 and 600 rev/min) where the increase in fatigue strength with speed is more rapid. Similar observations have been made by Wood and HEAD (1951) on annealed copper where this range was between 300 and 400 rev/min. In the tests of Mann, the fatigue strength was observed to increase, for example, at a life of $4 \times 10^8$ cycles from 29,000 lb/in² at 170 rev/min to 35,000 lb/in² at 12,000 rev/min.

Very high speeds have recently been attained. By means of a torsional vibrator, WADE and GROOTENHUIS (1956) tested Hiduminium alloy, RR56, in reversed bending frequencies from 24 c/s to 3835 c/s. A definite speed effect was observed, the increase in fatigue strength being only 2 per cent for 200 c/s (compared to a frequency of 24 c/s) while an increase of 12 per cent was recorded at a frequency of 3385 c/s. There was no evidence that a limit had been reached. This problem has been investigated from a physical standpoint by DANIELS and DORN (1957) who have attempted to correlate speed and temperature. VALLURI (1957) suggests, however, that critical frequencies associated with room temperature differ substantially from those frequencies customarily used in fatigue testing.

In an investigation by LOMAS, WADE, RAFT and COLBECK (1956), speeds up to 150,000 c/min were obtained by means of a pneumatic resonance system. Eight different steels were tested. Four standard engineering materials showed a steady increase in endurance limit with frequency up to a peak value between 1200 and 1800 c/s, and then a progressive decrease in endurance limit as the frequency increased up to 2500 c/s. The curves have the same tendency as those of JENKIN (1925) for similar materials, but the peak values are obtained at very different frequencies, which is believed to be explained by different dimensions of the test pieces and modes of vibration.

The effect of frequency on the time of endurance was represented by ECKEL (1951) from bending tests on lead at room temperature by the following expression

$$\log L = \log k - m \log f$$

where $L$ is the life in days, $f$ the frequency and $k$ a constant.

Since the time-to-failure and the number of cycles-to-failure is

$$fL = N$$

we have

$$\log N = \log k - (m - 1) \log f$$

Here $k$ is a function of the applied load $S$, and $m$ is a function of the temperature only. If we now postulate that the $S$-$N$ curve is represented by the equation

$$S = bN^{-a} + S_e$$

for a given temperature and for $f = 1$, where any value of the frequency may be taken as unity, it follows that the $S$-$N$ equation for an arbitrary value of the frequency $f$ takes the form

$$S = bf^{-(m-1)}N^{-a} + S_e$$

ALLEN and FORREST (1956) suggest that $m = 1$ in the low-temperature case, while $m = 0$ in the high-temperature case. It was found by ECKEL (1951) that $m = 0.7$ for lead at room temperature. For other materials, values of $m$ are quoted by ALLEN and FORREST (loc. cit.) at various temperatures. For example, $m = 0.75$ for 0.17 per cent carbon steel at 20°C.

It may be pointed out that according to the above formula, the endurance limit $S_e$ is independent of the frequency $f$. This conclusion does not appear to be confirmed by the results mentioned in the paper by LOMAS, WADE, RAFT and COLBECK (1956).


64.4 Accuracy of Individual Machines

It is apparent from the above that differences between the nominal load and the actual load applied to the test piece may easily arise. For this reason calibration of the testing machine is an urgent requirement. There are two ways of carrying out this procedure. The simpler one is a static calibration which includes checking of weights, springs, and hydraulic or other devices by which the loading is produced, and the weighing of all levers and other parts of the lever system, and experimental determinations of the centre of gravity of these parts. The other way of calibrating the machine is called dynamic calibration. It is not as simple as the static method, but, correctly performed, it is more reliable. More details on calibration are to be found in the ASTM Manual on Fatigue Testing (1949, pp. 49–52).

The necessity of calibrating fatigue testing machines will be demonstrated by some data. WILKINS (1956) found as a result of static calibration that the correction factor of twenty identical rotating-beam machines of reputable manufacture varied between 1.05 and 1.11.

Experiments designed to determine the variations in fatigue life obtained from individual testing machines are discussed in a paper by ERLINGER (1936) and also by CLAYTON-CAVE, TAYLOR and INESON (1955).
65.0 General

The environment of the test piece is defined by the temperature and the surrounding medium, which may consist of inert or chemically aggressive gases or liquids.

