Three-dimensional Numerical Analysis of Microstructural Evolution in and after Bar and Shape Rolling Processes

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(Received on January 28, 2002; accepted in final form on May 14, 2002)

An integrated numerical model predicting microstructural evolution, three-dimensional plastic deformation and temperature changes has been applied to industrial hot bar rolling and H-beam rolling. This model enables us to predict three-dimensional metal flow and temperature changes as well as transient in grain size change and dislocation density distribution in and after hot rolling. To demonstrate the successfullness of the proposed model, it was applied to the analysis of two different industrial bar rolling schedules, in which total number of passes and caliber systems were different with each other. It was also applied to the analysis of the H-beam rolling sequences with different heat treatment conditions. Microstructural evolution starting from deformed austenite to ferrite/pearlite/bainite after phase transformation was successfully simulated. Microstructural evolution in and after hot rolling as well as metal flow and temperature can be easily obtained through the proposed model using rolling condition and alloy composition as the functional variables. This model is a very useful tool for designing and optimizing rolling conditions so that products with the best internal quality and dimensional accuracy can be obtained.

KEY WORDS: hot rolling; numerical analysis; plastic deformation; microstructure; phase transformation.

1. Introduction

It has been the motivation of the steel industry to continuously produce better performance steel and at the same time develop new forming technology for realizing the higher yield of steel products. It is important to seek the best rolling condition and optimize the geometry and microstructure of steel products. It has been known that Microstructural evolution is closely related to temperature changes and plastic deformation. Plastic deformation is also the determining factor for the dimensional accuracy of the formed product. Conventional renovation of rolling procedure for microstructure improvement requires long time of experiments and huge cost. It is essential to develop a three-dimensional integrated analysis of deformation, temperature changes and microstructural evolution in and after hot rolling of various products such as sheets, plates, bars, wire rods and various sections. So that geometry and inner microstructure can be flexibly controlled according to the requirement.

The mechanical properties are strongly dependent on the inner microstructure of metal product. Metal with smaller grain size exhibits higher tensile strength and elevates the ductility at lower temperature. It has been the motivation of the steel industry to continuously produce better performance steel and at the same time develop new forming technology for realizing the higher yield of steel products. It is important to seek the best rolling condition and optimize the geometry and microstructure of steel products. It has been known that Microstructural evolution is closely related to temperature changes and plastic deformation. Plastic deformation is also the determining factor for the dimensional accuracy of the formed product. Conventional renovation of rolling procedure for microstructure improvement requires long time of experiments and huge cost. It is essential to develop a three-dimensional integrated analysis of deformation, temperature changes and microstructural evolution in and after hot rolling of various products such as sheets, plates, bars, wire rods and various sections. So that geometry and inner microstructure can be flexibly controlled according to the requirement.

The mechanical properties are strongly dependent on the inner microstructure of metal product. Metal with smaller grain size exhibits higher tensile strength and elevates the ductility at lower temperature.1,2) So that one of the objective to improve mechanical properties is to minimize the grain size of the products in hot forming process. As temperature controlled rolling and thermo-mechanical treatment are realized to generate finer grain structure in industrial scale, this technology, called TMCP technology,3) is widely used in hot rolling industry. For the microstructural changes of austenite phase in hot forming, the kinetics for dynamic/static recrystallization rate and grain growth have been studied and described by deformation rate, amount of deformation, temperature and alloy composition by Yada et al.4–6) For continue cooling phase transformation procedure, the transformation rate of ferrite/pearlite/bainite has been modeled theoretically by Suehiro7) and Kirkaldy8) etc.

These numerical models have been successfully applied to predict grain evolution on controlled rolling of plates with better strength, elongation and toughness. But these conventional models have given a greater attention to the metallurgical aspects compared to the three-dimensional metal flow and, it can not be extended directly to the rolling of tandem hot strip rolling with short inter-pass time, bar/wire rolling and shape rolling. Even though thermo-mechanical FEM analyses have applied to the hot rolling processes,9–11) the important metallurgical aspects, which are caused by combined dynamic/static recrystallizations and their repetitions are still missing. Also, it is not available in the literature to describe the phase transformation analysis, it should be coupled with microstructure analysis of austenite state in hot forming process. For this reason, authors had proposed the incremental formulation for the prediction of microstructural changes in austenite state and phase transformation state.12–16) In the model, authors used dislocation density and grain size as representatives to trace the microstructural evolution procedure. By this model, the microstructural changes in austenite state has been evaluated continuously, and the effect of plastic deformation on phase transformation prior to cooling can described by the resid-

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ual dislocation. It can be considered the proposed model is more suitable for tandem rolling, and more precise microstructural change prediction can be succeeded.

