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MICROSTRUCTURE EVOLUTION MODELING OF SQUARE-DIAMOND PASS HOT BAR ROLLING OF AISI 4135 STEEL

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Abstract

In this study, kinetics of the static (SRX) and metadynamic recrystallization (MDRX) of AISI4135 steel was investigated using hot torsion tests. Continuous torsion tests were carried out to determine the critical strain for dynamic recrystallization (DRX). The times for 50% recrystallization of SRX and MDRX were determined, respectively, by means of interrupted torsion tests. Furthermore, austenite grain size (AGS) evolution due to recrystallization (RX) was measured by optical microscopy. With the help of the evolution model established, the AGS for hot bar rolling of AISI4135 steel was predicted numerically. The predicted AGS values were compared with the results using the other model available in the literature and experimental results to verify its validity. Then, numerical predictions depending on various process parameters such as interpass time, temperature, and roll speed were made to investigate the effect of these parameters on AGS distributions for square-diamond pass rolling. Such numerical results were found to be beneficial in understanding the effect of processing conditions on the microstructure evolution better and control the rolling processes more accurately.

Key words: austenite grain size, recrystallization, hot bar rolling, numerical prediction, AISI4135

1. INTRODUCTION

It has been main goal of steel companies to make better quality steel products with higher strength and better ductility. It is well known that metals with smaller grains have higher tensile strength and better ductility at low temperature. Thus, design of pass schedule considering local microstructure evolution has been highly desired. In order to achieve this goal, accurate modeling and prediction of microstructure evolution should be required.

Because of this, many studies for modeling the kinetics of recrystallization and the microstructure evolution have been carried out so far (Beynon & Sellars, 1992; Hodgson & Gibbs, 1992; Kwon, 1992; Lee et al., 2001; Saito et al., 1985; Sellars & Whitemann, 1979; Suehiro et al., 1987). These models were mostly applied for predicting microstructure evolutions in the plate and strip rolling processes over the past several decades (Kumar et al., 1991; Laasraoui & Jonas, 1991; Saito & Shiga, 1992; Watanabe et al., 1992).

Recently, prediction of microstructures in the hot bar rolling process was investigated. Maccagno et al. (1996) predicted the grain size to explore the potential for refining the austenite grain size in the bar rolling using spreadsheet. In their study, the effect of temperature and strain rate on the grain size was investigated. However, process parameters such as

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strain, strain rate and temperature were assumed to be constant in an average sense.

To make better prediction of the grain size during the process, more accurate calculation of process parameters is highly desirable. Thus, Glowacki et al. (1992) predicted the grain size using two dimensional finite element (FE) simulations under the generalized plane strain assumption. Yanagimoto et al. (1998) proposed the incremental formulation and applied it to the analysis of the bar rolling process (Liu & Yanagimoto, 2002). Kwon et al. (2003a, 2003b) also investigated the change of the AGS distribution for the multi-stage bar rolling process of AISI1020 by combining the AGS evolution model proposed by Hodgson and Gibbs (1992) with the three dimensional FE program.

Recently, few studies for design of roll pass schedule considering microstructure evolutions have been done (Hong & Park, 2003; Kwon & Im, 2005). However, extensive studies considering local microstructure changes have yet to be carried out because of complexity of the problem. To achieve such a goal, the effect of process parameters should be carefully investigated a priori.

Thus, the goal of this study is to investigate the effect of process parameters on microstructure during hot bar rolling. In order to do that, recrystallization and AGS evolution of AISI4135 steel was investigated in the present study by conducting hot torsion tests. Then, fully three-dimensional non-isothermal FE analyses were conducted for more accurate prediction of the AGS of AISI 4135 in the bar rolling process. To verify the proposed AGS evolution model, the simulation results obtained from the current model were compared with the results based on the model by Lee et al. (2001) for the square-diamond (S-D) and round-oval (R-O) pass bar rolling and the experimental data given in the previous work (Lee et al., 2005). Then, numerous three-dimensional FE analyses were carried out for the S-D pass bar rolling for examining the effect of various rolling process parameters such as inter-pass time, temperature and rolling speed on the AGS distributions according to the current model developed in the present work to check the predictive capability of the existing microstructure evolution model.

2. EXPERIMENTAL

The AISI 4135 steel was investigated in the current work and its chemical composition is given in table 1. Torsion specimen with a gauge length of 20mm and a gauge diameter of 6.7mm were prepared by machining. Two types of torsion tests were conducted using a computer controlled torsion machine available at the Deakin University. At first, continuous torsion test was performed to identify the flow curve that was used for estimating the critical strain at each experimental temperature and strain rate. The surface of the specimen was protected from oxidation using argon gas. True stress and true strain curves were derived from the raw data using the general method suggested by Fields and Backofen (1957).

Table 1. Chemical composition of AISI4135 steel used

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

Before isothermal deformations, a roughing pass at strain rate 1 sec^{-1}, strain 0.4 and temperature 1100°C was applied to obtain homogeneous austenite grain size which was measured to be 30 μm. Some specimens were in a different roughing pass at strain rate 1sec^{-1}, strain 0.4 and temperature 900°C to investigate the effect of initial grain size. The resulting grain size measured was 18 μm. After roughing pass, isothermal deformations were conducted with the temperatures from 800 to 1100°C and the strain rates from 0.1 to 10 sec^{-1}.

