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Influence of deformation temperature on the ferrite grain refinement in a low carbon Nb–Ti microalloyed steel

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Abstract

Grain refinement is one of the effective methods to develop new generation low carbon microalloyed steels possessing excellent combination of mechanical properties. In the present work, the microstructural evolution and ferrite grain refinement at various deformation temperatures were investigated using single pass isothermal hot compression experiments for a low carbon Nb–Ti microalloyed steel. The physical processes that occurred during deformation were discussed by observing the optical microstructure and analyzing the stress–strain responses. The results show that there is a close relation between the microstructural evolution and true stress–true strain responses during the deformation. Microstructural observation indicates that very fine ferrite grains of about 1.8–3 μm are obtained by deformation at 830–845 °C, about $Ar_3 \pm 10\,°C$. The obtained stress–strain curves suggest the occurrence of strain-induced dynamic transformation (SIDT) of γ to α at this deformation temperature range.

Keywords: Low carbon microalloyed steel; Hot compression; Grain refinement; Strain-induced transformation

1. Introduction

The thermomechanical controlled processing (TMCP) of microalloyed steels has been employed for some times in the production of plates and sheet material in order to optimize mechanical properties. The central feature of thermomechanically processed steel is the ultrafine grain size in the final product. Therefore, the ferrite grain refinement of structural steels has attracted considerable interest from engineering scientists due to its unique role of increasing both strength and toughness. Demand for steels possessing good combination of these properties, and weldability has led to the development of low carbon microalloyed steels.

There are several TMCP routs to obtain the fine ferrite grain microstructure. Controlled rolling is one of the most important operations for producing low-cost, high strength steels with yield strength as high as 600 MPa [1]. A limiting ferrite grain size of around 5 μm appears to exist using commercial controlled rolling. In recent years, several groups have reported achieving ferrite grain size below the nominal 5 μm limit of controlled rolling steels, using laboratory scale TMCP methods for low carbon microalloyed and plain carbon steels [2–5]. For producing ultra fine ferrite grain size (<2 μm), there are potentially three mechanisms [6–9]: (1) strain-induced transformation (SIT), (2) transformation from dynamically recrystallized austenite, and (3) dynamic recrystallization of ferrite. In recent years, several research groups have reported achieving very fine ferrite grain sizes via strain-induced transformation in plain carbon steels, which has been confirmed by optical microstructural observations [10–15]. However, there is very little information concerning ferrite grain refinement by SIT mechanism in the case of microalloyed steels. Furthermore, it is well known that hot deformation has important effect not only on the microstructural changes but also on the hot flow stress–strain curves. Therefore, in addition to optical microstructural observation, hot flow stress–strain curves can be used as another evidence to determine if SIT has been occurred during the deformation.

In the present work, the isothermal hot compression tests were conducted on a low carbon Nb–Ti microalloyed steel to study the effects of deformation temperature on the evolution of ferrite grain refinement. In particular, attention is paid to ferrite grain refinement through SIT by both microstructural observation and stress–strain curves.

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Table 1
Chemical composition of experimental steel (wt.%)

C	0.032
Si	0.15
Mn	0.74
P	0.009
S	0.007
Nb	0.014
Ti	0.013
Al	0.028
N	0.0031

2. Experimental procedure

The material used in the experimental work was a low carbon Nb–Ti microalloyed steel with the chemical composition shown in Table 1. The steel was prepared as 35 kg ingot in an induction furnace operating under argon atmosphere, and then refined by electro-slag remelting (ESR) in a laboratory unit. The ingot was reheated to 1250 °C for 1 h and hot rolled in 6 passes to 25 mm thick plate. The differential scanning calorimetry (DSC) technique was applied to measure the critical transformation temperatures. The Ar_1 and Ar_3 temperatures were found to be 751 and 837 °C, respectively. The cylindrical compression samples were machined out from hot rolled plate. The deformation tests were carried out according to the test schedule in Fig. 1. The samples were 18 mm in length and 12 mm in diameter, with the axis aligned in the rolling direction of the plate. Care was exercised to minimize friction between the test dies and the sample surface by machining flat-bottomed grooves on the end faces of samples. Graphite powders and thin pieces of mica sheet were used as lubricants in compression, resulting in fairly uniform deformation with negligibly small barreling.

