EFFECT OF PRIOR COLD WORK ON LOW CYCLE FATIGUE BEHAVIOUR OF AISI TYPE 304 STAINLESS STEEL

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Strain controlled low cycle fatigue behaviour of 304 stainless steel with various degrees of prior cold work has been evaluated at 300,823 and 923K. Fatigue life decreased with prior cold work at 300 and 823 K while at 923 K, a recovery in fatigue life has been noticed for 20% and 30% prior cold work levels. Fractographic observations of fatigue crack initiation and propagation are presented.

INTRODUCTION

It has been demonstrated by various investigators that the low cycle fatigue (LCF) and fracture behaviour of austenitic stainless steels depend significantly on heat to heat variations (Maiya and Majumdar (1) and Brinkman and Korth (2)), on grain size (Yamaguchi and Kanazawa (3), Foire and Diericks (4) and K.B.S. Rao et al(5)) and on thermal and thermomechanical history (Plumbridge et al (6) and Cheng et al (7)). In nuclear reactor applications of austenitic stainless steels, prior cold work (PCW) is often specified to take advantage of its beneficial effects on certain properties or is introduced in components during fabrication. The present investigation has been undertaken to evaluate the effect of PCW in strain controlled LCF properties of AISI 304 stainless steel, with particular emphasis placed on the characterization of crack initiation and propagation modes.

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EXPERIMENTAL

A 25 mm thick mill annealed plate was machined to rods of 23 mm diameter. A solution annealing (SA) treatment was given to the rods at 1323 K for 0.5 hrs for stuyding fatigue behaviour in SA condition. Cold work was imparted by swaging the mill annealed rods to reduction in area of 10, 20 and 30% . LCF tests were carried out on cylindrical ridge specimens of 50 mm gauge length and 10 mm gauge diameter with the loading axis parallel to the rolling direction in air in an Instron Servohydraulic System under total axial strain control mode with a triangular wave input signal. All tests were conducted over strain ranges 0.005-0.025 at a constant frequency of 0.1 Hz. At 300 K tests were done on SA and 20% PCW materials and at 823 K and at 923 K on SA and all PCW conditions. Fractography of fatigue tested samples was carried out using Philips PSEM 501 Scanning Electron Microscope. The chemical composition of the alloy is given in Table 1.

TABLE 1 - Chemical composition of AISI 304 Stainless Steel

Element	C	Si	Mn	P	S	Cr	Ni	Fe
Weight %	0.042	0.38	1.65	0.024	0.003	18.2	9.2	balance

RESULTS AND DISCUSSION

Fatigue Life

SA material was found to harden during cycling, followed by a saturation behaviour, while PCW material softened continuously during cycling. Plots of plastic strain amplitudes $\Delta\epsilon_P/2$ corresponding to the saturation stress strain curve of SA material and those corresponding to half the fatigue life of PCW material versus number of reversals to failure ($2N_F$) are shown in Figs.1,2 and 3 at 300, 823 and 923 K respectively. Coffin-Manson relationship is obeyed at all the temperatures by SA as well as by PCW materials.

SA material exhibited better fatigue life than PCW material under all testing conditions. At 300 and 823 K the fatigue life has been found to decrease with increase in PCW. On the other hand at 923 K (Fig.3), 20% and 30% PCW materials showed better fatigue life than 10% PCW material. This recovery in fatigue life is more pronounced in 30% PCW material and at the lowest strain range (0.005) (Fig.4).

Fracture Behaviour at 300 and 823 K

Fractographic investigations on fatigue tested samples at 300 and 823 K revealed that fatigue crack initiation occured from the specimen surface in persistent slip bands (PSB's) in both SA (Fig.5a) and PCW materials. A marked increase in density and fragmentation of PSB's has been observed with increase in strain range.

Inclusions larger than 5 μm in size appeared to initiate secondary cracks (Fig.5b) in the matrix, whereas it has been stated by Turner (8) that inclusions are not important sites for crack nucleation in LCF. In the present study, crack initiation has been found to occur from the surface in PSB's. However the propagation stage could be influenced by the link up of inclusion-matrix interface cracks that form at large (> 5 μm) inclusions with the main crack.

In 20% PCW material, at 823 K, the cracks on parallel slip bands are coalesed to form a major crack (Fig.5c) with a zipper pattern, on the specimen surface. Villagrana et al (9) has made similar observations in alloy 800 H tested at higher stress ranges. This has been attributed to an increase in the number of crack nucleation sites. The coalescence of such slip band cracks on the surface and the transition from stage I propagation along the slip bands to stage II perpendicular to the specimen axis might occur simultaneously (9). In PCW materials crack density was relatively high and parallel cracks formed on adjacent slip bands would have coalesed to give this zipper pattern.

