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The Effect of Surface Finish on High Cycle Fatigue of a Low Alloy Steel

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ABSTRACT As fatigue cracks initiate predominantly at the free surface of a material, the condition of the surface can be assumed to be critical with regard to fatigue strength. Two features of a mechanically prepared surface which are considered to be major factors affecting fatigue strength are the surface roughness and the residual stress in the surface layer. It has been noted that little of the general body of published data on the effect of surface finish on fatigue has separated or, in many cases, recognized the additional effects of residual stress introduced by the finishing process which would interfere with the evaluation of surface irregularities. To understand fully the effects of surface irregularities they must be examined in isolation from residual stress effects using stress free specimens. This paper describes such an investigation on a low alloy steel to examine the relationship between fatigue limit and depth of shallow surface defects which were either inherent in the material or the result of the surface finishing process.

Introduction

As fatigue cracks initiate predominantly at the free surface of a material, the condition of the surface can be assumed to be critical with regard to fatigue crack initiation. Two features of a mechanically prepared surface which are considered to be major factors affecting fatigue strength are the surface roughness and the residual stress in the surface layer.

A measure of the surface roughness introduced by a particular machining process can be obtained from a profile scan of the surface and is often expressed as the centre line average or R_a value. The R_a value might vary from 0.2 microns for a good ground finish to 8 microns for a rough turned finish. Where the effects of surface finish on fatigue have been examined in carbon steels, reductions in fatigue limit varying between 10 and 25 per cent have been observed when comparing rough turned or rough ground with a fine ground or polished surface **(1)**–**(7)** and the effect of surface roughness has been shown **(8)** to be even more pronounced in high strength steels.

It may be that the most significant parameter categorizing the quality of a machined surface from the fatigue standpoint is maximum depth of the surface irregularities. Siebel and Gaier **(9)**, for instance, compared fatigue strength with maximum depth of surface irregularities (R) and found a critical depth (R_0) below which there was no change in fatigue strength and above which there was a linear fall in fatigue strength with log R.

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residual stress introduced by the machining process which would interfere with the evaluation of surface irregularities. To understand fully the effects of surface irregularities, they must be examined in isolation from residual stress effects on stress-free specimens.

In this paper, the effect of surface finish on the high cycle fatigue life of a low alloy steel forging is examined using a variety of surface finishes.

Material

The material employed was taken from a low alloy steel forging of composition (% wt) 0.29C, 0.21Si, 0.55Mn, 0.01S, 0.005P, 1.99Ni, 1.30Cr, 0.57Mo, 0.09V. This had been steam quenched from 850°C, and tempered at 610°C to give the mechanical properties of 844 MPa tensile strength, 710 MPa 0.2 per cent proof stress, 18.3 per cent elongation, 63 per cent reduction in area, and a hardness of 280 Hv30. The microstructure of the material (shown in Fig. 1) consisted of a tempered bainite structure with a grain size of ASTM 8. All test specimens used in this investigation were given a further heat treatment of 590°C for four hours, applied after specimen manufacture, to remove residual machining stresses from the surfaces. This treatment, conducted in vacuum, had no effect on the tensile properties of the material. Residual stress measurements showed residual stress levels of between +17 MPa and −22 MPa, which are of the same order as the accuracy of the X-ray diffraction method employed, and indicated full stress relief had been achieved.

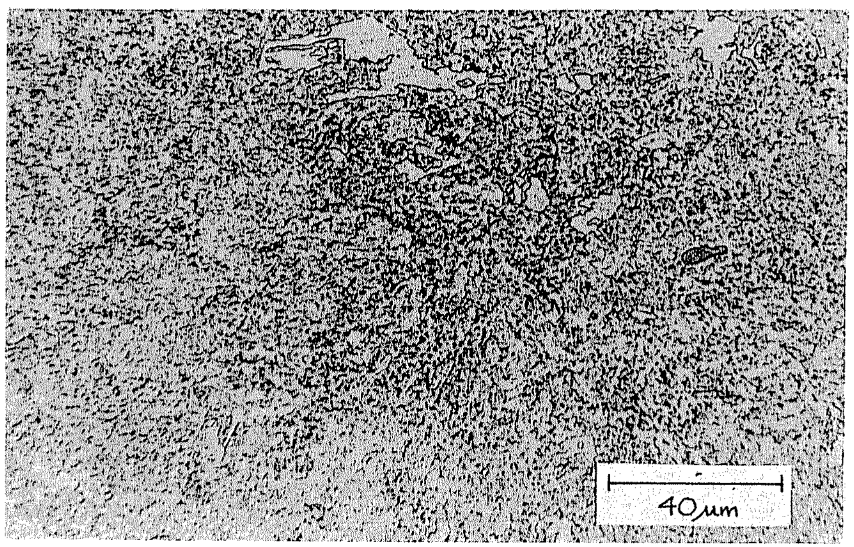


Fig 1 Microstructure of the material

Experimental details and results

The fatigue programme was conducted on test specimens in both the bending and push–pull modes in air at room temperature using Amsler Vibrophore machines under constant amplitude loading conditions.

Bending tests

The bending tests were carried out under four point loading using a specimen designed, as shown in Fig. 2(a), to give a uniform stress along a central 32 mm section of surface and to ensure that crack initiation occurred away from the edge with no stress concentration feature apart from that produced by the surface finishing process or the presence of surface inclusions. The design allowed the specimen surface to be easily machined in either the longitudinal or transverse direction.

In order to produce a range of surface roughness, test specimens were given a variety of ground finishes and in one case a series of shallow grooves were introduced into the surface by careful machining. The following types of surface finish were examined:

(A) fine longitudinal ground;
(B) rough longitudinal ground;
(C) fine transverse ground;
(D) rough transverse ground;
(E) 0.05 mm deep (90 degree included angle) transverse grooves;
(F) transverse emery finish.

