1. Introduction

Dimensional accuracy and mechanical quality are two major goals required to achieve in process design of bar rolling. These two objectives have been widely sought in the past decade by many researchers. Its importance has been doubled in recent years due to ever increasing competition in steel market. Particularly for improvement in mechanical quality, microstructural change during rolling must be accurately modeled because the mechanical properties are highly dependent on it.

According to the review paper by Kwon, recent progress in developing the austenite grain size (AGS) prediction models in plate rolling process and improving the mechanical properties of the rolled products based on such prediction models has been reported. One of the most important contributions was first made by Sellars and Whiteman and their pioneering work was followed by many researchers for two decades. In these works, the mathematical model describing the correlation between the process parameters such as strain, strain rate, temperature and microstructure has been investigated extensively. Most of the application of such model had been concentrated on hot strip rolling.

To make better prediction of the AGS distribution, more accurate information of flow stress as a function of microstructural state at any given instant of forming process is required. Thus, Karhausen and Kopp proposed an incremental model for dynamic recrystallization which can predict the microstructural change and flow stress at any given instant during the forming process. In this study, modeling both the forming parameters and microstructural phenomena was semi-empirically made based on a simple hot compression test. Recently, Yanagimoto et al. also proposed a new incremental formulation in which the dislocation density was used as a representative variable based on the microstructure evolution model suggested by Yada and Senuma. In this work, the grain coarsening phenomenon during hot rolling was investigated by combining the deformation analysis with three-dimensional steady-state finite element (FE) method and temperature analysis by a two-dimensional finite difference method.

In addition, Maccagno et al. conducted the analysis of the pass-by-pass evolution of austenite grain size during hot rod rolling of plain carbon steel. In their work, deformation
parameters for each pass in an average sense were used as input values for the AGS evolution model proposed by Hodgson and Gibbs.\(^6\) In this study various strategies to achieve grain refinement were discussed but only average value of the AGS was predicted.

Compared to plate rolling, it is well known that deformation mechanics for shape rolling is rather complex in the roll gap because of the material flow in all three directions. To predict the microstructural change in shape rolling process by utilizing the AGS evolution model, the deformation of material during rolling must be accurately determined in couple with temperature and then the AGS model should be integrated with it. In this aspect, the FE method, which can provide the detailed information on material flow during rolling, has been widely employed. Several research groups applied the FE analysis to model the deformation in shape rolling and to predict the AGS distribution in rolled sections. Glowacki et al.\(^10\) predicted the AGS distribution using two-dimensional FE simulations based on the generalized plane strain assumption in consideration of computational efficiency. The predicted AGS distribution for a square-oval rolling pass was compared with the experimental results.

To make better prediction of the AGS distribution, more accurate information of the material flow and temperature distribution during rolling is required. With this in mind, in this study, a fully three-dimensional FE analysis, which can calculate the three-dimensional heat transfer, was conducted and the results were integrated with an AGS evolution model proposed by Hodgson and Gibbs.\(^6\) The proposed approach was then applied to four-pass round-oval-round bar rolling sequence designed for this study and the characteristics of the AGS distribution in a section with the rolling sequence of material flow and area reduction ratio changed was examined.

Although the information of AGS distribution predicted from the FE analysis is invaluable for the process design, it may not be efficient due to its long computing time required for bar mill which usually consists of 30 passes. Thus, several researchers\(^11-13\) have proposed approximate modeling and process design utilizing analytical methods based on geometrical simplification of three-dimensional material flow. Maccagno et al.\(^9\) predicted the AGS evolution in rolling practices by applying the area strain based deformation model.

Recently, Lee et al.\(^11\) proposed an approximate analytical approach based on the elementary theory of plasticity, which overcomes the limitation of the area strain model. This approximate approach has the advantage of the computational efficiency but only provides the AGS value in average concept. Thus, it is necessary to examine the validity of the approximate analytical approach in terms of the AGS prediction. In this aspect the AGS value obtained from the approximate analytical approach was compared with the predicted AGS distribution from the FE based approach.

2. Integrated Approach for AGS Prediction

For prediction of the detailed material flow during bar rolling, FE simulations were carried out using an in-house FE program, CAMProll,\(^14,16\) which was developed based on the thermo-rigid-viscoplastic formulation with a specialized contact treatment algorithm for shape rolling in couple with temperature. Since the detailed information is available in these references, the finite element formulation is omitted here.

In order to determine the accuracy of the CAMProll program, the predicted surface profiles for round-oval and oval-round passes from the FE analysis were compared with the experimental measurements.\(^17\) The material used and the simulation conditions in this FE analysis were summarized in Table 1.

