THE FATIGUE PROPERTIES OF A CORROSION PROTECTIVE SURFACE COATING

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ABSTRACT

This study examined the influence of porosity on the intermediate and threshold fatigue crack growth behaviour of a corrosion protective 80% Ni - 20% Cr surface coating. The microstructure of the plasma spray coating consisted of an austenite matrix which contained varying amounts of chromite non-metallic inclusions and porous regions; the true porosity was taken as the sum of the chromite inclusions and the porous regions.

The presence of porosity significantly increased fatigue crack growth rates and reduced the threshold stress intensity range, ΔKth. However, at a specific level of porosity little effects of R-Ratio on ΔKth were observed; this was attributed to a combination of (a) the fine grain of the plasma spray microstructures and (b) the plane stress conditions under which the fatigue tests were conducted which inhibit crack closure effects.

Fatigue crack growth data showed good commonalty with other data reported in the literature and porosity effects on the fatigue crack growth characteristics could be explained by the elastic modulus values of the plasma spray microstructures. Detailed fractography of the fatigue surfaces observed that the growing fatigue crack preferentially encountered porous regions and that this propensity increased with increase K_{max} in the fatigue cycle.

KEYWORDS

Fatigue Threshold, R-Ratio, Corrosion Coating, Porosity.

1. INTRODUCTION

About thirty years ago there was an evident upsurge in the use of sintered steels and other alloy materials in the fabrication of many engineering components, most especially in automobile applications. A common feature in sintered materials was the existence of a varying level of residual porosity and it was observed that their material characteristics were similar to those of ductile spheroidal graphite cast irons. The fracture resistance of sintered steels was shown, by Ingelstrom and Ustimenko (1975), to increase with increasing yield strength which was related to either or a combination of decreased porosity or an increase in the amount of alloying elements. Fleck and Smith (1981) have reported that the fatigue limit of sintered alloys was significantly reduced with increasing porosity. In completely dense materials, voids are created during straining, while sintered materials or power metallurgy consolid-alloys contain pre-existing voids or a level of residual porosity.

The present study investigated a 80% Ni-20% Cr plasma spray material, which is used as a surface corrosion protective layer on various engineering components. Obviously such a material, by the very nature of its surface deposition, contains pores or voids. This point, together with the fact that engineering components are usually subjected to fatigue or cyclic loading conditions, makes the assessment of the fatigue properties of such a surface protective coating a prudent exercise. The present paper reports such a fatigue study.

2. EXPERIMENTAL PROCEDURES

The 80% Ni - 20% Cr plasma spray surface protective coating material was deposited on to a clean steel baseplate until each spray deposit was about 30mm thick and about 200mm in length. Two different plasma spray microstructures were tested, viz, microstructure P1 which contained an austenite matrix within which were 17% of inclusions and 5% porosity and microstructure P2 which contained 20% inclusions and 18% porosity.

Fatigue crack extension rate tests were conducted on three point bend, test specimens of dimensions length 90mm, width 16mm, thickness 7mm. Crack growth direction was perpendicular to the various spray "build up" deposition runs. Fatigue crack growth rate tests were conducted at R-Ratio values of 0.05 and 0.6 at frequencies between 1 to 30 Hz. All fatigue tests were conducted in an ambient air environment and the fatigue crack growth behaviour was monitored optically using a low powered (X10) travelling microscope.

3. EXPERIMENTAL RESULTS

A detailed view of the globular nature of the plasma spray microstructure is given in Fig.1 and the dark grey areas, see arrow, were identified as non metallic chromite inclusions where the iron had been substitutionally replaced by silicon i.e. $Fe-SiO-Cr_2O_3$ (Kiessling & Lange, 1978).

The influence of R-Ratio on the fatigue crack growth characteristics of the two plasma spray microstructures and the dense pure nickel are illustrated in Fig. 2. From this figure it can be seen that the dense nickel exhibited significant R-Ratio effects on the ΔK_{th} value, viz, through increasing the R-Ratio from 0.05 to 0.6 the ΔK_{th} value was decreased by about 40%. The plasma spray microstructures showed different R-Ratio responses in as much that the lower porosity microstructure, P1, exhibited a 20% drop in the value of ΔK_{th} with increasing R-Ratio while the higher porosity microstructure, P2, showed little effects of R-Ratio on the threshold fatigue behaviour. Also at intermediate crack extension rates, typically 10^{-5} to 10^{-3} mm/c, the porous plasma spray microstructures exhibited marked R-Ratio effects; the higher R-Ratio crack growth rates were up to an order of magnitude faster than the R=0.05 data and exhibited the occurrence of fast failure at lower ΔK values. This contrasted significantly with the dense pure nickel data where little or no effects of R-Ratio on the intermediate crack rates were recorded.

