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High Temperature Ductility Loss of 16MnCr5 Pinion Steels

Haiwen Luo, Pei Zhao, Zijiu Dang

Metallurgy School, University of Science and Technology Beijing, Beijing 100083, China

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Abstract: A wide ductility trough covering from 700 to 1100 is observed in the curve of Reduction of Area (RA) *vs.* temperature for 16MnCr5 pinion steel. At 750℃, corresponding to the minimum of RA, it is grain boundary sliding that controls its hot ductility rather than usual Deforming Induced Ferrite (DIF), which can only appear just below 750℃ and slightly improve hot ductility. The volume fraction of ferrite is dependent on the strain and strain rate. Firstly a critical strain must be necessary for formation of DIF, then with strain rate increasing, the volume fraction of DIF decreases but RA is elevated. In the γ phase region, hot ductility is seriously deteriorated because of grain boundary sliding promoted by oxides and sulfides at the grain boundary and recovered because of dynamic recrystallization at higher temperature; when strain rate increases, ductility is improved as there is insufficient time for cracks to propagate along the γ grain boundary as well as dynamically precipitating, and ductility trough becomes narrower because the temperature for onset of dynamic recrystallization decreases. In addition, $\gamma \rightarrow \alpha$ phase transformation introduced by temperature drop before the tensile test encourages precipitation of AlN and impairs ductility.

Key words: hot ductility; deforming induced ferrite; grain boundary sliding; precipitates

Transverse cracking can be a serious problem in continuous casting when the steel strand is cast in a curved mould and has to be straightened. The cracks are found to be intergranular along the prior γ grain boundaries and encouraged by precipitation [1,3,5,7].

The simple hot tensile test has been found extremely useful in assessing the likelihood of the strand giving rise to transverse cracking. The hot tensile ductility is found to be poor in the temperature range of straightening operation when testing conditions are chosen to simulate those undergone by the strand, namely, a high initial solution temperature, 1 350 ℃, to dissolve all the microalloying elements and produce a coarse grain size reminiscent of the as cast grain size and the cooling rate to the test temperature and the strain rate chosen to be the same as that undergone by the strand. So based on the experimental results, the temperature range with poor ductility for this strand can be predicted and the cooling and straightening process can be designed to avoid transverse and edge cracks on strand [1~8].

1 Experimental

The chemical composition of commercial 16MnCr5 pinion steel investigated (mass fraction in %) is C, 0.16; Mn, 1.13; Si, 0.25; P, 0.011; S, 0.025; Cr, 0.97; Ni, 0.06; Mo, 0.04; Al, 0.05; N, 0.01; Cu, 0.14; W, 0.06. The tensile samples of 10 mm in diameter and 120 mm in length were taken with their longitudinal axes parallel to the rolling direction.

The high temperature tensile tests were performed on a computerized thermal stress/strain simulator, Gleeble 1500, and the Reduction of Area (RA) at fracture was used to evaluate ductility. The heating and deforming processes used to simulate the straightening operation are shown in **figure 1**(a). The reheating temperature of 1 350 ℃ was chosen to ensure the dissolution of almost all precipitation, and the deforming rate varied from 10^{-3} to 5×10^{-3}/s, particularly at 725 ℃ of $\gamma + \alpha$ duplex phase, deforming rate was chosen from 10^{-4} to 5×10^{-3}/s to investigate the effect of strain and strain rate on the volume fraction of deforming induced ferrite and hot ductility. In addition, temperature drop before the tensile test, shown in figure 1(b), is introduced to simulate the practical continuous casting process, on which the temperature on the surface of strands falls to 600~700 ℃ just after running out of the mould.