In this case a grooved roll with the maximum roll diameter of 310 mm was used for rolling the specimen with an initial diameter of 60 mm with a rolling speed of 34 rpm. The frictional behavior between the roll and workpiece was modeled using the constant shear friction model with the factor of 0.6. For the material modeling of the low carbon steel, the following formula reported by Shida\(^18\) was utilized.

\[
\bar{\sigma} = \sigma_t \cdot f \left( \frac{\bar{P}}{10} \right) \quad \text{...........................(1)}
\]

Here,

\[
\sigma_t = 0.28 \exp \left[ \frac{5.0}{t} \left( \frac{0.01}{C + 0.05} \right) \right] \quad \text{\(t \geq t_d\)}
\]

\[
= 0.28 \cdot g(C, t) \exp \left[ \frac{5.0}{t_d} \left( \frac{0.01}{C + 0.05} \right) \right] \quad \text{\(t \leq t_d\)}
\]

\[
g(C, t) = 30.0(C + 0.90) \left( t - 0.95 \frac{C + 0.49}{C + 0.42} \right)^2 + \frac{C + 0.06}{C + 0.09}
\]

\[C = \text{carbon % in weight}\]

\[t = \frac{T(t)^{0.01}}{1000.0} \]

\[t_d = 0.95 \frac{C + 0.41}{C + 0.32} \]

\[f = 1.3 \left( \frac{\bar{P}}{0.2} \right)^n - 0.3 \left( \frac{\bar{P}}{0.2} \right) \]

\[n = 0.41 - 0.07C \]

\[m = (-0.019 + 0.126)t + (0.075C - 0.050) \quad \text{\(t \geq t_d\)}
\]

\[= (0.081 - 0.154)t + (0.019C + 0.207) + \frac{0.027}{C + 0.320} \quad \text{\(t \leq t_d\)}
\]

| Specimen diameter | D = 60.0 mm |
|-------------------|-------------|
| Material          | Low carbon steel with C = 0.1 Wt % |
| Friction condition| m = 0.6 (constant shear friction model) |
| Specification of roll | Roll diameter = 310 mm |
| Roll speed        | 34 rpm |
| Computation time  | 1st pass 59 min, 2nd pass 50 min |

| Personal computer | AMD Athlon™ 900 MHz |
|-------------------|---------------------|
| RAM               | 256 MB              |
The predicted surface profiles were in good agreement with the experimentally measured ones in both passes, as shown in Fig. 1. In the second pass (round pass), some discrepancies in regions A and B might be attributed to the error in aligning specimen during rolling.

As previously mentioned, the detailed information of material flow obtained from the FE analysis was integrated with the AGS evolution model proposed by Hodgson and Gibbs.6) The procedure for calculating the AGS value in the AGS model used was schematically shown in Fig. 2. All equations and constants employed for the AGS model are summarized in Table 2. As noted previously, this model is mainly composed of two recrystallization behaviors, that is, the static and the meta-dynamic recrystallization.

When strain value was less than the critical strain, the static recrystallization was triggered. If the critical strain was less than strain value, meta-dynamic recrystallization occurred. When the grain was fully recrystallized, subsequent grain growth determined the final grain size. In contrast, if the partial recrystallization occurred, the average grain size could be finally calculated by the law of mixture in this AGS evolution model used.6)

The parameters used in this AGS model were summarized at each reference point in Fig. 3. The strain was determined at the roll exit, when no further change of the cross-sectional geometry was observed, that is, when the steady deformation state was reached in the FE analysis. The
strain rate was calculated by dividing the effective strain obtained from the FE analysis for each element by processing time for each pass. These values were given as the input for the AGS prediction. This calculation is compatible with the original definition of the strain rate, which was used in deriving the AGS evolution model from the hot torsion test by Hodgson and Gibbs.6) In torsion test, the strain rate was modeled as the value obtained by dividing the total effective strain with the time duration during distortion.

According to the work by Hodgson and Gibbs6) the microstructure model can be applied either for a single point in a large 3-dimensional body or the average for the body. Thus, the effect of heat transfer during rolling was not used due to the characteristics of AGS model used while the non-isothermal analysis is available in current analysis code. In addition, one of the major objective of this study is to evaluate the limitation of the approximate analytical approach proposed by Lee et al.11) In their approach the work-piece temperature at each pass was empirically determined based on the industrial data under the isothermal approximation. Therefore the same condition was applied in the present investigation.

