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Full Length Research Paper

Hot deformation behavior of Nb-V microalloyed steel

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In this research, hot deformation behavior of Nb-V microalloyed steel has been investigated by conducting hot compression tests at temperatures of 900-1100°C and under constant strain rates, ranging from 0.01 to 1^{s-1}. The stress-strain curves showed that dynamic recrystallization is responsible for flow softening at steady temperatures and strain rates. The relations between peak strain and peak stress with Zenner-Hollomon parameter, were developed and investigated via constitutive equations. The single peak and multiple peak flow curves at low and high Zenner regimes were observed and analyzed through later microstructural investigations. The values of apparent activation energy, strain rate sensitivity and stress exponent parameter were appraised to be 332, 0.18 and 5.6 kJ/mol, respectively. Microstructural investigations by optical microscopes were performed on deformed specimens to trace the occurrence of restoration processes.

Key words: Microalloyed steel, niobium, dynamic recrystallization, flow stress, carbonitride.

INTRODUCTION

Microalloyed steels are an important group of high strength low alloy steels which are being increasingly used in different industries such as automotive applications. Their behavior during and after hot working have got a great industrial importance from many years ago. Therefore, a large part of the research that has been carried out on microalloyed steels has focused on Niobium microalloyed steels. In this steel, grades heat treating process has been eliminated and usually desirable mechanical properties are attained by con-trolled rolling and controlled cooling (Shanmugama et al., 2006). Generally, strengthening mechanisms of steels are solid solutions, precipitation hardening and grain refining, that only the later improves strength and toughness simultaneously (Meyer et al., 1985). For this purpose (good strength and toughness), not only can we use microalloying elements but also we can also control thermomechanical parameters in hot deformation process. Niobium in small addition is most effective than other microalloying elements for improving mechanical properties (Klinkenberg et al., 2006). Niobium during hot deformation causes grain refining as follows. Nb(C, N) precipitations that formed in high temperatures in the austenite prevent grain coarsening in later stages of hot deformation and also in heat treating process. It is also shown that numerous dissimilarity in size of Nb and Fe atoms (~1.16) cause the suppression and recrystallizations that result to flattened grains of austenite and also high density of dislocations that ultimately lead to increasing the preferred places to nucleation of ferrite.

In metals and alloys with low and medium stacking fault energy (e.g. Ni, Cu, Austenite in steels) due to slow softening rate of recovery, work hardening do not equal with dynamic recovery. Therefore dislocation densities gradually increase during deformation. Recrystallization occurs during deformation if the driving force to perform recrystallization would be sufficient. In this situation stress-strain curves will be shown a maximum stress before steady state is reached (Anthony et al., 2001). All microstructure evolutions in various stages of hot deformation especially in restorations process could be affected by temperature and as explained with

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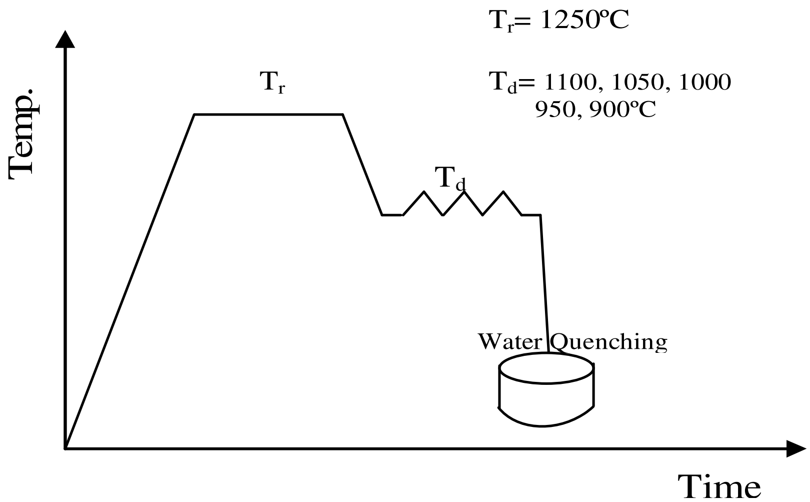

Figure 1. Schematic diagram of hot compression test specimens.

