The Effect of Intermediate High Stress Pulses on the High Cycle Fatigue Strength of Metals

D. H. ALLEN and P. GREENFIELD
GEC plc, Engineering Research Centre, Whetstone, Leicester LE8 3LH, UK

ABSTRACT

This paper details the experimentally determined effect of intermediate compressive high stress pulses on the high cycle fatigue strength of a widely used low alloy engineering steel.

The results show that intermediate high stress pulses (of magnitude less than the yield point) can severely reduce the high cycle fatigue strength of the material to an extent whereby the fatigue limit of the steel is apparently eliminated. Increasing the frequency of the high stress pulses reduces the fatigue strength of the material even further.

KEYWORDS

Intermediate pulses, high stress, high cycle fatigue.

INTRODUCTION

Despite continuous research and development into the factors controlling the phenomenon of fatigue, this fracture mechanism remains the most common in engineering components.

The fatigue of engineering components operating solely under high cycle (low strain) or low cycle (high strain) conditions is fairly well understood. However, there are many components which operate under conditions where both high and low cycle fatigue stresses are prevalent and in these situations a cumulative fatigue damage law, such as Miners law, (Miner 1945) accounting for a variety of stress amplitudes is used by design engineers to assess the fatigue life of the component. Regardless of the fatigue assessment used, there have been numerous instances where fatigue failure of components has unexpectedly occurred prematurely, well before that predicted by any damage law.

Only recently, a review (Greenfield & Suhr, 1986) of failures in low pressure steam turbine and generator rotors, showed that there were still many unknowns in quantifying the fatigue strength of production items. One possible factor, affecting the fatigue failure of several large rotors, was said to be the possible interaction of occasional plastic pulses on high cycle fatigue strength.

In the case of rotating shafts various parts such as discs or retaining rings are often shrunk onto the rotor shafts (often near changes in section or other stress raisers). During the maximum stressing situation of start-up or shut-down these rings or discs may impart local plastic pulses into the shaft. The magnitude of the plasticity effect will itself be magnified under local stress concentrations such as scratches or machining marks, which are often inadvertently present on engineering components. Even though design calculations may show that no yielding occurs during stress transients, the presence of surface imperfections such as machining marks will often ensure that yielding occurs at least in the small volume of material at the tip of the defect. It is from such material that a fatigue crack is likely to develop, particularly if it is in the vicinity of a geometric stress raiser.

It is the aforementioned phenomenon which has recently been put forward (Greenfield & Suhr, 1986) as a possible explanation for previously unexplained fatigue failures of large rotors.

In other engineering components, operating under fatigue conditions, it is possible that the effect could be just as severe if not designed against. The occasional plastic pulse could arise from thermal transients and would often be superimposed on high frequency vibrations which claim the major attention of the design engineer. Should these occasional plastic pulses, which by themselves would be totally innocuous, actually affect the high cycle fatigue strength of the material, then the highly rated component may move from a position of being fit-for-purpose, to a position where failure will unexpectedly occur.

The phenomenon could apply to many engineering components such as rotor shafts, pistons, nuclear components and many other widely diverse engineering parts, where a combined loading may occur.

The overall objective of this work has been to investigate the effect of occasional stress pulses on high cycle fatigue strength, the pulses being nominally elastic but which are in fact plastic under surface scratches. . The initial investigations have been carried out on a low alloy engineering steel (EN19) and it is these results which are reported here.

MATERIAL

The material employed in this work was EN19, a widely used low alloy steel containing 0.9-1.5% Chromium, 0.2-0.4% Molybdenum and 0.35-0.45% Carbon as shown in Table 1.

Table 1. Composition of EN19 employed

%C	%S	%P	%Cr	%Ni	%Si	%Mn	%Mo	%Cu
0.43	.041	.016	1.12	0.21	0.3	0.8	0.21	0.19

EN19 is a commonly used engineering low alloy steel with typical applications as crankshafts, connecting rods, gears, bolts and other diverse parts which are often subjected to fatigue stressing.

The material used was in the form of 100mm diameter forged bar quenched from 850°C and then tempered at 650°C to give a tensile strength of around 780MPa and a hardness of 260H_v. A summary of the heat treatment and mechanical properties is given in Table 2. The general microstructure of the steel was of a fine tempered 'bainite'. No discernible change in microstructure or hardness across the section of the bar was found.