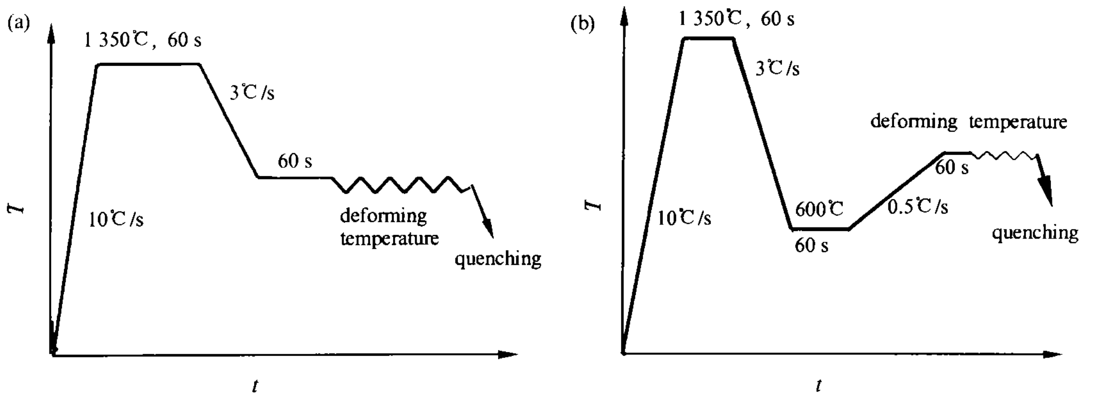

Figure 1 Heating and deforming process during the hot tensile test. (a) to simulate the straightening operation, (b) to simulate the practical continuous casting process

Immediately after rupture, the broken specimen was water quenched. Thus allowing a correlation between the microstructure and the hot ductility, and fracture were examined by a Scanning Electron Microscope (SEM). The quenched samples were sectioned longitudinally with respect to the test direction for metallography of the fracture subsurface region. The samples which were tested at temperatures corresponding to the duplex austenite-ferrite region were etched with 4% nital, thus delineating the austenite grain boundaries by ferrite, and the volume fraction of the phases present was estimated from the thickness of ferrite. In the case of single austenite phase, etching was performed by immersion into a hot solution of saturated aqueous picric acid to reveal the prior austenite grain size. Some limited extraction replicas were taken from the part close to fracture to examine the precipitate distributions using a transmission electron microscope.

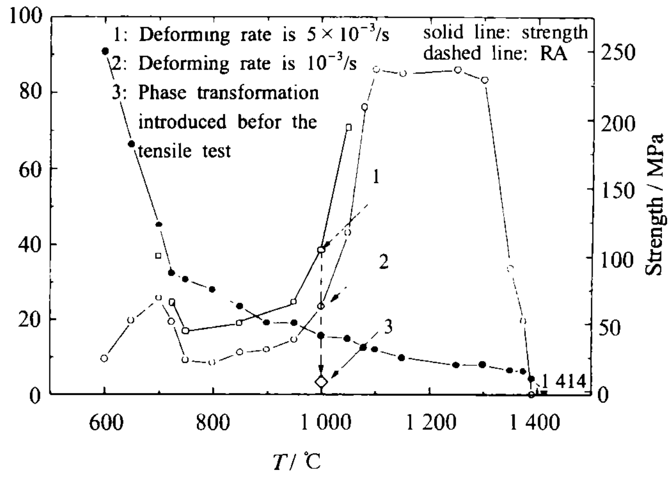

Figure 2 Curves of reduction of area and strength *vs.* temperature

2 Results

2.1 Hot tensile ductility and effect of strain rate and thermal history on ductility

The curve of hot strength and hot ductility *vs.* temperature is shown in **figure 2**. With the temperature increasing, the hot strength keeps decreasing but ductility shows a trough covering from 700 to 1100 ℃ at the deforming rate of 10^{-3}/s. Nib-strength temperature is 1 414 ℃ and Nib-ductility temperature 1 400 ℃. When the strain rate increases from 10^{-3} to 5×10^{-3} /s, RA value is almost doubled, but when temperature drop before the tensile test is introduced to result in $\gamma \rightarrow \alpha$ phase transformation, hot ductility is impaired and RA decreases from 23.5% to 3.38% at 1000 ℃.

