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FATIGUE CRACK MORPHOLOGY IN 304 STAINLESS STEEL CYCLED AT CONSTANT STRESS AMPLITUDE AT ELEVATED TEMPERATURE*

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INTRODUCTION

A number of mechanisms have been observed for the processes of crack nucleation and propagation in fatigue. Nucleation has been found to occur at coarse or persistent slip bands [1,2], at grain boundaries [3], and at inclusions [3 - 5] depending on the material and the experimental conditions. The propagation process is generally separated into two stages. During the early stage, cracks are crystallographic, usually following slip bands [6]. Stage II propagation is generally noncrystallographic and is generally believed to proceed by some sort of crack tip blunting process [7]. Recently, link up of independently nucleated cracks has been found to be an important mode of stage II growth in aluminum alloys [5]. This study was carried out to determine which modes of nucleation and propagation are operating during elevated temperature fatigue of 304 stainless steel.

EXPERIMENTAL PROCEDURE

The test material was commercial 304 stainless steel received in the form of 15.9 mm dia. rod. Button head samples with a 12.7 mm long straight gauge section of square cross-section 3.16 x 3.16 mm were machined from the rod. Samples were annealed at 1093°C for 1 hr and then aged for 50 hrs at 800°C. This aging treatment was designed to precipitate most of the $M_{23}C_6$ carbide and produce a microstructure which would be stable for the period of the mechanical tests. The resulting grain size was approximately 0.1 mm mean grain diameter. The gauge sections were electropolished prior to testing.

Tests were carried out at 300 and 560°C in air at a frequency of approximately 0.5 Hz, with stress amplitudes in the range 200 - 350 MPa. All tests were performed in nearly symmetric push-pull loading except that a feedback loop was used to bias the stress slightly in order to keep the mean strain constant after the first few cycles. This control always introduced a slight compressive mean stress into the loading cycle. The magnitude of this mean stress varied slowly during the test but was always in the range 1-4% of the stress amplitude. All tests were begun with the initial loading in the tensile direction, and went to the full stress amplitude on the first cycle. Since the samples were in an annealed condition, they experienced 5-10% strain during the first tensile quarter cycle.

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Tests were continued either until complete fracture had occurred or until the displacement amplitude began to increase rapidly indicating the presence of large cracks. Samples from tests stopped at this point were still in one piece but were within a few tens of cycles of failure. The fracture surface of samples tested to failure were examined in the scanning electron microscope to study the features produced by crack propagation. The lateral surfaces of samples from tests stopped prior to failure were examined to determine the density, orientation and other properties of the cracks.

RESULTS AND DISCUSSION

The stress amplitudes used in these experiments produced plastic strain amplitudes between 0.003 and 0.01. The strain amplitudes never truly saturated, but first decreased and then increased during the test. This behaviour is reported in detail elsewhere [8]. Failures occurred between 1000 and 10000 cycles as shown by the S-N curves in Figure 1. The fracture mode was in all cases transgranular.

Microscopic examination revealed that substantial differences existed in the distribution of "damage" in the gauge section between the highest and the lowest stress amplitudes. At the lowest stress amplitudes, which gave lifetimes near 10000 cycles, relatively few grains in the gauge section showed the presence of coarse slip bands although all grains had rumpled surfaces at failure indicating that considerable plastic deformation had occurred in all grains. Failure at these low stress amplitudes was caused by the nucleation and propagation of a single crack. As the stress amplitude was increased and the lifetime decreased, the percentage of grains exhibiting intense coarse slip bands increased and so did the number of independently nucleated cracks. At the highest stress amplitudes when the life was near 1000 cycles, well over 50% of the grains contained coarse slip bands, and the spacing between cracks was reduced to less than 1 mm. As the density of cracks increased, the linking up of independently nucleated cracks became an important mode of crack propagation in the direction parallel to the sample surface. At the highest stress amplitudes the linkup process created a multiply branched, highly interconnected fracture pattern as shown in Figure 2. Many smaller cracks with lengths 0.1 mm or less, which traverse only one or two grains, are present between the long cracks as shown in Figures 2 and 4.

Examination of the fracture surfaces of samples cycled to failure confirm the importance of the linkup process to crack propagation. For samples with endurances of less than about 7000 cycles, the fracture surfaces always had multiple points of nucleation indicating that several cracks had nucleated independently and coalesced to form the final fracture. For example, the fracture surface of a sample tested at 250 MPa stress amplitude at 560°C had at least five spearate crack initiation sites as shown in Figure 3. Three cracks had grown together to form a single long crack before the crack became unstable, and two additional cracks were joined to the fracture surface during the final rupture of the sample. Fracture surfaces of other samples cycled at high stress amplitudes at both 300 and 560°C were qualitatively similar to the one shown in Figure 3.