At second, interrupted torsion tests were conducted to decide the time for 50% recrystallization. To reduce the number of experiments required, rapid method introduced by Hodgson et al. (2004) was adopted. After applying the same roughing pass described earlier, interrupted torsion tests were conducted with the strain range of 0.04 to 4. Softening was determined using conventional methods introduced by Roucoules et al. (1994). Some specimens were held for around several or hundred seconds depending on the conditions to achieve a full recrystallization and quenched using water sprays for further microstructural investigation. A heated solution of saturated picric acid was used to reveal austenite grain boundaries.

3. INTEGRATED NUMERICAL APPROACH

For determination of the effect of the detailed process parameters on the AGS evolution during bar rolling, three-dimensional non-isothermal FE simulations were carried out using CAMP*roll* (Kim & Im, 2000; Kwak et al., 2002a; Kwak et al., 2002b), an in-house FE program developed based on the thermo-rigid-viscoplastic formulation with constant shear friction model. Since the details of mathematical formulation are available in references (Kim & Im, 2000; Kwak et al., 2002a; Kwak et al., 2002b; Kwon et al., 2003a; Kwon et al., 2003b), it is omitted here.

Table 2. Material and FE analysis conditions used

Friction condition	m_f=0.8 (constant shear friction model)		
Roll diameter	310 mm		
Mesh layout	S-D	80 mesh in a section	
		22 section in rolling direction	
	R-O	56 mesh in a section	
		22 section in rolling direction	
Rolling Temp.	1000, 1050, and 1100 °C		
Rolling speed	34, 51, and 68 rpm		
Interpass time	1, 5, 10, and 20 sec		
Interface HTC	24 (R-O), 72 (S-D) kW/m^{2}K		
Convection HTC	2.33 W/m^{2}K		
Emissivity	0.505 (R-O), 0.723 (S-D)		
Thermal Cond.	28.0328 W/mK		
Specific heat	3744 kJ/m^{3}K		
Roll temp.	60°C		
Room temp.	25°C		

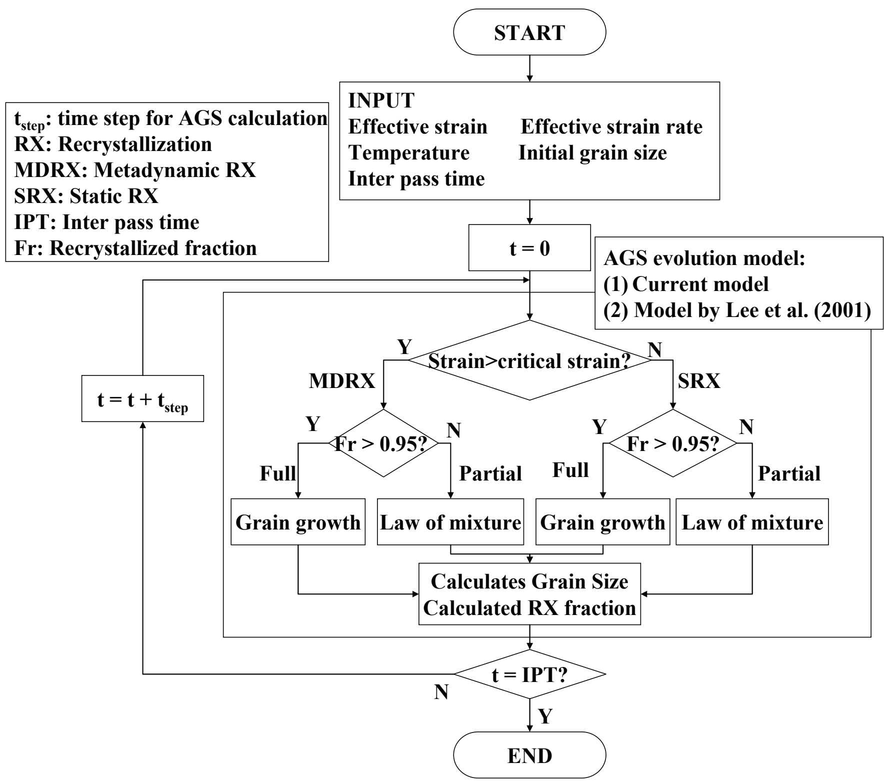


Figure 1. The flow chart of the integrated numerical prediction

The material property of the AISI 4135 steel used in FE simulations was obtained from hot compression tests using Gleeble machine at temperature ranges of 500 to 1100 °C and strain rates from 0.01 to 100 s^{-1}. The flow stress was modeled with the power law, $\bar{\sigma} = C(\bar{\varepsilon}, T)\dot{\bar{\varepsilon}}^m$ for non-isothermal simulations. The strength coefficient (C) and strain rate sensitivity (m) were provided in a tabular form at constant temperatures and strain values.

The simulation conditions used in the present investigation are summarized in table 2. The constant shear friction factor of 0.8 was used in simulations and the roll diameter was 310 mm. The interface heat transfer coefficients between the workpiece and rolls of 24 and 72 KW/m^{2}K were used for the R-O and S-D passes, respectively. The roll and room temperatures were assumed to be 60 and 25°C, respectively. The temperature distribution of the workpiece during the hot rolling process was calculated by applying the CAMP*roll*. And the temperature data was provided as an input for the cooling process during the interpass time to determine the temperature changes due to heat transfer by convection and radiation.

