FATIGUE CRACK PROPAGATION IN NOTCHED STAINLESS STEEL SPECIMENS UNDER VARIABLE AMPLITUDE LOADING

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In this work a study of the fatigue crack propagation and fracture mechanisms of two types of austenitic steels 18Cr-9Ni and 18Cr-12Mn-0.7N is done. The first steel is well known stainless steel but the second is a new Ni-free high strength stainless steels that exhibit strain hardening behavior. Single notched specimens were tested and loading histories applied were constant amplitude cyclic loading and constant amplitude loading with superimposed overloads excursions. Variation of cyclic crack growth rate with ΔK are derived from measured crack lengths and number of cycles. Retardation of fatigue life is observed due to introducing of periodic overloads. Near crack tip plasticity is considered to play important role in fatigue crack retardation.

INTRODUCTION

Many structural components are subjected to variable amplitude loading and developing of new high strength structural steels is an important task. The high nitrogen steels are new promising class of engineering materials [1,2] and they are characterised by stable nanophase austenite microstructure. The defects from the induced nitrogen atoms are topic of interest from the theoretical and practical point of view. The nitrogen added to the Ni-free steels can change significantly their mechanical properties [1,2] as increasing the yield strength and impact toughness, and stabilising the austenite under plastic deformation. The high nitrogen steels are stainless, and can be used in applications as conventional stainless steels. It is known that the loading history strongly influence the crack propagation - the size of the plastic zone ahead of the crack tip, crack growth rate, number of cycles to failure, morphology of the fractured surface. Therefore, it is important to have data for fatigue behaviour and fracture mechanisms but limited number of references was found for the high nitrogen steels, they mainly deals with low cycle fatigue [3,4] and engineering applications [5]. The investigations on the variable loading retardation effects [6] are directed mainly to aluminium alloys [7,8] and some conventional steels [9,10].

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This paper is directed exclusively to the load sequence effects in conjunction to mechanical response of the materials. By applying similar loading histories to two austenitic stainless steel 18Cr-9Ni and Ni-free high nitrogen steel 18Cr-12Mn-07N their behaviour is investigated. This study aims to combine the investigation of the fatigue crack propagation with the behaviour of micro and macro defects for both steels and therefore to give a better chance for understanding the fatigue mechanisms of both steels.

EXPERIMENTAL

An experimental programme aiming to investigate the fatigue crack propagation, the fracture morphology and the fracture mechanisms under variable amplitude loading was conducted.

The materials used in this study were 18Cr-9Ni (similar to type 304 stainless steel) and the new Ni-free high nitrogen steel 18Cr-12Mn-07N. The chemical composition (wt.%) and the yield strength, σ_y, ultimate tensile strength, UTS, and reduction in area, *d*, of both steels are given in Table 1. The high nitrogen steel was annealed, and Cr-Ni steel was tested in as received condition.

Table 1. Chemical and mechanical properties of used materials

Material	C	N	Cr	Ni	Mn	Si	σ_y MPa	UTS MPa	d, %
18Cr-12Mn-07N	0.05	0.75	18.35	-	12.4	0.29	601	970	48
18Cr-9Ni	0.03	-	17.70	9.0	1.35	0.46	299	694	60

The fatigue crack growth tests were carried out on 16 mm wide and 6 mm thick single side notched specimens. The notches on the specimens were made by electric discharge method. The notch was 2 mm wide and its radius was 0.125 mm. After fatigue pre-cracking the specimens were cycled until failure under variable loading. The loading pattern was applied as blocks of constant amplitude loading following by an overload. The blocks were repeated until failure. The maximum stress was chosen as half of yield strength for the tested material. The stress range for base constant amplitude loading and the maximum overload stress (OL) were 125 MPa and 216 MPa for Cr-Ni steel and 185 MPa and 370MPa for the high nitrogen steel.

Crack growth was monitored by optical microscope with resolution of 0.02 mm and fractured surfaces were observed by JEOL 733 scanning electron microscope.

RESULTS AND DISCUSSION

Fatigue life and crack propagation

Figure 1 shows the relationship between crack growth rate and crack length *a*. With applying the overload and increasing its amplitude the fatigue life is increased for both steels. The effect of every overload is not so visible as it is in the case of an single overload [11], but retardation in fatigue crack growth took place after every OL is applied.

