Metallurgical Aspects of Fatigue Failure of Steel-Part II

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ABSTRACT

Behavior of metal under cyclic load differs from that under monotonic load. Fatigue manifests in the form of initiation or nucleation of a crack followed by its growth till the critical crack size of the parent metal under the operating load is reached leading to rupture. Fatigue research has been intensified in recent years by the introduction of higher strength materials and the development of advanced applications such as offshore structures and the adoption of new design codes. In addition it is already recognized that features such as corrosion, type of bar, form of manufacture, etc. can cause the fatigue lives to be substantially lower than are normally given in reference data. In this article the main parameters associated with fatigue of steel are reviewed with particular attention given to conditions related to structural applications and the effect on fatigue strength of chemical composition, microstructure, geometry, metal soundness, residual stress of steel and also the type of applied loading, loading pattern, magnitude of peak stresses has been explained.

1 Introduction

In a specimen subjected to a cyclic load, a fatigue crack nucleus can be initiated on a microscopically small scale, followed by crack grows to a macroscopic size, and finally to specimen failure in the last cycle of the fatigue life. In the previous part of the review paper, the fatigue phenomenon was discussed as a mechanism occurring in metallic materials. Understanding of the fatigue mechanism is essential for considering various technical conditions which affect fatigue life and fatigue crack growth, such as the material surface quality, residual stress, and environmental influence. This knowledge is essential for the analysis of fatigue properties of an engineering structure. Fatigue tests are carried out for different purposes. The engineering objectives are the determination of fatigue properties of materials, joints, structural elements, etc., including comparisons of different design options. Research objectives of fatigue tests are concerned with understanding of the fatigue phenomenon and its variables. Different types of fatigue loads, specimens, environments, and test equipment are used. Fatigue tests generally require significant experimental effort and time, which implies that these tests are more expensive than simple tests of several other mechanical properties. This part of the review covers the basics of several metallurgical variables for fatigue failure for steel. Different fatigue life improvement techniques are also mentioned briefly. Some clauses requiring acceptance of fatigue testing of steel components are also mentioned as well.

2 Fatigue Tests

2.1 Specimens

Some elementary types of fatigue specimens are presented in Fig. 1. The specimen with a central hole can be characteristic for radii occurring in a structure.

Fig. 1 also shows three simple types of joints, each having some special characteristic features. The lug joint specimen is representative for load transmission by a bolt or pin. Fretting corrosion can occur inside the hole. In the riveted lap joint, a tension load introduces bending, while fretting between the two sheets can also be important. The welded butt joint is the most simple type of a welded joint. Joints are frequently the most fatigue critical elements of a structure

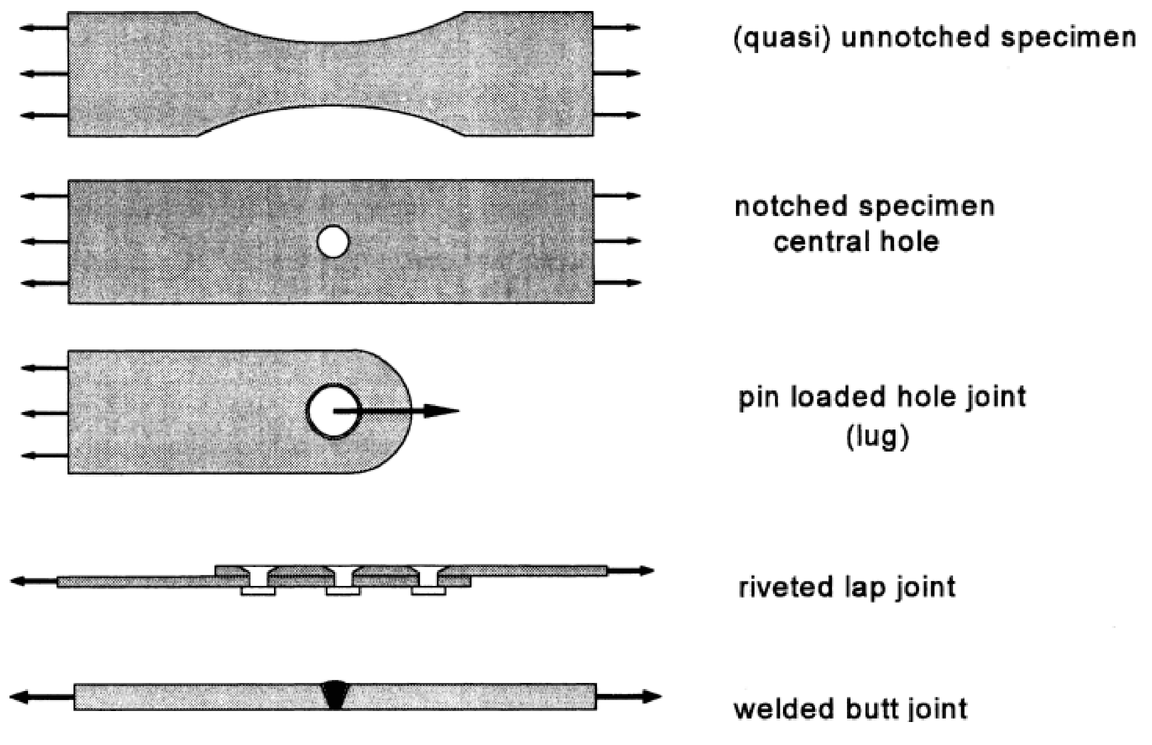

Fig. 1 Different types of simple fatigue specimens.

2.2 Fatigue test procedures

Various types of machines are available on the market for applying any of the three usual types loading (Fig. 2), namely, tension-compression, torsion and flexure. The most common of these tests is when tension-compression type loading is applied, since it is easier to perform such investigations. In a axial loading system, loading (uniaxial, tension-compression) can be strain or stress controlled, fluctuating (only tensile or only compression) or alternating (in tension and compression) at constant temperature (Fig. 2a). This method is capable of applying both mean and alternating axial loads in tension and/ or compression.In a rotating beam test, a dead weight-induced steady load is applied to the specimen as a cantilever with four point bending yokes (Fig. 2b). Bearings are provided to permit rotation of the specimen. The stress at a given point on the surface of the specimen will undergo a sinusoidal change in value about a zero point, with equal excursions in tension and compression. Constant load amplitude loading is normally possible with such equipment. Uniform bending moment along the specimen length is observed.

