ABSTRACT

This thesis presents the results on tensile, creep and low cycle fatigue (LCF) behaviour of thick section tube plate of 9Cr-1Mo ferritic steel forging in quenched and tempered (Q+T), simulated post weld heat treatment (SPWHT) and thermally aged conditions. The influence of strain rate ($6.31 \times 10^{-3} - 3.2 \times 10^{-5} \text{ s}^{-1}$) and temperature (300-873 K) on tensile behaviour was investigated. The results indicated that the yield (YS) and ultimate tensile strengths (UTS) decreased with increasing temperature gradually up to an intermediate temperature, followed by a rapid decrease at high temperatures. At intermediate temperatures, the alloy exhibited serrated flow, negative strain rate sensitivity and ductility minima. In the serrated flow regime, types A, B and C serrations were observed. The apparent activation energy of 83 kJ mol$^{-1}$ obtained for types A and A+B serrations suggests that the diffusion of interstitial solutes such as carbon is responsible for dynamic strain ageing in this alloy. The tensile stress-strain behaviour was described adequately by Ludwigson equation at room and intermediate temperatures, whereas at high temperatures, Hollomon equation was obeyed. Further, the anomalies in the variations of flow parameters with temperature and strain rate observed at intermediate temperatures have been attributed to dynamic strain ageing.

Prior thermal ageing of 10-5000 h at 793 and 873 K did not exhibit any significant influence on YS and UTS at room temperature. At intermediate temperatures, specimens aged for longer durations exhibited a significant reduction in YS and UTS values. The decrease in strength values is attributed to low propensity to DSA. The fracture mode remained transgranular at all test conditions. The strength values of tube plate forging in SPWHT condition were consistently lower than that of thin section in the normalised and tempered condition and in the heat treatment conditions intended to simulate thick sections.

Creep-rupture properties of 9Cr-1Mo steel in Q+T, SPWHT and thermally aged conditions remained similar at 793 K, whereas at 873 K, SPWHT specimens exhibited lower creep-rupture strength compared to that of Q+T specimens. Further, the creep-rupture strength of thick section forging was found to be inferior compared to that of thin section bar and tube materials. The alloy retained its high creep ductility and the failure mode remained transgranular in all test conditions. The stress dependence of
steady state creep rate \( (\dot{\varepsilon}_s) \) obeyed power law and exhibited two slope behaviour with stress exponents of \( \sim 5-6 \) at low stresses and 10.2 at high stresses in the range 773-873 K. The two slope behaviour was also reflected in two apparent activation energy values of 266 and 468 kJ mol\(^{-1}\) in the low and high stress regimes, respectively. Incorporation of resisting stress in the low and high stress regimes in the Dorn type equation yielded an universal stress exponent of about 4 and a true activation energy of about 250 kJ mol\(^{-1}\). These observations suggest that the creep deformation in 9Cr-1Mo steel is climb controlled in both the stress regimes.

The two stress regimes are also reflected in the two slopes in stress dependence of rupture life \( (t_r) \), two different constants in Monkman-Grant (MGR) and modified Monkman-Grant (MMGR) relationships and two creep damage tolerance factors of 5 at high stresses and 10 at low stresses. Analysis of transient and tertiary creep following Garofalo strain-time relationship and first order kinetics was carried out to examine the above two stress regimes. The above analysis indicated two \( \beta \) and \( \beta' \) in the two stress regimes; where \( \beta \) is the ratio of initial creep rate \( (\dot{\varepsilon}_i) \) to \( \dot{\varepsilon}_r \) and \( \beta' \) is the ratio of final creep rate \( (\dot{\varepsilon}_f) \) to \( \dot{\varepsilon}_r \). The stress dependence of the rate of exhaustion of transient creep \( (r) \) also indicated two regimes. Two different \( K' \) relating the rate of acceleration of tertiary creep \( (p) \) to \( \dot{\varepsilon}_s \) were observed in the two stress regimes. Separate master creep curves relating transient creep and steady state creep were obtained for respective stress regimes. Similarly, two master creep curves relating tertiary creep and steady state creep were also obtained for low and high stress regimes. Analogous to MGR and MMGR, the creep data were found to obey two recently proposed relationships involving transient creep \( (\dot{\varepsilon}_s, t_{oa} / \varepsilon_T = \text{constant} = C_{PC}) \), where \( t_{oa} \) is the time to onset of steady state creep and \( \varepsilon_T \) is the limiting transient creep strain) and tertiary creep \( (\dot{\varepsilon}_s, t_i / \varepsilon_i = \text{constant} = C_{TC}) \), where \( t_i \) is the time spent in tertiary creep and \( \varepsilon_i \) is the limiting tertiary creep strain) parameters. The values of \( \alpha \) and \( \alpha' \) were equal to unity. Two distinct values of \( C_{PC} \) and \( C_{TC} \) were also observed in the two stress regimes.

The fatigue life decreased with increasing strain amplitude and temperature. The effect of temperature was more pronounced at low strain amplitudes. The reduction in fatigue life was not governed by creep damage mechanisms but resulted from the combined effects associated with increased inelastic strain and oxidation. The elastic and plastic strain amplitudes and number of reversals to failure obeyed Basquin and Coffin-Manson relationships, respectively. The alloy generally exhibited cyclic softening
in all test conditions. Half-life cyclic stress-strain data obeyed a power law relationship. The alloy in thermally aged condition exhibited higher LCF resistance compared to that of SPWHT condition. The improved LCF resistance has been ascribed to the effects associated with reduced crack propagation rate caused by extensive particle decohesion and secondary cracks.

The LCF lives were predicted by Tomkins crack growth model and the fatigue design curves applicable to thick sections were generated. Creep-fatigue tests with one minute holds indicated that 9Cr-1Mo steel is not prone to creep damage. The analysis of creep-fatigue data on the tube plate forging and on thin section in normalised and tempered condition indicated that linear damage summation with total damage as unity can safely be employed for 9Cr-1Mo steel. The continuous cycling LCF resistance of thick section forging in SPWHT condition has been found to be consistently lower than that of thin section in normalised and tempered condition and in heat treatment conditions intended to simulate thick sections. The inferior fatigue resistance is attributed to the effects associated with coarse grain size of the forging.

Key words: Ferritic steel, 9Cr-1Mo steel, Thick section, Tensile properties, Flow behaviour, Dynamic strain ageing, Activation energy, Thermal ageing, Tensile ductility, Creep properties, Steady state creep rate, Stress exponent, Rupture life, Rupture ductility, Primary creep, Tertiary creep, First order kinetics, Low cycle fatigue, Life prediction, Design curve, Creep-fatigue interaction