Specific algorithm for the integrated numerical prediction used is described in figure 1. Most of input data such as strain, strain rate, and temperature for the calculation of the AGS were obtained from the FE analyses. However, an initial grain size used in simulations was determined from the hot rolling experiments. The specific values of the initial grain size used in the present studies were 81 μm for the S-D pass and 119 μm for the R-O pass, respectively. Such an input data was used in the current simulations integrated with the AGS evolution models.

In general, AGS evolution model describes the change in AGS by recrystallization and grain growth. During thermo-mechanical processing, grain is refined by recrystallization under the certain strain and temperature. Further grain growth may take place even in short interpass time, when recrystallization is completed.

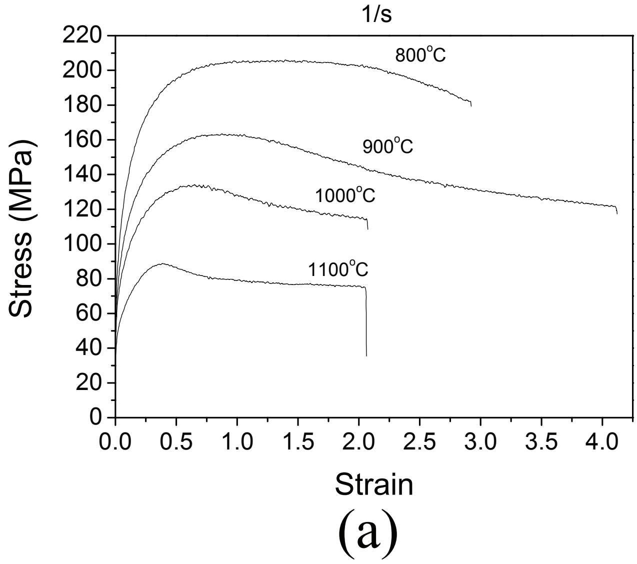
Three dominant recrystallization processes have been proposed earlier: dynamic, static, metadynamic. But recent work has shown that once significant dynamic recrystallization occurs there will be a metadynamic recrystallization, which will replace the initial dynamically recrystallized grains (Hodgson et al, 1991). 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. So, in this study only static recrystallization, meta-dynamic recrystallization, and grain growth were considered as a mechanism of AGS change.

In the present simulation, the critical strain which was a standard parameter to judge what kind of RX will happen was firstly calculated. If the strain was greater than this critical strain value, meta-dynamic recrystallization (MDRX) would happen. After determining the type of RX, RX fraction was calculated. If the calculated RX fraction was greater than 0.95, full recrystallization would occur. In this case, grain growth would follow the recrystallization. If the calculated RX fraction was smaller than 0.95, a partial recrystallization would be likely. Then, the AGS could be calculated by applying the rule of mixtures (Hodgson & Gibbs, 1992). After each step calculation, the AGS and RX fraction data was used as an input to the next step in the case of full recrystallization and partial recrystallization, respectively. In the present investigation, the model developed in the present work and model proposed by Lee et al. (2001) were, respectively, used for predicting the AGS values.

4. RESULTS AND DISCUSSION

4.1. AGS evolution modeling

The stress vs. strain curves were obtained in various temperatures and strain rates to investigate the effect of these parameters as shown in figure 2. The activation energy for hot deformation was identified to be 240 kJ/mol based on flow curves in this figure. From the stress vs. strain curves, plot of hardening rate vs. stress could be obtained. The critical stress and strain for initiation of dynamic recrystallization was decided from an inflection point based on the method described in reference (Poliak & Jonas, 2003). The relationship between critical strain and Zener Hollomon parameter, Z, was obtained by applying the regression analysis and it is summarized in table 3. In this table, ε_c is the critical strain, d_0 the initial austenite grain size, the $\dot{\varepsilon}$ strain rate, R the gas constant, T the absolute temperature, t the interpass time, $t_{0.5}$ the time for 50% recrystallization, $\bar{\varepsilon}$ the applied strain, t_{gg} the time for grain growth, X the volume fractions of recrystallized grains, and d_{RX} the recrystallized grain sizes.



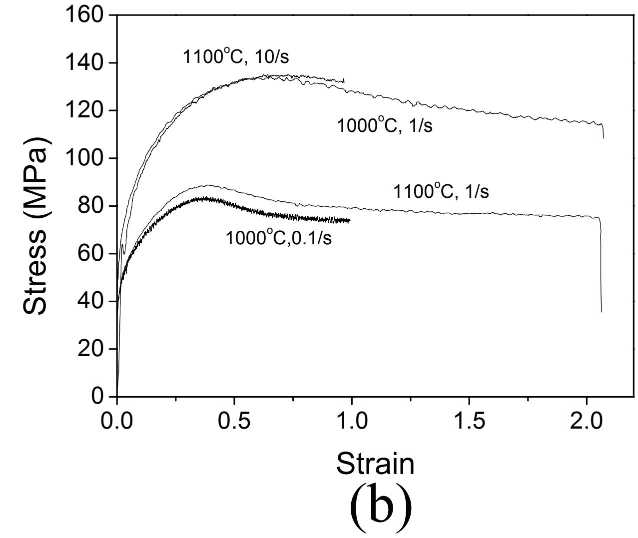


Figure 2. Effect of (a) temperature and (b) strain rate on flow curves

The kinetics of metadynamic and static recrystallization was decided by interrupted torsion tests. At first, the time for 50% recrystallization was obtained for various temperatures, strain rates, strain, and initial grain sizes as shown in figure 3. Then, according to Sellars and Whiteman (1979) the metadynamic and static recrystallization could be described based on the modified Avrami equation by conducting the regression analysis, as described in table 3.