Table 2. Mechanical properties and heat treatment

UTS (MPa)	0.2% Proof Strength (MPa)	% El	RinA (%)	VHN (H_v30)
780	560	21	60	260 rim 255 centre

Heat Treatment	(i)	Hot Forged
	(ii)	Solution Treated at 850°C, Oil Quenched
	(iii)	Tempered at 650°C

FATIGUE TESTING

Testpiece Design

All high cycle fatigue tests were carried out on the design of testpiece shown in Fig. 1. The testpieces were removed from a longitudinal orientation within the forged bar, ie. parallel to the forging direction. Such an orientation is likely to be of most relevance to forged components under fatigue loading. The testpieces were all removed from a position equidistant from the centre of the bar. In order to simulate scratches or other machining defects under which localised yielding would occur, five circumferential grooves, 0.05mm deep with a 90° included angle were machined in the centre of the gauge length of each testpiece, with a spacing of 1mm (Fig 1).

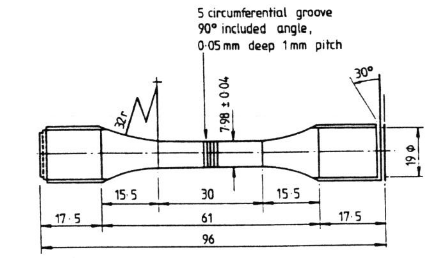

Fig. 1. Design of high cycle fatigue test piece

Testing

In order to establish the magnitude of any combined cycling effect it was first necessary to measure the high strain (stress) fatigue resistance of the material. This was done by testing, under strain control, specimens of the design shown in Fig. 2 which also contained 0.05mm deep scratches, in a servohydraulic Instron at ambient temperature and a frequency of 0.16Hz.

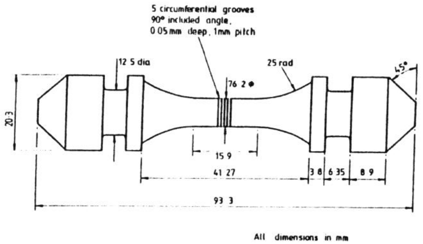

Fig. 2. Design of low cycle fatigue test piece

The combined cycling fatigue tests were performed in air at ambient temperature in the push-pull mode, using an Amsler Vibrophore resonance testing machine. A constant positive mean stress level of 193MPa (12.5tsi) was chosen for all tests and a test frequency of approximately 100Hz adopted. The computer controlled system of the fatigue machine enabled the effect of an intermittent stress pulse to be simulated automatically under load control.

The computer applied a high stress cycle which took the specimen into compression to an average stress of -500MPa (well below the general yield point of the material) every 10^5 cycles. This programme of combined high cycle and high stress cycling was repeated until failure or until run-out of the testpiece at 10^8 low stress cycles. A schematic diagram of the cycling programme applied to the test pieces is shown in Fig. 3.

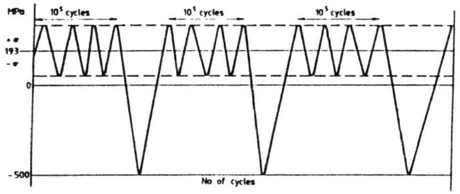

Fig. 3. Schematic diagram of combined fatigue cycling

In order to establish whether the frequency of high strain cycling affected the overall high cycle fatigue resistance of the material, a part of the programme involved the generation of a fatigue curve whereby the computer imposed the high stress cycle (-500MPa) every 10^4 cycles instead of 10^5 cycles.

RESULTS

The high strain (stress) fatigue results obtained for EN19 containing 0.05mm machined scratches are presented graphically in Fig. 4 in terms of both strain and stress range versus number of cycles to failure. The cycle imposed on the testpieces is also shown schematically. The results are tabulated in Table 3 in terms of both total strain range and measured stress range which was calculated from loads monitored during testing. The high strain results indicate a fatigue life of 800 cycles at 1% strain range (1048MPa stress range) and a life of 25,000 cycles at 0.4% strain range (789MPa stress range).

