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Determination of critical conditions for dynamic recrystallization of a microalloyed steel

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ABSTRACT

A low carbon Nb–Ti microalloyed steel was subjected to hot torsion testing over the range of temperatures from 900 to 1100 °C and strain rates from 0.01 to 1 s^{-1} to characterize its hot deformation behavior. The initiation and evolution of dynamic recrystallization were investigated by analyzing of hot flow curves. Two important dynamic recrystallization parameters, the critical strain and the point of maximum dynamic softening, derived from strain hardening rate- stress curves. These parameters then were used to predict the dynamic recrystallized fraction. The results showed that the critical stress and strain increase with decreasing deformation temperature and increasing strain rate. The hot deformation activation energy of the steel investigated in the present work is 375 kJ/mol, and the expression for steady state flow stress is

$$\sigma_{SS} = 0.07Z^{0.14} = 0.07 \cdot \left[\dot{\varepsilon}\exp\left(\frac{375,000}{RT}\right)\right]^{0.14}$$

The volume fraction of dynamic recrystallization as a function of processing variables was established. It was found that the model used for predicting the kinetic of dynamic recrystallization is in good agreement with the data directly acquired from experimental flow curves.

1. Introduction

Dynamic recrystallization (DRX) is an important mechanism for the microstructure control during hot deformation. DRX plays a major role in reducing the flow stress and the grain size and is a powerful tool for controlling mechanical properties during industrial processing [1–4]. Prediction of the critical condition for the initiation of DRX is of considerable interest for the modeling of industrial processes [5–8]. Several researchers have proposed mathematical relations to predict the initiation of DRX. For example, Ryan and McQueen suggested that the initiation of DRX can be identified from changes in the slope of the strain hardening rate versus flow stress curves [9]. Alternatively, Poliak and Jonas [5–8] proposed the use of the minimum in the absolute value of the strain hardening slope which can be calculated from strain hardening rate-flow stress curves. The objective of this investigation is to analyze the initiation of dynamic softening behavior through DRX under various deformation conditions in a low carbon Nb–Ti microalloyed steel. Accordingly, the method of Poliak and Jonas is used to determine the critical strain and the peak strain required for initiation of DRX in steel investigated. Additionally, the strain of maximum dynamic softening is determined by using the work hardening rate. These parameters are used to predict the kinetic of dynamic recrystallization.

2. Experimental procedure

The chemical composition (wt.%) of the steel investigated was 0.09C, 0.4Si, 1.55Mn, 0.008S 0.014P, 0.013Ti, 0.031Nb, 0.028Al, and balance Fe. Torsion specimens with a gauge length of 20 mm and diameter of 6.7 mm were machined from the as-received plates with the longitudinal axis parallel to the rolling direction. The deformation tests were performed on torsion equipment described elsewhere [10]. Specimens were enclosed in quartz tube with a positive pressure of Argon gas atmosphere to prevent decarburization during induction heating. The temperature was monitored by two thermocouples inserted in the drilled ends of the specimen. The temperature accuracy was within ±5 °C. Initially a continuous cooling torsion test was carried out to measure the critical transformation temperatures. The A_{r1}, A_{r3} and non-recrystallization temperature (T_{nr}) were found to be 750, 790, and 977 °C, respectively.

Thermomechanical treatment schedule is shown in Fig. 1. At first, each specimen was heated to 1200 °C and held for 2 min at

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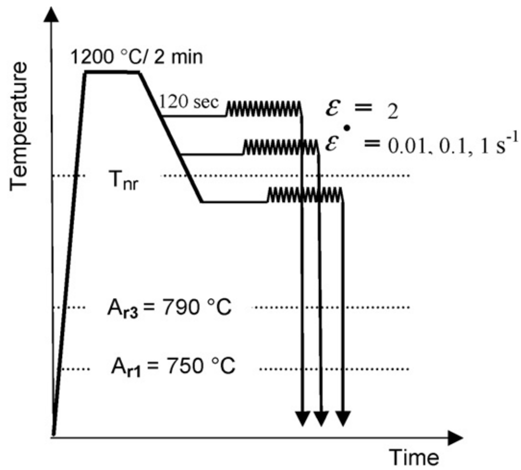

Fig. 1. A schematic diagram of thermomechanical processing schedule conducted in the present study.

temperature to fully austenitise the material. The temperature was then decreased at a rate of 1 °C/s to the test temperature (900, 1000, and 1100 °C) and held there for 2 min to homogenize the specimen temperature. The specimen was deformed isothermally at strain rates of 0.01, 0.1, and 1 s^{-1}. All specimens were deformed up to strain of 2. The specimens were quenched with water jet sprays immediately after deformation.

3. Results and discussion

3.1. Analysis of hot flow curves

The effect of strain rate and deformation temperature on the true strain–true stress curves of the steel investigated is shown in Fig. 2. It is seen that all flow curves exhibit a peak and then follow by a gradual fall to a steady state stress which is indicative of the occurrence of DRX, except for the 900 °C.

