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THE EFFECT OF THE COOLING RATE ON THE YIELD BEHAVIOUR IN Ti-V-Al INTERSTITIAL FREE STEELS

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ABSTRACT

In this work, steel chemistry and the effects of the cooling rate on the yield behaviour in Ti-V-Al interstitial free steel were investigated experimentally for six grades of steel plate. The steels were austenitised at 950 ± 10 °C for 15 minutes and then cooled at different cooling rates in order to see the effect of different cooling rates on yield behaviour of interstitial free steels. Reducing the cooling rate reduces the yield point elongation and is conducive to continuous yielding. Grains are coarsening during slow cooling, this decrease yield strength of the steels. Vanadium additions allow discontinuous yielding over a wide range of cooling rates compared to Ti steels.

Key Words : Cooling rate; Interstitial free steels; Yield strength

SOĞUMA HIZININ ARAYER ATOMU İÇERMEYEN Ti-V-Al ÇELİKLERİNDEKİ AKMA DAVRANIŞINA ETKİSİ

ÖZET

Bu çalışmada çelik kimyası ve soğuma hızının arayer atomu içermeyen Ti-V-Al çeliklerindeki akma noktasına etkisi altı çeşit çelik levha için deneysel olarak araştırılmıştır. Çelikler, 950 ± 10 °C de 15 dakika östenitleme işlemi uygulandıktan sonra farklı soğuma hızlarının arayer atomu içermeyen çeliklerdeki akma noktası üzerine etkisini araştırmak için farklı soğuma hızlarında soğutulmuştur. Soğuma hızının düşmesi akma noktası uzamasını düşürerek sürekli akma davranışına sebep olmuştur. Yavaş soğuma süresince taneler büyüyerek, çeliklerin akma dayanımını düşürmüştür. Çeliklere vanadyum'un eklenmesi, titanyum çelikleriyle karşılaştırıldığında geniş bir soğuma aralığında sürekli olmayan akmaya izin vermiştir.

Anahtar Kelimeler : Soğuma hızı; Arayer atomu içermeyen çelikler; Akma noktası

1. INTRODUCTION

In recent years, because of the world energy crisis, efforts have been made to develop high-strength steel to enable weight-reduction of automobiles etc. Therefore, an important task is to increase strength of steel while retaining optimum plasticity and ductility (Juanying et all., 1992).

Sheet steel has remained the main material used for the construction of the body and skin of a motor vehicle ever since mass production began earlier this century. Steel is relatively cheap and can be economically formed to make parts with complicated shapes. These parts can be welded to form a complete car assembly which has a high degree of rigidity, due in part to the high elastic modulus of steel. With a good design, a steel motor vehicle is also able to absorb energy in controlled manner in a crash situation as a result of the nature of the stress-strain relationship in steel (Dasarathy et all., 1990).

The formability of steel sheet is closely related to their mechanical properties. In general, low yield strength (YS) and high elongation (EL) improve stretchability, and a higher plastic strain ratio (r-value) improves the deep-drawability. Solute carbon and nitrogen remaining in steel sheet may cause not only the deterioration of mechanical properties due to strain ageing, but also a problem due to stretcher strain markings during press forming. Therefore steel sheets for forming must posses:

1) High ductility
2) High r-values
3) A good anti ageing property.

Steel sheets that meet these properties are generally called deep drawing quality (DDQ) steel sheet (Satoh et all., 1985). Automotive consumers of D.D.Q. sheet steels are requiring steel producers to develop steels with improved drawability. As a result, steel companies have developed ultra low carbon interstitial free steels (U.L.C.-I.F.) with carbon levels typically less than 50 ppm (by weight) and alloyed with titanium and vanadium to remove interstitial elements from solid solution (James et all., 1992) .

Although the effects of hot rolling conditions and annealing temperature on mechanical properties has been clarified, the influence of cooling rate has not been investigated in detail. It has been shown only that microstructure and mechanical properties were quite different between water-quenched and slowly cooled specimens (Obara et all., 1982). The purpose of this experiment is to examine in some detail in an attempt to explain how the cooling rate effects the tensile properties and grain size of the six grades of interstitial free steels.

