FRETTING FATIGUE IN A 3½NiCrMoV ROTOR STEEL

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ABSTRACT

The reduction in fatigue strength due to fretting has been studied by clamping 1CrMo contact pads to fatigue specimens machined from a 3½NiCrMoV generator rotor shaft steel. With the range of pad contact pressures and pad spans employed, the fretting fatigue strength could reduce to as low as ± 60MPa, a fatigue strength reduction factor of 3.6. Metallography revealed that small cracks could form by fretting early in fatigue life and fracture mechanics concepts have been used to describe crack growth.

KEYWORDS

Fretting fatigue; generator rotor steel; fatigue strength reduction; fracture mechanics; growth of short cracks.

INTRODUCTION

Fretting is the oscillatory sliding movement of small "slip" amplitude between two contacting surfaces. The surface damage introduced by fretting can take the form of fretting wear (with or without corrosion assistance) or fretting fatigue where the material fatigue properties can be seriously degraded. Fretting is promoted by high frequency, low amplitude vibratory motion and commonly occurs in clamped joints and assemblies of "built-up" construction i.e. shrunk-on components. In turbo generators, it is possible for fretting to occur at several locations, namely turbine blade root to disc fixing, turbine disc to shaft seatings, disc to disc and shaft to shaft joints and end ring fixings. A further possible location occurs in generators. The generator rotor is made from a single low alloy steel forging, two sets of longitudinal slots for the windings being machined diametrically opposite one another to leave two solid pole pieces between them. In order to compensate for the difference in flexural stiffness about the winding and pole axes of the rotor, either narrow transverse slots or longitudinal slots are machined in the pole pieces. In the case of the longitudinal pole slots, it is necessary to replace most of the removed steel in order to restore magnetic permeability. This is achieved by using steel filler blocks which, in common with the windings, are held in position with either short or continuous retaining wedges. The wedges are fitted into slots (rotor teeth) machined in the rotor. With short wedges, fretting can occur as a result of relative movement between the wedge ends and the rotor teeth under cyclic self weight bending stresses. Mean stresses in the rotor teeth at the fretting locations (the wedge ends) arise from several sources (1) thermal gradients in the rotor body which arise from the hydrogen gas cooling (2) a contact pressure between wedge bar and the contact land on the rotor tooth due to centrifugal loading. This contact pressure is proportional to rotor speed and under normal operation (3000 rpm) the pressure is sufficiently high for the wedge bar to be regarded as being effectively "stuck" to the rotor tooth land (3) residual stresses arising from slot machining.

With short wedges, both fretting and stress concentration occur at the same location, the interwedge position (wedge ends). In order to separate the contributions from fretting and the wedge gap stress concentration effect, and to define the conditions for the initiation and growth of cracks, fretting fatigue experiments have been carried out in which contact pads of 1CrMo wedge bar steel were clamped to fatigue specimens machined from 3½NiCrMoV rotor steel.

EXPERIMENTAL PROCEDURE

Fatigue specimens of the type shown in Fig. 1 were machined from material released from a generator rotor such that their axial orientations were coincident. Flats had been machined on opposite sides of the specimen gauge length. Bridge type contact pads (Fig. 2) having a span of 24.1mm and narrow, rectangular feet were machined from the 1CrMo wedge bar steel. The compositions and mechanical properties of the two steels are given in Tables 1 and 2.

