Research Note

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High Temperature Behavior of Dual Phase Steels

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Abstract

Dual phase steels with different martensite volume fraction and morphology were tensile tested at a temperature range of 25 to 550^{0}C. Stress-strain curves of all steels showed serration flow at temperatures of 250 and 350^{0}C, and smooth flow at the other temperatures. Both yield and ultimate tensile strengths increased with increasing testing temperature up to about 450^{0}C and then decreased at higher temperatures. At a given temperature, yield stress, tensile strength, and work hardening increased with increasing volume fraction of martensite. Similar behavior was observed by changing martensite morphology from network to fibrous martensite. The change in mechanical properties was related to the effects of dynamic strain aging, high temperature softening, and martensite tempering.

Keywords: Dual phase steels, Dynamic strain aging, High temperature deformation, Tension test, Tempering, Work hardening.

Introduction

Strain aging which is caused by the interaction of mobile dislocations with solute atoms results in the increased strength and decreased ductility of some metallic solid solutions. Strain aging can be divided into two categories; namely, static strain aging and dynamic strain aging. If straining and aging processes take place sequentially, it is called static strain aging. But when these two processes take place simultaneously, it is called dynamic strain aging (DSA). Static strain aging affects the yield stress whilst DSA affects the work hardening behavior of the material. In the DSA region, it is well known that under certain range of temperature and strain rate, metallic solid solution exhibits serration on the stress-strain curve1-4). This phenomenon is known as serrated yielding or Portevin Le Chatelier effect. Serrated yielding is accompanied by increased rates of strain hardening, negative strain rate and temperature dependence of flow stress, and decreased ductility. In iron based alloys, these effects have been attributed to the interaction of dislocations with interstitially dissolved nitrogen and carbon during deformation. Such regular pinning and unpinning is termed dynamic strain aging5-8). Effects of temperature, strain rate and solute concentration on the occurrence of serrated flow during tensile deformation of iron based alloys have been reported by other researchers 9-14).

Although some of these researchers e.g.12-13) take serrated yielding as a criterion for the occurrence of DSA, but Lou and Northwood15-16) reported that serrated yielding occurs only in a very confined range of temperature and strain rate compared with the range of DSA as evidenced by the increase in the ultimate tensile strength (UTS) and the negative strain rate dependence of UTS.

The present research was undertaken to investigate the behavior of a dual phase ferrite-martensite steel at high temperatures. The effects of volume fraction and morphology of martensite on the work hardening of steel were also considered.

Experimental Techniques

The steel used in this experiment was a plate with a thickness of 8mm. Its chemical composition in weight percentage was 0.07C, 1.33Mn, 0.34Si, 0.012S, and 0.031P. Bars of this material were first heated at 1100 ^{0}C for 2h and furnace-cooled to obtain a more uniform initial microstructure. Then it was normalized at 980 ^{0}C for 30 minutes and air-cooled. The dual phase microstructures with different volume fraction of network martensite were obtained by heating the normalized bars in the intercritical temperatures of 740 and 780^{0}C for 30 minutes, then quenching them into cold water. The dual phase microstructure with fibrous martensite was obtained by double quenching of normalized bars, i.e. heating the bars at 1000^{0}C for 30 minutes and quenching them into cold water then heating at 740^{0}C for 30 minutes followed by quenching them into cold water. Samples for microstructure studies were prepared and etched with Nital 2%, and volume fraction of martensite was measured by an image analyzer.