It was the purpose of current research by implying the incremental formulation proposed\(^\text{12}–\text{16}\) to demonstrate an integrated numerical model of predicting microstructural evolution, three-dimensional plastic deformation and temperature changes applied to the industrial hot bar rolling and H-beam rolling. Their characteristics of microstructural evolution in industrial rolling processes will be the topic of examination and discussion based on the information obtained from numerical analysis. Two bar rolling process, for the round products of 24 mm and 10 mm, was first selected, and the effect of caliber schedules to transient change in microstructure was investigated. Then, numerical analysis for H-beam rolling, was performed and the effects of cooling conditions to final microstructure distribution, which gives the really important information for ensuring the toughness in whole cross-section of products, were demonstrated. From the numerical data, optimum rolling conditions for H sections were also examined.

2. Analytical Method and Its Validation

2.1. Analytical Method

Integrated analysis of microstructure evolution, metal flow and temperature changes was applied for characterization of microstructure evolution in bar rolling and shape rolling processes. Figure 1 shows the schematic illustration of integrated analysis. Change in distribution of dislocation density and grain size during hot rolling were analyzed by incremental formulations for microstructure evolution,\(^\text{12,13}\) temperature transition and strain rate along each streamline was used as ‘process oriented’ boundary conditions. Material parameters, embedded in recrystallization kinetics, recoveries etc. for plain C–Si–Mn steels,\(^\text{17}\) were used as ‘material oriented’ boundary conditions. Microstructure evolution after forming was analyzed by incremental approach for phase transformation,\(^\text{16}\) and final microstructure after cooling was obtained. Transition in dislocation density at each point was continuously traced from forming stage to cooling stage to reflect the effect of hot forming on the accelerated nucleation at the beginning of transformation.\(^\text{16}\) Material parameters for phase transformation of Suehiro’s model\(^\text{18}\) were used in the analysis.

The analytical accuracy of currently used method had been validated earlier,\(^\text{13,15,16}\) and it was concluded that this model was accurate enough for predicting the evolution in microstructure in and after hot forming.

2.2. Validation of Analytical Results for the Evolution of Microstructure in Multi-pass Hot Rolling

Table 1 shows the changes of process parameters for the rolling of 127×127 mm square billet down to 12 mm diameter bar,\(^\text{19}\) which was given by Maccagno et al. Table 1 demonstrates the averages of temperature and strain rate, neglecting their distribution in cross-section and transition in rolling direction. The analysis of microstructure evolution was conducted, and the results were compared with the result of Maccagno’s analysis based on empirical model,\(^\text{19}\) with experimental measurements\(^\text{20}\) and with final austenite grain size calculated from Yada’s empirical equation.\(^\text{21}\) The result is shown in Fig. 2. The arrow of this figure represents the rolling passes. The pass number is also given in the same figure. The change in austenite grain size was successfully simulated by the incremental formulations for microstructure evolution. Because of its over simplification for dynamically recrystallized fraction in Maccagno’s model,\(^\text{19}\) it is difficult to be used for the analysis of rolling passes, where partial dynamic recrystallization takes place. In the roughing passes, the dynamically recrystallized fraction was low and static recrystallization has occurred be-
between the passes. For these passes, the austenite grain size from Maccagno's model was different from the one obtained by incremental formulation for the evolution of microstructure. The later predicted austenite grain size accurately for any combination of the partial dynamic/static recrystallizations. Figure 3 shows another application sample of 25-pass wire rod rolling from 127 mm square billet to 5.5 mm wire rod. The process parameters are shown in Table 2. It should be noted that the integrated model of Fig. 1 reflected a more accurately rolling conditions such as caliber profiles and resulted a more precise analysis of cross-sectional distributions of grain size and dislocation density. The results of integrated model application for the bar and shape rolling processes will be described in the next few chapters.