The uniaxial compression tests were performed on a servo-hydraulic 600 KN computerized Materials Testing System (MTS, Model 8500) equipped with a resistant furnace. Prior to deformation, the samples were solutionized at 1150 °C for 5 min. The solution temperature was selected according to the solubility product of Ti and Nb precipitates [16,17]. At this temperature, Nb is completely dissolved and Ti is partially precipitated in the form of nitrides; very high temperatures, even in excess of melting point, being necessary for its total dissolution [18,19]. After solutionizing, the samples were cooled at a rate of 5 °C s^{-1} to the different desired deformation temperatures (1100, 950, 845, and 830 °C), and held for 20 s to homogenize the temperature throughout the samples. Then samples were isothermally deformed with single pass strain of 0.8 and at constant strain rate of 0.01 s^{-1}. All specimens were water quenched in 2 s after deformation. Optical microscopy was conducted on mid-plane sections containing the axis of compression, in order to study the microstructural changes.

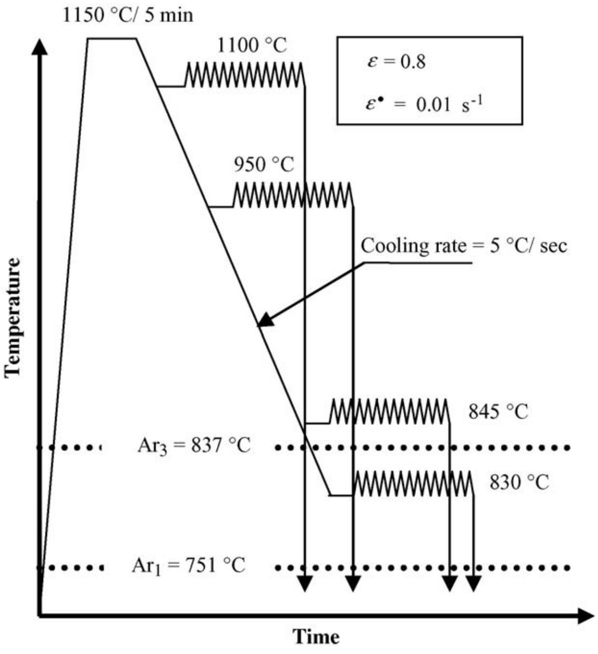

Fig. 1. Schematic representation of the TMCP conditions.

3. Results and discussion

3.1. Stress–strain curves and related dynamic softening processes

Fig. 2 shows the stress–strain curves up to the strain of 0.8 at different deformation temperatures (830–1100 °C) and constant strain rate of 0.01 s^{-1}. As it can be seen in this figure, at the deformation temperature of 1100 °C, the flow curve exhibits the DRC type without any evidence of DRX. With decreasing the deformation temperature to 950 °C, the flow curve indicates the work hardening behaviour. When the deformation temperature decreases to 845 °C, just above Ar_3, the flow curve does not exhibit work hardening after the strain of about 0.32, and flow stress level remains constant during the deformation. This type of dynamic softening, non-work hardening, is attributed to the SIT of austenite to ferrite [20,21]. In other words, during the deformation at this temperature, further transformation of austenite to ferrite would also lead to apparent dynamic softening, as produced ferrite is much softer than austenite under these deformation conditions [14]. At the deformation temperature of 830 °C, flow curve would not show work hardening behaviour after the strain of about 0.32. This non-work hardening behaviour is also due to the SIT of austenite to ferrite as discussed above. Further investigation is needed to study the influence of precipitation on SIT dynamic softening kinetics.

Fig. 3 shows the maximum stresses at strain of 0.8 taken from the true stress–true strain curves in Fig. 2. It is shown that at the deformation temperature of 1100 °C the maximum stress is lowest compared to other temperatures. This is due to the DRC of austenite. However, with decreasing the deformation temperature to 950 °C, the maximum stresses increase due to work hardening of austenite. With decreasing the deformation

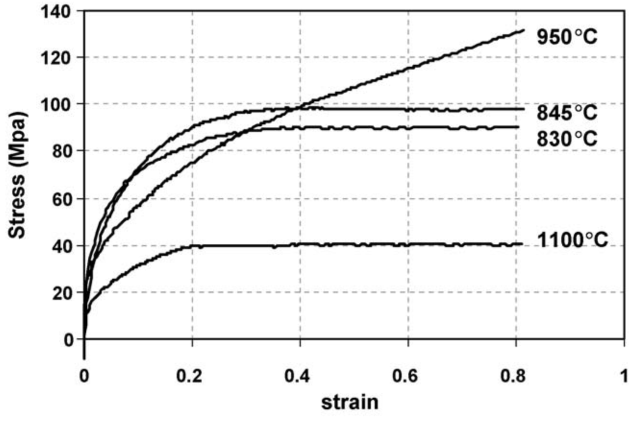

Fig. 2. Representative flow curves for the low carbon Nb–Ti steel obtained under various deformation temperatures and strain rate of 0.01 s^{-1}.