Crack propagation at 300 and 823 K was transgranular in both SA and PCW materials. Initial growth occured by stage I mode (Fig.5a) slip band cracking. This crystallographic crack growth has been suggested by Hertzberg and Mills (10) as a characteristic feature of low stacking fault energy materials where slip is restricted to specific crystallographic planes particularly at low strains. Stage I crack growth was followed by stage II crack growth (Fig.5b), characterised by well defined striations. Crack propagation at 823 K was marked by pronounced crack branching and link up (Fig.5d).

In general, coarse slip band cracking and striation cracking were found to increase with PCW. In strain controlled fatigue testing PCW materials experience higher stresses than SA material for the same total strain range and can lead to increased cracking. The decreased fatigue life with increased PCW is considered to arise from enhanced cracking and their link up. The link up of independently nucleated cracks has been found to be an important mode of stage II growth in aluminium alloys by Morris et al (11) and in 304 stainless steel by Turner (9).

Fracture Behaviour at 923 K

Oxidation has been found to influence crack initiation and propagation modes at 923 K. SA material in general exhibited transgranular crack initiation. PSB's in PCW material were found to be heavily oxidised (Fig.6a) and aided in crack initiation on the surface. The ridging of the surface grain boundaries and the associated intergranular crack initiation were also observed in PCW material (Fig.6b). Coffin (12,13) and McMohan and Coffin (14) have made similar observation in superalloys and suggested that chemical segregation and carbides at the grain boundaries cause selective oxidation and intergranular cracking.

Transmission electron microscopic (TEM) studies carried out by K.B.S. Rao et al (15) on samples fatigue tested at 923 K showed copious amount of carbide precipitated on the grain boundaries in PCW materials. It is suggested in the present case that grain boundary precipitation and subsequent oxidation lead to intergranular cracking in PCW materials. Coffin (16) based on comparative tests in air and vacuum has suggested that intergranular cracking in high temperature fatigue results mainly due to the oxidation of the grain boundaries. This oxidation is enhanced due to PCW and leads to increased intergranular cracking. Intergranular cracks were also observed in the interior of the material at the grain boundary tripple points, twin-grain boundary intersections and slip band-grain boundary intersections. Intergranular cracking was more pronounced in PCW materials and is considered responsible for reduction in life compared to SA material at 923 K.

The recovery in fatigue life at higher PCW levels observed at 923 K is now discussed. As seen in Fig.6c, intergranular cracks have propagated only to a very limited extent in 20% PCW material in comparison with 10% PCW material (Fig.6d). 30% PCW material also exhibited restricted intergranular crack growth. TEM studies on fatigue tested samples (15), 20% and 30% PCW materials have been found to show extensive recovery. As pointed out in (3) the structural recovery leads to increased fatigue life at high temperatures in austenitic stainless steels. More extensive recovery observed in 20% and 30% PCW may be responsible for higher observed life compared to 10% PCW. Extensive TEM studies are underway on samples deformed to various fraction of fatigue life on different PCW material to assess the influence of PCW on substructural recovery. Further the increased life observed for 30% PCW material at low strain range is in agreement with influence of recovery on crack propagation.

CONCLUSIONS

1. At 300 and 823 K, fatigue life decreased with PCW and this has been attributed to the increased cracking in PCW materials. At these temperatures, crack initiation and propagation are transgranular.

2. Inclusions larger than 5 μm in size have been found to initiate cracks at the inclusion-matrix interface and could influence life by link up.