Examination of the many small cracks on the highly stressed samples strongly suggests that the cracks nucleate at the intense coarse slip bands and that inclusions and grain boundaries are not favoured sites for nucleation. It was found that all cracks which were in a single grain or had traversed only two grains, were located along coarse slip bands in at least one of the grains as shown in Figure 4. Long cracks always were found to follow coarse slip bands for part of their length though they seemed to have no particular relationship to the slip band structure in other grains. In view of the evidence of the short cracks, it seems plausible that the longer cracks nucleated on the slip bands, but that when they became larger they could propagate across the slip bands. These observations strongly support the concept of crack initiation by surface roughening at persistent slip bands [1,2,9]. Although several samples contained prominent strings of inclusion particles strung out parallel to the rod axis, only one case was found where a short crack intersected an inclusion at the surface. Grain boundaries also appear to play no role in the fracture process either as sites for nucleation or as strong obstacles to crack propagation. Many small cracks were observed entirely within a single grain as in Figure 4 so that they could not have been nucleated at a boundary. There also did not appear to be any significant number of cracks which ended at a grain boundary as would be expected if the boundaries were strong obstacles to crack propagation.

SUMMARY

For the 304 stainless steel investigated in these experiments, the cracks formed by constant stress amplitude fatigue cycling at 300 and 560°C were nucleated at coarse slip bands. Microstructural features such as inclusions and grain boundaries were not important either as sites of initiation or as obstacles to propagation. One of the major effects of stress amplitude was that the number of cracks nucleated increased rapidly in part because increasing the stress amplitude increased the number of grains which contained coarse slip bands, but there was insufficient data to determine if the crack density increased simply in proportion to the slip-band density or if the slip bands also became more intense and more likely to nucleate cracks at the higher stress amplitudes. The increased density of cracks appears to have significant consequences for the crack propagation process because linkup of independently nucleated cracks becomes a prominent mode of propagation along the surface at the higher stress amplitudes. The process of crack linkup may not have had a large effect on the fatigue life of the specimens used in this study because the distance between independent nucleation sites on the fracture surface was never less than about a third of the critical crack size even at the highest stress amplitudes. However, this mode of propagation could have a large effect on the crack propagation portion of the fatigue life of large components particularly when they have large surface area to volume ratios like plates and pipes.

ACKNOWLEDGEMENTS

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REFERENCES

1. THOMPSON, N., International Conference on Fatigue of Metals, Inst. Mech. Engrs., London, 1956, 526.
2. WOOD, W. A., Phil. Mag. 3, 1958, 692.

3. BOETTNER, R. C., LAIRD, C. and McEVILY, A. J., Jr., Trans. AIME 233, 1965, 379.
4. GROSSKREUTZ, J. C. and SHAW, G. G., Fracture 1969, ed., P. L. Pratt, Chapman and Hall, London, 1969, 620.
5. MORRIS, W. L., BUCK, O. and MARCUS, H. L., 7th Annual TMS-AIME Spring Meeting, Toronto, 1975.
6. LAIRD, C., Fatigue Crack Propagation, ASTM STP 415, ASTM, Philadelphia, 1967, 131.
7. LAIRD, C. and SMITH, G. C. Phil. Mag. 7, 1962, 847.
8. TURNER, A. P. L., to be published.
9. LAIRD, C. and KRAUSE, A. R., Int. J. of Fracture Mechanics, 4, 1968, 219.

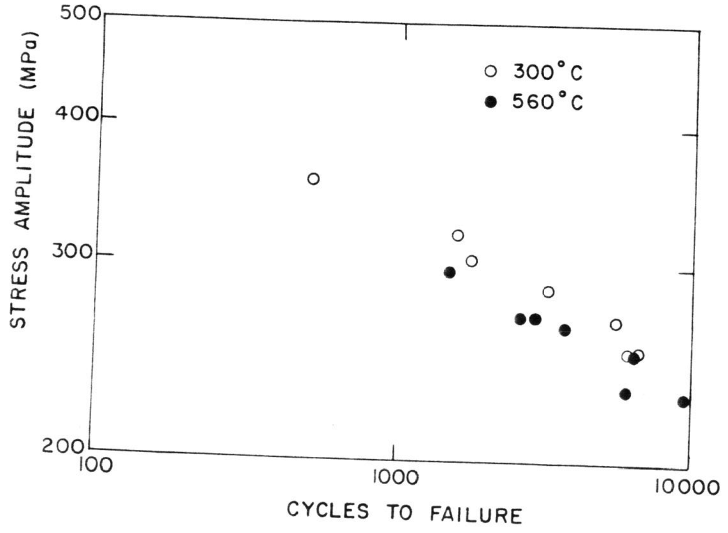

Figure 1 Fatigue Life of 304 Stainless Steel Cycled in Symmetric Tension-Compression at Constant Stress Amplitude

