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Effect of microstructural texture on the creep behavior

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The two steels were prepared with the same composition but different rolling processes. The equiaxed grain of TMCP EH36 steel was produced by thermo-mechanical control rolling (TMCP) with an accelerated cooling process. The banded structure of SM490C steel was produced using the conventional hot rolling process. After creep the results show that the apparent activation energy and apparent stress exponent in the band structure of SM490C steel are much higher than that in the equiaxed grain of TMCP EH36 steel. The second phase distribution and morphology have an important effect on the creep behavior in this study. © *2002 Kluwer Academic Publishers*

1. Introduction

High strength low alloy steels produced by thermo-mechanical controlled rolling (TMCP) with an accelerated cooling process possess high strength [1], high toughness [2], good weldability [3–5], good low temperature strength and toughness [6] and good corrosion resistance [7]. For example TMCP EH36 steel with equiaxed refined grains shows a good strength and ductility after hydrogen charging [7]. On the other hand, the relative hard band structure in SM490C steel and weldment are the major causes that render lower ultimate tensile strength and elongation [7] due to hydrogen trapped at the interface between the bands. Thus they are widely used in the marine engineering applications and in the ship building industry. Recent research on the high temperature mechanical properties of TMCP steel and its weldment under different strain rates and temperatures shows the serrated flow in the stress-strain curves [8]. The region of dynamic strain aging corresponds to the occurrence of negative strain rate sensitivity. The reason is attributed to dynamic strain aging of the specimens as dislocation interactions with mainly interstitial solid solutions [8]. However there is no report on the applicability of TMCP steels in intermediate high temperature environments for a prolonged time. In this study not only was the creep behavior investigated, but also the influence of microstructure morphology in creep deformation.

In this study two strengths of 490 MPa steels with very similar composition (Table I) but different microstructure morphologies were manufactured. One microstructure was characterized by the elongate banded grains of JIS G3106 SM490C steel, which is a rolled steel for weld structure produced by conventional hot rolling. The other was equiaxed grained TMCP EH36 steel which is a rolled steel for the construction of hulls using thermo-mechanical control rolling with an accelerated cooling process, known as TMCP, without Ti, V, Nb etc. microalloy addition. The appearance of the microstructural morphology resulted from the different rolling processes, as shown in Fig. 1. The microstructure of TMCP EH36 consists of an equiaxed ferrite grain mixed with little dispersive pearlite or banite phase [6–8]. The grain size is about 15–20 μm. The microstructure of conventional hot rolled SM490C steel is characterized by textured pearlite, and filled with ferrite in between the bands. The elongate grain size is about 35–40 μm long with an aspect ratio of three in width.

2. Materials and experimental methods

The dimension of the creep test specimen, machined from experimental steels, was according to ASTM E8-93 with a gage length of 25.4 mm [9]. Creep experiments were performed under SATEC Model D test apparatus. Before the test, the specimen is kept in a furnace one and a half hours to reach equilibrium. The test was terminated at about 120 hours. Creep tests were performed under constant load at temperatures of 808 K, 823 K, 848 K and 873 K (equivalent homologous temperature 0.447, 0.455, 0.469 and 0.483) with an initial applied stresses of 60 MPa, 80 MPa, 100 MPa, 120 MPa and 130 MPa. The displacement was measured using a super linear variable capacitor.

TABLE I The experimental steel composition (wt%)

Steel	Fe	C	P	S	Si	Mn	Ni	Cr
TMCP EH36	Bal.	0.13	0.02	0.01	0.31	1.32	0.03	0.03
SM490C	Bal.	0.15	0.02	0.01	0.31	1.41	0.03	0.03