3. Oxidation enhanced transgranular and intergranular crack initiation and propagation at 923 K.

4. Increase in fatigue life of 20% and 30% PCW materials at 923 K is attributed to structural recovery.

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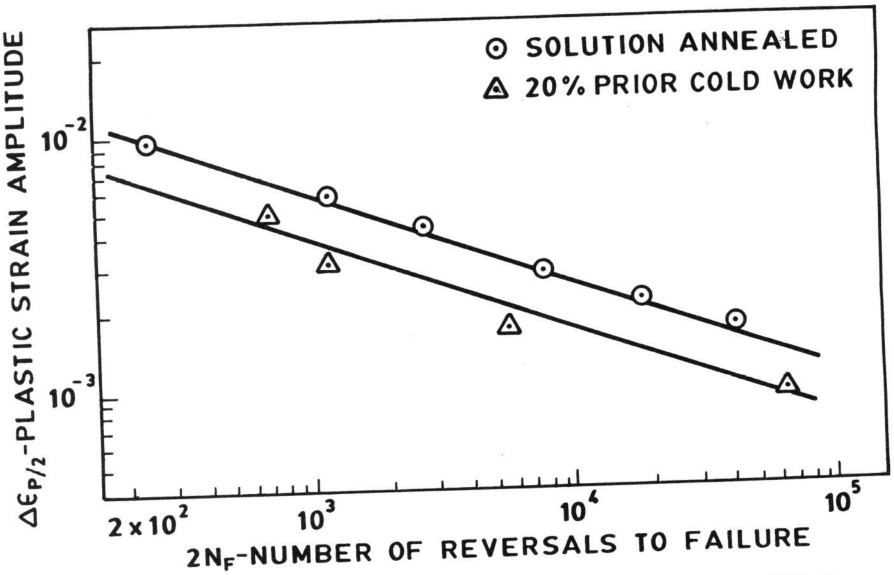

