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Numerical prediction of austenite grain size in a bar rolling process using an evolution model based on a hot compression test

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ABSTRACT

A microstructure evolution model was formulated by characterizing the kinetics of static (SRX) and metadynamic (MDRX) recrystallization in consideration of the experimental data using single and double compression tests of AISI 4135 at various temperatures and strain rates. The evolution model consisted of equations for SRX, MDRX, and grain growth was implemented into an in-house finite element program to simulate the process. Numerical prediction of austenite grain size (AGS) evolution during a hot bar rolling of AISI 4135 was conducted and presented. The predicted results were compared with the experimental data obtained from the hot bar rolling and the numerical results based on other AGS models available in the literature which were derived based on torsion tests. The present model determined in the current investigation based on compression tests shows better agreement with the experimental data than the earlier works. The critical strains determined from compression tests were relatively smaller than those from the torsion tests, which influenced the overall recrystallization and grain growth behaviors. Also, the current model was beneficial to understand the effect of recrystallization behavior and control the microstructure evolution during hot bar rolling.

1. Introduction

For accurate design of controlled schedules, good understanding of material behavior during hot forming processes is imperative. To achieve desired mechanical properties of the product, understanding of microstructural changes and deformation mechanism occurring inside the workpiece is required. For hot working processes such as hot rolling, it is essential to determine an accurate microstructure evolution model which is suitable for various forming conditions depending on strain, strain rate, and temperature.

One of the key issues in modeling microstructural changes during hot rolling is the recrystallization of austenite. Thus, many studies have been carried out so far using the hot torsion test to derive mathematical modeling of austenite grain size (AGS) evolution [1–5].

Compression tests were also used for characterizing recrystallization behavior. Andrade et al. [6] conducted compression tests to determine the effect of alloying elements on softening behavior, and Yanagida and Yanagimoto [7] applied an inverse analysis to double compression tests to calculate softening fractions. Lin et al. [8] investigated the effect of deformation parameters on softening using hot compression tests. Despite large amount of efforts to derive AGS models based on torsion tests, microstructure evolution modeling using compression tests still needs further investigation.

For better prediction of AGS, there were few attempts to combine the mathematical model of microstructure evolution with the finite element (FE) analysis. Kwon et al. [9,10] investigated change of the AGS distribution in the bar rolling process of AISI 1020 by combining the AGS evolution model proposed by Hodgson and Gibbs [2] with the FE analysis. Lee et al. [11,12] compared the experimental results with simulation results based on two prediction models by Hodgson and Gibbs [2] and Lee et al. [3]. According to these investigations, there are discrepancies at certain locations between bar rolling experiments and simulations. There might be a difference in the deformation mode between a bar rolling and a torsion test used for developing an AGS model. Since the stress state in bulk metal forming like rolling and forging was known to be similar to that of compression test, the compression test was considered to be better approximation than torsion and tension tests [13] and could be more suitable for developing an AGS model.

The objectives of the present study are to produce a mathematical model using double compression tests and to succinctly differentiate the AGS evolution model based on torsion and compression tests. In this study, mathematical modeling of the AGS evolution was carried out to improve accuracy of the prediction using the compression test for medium carbon steel AISI 4135. The evolution models were determined for SRX, MDRX, and grain

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Table 1
Chemical composition of AISI 4135 steel used.

	C	Cr	Mn	Mo	P	S	Si
Mass %	0.38	1.04	0.73	0.18	0.014	0.01	0.23

growth followed by the work of Hodgson and Gibbs [2] in which once significant dynamic recrystallization (DRX) took place, metadynamic recrystallization (MDRX) was initiated so that MDRX would determine the austenite grain size and there was no need for an accurate model for DRX. To evaluate the recrystallization behavior according to the proposed model during bar rolling and subsequent cooling, the three-dimensional non-isothermal FE analysis incorporated with the present model has been conducted. The predicted austenite grain sizes were compared with those obtained from other evolution models and the experimental data available in the literature.

2. Microstructure evolution modeling

2.1. Material and experimental procedure

AISI 4135 steel of which chemical composition is listed in Table 1 was investigated in this work. In order to characterize recrystallization kinetics, two types of compression tests were performed in this investigation: (i) single compression test and (ii) double compression test. Cylindrical specimens with a diameter of 10 mm and a height of 15 mm were manufactured by machining. Thermecmastor Z (Fuji Electronic Industrial Co.) thermomechanical simulator was used for experiments with preset temperature and strain rate conditions.

Single compression tests were carried out to determine the peak strain associated with the DRX at each experimental condition in the temperature range of 800–1100 °C and in the strain rate range of 0.1–10 s^{-1}.