2.2 Fractography and failure of mode analysis

When the testing temperature is below 1 050 ℃ and strain rate 10^{-3}/s, samples finally deforms to failure by intergranular rupture, but there are two types of fractography. At 700 ℃, shown in **figure 3**, there are many ductile dimples on the surface of separated grains; on the etching polished sample, ferrite film can be observed to form along the prior austenite grain boundaries, and it includes many oxides and sulfides as nuclei to form microvoid during deforming. But at the elevated temperature of 750 ℃, no ferrite is observed and separated grain facets on the intergranular fracture surface are predominantly flat, shown in **figure 4**; at a further increasing temperature of 1 100 ℃, a obvious necking and many voids on the fracture surface can be observed, shown in **figure 5**, which means that fracture mode changes from intergranular to transgranular

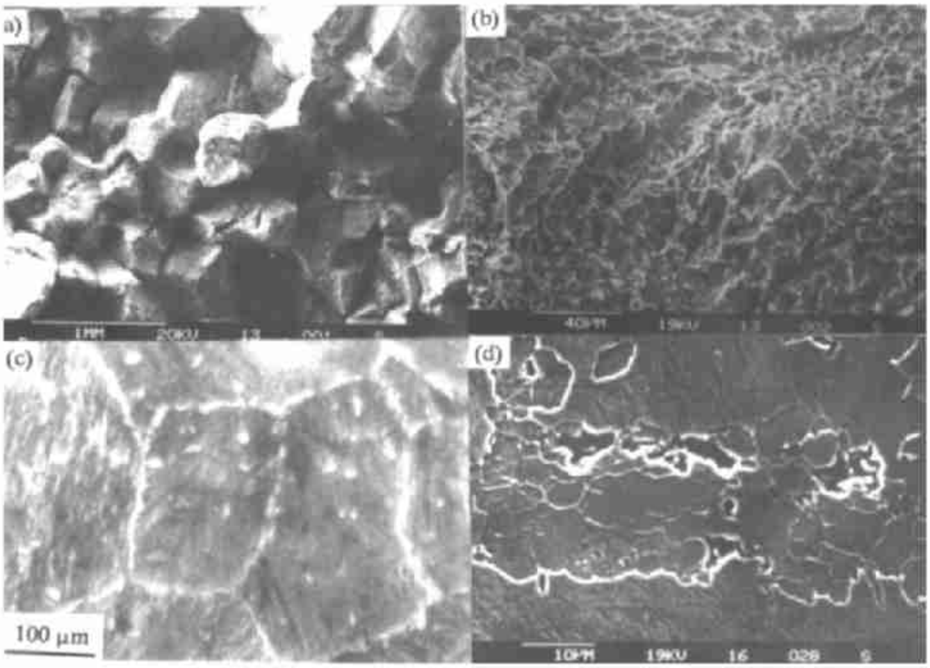

Figure 3 Fracture appearance and microstructure at 700℃. (a) intergranular fractography, (b) shallow dimples on the separated grain facet, (c) deforming induced ferrite along the γ grain boundaries, (d) formation of voids at the inclusions within the grain boundary ferrite film

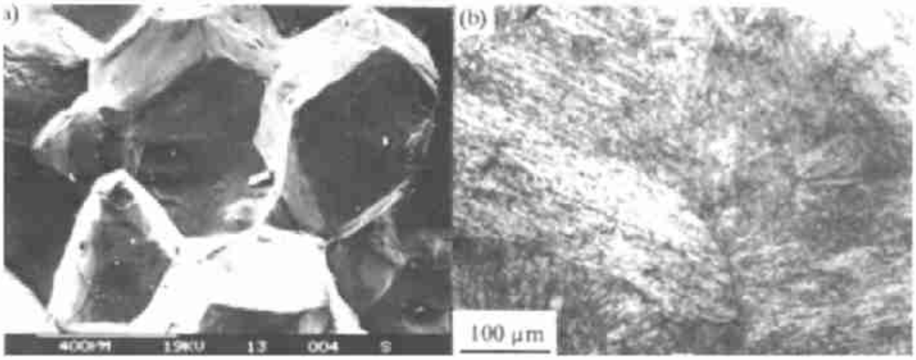

Figure 4 Fracture appearance and microstructure at 750℃. (a) intergranular fractography, (b) no ferrite observed, 4% nital etching

ductile fracture because of onset of dynamic recrystallization.

