THE EFFECT OF SMALL DEFECTS AND RESIDUAL STRESSES ON FATIGUE

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ABSTRACT

The damaging effects of small defects introduced by processing, fabrication and in-service operation on the fatigue properties of low alloy steels have been studied in relation to residual stress fields. The diverse roles played by inclusions, corrosion pits, fretting damage and where appropriate, their associated residual stress fields are each considered. The observed effects are discussed in relation to both S-N data and fracture mechanics and fatigue crack growth threshold concepts.

KEYWORDS

Small defects, residual stresses, fatigue crack initiation, crack growth, fatigue threshold concepts.

INTRODUCTION

Small defects introduced by processing, fabrication, and in-service operation can have a profound influence on the high cycle fatigue performance of engineering alloys. The observed degradation in properties can be assessed in two ways viz (1) the establishment of fatigue S-N curves and a Goodman type analysis in which combinations of applied mean and cyclic stresses are compared to a fatigue failure line. This classical S-N approach, is now invariably complemented by (2) a fracture mechanics appraisal incorporating fatigue threshold concepts. Here, from a knowledge of the threshold parameter for fatigue crack growth, ΔK_{th}, it is possible to predict whether a small defect subject to known mean and cyclic loads will be capable of growth or alternatively, be non-propagating. With either the S-N or ΔK_{th} methodologies, account is usually taken of the residual stresses simply by treating them as an extra source of mean stress (or stress intensity factor). In the present paper, consideration is given to several factors which can have a considerable influence on fatigue performance viz inclusions and their orientation, fretting, passive and active corrosion pitting and peening and associated residual stresses.

RESULTS

Inclusions and Material Anisotropy

In wrought products, both composition and degree of oxidation in the initial casting determine the degree of porosity, segregation and distribution of inclusions prior to working. Subsequent working can modify the shape and distribution of these defects as well as introducing grain texture and anisotropy of mechanical properties. Sulphide inclusions in low alloy steels are plastic at hot working temperatures and are rolled out into thin crack-like platelets up to 1mm in length. The inclusions can crack or decohere, providing preferred sites for crack initiation. Even in 'clean' vacuum carbon deoxidised (VCD) steels, fatigue strength displays marked anisotropy with respect to forging direction.
Experimentally determined S-N curves (Fig.1) show that the fatigue strength of a VCD 3.5% NiCrMoV low alloy steel is strongly dependent on whether specimens are machined either parallel (the axial orientation-L) to the direction of forging or perpendicular (the radial orientation-R). The global residual stresses were measured using an X-ray technique and were found to be near to zero. It has been shown that such behaviour is a direct consequence of the orientation of the non-metallic inclusions such as manganese sulphide and also complex silicates (Nix and Lindley, 1986). It is the volume fraction, orientation, shape and size of inclusions which strongly influence fatigue properties rather than their chemical species.

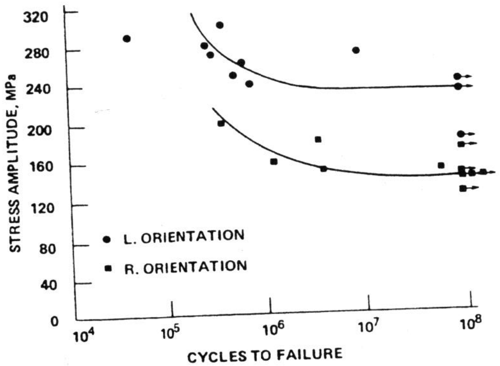

Fig.1 Fatigue S-N curves for axial(L) and radial(R) orientations of a vacuum de-oxidised low ally steel (mean stress 620MPa).

Fretting

Fretting is the oscillatory sliding motion of small 'slip' amplitude between two contacting surfaces and commonly occurs in clamped joints and shrink fitted assemblies. A consequence of fretting is that pits and small cracks are introduced at an early stage (<5-10%) in fatigue life. Figure 2 indicates that fretting can severely reduce the fatigue strength of a 3.5%NiCrMoV steel specimen (starting residual stresses near to zero) in contact with 3Cr1Mo steel pads. Although a

methology based on S-N data has been established (Lindley,1993) for assessing fretting fatigue, it relies on relating a fatigue strength reduction factor to the relative 'slip' range at the fretting contact. Here, experimental fatigue data, with and without fretting, are required for the contacting materials of interest. Since the fretting fatigue reduction factor for a simple geometry specimen will be quite different from the highly complex geometries found in real components, it is clear that this S-N based assessment is only capable of a general ranking of the susceptibility to fretting of various contacting material combinations.

