THE EFFECT OF THE PRE-STRAINING AND AGEING ON TENSILE BEHAVIOUR OF MICROALLOYED STEELS

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ABSTRACT

Two commercially available medium carbon and low carbon microalloyed steels were evaluated in this study. The steels were cold strained in tension 5 % and were aged at 100-450 ºC for 1 hour. Strained and aged specimens were then retested to fracture and mechanical properties of steels were measured. Changes in mechanical properties such as ultimate tensile strength and yield strength were observed at ageing temperatures. This ageing is associated with interaction between interstitial solutes and dislocations which are preferential sites for solute atom diffusion. Indications are that the medium carbon microalloyed forging steel is more susceptible to strain ageing than the low carbon microalloyed steel as evidenced an increase in yield strength and tensile strength.

Key Words : Strain ageing; Microalloyed steels; Yield strength; Tensile strength

ÖN DEFORMASYON VE YAŞLANMANIN MİKROALAŞIM ÇELİKLERİNDEN ÇEKME DAVRANIŞINA ETKİSİ

ÖZET

Bu çalışmada ticari amaçlı olarak üretilen orta karbonlu ve düşük karbonlu mikroalasım çelikleri kullanılmıştır. Çelikler % 5 soğuk olarak deform edildikten sonra 100-450 ºC sıcaklık aralığında 1 saat yaşandırılmıştır. Deforme edilen ve yaşandıran çelikler daha sonra kopuncaya kadar çekirdek mekanik özellikleri ölçülmüştür. Yansımlık olarak yaşandıran çeliklerin çeker ve akma dayanımı gibii mekanik özelliklerinin değiştiği gözlenmiştir. Yaşanma, arayer atomlarıyla dislokasyonların arasında meydana gelen etkileşim sonucunda oluşmuştur. Sonuçlar dövme amaçlı üretilen orta karbonlu mikroalasım çeliklerinin akma ve çekme dayanımlarının artmasından dolay, düşük karbonlu mikroalasım çeliklerine nazaran daha fazla gerinim yaşanmasından etkilendiğini göstermektedir.

Anahtar Kelimeler : Gerinim yaşandırma; Mikroalasılımlı çelikler; Akma dayanımı; Çekme dayanımı

1. INTRODUCTION

Strain ageing is a phenomenon that causes the yield strength of a steel to increase due to P'cking of disl*Cations following a prestrain and an ageing heat treatment. Strain ageing can either be dynamic or static, depending on whether the straining and ageing pr*Cesses occur simultaneously or sequentially (Herman et al., 1987). In his classic work Cotrell (1954) proposed that strain ageing effects were due to the segregation of interstitial solute atoms, such as carbon and nitrogen, to the disl*Cations present in the steel. The stress required to move a disl*Cation with an atmosphere is greater than that required once the disl*Cation has moved away from its atmosphere, so that in a tensile test at room temperature an upper and lower yield point
can be obtained. This model became the basis for much of the study of strain ageing.

The compositions of microalloyed steels are similar to low carbon steel, but they are considerably stronger. The added strength is often obtained by controlled hot-rolling and rapid, controlled cooling which results in a very small grain size. Further, by minor additions of appropriate alloying elements V, Nb, Al or Ti, additional stress is developed by both solution and precipitation hardening (Gladman, 1997). Medium carbon microalloyed steels have also been introduced as substitutes for quenched and tempered steels in some automotive components such as crankshafts and connecting rods. In such steels, the strength levels and other properties achieved after cooling from hot working temperatures are reported to be comparable with those obtained from conventional quenched and tempered steels. Vanadium has a high solubility in austenite, regardless of the carbon content, and is therefore the most suitable microalloying element for medium carbon steels (Llewellyne, 1994; Jahazi Eghbali, 2001; Ollilainen et al., 2003).

In spite of the alloying additions, free interstitial solute atoms may still be present in microalloyed steels. It is difficult to determine quantitatively the free interstitial content of commercial steel by established techniques because of the interactions between alloying additions and the interstitials, but the presence of free interstitials may be established indirectly. For instance, in the as-rolled condition most microalloyed steels exhibit a yield point elongation which increases when the steel is aged (Rashid, 1975). This suggests that on ageing, solute atoms frozen in a random distribution throughout the matrix during rapid cooling migrate to free dislocation cations, thereby causing an increase in the yield point elongation.