65.1 Temperature

A particular type of aggression is obtained by fretting corrosion. Radiation may in some cases be of influence; for example, plastics and rubber may be affected by sunlight or heat radiation. In recent years nuclear radiation has become an important subject of research.

Factors Affecting Test Results

The fatigue strength of technical creep-resisting alloy declines steadily with temperature for some alloys (titanium and aluminium alloy RR 59). Some of them (Y alloy and DTD 424) have a constant fatigue strength up to 100°C. The slope of the curve relating fatigue strength to temperature is exceptionally large for titanium and aluminium alloy RR 59 up to 400°C. This property implies that in tests at constant speed there will be a tendency for measured values of the fatigue strength at higher stresses to be too low.

Endurance tests at high temperatures made with various steels on rotating-beam machines by Moore and Jasper (1925), and on reversed axial-load machines by Tapsell and Clenshaw (1927), and more recently by Forrest and Tapsell (1954), and by Allen and Forrest (1956) indicate that the maximum endurance limit is usually obtained in the range 300 to 400°C, while at 100 to 200°C the endurance limit is less than at room temperature. It is of interest to note that the variation of tensile strength follows the variation of fatigue strength, while the curve of the yield point has quite a different shape. Experiments also show that the S-N curve at elevated temperatures does not approach the asymptote as rapidly as at room temperature, and that more than 10^7 cycles are required to determine the magnitude of the endurance limit.

The fatigue strength of technical creep-resisting alloy declines steadily with temperature for some alloys (titanium and aluminium alloy RR 59). Some of them (Y alloy and DTD 424) have a constant fatigue strength up to 200°C. From 400°C and upwards all of them have a declining fatigue strength.
strength as demonstrated graphically by Allen and Forrest (1956), who also give several sources.

Data on notch effect for various steels at room temperature and at 500°C are presented by Wever (1956). In every one of the seven steels examined the fatigue notch factor is lower at 500°C, in some considerably lower than at 20°C. The only exception is an austenitic chromium-nickel-molybdenum-niobium steel, which reveals exceptionally low notch sensitivity at room temperature.

A very complete and systematic survey of the fatigue properties of a wide variety of alloys suitable for high-temperature service is contained in the work by Toolin and Mochel (1947), who present data for more than 70 fatigue curves obtained at 1200 and 1500°F. The materials are classified into six groups. It is observed that all of these data show trends towards a continuing downward slope of the S–N curve even at lives exceeding 10⁸ cycles, which is the number corresponding to which the fatigue data are given.

Comparative endurance tests made at +20 and −40°C with Monel metal, stainless steel, nickel steel, and chromium–molybdenum steel performed by Russell and Welcker (1931) show in all cases an increase in the endurance limit with decrease in temperature. The fatigue properties at low temperatures of a number of alloys used in the aircraft industry have been investigated by Zambrów and Fontana (1949) and by Spretnak, Fontana and Brooks (1951). Hempel and Luce (1941) compared the bending fatigue strength of a number of steels, notched and unnotched, at room temperature, at −78, and at −188°C. All the steels showed an increase in fatigue strength with decreasing temperature, for carbon steel 20–40 per cent at −78°C and 130–200 per cent at −188°C, for alloy steels 5–10 per cent at −78°C and 40–70 per cent at −188°C.


Low temperatures: Boone and Wishart (1935), Hempel and Luce (1941), Russell and Welcker (1931), Spretnak, Fontana and Brooks (1951), Teed (1950), Wellinger and Hofmann (1948), Zambrów and Fontana (1949).

65.2 Vacuum and Air

Experiments in a vacuum performed by Gough and Sopwith (1932a,b) showed that the endurance limit of steel was about the same as in air, while experiments with copper and brass in a vacuum demonstrated an increase in the endurance limit of 14 to 16 per cent. Endurance tests in an atmosphere of dry steam carried out by Fuller (1931) showed no effect on the endurance limit. When the steam contained air or water, a lowering of the endurance limit was observed.

Factors Affecting Test Results

Humid air may affect stored specimens by oxidation or corrosion. Some protecting film of non-corrosive mineral oil or grease is therefore recommended.

References: Fuller (1931), Gough and Sopwith (1932a,b).

65.3 Non-corroding Environment

It has been observed that in some cases a non-corroding solvent may have a remarkable influence on the fatigue life. A few examples will be mentioned.