Zenner-Holomon parameter,

$$Z = \dot{\varepsilon} \exp(\frac{Q_{HW}}{RT}) \quad (1)$$

Where QHW and R are activation energy of high-temperature deformation and the gas constant, respectively.

In higher temperature, recrystallization is performed very quickly. The mechanisms that affect the recrystallization process are active by increasing temperature. The effect of strain rate varies by deformation temperature, kind of recrystallization and process (Ebrahimi et al., 2006). Strain rate has not effected on static recrystallization but dynamic and metadynamic recrystallization is affected strongly by strain rate (Ayada et al., 1998). In higher temperature and lower strain rate, stress- strain curves may show multiple peak stress but in reverse situation this behavior is not observed. Critical strain decreases by falling Zener-Holomon parameter (Manohar et al., 1998). In the present paper hot flow behavior of Nb-V microalloyed steel is investigated in different deformation temperature and strain rate.

EXPERIMENTAL PROCEDURE

Materials

A Nb-V microallyed steel of composition (wt %) 0.23 C, 0.28Si, 1.53 Mn, 0.02 S, 0.1 V, 0.045 Nb was used in this investigation.

Sample preparations

The cylindrical hot compression specimens of diameter 10 mm and height 15 mm (height to diameter ratio of 1.5) were machined from the bar with the deformation axis parallel to the hot rolling direction. Concentric grooves about 0.2 mm in depth were engraved on the specimen faces to facilitate the retention of lubricant. A chamber of 0.5 mm at 45° was machined along the edges of the faces to avoid fold over in the initial stages of the compression. The end faces of the specimens were lubricated with powdered glass.

In order to homogenize before the start of deformation, specimens were heated to 1250°C and held for 15 min, in an argon atmosphere and then cooled to the deformation temperature and held for 2 min to eliminate any thermal gradients before deformation. The hot compression tests were carried out in the temperature range of 900 - 1100°C with $\Delta T = 50$°C and strain rates 0.01, 0.1, 1 s^{-1}, as is schematically shown in Figure 1. The stress-strain data were recorded by the computer control system of the equipment. After the compression, the samples are quenched in water, resulting in cooling rates of approximately 500°C/sec, sufficiently fast to freeze the austenite grain structure.

Metallography

Microstructure observations were carried out at the center part of the hot-compressed specimens. The observed sections were parallel to the compression axis. The specimens were then tempered at 450°C for 4 h to improve grain boundary etching. After usual grinding and polishing operations they were etched in a supersaturated solution of warm picric acid and water with the addition of bivalent $CuCl_2$. Digital pictures were prepared by using optical microscopy and average austenite grain sizes were measured using the linear intercept method according to ASTM E112 standard.

RESULTS AND DISCUSSION

The typical stress-strain curves in the range of 900 - 1150°C and stress-strain rate of 0.01, 0.1 and 1 s^{-1} are shown in Figure 2. All flow curves at all strain rates exhibit a maximum, which is a result of dynamic softening (dynamic recovery and dynamic recrystallization). The maximum is very clear at high strain rates and high testing temperatures (Figure 2c, e, d), but in lower testing

