CHAPTER -8

Major Conclusions and Scope of Future Work

8.1 Introduction

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

8.2 Major Conclusions

Systematic investigation was carried out on tensile behaviour of the superalloy Inconel 617, at different temperatures ranging from RT to 900^{o}C and on work hardening behaviour in different heat treated conditions, at RT and 700^{o}C. The effect of temperature on LCF behaviour was studied at RT, 750^{o}C and 850^{o}C. The effect of oxidation and hot corrosion on LCF behaviour was studied at 850^{o}C. Role of TBC on LCF behaviour was examined at 850^{o}C. The major findings are listed below:

8.2.1 Tensile Behaviour

i. Tensile Behaviour of Inconel 617 alloy in solution annealed condition

1. Though it was reported earlier that dynamic strain aging occurs in this alloy but the regime is not defined. Dynamic strain aging was observed to occur in Inconel 617 alloy in the temperature range from 300^{o}C to 700^{o}C; at the strain rates of 5x10^{-4} s^{-1}, 5x10^{-3} s^{-1} and 1x10^{-2} s^{-1}. The attendant serrations in the stress-strain curve are of the B, (A+B) and C type, in agreement with the earlier report.
2. Critical plastic strain for the onset of serrations decreased with increase in temperature and reached a steady state at high temperatures, this fact was established in this study. Plateau in the YS, peaks in the flow stress, ductility minima and negative strain rate sensitivity are the various manifestations of DSA phenomenon exhibited by the Inconel 617 alloy which were checked to

confirm the DSA regime. UTS decreased with increase in temperature for all the three strain rates mentioned.

3. Ludwigson equation is found to be the best relationship to describe the flow behaviour of this alloy. Strength coefficient(K) and strain hardening exponent (n) values decreased with increase in temperature which is in good agreement with the previous observations. Peaks were observed in the variation of rate of work hardening with temperature, it is established in the present investigation.
4. The average activation energies for the serrated flow are calculated as 65 kJ/mol, 80 kJ/mol and 101 kJ/mol for the three types of serrations; type B, type (A+B), and type C respectively. The controlling mechanism of DSA is suggested to be diffusion of carbon through dislocation cores in the lower temperature range and those of substitutional elements Cr and Mo in the higher temperature range, based on the above activation energy values. These results are in line with the earlier reported research.
5. Through TEM study in the present investigation, new facts of increase in the number of slip bands with increase in temperature and a decrease in dislocation density with increase in temperature are established. Interaction of dislocations with solute atmospheres increased with increase in temperature in the DSA region. Precipitation of $M_{23}C_6$ and γ' particles was observed at 700^{o}C, whereas only carbides were present at 800^{o}C which redefined the previous research work related to temperature ranges for the formation of above precipitates at 750 and 850^{o}C, respectively.
6. SEM examination of fracture surfaces showed transgranular mode with dimples at room temperature. In the range of 400-600^{o}C, there was

completely ductile fracture. At 700°C, there was mixed mode of fracture with dimples, facets and intergranular cracks. The facets and intergranular cracks could be the cause of ductility minima at this temperature, this interesting observation was made in the present investigation. Evidence for the void nucleation at the hard second phase particles is established in this study through presence of carbide particles at the bottom of the voids.

ii. Work Hardening Behaviour of Inconel 617 alloy

1. A new fact was established that there was best combination of strength and ductility in the SQ condition, with coarse grained microstructure both at RT as well as 700°C. Marginal reduction in ductility was observed in this condition at 700°C due to precipitation of carbides. The YS and UTS were increased and ductility was reduced at RT, due to the aging treatments (SQ-AG1 and SQ-AG2). However, there was not any appreciable difference in the strength and ductility with increase in the duration of aging.
2. There was marked improvement in the YS of the cold worked material, both at RT and 700°C, in respect of the SQ, SQ-AG1and SQ-AG2 conditions, but the ductility parameters, in particular the uniform elongation was drastically reduced. Uniform elongation is an important parameter for mechanical processing and design of structural components. It will be useful to study the effect of varying degree of cold working and aging at elevated temperatures to achieve a better combination of strength and ductility both at RT and 700°C. This is one of the interesting observations in the present investigation.
3. Among the five relationships proposed for the characterization of work hardening parameters of metallic materials, the one proposed by Ludwigson was found to fit, the best with the experimental data, in agreement with

previous research.

4. A new finding of this study is that while there were three stages in variation of θ with stress (σ) both at RT and 700°C in the three conditions (SQ, SQ-AG1 and SQ-AG2), there was only stage I in the SQ-CW condition at RT and 700°C. Further, the rate of fall in θ in the cold worked condition is much higher than that in the other three conditions, which is an interesting observation for this alloy.
5. Slip was observed as dominant process of plastic deformation at RT whereas both slip and twinning were operative at 700°C. Twinning in this alloy is being reported for the first time. The interaction of dislocations with carbides and γ' precipitates, leads to high work hardening at 700°C is clearly established in this investigation through transmission electron microscopy.
6. Fracture surfaces resulting from tensile testing at RT and 700°C, revealed dimples of varying sizes in the different conditions. Though fracture surfaces of the CW alloy were analysed previously, the interesting fact observed is that there were facets on fracture surface of the cold worked material, tested both at RT as well as 700°C, resulting from cracking/de-cohesion of carbides at grain boundaries, due to 40% cold reduction; therefore, there was no improvement in ductility at 700°C.