The way to visualize the effects that strain ageing have upon the mechanical properties of a steel is through the use of a stress-strain diagram. Figure 1 shows a stress-strain curve for a mild, normalized steel (Herman et al., 1987). After initial loading to point A, and then unloading a certain amount of plastic deformation remains as a pre-strain. If the sample is retested immediately, the curve shows an extended elastic region up to point A. The curve then progresses exactly as if the unloading excursion had not occurred. Also note that the lower yield extension is not seen during second loading cycle. However, if the specimen is unloaded and allowed to age either at ambient or elevated temperatures, the lower yield point is again seen on reloading. Furthermore, it occurs at a higher level than the flow stress that prevailed at the end of the prestraining operation. This increase in yield strength after ageing is the most universal indication of the strain ageing process (Baird, 1963; Baird, 1963a; Baird, 1963b).

\[ \Delta Y_1 = \text{Increase in stress produced by pre-strain}; \quad \Delta Y_2 = \text{Increase in stress produced by ageing}; \quad \Delta Y_3 = \text{Increase in stress due to pre-straining and ageing} = \Delta Y_1 + \Delta Y_2; \quad \Delta U = \text{Change in UTS due to pre-straining and ageing}; \quad \Delta e = \text{Change in total elongation due to pre-straining and ageing} \]

Figure 1. Schematic representation of pre-straining and ageing on the stress/strain curve

While the tensile properties of the medium carbon and low carbon microalloyed steel were investigated, the effect of the strain ageing on these properties was not studied in detail. The purpose of this experiment is to gain an understanding of the ageing behaviour in low carbon microalloyed steel intended for strip application and medium carbon microalloyed steels manufactured for automotive applications. The effect of the strain ageing on mechanical properties of steels were determined by means of the measurement of strength properties. For the purpose of this study, only the static (sequential) case was examined experimentally, and therefore only this type will be discussed here.

2. EXPERIMENTAL PROCEDURE

The materials used for the present study were medium carbon (steel 1) and low carbon microalloyed steel (steel 2) containing different amount of C, V, Al and Ti. The chemical compositions of the tested steels are shown in Table 1. The specimens for tensile tests were prepared with specified dimensions according to TSE standard as shown in Figure 2. The specimens were submitted to a prestrain of 5% beyond the yield point. After this,
they were unloaded and aged to a predetermined temperature and time. After ageing of the specimens, they were subjected to a tensile test, at ambient temperature, at a crosshead speed of 1 mm/min. The increase in flow stress as a result of re-straining was taken as the strain ageing. As can be seen from Figure 1 that 5 % pre-strain will result in a corresponding increase in stress $\Delta Y_1$, and that subsequent ageing will produce a further stress increment, $\Delta Y_2$. The overall effect of pre-straining and ageing is therefore the sum of $\Delta Y_1$ and $\Delta Y_2$ and can be termed $\Delta Y_3$. The ageing treatments consistent of 1 hour at 100 °C, 150 °C, 200 °C, 250 °C, 300 °C, 350 °C, 400 °C and 450 °C using a furnace capable of operating up to 1200 °C.

In the present work, optical microscopy and scanning electron microscopy (JEOL 840A JXA) have been used to characterise steel microstructure and fracture surface of steels. Microspecimens were prepared for metallographic examination using the heads of the broken tensile pieces. The metallographic examination of samples was carried out using a Nikon microscope capable of magnifications between x5 and x400.

| Table 1. Chemical Compositions of Used Steels (wt %) |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|        | C      | Si     | Mn     | P      | S      | Cr     | Mo     | Ni     | Al     | N      | Ti     | V      | Nb     |
| St. 1  | 0.29   | 0.30   | 1.45   | .015   | .012   | -      | -      | .038   | .008   | .012   | 0.08   | -      | -      |
| St. 2  | 0.11   | .026   | 1.3    | .025   | .014   | -      | -      | 0.05   | .008   | .005   | -      | 0.029  | -      |

Figure 2. Schematic representation of tensile specimen

3. RESULTS AND DISCUSSION

The optical micrographs of the steels indicated that the microstructure consisted of ferrite and pearlite, shown in Figure 3 for steel 1 and steel 2 respectively. The measurement of phase volume fraction, as shown Table 2, showed that medium carbon microalloyed forging steel had a higher pearlite percentage compared to low carbon microalloyed steel, explaining the higher strength of these steels. The medium carbon microalloyed steel also showed a smaller grain size determined using intercept along a test line oriented at 45° to the rolling direction. At least 500 grain boundaries were counted for each samples.