The interpass time between two stands was determined from the rolling speed and the assumed interstand distance. Based on such input parameters, the final grain sizes in each element of the rolled section were predicted at the entrance of the next stand as illustrated in Fig. 3.
3. Results and Discussion

3.1. Application to a Four-pass Rolling Sequence

The proposed integrated approach for the AGS prediction was applied to a four-pass round-oval-round rolling sequence as shown in Fig. 4. Only a quarter part of the specimen was modeled in the current FE analysis due to the geometrical symmetry. The process conditions for the four-pass sequence were summarized in Table 3. The initial grain size at the entrance of the initial pass was assumed to be uniform as 100 μm in this study.

The predicted AGS distributions for each pass are shown in Fig. 5. The results show that AGS decreased as the pass number increased. In the first pass, the majority of AGS values was about 36.3 μm, while that in most part of the last pass was reduced to 29.0 μm. In the first and third passes, the grain size was almost uniform throughout the section but relatively large grains were predicted near the roll gaps. In the final pass, the AGS distributions were distinctively divided into two regions. The central region of the smaller grain size was dominated by meta-dynamic recrystallization, while the region near the roll gap had relatively larger grain size due to static recrystallization.

For the comparative study the average AGS values obtained from the FE analysis AGSFEavg and approximate analytical approach proposed by Lee et al.\(^1\) AGSanalytic are also given in this figure. The average value was in agreement with the AGS distribution obtained from the current approach based on the FE analysis although AGSanalytic was slightly smaller than AGSFEavg.

In addition, strain and strain rate values (two major input

| Pass No. | Temperature (K) | Rolling speed (m/sec) | Interstand distance (mm) | Interpass time (sec) |
|----------|-----------------|-----------------------|--------------------------|---------------------|
| 1        | 1323.0          | 0.582                 | 1500                     | 2.577               |
| 2        | 1317.1          | 0.725                 | 1500                     | 2.075               |
| 3        | 1292.0          | 0.859                 | 1500                     | 1.746               |
| 4        | 1283.3          | 1.000                 | -                        | 1.500               |

Table 3. Rolling conditions for the four-pass rolling sequence.

| Pass No. | Current FE approach (area average value) | Approximate analytical approach \(^1\) |
|----------|------------------------------------------|---------------------------------------|
|          | Strain | Strain rate (1/s) | AGS (μm) | Strain | Strain rate (1/s) | AGS (μm) |
| 1        | 0.496  | 5.711            | 35.8     | 0.418  | 7.237            | 34.5     |
| 2        | 0.399  | 5.381            | 34.5     | 0.381  | 7.798            | 32.8     |
| 3        | 0.401  | 7.924            | 31.2     | 0.376  | 11.18            | 29.5     |
| 4        | 0.358  | 8.557            | 30.5     | 0.360  | 11.49            | 27.5     |

Table 4. Comparison of strain and strain rate obtained from the current FE approach and the approximate analytical approach\(^1\) for the roll gap of 4 mm.

Fig. 4. Roll groove geometries in the designed four-pass rolling sequence: (a) pass 1, (b) pass 2, (c) pass 3, and (d) pass 4 (unit: mm).

Fig. 5. Predicted AGS distributions from the FE analysis including AGSFEavg and average AGS obtained from the approximate analytical approach AGSanalytic for the roll gap of 4 mm: (a) pass 1, (b) pass 2, (c) pass 3, and (d) pass 4 (unit: μm).
parameters in the AGS evolution model) obtained from the two approaches are compared in Table 4. The two parameters and resulting AGS values in the current FE based approach were calculated by taking the area average of each parameter value obtained from the FE analysis. The predicted strain values were almost similar between two approaches for each pass. According to this result in strain values, the meta-dynamic recrystallization, which was predicted to be dominant in the FE based approach, was also predicted in the approximate analytical approach. Unlike this, some differences were found in predicting the strain rate values. These discrepancies were partially attributed to the limitation of the approximate analytical approach in which the history of strain rate could not be accurately predicted. Despite of this limitation, a reasonable agreement was obtained in AGS predictions due to insensitivity of the AGS model to the strain rate value for the present condition.

3.2. Effect of Roll Gap Change on AGS

In order to investigate the effect of deformation on the AGS distribution, roll gap was reduced by 3.0 mm for each pass. The predicted AGS distributions are shown in Fig. 6 along with the average AGS predictions obtained from the approximate analytical approach. It shows that the overall grain size became smaller and that the distribution was more uniform compared to the pass sequence where normal roll gap of 4.0 mm was used at each pass. For example, the AGS distribution in the last pass was within the small range of 27.5 to 29.8 μm.