3. EXPERIMENTAL PROCEDURE

Six types of low carbon steels were ordered from British Steel Technical (BST). Table 1 shows chemical composition of the steels. The steels contained titanium, vanadium and aluminium in different proportion. These steels were vacuum melted and cast into 50 kg ingots which were then machined for surface finish and subsequently hot rolled to form flats. Before machining tensile test specimens, steels were heat treated. Eighteen tensile test specimens were prepared for six types of low carbon steels. All samples were austenitised at 950 ± 10 °C for 15 minutes. Batches of samples were either cooled in air (AC, 5.9 °C/s) or cooled in sand (SC, 4.2 °C/s), whilst others were cooled in a furnace (FC, 0.06 °C/s) in order to see the effect of different cooling rates on yield behaviour of interstitial free steels. After austenitisation at 950 °C for 15 minutes, the cooling rates between 800 °C and 500 °C were measured for AC (5.9 °C/s), SC (4.2 °C/s) and FC (0.06 °C/s) conditions with Flux Hydra data logger which recorded time and temperature as the specimen cooled.

Table 1. Compositions of Steels 1, 2, 3, 4, 5, and 6 Ordered From British Steel Technical

	Steel 1	Steel 2	Steel 3	Steel 4	Steel 5	Steel 6
C	0.004	0.007	0.005	0.003	0.007	0.007
Si	< 0.02	0.02	< 0.02	< 0.02	0.01	0.01
Mn	0.26	0.23	0.21	0.21	0.21	0.21
S	0.005	0.004	0.004	0.004	0.003	0.002
P	0.005	< 0.005	< 0.005	< 0.005	0.005	0.005
Ti	—	—	—	0.056	0.019	0.039
V	—	0.042	0.086	< 0.005	0.080	0.075
Al	0.049	0.046	0.017	0.029	0.028	0.044
O	0.0073	0.0033	0.0040	0.0026	0.066	0.0046
N	0.0025	0.0024	0.0026	0.0022	0.0023	0.0026

Manufacturing of the tensile test pieces was done after heat treatment to eliminate the effect of oxidation caused by the heat treatment. Tensile test pieces were manufactured in accordance with BS EN 10 002-1 : 1990 Annex C for nonproportional test pieces. The tensile test pieces were ground to ensure the removal of cavity, scratch and stress raisers.

The tensile test pieces were tested using a Mayes SM 50 tensile testing machine at a crosshead separation rate of 4.0 mm/minute. Plots of applied load against extension were obtained from a chart recorder. Values of yield point (YP), 0.2 % proof stress (0.2 % PS), ultimate tensile strength (UTS), percentage elongation to fracture and percentage yield point elongation were calculated from the plots. In order to determine workhardening index, n, it was necessary to calculate true stress, σ, and true strain, ε, for the region of uniform plastic deformation from the end of Luders extension up to the maximum load. The workhardening index, n, given by Ludwik-Hollman equation was estimated from the slope of a log σ / log ε plot as shown below:

$$\sigma = k\varepsilon^n \quad (1)$$

$$\log \sigma = \log k + n \log \varepsilon$$

Where σ is true stress, ε is true strain, k is the workhardening coefficient and n is the work hardening index (Roger, 1985).

Metallographic samples were prepared from the undeformed heads of the tensile specimens. Grain sizes were measured using intercepts along a test line oriented at 45° to the rolling direction. At least 500 grain boundaries were counted for each sample. After counting grain boundaries, the total length of the intersecting lines was recorded and the following formula was used to determine mean linear intercept grain size of the ferrite (Gladman, 1997).

$$i_\alpha = \ell\,(1 - f_p) / n_\alpha \quad (2)$$

Where:

i_α = mean linear intercept grain size of the ferrite
ℓ = total length of the measurement line
f_p = the volume fraction of pearlite
n_α = the number of the ferrite grains cut by the intersecting line

4. RESULTS

The microstructure of the optical micrographs consists of equiaxed grains of varying sizes. Table 2 shows grain size of the AC (5.9 °C/s), SC (4.2 °C/s) and FC (0.06 °C/s) samples after austenitisation at 950 °C for 15 minutes. It was observed that when the cooling rate is high such as AC (5.9 °C/s) cooling, steels have a fine grain size. If the cooling rate is lower than AC (5.9 °C/s) cooling, steels have medium grain size. At the lowest cooling rates, for example FC (0.06 °C/s) cooling, steels showed coarse grain sizes.

