ABSTRACT

This thesis deals with tensile and creep deformation behaviour of type 316 stainless steel subjected to thermal and mechanical treatments. Austenitic stainless steels are the universal choice for structural as well as core components in most of the prototype or commercial fast breeder reactors (FBR). Core materials in these reactors are subject to hostile environment involving high temperature sodium and high flux of energetic neutrons which leads to drastic changes in mechanical and physical properties of these materials.

Type 316 stainless steel and its modifications are employed in cold worked condition for in-core components with a view to improving resistance to radiation damage. Structural components are also subjected to different amounts of cold work due to forming operations. Further exposure to elevated temperatures would lead to precipitation of carbides and intermetallic phases that would have an influence on their performance. It is therefore important to study the influence of prior cold work and thermal ageing with a view to understanding the deformation and damage processes and developing a base line information against which deterioration in properties during service due to radiation and high temperature sodium could be assessed.

In this study, tensile flow behaviour of as-received, cold worked and aged type 316 stainless steels have been carried out. Special emphasis has been placed on the phenomenon of serrated yielding and it is shown that both prior cold work and thermal ageing have significant influence on serrated yielding. Influence of prior cold work on creep behaviour of type 316 LN stainless steel is also included in this investigation. In creep studies two modes of cold working, namely, tensile and swaging were employed to assess whether mode of cold working influences creep behaviour.

Dynamic Strain Ageing in Type 316 Stainless Steels.

Serrated flow behaviour of as-received and aged type 316 stainless steel and as-received, prior cold worked and prior cold worked and aged type 316 LN stainless steel has been studied in the temperature range 300-1023 K in the nominal strain rate range $3 \times 10^{-5} - 3 \times 10^{-3}$ s$^{-1}$. The type of serrations changed with temperature strain rate and microstructural conditions.

From the temperature dependence of critical strain for onset of serrations of as-received type 316 stainless steel, two distinct temperature ranges have been identified; one between 523-623 K and the other between 673-923 K with different activation energies suggesting that the serrated yielding phenomenon in type 316 stainless steel is due to more than one mechanism. In the high temperature region the
activation energy is close to the activation energy for self diffusion of chromium in austenite and is attributed to the diffusion of substitutional atoms to dislocations. In low temperature region the activation energy value obtained is close to the self diffusion of carbon or nitrogen and tends to support the contention that the interaction of interstitial atoms with dislocations is responsible for dynamic strain ageing.

In type 316 LN stainless steel only one activation energy in the temperature range 673-973 K was evaluated and is found to be independent of strain rate. This is in agreement with the value for diffusion of substitutional solute atoms to dislocations. Ageing for certain time-temperature combinations is found to eliminate serrated flow at 923 K which otherwise would have been present in unaged material. Though prior cold work (PCW) suppresses the serrated yielding at 923 K in type 316 LN stainless steel, ageing reintroduces serrated yielding under certain ageing conditions.

From the strain rate jump tests, negative strain rate sensitivity is always found to be associated with serrated flow. The observation of serrated flow at a particular strain rate could be correlated with the strain rate temperature plot for the occurrence/disappearance of serrated flow. The absence of serrated flow in aged material at 923 K is explained in terms of the model due to Hayes and Hayes.

Temperature Dependence of Strength and Ductility

It is observed that PCW increases both yield strength and ultimate tensile strength at all temperatures, the increase in yield strength being more pronounced when compared to the increase in ultimate tensile strength. The increase in yield strength depends on the temperature, being greater at lower temperature. For both modes of prior deformation and different levels of PCW, variation of strength with temperature shows a plateau or peak at intermediate temperatures followed by rapid fall at higher temperatures. Ductility is found to decrease with increase in PCW. The reduction in ductility of the cold worked material is more pronounced for the swaged material than the material cold worked by tension especially for the level of 10% PCW. At higher levels of PCW both tensile and swaging mode of prior deformation led to more or less similar values of ductility. The post necking elongation is more or less constant in the temperature range 300-823 K and then increases with increase in temperature. At a given temperature it was nearly independent of PCW.

The contribution towards strength as a result of substructural changes due to PCW was considered in terms of a parameter $S_{YS}$ (Yield strength ratio of PCW material to that of as-received material at a given temperature) and $S_{UTS}$ (Tensile strength ratio). The parameter $S_{YS}$ is found to be always greater than 1 and is found to increase with temperature up to 823 K and then decreases whereas $S_{UTS}$ is more or less independent of temperature. The observed variation indicates additional strengthening with increase in temperature. This strengthening could arise due to precipitation process at elevated
temperature or through locking of dislocations by solute-dislocation interaction. The decrease of $S_{YS}$ above 823 K probably results from substructural recovery.