In a machine designed for the purpose of subjecting thick-walled cylinders to repeated high internal pressures, developed by Morrison, Crossland and Parry (1956), it was found that the oil used, being a mixture of castor oil and about 16 per cent of brake fluid, in spite of not showing any signs of corrosion, had a very harmful effect on the fatigue specimens if the fluid was in direct contact with the surface of the specimen. As yet there is no satisfactory explanation of this weakening effect. It may be caused by penetration of the fluid into the surface or by some action which is enhanced by pressure. If the specimen was protected from the fluid by a thin film of rubber, the strength could be considerably raised as demonstrated by Crossland (1956) and in another paper by Parry (1956).

A similar effect was observed by Weibull (1954a). The propagation of fatigue cracks was studied using flat specimens from aluminium alloy 755–T. In some of the tests the specimen was coated with kerosene with a pencil. It was found that the propagation time for coated specimens was about 70 per cent longer than for uncoated specimens subjected to the same stress amplitude. No evidence of corrosion was observed.


65.4 Corroding Environment

In general, fatigue acting jointly with corrosion behaves as an intensified form of fatigue. There is a considerable difference between the results obtained when the specimen is exposed to corrosion prior to the endurance test and when the corrosion and the application of pulsating stresses take place simultaneously. This observation had already been made by McAdam (1926, 1927a,b). He tested steels of various carbon contents, having endurance limits in reversed stress varying from 20,000 to 40,000 lb/in². When the specimens were subjected to the action of fresh water during the tests, the endurance limits were greatly diminished and varied from 16,000 to 20,000 lb/in². The explanation appears to be that a metal exposed to active corrosion fatigue has a surface oxide film which is broken down by the induced mechanical strains which, in addition, may remove any products of corrosion that otherwise might have a stifling effect upon the electrochemical action. The electrochemistry of corrosion-fatigue is treated in a paper by Evans (1947). An introduction to the study of corrosion-fatigue is given by Pomey and Ancelle (1935). An extensive survey of corrosion-fatigue data is to be found in the book by Cazaud (1948) containing data for different materials, corrosive solutions and types of stressing.
FATIGUE TESTING AND ANALYSIS OF RESULTS

Factors associated with corrosion fatigue such as slip, composition and nature of the metal, nature and concentration of the corrosive solution, temperature, scale, metallography, manner of testing, mean stress and electrode potential have been discussed by Gould (1956).

References: Evans (1947), Fuller (1931a), Godger (1956), Gould (1956), Hara (1956), McAdam (1926, 1927a,b), Pomey and Angelle (1935), Wescott (1938).

65.5 Fretting Corrosion

Fretting is a frequent occurrence in engineering practice, particularly in elements in which mating surfaces repeatedly undergo relative motion, resulting in surface damage which may cause seizure or loss of fit and originate fatigue failures.

One of the first observations within this field was reported by Eden, Rose and Cunningham (1911) who detected fretting corrosion in the grip of a fatigue testing machine which caused premature failure. A similar incident happened to Gillett and Mack (1924) who found failures in machine grips which decreased the apparent fatigue limit by more than sixty per cent.

Since then, fretting corrosion has been extensively studied both as a physical process (Godfrey, 1950), and also in relation to its influence on the fatigue strength (Tomlinson, Thorpe and Gough, 1939).

Basin their experience on many years’ studies in the Lubrication Division of the Mechanical Engineering Research Laboratory, mainly dedicated to ferrous materials, Fenner, Wright and Mann (1956) state as well-established facts that fretting occurs in the presence of inert gas, but is more serious when oxygen is available, and then the debris consists almost entirely of finely divided α-ferric oxide. The debris accumulates between the surfaces. The degree of fretting damage is greatest under perfectly dry conditions, and decreases as the humidity of the environment is increased. Some results of fretting fatigue tests on specimens of aluminium alloy L65 are also reported. Various stress amplitudes and clamping pressures have been applied. A surprising feature of the tests is that even under very small values of normal pressure the fretting action still exerts an important influence on the location of the fracture and on the fatigue life.

