

Identification of fatigue crack propagation modes by means of roughness measurements

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Abstract

This paper is a study of the applicability of fracture surface roughness measurements to identify the crack propagation mode in nickel base superalloys (transgranular, intergranular or mixed). The results obtained indicated that this technique can be used as an alternative or as a complement to standard fractography. The best roughness parameters for identifying the crack propagation mode are average roughness, mean roughness depth and mean height profile peak (R_a , R_z and R_{pm}). Analysis of roughness spectra in terms of the frequency range showed that the amplitude values of the profiles with wavelengths identical to the grain size are significant when propagation is intergranular. The roughness measurements were used to study the influence of loading frequency and stress state on the fatigue crack propagation mode occurring in Inconel 718 tested at 600°C. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

A crack propagation mode can be defined as a characteristic and reproducible fracture surface appearance (typically on the scale of micrometers or tens of micrometers) [1]. This appearance provides evidence of the fracture micromechanism, i.e. of the fracture process operating on the scale of microstructure. The microscopic technique normally used to identify the crack propagation mode is fractography. It permits the identification of individual features on the fracture surface, which provide clues about the fracture or fatigue process. Fractographic characterization may comprise nothing more than the assignment of a descriptive term to the fracture surface appearance.

Fracture surfaces have also been studied using roughness measurements. Thompson and colleagues [2,3] studied the roughness of fracture surfaces produced by microvoid coalescence with a view to relating the void shape with the mechanism of fracture. Casado et al. [4]

studied a polymeric composite (thermoplastic polyamide reinforced with short glass fibers). They correlated the degree of damage, quantified by the surface roughness of the material, with the fatigue life. Roughness measurements have also been used to study crack closure induced by roughness. Ravichandran [5] proposed an equation relating grain size to K_{op} (crack opening stress intensity factor); on the basis of that work, one can write the following expression:

$$K_{op} = \alpha H^\beta \quad (1)$$

where α , β are experimental constants and H is the standard deviation of the surface roughness measurements. Hamberg et al. [6] studied the relation between the microstructure, the fracture surface roughness and the crack closure level in steels. They found that the crack closure level increases with the roughness of the fracture surface according to:

$$K_{cl} = 1.20 \bar{H}^{1/3} \quad (2)$$

where the K_{cl} units are MPa m^{1/2} and \bar{H} units (standard mean height) are μm . In this analysis, \bar{H} spanned values of a factor of approximately 30 (1.6–42.9 μm). More than 400 material grains were transversed, which is enough for good average values to be obtained.

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Nickel base superalloys are a class of metallic materials that retain good properties at high temperatures, and they are therefore widely used under conditions of high-temperature fatigue [7]. The damage micromechanisms that can act at the crack tip and cause crack growth in nickel base superalloys are cyclic plastic deformation and oxidation. Depending on which damage micromechanism is primarily responsible for crack growth, three crack propagation regimes can be observed: cycle-dependent, time-dependent or mixed. In the cycle-dependent regime, cyclic plastic deformation is the main micromechanism of damage. Crack growth is transgranular and is proportional to the number of loading cycles. In the time-dependent regime, oxidation is responsible for crack growth [8]. Propagation is intergranular because the grain boundaries are preferential paths for diffusion and have a greater reactivity than the bulk material. Intergranular crack propagation makes the fracture surface rough. In the mixed mode regime, cycle-dependent and time-dependent micromechanisms exist simultaneously, and both contribute to crack growth. When one of the micromechanisms is delayed locally, the other acts. The relative percentage of each can be measured by the transgranular and intergranular regions existing on the fracture surface. Solomon [9] was the first to report the existence of these three regimes. They have been observed in other nickel base superalloys (AP1 [10], René 95 [11], Inconel 718 [12,13], Waspaloy [14] and Udimet 720 [15]).

The use of roughness measurements to identify the fatigue crack propagation mode in nickel base superalloys is therefore important. One problem with quantitative fractographic measurements is that there is no generally accepted definition of fracture surface roughness. Significant differences in the absolute value of surface roughness have been reported in the literature on alloys with virtually identical microstructures [6]. It is important to decide which surface features are relevant and which roughness parameters give the best information about the surface roughness characteristics for each case. The main objective of this paper is to study whether fracture surface roughness measurements can be used to identify the different crack propagation modes in nickel base superalloys (transgranular, intergranular or mixed). The appropriate roughness parameters are identified and a procedure for obtaining their typical values is established. Finally, this technique is used to study the influence of loading frequency and stress state on the fatigue crack propagation mode occurring in Inconel 718, tested at 600°C.