In the cantilever arrangement the bending moment applied to the test specimen varies linearly with the distance from the load application point, and the specimen is also subjected to a transverse shearing load (Fig. 2c). Cantilever rotating beam machines are rather versatile, in regard to the size of test specimen that can be accommodated, since only a single load acting through a rotating bearing at the free end is required. Constant load amplitude and non-uniform bending moment along the specimen length is observed.

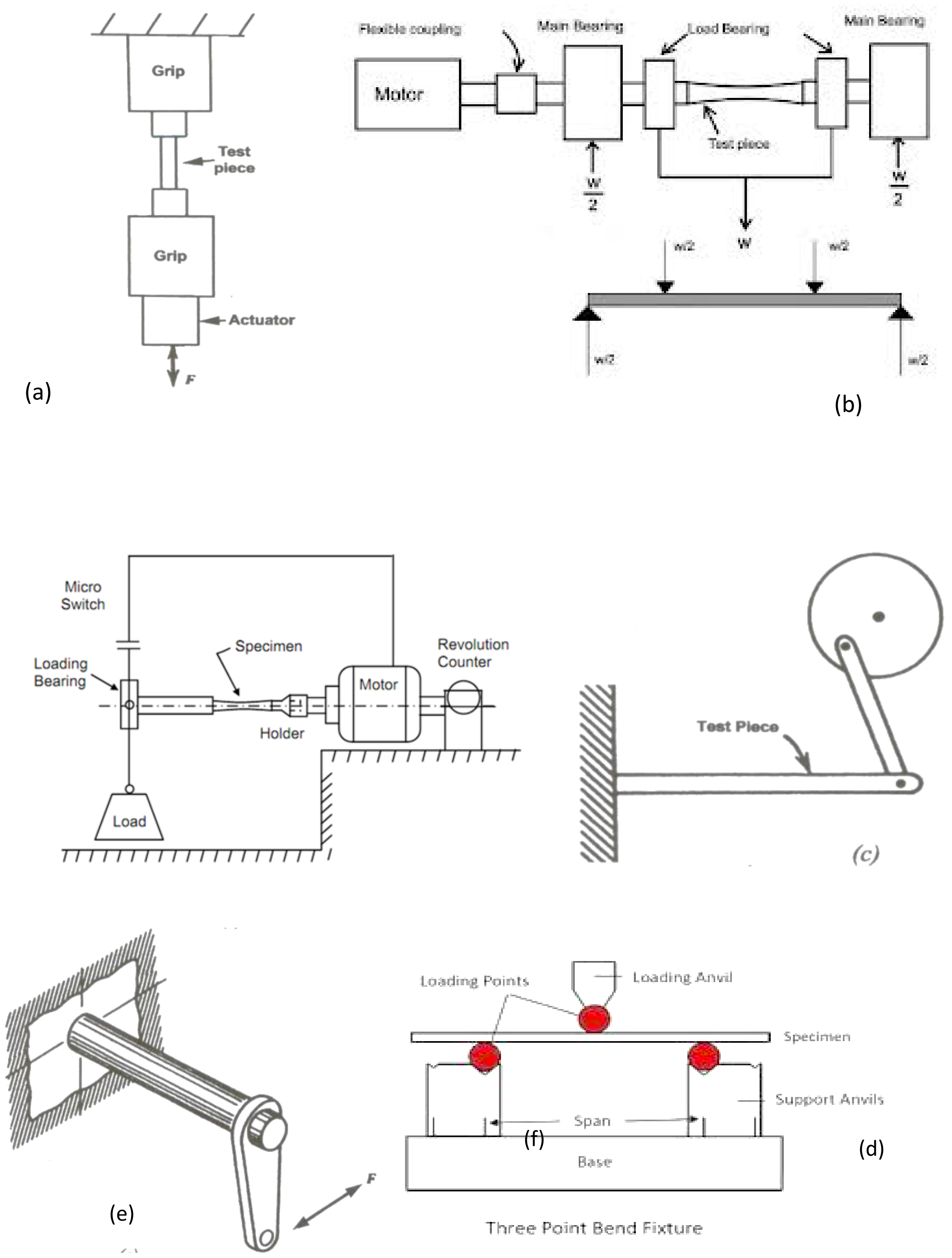

Fig. 2 Different types fatigue testing arrangements (a) axial loading, (b) rotating-bending, (c) rotating cantilever bending, (d) constant deflection amplitude cantilever bending, (e) combined in-phase torsion and bending and (f) three point flexural fatigue testing system.

A prepared test specimen of a flat-sheet or strip-spring material is mounted into a fixed cantilever, constant-deflection type fatigue testing machine (Fig. 2d). The specimen is held at one end, acting as a cantilever beam, and cycled by flexure followed by reverse flexure until complete failure. Load amplitude changes with specimen cyclic hardening or softening and decreases as cracks in the specimen nucleate and grow. The eccentric crank test machines do have an advantage over the rotating bending test machines in that the mean deflection, and hence the initial mean stress, can be varied.

Combinations of tension and torsion loading are used for another type test structure. Uniform torque and a non-uniform bending moment along the specimen length are applied (Fig. 2e). This often means that, at any point, the directions of the principal stresses can vary during the loading cycle and are therefore a function of time.

The flexural fatigue test is performed by placing a specimen in repetitive four point/ three point loading at a specified strain level. During the test, the beam is held in place by four /three clamps and a repeated sinusoidal load is applied to the two/ one inner clamps with the outer clamps providing a reaction load (Fig. 2f). The load rate is variable. This setup produces a constant bending moment over the center portion of the beam. The deflection caused by the loading is measured at the center of the beam.

2.3 Standards for fatigue tests

By simplifying and idealizing the test conditions, it would be possible to vary one or a few of the factors, which influence the fatigue life and to state their effects. Even if these conditions are fulfilled, there will always remain a number of unknown and uncontrollable factors which produce a large scatter in fatigue life even of test-piece which are considered to be identical. There are several standards in practices related to fatigue testing of metals for different loading conditions and systems (Table 1 and Table 2). These tests are useful for a comparison of the behavior of different materials subjected to repeated stresses, of the effects of various manufacturing processes, of the behavior of material in various environment, of various simple geometrical factors such as different sizes and shapes, of notches and different surface finishes.