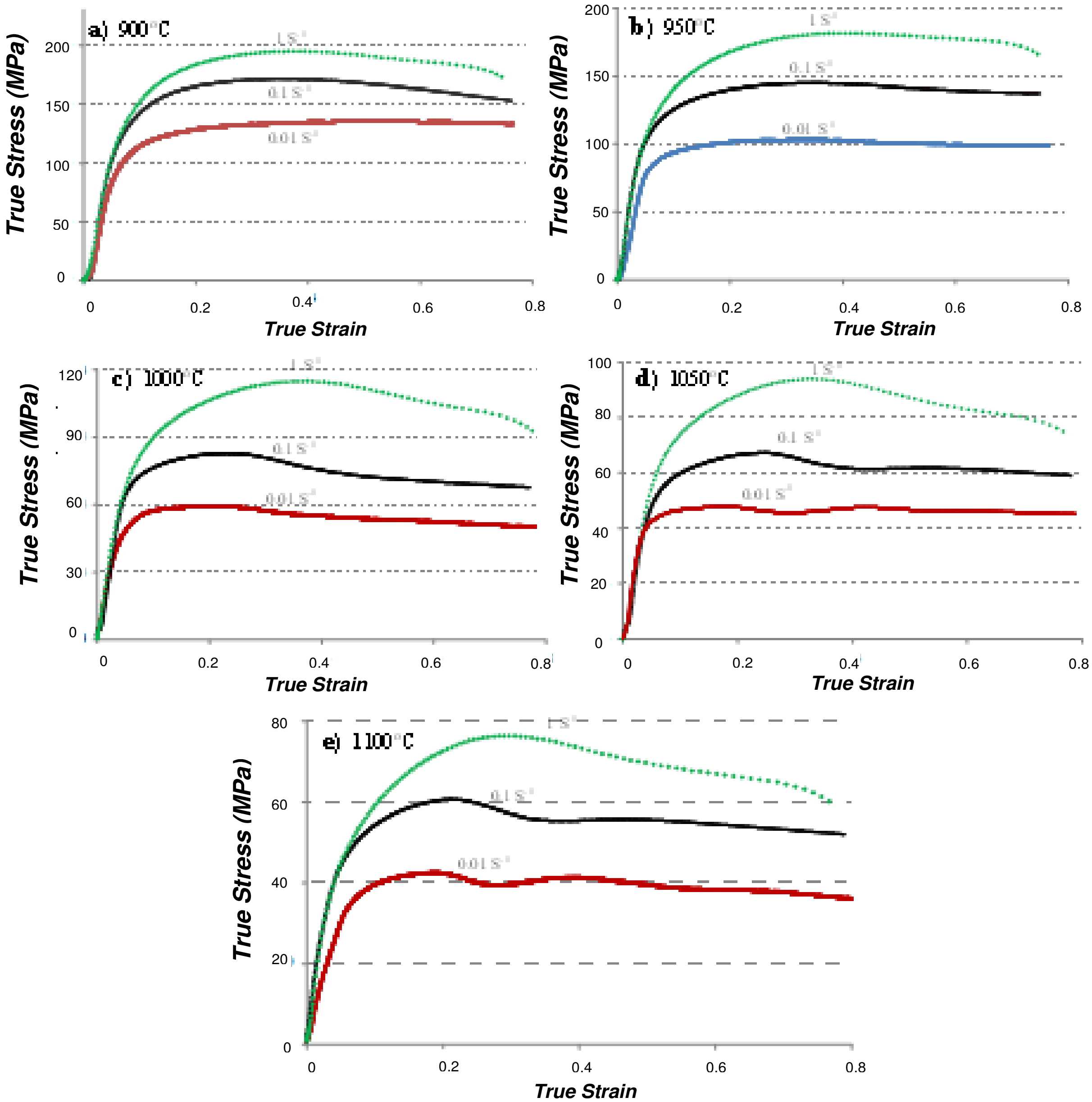

Figure 2. Stress-strain curves for the alloy studied at different compression temperatures (a: 900°C, b: 950, c: 1000, d: 1050, e: 1100°C) and strain rates.

temperature (Figure 2a, b) the maximum is not clear. Important characteristics of dynamic recovery in curves are a function of Zener-Holomon parameters. These parameters enhanced by increasing Z that is affected by strain rate and temperature. As illustrated in Figure 2, the peak and critical strains enhanced by decreasing temperature and increasing strain rate that indicates retarding of dynamic work softening. Maximum flow stress of curves is between 0.1 - 0.5 strains. Figure 3 shows the variation of maximum stress as a function of temperature at different strain rates. This clearly indicates that the strengthening effect of particle-dislocation interaction gradually decreases with increasing temperature. This in turn, is easily explained by coarsening and at higher temperature, dissolution of precipitates. Although, by increasing temperature and decreasing strain rate, the peak stress is increased but the slope of the curve vary between 950 - 1000°C that indicates rising of work hardening and falling dynamic softening in this temperature range (Pirtovsek et al., 2006). Lack of peak stress in Figure (2a, b) may be due to Nb (C, N) precipitations. In lower temperature by increasing precipitation density and