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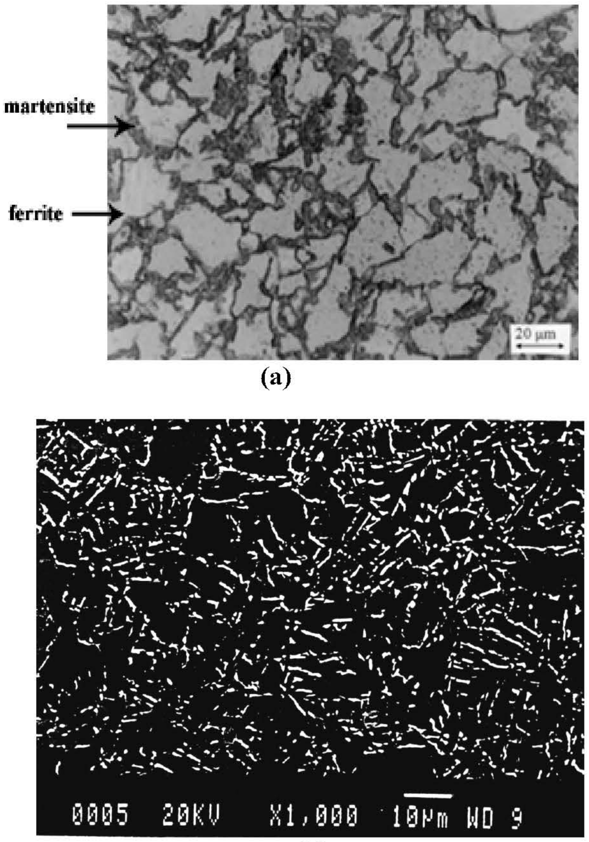
Tensile specimens were prepared with gauge length of 50 mm. Tensile tests were carried out at different temperatures between 25- 550 °C using an Instron tensile machine with a cross head speed of 2 mm/min(nominal strain rate of 6.7×10^{-4} 1/sec) .

Results and discussion

1. Microstructure

Martensite volume fraction of dual phase microstructures obtained by heating at intercritical temperatures of 740 and 780 °C was 0.25 and 0.37, respectively, and volume fraction of fibrous martensite in dual phase microstructure obtained by double quenching was 0.25. Figure 1 shows the microstructure of steels with 0.25 volume fraction of network and fibrous martensite.



(a)

(b)

Fig. 1. Microstructure of steels with 0.25 volume fraction of martensite: (a) Network martensite (b) Fibrous martensite.

2 Mechanical properties

2.1 Steel with 0.25 volume fraction of network martensite

Typical engineering stress strain curves of steels with 0.25 volume fraction of network martensite at different temperatures are shown in Figure 2. These curves exhibit smooth as well as serrated flow behavior at various temperatures. At temperatures of 250 and 350°C, clear serrated flows are seen. The serration might be attributed to the interaction of dislocation with solute atoms[5-8]. From this figure, it can be seen that serration occurs after a finite amount of plastic strain, which is in agreement with the result of other researchers[12-14] who have reported that serrated flow appears after a critical strain whose amount depends on temperature and strain rate. This critical strain is necessary for vacancies formation during plastic deformation to contribute to the diffusion process in substitutional solutions.[5] However the same mechanism has been confirmed for interstitial solutions.[3]

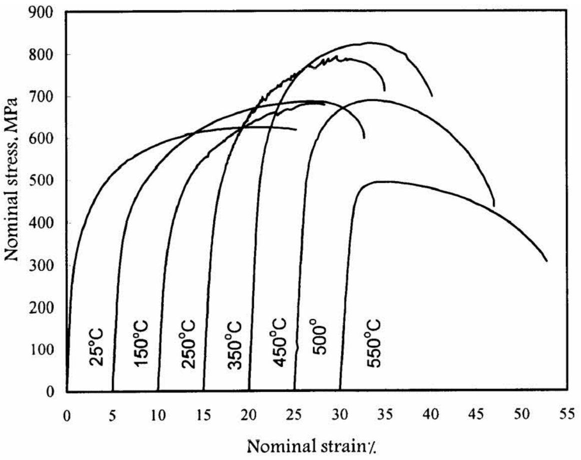


Fig. 2. Typical stress – strain curves of steel with 0.25 volume fraction of network martensite at different temperatures.