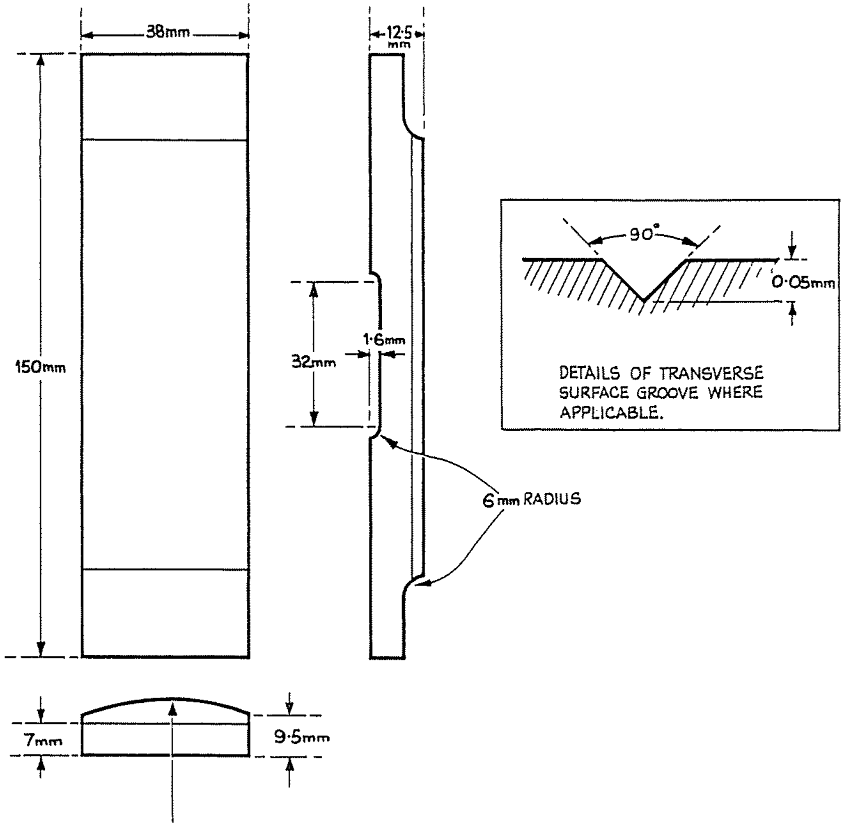
The results of the four point bending tests conducted with an R value of 0.1 are plotted in Fig. 3(a) for specimens taken axially from the forging and in Fig. 3(b) for specimens taken radially.

Push–pull tests

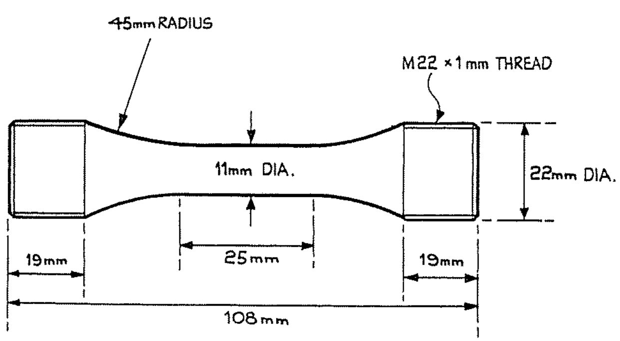
In order to examine the effect of mean stress from zero to 770 MPa, push–pull fatigue tests were conducted on specimens of the type shown in Fig. 2(b) with the following surface finishes (figure illustrations of results are as given in brackets):

(a) fine circumferentially ground (Fig. 4(a));
(b) 0.05 mm deep circumferential grooves (Fig. 4(b));
(c) 0.50 mm deep circumferential grooves (Fig. 4(c));
(d) rough circumferentially ground (Fig. 5(a));
(e) longitudinally polished with diamond paste (Fig. 5(a)).

The results of the push–pull fatigue tests are given in Figs 4 and 5(a) for specimens taken axially from the forging, and in Figs 5(b) and 6 for specimens taken radially.