Fretting corrosion in connexion with press-fitted assemblies has been the subject of several studies. Peterson and Wahl (1935) tested rotating-bending specimens with pressed-on collars and found that the highest radial pressure (16,000 lb/in²) reduced the fatigue limit to half that of the plain specimen without collars, whereas a light press-fit (90 lb/in²) resulted in a 30 per cent reduction in fatigue strength. Horger and Neifert (1941) and Horger (1953) confirmed the observation that the fatigue strength of press-fitted assemblies decreases with increasing pressure, and found that shrink-on rings result in a fatigue limit for the axle about 20 per cent lower than with a pressed-on wheel.

In a recent investigation, Horger (1956) determined the influence of fretting corrosion on the fatigue strength of press-fitted assemblies, using rotating-bending tests on sixty-six shafts of $\Phi 4$ in. diameter. It was observed that the flat portion of the $S$-$N$ curve requires testing for at least 30 million stress reversals, indicated by the result that broken shafts failed at 40, 45, 77 and 84 million reversals. It is concluded that the fatigue resistance of press-fitted assemblies was comparatively less influenced by: (i) type of steel; (ii) tensile properties; or (iii) whether the shafts were normalized and tempered, or quenched and tempered than by subcritical quenching to obtain favourable residual thermal compressive stresses on the surface, thus increasing the endurance by at least 64 per cent.

Another study of the process of fatigue in the case of contact friction which is worth mentioning is one by Osino and Ivanova (1956). Two kinds of chromium-nickel-molybdenum steel were used for the investigation. It is concluded that there is no reduction in a medium of molecular hydrogen, but a continuous reduction was observed both in air and an atmosphere of hydrogen. The endurance limit was found to be zero or at least to have a very low value. The reduction in the fatigue limit by contact friction is explained by the process of electrical erosion proceeding under the action of thermoelectric currents. By changing the direction of the thermo-electric current through the selection of the proper contact material or by applying a counter current, it was possible to retard or entirely eliminate the action of electrical erosion and thus to raise the fatigue limit. The mechanism of fatigue fracture due to contact friction is understood as the formation of vacant sites in the crystal lattice during the transfer of metal in the process of electrical erosion.


65.6 Sunlight and Heat Radiation

The heat radiation has no discernible effect on the fatigue properties of metallic materials other than a possible rise of temperature, the effect of which is discussed in Section 65.1. On the other hand, detrimental effects of radiation are not unlikely on test pieces of plastics and rubber.

65.7 Nuclear Radiation

Sparse but accumulating knowledge of the effects of nuclear radiation on materials is the present state in this field. Two symposia on radiation effects on materials sponsored jointly by ASTM and the Atomic Industrial Forum have been held. So far, no fatigue tests on irradiated materials have been reported.

SECTION 66. TESTING TECHNIQUE

In this section the following factors associated with the testing technique will be discussed: (1) definition of fatigue life; (2) runout number of cycles; and (3) rest interval.
66.1 Definition of Fatigue Life

The term "fatigue failure" is an ambiguous one. Customarily and if nothing else is explicitly said, it means the final breaking into two or more pieces of the specimen. This end-point definition of fatigue life may be regarded as an acceptable one in laboratory tests on small specimens, but it is not entirely satisfactory, because it does not take into account the completely different character of the pre-crack and the post-crack stages of the fatigue process. Moreover, in some machines it is impossible to continue the test until complete rupture occurs.

For these reasons, other definitions have been proposed and are frequently used. From a theoretical view-point, the first appearance of a visible crack would be the most rational definition. There are, however, practical difficulties. The term "visible" is not uniquely defined, as it depends upon the method of detecting the crack, and the first visible crack may even be a non-propagating one. Furthermore, at high stress levels multiple nuclei appear, which all contribute towards the fracture of the specimen (cf. CUMMINGS, STULEN and SCHULTZ, 1955b). One way out of this difficulty is to stipulate a certain crack length, not too small. DIETER, HORNE and MEHL (1953) have proposed a length of 0·015 to 0·030 in.

A still more elaborate method of defining the fatigue life is to split up the process into further stages based on the use of the electron microscope, being: (i) submicroscopic slip bands within individual grains, (ii) formation of extremely fine cracks within individual grains, (iii) joining of cracks across grain boundaries to form major cracks, and (iv) extension of these major cracks until sudden, complete, tensile failure of the specimen occurs. This division is suggested by HUNTER and FRICKE (1954) who have also presented S−N curves corresponding to the various stages. It is evident that this splitting-up of the process is not workable in routine testing, but investigations of this kind are very important and may contribute to a rational definition of fatigue life.