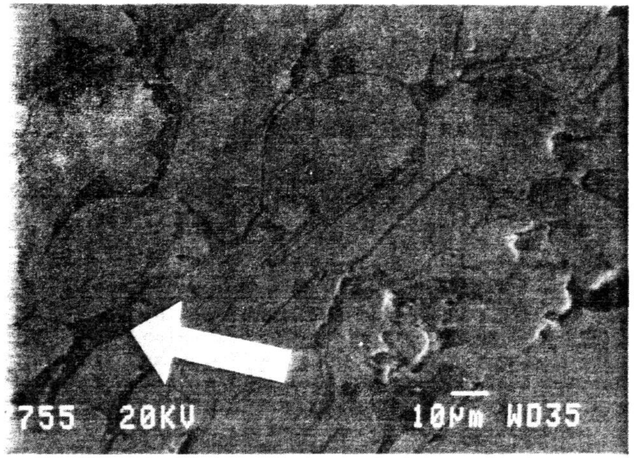

FIGURE 1 A DETAILED VIEW OF MICROSTRUCTURE P1.

A study of the fatigue crack profiles established that, in the case of the plasma spray microstructures, the growing fatigue cracks preferentially encountered regions of porosity and that this propensity increased with increasing porosity and ΔK level.

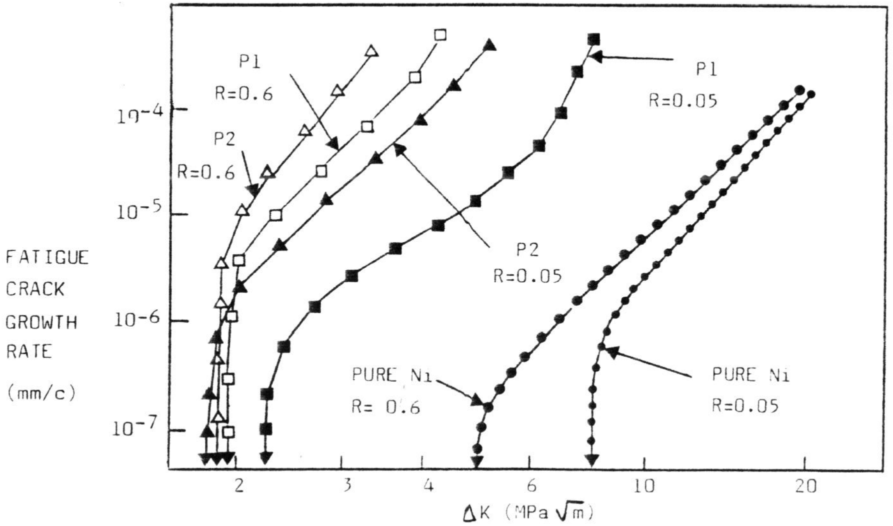

FIGURE 2 EFFECT OF R-RATIO ON FATIGUE CRACK GROWTH

Generally three main features were commonly observed on the fatigue fracture surface, viz., (i) discrete ductile striated regions, (ii) areas of porosity and (iii) smooth globular facets which were identified as easily decohesed austenite matrix-chromite non metallic inclusion interfaces.

Generally the extent of porosity prevalent on the fatigue fracture surfaces of both plasma spray microstructures increased with increasing level of ΔK. In the case of the pure nickel test specimens the fatigue failure surfaces exhibited no evidence of porous regions and the crack extended, almost exclusively, by a ductile striated fatigue failure mode.

4. DISCUSSION AND CONCLUSIONS

In the case of both plasma spray microstructures, which contained both matrix decohesed chromite non metallic inclusions and porous regions, when considering the fatigue crack growth process, it is pertinent to suggest that the chromite inclusions can be regarded as holes similar to the porous areas. Essentially a growing fatigue crack will sense and seek out chromite inclusions and regions of porosity with equal gusto; hence the true porosity of the plasma spray microstructures is the combined area fractions of porosity and chromite inclusions, viz., 22% and 38% for microstructures P1 and P2 respectively.