2. Experimental procedure

Fig. 1 presents the geometry of the Corner Crack (CC) specimens used in the high-temperature fatigue tests.

The material tested was Inconel 718, which is a nickel base superalloy (Ni, Cr, Fe, Nb, Mo, Ti, Al) [13,16]. The CC specimens were tested in a universal servo-hydraulic testing machine. The loading waveform was trapezoidal for loading frequencies, f , lower than 0.25 Hz (Fig. 2) and sinusoidal for $f > 0.25$ Hz. The loading frequency varied from 0.0017 to 5 Hz and the stress ratio had the value $R=0.5$. A resistance furnace was used to obtain a constant specimen temperature of 600°C during the test.

The fracture surfaces were analyzed by scanning electron microscopy (SEM) to evaluate the main surface features, and roughness measurements were used to establish the crack propagation mode. Roughness measurements were taken using laser equipment (Mahr RM600 3D). The size of the spot is 1 μm and the resolution of the equipment is 0.01 μm , giving better sensitivity than that achieved with stylus tip equipment. The geometry of the fracture surfaces was determined by analyzing the profiles from vertical sections perpendicular to the fracture surface and parallel to the main crack propagation direction. All measurements were carried out with an evaluation length of 1.5 mm, a cut-off wavelength of 0.35 mm and a measurement speed of 20 mm/min. Since the grain size is about 15 μm , the number of grains transversed in the analysis was approximately 100. ΔK varies with crack length, but, given the small length used for roughness measurement evaluation, the influence on the roughness parameter values is expected to be small.

Several roughness parameters are used to assess the surface topography (Fig. 3) [17,18]. R_a is the roughness average, i.e. the arithmetic average of the absolute values of the roughness profile ordinates:

$$R_a = \frac{1}{l} \int_0^l |Z(x)| dx \quad (3)$$

where $Z(x)$ is the profile ordinates as shown on Fig. 3(a).

R_z is the mean roughness depth, i.e. the arithmetic mean value of the single roughness depths of five consecutive sampling lengths, see Fig. 3(b):

$$R_z = \frac{R_{z1} + R_{z2} + R_{z3} + R_{z4} + R_{z5}}{5} \quad (4)$$

R_{pm} is the mean height profile peak, i.e. the arithmetic mean value of the single highest profile peak measured for five consecutive sampling lengths, see Fig. 3(c):

$$R_{pm} = \frac{R_{p1} + R_{p2} + R_{p3} + R_{p4} + R_{p5}}{5} \quad (5)$$

R_{sm} is the mean width of the profile elements, i.e. the arithmetic mean value of the width of the roughness profile elements:

$$R_{sm} = \frac{1}{n} \sum_{i=1}^n S_{mi} \quad (6)$$

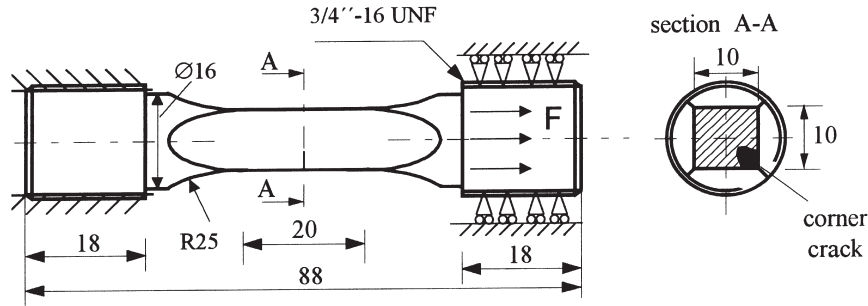


Fig. 1. Corner crack (CC) specimen.