Table 1 ASTM Standard Practices Related to Fatigue Testing of Metals

Designation	Title
ASTM E466	Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials.
ASTM E467	Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System.
ASTM E468	Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials.
ASTM E606	Strain-Controlled Fatigue Testing.
ASTM E647	Measurement of Fatigue Crack Growth Rates.
ASTM E739	Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (e-N) Fatigue Data.
ASTM E1012	Verification of Specimen Alignment Under Tensile Loading
ASTM E1049	Cycle Counting in Fatigue Analysis.
ASTM E1823	Standard Terminology Relating to Fatigue and Fracture Testing.

Table 2 ISO Standards Related to Fatigue Testing of Metals

Designation	Title
ISO 12106	Metallic Materials-Fatigue Testing Axial Strain-Controlled Method.
ISO 12107	Metallic Materials-Fatigue Testing Statistical Planning and Analysis of Data.
ISO 12108	Metallic Materials-Fatigue Testing Fatigue Crack Growth Method.

3 Metallurgical Variables of Fatigue Behavior

In order to understand more about fatigue under various practical conditions, several aspects of the fatigue mechanism are discussed in more detail. All these factors are related to crystallographic nature of the material; crack initiation at inclusions; small cracks, crack growth barriers, crack growth thresholds; number of crack nuclei; surface effects; macrocrack growth and striations; environmental effects; and cyclic tension and cyclic torsion. In this study, these factors are grouped into four categories:

1. Material factors;
2. Structural factors;
3. Loading factors;
4. Environmental factors.

3.1 Material effects

Basic material properties Material type (e.g., brittle cast iron, ductile steel, aluminum, titanium) and processing conditions (e.g., reheat, cold form, hot forge, cold extrude, quenched, tempered), grain type and size, and fundamental material properties (Brinell hardness, modulus of elasticity, yield strength at 0.2% offset, ultimate tensile strength, percent elongation at fracture, percent reduction in area, true fracture strength, true fracture ductility, strength coefficient, strain hardening exponent; cyclic strength coefficient, cyclic strain hardening exponent, cyclic yield strength, fatigue strength exponent, and fatigue ductility exponent) are all the important factors affecting the fatigue strength (Fig. 3).

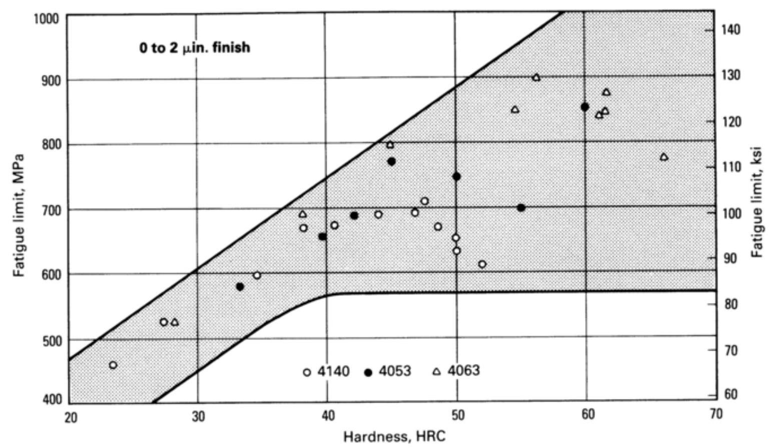

Fig. 3 Effect of carbon content and hardness on fatigue limit of through-hardened and tempered 4140, 4053, and 4063 steels.

3.1.1 Microstructure

For specimens having comparable strength levels, resistance to fatigue depends somewhat on microstructure. A tempered martensite structure provides the highest fatigue limit. However, if the structure as-quenched is not fully martensitic, the fatigue limit will be lower (Fig. 4). Pearlitic structures, particularly those with coarse pearlite, have poor resistance to fatigue. S-N curves for pearlitic and spheroidized structures in a eutectoid steel are shown in Fig. 5.

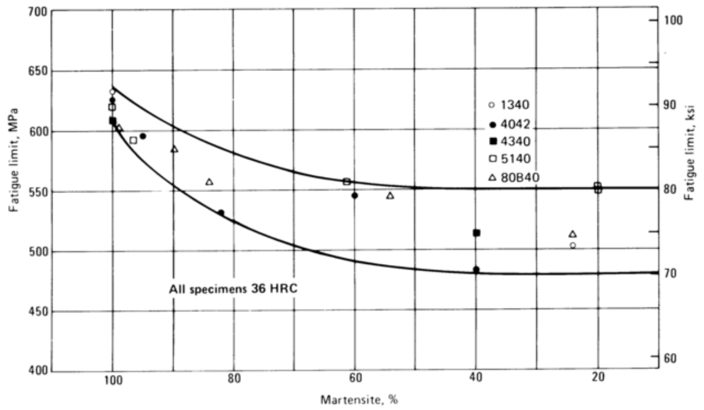

Fig. 4 Effect of martensite content on fatigue limit.

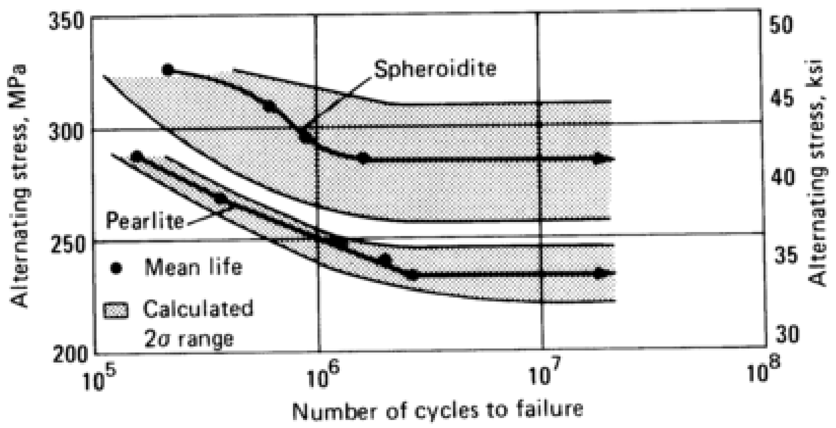

Fig. 5 Effect of microstructure on fatigue behavior of carbon steel (0.78% C, 0.27% Mn, 0.22% Si, 0.016% S, and 0.011% P).

3.1.2 Strength

For most steels with hardness below 400 HB (not including precipitation hardening steels), the fatigue limit is about half the ultimate tensile strength. Thus, any heat treatment or alloying addition that increases the strength (or hardness) of a steel can be expected to increase its fatigue limit as shown in Fig. 6 for a low-alloy steel (AISI 4340).