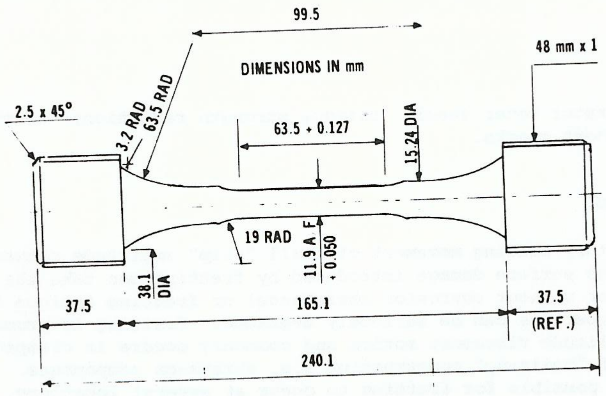

FIG. 1 FATIGUE SPECIMEN

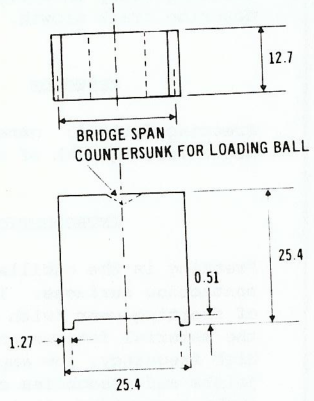

FIG. 2 BRIDGE TYPE CONTACT PAD

The fatigue specimen flats and the pad contact feet were polished down to 6/0 emery and degreased prior to testing in an Amsler Vibrophore machine typically resonating at about 150Hz. A pair of contact pads were clamped against the opposite flats of the fatigue specimen using a calibrated steel proving ring (Fig. 3). Steel balls were used to transmit the clamping load which was measured with strain gauges bonded to the proving ring or by dial gauges giving ring deflection. All the tests were carried out in air at about 20°C and 40-60% relative humidity.

TABLE 1 Chemical Composition of Fatigue Specimen and Contact Pad Steels

	C	Si	Mn	S	P	Ni	Cr	Mo	V
Fatigue Specimen	0.21	0.25	0.30	0.006	0.010	3.43	1.57	0.41	0.12
Contact Pad	0.42	0.30	0.59	0.022	0.030	0.29	1.42	0.75	-

TABLE 2 Mechanical Properties at Room Temperature of 3½NiCrMoV and 1CrMo Steels

	0.2% Proof Stress MPa	Tensile Strength MPa	Elongation %	Redn. in area %	Hardness VPN
3½NiCrMoV	600	733	25	70	222
1CrMo	841	999	21	59	340

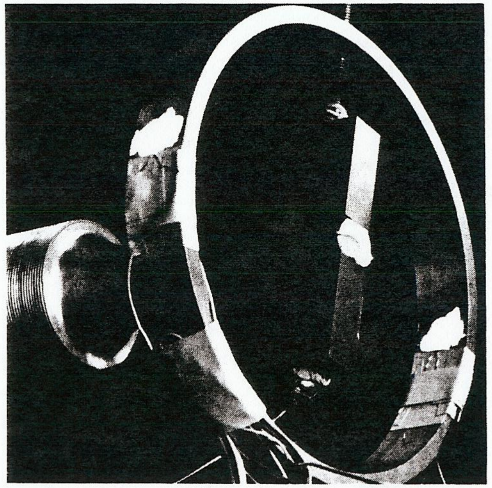

FIG. 3 Fretting fatigue assembly

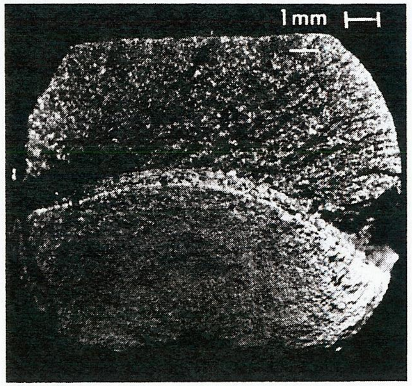

FIG. 4 Detail of fracture surface

EXPERIMENTAL RESULTS AND DISCUSSION

A series of base-line tests were carried out on polished unfretted specimens of similar pattern to those in Fig. 1 but without machined flats, at various mean stress values including 0 and 300 MPa (Figs. 5 and 6). At zero mean stress, fretting reduces the fatigue strength from 300 MPa to approximately 140 MPa, a fatigue strength reduction of about 2. For a mean stress of 300 MPa, the fatigue strength is reduced from 215 MPa to about 60 MPa, a fatigue strength reduction of approximately 3.6. Comparison with previously published work (Field and Waters, 1967) suggests that larger reductions in fatigue strength can be achieved by increasing pad span to the range 37-50mm, an effect which will be the subject of future investigation. At short fatigue lives of 10^5-10^6 cycles it can be seen (Figs. 5 and 6) that the higher pad contact pressure of 300MPa gives a lower fatigue strength compared to the low contact pressure of 30 MPa for both zero and 300 MPa mean stress.