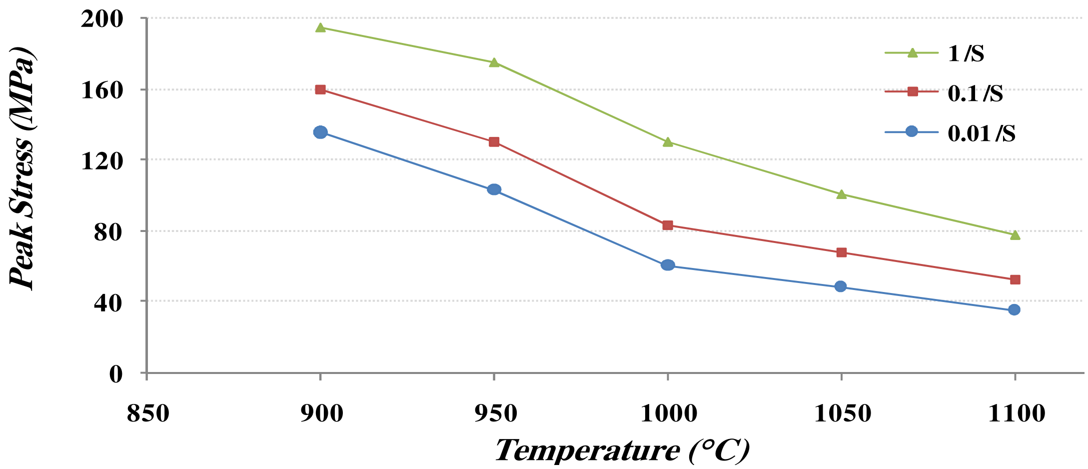

Figure 3. The variation of peak stress as a function of temperature.

Table 1. Inhibition rate of 1% solute atoms on the start time of recrystallization.

Solute	Inhibition ratio
Ni	0.13
Cr	0.17
Mn	0.36
Mo	8.5
Nb	210
Ti	39
V	2.3

dragging dislocation by them, work hardening enhances and dynamic recrystallization suppresses.

It is well known that the small Nb(C, N) particles can inhibit austenite recrystallization by pining down dislocation, so the ferrite grain after transformation becomes fine. Similarly, solid solution atoms can also inhibit austenite recovery and recrystallization, because the solid solution atoms segregating at dislocation can form Cottrell air mass so that the climbing velocity of edge dislocation decreases. If the size and electro-negativity of solute atom greatly differ with those of Fe atom, it would be easy to segregate under dislocation line. Therefore, the consistency of solid solution atoms segregating under dislocation line is obviously higher than average of solute atoms so that the driving force for dislocation to disengage Cottrell air mass becomes high. Therefore, the climb velocity of dislocation obviously decreases due to segregation of Nb atoms, which would inhibit austenite rescrystallization. Table 1 shows inhibition rates of 1% solute atom on the start time of austenite recrystallization. It can be seen that the solute atoms whose radius and electronegativity are similar to Fe atom, such as Ni, Cr, and Mn etc., have very weak hindrance to austenite recrystallization. Drag mechanism of solute plays an important role in inhibiting recovery and recrystallization under the circumstance that Nb(C, N) particles do not precipitate (Yong et al., 1989). In hot working processes, several constitutive equations have commonly been applied;

$$\dot{\varepsilon} = A'\sigma^{n'} \exp\left(\frac{-Q_{HW}}{RT}\right) \tag{2}$$

$$\dot{\varepsilon} = A'' \exp(\beta\sigma) \exp\left(\frac{-Q_{HW}}{RT}\right) \tag{3}$$

$$\dot{\varepsilon} = A''(\sinh\beta\sigma)^{n} \exp\left(\frac{-Q_{HW}}{RT}\right) \tag{4}$$

Where $\dot{\varepsilon}$ is the strain rate, σ is the stress and T is the absolute temperature.