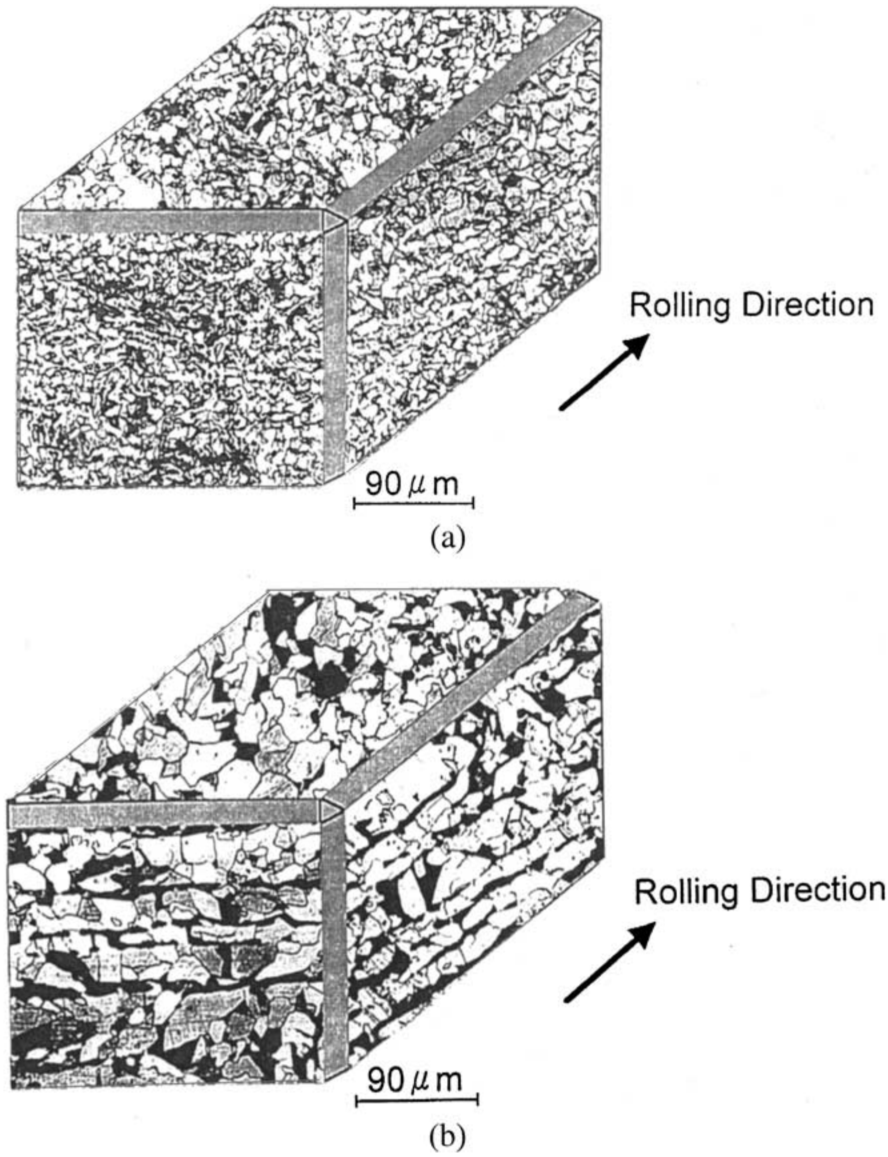

Figure 1 3-dimensional view of the optical metallographs (a) thermal-mechanical control rolling (TMCP) with accelerated cooling steel and (b) conventional hot rolled SM490C steel.

3. Results

For the purpose of comparing the creep behavior influenced by different microstructure morphologies, the creep tests must be performed under the same test conditions. The selected strain-time creep curves at different stress levels Fig. 2 and at different temperatures Fig. 3 show that a decelerating strain rate stage is followed by a steady creep rate for the textured band structure of SM490C steel. The equiaxed grain structure of TMCP EH36 steel exhibits an exponential like accelerating creep which ends in rupture under the same test conditions (Figs 2 and 3). A comparison of the creep curves between conventional hot rolled SM490C steel and thermo-mechanical control rolling with accelerated cooling TMCP EH36 steel in Figs 2 and 3, shows that SM490C steel with a textured microstructure exhibits a better creep resistance than the EH36 steel with the equiaxed grain microstructure. However, exponential accelerated creep curves (Figs 2 and 3) appeared in TMCP EH36 steel. The minimum creep rate at the initial short period of time was selected for analysis of the apparent activation energy and apparent stress