Table 3. AGS evolution model developed in the present investigation

Model	Equation
Critical strain	$\varepsilon_c = 4.1\times10^{-4} d_0^{0.3} Z^{0.25}$, $Z = \dot{\varepsilon}\exp\left(\frac{24000}{RT}\right)$
Static recrystallization	$X = 1-\exp\left(-0.693\left(\frac{t}{t_{0.5}}\right)^{0.9}\right)$, $t_{0.5} = 1.3\times10^{-17}\varepsilon^{-2.2} d_0^2 \dot{\varepsilon}^{-0.4}\exp\left(\frac{314000}{RT}\right)$, $d_{RX} = 350\varepsilon^{-0.5} d_0^{0.4}\exp\left(\frac{-45000}{RT}\right)$
Metadynamic recrystallization	$X = 1-\exp\left(-0.693\left(\frac{t}{t_{0.5}}\right)^{1.15}\right)$, $t_{0.5} = 0.1\,Z^{-1}\exp\left(\frac{255000}{RT}\right)$, $d_{RX} = 1.5\times10^3 Z^{-0.23}$
Grain growth - Static	If $t_{gg} < 1$ sec, $d^2 = d_{RX}{}^2 + 2\times10^4\, t_{gg}\exp\left(\frac{-113000}{RT}\right)$ If $t_{gg} > 1$ sec, $d^7 = d_{RX}{}^7 + 7.5\times10^{25}\, t_{gg}\exp\left(\frac{-400000}{RT}\right)$ $t_{gg} = t - 5.09\, t_{0.5}$
Grain growth - Metadynamic	If $t_{gg} < 1$ sec, $d^2 = d_{RX}{}^2 + 7.4\times10^4\, t_{gg}\exp\left(\frac{-113000}{RT}\right)$ If $t_{gg} > 1$ sec, $d^7 = d_{RX}{}^7 + 7.5\times10^{24}\, t_{gg}\exp\left(\frac{-400000}{RT}\right)$ $t_{gg} = t - 3.57\, t_{0.5}$
Rule of mixture	$d_o^{i+1} = (X^i)^{4/3}\cdot d_{RX}^i + (1-X^i)^2\cdot d_o^i$

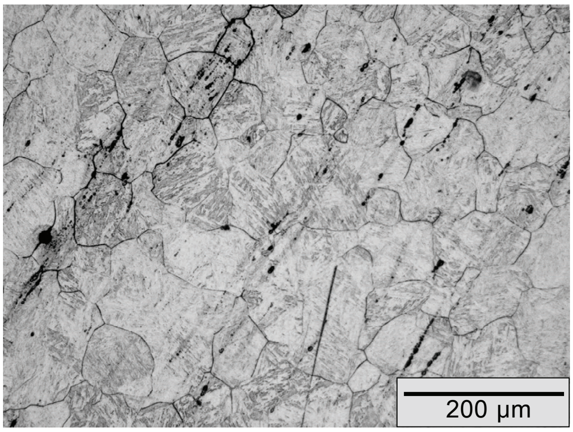


Figure 4. Optical micrograph of the specimen at strain rate 0.1sec^{-1}, strain 0.2 and temperature 900 °C

The grain size evolution was modeled based on methodology available in the literature (Hodgson & Gibbs, 1992). The deformed torsion specimen was water-quenched after holding the specimen for around several or hundred seconds depending on the conditions required for full recrystallization (95%). The microstructure was monitored using chemical etching as shown in figure 4 and the austenite grain size was determined with the help of computer program. Finally, the grain growth model was also derived in the same manner. The evolution model developed in the current study is available in table 3.

4.2. Comparison of two AGS evolution models

In order to validate the AGS evolution model developed in the current study, the predicted AGS results based on the current evolution model and model by Lee et al. (2001) were compared with the experimental results of the previous work (Lee et al., 2005) as shown in figure 5. The comparison was conducted for two different hot bar rolling processes of S-D and R-O passes. As shown in figure 5(a), the results based on the current model had better agreement at point 4 for the S-D pass under the currently investigated condition. The results obtained by applying both models generally had good agreement with the experimental results for the R-O pass except for the case shown in figure 5(b). Considering the error of the AGS measurements involved, it can be construed that both models were valid enough for practical use. The cause of having rather big errors in figure 5(b) could be due to inaccuracy of time measurements. The small error involved in time measurements could make a big difference to the AGS measurement results.