The fatigue crack growth can be described by the Paris law. Figure 2 shows the behaviour of the fatigue crack growth rate *da/dN* in terms of the stress intensity factor range ΔK. In general overloaded specimens showed a lover fatigue crack growth rate than these with constant amplitude loading. For the nitrogen steel the fatigue crack growth rate were nearly the same for the base line loading and OL loading, but a clear difference for Cr-Ni stainless steel is observed. The slope of *da/dN* -ΔK curves with OL matches well with the slope of base constant amplitude curves.

Fracture morphology and fracture mechanisms

The character of fracture under fatigue constant loading is transcrystalline for both investigated steels. The nitrogen steel shows a stronger macroscopic relief. Crystallographically oriented cleavage facets of a size that corresponds to the grain size are observed under angles that are proportional to 30 deg for nitrogen steel, Fig.3a.
The fractured surface of 18Cr-9Ni steel contains numerous micro-cleavage facets of micron size. The separate facets have various cystallographic orientation and forms feather-shaped terraces, Fig.3b. Their presence in the austenite has been explained by occurring of the deformation induced martensite transformation in the front of the crack tip [12]. No deformation martensite is found by X-Ray analysis on the fractured surface of the nitrogen steel.

Fatigue striations (FS) are observed on the fractured surface of the nitrogen steel from the very beginning of crack propagation. The first FS of poor contrast could be observed on the single facets in 18Cr-9Ni only when the crack length reached 1 mm. FS demonstrated some crystallographic orientation but it quickly disappeared with the crack growth. The mechanism of micro-cleavage is substituted by FS mechanism of fracture and a common front of crack propagation through the several grains is formed at the higher ΔK levels.

Scanning Electron Microscopy (SEM) observations shows that the influenced zone by single overload (OL) cycle is of very small size. The crack propagation mechanism changes only during the OL cycle and did not affect the morphology of the ligament.

The transcrystalline fracture mode in the OL affected zone differs from the transcrystalline fracture in the constant amplitude loading zone. There the plastic mechanism is realised by micro-voids initiation and coalescence. The deformation lines parallel to the crack propagation front as well as dimples of various sizes are observed on the leading wall of the OLZ at higher ΔK values, Fig. 4a. The features of plastic fracture are less expressed in the nitrogen steel, Fig. 4b. The successive OL affected zones have the macroscopic appearance of coaxial arc curves opened to the notch side, Fig. 5 The relief of arcs near to the notch are relatively flat but it became rougher with increasing the distance from the notch. The arcs relief, curvature radius, width and distance between the arches increase with increasing of ΔK. In the nitrogen steel the arc lines are usually broken and crystalografically orientated. A specific peculiarity of the nitrogen steel is the formation of secondary cracks in the OL influenced zone, Fig. 6. The crack branching process is more intensive at higher ΔK values.

The morphological features of the fractured surfaces indicates that the crack propagation retardation caused by OL is controlled by different mechanisms in both steels. The presence of high deformed plastic zone in front of the crack tip in 18Cr-9Ni steel leads to crack tip blunting. The deformation induced martensite transformation in the plastic zone ahead of the crack tip contributes to this effect too. In the nitrogen steel the process of crack tip blunting is less expressed but crack branching retardation mechanism is activated.

CONCLUSIONS

1. The load interaction under of constant amplitude loading and the OL produces retardation in fatigue crack growth rate. For the applied loading pattern, the retardation of high nitrogen steel is lower compared to Cr-Ni steel.

2. The overload affected zones in the high nitrogen steel is developed at higher ΔK values. They have smaller height and contain smaller number of plastic elements due to the higher strength and the lower plasticity of the high nitrogen steel compared to 18Cr-9Ni steel.

3. The activation of crack tip blunting mechanism in both steels is observed when the overload is applied. This mechanism of retardation is more effective for Cr-Ni steel.

4. The mechanism of crack retardation by crack branching is dominant for the nitrogen steel due to the dislocation structure behaviour.