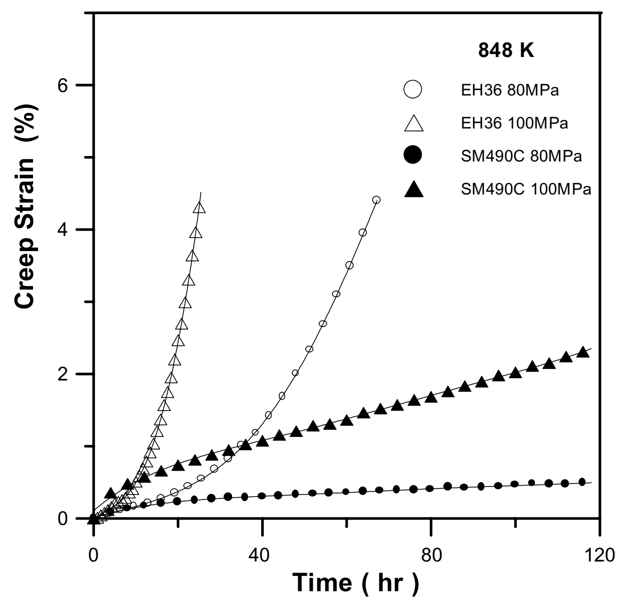

Figure 2 Examples of creep curves for TMCP EH36 steel with equiaxed grain and SM490C steel with textured grain at temperature 848 K.

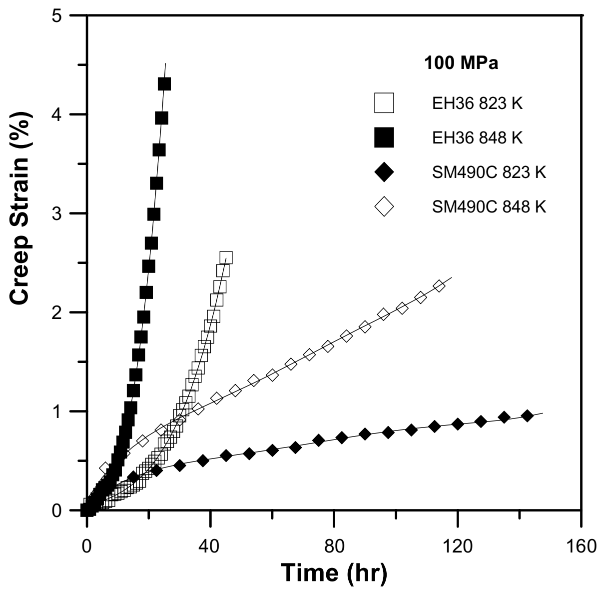

Figure 3 Examples of creep curves for TMCP EH36 steel with equiaxed grain and SM490C steel with textured grain at applied stress 100 MPa.

exponent. Essentially, it was assumed that the minimum creep rate at the accelerated creep stage was approximate by equal to that at the steady state stage.

3.1. Analysis of apparent activation energy and apparent stress exponent

High temperature creep deformation is controlled mainly by the activation energy, which relates to the deformation mechanism. If the deformation mechanism remains unchanged, the apparent creep activation, Q_{app} can be written as

$$Q_{\text{app}} = -R\frac{\ln\left(\frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1}\right)}{\frac{1}{T_2} - \frac{1}{T_1}} \quad (1)$$