2.3 Deforming induced ferrite and hot ductility loss

At 725 ℃ of duplex phase region, with strain rate increasing from 10^{-4} to 5×10^{-3}/s, the thickness of ferrite film tends to decrease but hot ductility is improved, shown in **figure 6**, and almost no ferrite can be observed at the grain boundaries without strain, which mean that the ferrite film at the grain boundaries is deforming induced ferrite and sufficient strain is necessary for its formation.

3 Discussion

3.1 Effect of grain inclusions and precipitates on formation of cracks

For the steel investigated two types of precipitates and inclusions can be present in austenite, namely, oxide-sulfide inclusions and sulfide precipitates, shown in **figures 7 and 8**. Although concentrations of Al and N are high and the soluble product exceeds 2.5×10^{-4}, which is a critical value for AlN precipitation in according to the research by Mintz [5], almost no AlN precipitates was observed, probably because

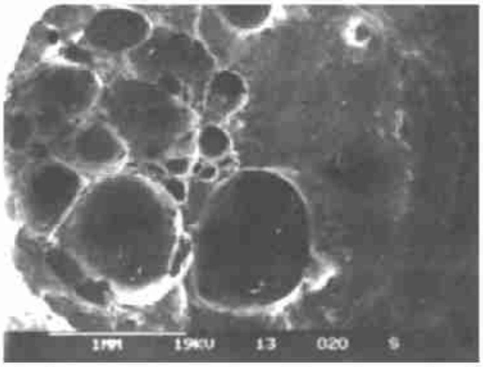

Figure 5 Ductile fracture appearance at 1100℃

reaction of AlN precipitation was very sluggish and the cooling (3 ℃/s) from high temperature solution was faster than one (1℃/s) adopted in the research carried out by Cardoso, *et al.* [1]. Oxide inclusions of CaO as a deoxidization product have not been removed from steel liquid in time and stay at the austenite grain boundaries in accompany with sulfides subsequently precipitating during solidification. So they can pin the grain boundaries and encourages cracks forming by grain boundary sliding to link up, shown in figure 7. A large quantity of fine MnS precipitated from high temperature austenite during cooling can be observed at 750℃, and it becomes coarse with increasing temperature, shown in figure 8.