(a) Four point bending specimen



(b) Push-pull specimen

Fig 2 Details of fatigue test specimens

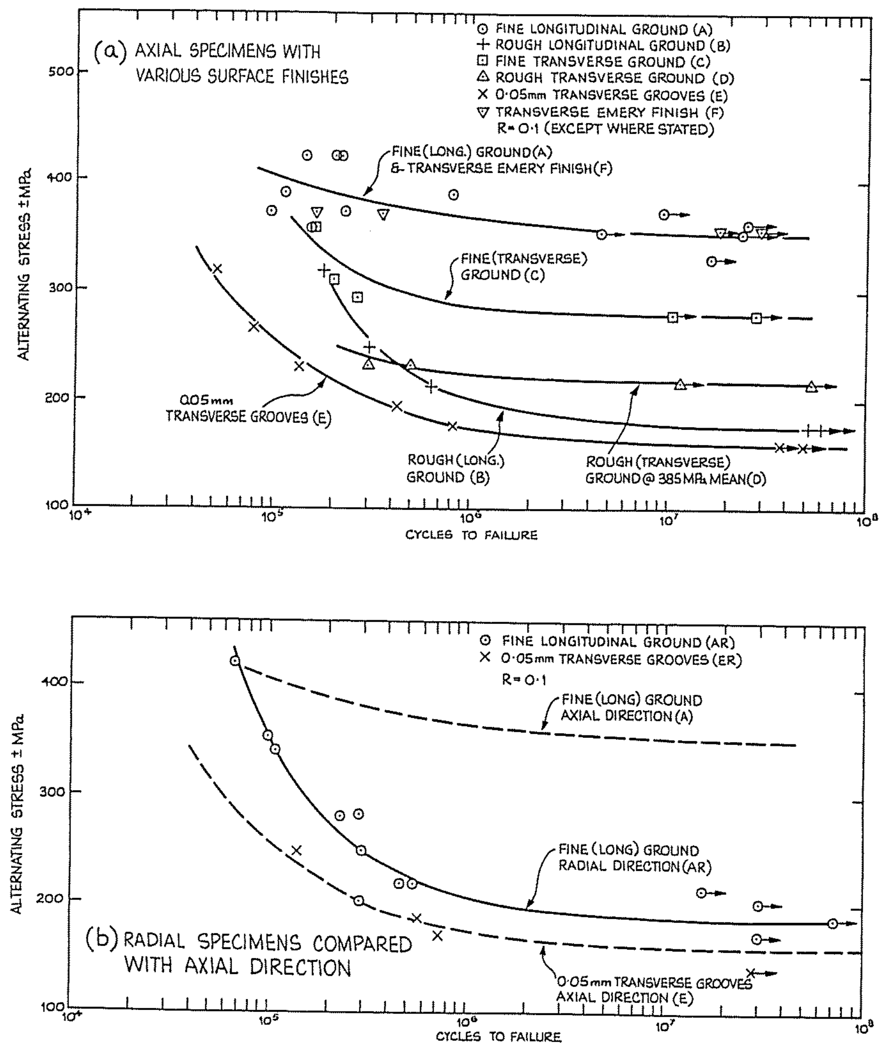
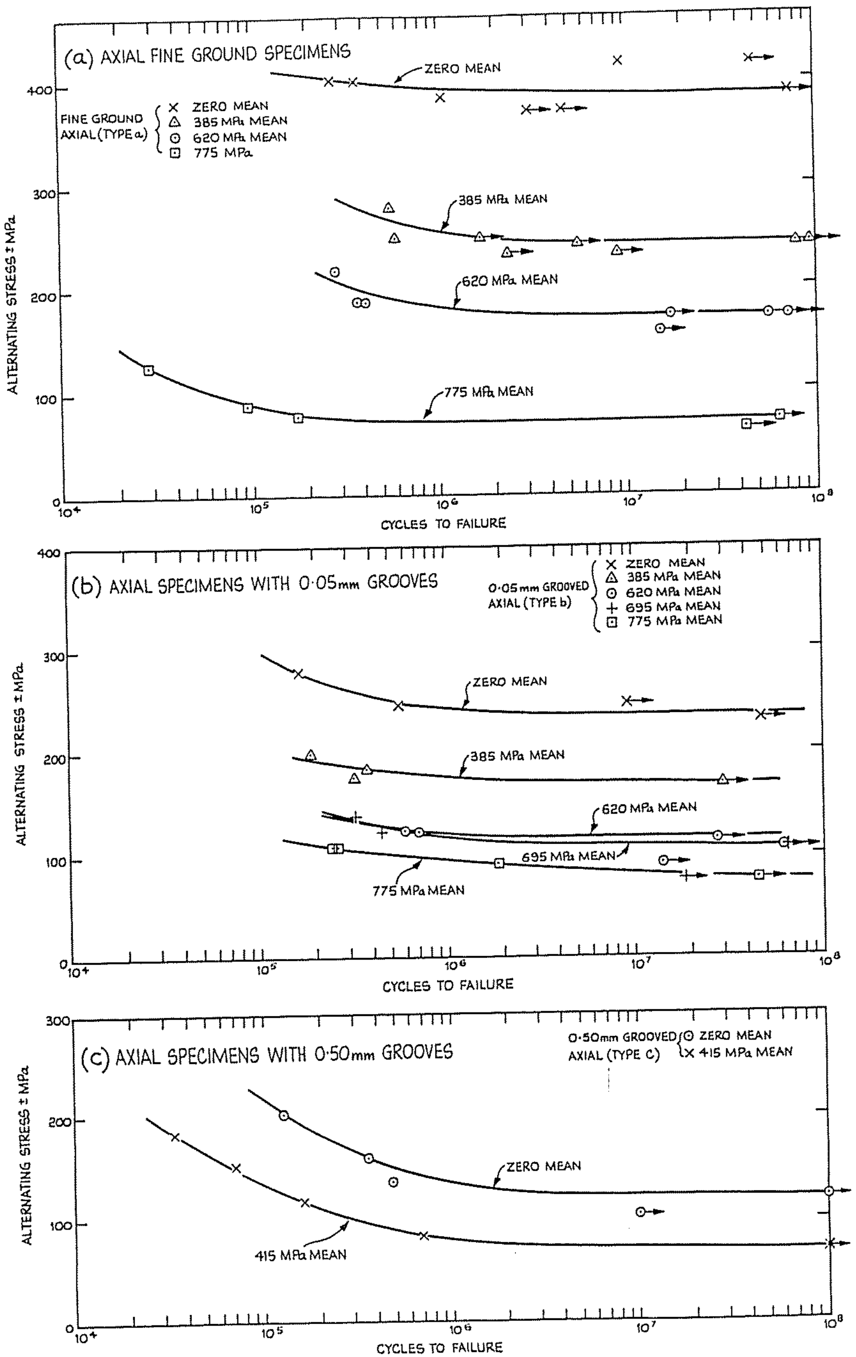