3.1.3 Ductility

As shown in Fig. 7 for medium-carbon steel, a higher hardness (or strength) may not be associated with improved fatigue behavior in a low-cycle regime (<10^3 cycles) because ductility may be a more important factor. Ductility is generally important to fatigue life only under low-cycle fatigue conditions (e.g. short with variable amplitude of loading during earthquake). Exceptions to this include spectrum loading where there is an occasional overload with millions of smaller cycles, or extremely brittle materials where crack propagation dominates.

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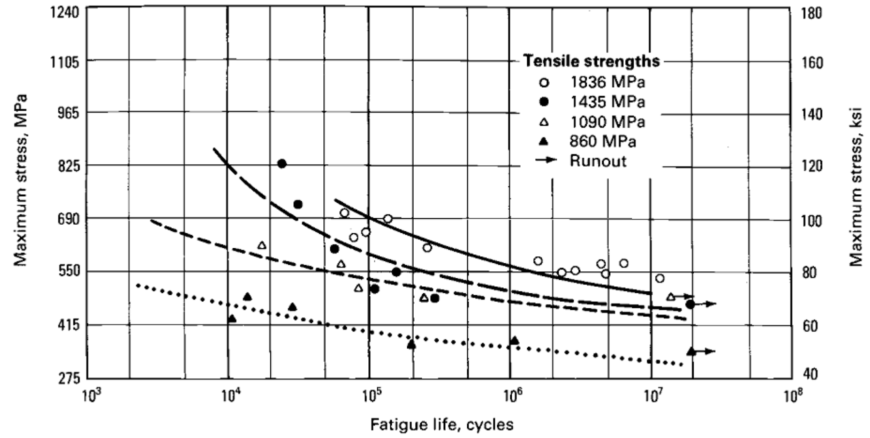

Fig. 6 Room temperature S-N curves for AISI 4340 alloy steel with various ultimate tensile strengths and with R = -1.0.

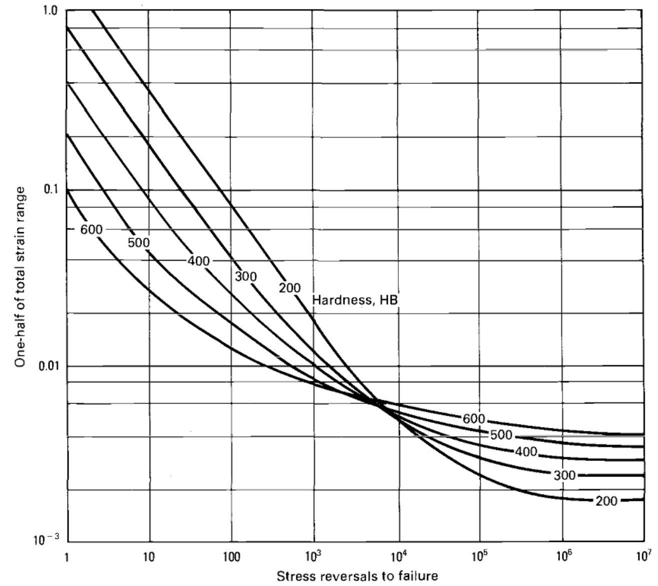

Fig. 7 Effect of hardness level on plot of total strain versus fatigue life.

3.1.4 Effect of surface finishing

Because the initiation of microcracks is associated, in general, with a free surface, the fatigue strength of a material, particularly after a long time, as determined by testing a given batch of similar specimens, depends on the roughness and condition of the specimen surfaces created by the particular techniques used in their preparation (Fig. 8). Decarburization is the depletion of carbon from the surface of a steel part. As indicated in Fig. 9, it significantly reduces the fatigue limits of steel. Decarburization of from 0.08 to 0.75 mm (0.003 to 0.030 in.) on AISI-SAE 4340 notched specimens that have been heat treated to a strength level of 1860 MPa (270 ksi) reduces the fatigue limit almost as much as a notch with K_t = 3 (Fig. 9).

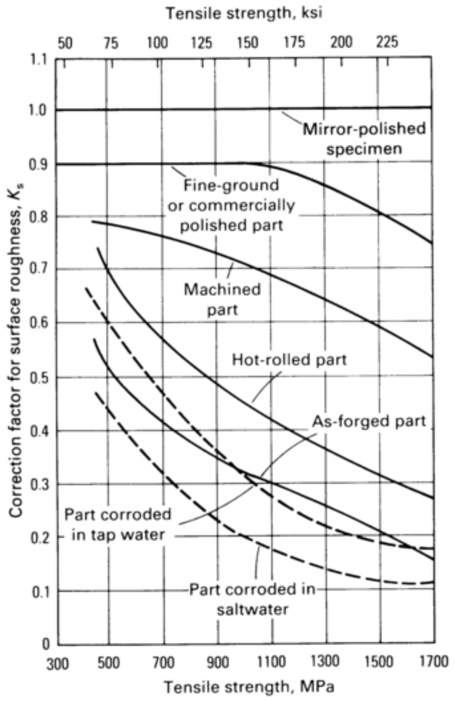

Fig. 8 Surface roughness correction factors for standard rotating-beam fatigue life testing of steel parts.

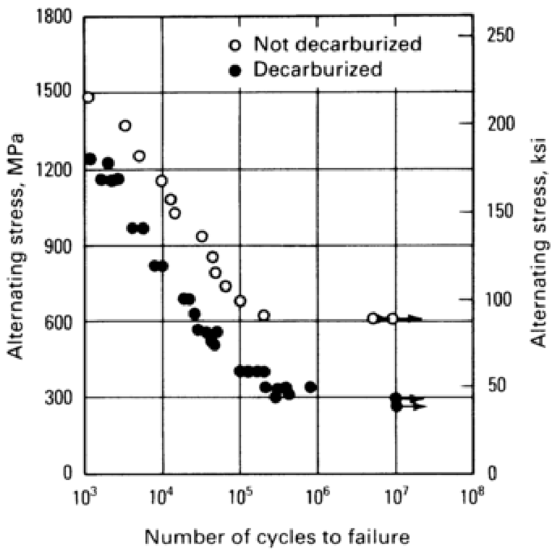

Fig. 9 Effect of decarburization on the fatigue behavior of a steel.

3.2 Structural effects

3.2.1 Structural geometry

It is obvious that the structural geometry decides the stress level and will affect the fatigue life. At the time of static failure, the average stress across the entire cross section would be the yield stress as shown in Fig. 10. However when the load is repeatedly applied or the load fluctuates between tension and compression, the points m, n in Fig. 10 experience a higher range of stress reversal than the applied average stress. These fluctuations involving higher stress ranges, cause minute cracks at these points, which open up progressively and spread with each application of the cyclic load and ultimately lead to rupture.