8.2.2 Low Cycle Fatigue Behaviour

i. Low Cycle Fatigue Behaviour of Inconel 617 alloy

1. Inconel 617 alloy showed initial cyclic hardening at room temperature, before saturation at lower strain amplitudes, due to pile ups of planar array of dislocations within the slip bands and their interaction with each other and

with stacking faults. This cyclic hardening is in agreement with the previous research work. At strain amplitude of ± 0.5%, the alloy showed cyclic softening caused due to cross slip and formation of cell structure, following very high rate of initial hardening. This is a new observation made in the present investigation.

2. At 750^{o}C, the alloy showed continuous cyclic hardening and the rate of hardening was high at 750^{o}C for all the strain amplitudes compared to that at room temperature and 850^{o}C, this result is in line with literature. A new observation is that of two slope behaviour of cyclic hardening due to precipitation of fine γ' and carbide particles after certain number of cycles.
3. The plastic strain amplitude increased with increase in temperature at all the strain amplitudes studied. The cyclic stress strain curves, developed from hysteresis loops at half-life, were above the monotonic stress strain curve at three temperatures, depicting cyclic hardening of the material. This comparison was made for the first time in this alloy.
4. Non-Masing behaviour was observed for the alloy at RT, 750^{o}C and 850^{o}C, which is the new observation in this alloy.
5. Fatigue life decreased with increase in temperature and strain amplitude. Coffin Manson relationship was followed at all the three temperatures studied.
6. Continuous decrease in dislocation density was observed with increase in temperature and strain amplitude. Fine carbide and γ' precipitates were formed at 750^{o}C, hardening was increased and fatigue life was decreased. γ' particles were not observed at 850^{o}C.

7. Inter striation spacing increased with increase in temperature and strain amplitude. Number of secondary cracks increased with increase in temperature. This is a new observation made in the present investigation.

ii. LCF Behaviour of Salt coated and Pre-exposed Inconel 617 alloy

1. There was no evidence of earlier research on the fatigue study of salt coated samples in the present alloy though there is evidence of formation of Cr and Al oxide layers from oxidation of IN617 alloy. Duration of pre-exposure for oxidation up to 1000 hours did not have significant effect on fatigue life of the Inconel 617 alloy. Stress amplitude decreased with increase in the duration of oxidation due to increase in the depth of porous layer resulting from oxidation. Strong surface oxide layer of Cr_2O_3 and inner oxide layer of Al_2O_3 were formed in the same vicinity of Cr depletion region.
2. Fatigue life of the salt coated and pre-exposed samples was reduced drastically with increase in the duration of pre-exposure up to 500h. Though this observation was made in other super alloys but was reported for the first time in IN617 alloy in the present investigation. Stress amplitude was reduced with increase in the duration of pre-exposure due to increase in the thickness of the hot corroded layer and consequent reduction in cross sectional area of the specimen.
3. Fatigue crack initiation occurred from the surface for the oxidised samples, whereas it was from the subsurface for the salt coated and pre-exposed samples. Crack propagation was intergranular and progressively transformed to transgranular. This is a new observation in this investigation.
4. Deformation behaviour was similar for the both oxidized as well as salt coated and pre-exposed samples, except the evidence of increase in the

number of precipitates with increase in the duration of pre-exposure. An interesting observation is precipitation of second phase particles during deformation, though the size of these precipitates were smaller than those formed during the pre-exposure.

5. Ingression of sulphur into base metal caused the formation of chromium sulphide (CrS) which reduced the fatigue life drastically, a new fact established in the present study. Crack propagation occurred along the intergranular corroded layer and the depth of this layer increased with increase in the duration of oxidation.

iii. LCF Behaviour of Thermal Barrier Coated Inconel 617 alloy

Fatigue testing of TBC coated samples of IN617 alloy is carried out, as a novel approach to examine the effect of TBC on fatigue behaviour, hence no comparison could be made. The new observations made from this study are listed below.

1. At low strain amplitude, fatigue life of the Inconel 617 alloy with TBC was increased whereas at high strain amplitude, there was no improvement in fatigue life compared to those of samples without TBC at respective strain amplitudes.
2. Precipitation of carbides occurred in the TBC samples, though they are fine and much less in number in comparison with the samples without TBC. This is an interesting observation made in this study but needs further investigations to establish the reasons.
3. Cracks were initiated from the substrate of the sample tested at the low strain amplitude and the coating was found adherent to the base metal.

4. At high strain amplitude, delamination of the TBC coating, initiation and propagation of cracks in TBC occurred and led to early fracture; hence, slight reduction in fatigue life was observed. This is in line with the reported fact for other superalloys.

8.3 Scope of Future Work

Following studies are suggested for future work.

- Effect of varying degree of cold working and aging at elevated temperatures to achieve a better combination of strength and ductility in Inconel 617 alloy, both at RT as well as at 700^{o}C.
- Effect of temperature and salt composition on low cycle fatigue behaviour of Inconel 617 alloy.
- Effect of salt environment on low cycle fatigue behaviour of TBC coated samples of Inconel 617 alloy as well as other superalloys like IN 625 etc.
- Effect of pre-exposure duration of TBC samples, on low cycle fatigue behaviour of Inconel 617 alloy.