Table 3. Summary of low cycle fatigue results

Total Strain Range %	Stress Range (MPa)	Max Stress (MPa)	Min Stress (MPa)	Cycles to Failure
1.006	1048	526	522	750
1.006	1048	526	522	790
0.602	899	434	465	2800
0.4	789	334	455	25000

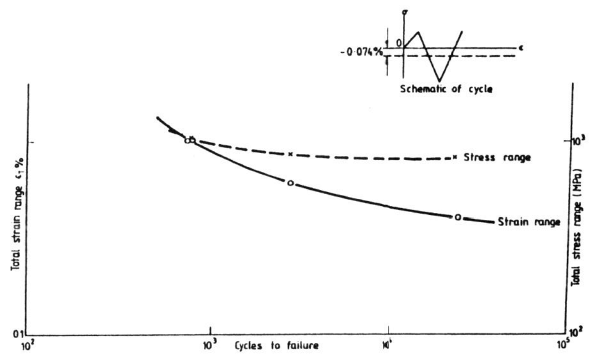

Fig. 4. High strain (stress) fatigue curve for EN19

The high cycle fatigue data for EN19 containing 0.05mm scratches with no intermediate high strain pulses is shown in Fig. 5. The results of fatigue tests on the same material and specimen type but without the surface scratches were available from another ongoing research programme and are shown in Fig. 5 for comparison. The results from Fig. 5 show that under these particular test conditions the material containing 0.05mm scratches has a fatigue strength of $\pm$175MPa at 10^7 cycles, compared with $\pm$260MPa for unscratched testpieces.

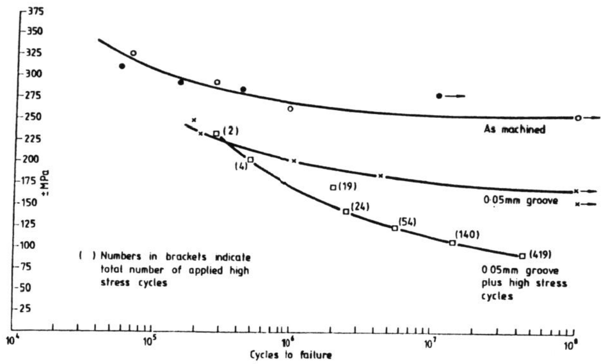

Fig. 5. Effect of intermediate high stress cycles on high cycle fatigue strength

Also shown in Fig. 5 are the results for the combined cycling tests. These tests were carried out under normal high cycle fatigue conditions but with a superimposed compressive (-500MPa) pulse every 10^5 cycles, as described previously. The effect of this combined cycling is clearly evident in Fig. 5.

The total number of applied high stress cycles is given in brackets against each failure point. It can be seen that the fatigue life at 10^7 cycles is reduced to ±110MPa, a reduction of approximately 40% compared with the fatigue strength of the material containing scratches but which had no high stress cycles imposed on it.

The effect of the frequency of the applied high stress cycles was investigated by increasing its frequency of application to one every 10^4 cycles instead of 10^5 cycles. The results of this change are shown in Fig. 6 which compares the combined cycling curves for both 10^5 cycling and 10^4 cycling. The increased frequency of the high stress cycle produces a further reduction in fatigue strength of approximately 30% at 10^7 cycles.

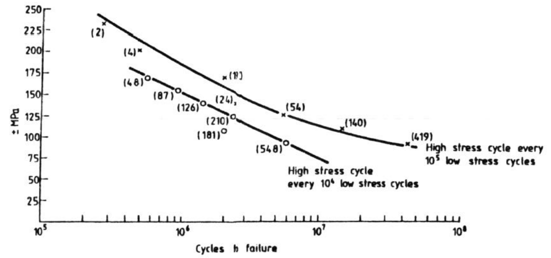

Fig. 6. Effect of frequency of stress cycle on high cycle fatigue strength

The combined cycling fatigue results produced in this work are tabulated in Table 4.

Table 4. Summary of all combined cycle fatigue tests

(a) +193MPa Mean Stress
Grooved Testpiece
No High Stress Cycle

Alternating Stress ±MPa	No. Cycles to Failure
247	1.82×10^5
232	2.03×10^5
201	1.92×10^6
185	4.21×10^6
170	1.06×10^8 Unbroken
154	1.08×10^8 Unbroken

(b) Combined Cycle - High Stress Interval 10^5 Cycles

Alternating Stress ±MPa	No. Cycles to Failure	No. High Stress Cycles
232	2.71×10^5	2
201	4.9×10^5	4
170	1.99×10^6	19
139	2.47×10^6	24
124	5.49×10^6	54
108	1.42×10^7	140
93	4.22×10^7	422

(c) Combined Cycle - High Stress Interval 10^4 Cycles

Alternating Stress ±MPa	No. Cycles to Failure	No. High Stress Cycles
170	5.35×10^5	48
154	9.43×10^5	87
139	1.38×10^6	126
124	2.28×10^6	210
108	1.96×10^6	181
93	5.80×10^6	548