Table 2. Grain Sizes of the AC (5.9 °C/s), SC (4.2 °C/s) and FC (0.06 °C/s) Steel Samples Austenitised at 950 °C for 15 Minutes

Medium	Steel 1 (μm) ±σ (st.d.)	Steel 2 (μm) ±σ (st.d.)	Steel 3 (μm) ±σ (st.d.)	Steel 4 (μm) ±σ (st.d.)	Steel 5 (μm) ±σ (st.d.)	Steel 6 (μm) ±σ (st.d.)
Air	72 ± 2.3	47 ± 1.5	47 ± 1.5	112 ± 3.5	82 ± 2.6	101 ± 3.2
Sand	77 ± 2.4	52 ± 1.6	50 ± 1.6	130 ± 4.1	86 ± 2.7	119 ± 3.7
Furnace	80 ± 2.5	67 ± 2.1	61 ± 1.9	163 ± 5.1	90 ± 2.8	145 ± 4.5

Figure 1 shows optical micrographs of the AC (5.9 °C/s), SC (4.2 °C/s) and FC (0.06 °C/s) samples from steels 2 and 4 respectively after austenitisation at 950 °C for 15 minutes. The variations in grain size are clearly shown. Table 3 also shows the tensile test results for the steels austenitised at 950 °C for 15 minutes and then cooled at different cooling rates.

Steels 1, 2, 3, and 5 which were austenitised at 950 ± 10 °C for 15 minutes and then AC (5.9 °C/s), SC (4.2 °C/s) and FC (0.06 °C/s) cooled showed discontinuous yielding behaviour. However AC (5.9 °C/s) steel samples showed sharper yield point than those cooled more slowly. SC (4.2 °C/s) steel samples showed weaker yield points than AC (5.9 °C/s) samples, but sharper yield point than FC (0.06 °C/s) samples. FC (0.06 °C/s) samples, having the lowest cooling rate, showed very weak yield points.

Both steels 4 and 6 showed continuous yielding after FC (0.06 °C/s) cooling. However steel 6 showed a sharp yield point after SC (4.2 °C/s) coolig while steel 4 showed a weak yield point, but both of them showed similar yielding behaviour after AC (5.9 °C/s) cooling.

5. DISCUSSION

After austenitisation at 950 °C for 15 minutes and cooling at the rates described in section 4, the steels showed differences in grain sizes as shown in Table 2. As expected, AC (5.9 °C/s) cooling, having the highest cooling rates, gave a smaller grain size. Conversely FC (0.06 °C/s) cooling, having the lowest cooling rate, gave coarser grain sizes. Because an increase in cooling rate lowers transformation temperature and gives faster ferrite nucleation and leads to a fine grain size (Gündüz, 2000).