Figure 1 Influence of prior cold work on fatigue life at 300 K

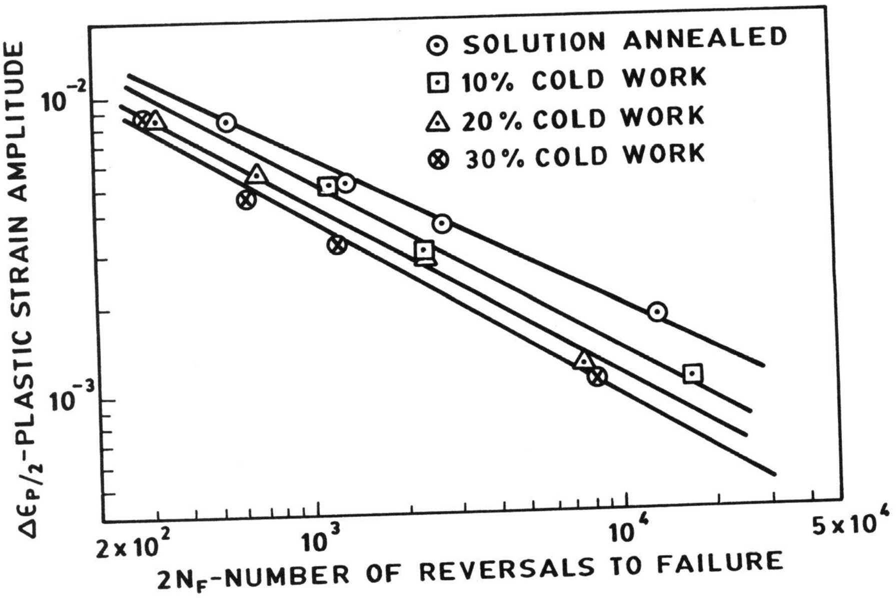

Figure 2 Influence of prior cold work on fatigue life at 823 K

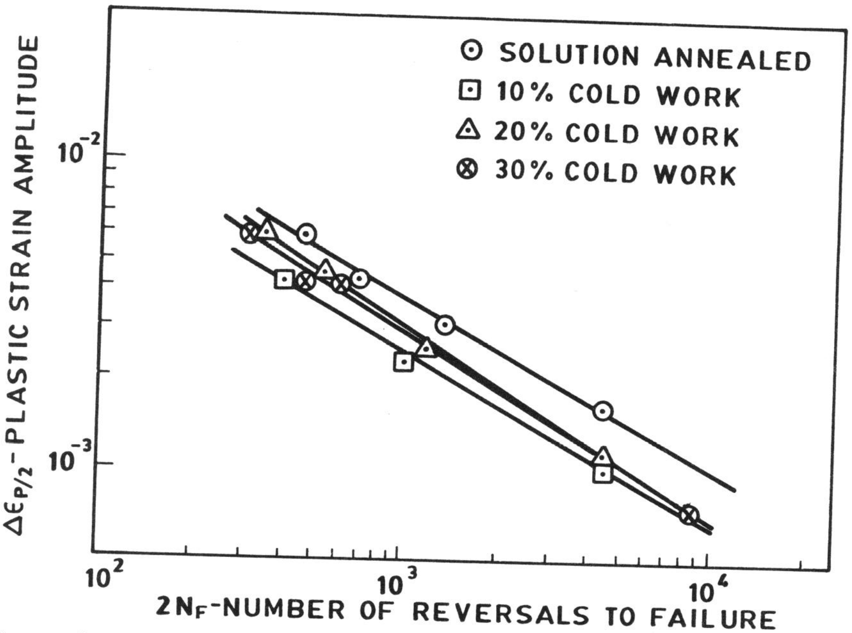

Figure 3 Influence of prior cold work on fatigue life at 923 K

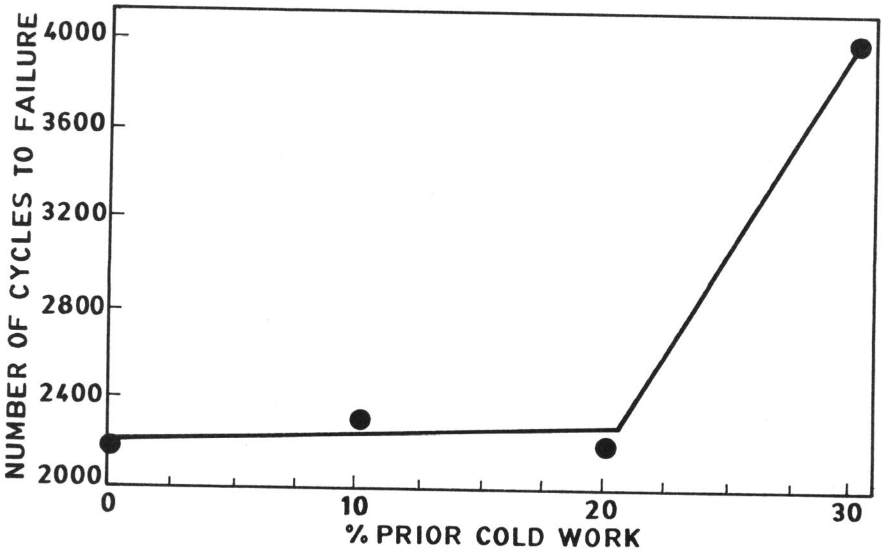

Figure 4 plot of fatigue life against % prior cold work at 923 K and $\Delta\epsilon_t$ = 0.5%

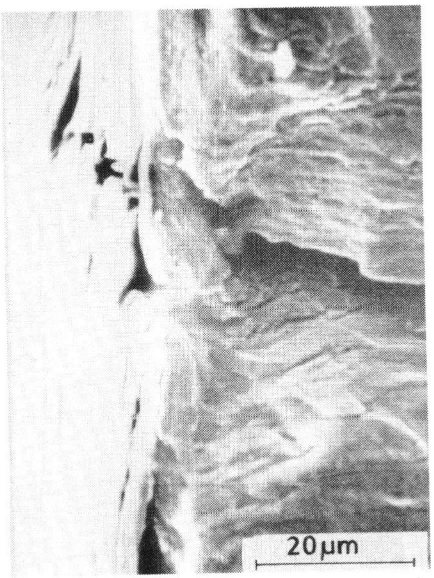

Fig.5a Crack initiation in PSB's (SA,300K,strain amplitude=0.25%)

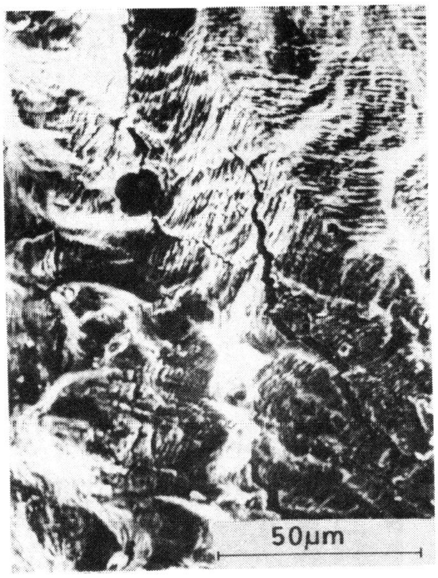

Fig.5b Secondary cracking near inclusion (SA, $\Delta\epsilon_{t/2} = 0.25\%$)