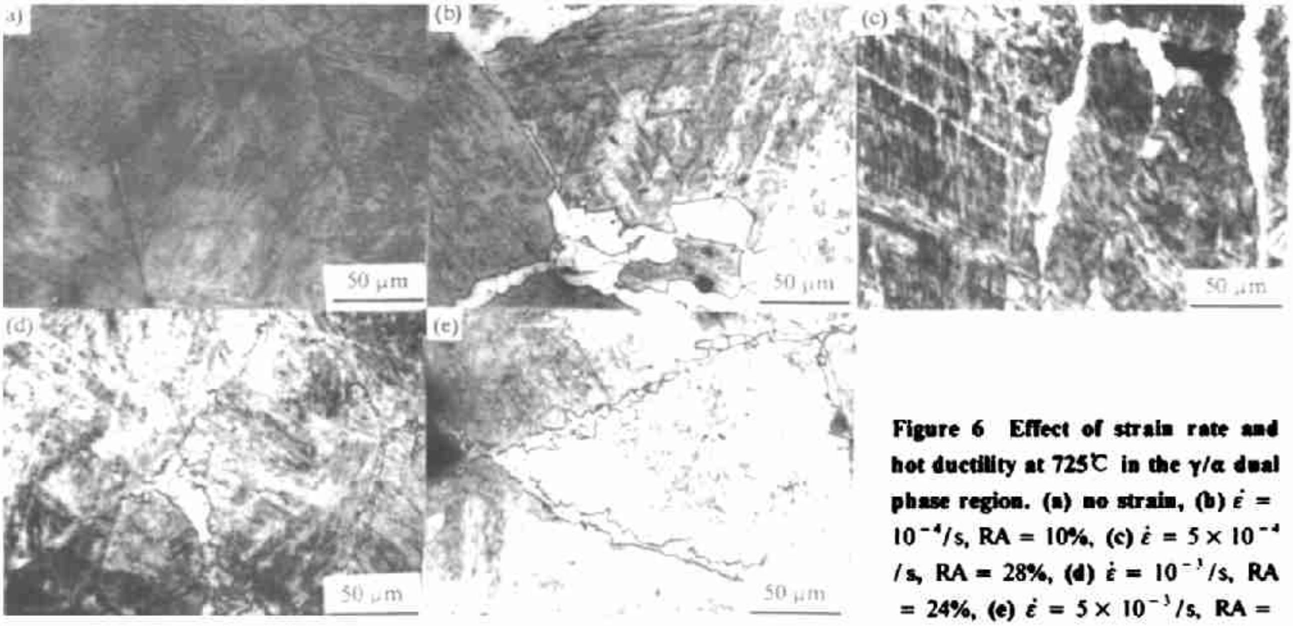

Figure 6 Effect of strain rate and hot ductility at 725℃ in the γ/α dual phase region. (a) no strain, (b) $\dot{\varepsilon}$ = 10^{-4}/s, RA = 10%, (c) $\dot{\varepsilon}$ = 5 × 10^{-4}/s, RA = 28%, (d) $\dot{\varepsilon}$ = 10^{-3}/s, RA = 24%, (e) $\dot{\varepsilon}$ = 5 × 10^{-3}/s, RA = 33%

When temperature drop is introduced to result in γ→α phase transformation, which simulates the process of continuous casting that temperature on the surface of strands firstly drops to 600~700℃ at the time of just running out of mould and then gradually increases to the straightening temperature, many AlN particles precipitates and deteriorates the hot ductility further, shown in **figure** 9.

3.2 Grain boundary sliding controlling hot ductility

At the bottom of ductility trough, grain sliding, often promoted by inclusion and precipitates, seriously deteriorates the hot ductility. Even if at the lowest temperature of ductility trough, namely 750℃, it was observed that not grain boundary ferrite deformation but grain boundary sliding results in intergranular fracture, which is different from previous researches. Many researchers [1~8] believe that deforming induced ferrite film of about 20 μm thickness results in the minimum ductility and ductility will keep being improved when its thickness increases. But for this investigated steel, when DIF appear from 750 to 725 ℃ (figure 6(c)), ductility increases from 10% to 20%, and is only slightly improved from 725 to 700℃ accompanying with increasing ferrite volume fraction. Particularly, when temperature decreases from 700 to 600℃, ductility decreases from 20% to 10% because of formation of a large quantity of intragrain ferrite and pearlite. It is assumed that grain boundary ferrite can usually deform to a certain strain before failure with reduction of area between 20%~40% [1,2,5,8], however, in this experiment, serious grain boundary sliding can cause ductility deteriorated to 10%. Thus, formation of grain boundary ferrite will not impair but