**Influence of Temperature and PCW on the Strain Hardening Parameters**

The stress strain behaviour of type 316 LN stainless steel was found to obey Ludwigson relation. The strain hardening exponent showed a hump in its variation with temperature in the dynamic strain ageing temperature range but in general decreased with increase in temperature and prior cold work. The strain hardening exponent was also found to decrease with increase in strength at all temperatures but showed a temperature insensitive region in the dynamic strain ageing temperature range. It can be shown that the strain hardening exponent $n = \frac{\varepsilon}{\sigma} \left( \frac{d\sigma}{d\varepsilon} \right)$ where $d\sigma/d\varepsilon$ is the work hardening rate or the slope of the stress strain curve at $(\varepsilon, \sigma)$. The dependence of $n$ on PCW and temperature has been attributed to the dependence of strength and work hardening on these parameters.

**A Substructure Characterising Parameter in Tension**

Yield strength, $\sigma_{YS}$, represents the strength of the initial obstacle structure opposing dislocation motion and the flow strength, $\sigma$, which can be considered as the sum of the yield strength and contributions from work hardening due to dislocation-dislocation interaction and from other strengthening sources like dislocation-precipitate interaction or dynamic strain ageing (DSA) due to dislocation-solute interaction. is the yield strength of the material at a given strain. The ratio of flow strength to yield strength, $(\sigma/\sigma_{YS})$, varies with temperature and strain *inter alia* the substructure developed at that plastic strain and the ratio can be appropriately described as an instantaneous substructure characterising parameter. The variation of this substructure characterising parameter with temperature shows a peak in the DSA temperature range.

The work hardening rate $d\sigma/d\varepsilon$ can be related to the product of the ratio of flow strength to plastic strain $(\sigma/\varepsilon)$ and the substructure characterising parameter. The strain hardening exponent $n$ is also a function of the substructure characterising parameter. A quantitative correlation has been established between the yield strength and ductility ratio of prior cold worked material to as-received material. This correlation would have practical consequences for damage monitoring and remanent life estimation of real structures from short term tensile tests.

**Creep Behaviour of As-received and PCW Material at 873 and 948 K**

While as-received material exhibited well defined primary, secondary and tertiary creep behaviours, the extent of primary creep was reduced or absent in PCW material. PCW material exhibited lower minimum creep rate, $\varepsilon_{\min}$, and larger rupture life, $t_r$, compared to the as received material. Between the two modes of deformation.
there was little difference in the rupture lives for a given applied stress level. A power
law of the type $\epsilon_{mn} = A \sigma^n$ is obeyed at these temperatures at all material conditions
with the exponent 8.5 at 948 K and 12 at 873 K.

Rupture ductility, $\epsilon_r$, measured as the percentage elongation at rupture was
almost same for as-received and 10% PCW by tensile deformation and showed a peak
in its variation with applied stress or rupture life. At and above 20% PCW, the mode
of PCW does not influence the rupture ductility which increased with applied stress.
The creep data can be described by the $\beta$-envelope method, each stage being given by
a power law of time. The minimum creep rate and the rupture time can be related
through the creep strains at the onset of tertiary stage, $\epsilon_{23}$ and at rupture, $\epsilon_r$ by

$$\epsilon_{mn} t_r = (\epsilon_{23}^2 \epsilon_r)^{1/3}$$

**Substructure Characterising Parameter in Creep**

A substructure characterising parameter which is the ratio of applied stress, $\sigma_a$, in creep test to yield stress, $\sigma_{ys}$, of the material at the test temperature is
introduced. A correlation is found to exist between this parameter and the creep rate
for data obtained in the temperature range 820-975 K when the initial yield strength
is modified by (i) introducing different amounts of prior cold work by two modes of
deformation at room temperature in a type 316 and 316 LN stainless steel and (ii) grain
size, grain size and chemistry variation in a type 316 stainless steel. The correlation
was found to exist also for a Cr-Mo-V steel at 823 K, in which different yield strengths
were due to different heat treatments. Minimum creep rate when plotted against the
substructure characterising parameter yields an exponent similar to Norton's creep
exponent and it is postulated that the value of the exponent reflects the type of
substructure developed in creep. Another parameter $\sigma_a F_{ys}$, where $F_{ys}$ is a function
of the ratio of the yield strength of a given microstructure to that of a reference
microstructure (zero cold work for cold worked material, largest grain size when the
microstructure variation is through grain size and solution annealed microstructure
among heat treatments) also gives a unique correlation with the minimum creep rate
at a test temperature with the exponent identical to Norton's creep exponent.