Here R is a gas constant 8.314 J/K mole, $\dot{\varepsilon}$ is the creep stain rate, and T is the temperature. Based on the Arrhenius Equation (1), the apparent activation energies at different stresses are obtained from the semi-logarithmic plots for TMCP EH36 steel (Fig. 4a) and SM490C steel (Fig. 4b). Furthermore, the values of the apparent activation energies for a specific stress at different stresses are also listed in Fig. 4. The average apparent activation energies of SM490C steel and TMCP EH36 steel are about 415 kJ/mole and 360 kJ/mole respectively. The apparent stress exponent n_{app} can be obtained from the relationship between the natural logarithmic creep strain rate and the natural logarithmic applied stress on the assumption that the activation energy which does not change. The apparent stress exponent values n_{app} for TMCP EH36 steel are 4, 4 and 5, as listed in Fig. 5a at 823 K, 848 K and 873 K respectively. The average value of the stress exponent is 4.5, which falls in the dislocation climb dominated range between 3 and 5 [10]. The apparent stress exponent values for the elongate band microstructure of SM490C steel are 9, 8, 8 and 7, as listed in Fig. 5b at 808 K, 823 K, 848 K, and 873 K respectively. These values are higher than normal value of 5.

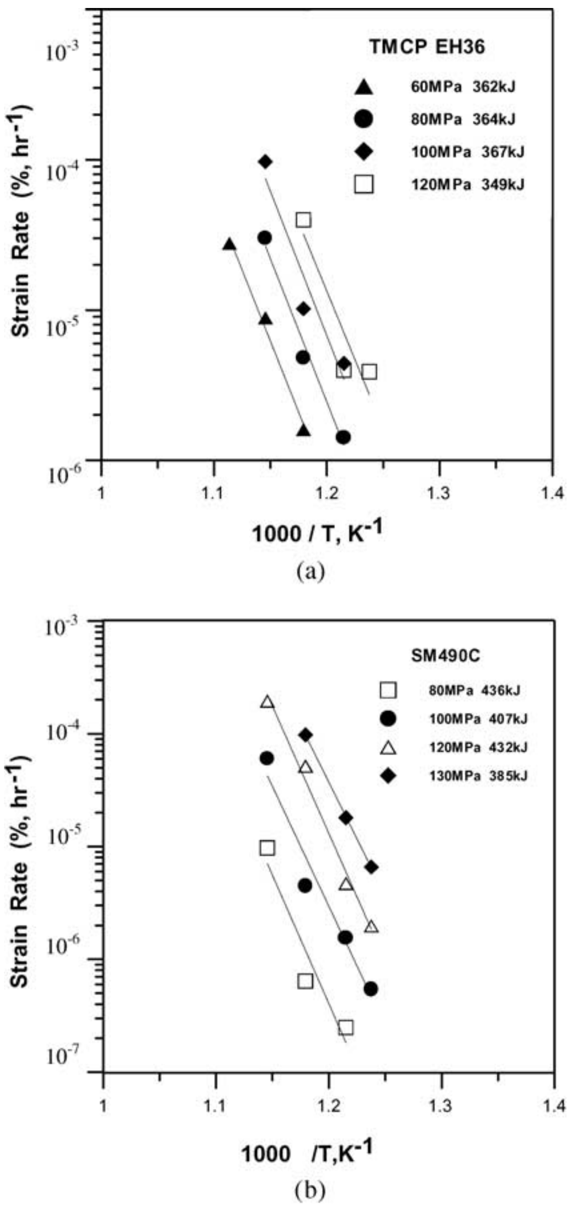

Figure 4 The apparent activation energy obtained from the steady state creep rate as a function of the inverse temperature (a) for TMCP EH36 steel with equiaxed grain structure, (b) for SM490C steel with textured structure.

4. Discussion

High temperature strengthening mechanisms under various microstructural morphologies were examined by performing a close comparison between the creep behavior of TMCP EH36 and SM490C steel. The data reveal that there are two main differences in creep behavior between the equiaxed grain steel (TMCP EH36) and elongate band grain steel (SM490C). The creep rates of the equiaxed grain are several orders of magnitude faster than those of the banded elongate grain. The apparent activation energy for the band textured grain SM490C steel is higher than that for the equiaxed fine grain TMCP EH36 steel in the entire stress range (Fig. 4). The values of the apparent activation energy listed in Fig. 4 for both steels are much larger than the self-diffusion activation energy of 250 kJ/mol [11] in low carbon steel and 300 kJ/mol [11] in medium carbon steel. But for TMCP EH36, the apparent activation energy is close to the activation energy of lattice diffusion 350 kJ/mol in α-Fe [12], and 346 kJ/mole activation

