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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 steel 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 ÇELİKLERİNDEKİ ÇEKME DAVRANIŞINA ETKİSİ

ÖZET

Bu çalışmada ticari amaçlı olarak üretilen orta karbonlu ve düşük karbonlu mikroalaşım çelikleri kullanılmıştır. Çelikler % 5 soğuk olarak deforme edildikten sonra 100-450 ºC sıcaklık aralığında 1 saat yaşlandırılmıştır. Deforme edilen ve yaşlandırılan çelikler daha sonra kopuncaya kadar çekilerek mekanik özellikleri ölçülmüştür. Farklı sıcaklıklarda yaşlandırılan çeliklerin çekme ve akma dayanımı gibi mekanik özelliklerinin değiştiği gözlenmiştir. Yaşlanma, arayer atomlarıyla dislokasyonların arasında meydana gelen etkileşim sonucunda oluşmuştur. Sonuçlar dövme amaçlı üretilen orta karbonlu mikroalaşım çeliklerinin akma ve çekme dayanımlarının artmasından dolayı, düşük karbonlu mikroalaşım çeliklerine nazaran daha fazla gerinim yaşlanmasından etkilendiğini göstermektedir.

Anahtar Kelimeler : Gerinim yaşlanması; Mikroalaşımlı çelikler; Akma dayanımı; Çekme dayanımı

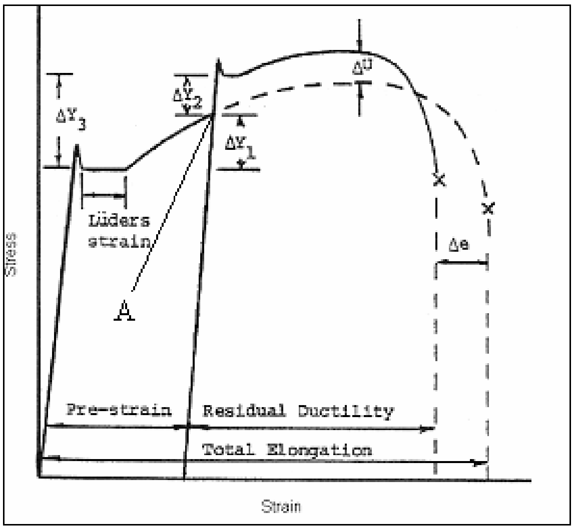
1. INTRODUCTION

Strain ageing is a phenomenon that causes the yield strength of a steel to increase due to lºCking of dislºCations following a prestrain and an ageing heat treatment. Strain ageing can either be dynamic or static, depending on whether the straining and ageing prºCesses 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 dislºCations present in the steel. The stress required to move a dislºCation with an atmosphere is greater than that required once the dislºCation 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 become 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 suggest that on ageing, solute atoms frozen in a random distribution throughout the matrix during rapid cooling migrate to free dislºCations, 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).



ΔY1 = Increase in stress produced by pre-strain; ΔY2 = Increase in stress produced by ageing; ΔY3 = Increase in stress due to pre-straining and ageing = ΔY1 + ΔY2; ΔU = Change in UTS due to pre-straining and ageing; Δe = 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 standart 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 ΔY1, and that subsequent ageing will produce a further stress increment, ΔY2. The overall effect of pre-straining and ageing is therefore the sum of ΔY1 and ΔY2 and can be termed ΔY3. 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 scaning 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 Nicon 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	-	.029

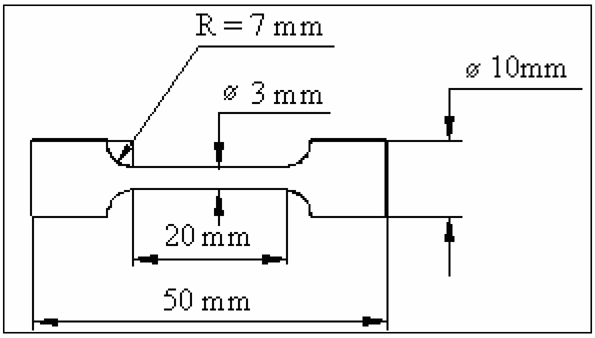
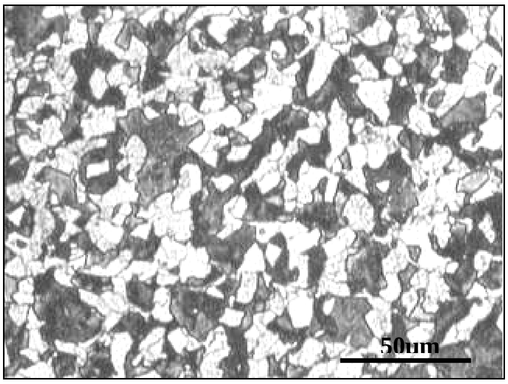