Fig 3 Bending fatigue results



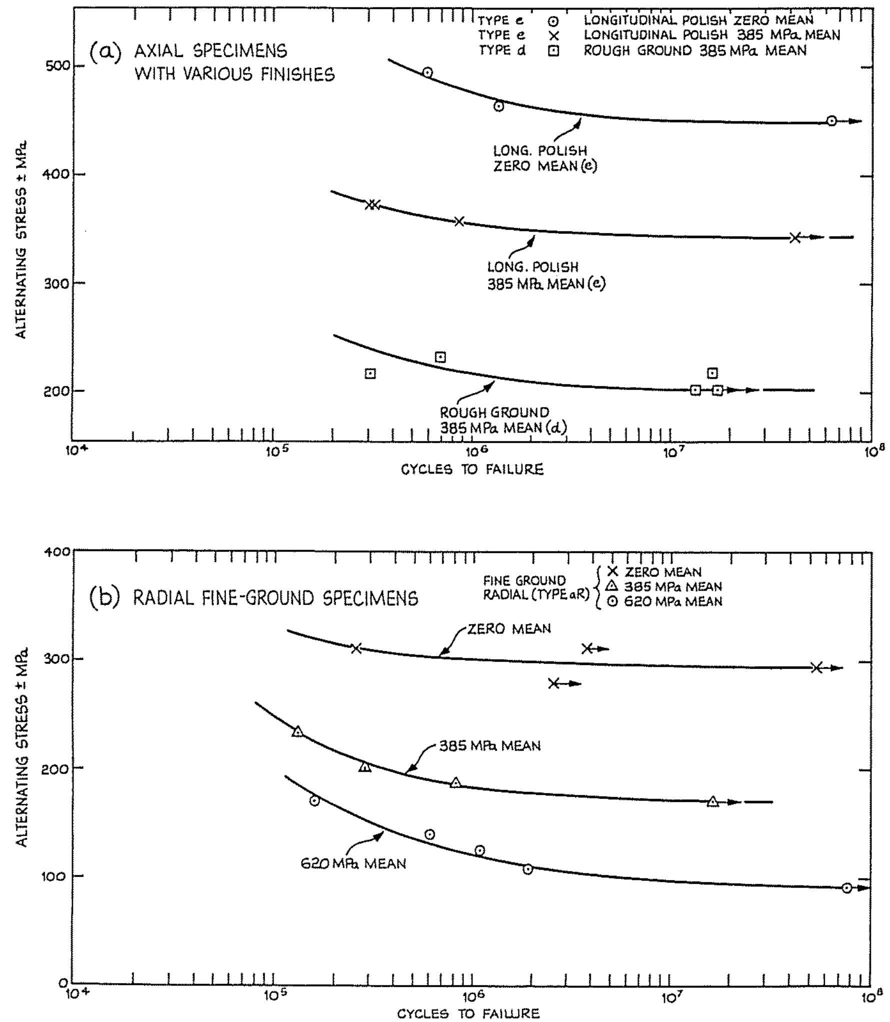
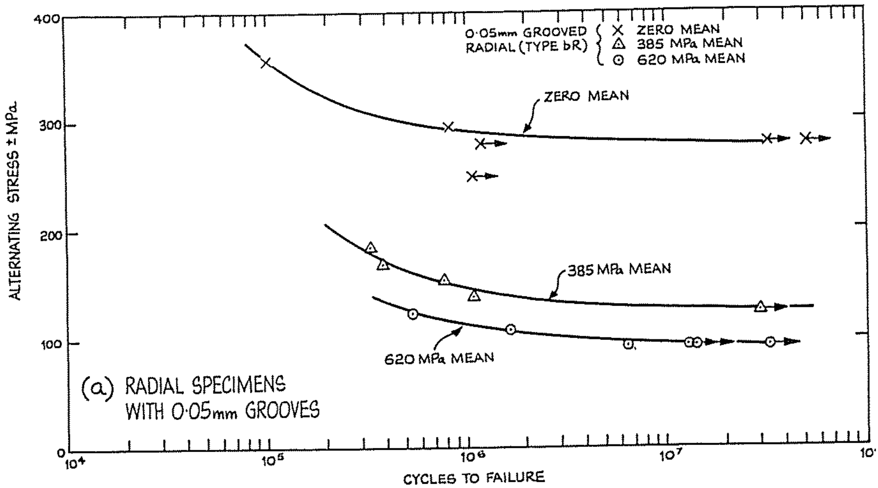