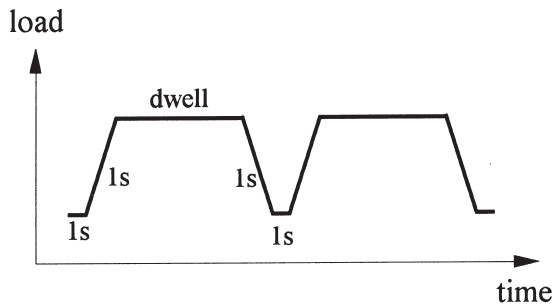


Fig. 2. Trapezoidal wave loading.

where n is the number of profile irregularities, S_{mi} , considered (see Fig. 3(d)). The other roughness parameters studied, such as R_k and R_{pk} , which are the core roughness depth and the reduced peak height, are well defined in standard DIN EN ISO 13565 [19].

3. Presentation and analysis of results

Fig. 4 presents two micrographs obtained by SEM examination, corresponding to cycle-dependent and time-dependent crack growth, respectively. The fracture surface presented in Fig. 4(a) is quite flat, indicating that propagation is mainly transgranular. Striations can be seen, signifying that propagation is produced by cyclic plastic deformation. The crack propagation observed in

Fig. 4(b) is intergranular, which gives a rough aspect to the fracture surface. The surface of the grains is irregular. Secondary cracking, perpendicular to the fracture surface, can also be observed. Fig. 5 gives a schematic representation of intergranular and transgranular crack growth. Figs. 4(a) and 4(b) show that the fracture surfaces are much rougher when propagation is intergranular, as expected.

Fig. 6 presents the roughness profiles obtained for different crack propagation modes. It can be seen that these modes significantly influence the crack path geometry, confirming the SEM observations. Roughness measurements were therefore performed on the fracture surfaces of specimens previously analyzed by SEM. Table 1 gives the results obtained for different roughness parameters. One of the objectives of this work was to find the parameter (or parameters) best suited to identifying a particular crack propagation mode. A parameter is adequate if

1. it presents stable mean values and low scatter of results for each crack propagation mode;
2. the values for different crack propagation modes are appreciably different.

The results in Table 1 show that almost all the parameters exhibit typical values for each of the crack propagation modes. These are stable within each mode and vary significantly from mode to mode.

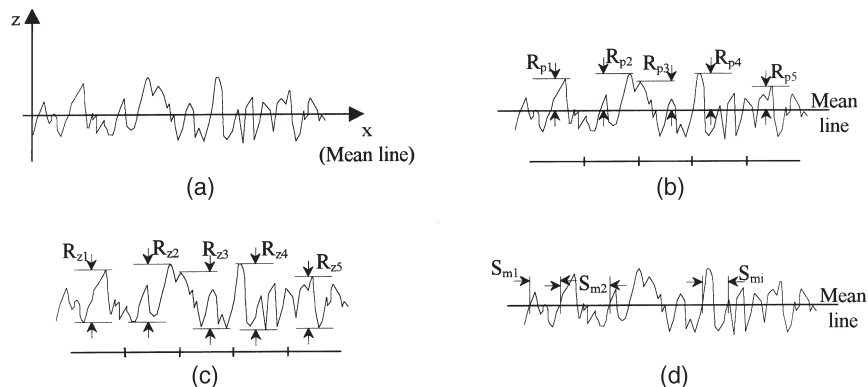


Fig. 3. Roughness parameters.