Fig. 1 shows the procedure of double compression tests. The specimens were heated to 1250 °C at a heating rate of 10 °C/s, soaked for 5 min, then cooled down to the deformation temperature at the rate of −10 °C/s, and held for 1 min to eliminate thermal gradients in the specimen. For microstructure analysis, the specimens were quenched with cold helium gas immediately after interpass time. To evaluate the effect of deformation variables on static and metadynamic softening, double compression tests were conducted over the temperature range of 900–1100 °C, strain rate range of 0.1–10 s^{-1}, interpass time range of 0.1–100 s, and strain range of 1/4–2 times the peak strain.

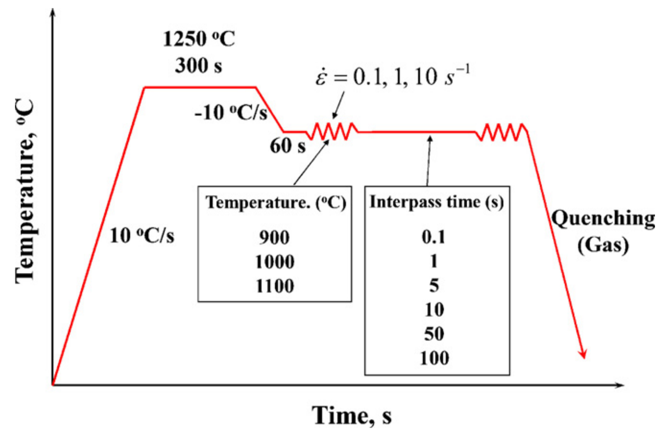

Fig. 1. Experimental procedure for double compression tests.

2.2. Determination of Zener–Hollomon parameter and critical strain

The characteristic stress–strain curve of a material exhibits a single peak behavior depending on the deformation parameters, i.e. temperature and strain rate as shown in Fig. 2. The flow stress curves which undergo dynamic recrystallization generally exhibit that as strain increases, stress increases up to peak stress σ_p and then decreases until it reaches a steady state stress. At sufficiently high temperature, DRX is initiated at a critical stress σ_c attained at a corresponding critical strain ε_c, however, a decrease in flow stress does not occur immediately after critical strain. After the balance between the softening caused by DRX and continuing strain hardening in the unrecrystallized parts of the material, DRX leads to a decrease in flow stress with increasing strain. This balance is completed at the peak strain ε_p. It was also found that as the temperature decreased and the strain rates increased, the peak strain ε_p and peak stress became higher as shown in Fig. 2.

The mechanical behavior can be described by introducing the Zener–Hollomon parameter as follows,

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) = A[\sinh(\alpha\sigma)]^n \qquad (1)$$

where Q is the activation energy of deformation, R the universal gas constant, T the absolute temperature, and Z the Zener–Hollomon parameter. The average value of n was determined to be 4.14 from the graph in Fig. 3(a). The determination of Q can be made from the graph as shown in Fig. 3(b). From this graph, the average value of Q

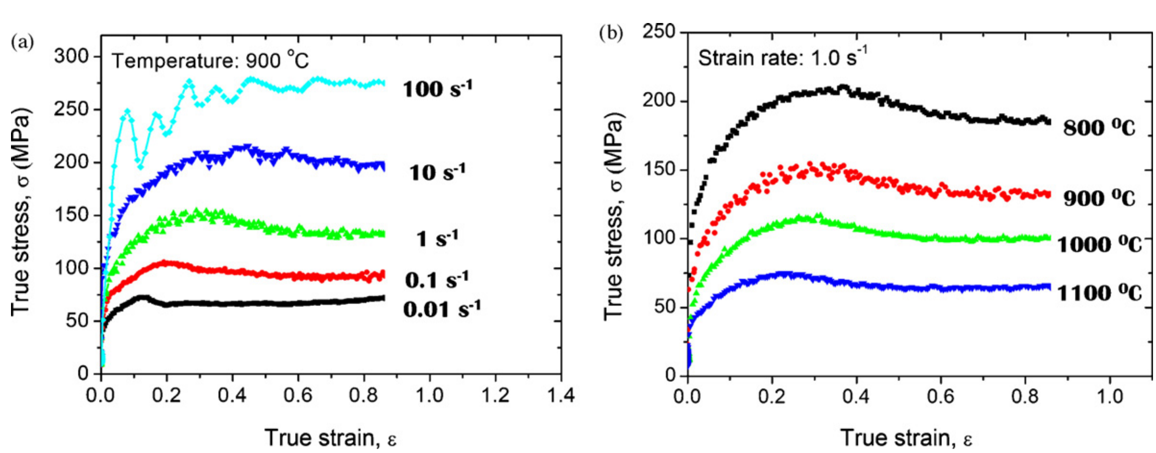

Fig. 2. Effect of (a) strain rate and (b) temperature on the flow curves of AISI 4135.