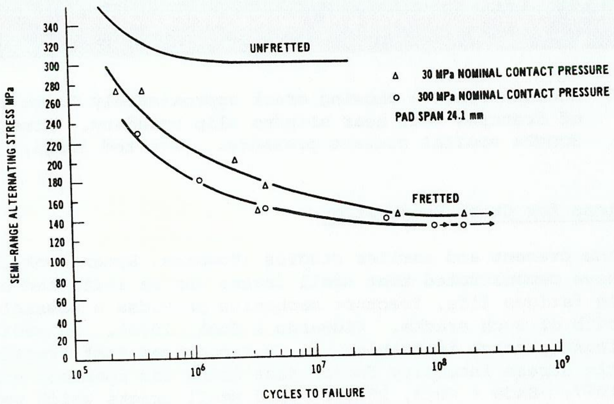

FIG. 5 FRETTING FATIGUE 3½NiCrMoV STEEL
ZERO MEAN STRESS
SINGLE PAIR OF CONTACT PADS

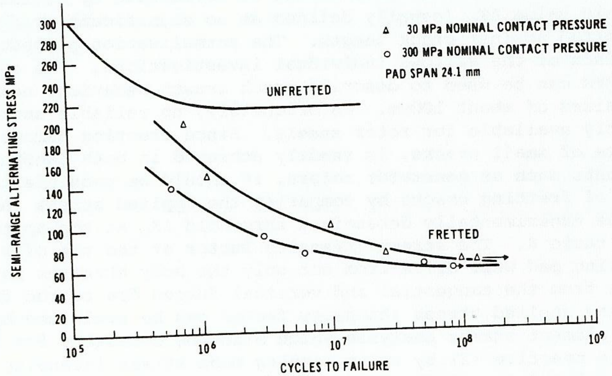

FIG. 6 FRETTING FATIGUE 3½NiCrMoV STEEL
300 MPa MEAN STRESS
SINGLE PAIR OF CONTACT PADS

The low and high contact pressures of 30 and 300 MPa are considered to be representative of the centrifugal loading of wedge bar against rotor tooth at low and high speed of rotation of a generator rotor. Since turbogenerator rotors can accumulate in excess of 10^{10} cycles during a typical lifetime of 20 years, long endurances are more relevant to practice. Figs. 5 and 6 indicate that there is little difference in fatigue strengths at 10^8 cycles for pad contact pressures of 30 MPa or 300 MPa at either mean stress (zero or 300 MPa). The nominal range of slip "S" at the end of each centrally clamped pad is given by $S = \sigma x/E$ where $\pm\ \sigma$ is the alternating stress, x the mean span of the fretting pad and E is Youngs Modulus. At 10^8 cycles endurance, the nominal slip ranges were 16.1μm (at zero mean stress) and 6.9μm (at 300 MPa mean stress). Previous workers (Fenner and Field, 1958) have demonstrated that slip in the range 9-15μm commonly produces the maximum reduction in fatigue strength for a wide range of mean stresses. It should be noted that the "true" slip range will be less than the nominal range due to contact pad deflection.

In order to explore more closely the effect of a number of short wedges in a generator and in particular the effect of a "wedge gap", fretting fatigue experiments were performed with double pairs of pads clamped at the high contact pressure of 300 MPa. Figure 7 indicates that the single and double pair of contact pads give very similar fretting fatigue strengths at mean stresses of both zero and 300 MPa. The space between the pads on each side of the fatigue specimen was 1mm, a similar separation commonly being found between wedge bars in generators.

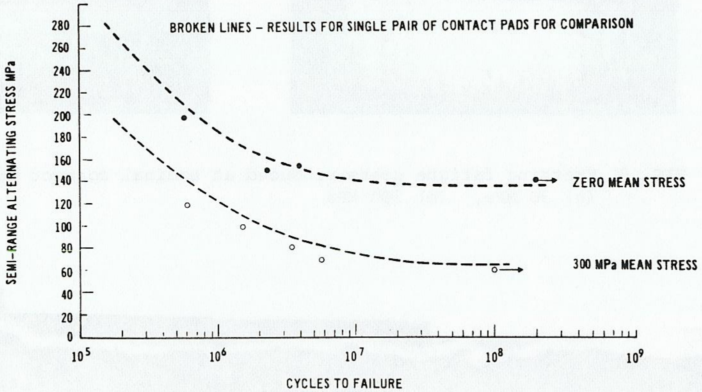

FIG. 7 FRETTING FATIGUE 3½NiCrMoV STEEL
DOUBLE PAIR OF CONTACT PADS AT 300 MPa NOMINAL CONTACT PRESSURE
GAP BETWEEN PADS 1 mm