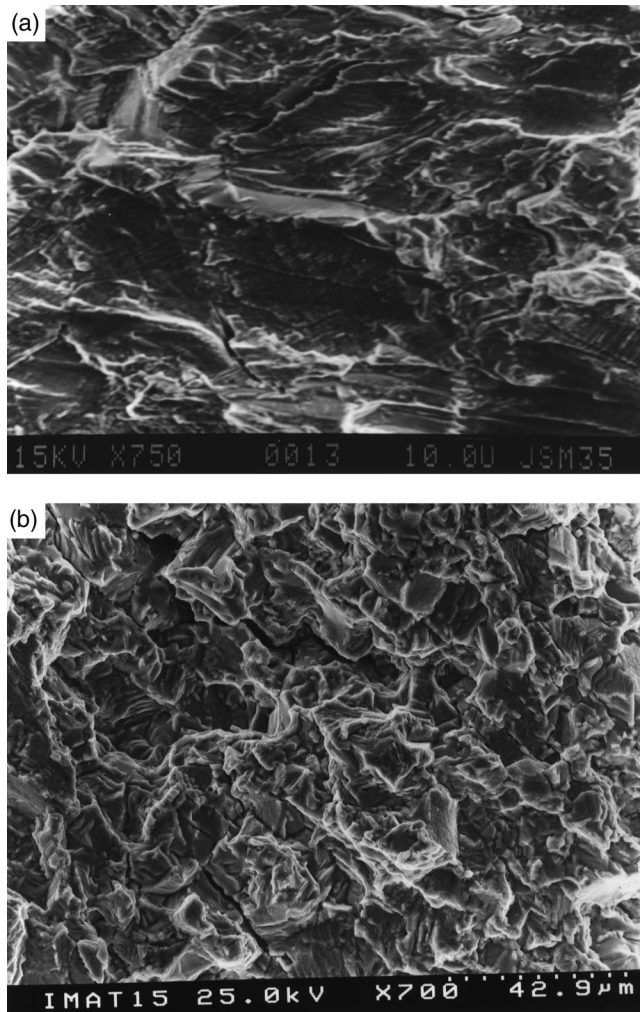


Fig. 4. Micrographs of fracture surface: (a) transgranular mode; (b) intergranular mode.

For comparison of the ability of the roughness parameters to characterize the fracture surface morphology, Fig. 7 shows the mean values and the scatter of the results obtained with the different parameters when analyzing fracture surfaces resulting from intergranular, transgranular and mixed propagation modes. The results obtained indicate that the parameters R_k , R_{pk} and S_m cannot be used with confidence to identify the propagation mode, as they show superposition of the ranges obtained

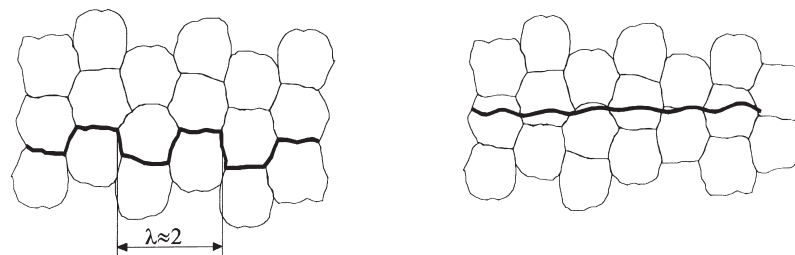


Fig. 5. Intergranular and transgranular crack propagation.

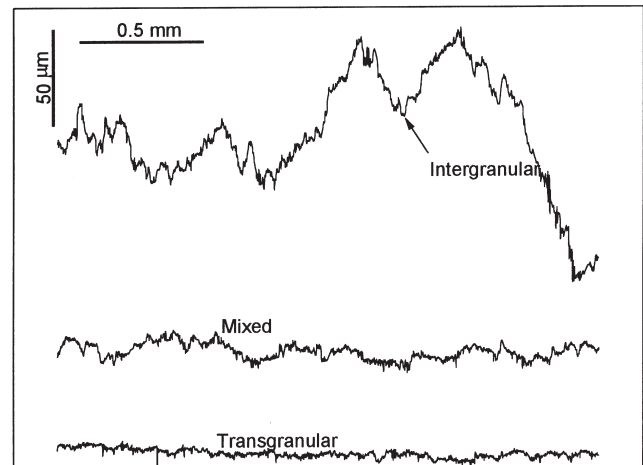


Fig. 6. Roughness profiles for the different crack propagation modes.

Table 1
Roughness of the crack surface

	R_a	R_z	R_{pm}	S_m	R_k	R_{pk}
Transgranular	3.43	22.11	10.95	14.16	9.39	7.23
	2.43	17.19	6.29	6.72	6.95	1.63
	2.94	21.57	9.09	8.33	8.36	4.74
	2.2	16.99	7.86	10.31	6.71	2.37
Mean	2.75	19.46	8.55	9.88	7.85	3.99
Intergranular	11.61	58.37	28.61	48.76	37.23	10.67
	7.38	39.58	19.57	27.98	23.47	8.81
	8.89	48.39	23.08	32.97	28.04	6.79
	6.67	38.94	22.16	21.74	17.67	9.29
10.54	57.47	27.49	39.77	32.81	9.64	
Mean	9.02	48.53	24.18	34.24	27.84	9.04
Mixed	6.06	33.90	16.17	29.44	18.74	5.02
	3.56	21.83	10.65	16.34	11.09	3.54
	4.3	27.2	12.79	19.02	13.14	4.37
Mean	4.64	27.47	13.20	21.6	14.32	4.31

for different propagation modes. However, different values were obtained for the parameters R_a , R_z or R_{pm} for the propagation modes analyzed, so the roughness measurement of the fracture surfaces can be used as a tool to identify the crack propagation mode in nickel base superalloys, if suitable parameters are used.