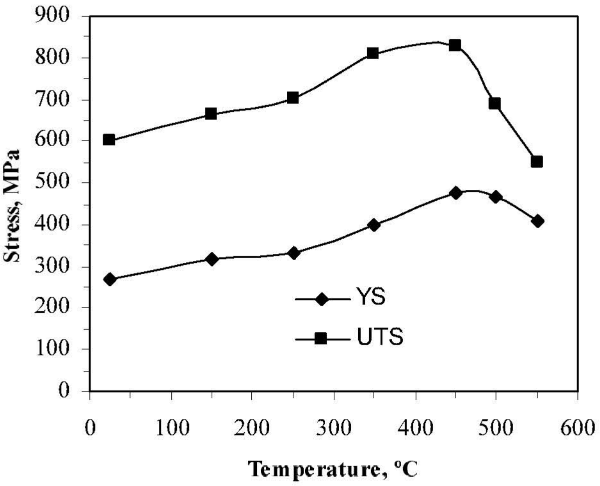


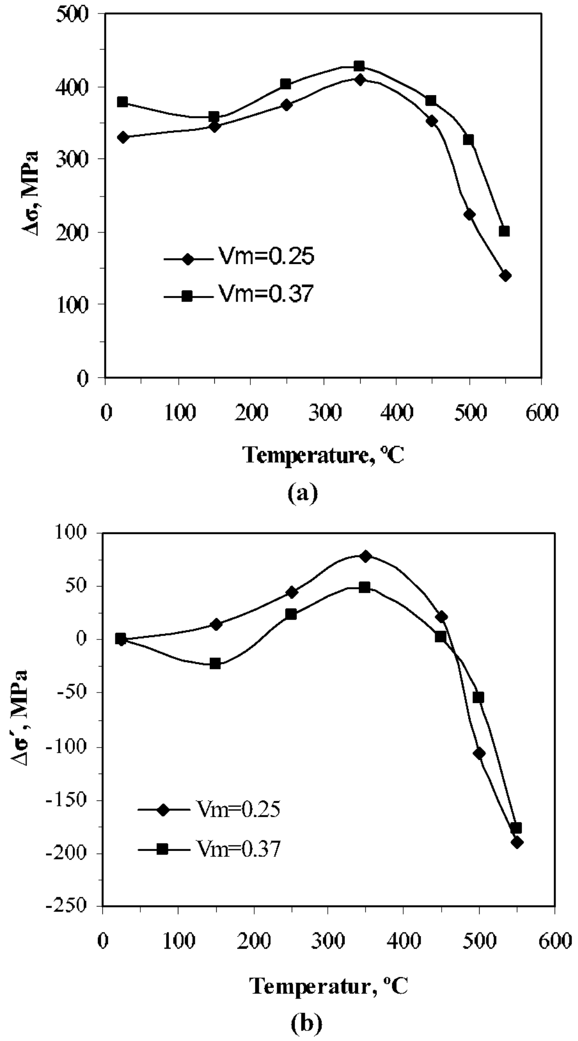
Fig. 3. The effects of temperature on yield stress and ultimate tensile strength in steel with 0.25- volume fraction of network martensite.

The variation of 0.2% yield stress (YS) and ultimate tensile strength with testing temperature are shown in Figure 3. It is seen that both YS and UTS increase with increasing temperature up to about 450°C and then decrease at higher temperatures. The increase in YS and UTS with temperature is considered to be related to the dynamic strain aging effects[10, 13]. But Lou and Northwood[15] reported that static strain aging affects the yield stress, while ultimate tensile strength is controlled by both yielding and work hardening processes. At high temperatures, besides the dynamic strain aging hardening effect, there is also a high temperature softening effect (dynamic recovery) which decreases the strength.[12,15)] But in this research the third effect which is the tempering of ferrite and martensite at high temperatures, must also be considered. During the tempering of dual phase steels, segregation of carbon to dislocations and elimination of residual stresses (due to the volume contraction of ferrite), which may result in an increase in yield stress, take place within the ferrite phase. In the martensite phase, recovery of defect structure, precipitation of carbides, and transformation of retained austenite (if there is) take place. [17)] Therefore, the effects of tempering on the strength of dual phase steels depend on the combination effects of these processes. Speitch[17)] reported an increase in the yield stress and decrease in the flow stress, in the whole stress-strain curve, of dual phase steels tempered at different time and temperature. The changes in the yield and flow stresses depend on the martensite volume fraction and tempering time and temperature. Therefore, the strength of the material deformed at high temperatures is determined by relative magnitude of these effects, (that is DSA effects, softening effects, and tempering effects) which may be decreased or increased at high temperatures compared with its room temperature value. According to Figure 3, it seems that up to about 450^{0}C the dynamic strain aging effects are dominant, and at higher temperatures the softening effects are dominant.