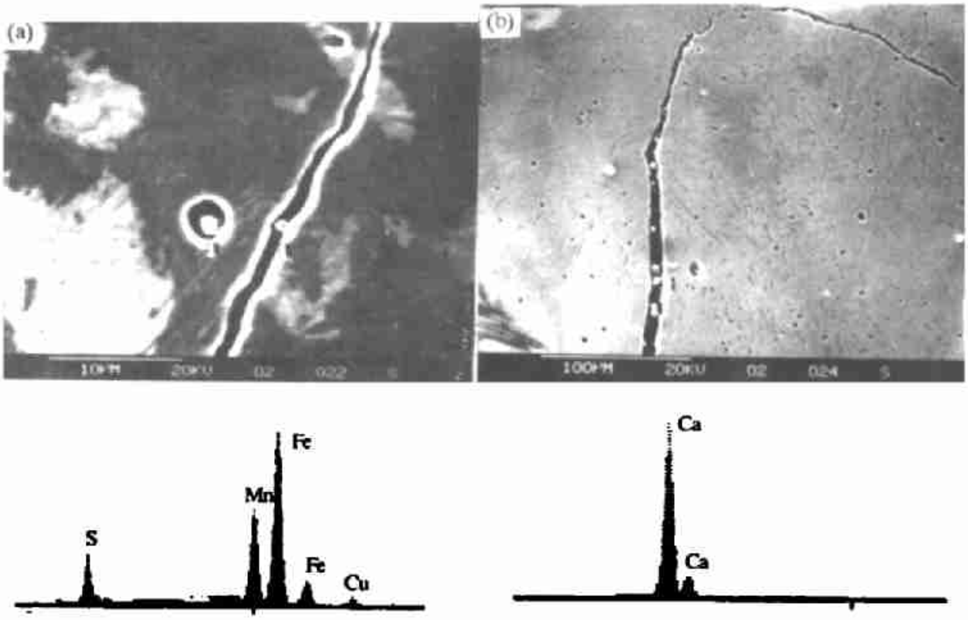

Figure 7 Cracks propagating along the grain boundary next to inclusions of oxides and sulfides. (a) 800℃, (b) 900℃

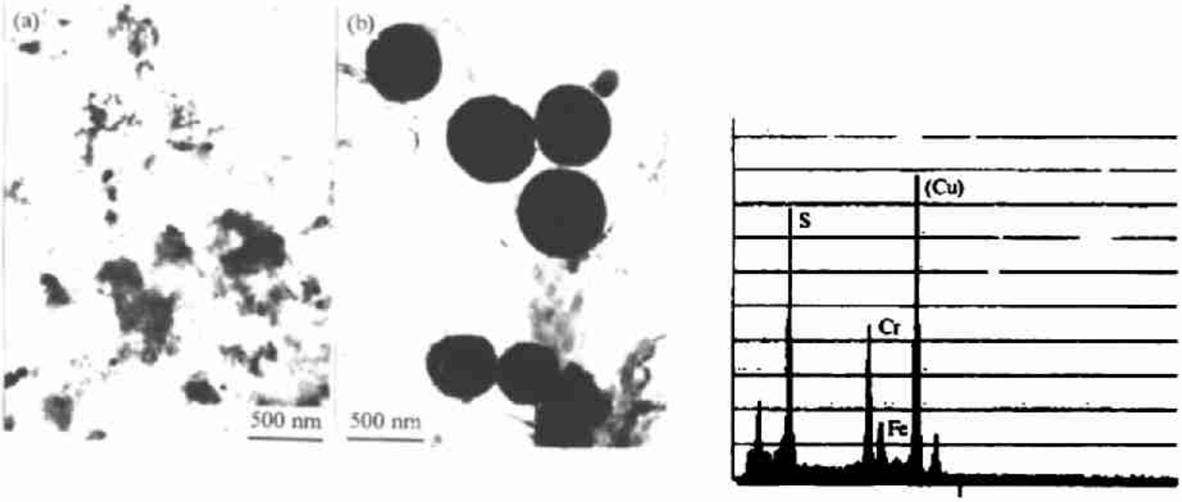

Figure 8 Sulfide particles growing with increasing temperature. (a)750℃, (b)1100℃

slightly improve hot ductility. In conclusion, grain slid-ing, promoted by inclusions and precipitates, can deteriorate hot ductility more seriously than grain bound-ary ferrite film.

3.3 Effect of strain rate on deforming induced ferrite and hot ductility

It is known from figure 6 that a certain strain must be needed to promote ferrite film forming along austenite grain boundaries, and when strain rate increases, the thickness of ferrite film tends to decrease but ductility is improved, which agrees well with the previous research results [1,2,4]. It is assumed that hot ductility in the dual γ/α phase region not only depends on thickness of grain boundary ferrite film, which usually increase with strain, but also strain rate. At a high strain rate, work hardening can take place in the relatively soft ferrite so that the strength of ferrite approaches to that of austenite and ductility is improved. When the strain rate increases from 10^{-4} to 5×10^{-4} /s, the difference between ferrite and austen-ite is reduced but there is also enough time for a larger volume fraction ferrite to form. But when strain rate further increases, the thickness of ferrite film tends to decrease though its strength approach closer to that of austenite so that hot ductility changes only a little.