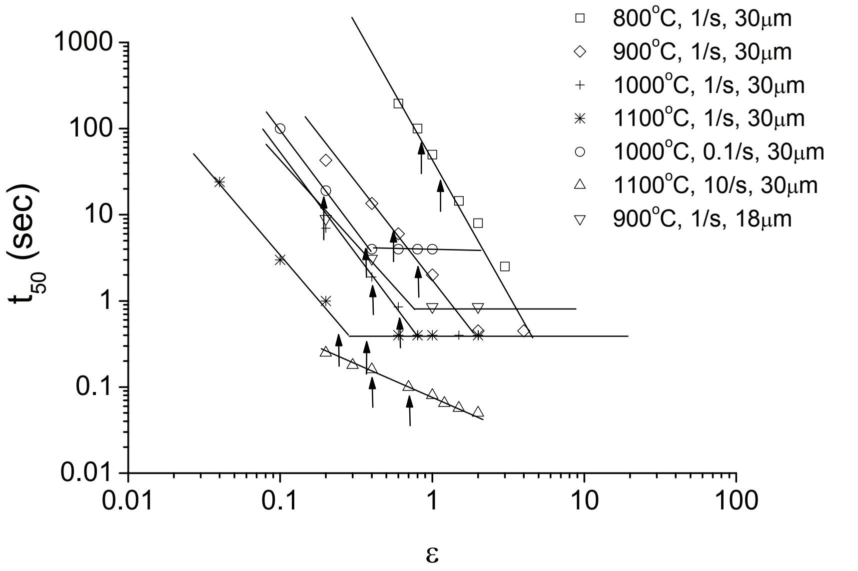


Figure 3. Time for 50% recrystallization as a function of strain

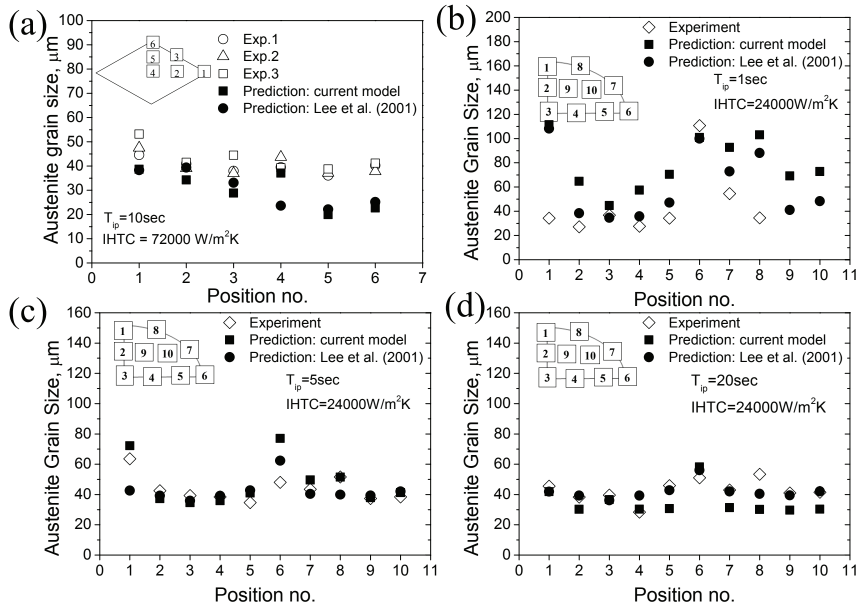


Figure 5. Verification of the current model by comparing with the experiment and result using the evolution model by Lee et al. (2001): (a) S-D and R-O passes for the interpass times of (b) 1 sec, (c) 5 sec, and (d) 20 sec

To compare the difference of two AGS evolution models in detail, types of RX and AGS distributions are also compared for the S-D pass in figure 6. As shown in this figure, the MDRX region was appeared in the predicted result based on both models. However, results based on the evolution model by Lee et al. (2001) showed a bigger region of MDRX than those based on the current model. It means that the critical strain value of Lee et al.'s model was smaller than that of the current model for the given condition of the strain rate, initial grain size, and temperature. According to the results of figure 5(a), this might be the reason for under-predicting the AGS value at point 4 for the S-D pass with Lee et al.'s model (2001).

4.3. Effect of the temperature on the AGS

In order to check the effect of the temperature, numerical predictions with several initial working temperatures of 1000, 1050, and 1100 °C and interpass times of 1, 5, 10, and 20 sec were conducted for the S-D pass. The roll speed was fixed as 34 rpm for each case and any other conditions were the same as given in table 2.

It is clear that higher initial working temperature accelerates the initiation of MDRX according to the current model as shown in figure 7. The average and standard deviation values of the AGS were calculated and are shown in figures 8 and 9 to check the level of refinement and homogeneity of the grain size distribution, respectively. For the case of the interpass time of 1 sec, higher temperatures ensure the smaller grain size, depending on the faster rate of the initiation of the MDRX process due to higher temperature. MDRX process can be initiated even in a short period of time. For the case of the interpass time of 5 sec, the temperature of 1050°C was suitable for grain refinement since the grain growth was occurred for the case of 1100°C. For the case of the interpass time of 10 and 20 sec, the temperature of 1000°C was suitable for grain refinement aspect. This was due to a continuous SRX process in this case.

According to a viewpoint of homogeneity of the AGS, suitable cases of the temperature for homogenization of the grain size were 1100, 1000, 1000, and 1000 °C for the interpass times of 1, 5, 10, and 20 sec in that order. Thus, it was found out that the optimal temperature conditions to get the homogeneous small grain size vary depending on the processing conditions.