The magnitude of work hardening which is the difference between the UTS and YS, i.e. $\Delta\sigma = \sigma_{uts} - \sigma_{ys}$, is plotted versus testing temperature in figure 4a. As can be seen, the work hardening increases with increasing temperature up to about 350^{0}C and then decreases. According to the model proposed by Lou and Northwood[15)], the difference between the magnitude of work hardening at an elevated temperature and that at room temperature, $\Delta\sigma' = \Delta\sigma_T - \Delta\sigma_0$, will show the dynamic strain aging effects more directly. Figure 4b shows the effect of testing temperature on $\Delta\sigma'$. According to this figure, $\Delta\sigma'$ increases with increasing temperature up to about 350^{0}C. This means that at this temperature range, the effect of dynamic strain aging is dominant. At higher temperatures, $\Delta\sigma'$ decreases with increasing temperatures. But the dynamic strain aging effect is still dominant up to about 450^{0}C ($\Delta\sigma' > 0$), above this temperature $\Delta\sigma' < 0$ which means the softening effects become dominant.

2.2 Effect of martensite volume fraction

The stress–strain curves of steel with 0.37 volume fraction of network martensite at different temperatures were similar to those of steel with 0.25 volume fraction of network martensite; that is serrated flow at temperatures of 250 and 350^{0}C and smooth flow at other temperatures means there is no volume fraction effect of martensite on the temperature range of serrated flow.



(a)

(b)

Fig. 4. Effects of deformation temperature and volume fraction of martensite on: (a) Δσ and (b) Δσ′.

The variations of YS and UTS with testing temperatures are shown in Figures 5a and 5b, respectively. It is seen that the variation of both YS and UTS are similar to those in steel with 0.25 volume fraction of network martensite. But there is little change up to about 150^{0}C . At a given testing temperature, both YS and UTS increase with increasing volume fraction of martensite, which are in agreement with previous works at room temperature[18-22)]. Increase in YS and UTS has been related to the increase in dislocations density within the ferrite phase and more barriers to dislocations movement as a result of martensite volume fraction increment. [e.g22)]

The work hardening of dual phase steel with 0.37 volume fraction of martensite is also shown in Figure 4a. Variation of work hardening with testing temperature is similar to that in steel with 0.25 volume fraction of ferrite, except at 150^{0}C. Decrease of work hardening at this temperature may be due to the YS increment as a result of residual stresses elimination. Residual stresses increase with increasing volume fraction of martensite. At 150^{0}C, the DSA effect on UTS is less than its effects at higher temperatures. As a result of the difference between UTS and YS, work hardening decreases.

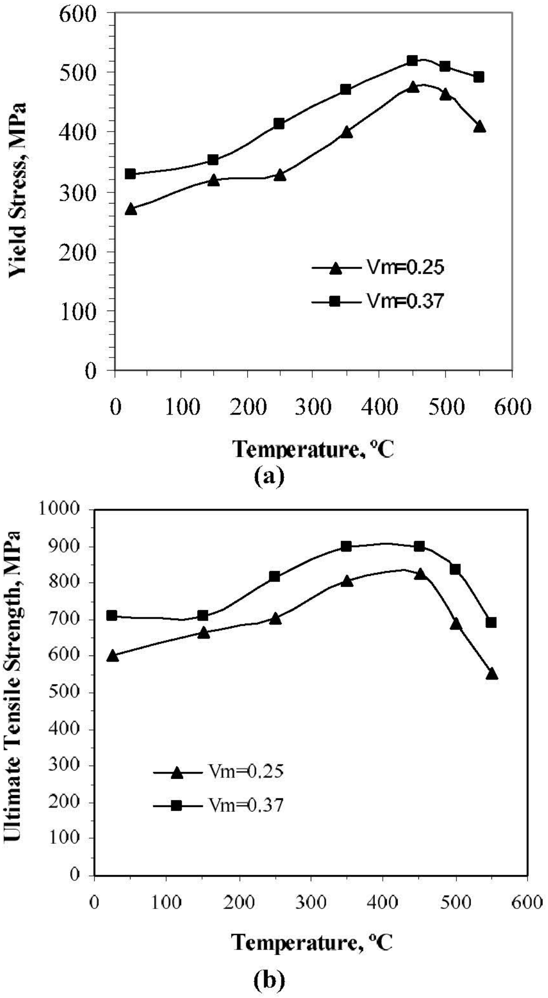


Fig. 5. Effect of network martensite volume fraction at different temperatures on: (a) Yield stress and (b) Ultimate tensile strength.