Fig 5 Push–pull fatigue results

◄ **Fig 4 Push–pull fatigue results**



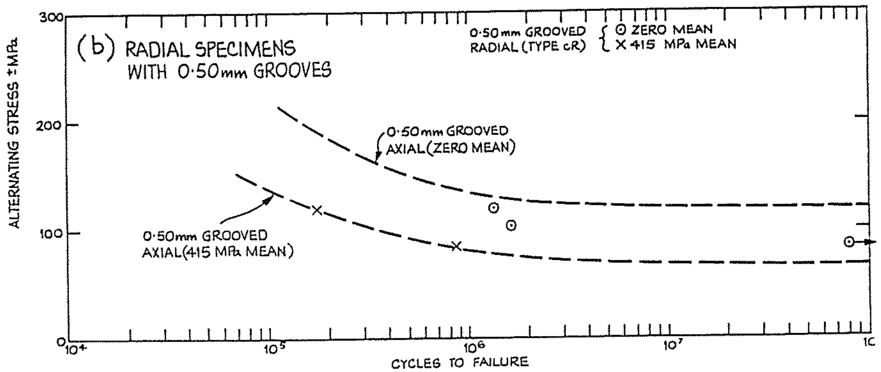


Fig 6 Push–pull fatigue results

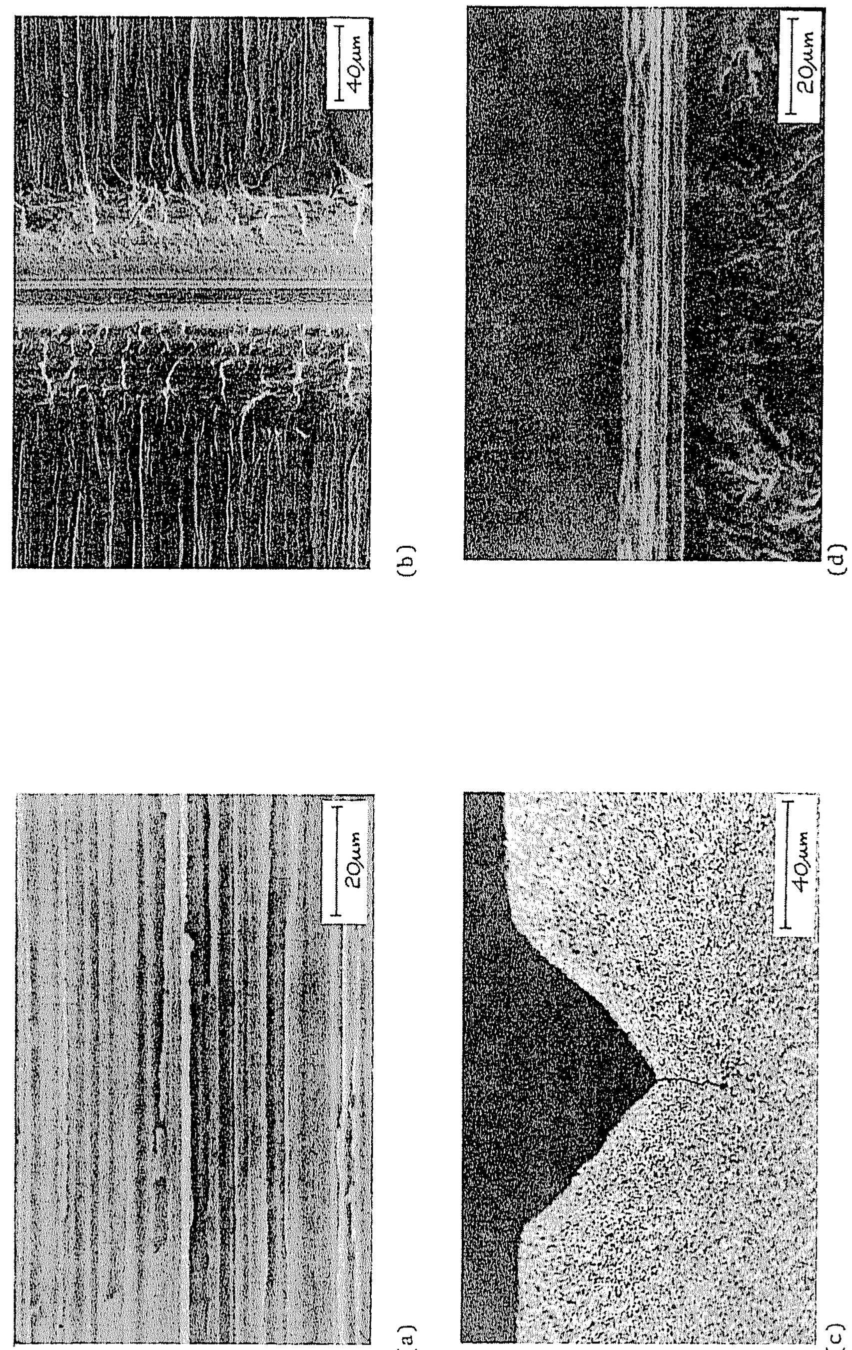
Fig 7 Surface features introduced by machining

(a) Fine transverse ground surface (Type C) showing side flow of material

(b) 0.05 mm deep groove (Type E) showing tear marks on the flanks and a smooth finish at the base which contains a fatigue crack

(c) Profile of a 0.05 mm groove containing a fatigue crack

(d) Fatigue crack initiation from a surface groove introduced by transverse grinding (Type D)



Metallographic examination

Surface features

An examination of the various surfaces generated was made using a scanning electron microscope with the following observations.

(*a*) *Ground finishes*. In all cases there was a considerable amount of plastic deformation or side flow of the material transverse to the direction of the grinding marks. This is shown typically in Fig. 7(a) for a fine ground finish. No significant difference was observed between the equivalent finishes in the bending and push–pull specimens or between the equivalent transverse and longitudinal grinding in the bend specimens.

(*b*) *Emery or polished finishes*. The transverse finish given to the bend specimens was similar in appearance to the fine ground finish except that there was little evidence of plastic deformation or side flow. Longitudinal polishing on push–pull specimens resulted in an extremely smooth surface which showed few surface irregularities even at high magnifications on the SEM.

(*c*) *Grooved finishes*. Examination of the 0.05 mm deep transverse grooves, which were machined in the surface of both bending and push–pull specimens, generally showed a fairly smooth finish at the base of the groove with tear marks along the flanks of the grooves. A typical groove is shown in Fig. 7(b) which indicates a fatigue crack running along the base of the groove after testing. Figure 7(c) shows a section through the groove.

Fracture features

Examination of the fracture faces after fatigue testing revealed that fatigue cracks usually initiated from some form of surface irregularity which was either the result of the surface finishing process or inherent in the material. These irregularities could be categorized as follows.

(*a*) *Machining*. Where specimens contained grinding or emery marks transverse to the direction of loading, fatigue cracks almost invariably initiated at the root of one of the grooves introduced by the process (Fig. 7(d)).

(*b*) *Inclusions from grinding*. Rough longitudinal grinding resulted in particles of the grinding wheel becoming detached and either embedding in the surface or leaving sharp notches in the surface. These inclusions or notches provided the usual initiation point for fatigue cracks in the rough longitudinal specimens and Fig. 8(a) is a typical example. Similar defects provided the occasional initiation site in fine longitudinal ground specimens.