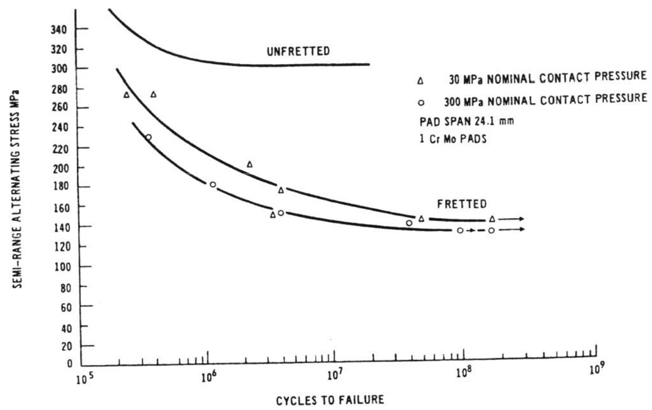

Fig.2 The effect of fretting on the fatigue strength of a 3.5NiCrMoV steel at zero mean stress

As well as small cracks (<1mm in depth) being found at an early stage of fretting fatigue life, non-propagating cracks have been observed in specimens tested at stresses significantly below the fretting fatigue limit (Nix and Lindley,1986). Fretting fatigue performance will therefore be determined by the conditions for the growth of these small defects. A fracture mechanics model has been developed for which the required input parameters are the externally applied stresses and the frictional forces developed between the contacting surfaces. The stress intensity factor at the tip of a crack growing beneath a fretting contact will arise not only from the 'body' stresses but also from tangential and vertical forces due to the fretting contact. The composite stress intensity factor can be evaluated by several diverse methods but the present author has used Green's functions. The method then involves comparing the composite applied stress intensity factor ΔK_{app} with the experimentally determined threshold ΔK_{th} (see Fig.3) at the appropriate value of stress ratio 'R' and has been successfully used to explain fretting fatigue behaviour in rotor components.(Fig.4).

Passive and Active Corrosion Pitting

Pre-corrosion pitting in water, followed by drying out of pitted specimens prior to fatigue testing in air, can have a devastating effect on fatigue strength which reduces from +/-315MPa (polished) to +/-140MPa (pitted) as shown in Fig.5 for a 3.5NiCrMoV steel tested at stress ratio R =0.1 for 'passive' pitting conditions. A further case involves 'active' pitting where the

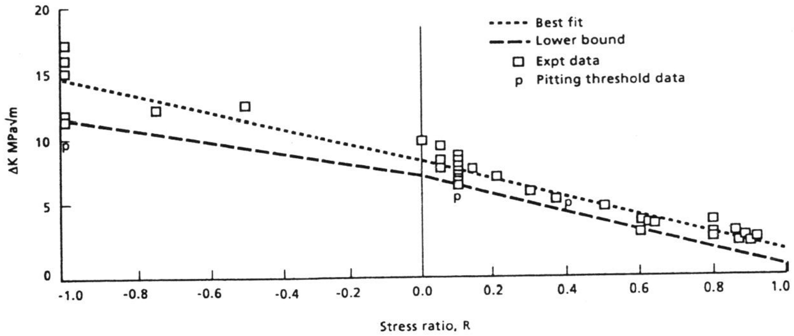

Fig.3 Fatigue threshold parameter ΔKth as a function of stress ratio R for NiCrMoV steels in air
Best Fits: For R>0, ΔKth = 8.18-6.96R For R<0, ΔKth = 8.18-6.1R
Lower Bounds: For R>0, ΔKth = 7.06-6.96R For R<0, ΔKth = 7.06-4.34R

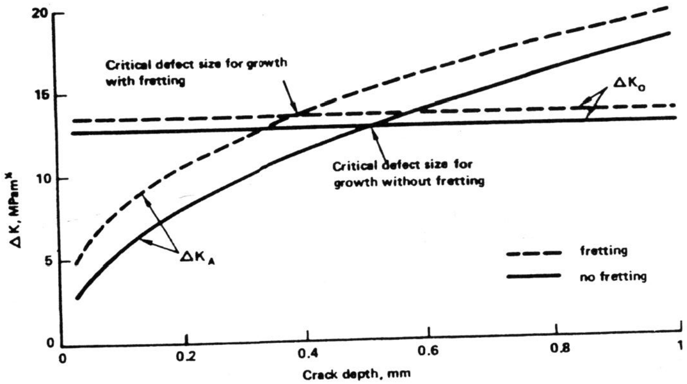

Fig.4 Fracture mechanics analysis showing the near threshold conditions for fatigue crack growth with and without fretting (applied ΔK_A and threshold ΔK_0).

environmental attack and fatigue cycling occur concurrently. Recent results (Sparkes et. al.,1987) have demonstrated that the fatigue strength can be reduced to as low as +/-42MPa at stress ratio values of 0.1 and 0.5. The corrosion pits initiate at manganese sulphide inclusions for the cases of both passive and active pitting and the observations currently available for the specimen axial orientation should be extended to the radial orientation. Apparent fatigue crack growth threshold values can be calculated for a given pit depth and fatigue limit (from the S-N curve). In the 'passive' and 'active' pitting experiments described in this section, the residual stresses were near to zero.