From this figure, it can be seen that at a given testing temperature, the work hardening increases with increasing martensite volume fraction, which can be related to more barriers to dislocations movement and higher rate of dislocations multiplication with increasing volume fraction of martensite. The variation of $\Delta\sigma'$ with testing temperature in dual phase steel with 0.37 volume fraction of martensite is also shown in Figure 4b. $\Delta\sigma'$ decreases with increasing temperature up to about 150^{0}C, i.e. the softening effects are dominant. Between 150 to 350^{0}C, $\Delta\sigma'$ increases with increasing testing temperature which means dynamic strain aging, hardening is dominant. At higher temperatures, $\Delta\sigma'$ decreases with increasing temperature but the dynamic strain aging effect is still dominant up to 450^{0}C ($\Delta\sigma'>0$). Above this temperature $\Delta\sigma'< 0$ which indicate that softening effects are dominant. By comparison of $\Delta\sigma'$ in dual phase microstructures with different volume fraction of martensite (Figure 4b), it is seen that $\Delta\sigma'$ decreases with increasing volume fraction of martensite up to about 450^{0}C and then increases at higher temperatures. Decreasing $\Delta\sigma'$ with increasing volume fraction of martensite may be due to the softening effects which occur during the high temperature deformation of steel (dynamic recovery and tempering of martensite).

2.3 Effect of martensite morphology

The stress–strain curves of steel with 0.25 volume fraction of fibrous martensite were similar to those in other steels, i.e. serrated flow at 250 and 350^{0}C and smooth flow at other temperatures.

Variation of YS and UTS of steels with 0.25 volume fraction of martensite with different martensite morphology are shown in Figures 6a and 6b, respectively. It can be seen that the martensite morphology has no effect on the trend of YS and UTS variation with testing temperature. But at a given testing temperature, both YS and UTS of steel with fibrous martensite are greater than those of steel with network martensite. These results are in agreement with the results obtained by other researchers at room temperature[22, 23)]. The higher strength of steel with fibrous martensite has been related to the higher strength of ferrite phase and more uniform deformation within this phase. [23)]

The effect of martensite morphology on the work hardening and $\Delta\sigma'$ are shown in figures 7a and 7b, respectively. It is seen that the martensite morphology has little effect on the work hardening increment (figure 7a) and temperature range of dynamic strain aging (figure 7b).

Conclusions

Dual phase microstructures with different volume fraction and morphology of martensite were produced by heat treating a carbon - manganese steel. Tensile tests were carried out at temperature range of 25- 550^{0}C. From the results the following can be deduced:

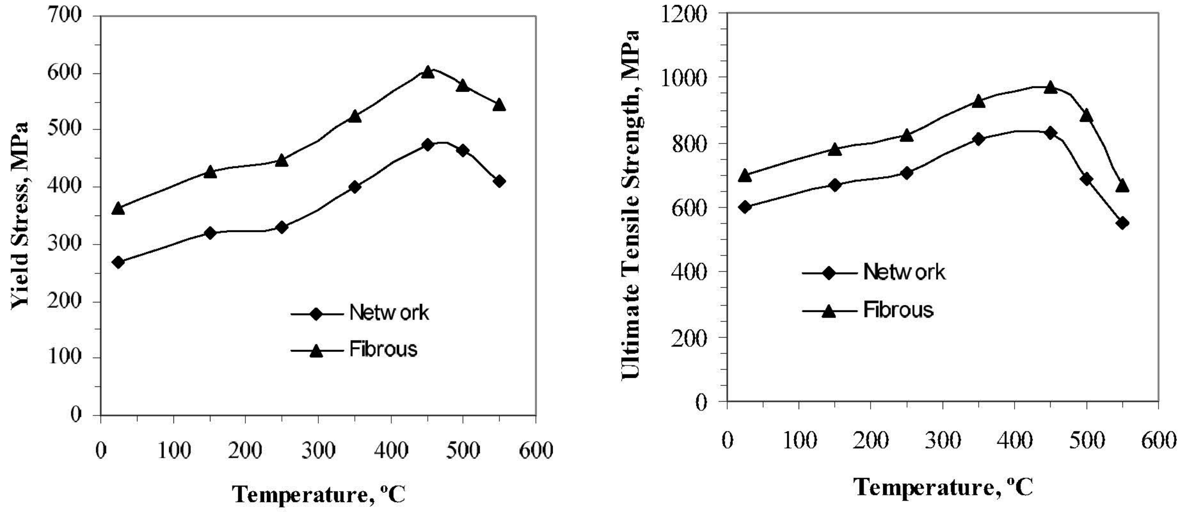
1- Stress- strain curves showed serration flow at temperature range of 250 - 350^{0}C and smooth flow at other temperatures. There was no effect of martensite morphology and volume fraction on the temperature range of serrated flow.