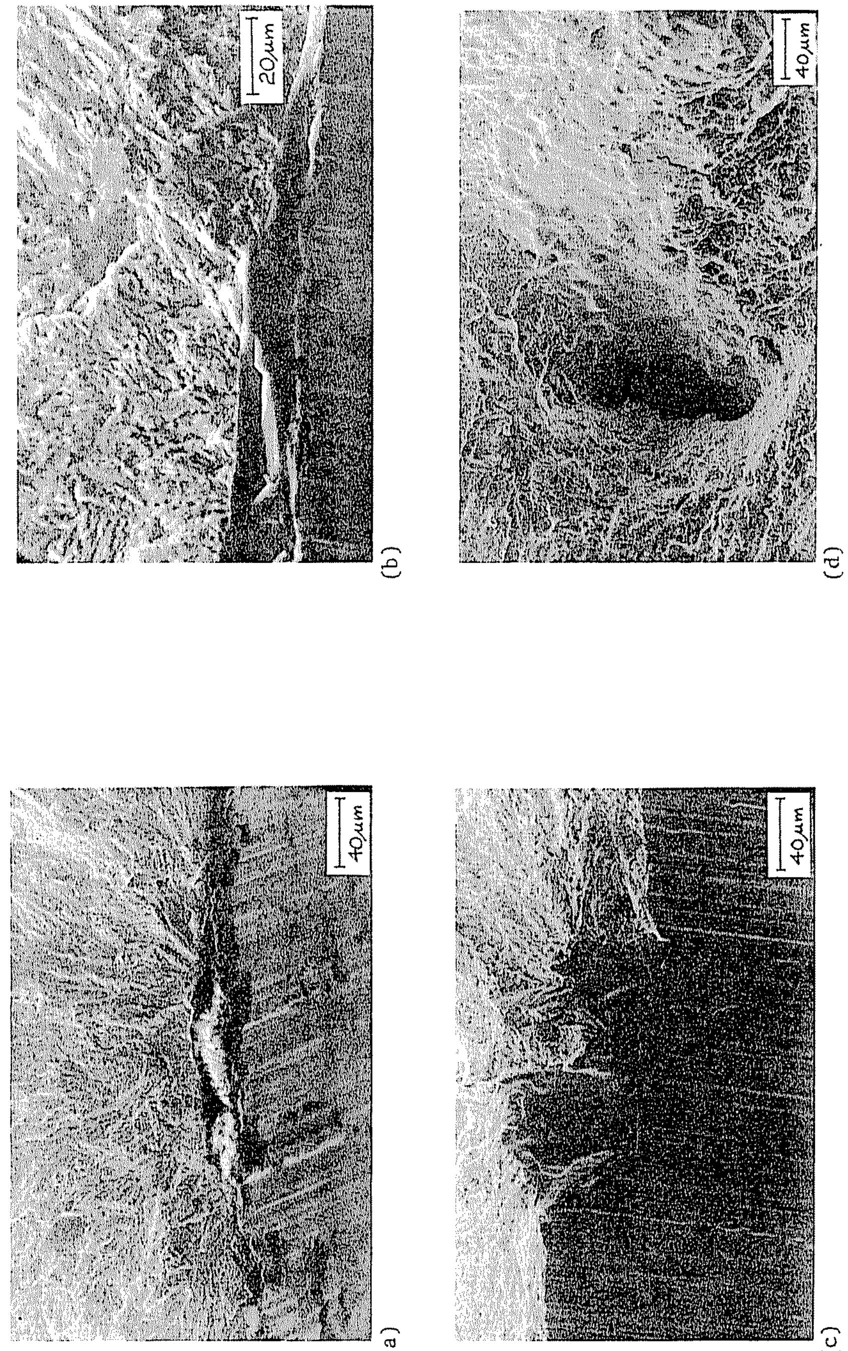
Fig 8 Fracture features of fatigue specimens ▶

(a) Fatigue crack initiation from an alumina/silica inclusion embedded in the surface during grinding

(b) Fatigue crack initiation from a MnS inclusion at the surface when stressed in the radial direction

(c) Fatigue crack initiation from a closed pore at a surface with a fine longitudinal ground finish

(d) A pore on a fracture face showing the featureless type of surface associated with this type of defect



(c) *Inherent defects*. MnS inclusions, inherent to the material, were elongated in the axial direction of the forging. Crack initiation was almost exclusively from these inclusions lying parallel and very close to the surface at 90 degrees to the direction of loading in specimens taken in the radial direction, but occasional instances occurred in specimens taken in the axial direction where an inclusion intersected the surface. A typical example of failure is shown in Fig. 8(b) and and evaluation of the MnS inclusion size found at crack initiation sites indicated lengths of up to 1.0 mm and depths of up to 0.038 mm.

Another inherent defect, from which occasional fatigue cracks were found to initiate in longitudinally ground or polished specimens, was a featureless type of area shown typically in Fig. 8(c). Analysis of the surface of these defects on the SEM showed no variation in chemical composition from the forging composition and it was considered that this type of defect might be a closed or partially closed pore. Evidence for a pore was found on one fracture face remote from the initiation site (Fig. 8(d)).

Discussion

Surface roughness

In general terms an increase in surface roughness as indicated by a Talysurf scan is accompanied by a decrease in fatigue limit in both bending and push–pull fatigue as expected. For example, a rough longitudinal ground finish with a recorded peak to valley height four times greater than a fine longitudinal ground finish has a fatigue limit which is 50 per cent less. From an examination of the fracture faces of failed specimens, however, it was apparent that for ground, emery and polished surfaces, fatigue initiation occurred from transverse surface grooves, inclusions or inherent defects which were all greater in depth than the maximum peak to valley height measured by a Talysurf scan. Tables 1 and 2 give the depth of these defects at the fatigue crack initiation point

Table 1 Surface measurements on bending fatigue specimens

Type	*Surface finish*	*Depth of defect at crack initiation site (microns)*
A	Fine longitudinal ground	8.4
B	Rough longitudinal ground	43.1
C	Fine transverse ground	6.3
D	Rough transverse ground	21.3
E	0.05 mm grooves	50.0
F	Transverse emery finish	4.3
AR	Fine longitudinal ground (Radial)	38.1
ER	0.05 mm grooves (Radial)	90.0

and it was clear that a profile scan made prior to testing failed to reveal the surface irregularities from which fatigue cracks could initiate.

The depths of defects at the crack initiation sites given for the various surface finishes in Tables 1 and 2 have been plotted against the corresponding fatigue limits for R values of 0.1 and -1 in Fig. 9(a) and (b). It is well known from specimens containing long cracks that a threshold condition exists below which the crack will not grow. This threshold is represented by the standard fracture mechanics equation

$$\Delta K_o = C \Delta\sigma_{(a)o} a^{1/2} \quad (1)$$

where ΔK_o is the threshold stress intensity, $\Delta\sigma_{(a)o}$ the limiting fatigue stress range for a test piece (component) with a crack of depth a, and C a geometry constant. For the material employed in this investigation, ΔK_o has been measured as 6.0 MPa$\sqrt{m}$ when $R = 0.1$ and 8.8 MPa$\sqrt{m}$ when $R = -1$. Lines representing equation (1) with the appropriate values of ΔK_o have been constructed in Fig. 9, C being taken as $\sqrt{(1.25\pi)}$ (**10**) and it becomes apparent that small defects will grow at reversing stresses below those given by equation (1). Such deviations have been reported by Kitagawa *et al.* (**11**) for short cracks of similar length and to allow for such deviations El Haddad *et al.* (**12**) have proposed a modified relationship of the form

$$\Delta K_o = C \Delta\sigma_{(a)o}(a + a_o)^{1/2} \quad (2)$$

where a_o is given by

$$a_0 = \frac{1}{1.25\pi}\left(\frac{\Delta K_o}{\Delta\sigma_o}\right)^2 \quad (3)$$