3.2.2 Fabrication defects

Fatigue is mainly a local type of failure, and thus the defect geometry (size and distribution) will have a significant influence on fatigue life. Defect geometry will be greatly influenced by fabrication methods and quality control procedures. Currently, the macroscopic notch effects have been accounted for, but the micro-level defects have not yet been fully considered. This is the main reason for the wide scatter of fatigue test results. One of the most important fabrication defects which result in fatigue are welds. Therefore, most of the existing fatigue design rules mainly concern fatigue of welded structures. The type, number, size, and distribution of nonmetallic inclusions may have a greater effect on the fatigue life of carbon and alloy steel than will differences in composition, microstructure, or stress gradients (Fig. 11 and Table 3).

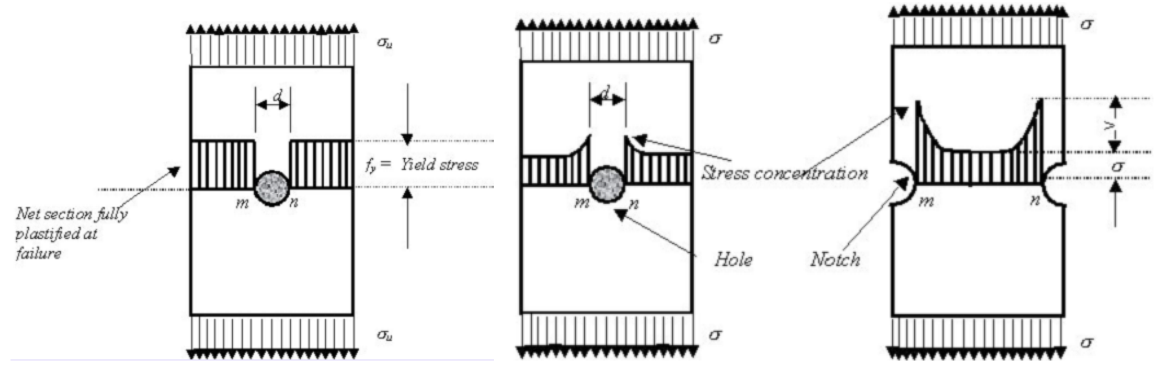

Fig 10 (a) Stress pattern at the point of static failure and (b) stress concentrations in the presence of notches and holes

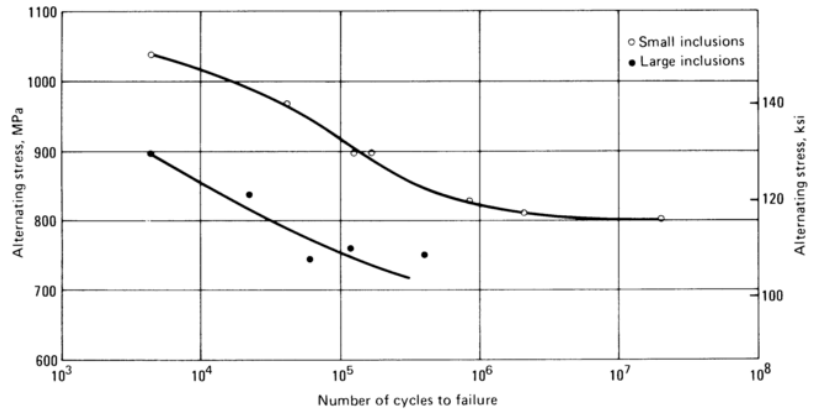

Fig. 11 Effect of nonmetallic inclusion size on fatigue. Steels were two lots of AISI-SAE 4340H; one lot (lower curve) contained abnormally large inclusions; the other lot (upper curve) contained small inclusions.

Table 3 Improvement in the fatigue limits of SAE 4340 steel with the reduction of nonmetallic inclusions by vacuum melting compared to electric furnace melting

Process	Longitudinal fatigue limit		Transverse fatigue limit		Ratio of transverse to longitudinal	Hardness, HRC
	MPa	ksi	MPa	ksi		
Electric furnace melted	800	116	545	79	0.68	27
Vacuum melted	960	139	825	120	0.86	29

The orientation of cyclic stress relative to the fiber axis or rolling direction of a steel can affect the fatigue limit of the steel. Fig. 12 shows the difference between the fatigue limit of specimens taken parallel to the rolling direction and those taken transverse to it. Any nonmetallic inclusions present will be elongated in the rolling direction and will reduce fatigue life in the transverse direction. The use of vacuum melting to reduce the number and size of nonmetallic inclusions therefore can have a beneficial effect on transverse fatigue resistance (Table 3).

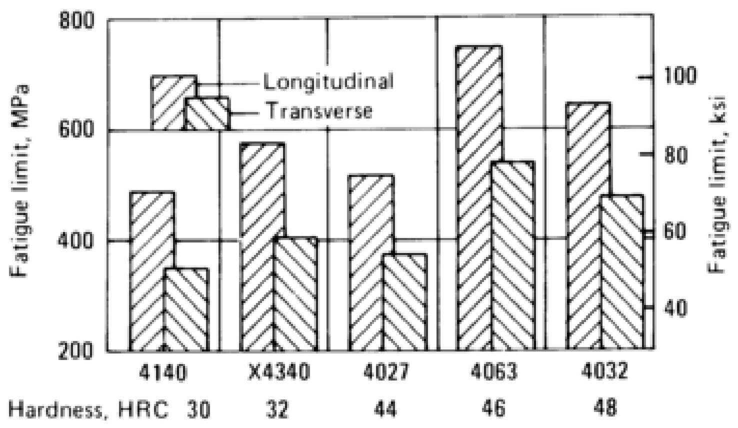

Fig. 12 Effect of specimen orientation on fatigue limit. Orientations are relative to the f iber axis resulting from hot working on the fatigue limit of low-alloy steels.

3.2.3 Residual stresses

Fatigue damage accumulation is modeled using the stress range as the main parameter, and correcting the fatigue strength by the mean stress. Tensile mean stress reduces fatigue strength and compressive increases. The effect of quenching medium (quench severity) on the magnitude of the residual stress and its variation along the cross-sectional area is shown in Fig. 13. In welded joints, the residual welding stresses can be regarded as mean stresses and therefore they will affect the fatigue strength. However, unlike the usual mean stress, residual stresses may have relaxation as a fatigue loading cycle.