2- Both yield and ultimate tensile strengths increased with increasing temperature up to about 450^{0}C and then decreased at higher temperatures. The change in these parameters was related to the combined effects of dynamic strain aging, high temperature softening and martensite tempering.

3- At a given testing temperature, both yield and tensile strengths increased by increasing the martensite volume fraction or changing the martensite morphology from network martensite to fibrous martensite.

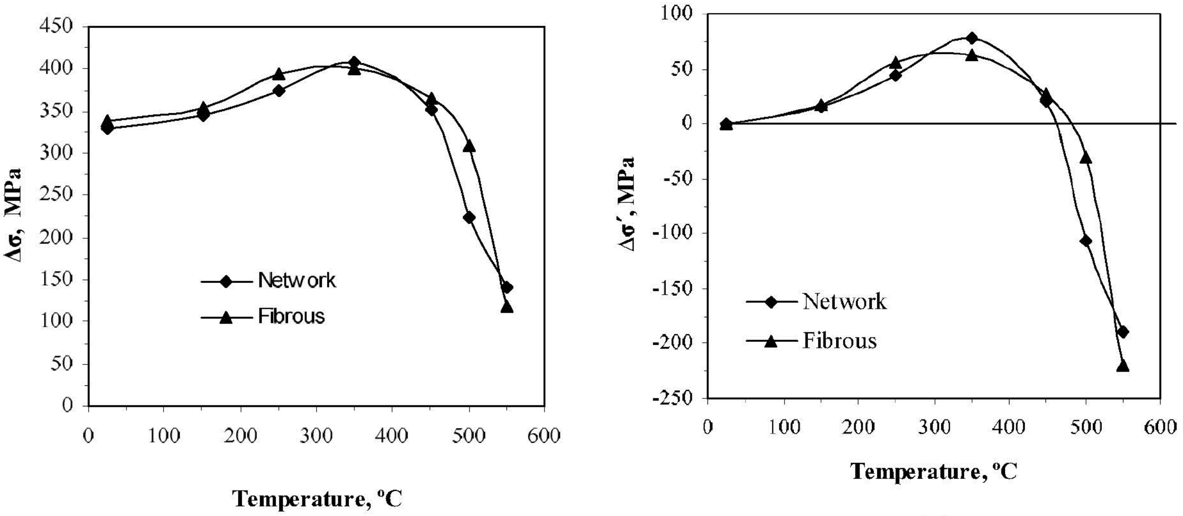
4- Work hardening increased with increasing temperature up to about 350^{0}C and then decreased at higher temperatures. Increasing the martensite volume fraction or changing the martensite morphology from network martensite to fibrous martensite caused an increase in the work hardening magnitude.

5- The difference between work hardening at a given temperature and that at room temperature, $\Delta\sigma'$, was increased with increasing temperature up to about 350^{0}C and then decreased at higher temperatures. Changing the martensite morphology had little or no effect on $\Delta\sigma'$, but at a given temperature, increasing the martensite volume fraction decreased $\Delta\sigma'$ which was related to the contribution of the martensite tempering and high temperature softening.



(a) (b)

Fig. 6. The effect of martensite morphology at different temperatures, for steel with 0.25 volume fraction of martensite, on: (a) Yield stress, and (b) Ultimate tensile strength.



(a) (b)

Fig. 7. The effect of martensite morphology at different temperatures on: (a) $\Delta\sigma$, and (b) $\Delta\sigma'$.

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