Other definitions which have been proposed are related to the operating characteristic of the testing machine. Machines of the resonant type are the influence of temperature and corrosion on the flat portion of the S−N curve.

In his book on fatigue of metals, Gough (1924) states, on the basis of the experience of many years' testing at the NPL, that a direct-stress machine will reveal the limiting range of stress at a lower number of stress reversals than either a rotary bending machine or an alternating torsional machine. Further, hollow specimens reveal the limiting range after fewer reversals than solid specimens, when a rotating bending machine is employed. "It is our custom", he continues (1924), "to test on a 12 × 10⁶ reversals basis for solid specimens and on a 6 × 10⁶ reversals basis for hollow specimens."

These statements have been proved for ferrous metals. For light alloys a greater number than 10⁷ is required, he says, before the limiting range is disclosed.

The above rule is still valid for ferrous materials as confirmed in a recent investigation by TAYLOR (1956) who has analysed the influence of the runout number (maximum number) on the 50 per cent fatigue limit of a mild steel (B.S. 970 En 4), determined by a probit and by a staircase method. He found that the estimate remained unaltered for an appreciable range of threshold values, as demonstrated by the following Table:

<table>
<thead>
<tr>
<th>Runout Number</th>
<th>Number of Non-Breaks</th>
<th>Estimate of 50% Fatigue Limit (tons/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-50</td>
<td>60</td>
<td>32-40</td>
</tr>
<tr>
<td>7-47</td>
<td>64</td>
<td>32-43</td>
</tr>
<tr>
<td>7-00</td>
<td>64</td>
<td>32-43</td>
</tr>
<tr>
<td>6-50</td>
<td>65</td>
<td>32-43</td>
</tr>
<tr>
<td>6-25</td>
<td>76</td>
<td>32-55</td>
</tr>
<tr>
<td>6-00</td>
<td>122</td>
<td>33-50</td>
</tr>
</tbody>
</table>

A threshold value of 10 × 10⁶ (log N = 7-00) instead of the used value 30 × 10⁶ (log N = 7-47) would have given a saving exceeding 100 × 10⁶ cycles. If, on the other hand, N = 10⁷ had been chosen, a fatigue limit 3-7 per cent too high would have resulted.
FATIGUE TESTING AND ANALYSIS OF RESULTS

At elevated temperatures (Toolin and Mochel, 1947) or under corroding conditions, a number of cycles higher than $10^7$ will be required. As an illustrative example, an investigation by Horger (1956) may be mentioned. He found that the flat portion of the $S-N$ curve of a specimen subjected to fretting corrosion requires testing for at least 30 million stress reversals. This conclusion is based on observed fatigue failures at 40, 45, 77 and 84 million reversals in a sample of sixty-six shafts, tested in rotating bending on the basis of 85 million stress reversals.


66.3 Rest Interval

Very frequently tests are stopped over-night and continued the following morning. It is of importance to know whether or not such rest intervals have any influence on the fatigue strength of the specimen.

This problem had already been examined by Moore and Putnam (1919) with the result that rest intervals had no influence on the fatigue strength for stresses below the yield point. A slight effect was found for higher stresses. This conclusion was confirmed by Bollenrath and Cornelius (1940) who stated that rest intervals did not affect the $S-N$ curves of alloy steels.

Divergent results have been obtained by Daveys, Gerold and Schulz (1940) as demonstrated by the following Table corresponding to a steel of 160 kg/mm² ultimate tensile strength subjected to reversed stresses of 55 kg/mm² amplitude.

<table>
<thead>
<tr>
<th>Rest Interval</th>
<th>Fatigue Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>(days)</td>
<td>(kc)</td>
</tr>
<tr>
<td>Uninterrupted</td>
<td>0</td>
</tr>
<tr>
<td>Interrupted after 13-0 kc</td>
<td>3</td>
</tr>
<tr>
<td>Interrupted after 6-5 kc</td>
<td>3</td>
</tr>
<tr>
<td>Interrupted after 13-0 kc</td>
<td>4</td>
</tr>
<tr>
<td>Interrupted after 6-5 kc</td>
<td>4</td>
</tr>
</tbody>
</table>

The effect was still more pronounced when the specimen was kept at a temperature of 50°C.

References: Bollenrath and Cornelius (1940), Cornelius (1941), Daveys, Gerold and Schulz (1940), Moore and Putnam (1919).