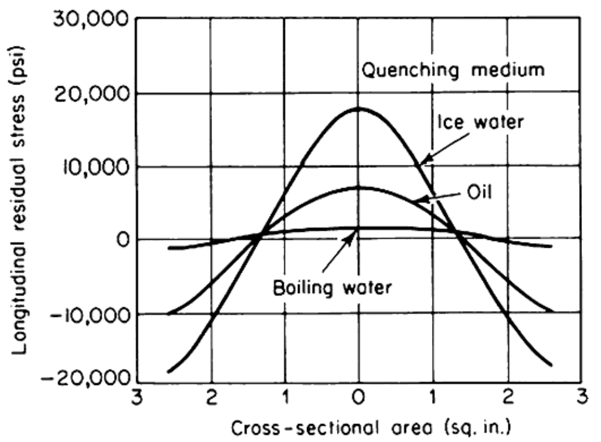

Fig. 13 Residual stress formation along the cross-sectional area for different quenching medium.

3.3 Loading effects

3.3.1 Mean stress effect

Fatigue tests have shown that a tensile mean stress resulted in shorter lives than a zero mean stress. A number of methods of allowing for the effect of mean stress have been reported.

3.3.2 Variable amplitude loading

Fatigue crack growth under variable amplitude loading is usually accompanied by the load interaction phenomena, because of which the fatigue crack growth rate in a given load cycle can differ from the growth rate observed for the same cycle in constant-amplitude tests. The character and magnitude of load interaction effects depend in a complex way on loading variables, specimen geometry, material properties, microstructure, and environment.

3.3.3 Multiaxial fatigue

Multiaxial fatigue was often treated with some equivalent stresses or other quantities. Experiments showed that a nonproportional loading history results in an order of magnitude shorter fatigue life than proportional loading when identical principal stress amplitudes are compared.

3.3.4 Frequency effects

Many experiments have shown that over the frequency range 1–200 Hz, the fatigue limit or strength after a long period of time of a material which does not heat up or whose surface is not chemically attacked during a test remains constant for all practical purposes, although there is, in fact, a slight increase with increasing test speed. At higher testing speeds, the fatigue limit continues to increase with testing speed up to frequencies of about 2 kHz, but beyond this frequency, the experimental data do not agree.

3.4 Environmental effects

Environmental effects on the fatigue of metals may be more severe than sharp stress concentrations or almost harmless. Quantitative fatigue life predictions are often not possible because of the many interacting factors that influence environmental fatigue behavior and the lack of significant data. Corrosion and temperature are the two main environmental factors affecting the fatigue behavior of metal structures.

3.4.1 Corrosion

Fatigue under a corrosive medium (known as corrosion fatigue) is a very complex problem. Corrosion fatigue refers to the joint interaction of a corrosive environment and repeated stress. The combination of both actions together is more detrimental than either acting separately. That is, repeated stress accelerates the corrosive action, and the corrosive action accelerates the mechanical fatigue mechanisms. Corrosive environments may also be detrimental under static loads, particularly in higher strength alloys.

3.4.2 Temperature

At elevated temperatures, mean stress effects are extremely complex because of interactions among creep, fatigue, and environment. The linear elastic stress intensity factor Kalso has more limitations at elevated temperatures because of appreciable plasticity. A substantial reduction in fracture toughness can occur at low temperatures, which reduces critical crack sizes at fracture. Irradiation can reduce both fatigue resistance and fracture toughness.

4 Application of Fatigue Life Improvement Techniques

Fatigue life improvement can be achieved through various treatments. These include grinding, shot peening, contouring, water-jet eroding, needle peening, spot heating, explosion treatment, hammer peening and so on. Each employs at least one of the following strategies:

1. Reduction of local stress concentration;
2. Removal or neutralization of preexisting defects;
3. Reduction of tensile residual stress and the introduction of compressive residual stress.

The effort of fatigue prevention/reduction can be summarized as

a) Use of stronger, more capable materials

Selecting materials with high fracture toughness and slow crack growth can be the initial choice for better fatigue resistance. That's also includes the consideration of materials that are suitable for the major challenge of the working environments, such as corrosion resistance, better/worse heat conductivity.

b) Reduce the margin of errors in assembly and manufacture

Tighter requirements should be specified when possible during manufacturing with lesser of number defects. Works done in controlled environment is usually better than in the field.

c) Avoid, soften when inevitable, stress concentrations

To remove stress concentration at sharp edges in the structure, any changes in geometry should be gradual. Any changes of geometry or openings at high stress area should be avoided. Symmetry and simplicity of design is encouraged. Extra attention on joins should be taken care (e.g. double shear joints when possible, rivets require less maintenance but not as durable as bolts).

d) Keep residual stress at surface, if any, in compression

Proper surface finishes should be chosen. Shot peening and cold rolling are good for the fatigue life in general. The effect of shot peening in an AISI 4340 steel is indicated in Fig. 14 at various conditions. Here, the base metal is compared with a shot-peened steel surface. Metallic plating with widely different properties than underlying material should be avoided. Prestressing should be considered when feasible. Carburizing is of great importance for the development of fatigue resistance and good wear in steels (Fig. 15). Gas nitriding is a thermochemical treatment commonly used to enhance wear, fatigue and corrosion properties of mechanical components, such as: gears, crankshafts, extrusion and forging dies, valves and springs, to name a few (Fig. 14).

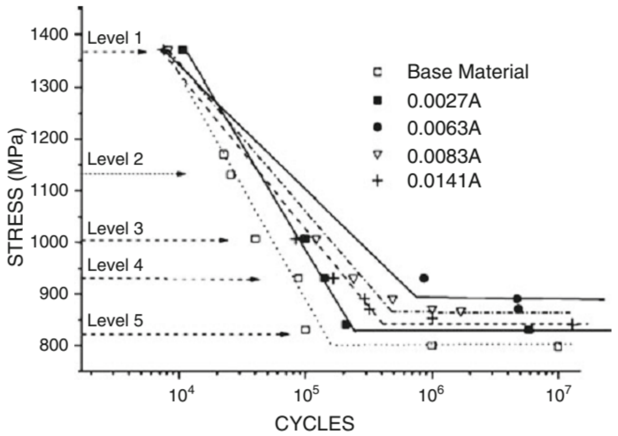

Fig. 14 S-N curves of AISI 4340 steel shot peened are compared with the base metal.
Take service environment into account

Protection against corrosion should be provided. Monitoring of extreme or frequent changes in temperature should be done periodically. Materials with less mismatch of thermal coefficients of expansion for mating parts should be Chosen. The natural frequency of the structure must stay away from the frequency of its working environment or loading

e) Schedule routine maintenance, firm and thorough

Maintenance including inspections and protection against corrosion, wear, abuse, overheating, and repeated overloading should be performed.