Equation (3) is for the condition $\Delta\sigma_{(a)o} = \Delta\sigma_o$ which is a limiting value where the maximum fatigue limit is achieved and no further reduction in crack depth has any effect. Applying this modified relationship, a regression analysis has been used to obtain a least squares fit for the data with defect depths of 0.05 mm

Table 2 Surface measurements on push–pull fatigue specimens

Type	*Surface finish*	*Depth of defect at crack initiation site (microns)*
a	Fine circumferential ground	17.8
b	0.05 mm grooves	50.0
c	0.50 mm grooves	500.0
d	Rough circumferential ground	30.5
e	Longitudinal polish	5.1
aR	Fine circumferential ground (Radial)	40.0
bR	0.05 mm grooves (Radial)	90.0

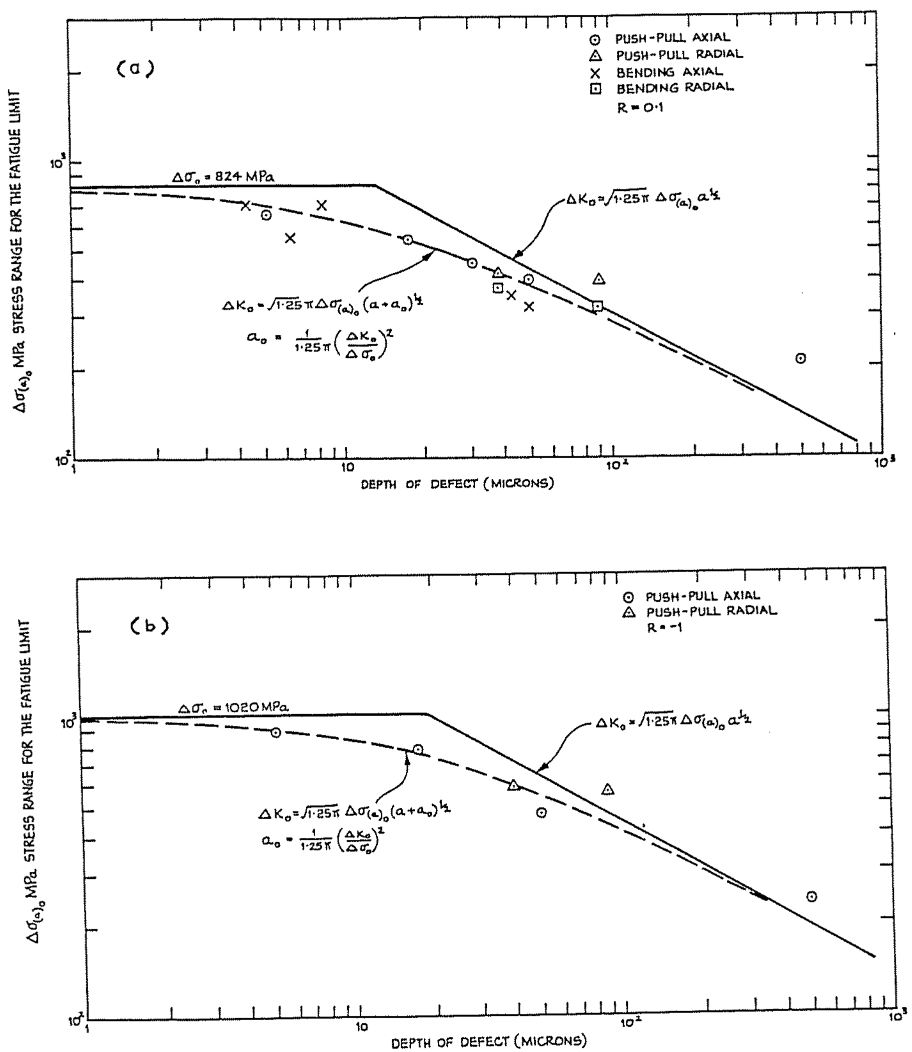


Fig 9 Variation in fatigue limit with depth of surface defect

or less. Mean curves have been constructed in Fig. 9 for which limiting values for the stress range $\Delta\sigma_0$ of 824 and 1020 MPa have been obtained for R values of 0.1 and -1, respectively. The agreement between the data and the modified threshold curve suggests that this form of equation gives a good representation of the data for stress free specimens and that defects below 0.05 mm might be regarded as equivalent to short cracks. In this material it would appear that the fatigue strength is limited by surface defects that are inherent in the material.

Under these circumstances no increase in $\Delta\sigma_{(a)0}$ could be achieved by an improvement in surface finish although it is recognized that smaller defects could lead towards the limiting value $\Delta\sigma_0$.

As already stated the data presented has been obtained on stress free specimens and therefore residual stresses arising from the surface finishing process do not have to be taken into account. Clearly, if there is a residual surface stress it may act as a superimposed mean stress varying in magnitude with depth and should be considered when analysing short crack growth behaviour. It is not apparent from the published work on this subject, however, that this aspect has been taken into account. For instance, the work already referred to by El Haddad *et al.* **(12)** does not consider the influence of possible shallow machining stresses in the experimental work conducted to correlate threshold and short crack results. Such machining stresses would have introduced an effective mean stress although the tests were carried out with an R value of -1.

Orientation

Fatigue specimens taken from the radial direction in the forging were tested in both the bending and push–pull mode of loading. The results of the bending tests given in Fig. 3(b) show that for a fine ground finish the fatigue limit in the radial direction is almost 50 per cent lower than in the axial direction for an R value of 0.1. The same comparison in push–pull loading, which can be made from the data presented in Fig. 10(a) and (b), shows that the radial tests give fatigue limits progressively lower by 24, 29, and 45 per cent at increasing mean stress levels of 0, 385, and 617 MPa, respectively. These reductions in fatigue limit are attributed solely to the effect of MnS inclusions from which fatigue cracks invariably initiated in the radial specimens.