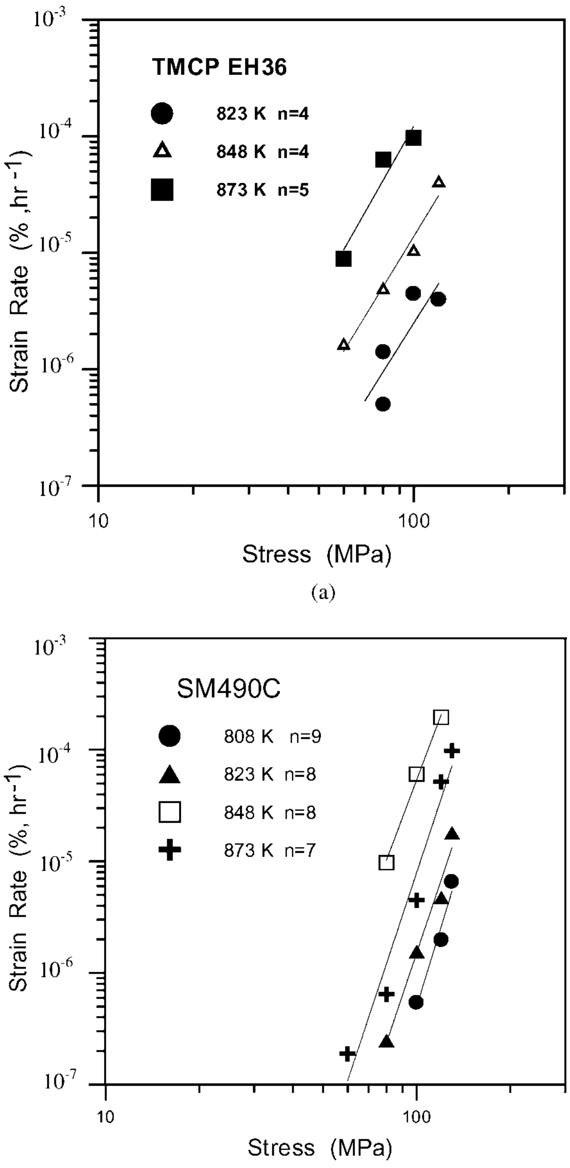

Figure 5 The apparent stress exponent obtained from the steady state creep rates as a function of the applied stress (a) for TMCP EH36 steel with equiaxed grain structure (b) for SM490C steel with textured structure.

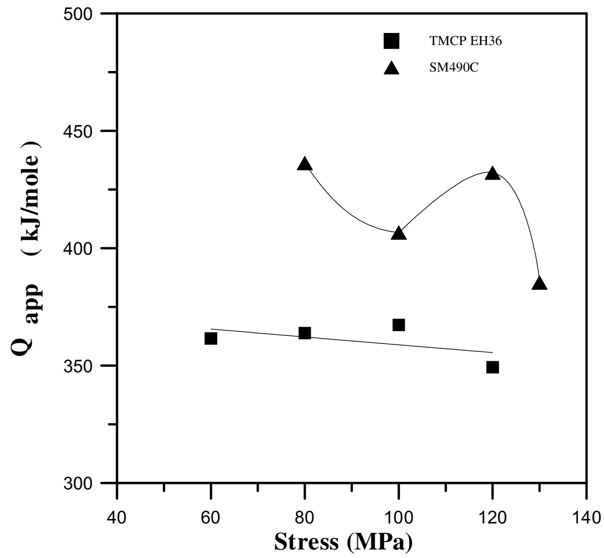

Figure 6 The variation of the apparent activation energy with the applied stress for TMCP EH36 steel and SM490C steel.