Table 3 shows tensile test results of steel 1 and steel 2 under as received condition. However, Table 4 and Table 5 show static strain ageing results of steel 1 and steel 2 respectively. Tables show initial lower yield point, final lower yield point, load after straining, increase in stress produced by pre-strain ($\Delta Y_1$), increase in stress produced by ageing ($\Delta Y_2$), increase in stress due to pre-straining and ageing ($\Delta Y_3$), ultimate tensile strength, percentage elongation to fracture, change in UTS due to pre-straining and ageing ($\Delta U$) and change in total elongation due to pre-straining and ageing ($\Delta e$).

Figure 3. Microstructure of medium carbon (a) and low carbon (b)
Table 2. Volume Fractions of Ferrite and Pearlite Phases in Steel 1 and Steel 2

<table>
<thead>
<tr>
<th>Steel</th>
<th>Ferrite (%)</th>
<th>Pearlite (%)</th>
<th>Grain size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel 1</td>
<td>52 ± 2.5</td>
<td>48 ± 2.4</td>
<td>8.1 ± 0.25</td>
</tr>
<tr>
<td>Steel 2</td>
<td>79 ± 2</td>
<td>21 ± 2</td>
<td>9.8 ± 0.31</td>
</tr>
</tbody>
</table>

Table 3. Tensile Test Results of Steels 1 and 2 Under as Received Condition

<table>
<thead>
<tr>
<th>Steel</th>
<th>LYP (MPa)</th>
<th>UTS (MPa)</th>
<th>Elong. to Fracture (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel 1</td>
<td>500</td>
<td>702</td>
<td>15</td>
</tr>
<tr>
<td>Steel 2</td>
<td>380</td>
<td>506</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 4. Static Strain Ageing Results for Steel 1, Pre-strained 5 % and Then Aged at Different Temperatures

<table>
<thead>
<tr>
<th>Ageing Temp (°C)</th>
<th>Init. LYP (MPa)</th>
<th>Strength After Str. (MPa)</th>
<th>Final LYP (MPa)</th>
<th>ΔY1 (MPa)</th>
<th>ΔY2 (MPa)</th>
<th>ΔY3 (MPa)</th>
<th>UTS (MPa)</th>
<th>Total Elong. (%)</th>
<th>ΔU (MPa)</th>
<th>Δe (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>510</td>
<td>574</td>
<td>597</td>
<td>64</td>
<td>23</td>
<td>87</td>
<td>707</td>
<td>16</td>
<td>5</td>
<td>+1</td>
</tr>
<tr>
<td>150</td>
<td>500</td>
<td>574</td>
<td>603</td>
<td>74</td>
<td>29</td>
<td>103</td>
<td>710</td>
<td>16</td>
<td>8</td>
<td>+1</td>
</tr>
<tr>
<td>200</td>
<td>500</td>
<td>610</td>
<td>649</td>
<td>110</td>
<td>39</td>
<td>149</td>
<td>719</td>
<td>14</td>
<td>17</td>
<td>-1</td>
</tr>
<tr>
<td>250</td>
<td>522</td>
<td>650</td>
<td>701</td>
<td>128</td>
<td>51</td>
<td>179</td>
<td>762</td>
<td>10</td>
<td>60</td>
<td>-5</td>
</tr>
<tr>
<td>300</td>
<td>500</td>
<td>635</td>
<td>705</td>
<td>135</td>
<td>70</td>
<td>205</td>
<td>780</td>
<td>8</td>
<td>78</td>
<td>-7</td>
</tr>
<tr>
<td>350</td>
<td>539</td>
<td>669</td>
<td>727</td>
<td>130</td>
<td>58</td>
<td>188</td>
<td>785</td>
<td>9</td>
<td>83</td>
<td>-6</td>
</tr>
<tr>
<td>400</td>
<td>526</td>
<td>669</td>
<td>700</td>
<td>143</td>
<td>31</td>
<td>174</td>
<td>753</td>
<td>11</td>
<td>51</td>
<td>-4</td>
</tr>
<tr>
<td>450</td>
<td>535</td>
<td>667</td>
<td>670</td>
<td>127</td>
<td>3</td>
<td>130</td>
<td>730</td>
<td>17</td>
<td>28</td>
<td>+2</td>
</tr>
</tbody>
</table>

As it is seen from tables the increases in ageing temperature between 100-350 ºC were matched by increases in stress due to ageing (ΔY2) and tensile strength, averaging 10 % for ΔY2 and 10 % for tensile strength of steel 1. However, ΔY2 and tensile strength of steel 2 increased an average 6 % and 5 % respectively. Tables 3 and 4 also indicated that steel 1 showed an increase of 24 % in ΔY3 (increase in stress due to pre-straining and ageing). On the other hand ΔY3 of steel 2 increased 6 %. Within this broad picture, it should be noted that, for the two steels studied in the pre-straining and ageing conditions, the steel 1 had larger increases in ΔY2, ΔY3 and tensile strength compared to steel 2. Figure 4 also shows the effects of ageing on ΔY2, lower yield strength (LYS) and ultimate tensile strength (UTS) for steels 1 and 2.