Radial specimens containing shallow machined grooves of 0.05 mm in depth were also tested in the bending and push–pull modes (Figs 3(b) and 10(b), respectively). These results show that the MnS inclusions, which are typically 0.04 mm in depth and of a similar size to the groove depth, act as extensions to the groove to give an effective 0.09 mm defect. Tables 1 and 2 give the details of the radial fatigue tests and these are included in Fig. 9, showing good agreement with the corresponding axial tests.

Mean stress

The effect of tensile mean stress on the push–pull fatigue limit for various finishes is summarized in Fig. 10 for the axial and radial directions. The fatigue limits have been plotted against the mean stress levels and mean curves have been constructed for each type of surface finish. In general the relationship between fatigue limit and mean stress tends to be linear for mean stresses up to 620 MPa, but neither a modified Goodman nor a Gerber type relationship can be used to represent the data over the full range of tensile mean stress.

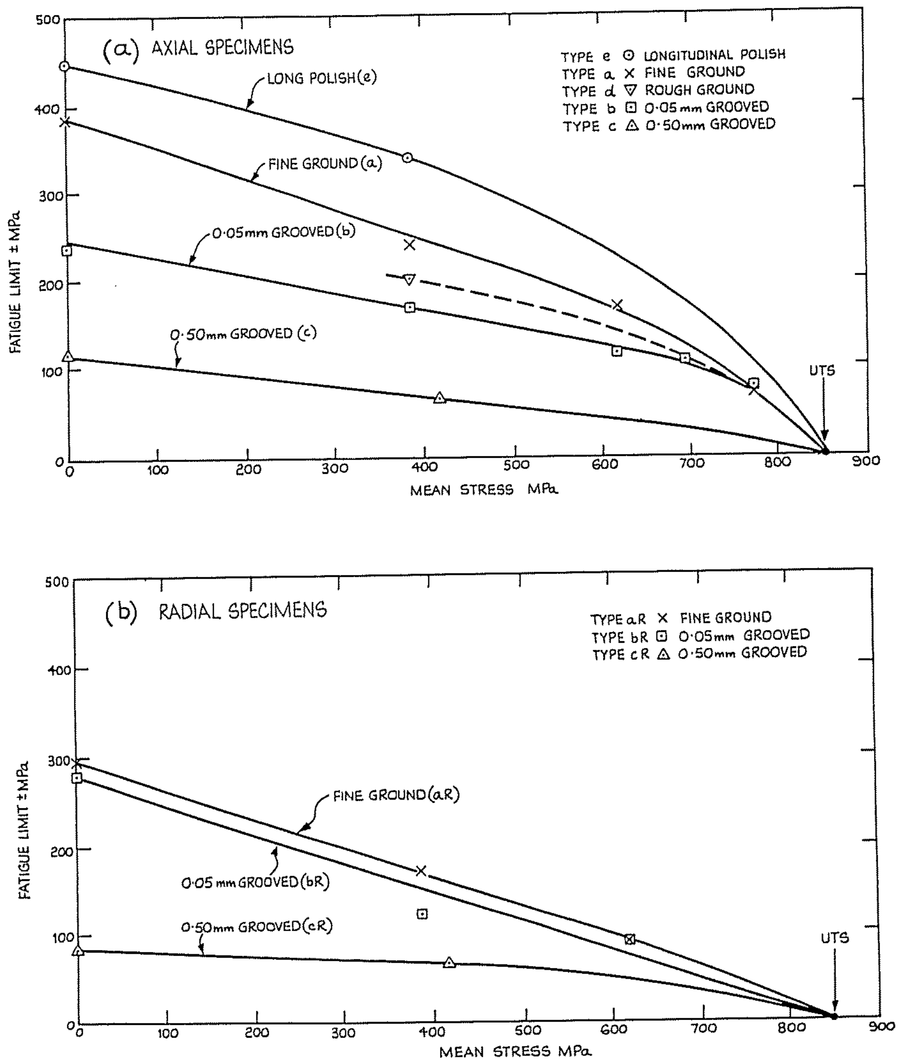


Fig 10 Effect of mean stress on fatigue limit tested in the push–pull mode

Fatigue limits are often regarded as approximating to half the tensile strength but Fig. 10 indicates that such a generalization only applies to polished specimens at zero mean stress. For specimens with significant surface irregularities or an orientation which aligns inclusion stringers at 90 degrees to the applied stress, the fatigue limit may be drastically reduced.

Conclusions

From an investigation into the effect of surface finish and orientation on the fatigue strength of a low alloy steel forging the following conclusions have been formed.

(1) Fatigue crack initiation was usually from surface irregularities either introduced by the finishing process, such as surface scratches, or inherent defects in the material such as inclusions and closed pores.

(2) The surface irregularities providing the fatigue crack initiation sites were not usually detected by either surface roughness scanning methods or random metallographic sectioning techniques and were only identified from examination of fracture faces.

(3) The fatigue limit decreased with increasing depth of defect at the crack initiation site and surface grooves or inclusions about 0.05 mm in depth reduced the fatigue limit of a fine ground surface by 50 per cent when the defects were aligned transverse to the applied stress. Hence radial specimens had lower fatigue strengths than axial specimens due to the presence of MnS inclusions elongated in the axial direction.

(4) Defects providing the crack initiation sites of approximately 0.05 mm in depth or less were found to grow below the threshold represented by the standard fracture mechanics equation

$$\Delta K_o = C\Delta\sigma_{(a)o}a^{1/2}$$

Using a modified equation of the form $\Delta K_o = C\Delta\sigma_{(a)o}(a + a_o)^{1/2}$ curves were constructed which suggested that this form of equation gives a good representation of the threshold for the defects observed. Values for a_o of 0.013 mm and 0.019 mm were obtained for R values of 0.1 and −1, respectively.

Acknowledgements

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