The simultaneous influence of the crack propagation mode on the amplitude of roughness, which is confirmed

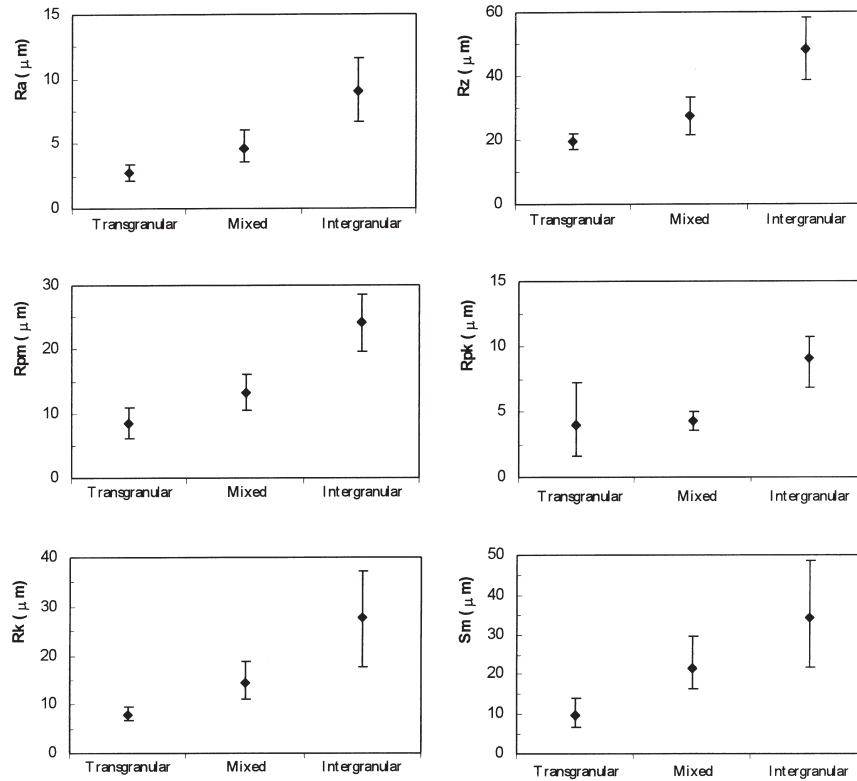


Fig. 7. Influence of crack propagation modes on roughness parameters.

by the change in parameters R_a , R_z or R_{pm} , and on the wavelength of profile irregularities (change of S_m), led to the conclusion that the treatment in the frequency domain could be of great importance. Spectra of surface irregularities (amplitude versus wavelength) were thus produced using FFT (Fast Fourier Transform). Figs. 8(a) and 8(b) give some typical spectra obtained from fracture surfaces corresponding to intergranular and transgranular crack growth, respectively (previously identified by SEM). Comparison of these spectra shows that they vary significantly with crack propagation mode. In fact, an intergranular propagation produces rougher fracture surfaces, with the difference being more important for frequencies higher than 20 l/mm, i.e. for wavelengths lower than 50 μm . Careful analysis of the spectra shows that intergranular crack growth produces an important increase in amplitude for frequencies in the range 20–50 l/mm. As the grain size ranges from 10 to 20 μm for this material, the frequency range corresponding to an intergranular propagation through the grain boundaries varies over the range 25–50 l/mm (Fig. 4). Therefore, the analysis of the spectrum in the frequency range corresponding to medium grain size can be used to decide whether the propagation is mainly intergranular or mainly transgranular.

In the light of the results obtained, the following strategy can be proposed to identify the crack propagation mode in a nickel base superalloy:

1. Find the spectrum in the frequency range to identify the crack propagation mode. A significant amplitude for the wavelength corresponding to grain size indicates that propagation is mainly intergranular, while the opposite indicates that it is mainly transgranular. The roughness values measured on the fracture surfaces can be used as typical values for intergranular and transgranular crack growth.
2. Identify the crack propagation mode for different loading or environmental conditions, comparing the roughness parameters with the characteristic values. The best roughness parameters for this study are R_a , R_z or R_{pm} .