3. Application of Integrated Analysis to Industrial Bar Rolling

3.1. Rolling Conditions

The design and optimization of stand type, mill layout, temperature controlling systems and calibers are the required parts of industrial rolling process. The basic construction of rolling plant, such as stand type, mill layout and temperature controlling systems, should be determined when the rolling plant is newly designed or a significant renovation is being made. The rolling plant operation of and the caliber systems should be optimized given the rolling plant quality production conditions. An integrated analysis for microstructure evolution, temperature changes and plastic deformation would be one of the most important tools for the designing and operations of rolling. For demonstration purpose, an integrated analysis was applied to the industrial bar rolling processes. Two different types of rolling sequences were selected with one of them being Square-Diamond (SD) sequence of 12 passes producing 24 mm bar from 60 mm square billet. Another one was the Square-Oval-Round (SOR) sequence of 14 passes producing 10 mm bar from the same square billet as mentioned above. The SD sequence is given in Fig. 4, and SOR sequence given in Fig. 5. Analytical conditions commonly used for the two sequences are listed in Table 3.

For the rolling of SD sequence, the bar being rolled was cooled by air between the rolling stands. To detect microstructure changes of bar rolling with SOR sequence several cooling conditions were applied. The cooling conditions for SOR sequence are shown in Table 4. It was assumed that two cooling devices were installed at the point between the roughing and intermediate stands and between intermediate and finishing stands, respectively. Cooling time depended on the bar speed and length of the cooling zone. The length of the cooling zone was 13 m from roughing to the intermediate stands and 18.5 m from intermediate to the finishing stands. The predicted bar speed in these cooling zones were 1.98 m/s and 6.88 m/s, respectively, based on the deformation analysis with an entrance speed of 0.5 m/s. Cooling time of these cooling zones were 6.6 s and 2.7 s, respectively. To study the effect of accelerated cooling on final microstructure, two additional cooling zones after finishing stands were also imposed. The bar after rolling passed the first cooling zone in 10 s, and then entered second cooling zone, where the rolled bar was cooled to room temperature. A total of five conditions of cooling were simulated. Cases (a), (b) and (c) was the bar rolling without cooling of water at the points between roughing and intermediate stands and between intermediate and finishing stands. But cooling zones after finishing stands were activated in Case (b) and Case (c) to measure the effect of accelerated cooling after rolling. In Cases (d) and (e), cooling devices at the points between roughing and intermediate stands and between intermediate and finishing stands were activated to attain lower finishing temperature. In Case (d), only the first cooling zone after finishing rolling was activated, but all cooling zones were activated in Case (e). The heat transfer coefficients used in the analyses are shown in Table 3.

For SD sequence, only a quarter of material was analyzed, as there were two fixed symmetric planes along rolling direction. SOR sequence required 45° rotations between the passes. Its whole cross section was analyzed by the integrated model for microstructure evolution, temperature changes and plastic deformation. The position of top center point of the billet is shown by “|” in Fig. 5.

![Fig. 3. Austenite grain size change on whole rolling line for the 5.5 mm wire rod.](image)
Fig. 4. Mill layout and roll caliber for rolling 24 mm bar.

Fig. 5. Mill layout and roll caliber for rolling 10 mm bar.
### 3.2. Results of Analysis

Figure 6 shows temperature changes representing the three points of the cross section during rolling from the SD sequence. At point A, which is the center of the cross-section, temperature was gradually reduced at the roughing and intermediate stands, but increased a little at the finishing stands through heat generation, which was from the plastic deformation under high deformation rate. At point C, located at the surface, its temperature exhibited an acute drop because of the heat dissipation to work roll. These rapid temperature drops were observed in every two passes. This was because point C was close to the work roll only in horizontal (odd) passes. In the vertical (even) passes, temperature changed slightly as point C located at the free surface.

Figure 7 shows the evolution of austenite grain size for the same three points. In the roughing stands, austenite grain size decreased rapidly due to the effect of dynamic recrystallization and static recrystallization. But after the intermediate passes, austenite grain size reached a near steady state as the whole cross-section was perfectly covered by the dynamically recrystallized grains. A rapid growth of grain size was also observed in these stands due to the post-dynamic recrystallization. The Yada’s empirical equation, for which the grain size is expressed as a sole function of Zener–Hollomon parameter for final pass, gave a rough description of the observations. However, a more precise description had been observed by the integrated analysis. This is contributed to its better history reflection deformation of the entire stands, including its distribution in cross-section.