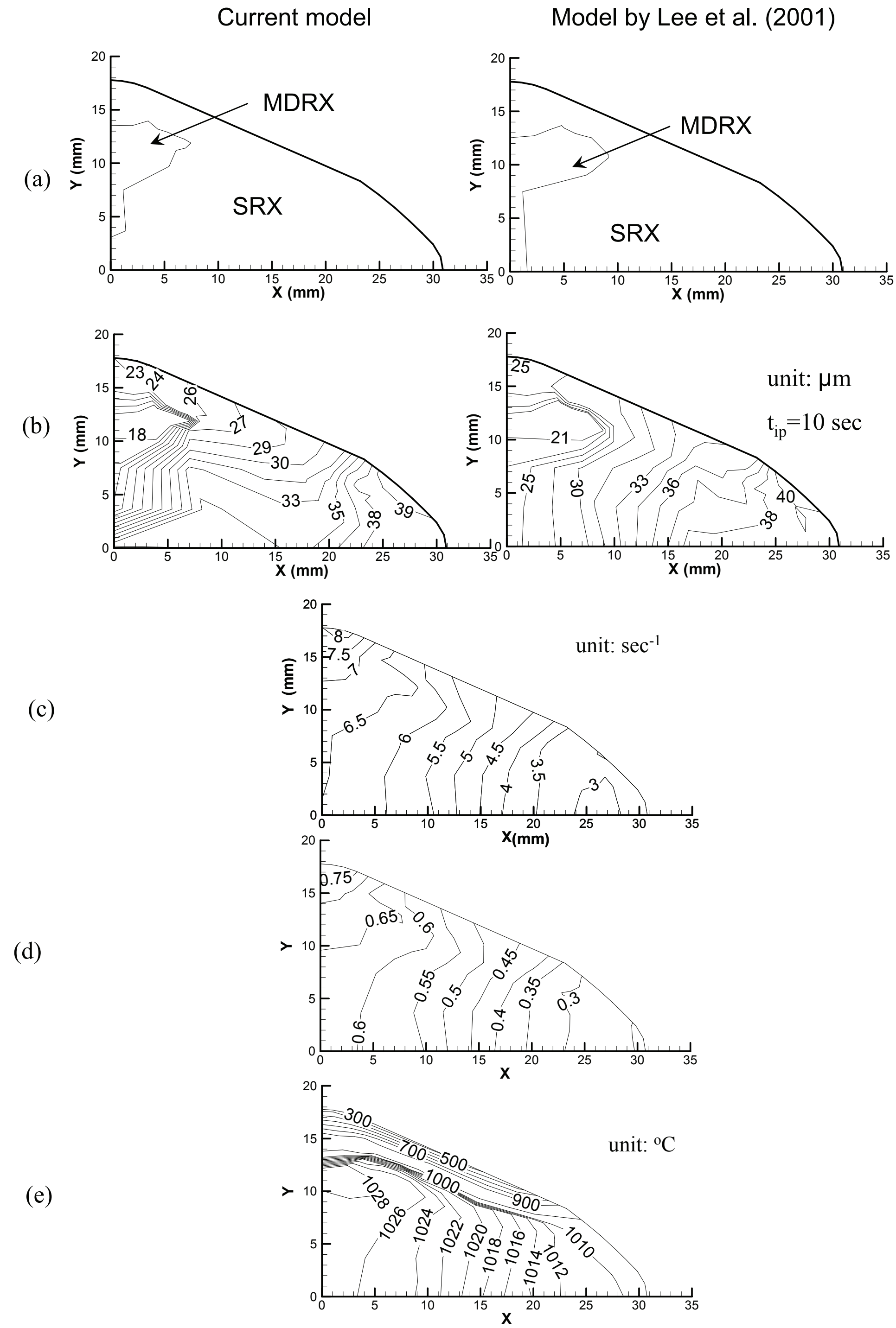


Figure 6. Local distributions of (a) the type of recrystallization, (b) the AGS, (c) the effective strain rate , (d) the effective strain, and (e) the temperature for the S-D pass (t_{ip}=10sec)

4.4. Effect of the roll speed on the AGS

In order to check the effect of the roll speed, numerical predictions with several roll speeds of 34, 51, and 68 rpm and interpass times of 1, 5, 10, and 20 sec were conducted for the S-D pass. The temperature was fixed as 1000°C for each case.

The higher roll speeds decelerate the initiation of MDRX as shown in figure 10. The average and standard deviation values of the AGS were calculated and are shown in figures 11 and 12, respectively, similar to the earlier investigation. For the case with the interpass time of 1 sec, the case of 68 rpm was suitable for grain refinement purpose. For the case of the interpass times of 5, 10, and 20 sec, the case with the roll speed of 34 rpm was suitable for grain refinement according to the continuous SRX. In summary, the suitable roll speed for grain refinement became slower when the interpass time became longer. In the view point of homogeneity of the grains, higher roll speeds resulted in uniform grain size because of a small difference in the AGS due to a higher RX rate.

