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METALLOGRAPHIC ASPECTS OF FATIGUE IN PEARLITIC STRUCTURES

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INTRODUCTION

Throughout this century a great number of research workers have studied the basic mechanisms of fatigue damage. This work, and in particular that of the past twenty five years, has substantially increased our knowledge of the fatigue failure process. Much of this work is covered in a number of reviews [1-4]. Unfortunately, this increase in knowledge has been accompanied by increasingly rigorous demands on materials in service with the result that fatigue fracture remains the most common source of service failure.

This paper reports an investigation into the mechanisms of fatigue damage in three pearlitic steels; a coarse pearlite, a fine pearlite and a spheroidised carbide. The major emphasis in the work was on observation of the progress of fatigue damage in the three different microstructures. Pearlitic structures were selected for this study because of their practical importance and because multi-phase alloys have, until recently, received little attention from research workers. On the other hand there have been extensive studies of fatigue mechanisms in pure metals and single phase alloys [1-4].

Although the range of microstructures that can be developed in steels is very wide, the most common structure associated with good strength is that based on pearlite. Pearlite is composed largely of the ductile ferrite phase containing about 13% by volume of the hard intermetallic compound, cementite. In some steels it may constitute almost the whole structure as in the case of those used for ropes and springs. Previous studies [5,6] of basic mechanisms of fatigue in steels are few and where materials containing pearlite have been involved, the constituent has occupied only a small proportion of the structure. Its influence on the basic mechanisms has therefore been difficult to evaluate. This investigation was started to fill this gap in knowledge.

A series of fatigue tests were carried out using pre-polished specimens and damage was examined at various stages of the life using a number of metallographic techniques. Cyclic properties and changes of deformation resistance during testing were also determined. The results of the investigation are presented in this paper.

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EXPERIMENTAL PROCEDURE

Three different steels were used in the work and their composition is shown in Table 1. All produced a fully pearlitic structure on suitable heat treatment. Specimens were machined and roughly polished prior to heat treatment under controlled atmosphere conditions. Three pearlitic structures were examined, these being coarse pearlite, fine pearlite and spheroidised carbide. Prior to testing, specimens were electro-polished for about 15 minutes so as to provide a non-distorted surface layer.

Two types of fatigue tests were used. Small flat specimens were tested in a reverse plane bending machine. The majority of tests were carried out on small cylindrical specimens (dia. = 5 mms., gauge length = 7 mms) using a servo-hydraulic machine and all were tested in strain control. Three kinds of tests were carried out. An incremental step test [7] produced data for derivation of the cyclic stress strain curve. A monotonic test gave the static stress strain curve. In constant amplitude tests, specimens were examined at various stages of their fatigue life and after failure. A number of metallographic techniques were used. Surface damage was examined by producing taper sections for optical microscopy. For high resolution microscopy, the transmission and scanning electron microscopes were used. Transmission electron microscopy was used for examination of carbon replicas of surface damage and also thin foils produced from within the specimen. The scanning electron microscope was mainly used for fracture surface examination.

RESULTS

The values of several monotonic and cyclic properties for steel C are presented in Table 2. Values for the cyclic strain hardening exponent lie in a narrow range, 0.228 - 0.248, and are high compared with values for a number of materials. The fine pearlite had the lowest value whereas those for coarse pearlite and spheroidised carbide were similar. Comparison of the monotonic and cyclic stress-strain curves showed a cyclic softening effect in fine pearlite over a range of strain amplitudes. Both coarse pearlite and spheroidised carbide structures showed cyclic softening at low levels of amplitude but a change to cyclic hardening at levels above about 0.003. The strain-fatigue life relationship predicted using the cyclic and monotonic stress-strain curves and the well known techniques of Morrow [8] showed that fine pearlite has the greatest fatigue resistance under high cycle conditions whereas in the low cycle region, the spheroidised carbide is superior.

Surface damage was observed in all structures as early as 1% of the fatigue life. It appeared as slip bands in the ferrite as shown in Figure 1. The location of surface damage in coarse and fine pearlite was dependent on cementite lamellae orientation to the principal stress axis. Damage was more uniformly dispersed throughout fine pearlite than in coarse pearlite at similar stages of the fatigue life. Damage in all structures was associated with a very shallow surface topography.

During cycling, there was a build-up of dislocations in the ferrite. The principal source of dislocations was the ferrite-cementite interface. The overall dislocation arrangement after cycling was not the same in all three structures.

Cracks were observed in coarse pearlite and spheroidised carbide after cycling to about 25% of the life. In fine pearlite they could not be detected until about 75%. Figure 2 shows cracking in fine pearlite. In both lamellar structures, the major initiation sites were slip bands, ferrite-cementite interfaces and pearlite cell boundaries. In spheroidal carbide, the sites were slip bands and ferrite grain boundaries.

All structures showed mainly transgranular crack propagation. The principal paths in lamellar structures were along ferrite-cementite interfaces, across lamellae and ferrite and, in the case of fine pearlite some grain boundaries. In spheroidised carbide, the path was almost always in ferrite and along the ferrite-carbide interface. Results suggested the greatest propagation rate was in fine pearlite and the lowest in the spheroidised carbide. The extent of fatigue crack growth before catastrophic failure was greatest for spheroidised carbide and least for the coarse pearlite.