Equation 2, break at a high stress and a low stress where as equation 4 is a more general form a wider range of stresses. For the alloys tested in stable conditions, equation 2 results in the activation energy of self-diffusion in steels. Indeed, after slow cooling, due to the coarser particle size and larger spacing, the precipitates have a minor strengthening effect. In addition the solute level is also low in this condition. By contrast, where the alloy is examined in solution treated condition, very high values of the activation energy can be observed (Yu et al., 2004).

Figure 4 shows the optical microstructure showing prior austenite grains of the deformed specimens. Figure 4a shows that austenite grains completely recrystallized and partially coarsened. Figure 4c shows that non-recrystallized and elongated grains. The grain sizes are

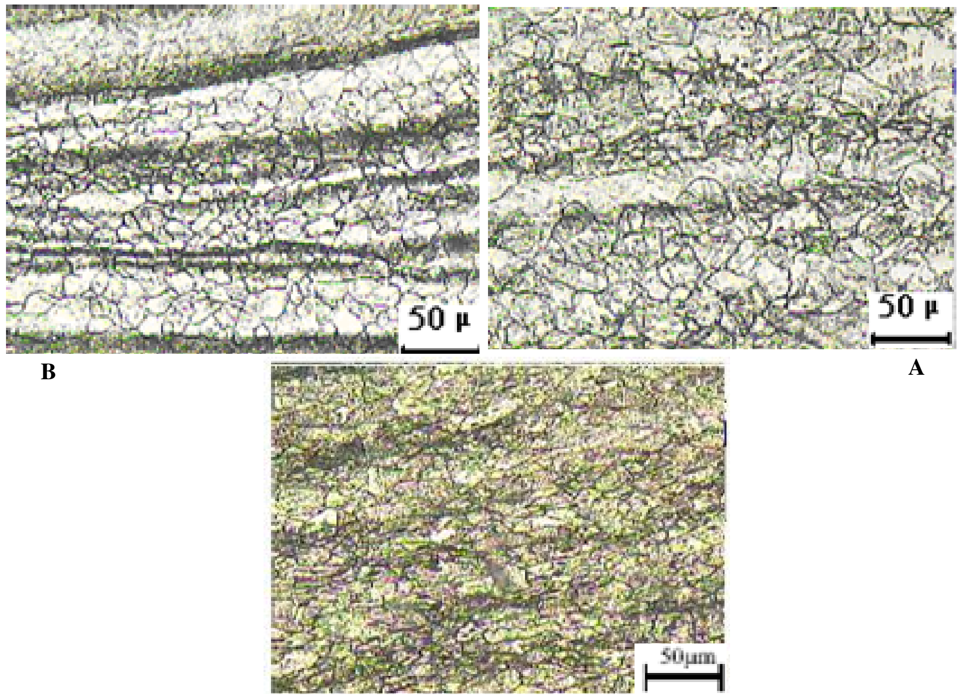

Figure 4. Austenitic microstructure of the alloy at different hot compression temperatures (A: 1050℃, B: 1000℃, C: 900℃) and strain rates of 0.1 s-1.

somewhat inhomogeneous, and the grain boundaries show serrated shape. Figure (4b) shows the grain boundaries have concave shapes and fine recrystallized grains are observed. Almost all grains are equiaxed without elongated grains. This indicates that the occurrence of recrystallization.

Conclusion

At temperature lower than 950℃ the deformation behavior of the alloy seems to be controlled by carbonitride precipitations and the work softening is minimal and flow stress becomes stable. The DRX is the deformation controlling mechanism. This was concluded form the DRX activation energy and also from the flow curves. The activation energy of DRX at studied steel was calculated to be about Q = 332 kJ/mol. In hot compression test with decreasing deformation temperature εc was increased. Also reduction of temperature cause the decrease of diffusion rate, whereas in recrystallization phenomena diffusion is necessary, thereby εp also increases.

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