Bompard and Francois (1984) have recently examined the fatigue crack growth characteristics in the intermediate stage II fatigue range of sintered nickel at various levels of porosity from zero to 40% porosity and this data together with the present data and other relevant threshold fatigue crack growth data for pure nickel (Spiedel, 1974) and nickel based superalloys (Hicks & King 1983, McCarver & Ritchie, 1982) are displayed in Fig. 3. One clear general observation from this figure is the significant effect that porosity exerts on the threshold stress intensity value, ΔK_{th}, for R-Ratio value approaching zero. This figure also portrays the good agreement that existed between the data reported by Bompard & Francois (1974) for sintered nickels and the present plasma spray microstructures and pure nickel data inasmuch that (a) the pure nickel fatigue data reported by Spiedel (1974) and the 1% porosity sintered nickel material resided respectively slightly above and below the present pure nickel results at intermediate crack growth rates and the nickel based superalloy ΔK_{th} values were quite close to the ΔK_{th} level established for pure nickel in the present study (b) the 22% porosity plasma spray microstructure fatigue data resided between the 20% and 30% porosity data reported for sintered nickel, and (c) the 38% porosity plasma spray microstructure results exhibited excellent commonalty with the 40% porosity sintered nickel fatigue crack extension data.

The pure nickel data show a significant influence of R-Ratio on the threshold stress intensity range value, ΔK_{th}, while the porous plasma spray microstructures exhibited little effects of R-Ratio on ΔK_{th}; the value residing round about 2MPa√m. Hicks and King (1983) have reported marked R-Ratio effects in a fine grained (grain size typically 5 - 12 μm) powder-formed nickel based Nimonic AP1 superalloy and little or zero effects or R-Ratio on ΔK_{th} in coarse grained microstructures where the average grain size approached 50 μm. This study suggested that these effects were the result of roughness induced crack closure effects which occurred in coarse grained microstructures but which were absent in fine grained microstructures. The present plasma spray microstructures had an average austenite grain size of about 30 μm, i.e., intermediate grain size microstructures, which could account for the lack of R-Ratio effects in the present study.

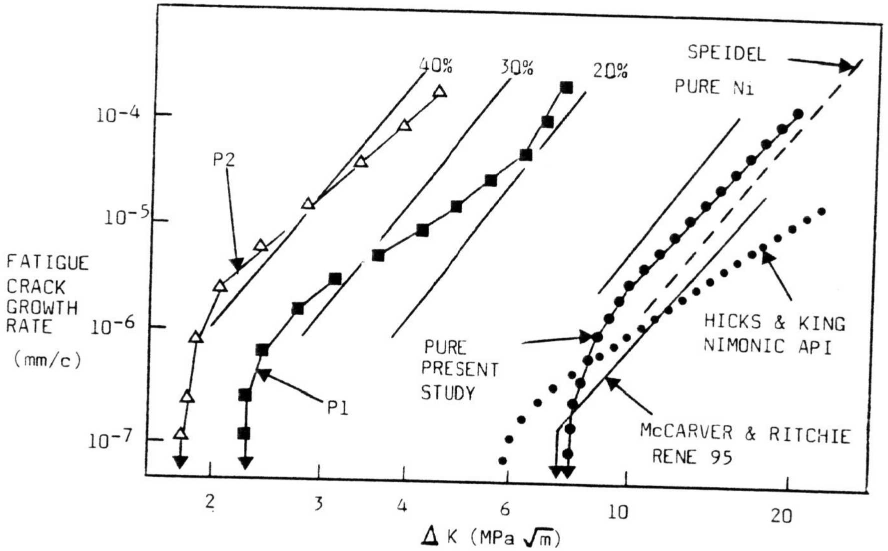

FIGURE 3 VARIOUS LOW R-RATIO DATA. SOLID LINES ARE POROSITY RESULTS FROM BOMPARD & FRANCOIS IN SINTERED NICKELS.

A second factor which could contribute to the lack of R-Ratio effects in the present study was the experimental fact the through thickness plane strain conditions were most probably not attained during fatigue testing. Indeed Ritchie (1988) has shown that fatigue tests conducted under plane stress conditions exhibited reduced crack closure effects.

Essentially in porous type materials the load bearing section S_{local} is reduced and this results in an increase in the local stress and hence, in a defect containing structure, the local ΔK level, ΔK_{local}, to

$$\Delta K_{local} = \frac{\Delta K}{1 - D} \qquad (1)$$

where D is the Kachanov damage term, i.e.,

$$D = 1 - \frac{S_{local}}{S_o} \qquad (2)$$

and S_o is the total section.