These changes are due to the segregation of interstitial solute atoms, such as carbon and/or nitrogen, to the dislocations present in the steels.

Further, as little as 0.0001% to 0.001% free C and/or N is sufficient to cause strain ageing (Rashid, 1975). For example, steel 1 contains larger amount of carbon compared to steel 2, as well as Al, Ti and V. According to stoichiometry, V (atomic weight 50.94) and Ti (atomic weight 47.9) will combine one quarter its weight of carbon (atomic weight 12), so that for a 0.29 wt. % V vanadium or titanium microalloyed steel, 1.16 wt % V or %Ti will provide carbide of the stoichiometric composition. However, the amount of vanadium and titanium is 0.08 and 0.012 wt % respectively in steel 1, which is not enough to combine with all the carbon, therefore free carbon should be always expected in solid solution after rolling and controlled cooling. The changes in mechanical properties of steel 1 and steel 2 due to ageing effect at different temperatures (Figure 4) showed an increase in the yield and ultimate tensile strength of these steels. This is associated with a reduction in the number of
mobile dislocations, due to the formation of cottrell atmospheres around dislocations.

It was also observed that the colour of specimens was changed by increasing temperature. For example, sample aged at 350 °C had blue colour and also showed the largest increase in lower yield strength and ultimate tensile strength. The phenomenon is referred as blue brittleness, blue being the interference colour of the steel surface when oxidized in this temperature range (Honeycombe et al., 1995).

Baird and Jamieson (Baird and Jamieson, 1963) have shown that the blue brittleness effect is due to the presence of carbon and nitrogen. They used strip tensile specimens from which all carbon and nitrogen had been removed by annealing in moist hydrogen. Some specimens were tested in this condition and others were recarburized or renitrided, homogenised and then tested. The tensile properties of the specimens free of carbon and nitrogen fell smoothly with increasing testing temperature in the range studied (20-500 °C) whereas in those to which carbon or nitrogen had been added, pronounced strengthening effects were present in the range 100-350 °C. After ageing at 400 °C and 450 °C, overageing occurs and the associated decreasing of the lower yield point and ultimate tensile strength is observed.

The steel 2 showed greater ductility than steel 1 at ageing temperatures between 150 and 350 °C, (see Figure 4). This was shown by elongation values as well as by fracture surface analysis. Steel 2 pre-strained 5% and then aged at 300 °C for 1 hour showed ductile dimple fracture surface at the microscopic level (Figure 5b). Microscopically a surface covered by dimples of several sizes as it is seen. In contrast the sample of steel 1 showed dimples and cleavage facets indicating that the fracture is of mixed type (Figure 5a).

Figure 4. The effect of the static strain ageing on mechanical properties of microalloyed steels pre-strained 5% and than aged at different temperatures.
Figure 5. Fracture surfaces of steel 1(a) and steel 2 (b) pre-strained 5 % and than aged at 300 °C for 1 hour

4. CONCLUSION

The effect of the static strain ageing on mechanical properties of medium carbon and low carbon microalloyed steel has been studied. The main results obtained as follows.

1. Static strain ageing takes place in medium carbon and low carbon microalloyed steel. However, medium carbon microalloyed steel is more susceptible to static strain ageing compared to low carbon microalloyed steel as evidence larger increase in yield strength and tensile strength.

2. The ageing treatment, caused an increase mainly in yield strength and to the lesser extent in tensile strength. This was taught to be due to the formation of solute atom atmospheres around the dislocations.

3. Increase in ageing temperature to between 200 and 350 °C accelerate ageing effect, due to the increase solute atom mobility.

4. Fracture surface analysis indicated that low carbon microalloyed steel showed a surface roughness and dimple fracture surface which is characteristic of ductile fracture, however medium carbon microalloyed steel showed dimples and cleavage facets indicating that the fracture is of mixed type at ageing temperature of 300 °C.

5. REFERENCES


