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Process design for refinement and homogenization of microstructure in bar rolling

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Abstract

Depending on process design of the bar rolling process, the final microstructure distribution varies. In this final distribution two perspectives should be taken into account: homogenization and refinement. Most of the studies carried out so far are focused on minimization of the grain size but the uniformity of the grain size is also important because the locally coarse grain sizes significantly deteriorate the overall performance of the rolled bar. In this study two criteria are proposed as a measure of the refinement and homogenization of the austenite grain size (AGS) distribution. The effect of process parameters on these two parameters was investigated to determine the major controlling parameter for better process design of round-oval-round pass sequence in the bar rolling under the isothermal and non-isothermal conditions. The investigation revealed that the temperature was the most important controlling parameter and the decrease of initial processing temperature was effective not only in the grain refinement but also in the grain homogenization.

Keywords: Process design; Grain refinement; Microstructure evolution; Bar rolling

1. Introduction

As the market need for environment-friendly light materials with better mechanical strength increases, the importance of manufacturing steel with high strength is ever increasing. The importance of high strength steel stands out not only for social infrastructure areas but also for automobile and aerospace industries. Thus, the challenge lies in developing manufacturing processes to achieve the desired mechanical properties by finding a practical approach to increase the strength and toughness of steel.

In order to increase the strength of steel, hardening by grain refinement was heavily investigated among other methods since the effect of grain size on hardening by grain refinement was widely known as the Hall–Petch relationship. It is known that the yield stress can be increased by about 350 MPa due to grain refinement from 20 to 1 μm. This increase means that the yield stress can be almost doubled in plain carbon steel.

Thus, techniques to materialize much finer grains in an industrial manufacturing process are expected to be developed to further increase material strength. For this purpose, better understanding of basic phenomena, such as diffusion, recrystallization, grain growth, precipitation and transformation is required. Therefore, many studies were carried out to determine the microstructure evolution during deformation in the process after the work by Sellars [1].

These studies have focused on the application of empirically obtained mathematical models to predict the properties of a material as a function of process parameters during manufacturing and heat-treatment operations [2–5]. The most important process parameters in the mathematical models are temperature, strain, strain rate and initial microstructure. According to these parameters, steel undergoes different metallurgical phenomena, resulting in final rolled products with different mechanical properties.

In shape rolling areas of investigation, Maccagno et al. [6] conducted a study on the austenite grain size (AGS) prediction associated with multi-pass oval-round-oval pass rolling sequence under the industrial rolling conditions. This investigation revealed that metadynamic recrystallization was the

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dominant microstructure process under the bar rolling conditions and the cooling rate and workpiece temperature should be used as a control parameter for grain refinement.

To make better prediction of the analysis, Karhausen and Kopp [7] presented a model offering improved simulation of material behavior, using the semi-empirical equations determining the state of dynamic recrystallization. In this model, more accurate flow stress was calculated as a function of microstructural state at any given instant of forming. In this work hot upsetting tests were used to determine the deformation characteristics of Cr-V steel. The developed microstruture evolution model was coupled with finite element method to predict the microstructure changes in the break-down rolling of H beams.

Yanagimoto et al. [8] proposed a new incremental formulation for the AGS modeling. The accuracy of the proposed model was verified through the analysis of hot upsetting of 50CrV4 steel. Later, Liu et al. [9] extended this work for the analysis of phase transformation. In this modeling it was combined with modeling the microstructure variation in and after bar and shape rolling processes. To verify the microstructure change at the austenite state, hot bar stretching experiments were conducted using a newly developed quenching system.

Recently, Kwon et al. and Lee et al. [10–12] have applied the Hodgson and Gibbs microstructure evolution model [4] for predicting the micrsostructure distribution for the round-oval-round and square-diamond pass bar rolling using the rigid-viscoplastic finite element approach. They found out the microstructure evolution model should be carefully determined in order to improve the solution accuracy.

In the area of process design of bar rolling, some studies were carried out after the work of Wusatowski [13] in prediction of the workpiece deformation. Among the suggested deformation models, the spread model of Shinokura and Takai [14] was the most popular one because of its generality and accuracy. Recently, Lee et. al. [15] proposed a method for predicting the free surface geometry based on the spread formula. Min et al. [16] have investigated such spread models for three-roll rolling system to improve the spread formula for better roll profile design.

For more efficient process design of the multi-pass bar rolling sequence, Akgerman et al. [17] developed roll pass design CAD system. Kim and Im [18] also developed an expert system for roll pass design using the backward chain algorithm and Kwon and Im [19] proposed an automatic roll pass design algorithm. In this study, an approximate temperature prediction model based on lumped heat capacity system and an automatic roll speed balancing module were included for the practical process design, respectively.

Although most of these studies have been focused on the process design for dimensional accuracy, extensive studies in the process design considering the local microstructure changes have yet to be carried out. Relatively few studies are available in this aspect because of complexity of the problem. In order to achieve such a goal the system can conduct the microstructure based process design, providing overall microstructure prediction as well as geometric prediction in a simplified manner.

Therefore, the goal of this study is to develop the automatic design system of microstructure based. In order to do that, the major controlling parameter for design for better mechanical property should be identified. As pointed out before, the related studies are mainly focused on the minimization of grain size. The grain size, however, should be controlled in terms of two perspectives: refinement and homogenization. The uniformity of the grain size in the rolled bar is also of great importance because the irregular local grain size can significantly deteriorate the overall performance of the rolled bar.

Thus, two measures for the evaluation of grain refinement and homogenization are proposed in the present study. Based on the proposed criteria, the effect of major process parameters on the final microstructure distribution was investigated for the round-oval-round pass sequence in the bar rolling under the isothermal and non-isothermal approaches in order to expand the capability of the automatic design system developed by the authors [19].

2. Criteria for grain refinement and homogenization

It is necessary to define an average grain size to evaluate the grain size refinement. In this work following criterion for grain refinement of F_1 which means the average AGS value is proposed:

$$F_1 = \frac{\sum_{i=1}^{N}(d_i A_i)}{\sum_{i=1}^{N} A_i} \tag{1}$$

where the number N indicates the number of the finite elements in a cross-section of the workpiece, d_i represents the grain size and A_i is the area occupied by the ith element. The grain size for each element d_i was determined to be the average AGS value at the four nodal points at the cross-section normal to the rolling direction.

Another criterion for evaluation of the grain homogenization is suggested as follows. This is the standard deviation of the grain size multiplied by the corresponding area for each element from the value of average grain size multiplied by the average area of the elements at the cross-section of the rolled workpiece.

$$F_2 = \sqrt{\sum_{i=1}^{N}\left\{d_i A_i - d_{\mathrm{avg}}\left(\sum_{i=1}^{N}\frac{A_i}{N}\right)\right\}^2} \tag{2}$$

where d_{avg} means the average grain size and is the same as F_1 in Eq. (1).

Based on the two criteria, the characteristics of AGS distribution were examined under different process conditions of isothermal and non-isothermal approaches.