Figures 8 and 9 are the temperature transition and grain size of SOR sequence with air cooling (Case (a)). The remarkable change in austenite grain size can be observed in Figure 10, responding to the temperature changes from the cooling at points between roughing and intermediate stands.
and intermediate and finishing stands. As being generalized, lower finishing temperature is more suitable for manufacturing bar with smaller austenite grain size. This situation is also suitable for attaining a higher dislocation density accelerating the transformation rate and obtaining a finer ferrite grain size. But a higher dislocation density would cause the elevation of flow stress and roll separating force and in turn yield a poor geometry of rolled products due to the finite value of rolling mill's stiffness. Integrated analysis will supply the results for the rolling plants design and mill operations. The austenite grain size difference between Case (a) and Case (b) increased from the cooling after finishing stands. Finer austenite grain size could be obtained in Case (d), for which bar was also cooled through water at the points between roughing and intermediate stands and between intermediate and finishing stands. Higher residual dislocation density could also be obtained under this cooling condition, which would affect the nucleation rate during phase transformation.

Figure 11 shows the ferrite grain size distribution of after phase transformation for Cases (a) to (e). Comparing the ferrite grain sizes among Cases (a), (b) and (c) for the different cooling conditions after finishing stands, it was interesting to see that finer ferrite grain size had been obtained only through the accelerated cooling after finishing rolling. The volume fractions of ferrite, pearlite and bainite phases are shown in Table 5. It is worth noting that, for the Case (c), larger amount of bainite fraction occurred, which reduced elongation of rolled bar. Fine ferrite grain structures without bainite had been obtained for Case (d). It can be concluded that temperature controlled rolling through inter-stand water cooling was helpful to get fine ferrite grain structure with sufficient elongation. Comparing Cases (d) and (e), it can be concluded that that cooling condition after finishing rolling should be carefully controlled even for temperature controlled rolling by inter-stand cooling. This is because of the increased amount of bainite when excessive cooling is applied to the bar after finishing rolling.

4. Application of Integrated Analysis to Industrial Shape Rolling

4.1. Rolling Conditions

Shape steel, such as H-beam, has a complex sectional geometry, so that it requires large volume of metal flow during hot rolling. Higher forming temperature have been popularly used because of lower flow stress at the elevated temperature being favorable to guarantee the precise requested geometry. But coarse microstructure can be produced from the fast grain growth at elevated temperature, which yields poor toughness on rolled sections. In fact, there have been general trends that mechanical property such as strength and toughness should be guaranteed in whole cross-section of rolled products. To improve the mechanical property of shape steels, controlled rolling has been employed in industrial rolling plant, and it has been confirmed as a feasible way to control microstructure through practical applications.

The integrated analysis to predict microstructure evolution, three-dimensional plastic deformation and temperature changes is being strongly recommended for the design of rolling conditions and mill operations of the controlled section rolling. In the current project, the rolling of H-section steel was selected. The effects of controlled rolling conditions on microstructure evolution will be given in the following continuous discussion. Figure 12 shows the layout of stands, distances between stands, and the location of temperature controlling device used in the controlled rolling. Temperature controlling device was located at the entrance and exit of intermediate universal mill and edging mill. It will be named the IMC (Inter-Mill-Cooling) device in the following discussion. In addition, cooling zone after finishing universal mill, which was named TMCP device, was also installed. The rolling conditions are shown in Tables 6 and 7. Large H-beam section (H550×200−6×16H) for heavy structure had been selected. The slab with width 600 mm and height 200 mm was rolled by three passes with a 2-Hi reverse roughing mill. In the intermediate block consisting of one universal mill and one edging mill, a combination of five rolling passes and three edging passes.
are imposed. The IMC device was identified at the entrance and exit of intermediate block, and the length of cooling zones was 20 m. Finally, one universal pass and edging pass was used to form the product with final geometry. The TMCP device was located at the exit of finishing block that cooled the product and controlled the final microstructure. The length of the cooling zone was 30 m. The caliber dimension is shown in Fig. 12 and Table 6. The initial temperature before rough rolling is 1473 K. The plastic deformation and temperature changes were calculated from the roughing block, but the microstructure analysis was coupled to the intermediate block with the uniform grain size of 100 μm at the entrance of intermediate block. This was because the inter-pass time between roughing block and intermediate block was 30 s, which can be considered being long enough for the steady-state growth of austenite grains. Two cases of cooling were analyzed to study the effect of cooling on cross-sectional microstructure changes of product.