Figure 2. Schematic representation of tensile specimen

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 (ΔY1), increase in stress produced by ageing (ΔY2), increase in stress due to pre-straining and ageing (ΔY3), ultimate tensile strength, percentage elongation to fracture, change in UTS due to pre-straining and ageing (ΔU) and change in total elongation due to pre-straining and ageing (Δe).



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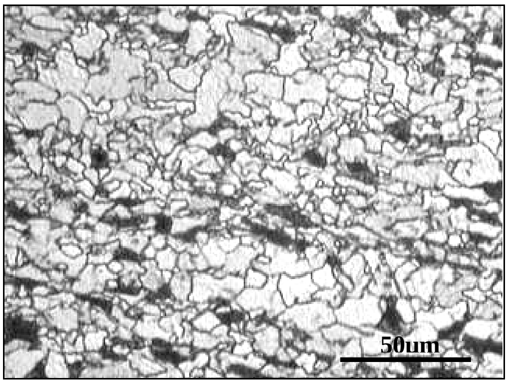

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Figure 3. Microstructure of medium carbon (a) and low carbon (b)

Table 2. Volume Fractions of Ferrite and Pearlite Phases in Steel 1 and Steel 2

Steel	Ferrite (%)	Pearlite (%)	Grain size (μm)
Steel 1	52 ± 2.5	48 ± 2,4	8.1 ± 0.25
Steel 2	79 ± 2	21 ± 2	9.8 ± 0.31

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

Steel	LYP (MPa)	UTS (MPa)	Elong. to Fracture (%)
Steel 1	500	702	15
Steel 2	380	506	33

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

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

Table 5. Static Strain Ageing Results for Steel 2, Pre-strained 5 % and Then Aged at Different Temperatures

Ageing Temp (°C)	Init. LYP (MPa)	Strength After Str. (MPa)	Final LYP (MPa)	ΔY1 (MPa)	ΔY2 (MPa)	ΔY3 (MPa)	UTS (MPa)	Total Elong. (%)	ΔU (MPa)	Δe (%)
100	380	458	477	78	19	97	515	33	9	0
150	383	460	481	77	21	98	518	34	12	+1
200	385	464	492	79	28	107	521	33	15	0
250	388	463	504	75	41	116	532	32	26	-1
300	384	457	503	73	46	119	532	31	26	-2
350	393	468	510	75	42	117	545	31	39	-2
400	393	464	492	71	28	99	540	32	34	-1
450	388	466	467	78	1	79	535	34	29	+1

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). Forexample, 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. % C 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.