DISCUSSION

Results show that the microstructural characteristics of pearlite influence material performance under high cycle fatigue conditions. This effect is attributed to structural influence on the following stages of fatigue:-

(a) ease of crack initiation
(b) rate of fatigue crack growth through the specimen
(c) extent of fatigue crack growth before catastrophic failure conditions are achieved.

The highest resistance to crack initiation under high cycle fatigue conditions is found in the fine pearlite. This is attributed to a capacity for more homogeneous distribution of plastic strain in this structure than the others. This arises from the extensive interface area between ferrite and cementite. It is from this interface that dislocations move into ferrite.

The differences in crack growth rates can be attributed to

(a) the behaviour of material at the crack tip
(b) the effects of cyclic properties, e.g. the cyclic strain hardening exponent and
(c) the route followed by the propagating cracks.

If strain levels in the plastic zone are sufficiently high, localised cyclic hardening occurs in both coarse pearlite and spheroidised carbide as predicted from the comparison of cyclic and monotonic stress-strain curves. This promotes a re-distribution of plastic strain whereas the fine pearlite shows a softening effect and hence plastic strain is concentrated within the tip of the growing crack.

The routes followed by a propagating fatigue crack are mainly transgranular but the mechanisms of growth may not be consistent in all three structures. A fibre loading mechanism [9] can explain some of the results. In coarse pearlite, growth along ferrite-cementite interfaces is more preferred than in a fine pearlite where cutting across cementite lamellae is prevalent. In a spheroidised carbide, cracking across a spheroid is rare.

CONCLUDING REMARKS

(a) The mechanisms of crack propogation in the three structures are not the same. In the coarse pearlite, there are large areas of microcleavage at ferrite-cementite interfaces and crack cutting across cementite lamellae. In the fine pearlite, there is extensive cutting across lamellae by a growing crack and some intergranular cracking. A striation mechanism is detected. In the spheroidal structure, crack growth is concentrated within ferrite and along the ferrite-cementite interface.

(b) Fatigue damage appears early in the life in all structures and exists as slip bands in the ferrite. In both lamellar structures the location of damage is preferred in regions having cementite oriented at between 30 and 90° to the principal stress axis. At a given stage in the life, fatigue damage is more localised in coarse than fine pearlite. All observed damage is associated with a very shallow surface topography.

(c) Cracks appear in slip bands and at ferrite-cementite interfaces in all three structures. Cracks can be detected in coarse pearlite and spheroidised carbide structures at up to 25% of the life whereas in fine pearlite they are detected at about 75% of the life.

(d) Surface crack propagation rates are greater in lamellar than spheroidised carbide structures. The proportion of the full fracture zone occupied by the fatigue crack area is greatest in the spheroidised structure and least in the coarse pearlite.

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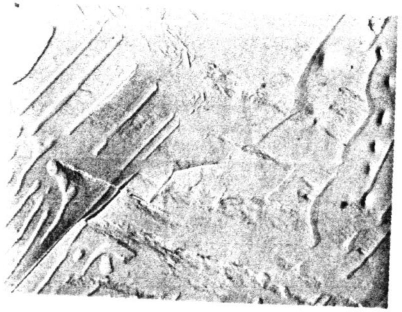
Table 1 Chemical Composition of Steels Used in the Work

	C	Si	Mn	S	P	Ni	Cr	Cu	Aℓ	Pb
Steel A	0.78	0.20	0.70	0.039	0.020	0.40	0.24	0.12	0.015	0.05
Steel B	0.78	0.20	0.68	0.025	0.010	0.42	0.28	NOT	ANALYSED	
Steel C	0.74	0.21	0.66	0.020	0.010	0.37	0.22	NOT	ANALYSED	

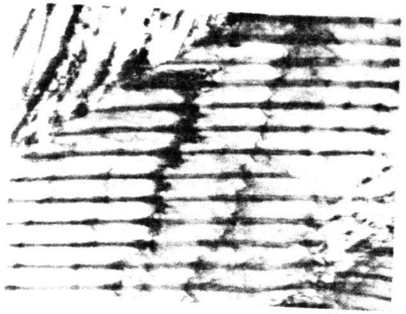
Table 2 Monotonic and Cyclic properties of Steel C

	MONOTONIC PROPERTIES				CYCLIC PROPERTIES		
	0.2% Proof Stress	Tensile Strength	True Fracture Stress	True Fracture Strain	Cyclic Yield Stress	Cyclic Strength Coefficient	Cyclic Strain Hardening Exponent
	N/mm^2	N/mm^2	N/mm^2		N/mm^2	N/mm^2	
Coarse Pearlite	375	776	945	0.28	220	1750	0.245
Fine Pearlite	780	1145	1285	0.16	275	2620	0.228
Spheroidised Carbide	392	724	1080	0.71	210	1670	0.248



x 5000

Figure 1



x 30,000

Figure 2