One was the normal rolling without cooling from IMC and TMCP devices. The other is the controlled rolling with cooling from IMC and TMCP devices, which cools the outer surface of flange through water spray.

4.2. Results of Analysis

Figure 13 shows the transient temperature change for the three representative points in the cross-section of H-beam. The temperature at point A, located at the center of web, was very similar between the two different cooling conditions. Temperature of points B and C responded the changes of cooling condition remarkably. Especially, for the lower temperature of fillet portion cooled through the IMC device, it was effective to avoid coarse grain, which could reduce the toughness of this area.

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**Table 6.** Rolling schedule for H550×200–6×16.

<table>
<thead>
<tr>
<th>Pass No.</th>
<th>Roll radius (mm)</th>
<th>Height (H1)/2 (mm)</th>
<th>Entrance (mm)</th>
<th>Exit (mm)</th>
<th>Reduction (%)</th>
<th>Time of inter-pass (s)</th>
<th>Roll Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>350</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>50</td>
<td>5</td>
<td>1013</td>
</tr>
<tr>
<td>R2</td>
<td>350</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>50</td>
<td>5</td>
<td>1013</td>
</tr>
<tr>
<td>R3</td>
<td>350</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>50</td>
<td>5</td>
<td>1013</td>
</tr>
<tr>
<td>U1</td>
<td>500</td>
<td>16.4</td>
<td>11.5</td>
<td>30</td>
<td>335</td>
<td>318</td>
<td>20</td>
</tr>
<tr>
<td>U2</td>
<td>500</td>
<td>11.8</td>
<td>8.1</td>
<td>30</td>
<td>338</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>U3</td>
<td>500</td>
<td>8.1</td>
<td>5.6</td>
<td>30</td>
<td>331</td>
<td>287</td>
<td>30</td>
</tr>
<tr>
<td>U4</td>
<td>500</td>
<td>5.6</td>
<td>3.9</td>
<td>30</td>
<td>297</td>
<td>278</td>
<td>30</td>
</tr>
<tr>
<td>U5</td>
<td>500</td>
<td>3.9</td>
<td>2.2</td>
<td>20</td>
<td>278</td>
<td>276</td>
<td>20</td>
</tr>
<tr>
<td>UF</td>
<td>500</td>
<td>3.2</td>
<td>3</td>
<td>6</td>
<td>278</td>
<td>276</td>
<td>6</td>
</tr>
</tbody>
</table>

**Table 7.** Rolling condition for H-section.

<table>
<thead>
<tr>
<th>Material</th>
<th>Flow stress (MPa)</th>
<th>Friction coefficient</th>
<th>Mesh system for deformation analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>S45C</td>
<td>85.62×10(-2)</td>
<td>μ = 0.3</td>
<td>N1 = 11, N2 = 5, N3 = 4+12×2</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>Hc = 30000(W/m·K)</td>
<td>Hcp = 709.49(W/m·K)</td>
<td></td>
</tr>
<tr>
<td>Specific heat</td>
<td>C = 996(J/kg·K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>k = 23.6(W/m·K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation coefficient</td>
<td>ε = 0.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape factor</td>
<td>F = 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mesh system for temperature analysis</td>
<td>Ns = 38, Ny = 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ns = 6800(for each pass)</td>
<td></td>
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</tr>
</tbody>
</table>

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Fig. 12. Mill layout of H-beam rolling.

Fig. 13. Transition in temperature.
of the flange, especially near the fillet area. But when the IMC and TMCP devices were activated, finer austenite grains appeared in the flange area. Similarly, the growth rate of austenite grains with the controlled cooling was much smaller than that of normal air cooling. Cross-sectional distribution of ferrite grain size has been shown in Fig. 15. It is very clear that the ferrite grain size control in fillet can be achieved through applying the IMC and TMCP devices.

### 5. Conclusion

The integrated analysis of microstructure evolution, three-dimensional plastic deformation and temperature changes has been demonstrated by selecting the industrial bar rolling and section rolling as the models of research. The characteristics of microstructure evolution with different rolling sequences, different rolling and cooling conditions were also analyzed.

The integrated analysis can be effectively applied to the other rolling processes, such as rolling of sheet, plate, wire and rod etc. Because the geometry and microstructure are the two most important topics for rolling optimization, the integrated analysis described in this paper will definitely be accepted as an important method in developing the novel rolling technology.

### REFERENCES