Congleton (1985) has proposed a fairly simple model which is based on the suggestion that isolated regions of easy fracture, such as transgranular cleavage, grain boundary film decohesion or porosity, along a growing crack front caused an increase in the ΔK level exerted on the remaining uncracked ligaments. This resulted in enhanced crack extension rates in the uncracked ligaments due to purely mechanical considerations, viz., fatigue crack growth rates generally increased with increasing ΔK level. Hence if some fraction, C, of the crack front exhibits an easy failure crack extension mode, e.g. porosity, the stress intensity range, ΔK, on the remaining ligaments will be increased by:

$$\Delta K_{(ligament)} = \frac{\Delta K}{1 - C} \qquad (3)$$

Both these approaches are similar and essentially D = C or

and thus,

$$C + \frac{S_{local}}{S_o} = 1 \qquad (4)$$

The influence of porosity on the fatigue crack growth characteristics of the present plasma spray microstructures can be explained by considering a continuum-based crack growth law based on first principals and the influence that porosity exerted on the mechanical properties of a sintered nickel material as reported by Bompard & Francois (1984). Lardner (1967) has calculated the change in the crack tip opening displacement during the decrease in stress from σ_{max} to σ_{min} and equated this to the increment of crack extension during a complete fatigue or stress cycle. The resulting crack growth law could be expressed as:

$$\frac{da}{dn} = \frac{(1 - \upsilon^2)}{2E\sigma y} (\Delta K)^2 \qquad (5)$$

where E is Youngs Modulus and υ is Poissons Ratio. A similar crack growth law has been developed by Pook and Frost (1976) for the case where R = 0 and ΔK = K, viz.,

$$\frac{da}{dn} = \text{Const.} \frac{(1 - \upsilon^2)}{E} (\Delta K)^4 \qquad (6)$$

In this case an exponent value of 4 has been used because (i) the exponent value does normally vary between 2 to 4 and (ii) the exponent value of 4 suitably reflects the crack growth rate - ΔK trends in the present porous plasma spray microstructures. By inserting the values of E and υ reported by Bompard and Francois (1984) for porous materials the predicted crack growth trends from equation (6) can be calculated and these are given in Fig. 4 together with the low R-Ratio data from the present study. From this figure it can be seen the predictions of this simple growth law exhibited quite a good agreement with the experimental results and clearly demonstrated that the porosity effects on fatigue crack growth could be related almost totally to changes in the Youngs Modulus of the microstructures. It is interesting to note that in the case of the higher porosity microstructure, P2, the experimental data increasingly resided above the predicted trend with increasing ΔK level. This can be explained by the fractographic observations which showed that the amount of porosity prevalent on the fatigue fracture surfaces increased with ΔK level. Also such increases were greater in microstructures which contain more residual porosity.

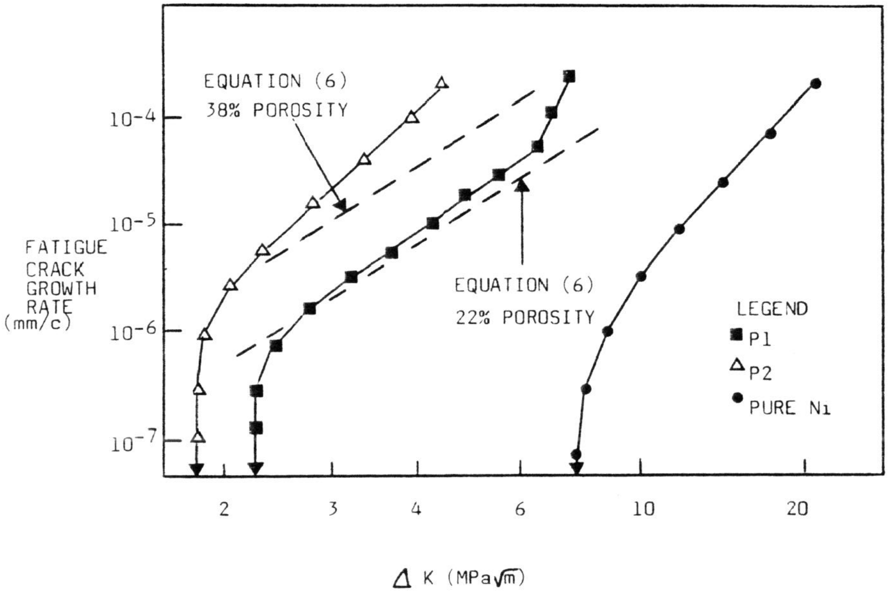

FIGURE 4 COMPARISON OF PREDICTED AND EXPERIMENTAL DATA.

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