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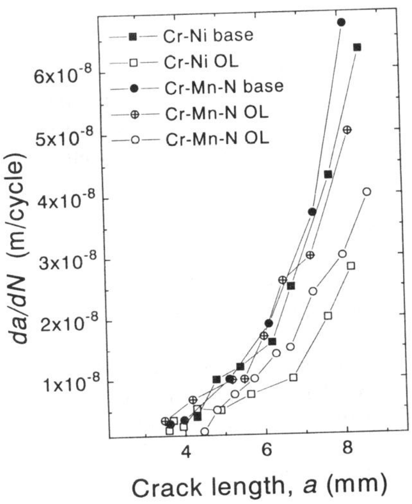


Fig. 1 Comparison of fatigue crack growth rate *da/dN* with crack length *a*

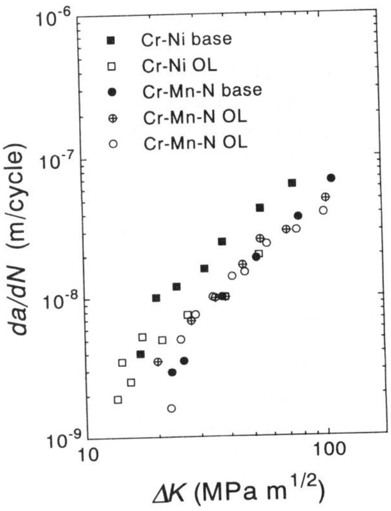
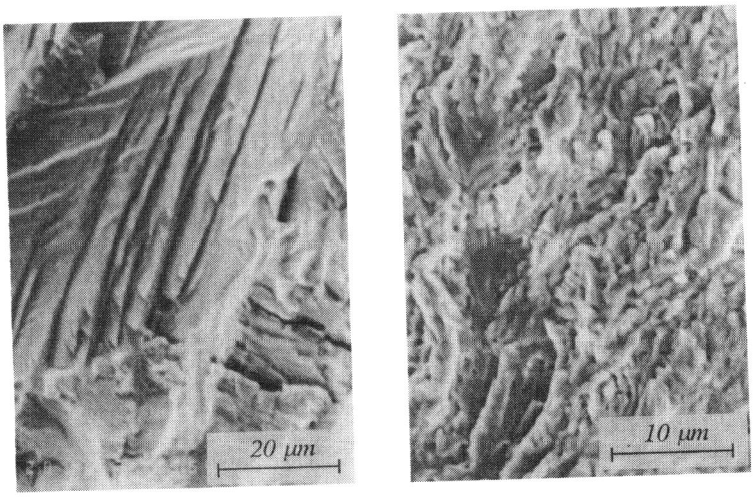
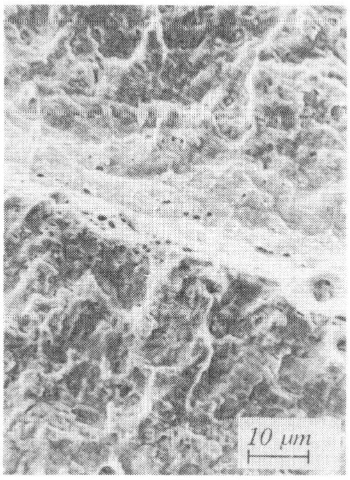


Fig. 2 Comparison of fatigue crack growth rate *da/dN* with ΔK



a/ 18Cr-9Ni steel b/ 18Cr-12Mn-07N steel

Fig. 3 Morphology of the fracture surface under fatigue constant amplitude loading



a/ 18Cr-9Ni steel

b/ 18Cr-12Mn-07N steel

Fig. 4 Overload affected zone

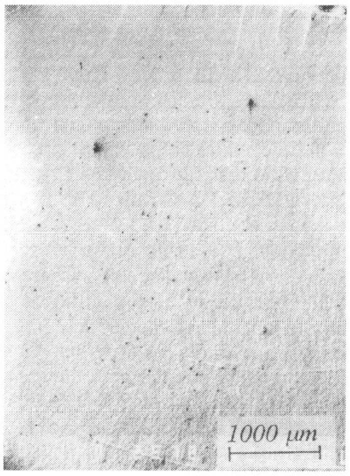


Fig. 5 Coaxial arc curves in the overload affected zone, 18Cr-9Ni steel

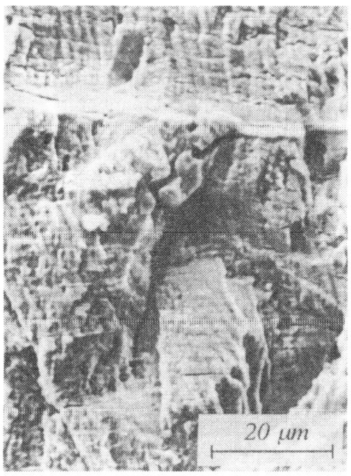


Fig. 6 Crack branching during the overload application for Cr18Mn12N07 steel