Ratcheting Fatigue Behaviour of Modified 9Cr-1Mo Steel and Superalloy Inconel 617

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By

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Chapter 7

Major Conclusions and Scope for Future Work

7.1 Introduction

This chapter summarises the major findings of the present investigation and gives brief incitement of scope for future research work that can be carried out.

7.2 Major Conclusions

Systematic investigation on ratcheting fatigue behaviour of modified 9Cr-1Mo steel and Inconel 617 alloy under various parameters (mean stress, stress amplitude and stress rate) was conducted at room temperature. The effect of service temperature on the ratcheting fatigue behaviour under mean stress effect of the alloys was also studied and a comparison has been made with room temperature ratcheting fatigue behaviour for the individual alloys. A comparative study of the ratcheting fatigue behaviour of both the alloys at the same homologous temperature was also performed. The effect of pre-ratcheting on tensile properties of modified 9Cr-1Mo steel and Inconel 617 alloy under various parameters (mean stress, stress amplitude and stress rate) was also studied at room temperature.

The major findings are summarised below:

7.2.1 Ratcheting fatigue behaviour of modified9Cr-1Mo steel at RT

1. There was accumulation of plastic strain under asymmetric cyclic loading. The accumulated plastic strain was tensile in nature and increased with increase in mean stress and stress amplitudeand consequently, fatigue life was reduced, whereas the accumulation of plastic strain was reduced with increase in stress rate and fatigue life was increased.
2. With increase in the mean stress from 190 to 210 MPa and stress amplitude from 400 to 420 MPa, the width of hysteresis loops increased and plastic strain energy

also increased due to higher plastic deformation of the material. On the other hand, with increase in number of cycles the material exhibited cyclic hardening, for a particular value of a parameter.

3. With increase in stress rate, the plastic strain energy as well as hysteresis loop width decreased, due to higher cyclic work hardening of the material. This resulted from combined effects of higher density of dislocations produced at higher stress rate and less effective annihilation of dislocations, during the tensile and compressive load cycles. Thus, the overall density of dislocations was higher at higher stress rate, due to which the work hardening increased with increase in stress rate. The extent of hardening increased with number of cycles at all the three stress rates of 50, 150 and 450 MPa/s. The decrease in the ratcheting strain in consecutive cycles was due to the increase in rate of hardening.

4. Under symmetrical loading, there was characteristic fatigue fracture with typical striations on the fracture surface resulting from crack propagation from surface to interior, finally leading to overload ductile failure with dimples. However, under asymmetrical loading, there was increase in gauge length and appreciable necking before fracture. There were striations on the surface of tapered necked region resulting from cyclic plastic flow on the tapered surface and the transverse fracture surface was similar to that resulting from tensile loading of ductile material exhibiting characteristic dimples.

5. The observation and understanding of the unique fracture behaviour with striations like features on the smooth circumferential surface in necked region, and ductile tensile cup and cone features with equiaxed dimples on the fracture surface, are interesting aspects of this investigation.

6. There was considerable variation in the deformed microstructures, resulting from different variables such as mean stress, stress amplitude and stress rate. While the laths of martensite were seen in the specimens tested at stress amplitude of 400 MPa, equiaxed structure resulted at stress amplitude of 420 MPa. There was incomplete recovery at mean stress of 190 MPa and formation of recovered substructure at mean stress of 210 MPa. While there was recovered substructure at stress rate of 50 MPa/s, dislocation cells along with forest dislocations were seen at stress rate of 450 MPa/s.

7.2.2 Ratcheting fatigue behaviour of Inconel 617 alloy at RT

1. The permanent strain and its rate increase with mean stress and stress amplitude whereas both of these decrease with increase in stress rate.
2. With rise in stress amplitude, cyclic life decreases. At lower stress amplitude, there is formation of bands and pinning of dislocations by carbide particles, whereas at higher stress amplitude, there is formation of more slip bands at regular intervals.
3. Plastic strain accumulation increases with mean stress and fatigue life is reduced and dislocation density is increased with mean stress.
4. Accumulation of permanent strain is reduced with increase in stress rate and fatigue life is increased under asymmetric cyclic loading.
5. On comparing the ratcheting behaviour of the alloys at ambient temperature, Inconel 617 alloy showed higher fatigue life in comparison with that of the modified 9Cr-1Mo steel. The reason behind this is higher uniform elongation value (54%) for Inconel 617 alloy. Thus, uniform strain can be considered as an important tensile parameter for selection of materials for piping and tubing components, experiencing ratcheting fatigue.