Metallography of Fretting Damage

Fretting damage on the fatigue specimen surface under the pad contact strips is shown in Fig. 8. At the low contact pressure (30 MPa), slip and fretting damage occurs over virtually all of the contact strip (Fig. 8a). By contrast, at the high contact pressure, slip and associated fretting damage was confined to the edges of the contact strip. The surface damaged regions had an overlay of brown debris which was identified by X-ray analysis as α and γ-Fe_2O_3 and particulate iron. After plating the fatigue specimen surface with nickel, metallographic examination of a longitudinal section taken through a fretting 'scar' revealed the presence of typical fretting fatigue cracks (Fig. 9). These shallow angle cracks are up to 250µm long (measured in the direction of propagation). A fretting fatigue failure showing that the crack had initiated obliquely to the surface before subsequently propagating transverse to the applied stress is shown in Fig. 4. In order to determine the endurance at which fretting fatigue cracks were initiating, some tests per periodically interrupted in order to take acetate film replicas of the fretted regions. The replicas were examined in the scanning electron microscope and Fig. 10 shows a small crack 0.4mm long formed at the front of a fretting foot near the fretted/non-fretted boundary. Using this technique, it was found that small fatigue cracks up to 250µm deep were present at an early stage (up to 20%) of specimen fatigue life. Small, non-propagating cracks were sometimes found in fretted specimens "running out" at 10^8 cycles, when tested just below the fretting fatigue limit as found by other investigators. (Nishioka and Hirakawa, 1972).

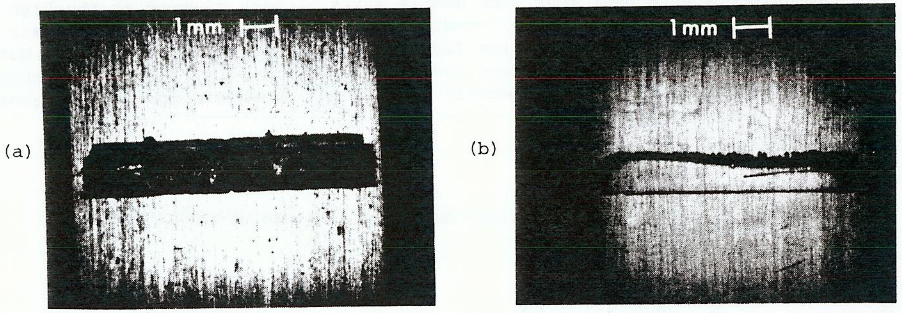

FIG. 8 Fretting fatigue scars produced at nominal contact pressures of (a) 30 MPa, (b) 300 MPa

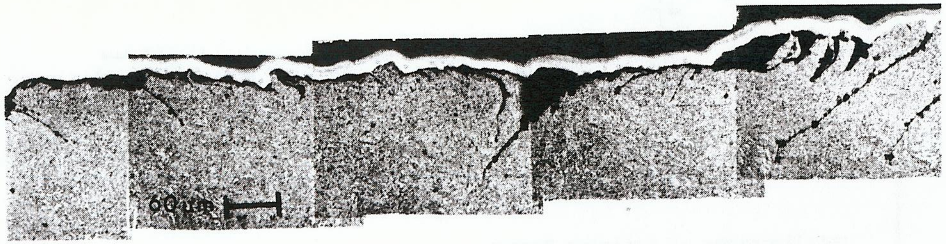

FIG. 9 Longitudinal section through fretting scar showing shallow angle fatigue cracks

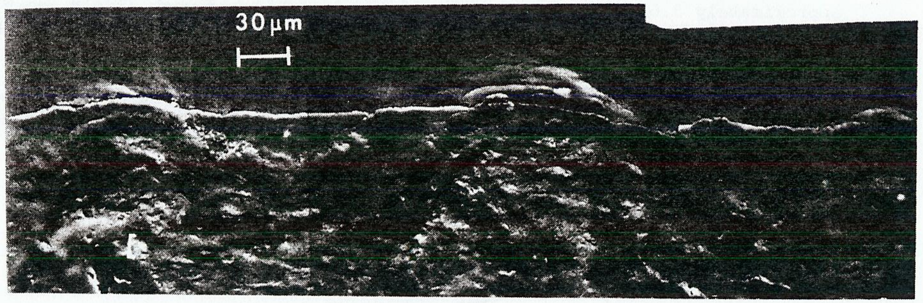

FIG.10 Acetate replica showing crack approximately 0.4mm long at front of fretting foot near slip/no slip boundary. Stresses 308 ± 65MPa; 300MPa nominal contact pressure. Inverted image.