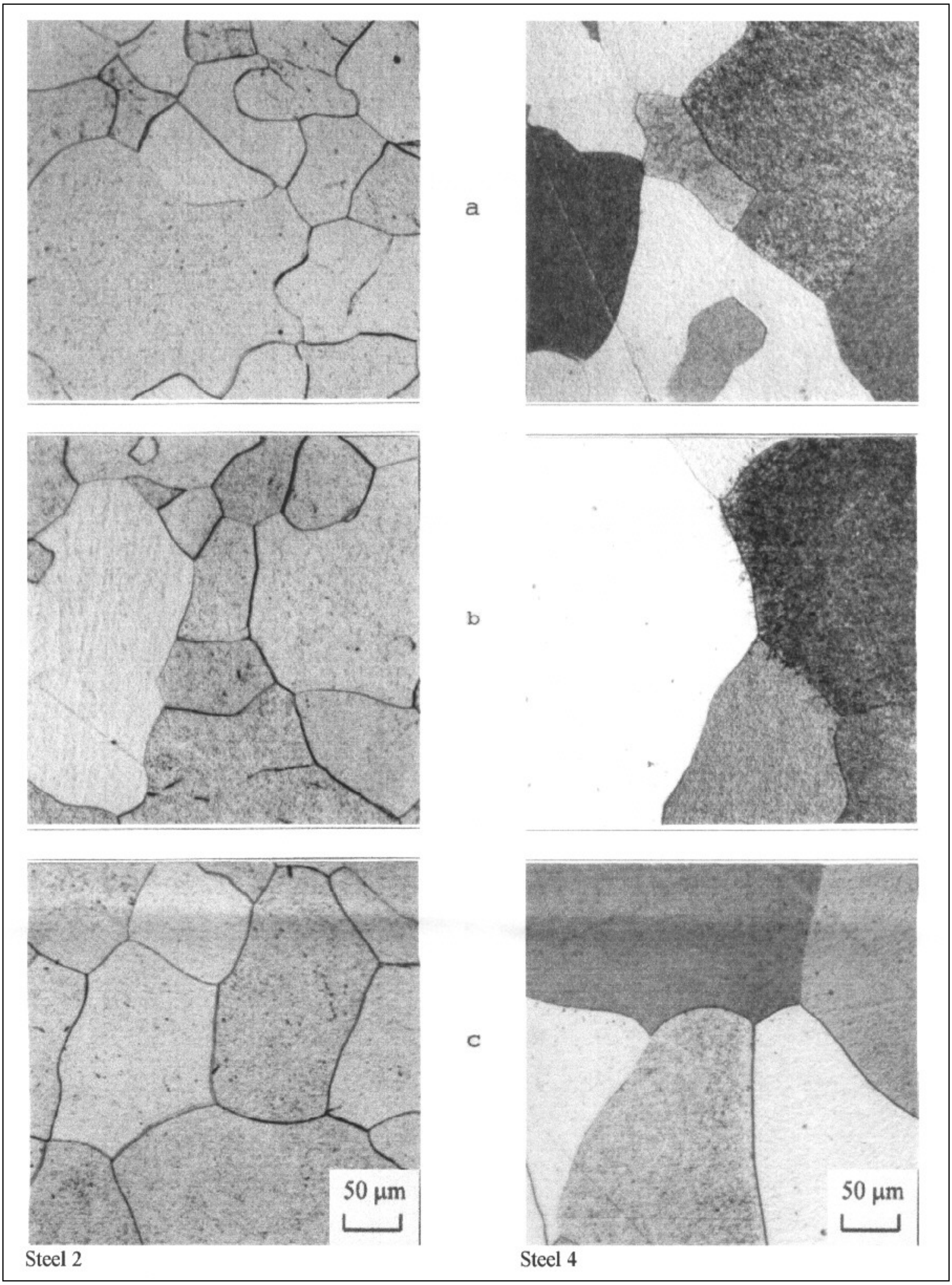

Figure1. Optical micrographs of steel 2 and steel 4 austenitised at 950 °C for 15 minutes and then a) AC (5.9 °C/s) b) SC (4.2°C/s) and c) FC (0.06 °C/s).

Table 3. Tensile Test Results of the AC (5.9°C/s), SC (4.2°C/s) and FC (0.06°C/s) Steel Samples Austenitised at 950 °C for 15 Minutes

Sample	LYP (MPa)	UTS (MPa)	El.toFrac. (%)	YP.El. (%)	W.Har.In (n)
Steel 1					
Air	158	262	42	0.3	0.288
Sand	146	259	46	0.6	0.294
Furnace	143	258	47	0.6	0.297
Steel 2					
Air	174	290	36	0.8	0.262
Sand	173	276	37	0.8	0.270
Furnace	150	265	38	0.6	0.280
Steel 3					
Air	187	273	38	1.47	0.269
Sand	168	271	41	1.26	0.271
Furnace	148	260	52	1.05	0.282
Steel 4					
Air	130	248	50	0.31	0.295
Sand	129	238	53	0.31	0.304
Furnace	112*	232	56	—	0.316
Steel 5					
Air	161	256	46	0.63	0.263
Sand	159	254	44	1.05	0.270
Furnace	133	238	47	63	0.279
Steel 6					
Air	151	252	46	0.42	0.267
Sand	137	245	33	0.21	0.277
Furnace	107*	238	54	—	0.299

* : No yield point - 0.02 % Proof stress

Therefore, AC (5.9°C/s) or SC (4.2 °C/s) cooling would be expected to give smaller grains compared to FC (0.06 °C/s) cooling.

All of the steels showed lower yield point elongation under certain condition. For steel 4 and steel 6 the yield point elongation disappeared after FC (0.06 °C/s) cooling. It is known (Snoek, 1941 and Low, 1944) that removal of carbon and nitrogen from steel eliminates discontinuous yielding. It was also observed that AC (5.9 °C/s) cooling, having the highest cooling rate, showed the sharpest yield points. On the contrary FC (0.06 °C/s) cooling, having the lowest cooling rate, showed very weak or continuous yield behaviour. SC (4.2 °C/s) cooling also showed weaker yield points than AC (5.9 °C/s) cooling but sharper yield points than FC (0.06 °C/s) cooling.

Usually the yield point can be associated with small amounts of interstitial impurities. Only 0.0001 % of carbon and nitrogen is required for the appearance of a yield point (Baird, 1963) It is possible that the cooling rate during AC (5.9 °C/s) cooling was not sufficiently slow to allow full precipitation of all carbides (TiC, V4C3, NbC or Fe3C), this indicates presence of carbon and/or nitrogen interstitials in solution (Krupik and Gladman, 1992). Therefore AC (5.9 °C/s) cooling showed discontinuous yielding behaviour and the sharpest yield points. On the other hand FC (0.06 °C/s) cooling, which has the lowest cooling rate tended to continuos yielding behaviour indicating the removal of carbon and nitrogen interstitials.