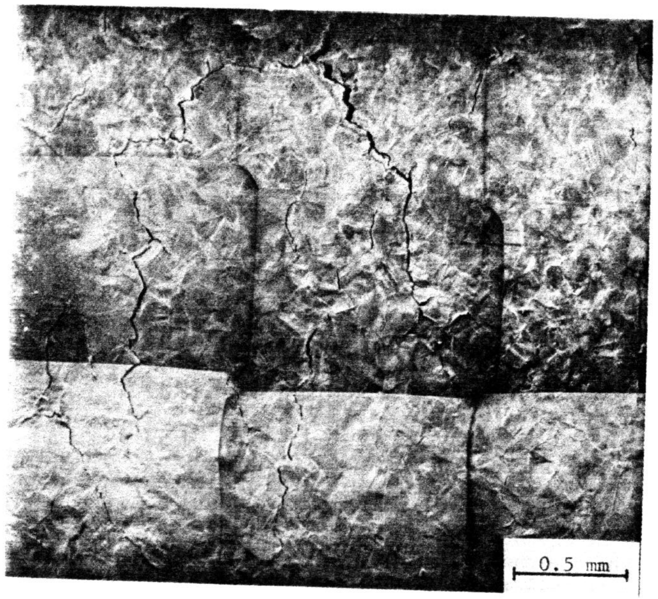

Figure 2 Fracture Pattern on the Lateral Surface of Sample Cycled at 560°C at a Stress Amplitude of 296 MPa Showing Multiple Crack Nucleation and Link Up of Independently Nucleated Cracks

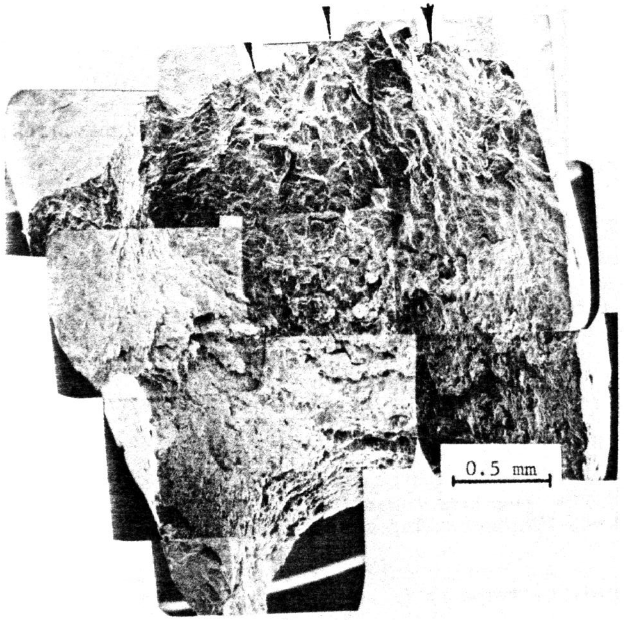

Figure 3 Fracture Surface of Sample Tested at 560°C and 250 MPa Stress Amplitude. Three Separate Nucleation Sites on Major Cracks are Indicated by Arrow Heads. Two Additional Independent Cracks Appear at Upper and Lower Left

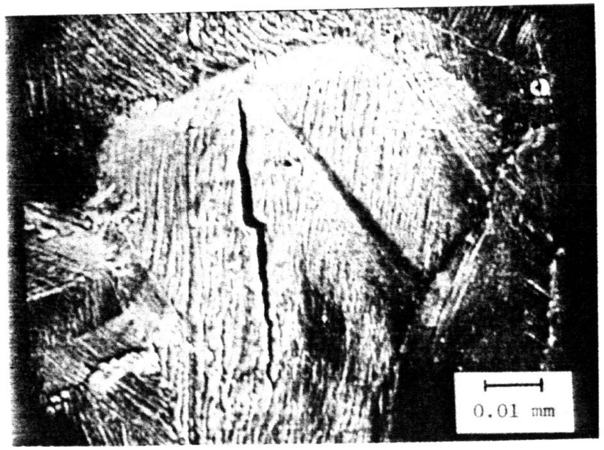

Figure 4 Small Crack Contained in Single Grain Showing Relationship of Crack to Slip Bands