DISCUSSION

Whilst fatigue tests are conducted using specimens with excellent surface finishes, often polished, it is widely recognised that adequate allowance must be made in design for the somewhat poorer quality of surface on engineering components. Such components are put into service with machined finishes of variable quality and, even if great care is exercised in producing them, occasional scratches may inadvertently be present for a variety of reasons. Such possible blemishes are taken into account during the design process and, for instance, the way this is done for large rotors has recently been detailed (Greenfield & Suhr, 1986). Generally, this is not done by detailed finite element analysis of stresses under surface scratches, but by making adequate allowance for deterioration in fatigue strength caused by surface finishes which are less than perfect. In the work presented here, the continued presence of transverse scratches 0.05mm deep and a mean stress of around 190MPa has reduced the fatigue limit of EN19 heat treated to a U.T.S. of 780MPa to about $\pm$175MPa - see Fig. 5. This can be compared with a fatigue strength of $\pm$260MPa on material without surface scratches at the same level of mean stress. It can also be compared with a fatigue limit of 40-50% of the U.T.S., namely $\pm$300-390MPa for a polished specimen at zero mean stress, such fractions of the U.T.S. often being used as a first approximation of expected fatigue strength.

Whilst there are still some design difficulties associated with designing against variable surface finish, the problems are well known and can be guarded against. The application of an occasional pulse in stress which may lead to plastic deformation at the tips of scratches presents the designer with the problem of assessing how much damage each stress amplitude will produce.

There are a number of so-called Cumulative Damage Laws available in the literature but none of them has been found to be universally applicable to all situations. The most widely used method of estimating the life of the component, which is subjected to a number of amplitudes of stress is Miners Law (Miner, 1945). The basis of this law is that if n_i cycles are applied at a stress amplitude of σ_i, for which the average number of cycles to failure is N_i, then the amount of damage which will be caused by this particular stress amplitude will be n_i/N_i. It follows from this theme when $\sum(n_i/N_i)=1$, failure will occur.

Applying such a method to the work described here would not have anticipated such dramatic effects of the intermittent pulses and in fact failure would not have been predicted. However, damage laws are usually investigated using specimens of excellent surface finish, totally unrepresentative of engineering components. Local plastic strains under machining marks, for instance, are not simulated in such work. As can be seen the infrequent application of a pulse producing plastic deformation under a simulated machining mark has resulted in a very severe deterioration in fatigue strength in this work and the apparent elimination of the endurance limit.

Using standard summation laws the plastic pulse itself would be totally innocuous if assessed by itself. As can be seen from Fig. 4, the material would have almost infinite life (in terms of high strain pulses) if subject solely to pulses of the magnitude applied in these tests.

Whilst it is often considered that fatigue can be split into an initiation phase and a propagation phase, it has also been suggested (Miller, 1984) that there is no crack initiation phase in polycrystalline materials, i.e. that in the formula

$$N_f = N_i + N_p$$

the number of cycles to initiate a crack, N_i, is zero. The fatigue

lifetime, N_f, is then the number of cycles, N_p, to propagate a crack from the first cycle of loading. When long cracks are present, such a philosophy is widely accepted and linear elastic fracture mechanics can be employed to predict fatigue life-times. The integration of a linear elastic fracture mechanics growth function suffices to predict life and curves of the type shown in Fig. 7 and been widely obtained experimentally. A threshold stress is thus predicted below which cracks will not grow. ΔK_{th}, however, can only be used as a threshold when long cracks are present. Since fatigue failures can be produced in polished specimens where defect size, a, is vanishingly small, then short cracks obviously grow below the LEFM stress intensity threshold. A schematic description can then be produced (Miller, 1984) as shown in Fig. 8. In this, some short cracks will grow at stress intensities below the level predicted by LEFM and other short cracks will not propagate at all, resulting in infinite life. Fatigue life is thus controlled by the creation of a crack that is big enough to propagate to failure.