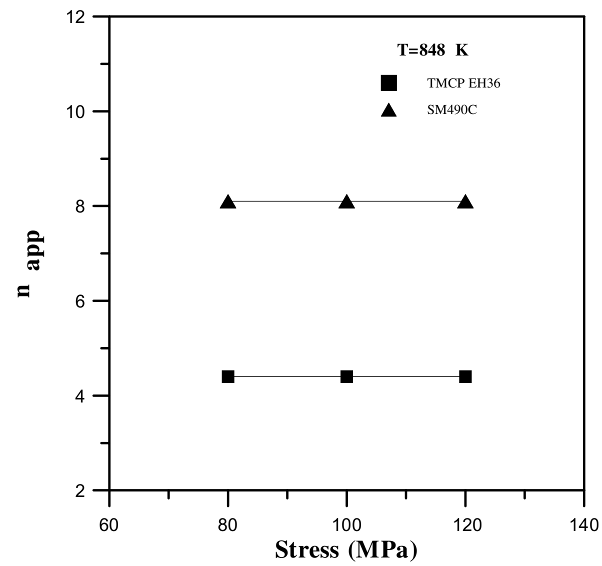

Figure 7 The variation in the apparent stress exponent with the applied stress for TMCP EH36 steel and SM490C steel.

energy for cross-slip in 301 stainlees steel [13]. Although the apparent activation energy is higher for band textured SM490C steel, it is inferred that the dislocation climb predominates the creep deformation for TMCP EH36 steel and SM490C steel. This strong variation of the apparent activation energy with the applied stress in SM490C contrasts with the results of equiaxed fine grain EH36 yielding a linear stress dependent apparent activation energy and increasing slightly with decreasing applied stresses, as dipicted in Fig. 6.

The apparent stress exponent, n_{app}, inferred from Fig. 7 is much higher for band textured SM490C steel. The results of band textured grain of SM490C and equiaxed fine grain of TMCP EH36 yield a stress-independent stress exponent, as dipicted in Fig. 7. The higher value of apparent stress exponent, n_{app}, of SM490C steel in comparison to the normal dislocation climb value of 5, it seems that the second phase of textured pearlite resembles whiskers or a short fiber strengthened phase and plays a very important role in hindering creep deformation.

As demonstrated by the figures, SM490C steel exhibits better creep resistance than TMCP EH36 steel over the entire stress range examined. This explains that the smaller equiaxed grain in TMCP EH36 steel causes grain boundary sliding much easier than the relative long and thin grain in SM490C steel. In other words, the elongate band of second phase pearlite and ferrite constituents can more effectively block the dislocation glide and restrain climb and grain boundary sliding of adjacent ferrite.

By observing the results listed in Figs 4 and 5, SM490C steel definitely satisfies the three required features of threshold stress mentioned by Park [14]: (1) It has the higher apparent stress exponent value, $n_{app} > 7.4$. (2) The apparent stress exponent value decreases when the temperature increases. (3) The creep activation energy is greater than the self-diffusion energy. It is suggested that the textured SM490C steel may have a higher threshold stress barrier than the equiaxed grain of TMCP EH36 steel. The textured structure of banded pearlites in SM490C steel might be analogous to SiC particles in MMC having the same effect of obstructing the dislocation gliding and climbing in creep deformation, and contributing to stabilizing the fine dislocation substructure.

5. Conclusion

The activation energy for creep in the equiaxed grain steel is lower than that in the banded elongate grain steel. Analysis of the experimental data indicates that the distinct difference in creep behavior can be explained in terms of the strengthening processes that are related to the second phase different distribution and morphology for creep in both materials. Creep deformation is controlled by lattice diffusion assisted dislocation climb for TMCP EH36 steel and SM490C steel. The good creep resistance of SM490C steel, with a textured pearlite phase, produced by a conventional hot rolled process, appears to have a higher creep activation energy value and apparent stress exponent value. The elongated second pearlite phase shape is an effective barrier for dislocation movement (gliding, cross-slip and climbing), and effectively hinders grain boundary sliding and grain growth due to the restraint of the pearlite with elongate grain boundary.

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