Conditions for Crack Propagation

Since the present and earlier studies (Edwards, Ryman Cook 1977; Endo and Goto, 1975) have demonstrated that small cracks can be initiated at an early stage of fretting fatigue life, fracture mechanics provides a possible method of describing the growth of such cracks. (Edwards & Cook, 1978). In addition to accelerating significantly crack initiation, it is recognised that fretting can increase the crack tip stress intensity factor just below the specimen surface. (Edwards & Cook, 1977; Endo & Goto, 1975). Thus small cracks which would be non-propagating without fretting, might propagate through this near-surface region due to the elevation of stress intensity factor provided by the fretting pads. The validity of application of linear elastic fracture mechanics (LEFM) at small crack sizes is supported by fatigue crack growth data in the literature (Fig. 11 - data due to El Haddad and others 1978; Frost, 1959; Kitagawa & Takahashi, 1976; Kobayashi & Nakazawa 1971; Ohuchida, Nishioka & Usami, 1973) when the apparent threshold ΔK_a for measurements on small cracks is normalised by dividing by the long crack threshold value ΔK_o (usually defined as no significant crack growth in 10^7 cycles) and plotted against crack length. The normalisation procedure facilitates comparison of the various individual investigations. The collated data suggests that LEFM can be used to describe crack growth behaviour near threshold down to crack sizes of about 100µm. Unfortunately, no reliable short crack data is presently available for rotor steels. Since fretting damage, including the presence of small cracks, is readily achieved in both laboratory specimens and components such as generator rotors, it should be possible to predict growth arrest of fretting cracks by comparing the applied stress intensity range ΔK_{app} with the experimentally determined threshold ΔK_o at the appropriate value of stress ratio R. The stress intensity factor at the tip of a crack growing beneath a fretting pad will arise from not only the body stresses but also components arising from the tangential and vertical forces due to the fretting pads. The composite applied stress intensity factor can be evaluated by several methods (1) finite element stress analysis which might be necessary for the complex assemblies found in practice (2) by using opening mode stress intensity factors arising from tangential and normal forces at the fretting position which have been computed by Rooke and Jones, (1979). This method requires the measurement of the frictional forces by strain-gauging the underside of the pad clamped to the fatigue specimen, a procedure (Edwards & Cooke, 1978b; Endo, Goto & Fukunaga, 1974) which is described in detail elsewhere. Frictional forces measured for constant amplitude loading with a pad span of 24.1mm and a nominal pad contact pressure of 300 MPa are shown as a function of semi-range fatigue stress in Fig. 12. Similar measurements can be made for other fretting pad span and loading conditions. Following the method of Edwards & Cooke (1978a) the alternating stress intensity K_{app} is given by the components due to alternating body stresses σ_a and frictional force F_f:

$$\Delta K_{app} = 1.12\sigma_a\sqrt{\pi a} + CF_f\,K_{fpl} - 1.12\,\frac{F_f}{A}\sqrt{\pi a} \qquad (1)$$

The mean stress intensity factor is given by

$$K_m = 1.12\sigma_m\sqrt{\pi a} + C\,F_n\,K_{np} \qquad (2)$$

where a is the crack length, A the specimen cross-sectional area and C the fretting scar width. The stress intensity factors K_{fpl} and K_{np} for frictional and normal loads depend upon the assumed distribution of pad loads. They are conveniently presented in terms of a frictional or normal load per pad foot of 1N and a scar width of 8mm (the specimen width). The measured frictional forces are required in order to scale K_{fpl} and K_{np} as indicated in equations (1) and (2). Components can commonly tolerate the presence of superficial fretting damage even in the presence of small cracks. As already indicated, a fracture mechanics approach in which the applied ΔK_{app} is compared to the threshold value ΔK_o at the appropriate value of stress ratio R, should enable the prediction of continued growth or arrest of small defects subject to fatigue loading. Such an approach has been successfully used to predict the growth of fatigue cracks from corrosion pits in turbine shafts (Jack & Paterson, 1977). Figure 13 illustrates this approach for small cracks growing in a body with or without fretting. The variation of threshold ΔK_o will depend on mean stress and environment, hydrogen being the gas coolant commonly used in generators. The factors influencing mean stress at the surface of a generator rotor has already been discussed in the introduction. The variation of applied stress intensity ΔK_{app} with crack depth will depend on the applied stress field. Fretting will introduce an additional component in ΔK_{app} as already discussed.