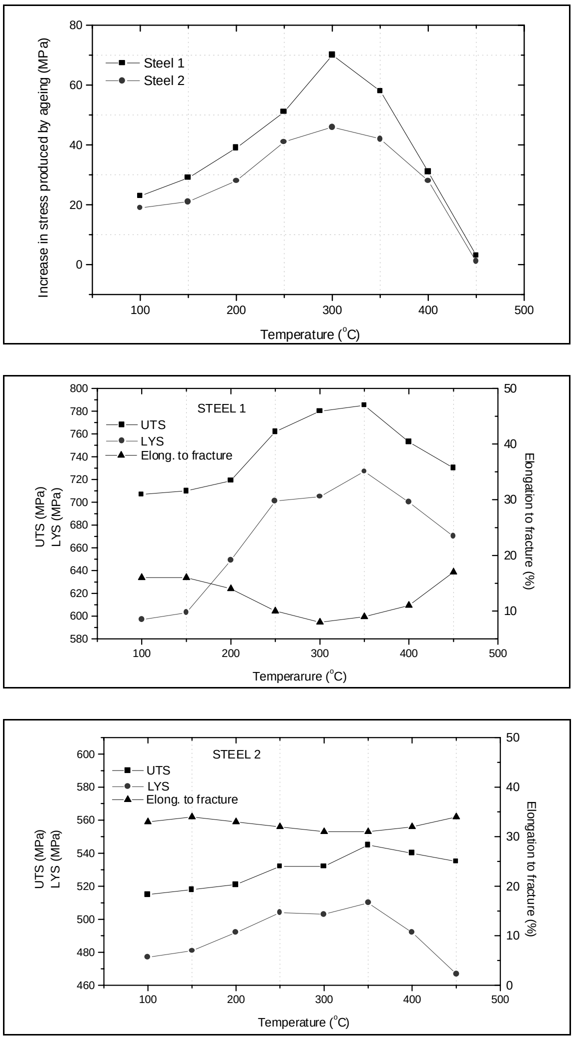
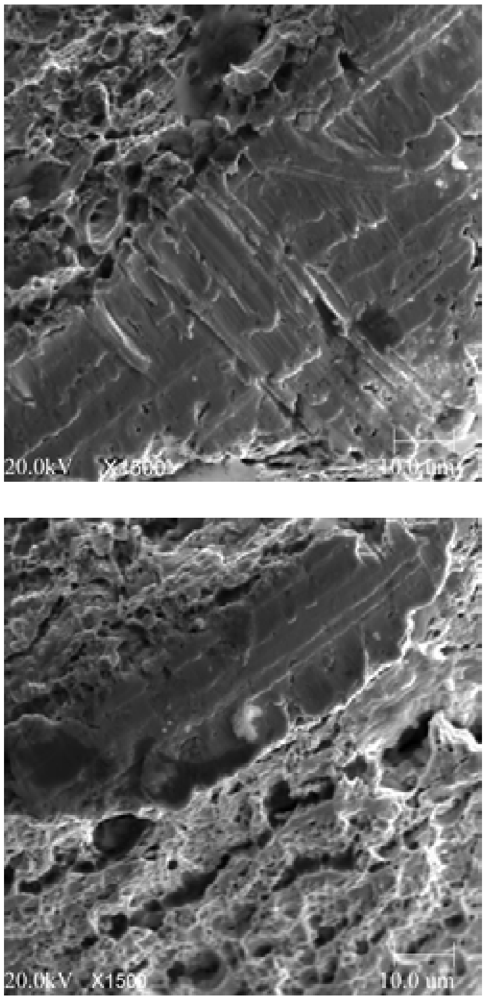


Figure 4. The effect of the static strain ageing on mechanical properties of microalloyed steels pre-strained 5% and than aged at different temperatures

It was also observed that the colour of specimens was changed by increasing temperature. For example, sample aged at 350 ºC 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 (BairdJamieson, 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 ºC) whereas in those to which carbon or nitrogen had been added, pronounced strengthening effects were present in the range 100-350 ºC. After ageing at 400 ºC and 450 ºC, overageing ºCcurs and the ass ºCiated 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 ºC, (see Figure 4). This was shown by elongation values as well as by fracture surface analysis. Steel 2 pre-strained 5 % and than aged at 300 ºC for 1 hour showed ductile dimple fracture surface at the microscopic level (Figure 5b). Microscopically a surface covered by dimples of severel 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).



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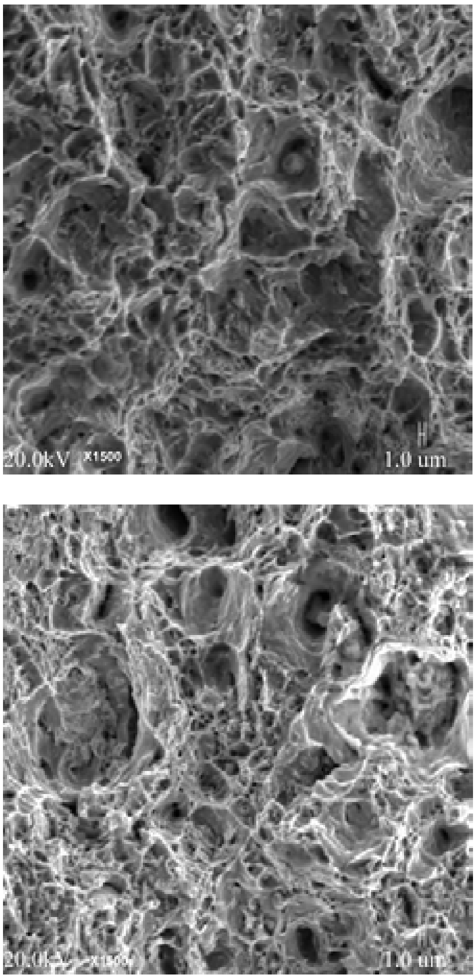

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Figure 5. Fracture surfaces of steel 1(a) and steel 2 (b) pre-strained 5 % and than aged at 300 ºC for 1 hour

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.

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