4. Identification of crack propagation mode in Inconel 718

4.1. Influence of loading frequency on crack propagation mode

Roughness measurements were used to identify the crack propagation mode in Inconel 718. Fig. 9 gives the variation of roughness (quantified by R_{pm}) with loading frequency (f), for $R=0.5$ and $T=600^\circ\text{C}$. More than one measurement was considered for each specimen. The heterogeneous character of a fracture surface can explain

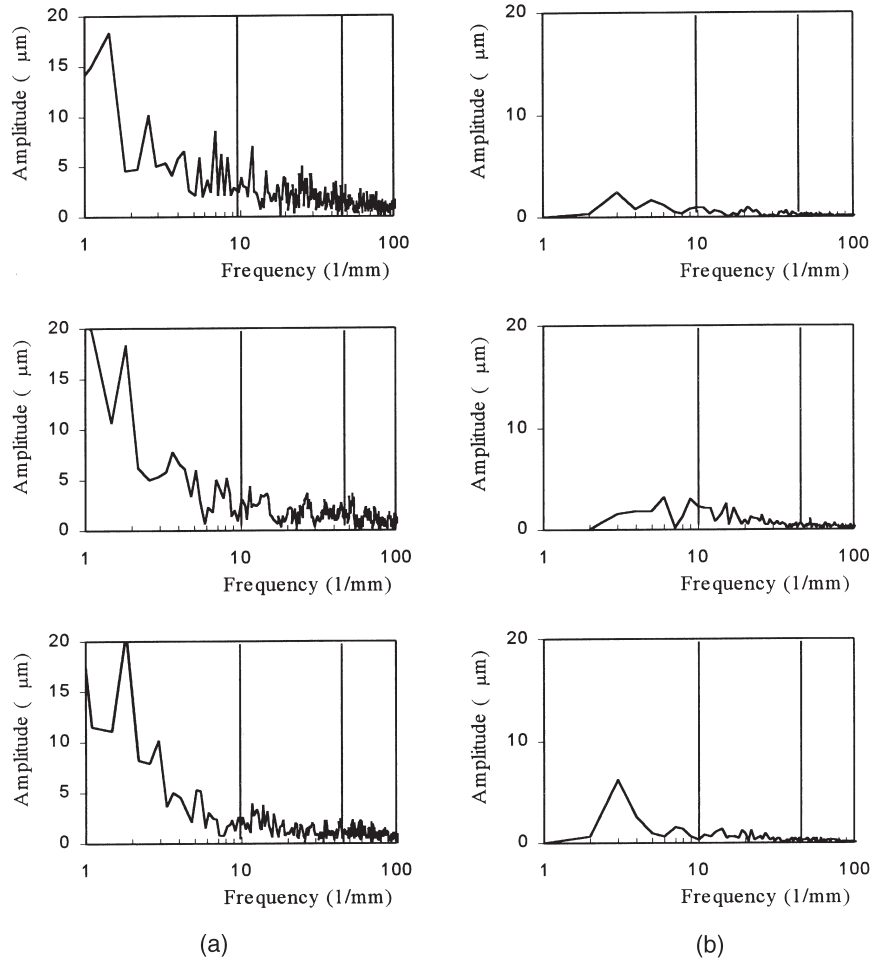


Fig. 8. Spectra of fracture surface roughness: (a) intergranular mode; (b) transgranular mode.

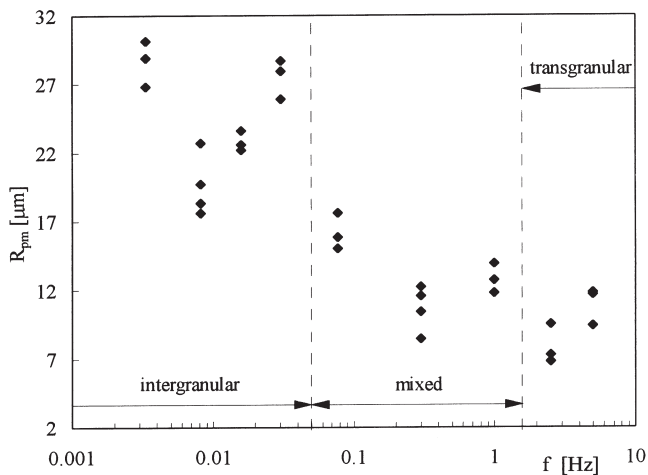


Fig. 9. Variation of fracture surface roughness with loading frequency.