In addition, when phase transformation is introduced by temperature drop before the tensile test, AlN particles is promoted to precipitate because less nitro-

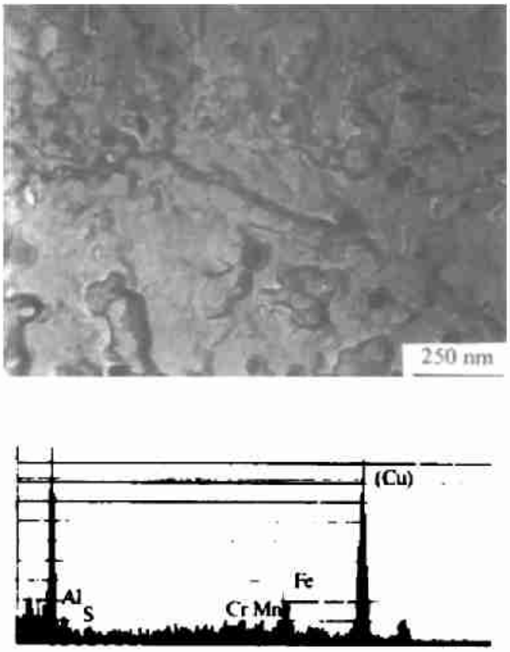

Figure 9 AlN precipitates in the samples undergoing γ→α phase transformation when temperature drop before the tensile test is introduced

gen atom as a interstitial is solved in ferrite than in austenite. This result is in good agreement with those of previous researchers [1,7,9].

In the γ phase region, with strain rate increasing, hot ductility is improved because there is insufficient time for dynamically precipitating and formation and growth of voids next to the inclusions and precipitates present in steels, and the ductility trough become narrower because dynamical recrystallization can appear at a lower temperature, shown in **figure 10**.

4 Conclusions

(1) Grain sliding, which is promoted by oxide inclusions and sulfide precipitates, deteriorates the hot ductility more seriously than deforming induced ferrite at grain boundaries.

(2) Enough strain is necessary for the formation of grain boundary ferrite film. With strain rate increasing, the thickness of ferrite film tends to decrease but hot ductility is improved because the difference of strength between austenite within grains and ferrite at grain boundaries is reduced by work hardening on ferrite.

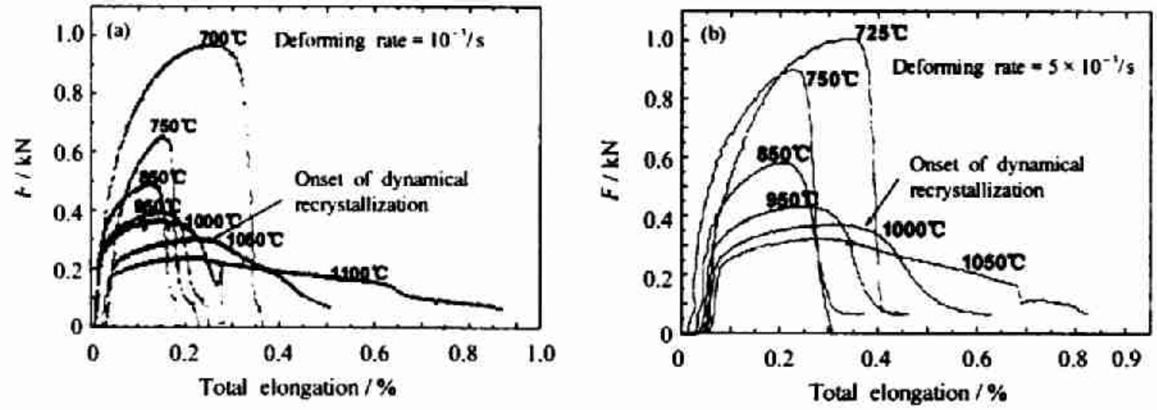

Figure 10 The curves of force *vs.* elongation for samples to deform at various temperature. (a) $\dot{\varepsilon} = 10^{-3}/s$, dynamical recrystallization starting at 1 000℃, (b) $\dot{\varepsilon} = 5 \times 10^{-3}/s$, dynamical recrystallization starting at 1 050℃

(3) With the strain rate increasing, the hot ductility is improved because there is insufficient time for dynamically precipitating and formation and growth of void next to the inclusions and precipitates. And the ductility trough becomes narrower because the temperature for onset of dynamical recrystallization decreases.

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