For steel 2 and steel 3 containing vanadium showed discontinuous yielding behaviour, a smaller grain size and higher yield points compared to the other steels for all cooling conditions. In steel 2 the amount of vanadium is not sufficient as much as steel 3 to fix all the carbon and nitrogen. In steel 3, although the amount of vanadium is sufficient the cooling rate was not sufficient to allow full precipitation. Also the solubility of TiN and AlN is very low at 950 °C compared to VCN, (Gladman, 1989). This means that vanadium can contribute to fixing carbon and nitrogen only at lower temperature. It is also considered that precipitates of VN in ferrite can prevent grain growth of ferrite and lead to a fine grain size in the final steel after annealing (Sage, 1992). For steel 4, the ratio of the amount of titanium to that of C+N is greater than 10 which makes the amount of titanium sufficient to fix all the carbon and nitrogen. Therefore steel 4 showed the lowest yield point and ultimate tensile strength but larger elengotion to fracture for all cooling condition compared to steels 1, 2, 3, 5 and 6, see Table 3. As also discussed before that steels 2 and 3, containing vanadium, showed the smallest grain size and higher yield strength. This is consistent with the Hall-Petch relationship. On the contrary steels 4, 5 and 6, containing titanium, showed the biggest grain sizes and lowest yield strengths. It is belived that this is due partly to differences in precipitate size and distributions.

It was also observed that when the yield strength of the materials is high, work hardening index, n, is low, see Figure 2. It means that stretchability, which is a measure of the steels ability to be stretched without splitting or local necking, decreases with increasing yield strength. This is consistent with the suggestions of Roger, (1985) who found in general that for each type of steel the work hardening index, n, decreases as the yield and tensile strength increases.

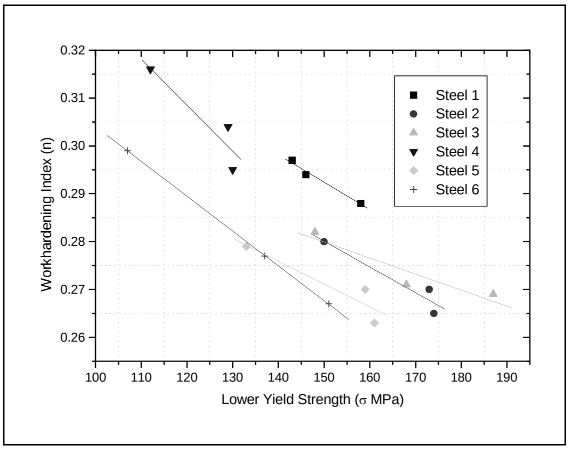

Figure 2. Relationship between lower yield strength and workhardening index (n) for steel austenitised at 950 °C for 15 minutes and then cooled at different cooling rates.

6. CONCLUSION

Steel chemistry and the effect of the cooling rate on the yield behaviour in Ti-Al-V interstitial free steel were investigated. The obtained results are summarised as follows.

1. Reducing the cooling rate reduces the yield point elongation and is conducive to continuous yielding.
2. AC (5.9 °C/s) cooling, having the highest cooling rate, showed the sharpest yield points, while FC (0.06 °C/s) cooling, having the lowest cooling rate, showed very weak or continuous yielding. It is believed that the highest cooling rate does not allow sufficient time for full precipitation of all carbides and nitrides. This indicates presence of carbon and/or nitrogen interstitial in solution.
3. Vanadium additions allowed discontinuous yielding over a wide range of cooling rates compared to Ti steels.
4. High vanadium addition (0.086 wt %) gave the highest yield strength due to undissolved precipiatates at heat treatment temperature (dispersion strengthing) and also precipitates during cooling (dispersion and precipitation strengthing).
5. High Titanium additions (0.056 wt %) gave the lowest yield strength and a coarse grain size due to decreased dispersion strength. It is belived that particles of the titanium carbo-nitrides were coarse during austenitization. Therefore they were less effective for preventing grain growth.
6. Increasing the yield strength decreases the work hardening index and elongation. It means that stretchability, which is a measure of the steels ability to be stretched without splitting or local necking, decreases with increasing yield strength.

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