the scatter of measurements taken on the same surface. Three regimes of crack propagation can be identified: cycle-dependent (lower values of R_{pm}), time-dependent (higher values of R_{pm}) and mixed. The transition fre-

quencies, identified by the vertical lines in Fig. 9, are: from cycle-dependent to mixed crack growth $f_{cm} \approx 1.6$ Hz, and from mixed to time-dependent crack growth $f_{mt} \approx 0.05$ Hz.

4.2. Influence of stress state on crack propagation mode

Fig. 10 presents roughness values for two test conditions (T1, T2). These values were obtained from profiles parallel to a free surface and at different distances (x) from it. The interior roughness of specimen T1 (i.e. at a distance from the surface) indicates that crack propagation is intergranular, while the interior roughness of specimen T2 indicates that propagation is transgranular. This conclusion is based on the comparison with the values given in Fig. 9. The values obtained at the surface indicate that propagation is transgranular in both specimens. Therefore, the plane stress state inhibits time-dependent crack propagation (intergranular). This can be explained by the reduced oxygen diffusion produced by the planar stress state. In fact, higher diffusion rates are associated with triaxial stress states. The near-surface

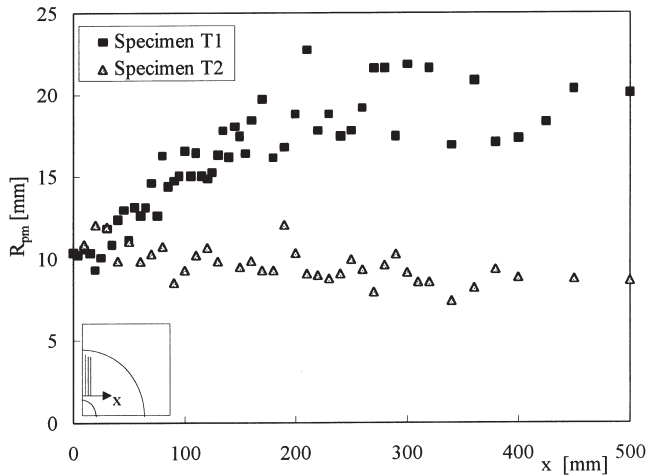


Fig. 10. Variation of fracture surface roughness with stress state (T1, $R=0.8$, $f=0.14$ Hz; T2, $R=0.05$, $f=0.1$ Hz).

region extends for approximately 200 μm for this loading and crack length.

These results may explain the crack shapes for the corner cracks. When the crack propagation mode is the same inside the specimen and near the surface, the crack adopts an almost quarter-circular shape because the fatigue crack growth rate (FCGR) is not greatly affected by stress state. However, when the crack propagation modes are different, a quarter-circular crack has a lower FCGR near the surface, and so a tunnelling effect is observed. This agrees with findings of Tong et al. [15] in Waspaloy at 650°C. In fact, a greater tunnelling effect of the crack front (i.e. a higher influence of stress state) was observed when the interior crack growth was time-dependent.

5. Conclusions

1. Roughness measurements can be used to identify the fatigue crack propagation mode in nickel base superalloys at high temperature. Although roughness measurements can be used as an alternative to fractography, they are better used as a complement to this technique.
2. The parameters R_a , R_z and R_{pm} are the most suitable ones for identifying the crack propagation mode.
3. Analysis of spectra in the frequency range showed that the profiles with wavelengths identical to the grain size are dominant when the propagation is intergranular.
4. Three crack propagation modes were identified in the frequency range for Inconel 718 tested at $T=600^\circ\text{C}$ and $R=0.5$. The transition frequencies are: from cycle-dependent to mixed crack growth $f_{cm} \approx 1.6$ Hz, and from mixed to time-dependent crack growth $f_{mt} \approx 0.05$ Hz.

5. Stress state was found to have a strong influence on crack propagation mode. Near the free surfaces, the plane stress state promotes a change from time-dependent to cycle-dependent crack growth. This is explained by a reduction of oxygen diffusion induced by plane stress. The occurrence of tunnelling can be explained by the influence of the stress state.

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