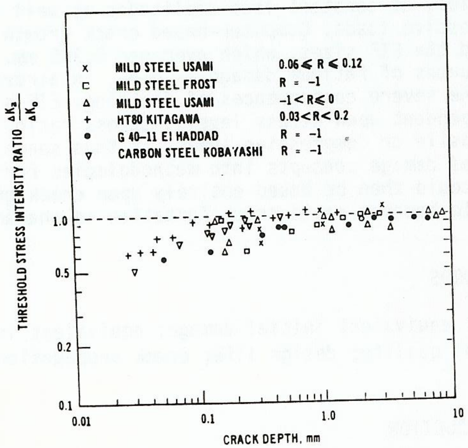

FIG. 11 EFFECT OF CRACK DEPTH ON FATIGUE CRACK GROWTH THRESHOLD BEHAVIOUR

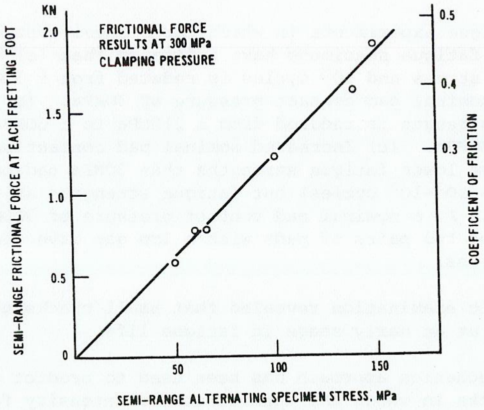

FIG. 12 FRICTIONAL FORCES FOR CONSTANT AMPLITUDE LOADING WITH PAD SPAN OF 24.1 mm AND NOMINAL CONTACT PRESSURE OF 300 MPa

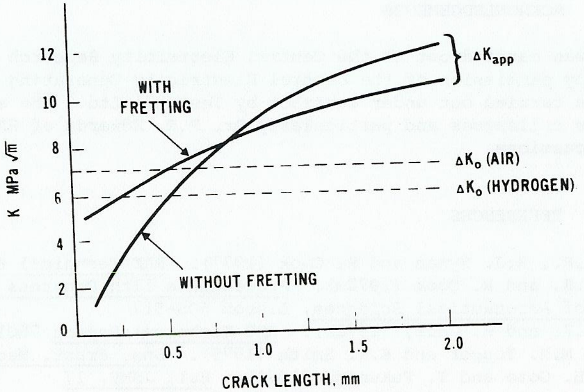

FIG. 13 APPLIED STRESS INTENSITY FACTOR ΔK_{app} AND THRESHOLD ΔK_o AS A FUNCTION OF CRACK DEPTH

In particular, the near surface stress intensity factor of a small crack will be increased, possibly enabling propagation when the crack would remain dormant in a non-fretting situation (Fig. 13). Several simplifications have been introduced in the fracture mechanics application notably (1) although mode II stress intensity factors are present under fretting conditions, they were ignored in view of the very limited mode II data on near-threshold fatigue crack growth and cracks were assumed to grow normally to the applied stress, (2) the stress field would be modified in the presence of multiple cracks, (3) more information is required on the growth of short cracks by fatigue in rotor steels without fretting.

CONCLUSIONS

1. Fretting fatigue experiments in which 1CrMo steel contact pads were clamped to 3½NiCrMoV fatigue specimens have indicated that (a) the fatigue strength at zero mean stress and 10^8 cycles is reduced from ± 300MPa (unfretted) to ± 140MPa at a nominal pad contact pressure of 30MPa. (b) At 300MPa mean stress the fatigue strength is reduced from ± 215MPa to ± 60MPa at a nominal contact pressure of 30MPa. (c) Increased nominal pad contact pressure of 300MPa tended to give lower fatigue strengths than 30MPa pad pressure at shorter endurances ($\sim 10^5$-10^6 cycles) but fatigue strengths at 10^8 cycles were similar. (d) At a nominal pad contact pressure of 300MPa, using either a single pair or two pairs of pads with a 1mm gap gave similar fretting fatigue endurance curves.

2. Metallographic examination revealed that small cracks produced by fretting were present at an early stage in fatigue life.

3. A fracture mechanics approach has been used to predict growth or arrest of fretting cracks in which the applied stress intensity factor ΔK_{app} (composed of both body stress and frictional pad stress components) is compared with threshold parameter for growth ΔK_o at the appropriate value of stress ratio R. More data on the fatigue crack growth in rotor steels is required in order to substantiate this approach.

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