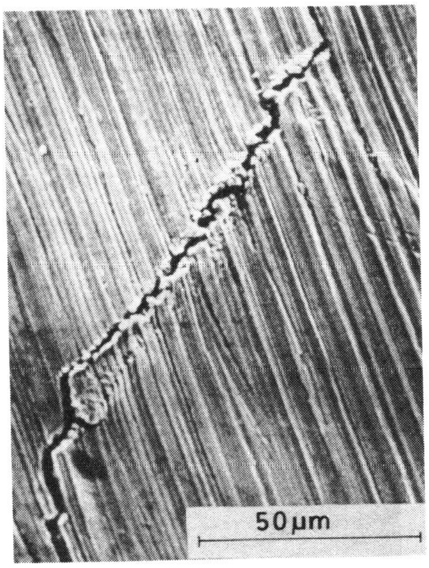

Fig.5c Zipper crack on the surface (20% PCW,823 K,$\Delta\epsilon_{t}/_{2} = 0.4\%$)

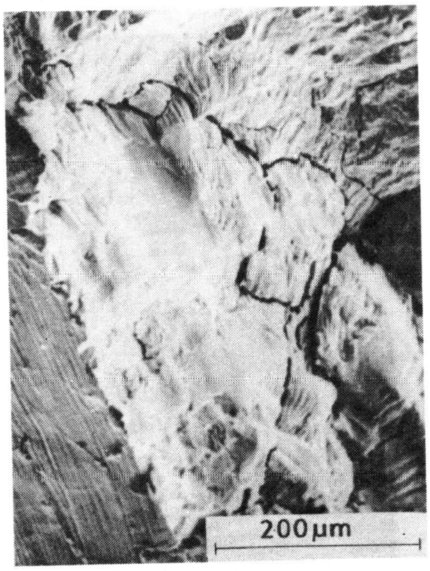

Fig.5d Link up of branched cracks(10% PCW,823K,$\frac{\Delta\epsilon_t}{2} = 0.6\%$)

Fig.6a Oxidation of PSB's
(20% PCW,923 K,$\frac{\Delta\epsilon_t}{2}$=0.25%)

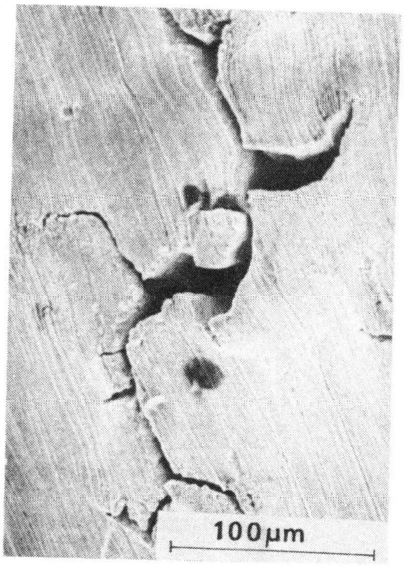

Fig.6b Grain boundary cracks
at ridges(20% PCW,$\frac{\Delta\epsilon_t}{2}$=0.6%)

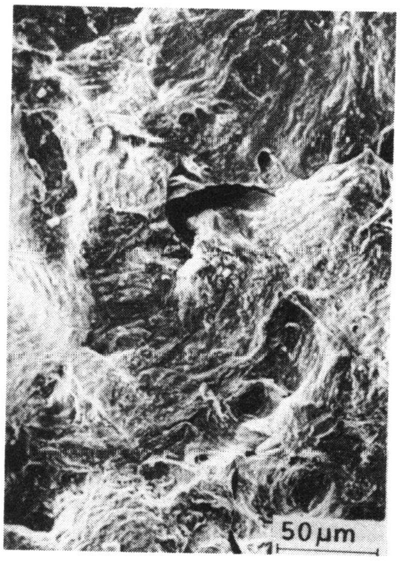

Fig.6c Fracture surface of 20%
PCW (923 K,$\Delta\epsilon_{t/2}$ =0.6%)

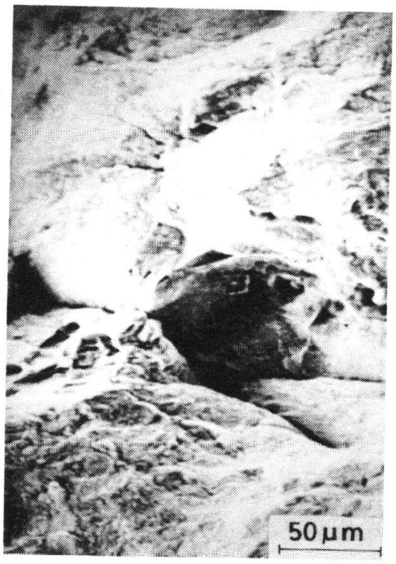

Fig.6d Fracture surface of 10%
PCW (923 K, $\Delta\epsilon_{t/2}$ =0.6%)