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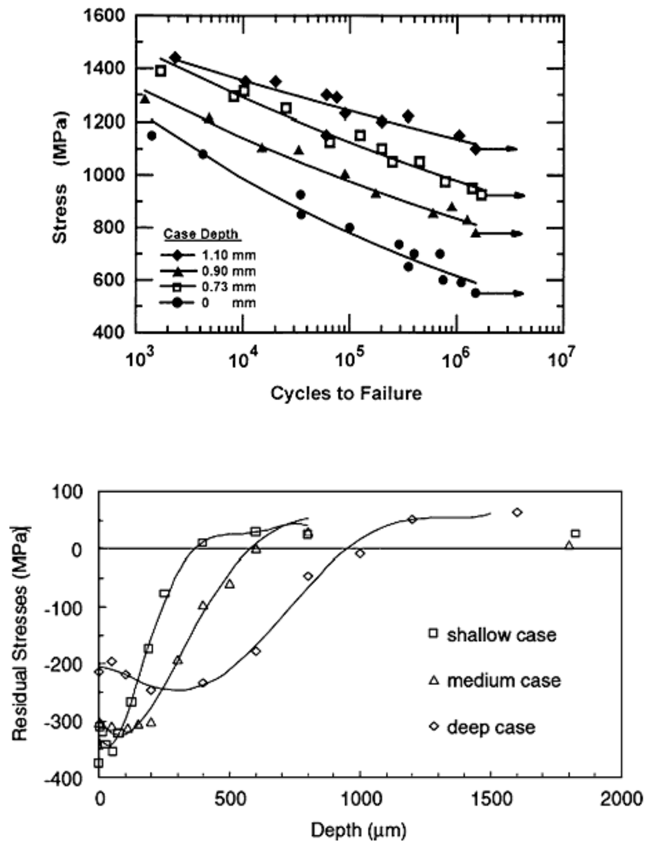

Fig. 15 (a) Fatigue curves of heat treated and carburized AISI 8620 steel and
(b) residual stress profile for three case depths in AISI 4140 steel.

5 Design for Fatigue

The basic characteristics of fatigue and some of the parameters affecting it have been discussed in this study. The resistance to fatigue failure, required to overcome crack initiation and propagation are clear. These aspects of fatigue should be translated to the design phase for structural components that will be operated under fatigue conditions. It is virtually impossible to provide design prescriptions for each specific case, due to the divergent applications of structural constructions, the different environments in which they operate and their various sizes (to mention only some of the factors that make general design guidelines difficult). Nevertheless, here are a few of basic principles that may apply to each case, as follows:

(a) In steel with definite fatigue limit, the stress applied should be kept below the endurance limit, at which the material is expected to have an infinite life-time. This design concept is also known as the 'infinite life-time concept'. In cases nonferrous metals without definite endurance limit, the use of an empirically evaluated life-time at a specific stress is sound. A stress level of 10^7 –10^8 cycles is a reasonable design criterion.

(b) Safe life design is a conservative approach. Parts are designed to operate for certain life-times, after which they are replaced by new parts. Thus, as per the designers' instructions, the empirically determined life-time is only used with the proper safety factor. Clearly, in either (a) or (b), the random appearance of an unexpected stress, due to some irregular-stress cycle cannot always be foreseen.

(c) Damage-related design requires periodic, nondestructive inspection of crack formation and growth. By using one of the nondestructive-testing methods, it is possible to perform such inspections to see if existing cracks are nearing the critical-crack size. There are mathematical methods for making reasonably accurate predictions of crack growth between inspections and for evaluating the time left for further safe use of that part following its inspection.

Despite these crucial design rules, a fatigue problem exists, since failure is usually sudden and often occurs at a stress level much lower than the ultimate stress level. Frequent attempts have been made to relate static deformation data to fatigue, but experiments have indicated little direct relation between the fatigue limit and yield strength, ductility and other static-deformation properties. However, some connection between the fatigue limit and the tensile strength, σ_{UTS}, has been established for un-notched, polished specimens tested by the rotating-beam method.

The commonly used relation for the fatigue limit of steel, S_{FL}, is: approximated as one half of the tensile strength

$$S_{FL}=0.5\sigma_{UTS} \quad (8)$$

Another empirical relation is:

$$S_{FL}=140+0.25\sigma_{UTS} \quad (9)$$

In addition, empirical hardness and fatigue life relations do exist. Empirical relations for other metals have also been suggested. Attempts have been made to relate fatigue properties to static parameters, based on the similarity between monotonic and fatigue mechanisms, which control cyclic straining and plastic flow. Various degrees of stress concentration are usual features of fabricated structural parts. Stress concentration acts at certain locations for fatigue-crack initiation. Residual stresses are common in machine parts (e.g., welded structures), but only compressive stresses do not contribute to crack initiation or propagation.

Residual-tensile stress or tensile components of applied loads are to be avoided, in so far as possible while designing for fatigue, because of its damaging nature. It has been observed that, all other things being equal, increasing specimen dimensions results in decreased fatigue. One explanation is that smaller-sized specimens have fewer microcracks than larger ones. Fatigue performance designers generally correct for the dimensions of the various parts.

6 Product Base Standards

Because of cost and time constraints, simplified service is used as much as possible for acceptance testing purposes, in which prototypes are required to withstand a specific fatigue loading without failure. A striking feature of an analysis of documents issued by the British Standards Institution is the large number which include clauses requiring acceptance fatigue testing of components. Most of them product standards. Some examples are given below.

BS 2A 241: 2005. General requirements for steel protruding head bolts of tensile strength 1250 MPa or greater. This gives requirements for high strength steel bolts for aerospace use. A bolt is ubiquitous engineering component. It is not surprising that a long established standard for high quality high strength steel bolts includes an acceptance fatigue test. Sophisticated statistical criteria are used to determine the acceptability of a particular bath of bolts. The constant amplitude direct stress fatigue loading specified is obviously not intended to represent any particular service loading.