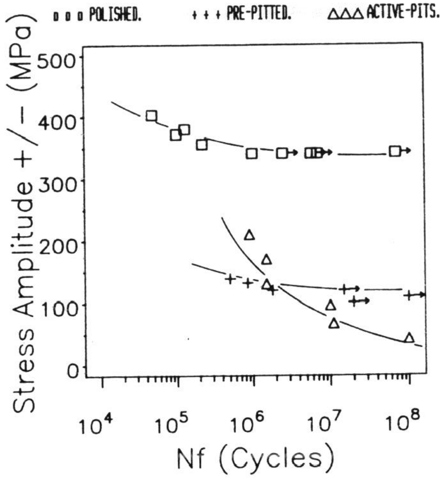

Fig.5 The effect of passive and active corrosion pitting on the fatigue of 3.5NiCrMoV steel. (R = 0.1).

Peening and Residual Stresses

In order to evaluate the effect of small defects situated in residual stress fields on fatigue behaviour, specimens were longitudinally polished and then stress relief annealed (to give near zero residual stresses). After establishing in air the S-N curve for the polished condition two further conditions were prepared:

(1) polished fatigue specimens were pre-corrosion pitted by exposure for 600 hours at 65°C in de-aerated, de-ionised water to give a general distribution of pits, typically 0.25mm deep. Figures 5 and 6 show that pre-pitting has a large deleterious effect on fatigue strength which reduces from +/-315MPa (polished) to +/-140MPa (pitted).

(2) pre-pitted specimens were peened with steel shot (Almen Intensity 0.008-0.012A) in order to introduce near surface residual stresses (Fig.7- fatigue tests on the compression peened samples are incomplete and are not reported). It can be seen in Fig.6 that the peening of pitted specimens significantly increases the fatigue strength from +/-140MPa (pre-pitted) to +/-250MPa (pitted and peened). The effect of peening on the pitting process is the subject of a current study.

Fracture mechanics and fatigue threshold concepts have been used to model the growth of fatigue cracks from corrosion pits sited in polished (near zero residual stresses) and peened (compressive residual stresses-seeFig.8) samples.The stress intensity variation with crack depth is given where Kcomp is the applied mean K added to the K resulting from residual stresses (Kres). The fatigue threshold ΔKth, with and without the presence of residual stresses is

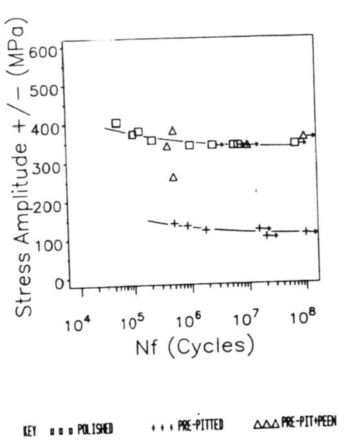

Fig.6 Effect of corrosion pitting with and without peening on the fatigue strength of 3.5NiCrMoV steel (R=0.1).

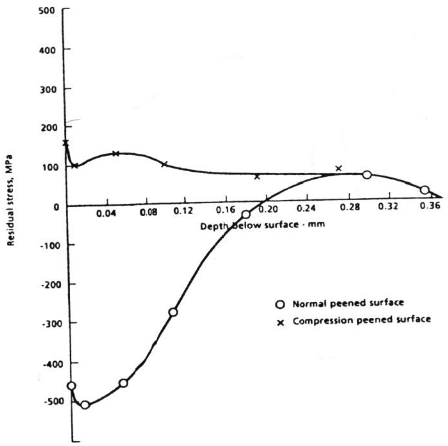

Fig.7 Variation in near surface residual stresses after peening in a low alloy steel from X-ray measurements.

estimated from the experimentally derived relation between ΔKth and stress ratio R. This analysis indicates that the critical defect size at which crack growth is sustained is increased from 0.10mm the pitted condition) to 0.27mm the pitted and peened condition (Fig.8).

Peening therefore provides a possible route toward refurbishing corrosion damaged components subjected to fatigue.

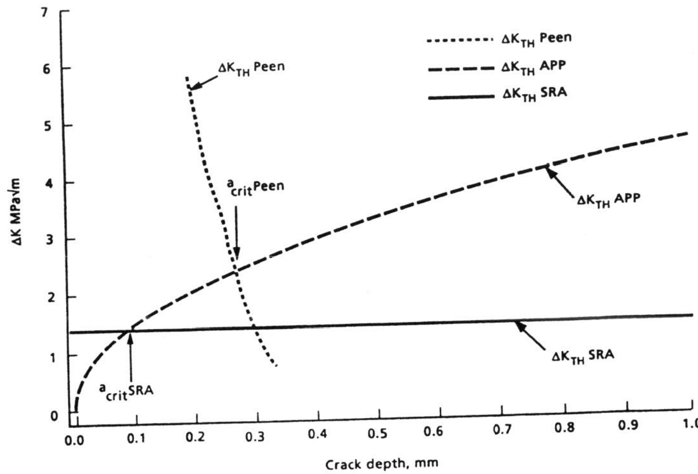

Fig.8 The effect of peening on the size of defect at which continued fatigue crack propagation can be sustained (applied stresses 590 +/- 65MPa).

CONCLUSIONS

It has been demonstrated that the presence of inclusions, fretting, corrosion pitting and residual stresses can each have an important influence on fatigue properties of a low alloy steel and the results have been modelled in terms of both S-N and fracture mechanics and fatigue threshold concepts.

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