7.2.3 Ratcheting fatigue behaviour of modified 9Cr-1Mo steel and Inconel 617 alloy at elevated temperatures

1. On comparing the ratcheting behaviour of the alloys at RT with respect to their service temperatures, it was observed that ratcheting strain decreased with increase in temperature thus there was enhancement in fatigue life of the alloy with increase in temperature.
2. The reason behind enhancement in fatigue life with increase in temperature may be attributed to the combined effect of DSA and lower modulus of elasticity in case of modified 9Cr-1Mo steel, whereas in case of Inconel 617 alloy it is due to the formation of precipitates as well as lower modulus of elasticity which imparts strengthening in comparison to RT
3. On comparing the alloys at 0.42 T_m, modified 9Cr-1Mo steel exhibited more significant and stable result with higher fatigue life in comparison with the Inconel 617 alloy.
4. Inconel 617 alloy showed very high stain accumulation of approximately 65% in comparison to modified 9Cr-1Mo steel and the difference in fatigue life was also of about 600 cycles; thus it can be attributed that under the same parameters though cyclic life is less for Inconel 617 alloy but it can sustain very high strain values.
5. Inconel 617 alloy showed abrupt increase in plastic strain accumulation at 0.42 T_m. The reason behind this may be due to dynamic strain aging of the alloy resulting from unpinning effect. Plastic strain accumulation resulting from pinning of dislocations causes hardening but release of dislocations resulting from unpinning of dislocations causes softening. Strain is localized.
6. Modified 9Cr-1Mo at 0.42 T_m under the same parameters exhibited very stable

behaviour and higher cyclic life as compared to Inconel 617alloy. The capability to withstand such high strain values in case of Inconel 617 alloy is very high as compared to Modified 9Cr-1Mo steel. Thus it can be concluded that uniform strain plays a very important role at room as well as at elevated temperature for ratcheting fatigue.

7. In ratcheting fatigue, with tensile mean stress, there is progressive increment in the overall length of the specimen; thus, it is obvious that plastic strain in the specimen does not remain localized in the region of slip bands, like that in fatigue under symmetrical loading. Thus, consideration of uniform plastic strain in analysing ratcheting fatigue is quite relevant and important and tensile ductility of material can be considered an important parameter for LCF resistance.
8. The result has been correlated with microstructural features, in case of modified 9Cr-1Mo steel dislocation pile ups and precipitates were observed on the boundaries whereas in case of Inconel 617 alloy intersection of slip bands with dislocation tangles were observed.
9. At elevated temperatures the fractographic features were similar for both the alloys as observed at room temperature. Modified 9 Cr-1Mo steel exhibited cup and cone type of fracture with striations like features and dimples whereas Inconel 617 alloy showed fatigue type of flat fracture with striations at regular intervals finally leading to overload failure exhibiting dimples.

7.2.4 Effect of pre-ratcheting on tensile properties of modified 9Cr-1Mo steel and Inconel 617 alloy at RT

1. The accumulated ratcheting strain increased with increase in the mean stress and stress amplitude and decreased with increase in the stress rate for the two alloys.

2. Tensile data of the pre-ratcheted specimens showed increase in the strength parameters and decrease in the ductility parameters for modified 9Cr-1Mo steel and Inconel 617 alloy.
3. For, modified 9Cr-1Mo steel, the values of strength parameters for the ratcheted specimens were higher than those of the un-ratcheted one. The increase in the yield strength was about 21% and in the ultimate tensile strength was about 13%, with respect to the un-ratcheted sample. On the other hand, the ductility of the ratcheted specimen decreased 12% with respect to that of un-ratcheted specimen.
4. Similarly for Inconel 617 alloy, the values of strength parameters increased in comparison to un-ratcheted one. There was tremendous increase in yield strength of the alloy of about 200% and the ultimate tensile strength increased upto 28%. There was decrease in ductility of about 69% as compared to un-ratcheted specimen.
5. Fractographs of the ratcheted specimens of modified 9Cr-1Mo steel showed both dimples and striations like features whereas the fracture surface of the un-ratcheted specimen exhibited rosette fracture. In case of Inconel 617 alloy, both the ratcheted and un-ratcheted specimen exhibited purely tensile fracture showing dimples.
6. The reason for the difference in fracture surfaces of the 9Cr-1Mo steel and Inconel 617 alloy is due to difference in their crystal structure, the types of second phase particles and their distribution.
7. For the modified 9Cr-1Mo steel, the TEM analysis revealed that with increase in the mean stress, there was an increase in dislocation density, the particles pinned the boundaries and imparted strength to material. In the case of rise in stress amplitude, solute atmospheres surrounded the dislocations and interaction between

them enhanced the strength. On the other hand, increase in stress rate resulted in shearing of the precipitates due to which there was less effective cyclic hardening of the material and the strength was decreased.

8. Deformation behaviour revealed formation of slip bands for un-ratcheted specimen whereas twinning was observed for ratcheted specimen. There was increase in dislocation concentration for ratcheted specimen.

7.3 Scope for Future Work

Following studies can be suggested for future work

1. Study and comparison of ratcheting fatigue behaviour of both the alloys in the region of dynamic strain aging.
2. Experimental investigation and microstructural correlation of ratcheting response of advance high strength steel (AHSS) and advance materials, where more than one deformation mechanisms are active.
3. Establish relationships between microstructure evolution and of component level ratcheting response.
4. Observation of HCF-ratcheting, ratcheting-HCF and LCF-ratcheting interaction.
5. Quantitative analysis of microstructural evolution during ratcheting and its use as an input to develop model.