BS ISO 10771-1:2002. Fatigue pressure testing of metal pressure containing envelopes. This was prepared as the result of research, during which it became apparent that both the frequency and the wave form have pronounced effect on the internal pressure fatigue life of metal hydraulic fluid power components made from materials that are normally frequency independent. The wave form of the pressure cycle, the maximum permissible viscosity of the pressurizing medium and the maximum permissible pressure cycling rate are all specified. Hydraulic system components are examples of safety related industrial components. The constant amplitude fatigue loading specified does not represent any particular service loading. The standard uses fatigue tests to define a fatigue pressure rating rather than precise acceptance criteria.

BS AU 50-2c:1996. Specification for road wheels manufactures wholly or partly of cast light alloy for passenger cars. This includes a radial fatigue acceptance test. For this test the wheel is fitted with an appropriate tyre and a constant radial force, which rotates around the wheel, is applied. A car wheel is an example of a safety related vehicle component. It is not surprising that a long established standard for car wheels includes an acceptance fatigue test. A constant amplitude fatigue loading is representative only of a vehicle running at constant speed on a straight and level road. The number of cycles specified is small compared with the number of service cycles, but to compensate for this a high fatigue load is specified.

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BS EN 60669-1:2000, BS 3676-1:2000. Switches for house hold and similar fixed electrical installations. General requirement. This dual numbered standard includes a normal operation acceptance test. In this test switches make and break a resistive load to their rated voltage, in a substantially non inductive alternating current circuit. Switches are operated for a specified number of operations. The acceptance criteria are that a switch must remain operational and mechanically and electrically sound, throughout a test. An electrical component with mechanical parts which might fail in fatigue due to repeated operation. The test specified is defined in terms of a number of normal operations. It is effectively a constant amplitude fatigue test on the mechanical components of the switch.

BS EN 12983-1:2000 Domestic cookware for use on top of a stove, cooker or hob. This was originally prepared in response to accident statistics which demonstrated that serious accidents can occur as the result of the premature failure of handles of domestic cookware. It sets level of performance for cookware for use on top of stove, cooker or hob by the accelerated simulation of hazards experienced in normal use. The acceptance fatigue test specified involves continuously raising and lowering a loaded item of cookware from a level surface once per minute by means of its handle. This is constant amplitude fatigue test. A cookware handle is an example of a safety related item in domestic use. The acceptance criterion is that there must be no permanent distortion or loosening of the handle or fixing system.

7 Standard for Steel Bars for Concrete Reinforcement

Reinforcing steel bar (i.e. rebar) commonly used in reinforced concrete and reinforced masonry structures, to strengthen and hold the concrete in compression. Steel for the reinforcement of concrete shall be subjected to fatigue testing as per BS 4449: 2005+A2:2009. Fatigue requirement as per standard for steel for the reinforcement of concrete are specified with a stress range under uniaxial loading. When submitted to axial force controlled fatigue testing, using a stress ratio $(\sigma_{min}/\sigma_{max})$ of 0.2, and stress range as given in Table 4, test samples shall survive 5×10^6 cycles generally under a servohydraulic machine (Fig.16).

The batch shall be deemed to comply with this Standard if all five test specimens endure 5×10^6 cycles of stress. Where two or more test specimens of the five initially selected fail to endure 5×10^6 cycles, the batch represented shall be deemed not to comply with this Standard. If one valid test specimen fails, a further five test specimens shall be selected from the batch represented. If one or more of these test specimens fails, the batch shall be deemed not to comply with this Standard.

Figure 16 Servohydraulic testing frame for axial loading

Table 4 Test stress ranges for nominal bar sizes

Bar size, mm	Stress range, MPa
Up to and including 16	200
Over 16 up to and including 20	185
Over 20 up to and including 25	170
Over 25 up to and including 32	160
Over 32 up to and including 40	150

Table 5 shows a typical fatigue test results from a standard lab test for 32mm dia TMT rebars of a local steel industry. As all the five rebars tolerated 5x10^6 cycles of stress, the batch was certified to be complied with the BS 4449: 2005 standard.

Table 5 Typical fatigue test results and conformation comment

Specimen Identification	No of Cycles X10^6	Frequency (Hz)	Position of Failure	Comments
130868/1/2	5.0	131	n/a	Test stopped at 5.0 x 10^6 cycles
130868/1/4	5.0	131	n/a	Test stopped at 5.0 x 10^6 cycles
130868/1/5	5.0	134	n/a	Test stopped at 5.0 x 10^6 cycles
130868/1/6	5.0	130	n/a	Test stopped at 5.0 x 10^6 cycles
130868/1/7	5.0	131	n/a	Test stopped at 5.0 x 10^6 cycles
Statement of compliance This batch of specimens complied with the requirements of BS 4449:2005 clause 7.2.4				

8. Concluding remarks

Fatigue in the crack initiation period is a surface phenomenon, which is very sensitive to various surface conditions, such as surface roughness, fretting, corrosion pits, etc. Microstructurally small cracks can be nucleated at stress amplitudes below the fatigue limit. The fatigue limit as a threshold property is highly sensitive to various surface conditions. At high stress amplitudes, and thus relatively low fatigue lives, the effect of the surface conditions is much smaller. All factors which affect the fatigue life of metal structures are grouped into four categories: material, structure, loading, and environment. The effects of these factors on fatigue behavior are also addressed. To summarize the requirements for fatigue design, the following is a list of some of the many factors that influence fatigue life and must be taken into account during the design process:

i. The material.

Usually materials with high melting points are preferred, since, in general, physical and mechanical properties are related to the melting point via the cohesive properties. Materials should be free of inclusion porosity and other voids that interrupt material continuity.

ii. The conditions of material processing.

The cyclic properties are dependent on the processing of the machine elements, whether they have been quenched, annealed, normalized or tempered.

iii. The surface conditions of a part.

Parts should be scratch-free and polished specimens perform better than unpolished ones.

iv. The geometry of machine elements.

Machine element geometry is an essential design parameter; length, width, thickness and diameter produce the size effects of materials. Furthermore, the radius (size and sharpness) and transition radius from location to location are of utmost importance, since they act as stress raisers.

v. The effect of the environment.

Environmental effects are important design considerations. Corrosive environments are detrimental. Some structures (e.g., ships) are often located in the corrosive environment of salty water; appropriate design steps should be taken to select the most resistant materials for parts exposed to seawater. Cathodic protection reduces the impact of this detrimental effect to some extent.

vi. The effect of temperature.

Temperature is a significant factor to be considered. Combined creep and fatigue deformation may act at high temperatures.

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