In this modified process with the reduced roll gap, meta-dynamic recrystallization occurred in the entire specimen because the amount of deformation increased while the other rolling conditions were unchanged. The average AGS values predicted by the approximate analytical approach were also in good agreement with the AGS distributions in each pass obtained from the current approach based on the FE analysis. The difference between AGS_analysis and AGSFEavg became even smaller for the reduced roll gap case.

From the above study using the four-pass sequence, it was found that as the pass number increased the overall grain size was reduced. When the overall roll gap was reduced more uniform and refined grain was predicted. To check the effect of rolling speed in wide range of rolling conditions the rolling speed was increased and the subsequent change of the AGS distribution was considered in the following.

3.3. Effect of Rolling Speed on AGS

To investigate the effect of roll speeds on the AGS, the roll speeds varied from 37 rpm to 74 rpm, 148 rpm, and 296 rpm for the first pass in the previous four-pass rolling schedule. The resulting AGS distributions according to the rolling speeds are shown in Fig. 7. It can be seen that the austenite grain size was refined gradually in the most of the region, where meta-dynamic recrystallization occurred with the increase of rolling speeds. Also the region with large grain size was also expanded near the roll gap region due to the increase of statically recrystallized zone. The average AGS value predicted by the approximate analytical approach was in good agreement with the AGS distribution obtained from the FE approach in the initial three cases. However, large discrepancy was observed when the rolling speed was 296 rpm. The approximate approach predicted the AGS value as 44.4 μm compared to 26.3 μm according to the current approach.

To investigate the difference, the average AGS value obtained by taking the area average of the AGS distribution was compared in Fig. 8 with the average AGS value obtained from the approximate analytical approach by Lee et al. Table 5 summarizes the predicted AGS values ob-

![Fig. 6. Predicted AGS distributions from the FE analysis including AGSFEavg and average AGS obtained from the approximate analytical approach AGS_analysis for the roll gap of 1 mm: (a) pass 1, (b) pass 2, (c) pass 3, and (d) pass 4 (unit: μm).]
tained from two approaches, when the rolling speed increased. When the roll speed was low, the meta-dynamic recrystallization (MDRXN) was dominant in the rolled section. As the rolling speed increased, however, the region affected by the static recrystallization (SRXN) behavior increased from the far right corner of the rolled specimen. The current approach predicted gradual change of each region with two different recrystallization behaviors and gradual decrease in average grain size with the increase of rolling speed.

In contrast, the approximate analytical approach predicted only one recrystallization behavior in a pass. When the rolling speed was high, the approximate approach predicted too high AGS value by predicting the static recrystallization behavior in the whole section. Thus, it is required to improve the accuracy of the approximate analytical approach in order to predict the accurate AGS value from the approximate approach.

4. Conclusion

In this study, the AGS evolution model proposed by Hodgson and Gibbs was integrated with the fully three-di-

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Table 5. Comparison of AGS values predicted by the current FE approach and the approximate analytical approach for the various roll speeds (unit: μm).

| Rolling speeds | 37 rpm | 74 rpm | 144 rpm | 222 rpm | 296 rpm |
|---------------|-------|-------|--------|--------|--------|
| Current approach (area average value) | 36 | 32 | 30 | 27 | 26 |
| Approximate analytical approach | 34 | 30 | 27 | 44 | 45 |

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**Fig. 7.** AGS distributions including AGS\_\text{FEavg} and the average AGS obtained from the approximate analytical approach AGS\_\text{analytic} for various roll speeds of (a) 37 rpm, (b) 74 rpm, (c) 148 rpm, and (d) 296 rpm (unit: μm).

**Fig. 8.** Comparison of AGS predictions by two approaches for various roll speeds of 37, 74, 14, 222, and 296 rpm.
dimensional finite element program for predicting the AGS during round-oval-round bar rolling. The following conclusions were arrived at from the current study:

1. A fully three-dimensional finite element program was successfully developed for predicting the AGS distribution for multi-stage bar rolling.

2. The predicted AGS could be divided into relatively small and large grain size regions, depending on the dominance of meta-dynamic or static recrystallization.

3. Reduced roll gap led to more refined and uniform grain distribution.

4. Roll speed increase led to refinement of austenite grain size in the meta-dynamic recrystallization region, but also resulted in expansion of the grain coarsening region.

5. The average AGS predicted from the approximate analytical approach agreed well with the results from the FE approach but showed discrepancies at higher rolling speed conditions investigated.

Since an integrated three-dimensional FE analysis system is available, it might be beneficial to investigate various microstructure evolution models including temperature effect for better understanding of determining final properties of the workpiece in the future.

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