In other words, dynamic recrystallization conditions were apparently not achieved in the tests performed at temperature lower than T_{nr}, i.e. at 900 °C. It has been reported [11–13] that the dynamic strain induced precipitation would take place during deformation in this temperature range in microalloyed steels. This precipitation is in turn responsible for the formation of pancaked austenite grains by retarding the occurrence of DRX [13]. Thus, it can be realized that the softening behavior during deformation at this deformation temperature results from the counteracting effects of partial dynamic recrystallization and work hardening of austenite.

It can be seen that at a given temperature with increasing strain rate working hardening rate increases. Thereby the peak stress (σ_p), the peak strain (ε_p), and the steady flow stress increase. At a certain strain rate, with increasing deformation temperature the rate of dynamic softening increases. Thus the peak stress, peak strain, and steady state stress decrease correspondingly. In other words, the peak stress and peak strain are dependent on deformation conditions.

3.2. Hot deformation characteristics

So far, several empirical equations have been proposed to determine the deformation activation energy and hot deformation behavior of steels. The most frequently used one is as follows [14]. This equation describes the behavior of the material deformed at different temperatures and strain rates:

$$\sigma_{SS} = AZ^q = \mathrm{A} \cdot \left[\dot{\varepsilon}\, \exp\left(\frac{Q_d}{RT}\right)\right]^q \quad (1)$$

where σ_{ss} is the steady state stress, A is a constant depending on chemical composition and initial austenite grain size, Z is the Zener–Hollomon parameter, $\dot{\varepsilon}$ is the strain rate, Q_d is the activation energy of deformation, R is the gas constant, T is the absolute temperature and q is the power low exponent. On taking natural logarithms of both sides of Eq. (1) the expression for steady state flow stress is as:

$$\ln \sigma_{SS} = \ln A + q\, \ln \dot{\varepsilon} + q\frac{Q_d}{RT} \quad (2)$$

From Eq. (2) it can be seen that when the deformation temperature is constant, there exists a linear relation between natural logarithm of the steady state flow stress and the natural logarithm of strain rate. When the deformation temperature is constant, on taking partial derivatives of both sides of Eq. (2) to $-\ln \dot{\varepsilon}$ we have:

$$\left[\frac{\partial \ln \sigma_{SS}}{-\partial \ln \dot{\varepsilon}}\right]_T = -q \quad (3)$$

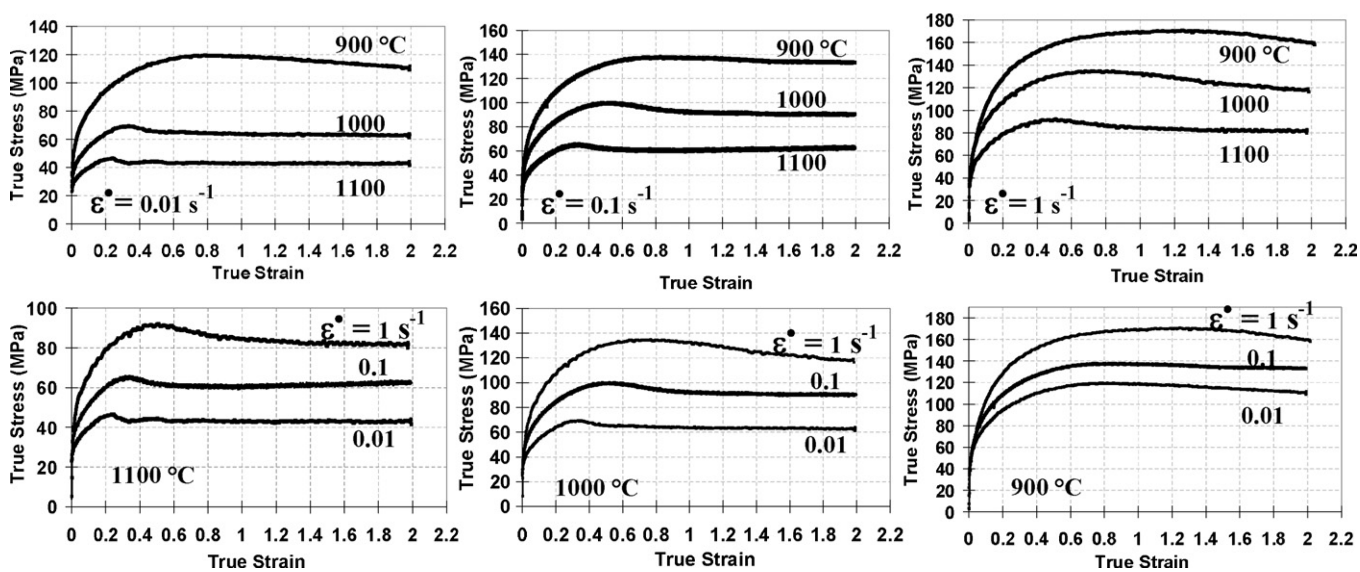

Fig. 2. True stress–true strain curves of Nb–Ti microalloyed steel under different deformation conditions.