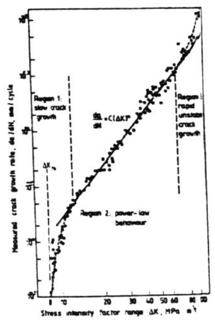

Fig. 7. A typical experimental LEFM fatigue crack growth and threshold stress intensity curve

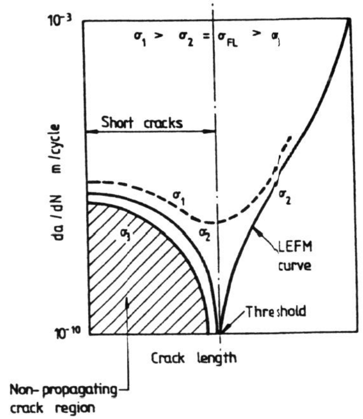

Fig. 8. A schematic diagram predicting the behaviour of long and short cracks

It is recognised that when addressing errors in laws which sum the effects of varying fatigue cycles, then the order in which such blocks of fatigue are applied is of crucial importance. At high stress levels where gross plastic straining can be involved, particularly under scratches, the fatigue lifetimes are dominated by crack propagation. At low stresses, lifetime is controlled by the development of a crack which can subsequently propagate to failure. If the high stress level is the first to be applied in a combined cycling test, then the entire initiation period is bypassed and linear summations of damage, $\sum n/n_f$ will be significantly less than one. This is illustrated in Fig. 9 by the dotted line. If, on the other hand, the low stress cycles are applied first, then linear summations will exceed one - again see Fig. 9 (Miller, 1984). Such considerations to date have only been addressed to errors in linear summation laws but the work in the present investigation indicates most strongly that if the high strain blocks of fatigue damage are suitably combined then, a fatigue life curve of the type incorporated schematically in Fig. 9 is produced. This represents a total breakdown of summation laws. Such a curve is not simply a deviation from the linear summation life but represents a situation which prevents normal methods from being applied to fatigue life estimates. It would appear that each of the high stress cycles, acting at the bottom of a scratch, causes plastic deformation and some propagation of the crack which is prevented from becoming stable by the next high stress application. The low stress, high frequency pulses may also cause some propagation for a time because of the residual tensile stresses left at the cracktip by the occasional compressive high stress cycle.

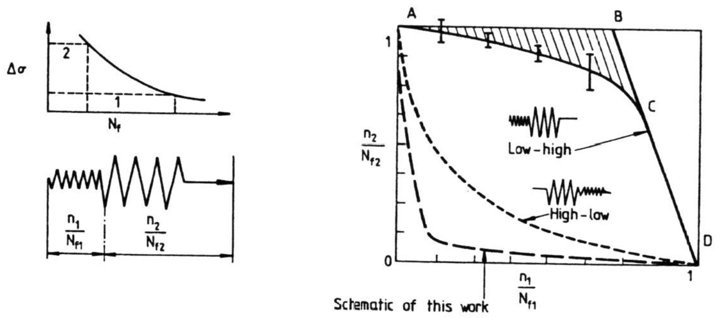

Fig. 9. Cumulative damage ratios in mixed stress range tests

Eventually, what was a sub-critical defect is large enough to grow under the action of the low stress cycles alone, leading to failure. Clearly in these circumstances, the more frequent application of a high stress cycle will reduce overall component life. This is illustrated in Fig. 6 which shows the affect of applying the high stress cycle once in every 10^4 cycles rather than in every 10^5.

The implication of this experimental work is serious in design against fatigue for those components where there is no large margin of safety. For instance, should a rotating shaft carry shrunk on components which apply an occasional high compressive stress during start up or shut down, then the fatigue life of the shaft cannot be relied on as that measured by the application of the reversing stresses produced by rotation alone. In the experimental work reported here, for instance, the application of 54 high stress cycles to a scratched component every 10^5 cycles has reduced fatigue life from about ±175MPa to ±110MPa at 10^7 cycles. Furthermore, the fatigue limit has been apparently eliminated. A high stress produced by a thermal transient is expected to have an equally serious effect, though potentially this could be an even more serious situation if the transient raises the level of tensile residual stress.

CONCLUSIONS

1. A series of tests to establish the effect of intermediate high stress pulses on the high cycle fatigue strength of a low alloy steel (EN19) containing surface scratches has been carried out.

2. The high cycle fatigue strength of EN19 is reduced dramatically such that the fatigue limit is apparently eliminated by the imposition of intermediate compressive stresses, of magnitude less than the yield strength of the material, every 10^5 cycles.

3. Increasing the frequency of the high stress cycles from every 10^5 to every 10^4 low stress cycles reduces the fatigue strength of the material further.

REFERENCES

Greenfield, P. and Suhr, R.W. (1986) Factors affecting the high cycle fatigue strength of low pressure turbine and generator rotors. I.Mech.E Conference, Sheffield.
Miller, K.J. (April 1984) Initiation and growth rates of short cracks. Eshelby Memorial Conference, Sheffield.
Miner, M.A. (1945) J.Appl.Mech 12, A195