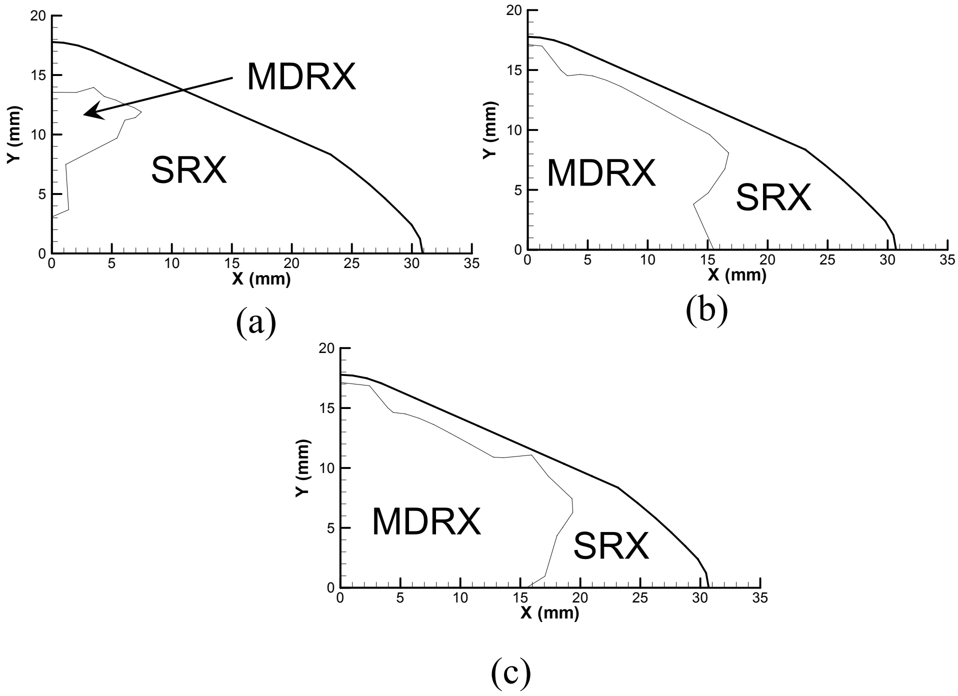


Figure 7. The type of recrystallization with the roll speed of 34 rpm and temperatures of (a) 1000, (b) 1050, and (c) 1100 °C

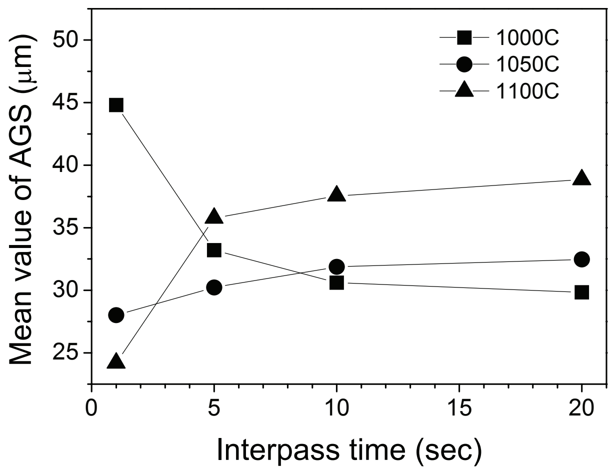


Figure 8. Average values of AGS values with the roll speed of 34 rpm and various temperature conditions of 1000, 1050, and 1100 °C

4.5. Effect of the interpass time on the AGS

The effect of interpass times was also investigated from the above FE results. For the case of the roll speed of 34 rpm, the suitable interpass times for grain refinement became shorter when the temperatures became higher as shown in figure 8. It was 20, 1, and 1 sec for the temperatures of 1000, 1050, and 1100°C in that order. It was found out that the dominant type of RX was the SRX process for the lower temperature case (1000°C) but the MDRX process for the higher temperature case (1100°C), respectively. In the viewpoint of homogeneity of the grains, the interpass time of 20 sec was suitable because of continuing RX in the least recrystallized region.

For the case of the temperature of 1000°C, the suitable interpass time for grain refinement became shorter when the roll speeds increased as shown in figure 11. It was 20 sec for the cases with roll speeds of both 34 and 51 rpm and 5 sec for the roll speed of 68 rpm, respectively. And longer interpass time (20 sec) would provide more uniform AGS because of further recrystallization in the least recrystallized region as explained earlier.

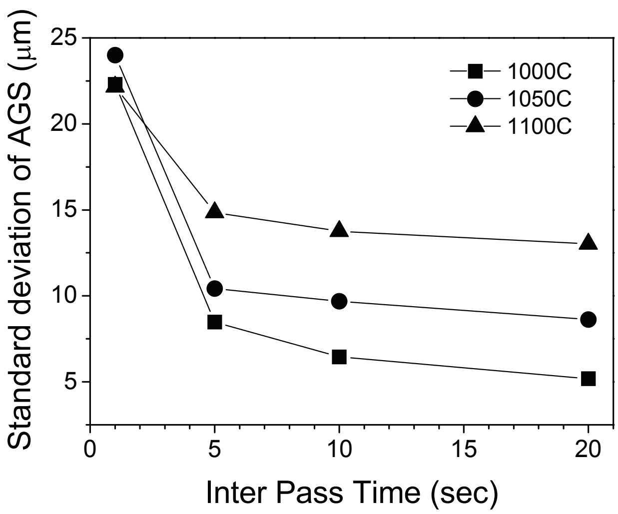


Figure 9. Standard deviation values of AGS values with the roll speed of 34 rpm and various temperature conditions of 1000, 1050, and 1100°C

5. CONCLUSIONS

In this study, AGS evolution model was developed and integrated with the three-dimensional finite element program for predicting the AGS during hot bar rolling of AISI 4135 at various processing conditions. The following conclusions were arrived at from the current study:

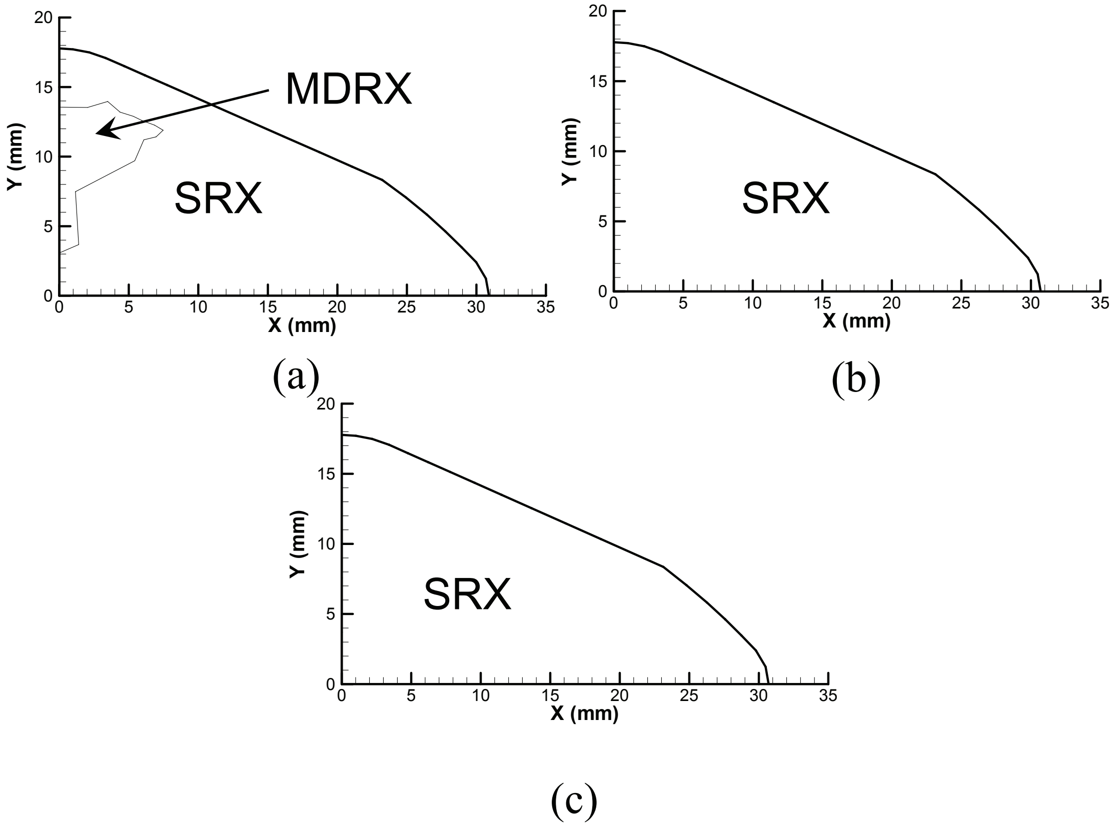


Figure 10. The type of recrystallization with the temperature of 1000 °C and roll speeds of (a) 34, (b) 51, and (c) 68 rpm

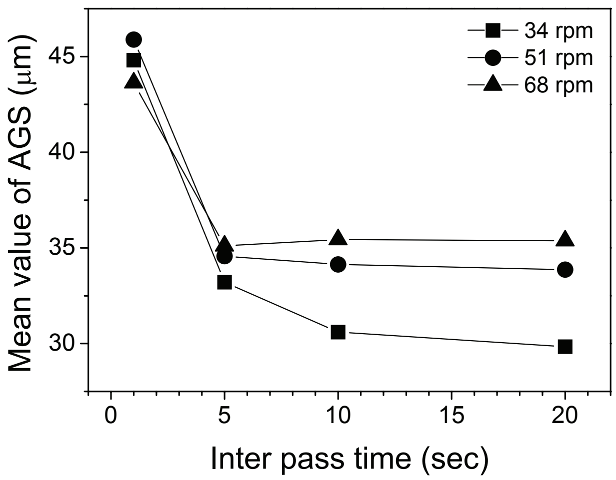


Figure 11. Average values of AGS values with the temperature of 1000 °C and various roll speeds of 34, 51, and 68 rpm

1) The predicted AGS values using the current model and Lee et al.'s model were in good agreement with the experimental results. It suggested that both AGS evolution models were reasonably good although the specific values might be different at certain locations resulting in different AGS distributions.
2) As temperatures increased, the initiation of the MDRX and RX rates was accelerated. And higher roll speeds decelerated the initiation of the MDRX but accelerated the RX rate.

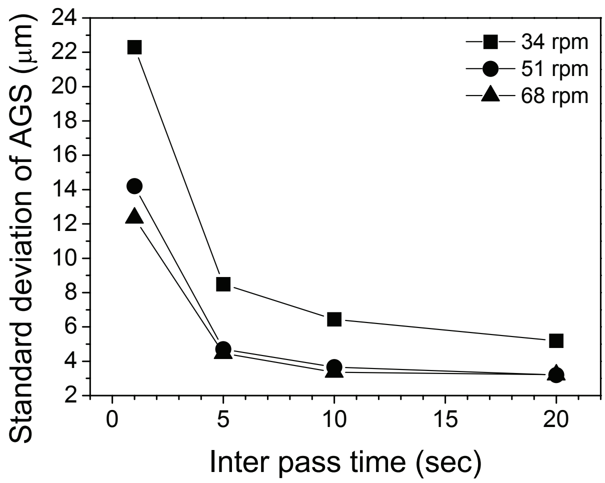


Figure 12. Standard deviation values of AGS values with the temperature of 1000 °C and various roll speeds of 34, 51, and 68 rpm

3) As temperatures and roll speeds increased, the suitable interpass times became shorter to achieve a finer grain size distribution. According to the point of homogeneous grain size, longer interpass times were beneficial for all cases simulated.
4) In order to decrease the discrepancy between experimental and numerical AGS values, further experimental study is necessary.

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MODELOWANIE ROZWOJU MIKROSTRUKTURY DLA PRZEPUSTU KWADRAT-ROMB PRZY WALCOWANIU NA GORĄCO PRĘTÓW ZE STALI AISI 4135

Streszczenie

W pracy badano kinetykę statycznej (SRX) i metadynamicznej (MDRX) rekrystalizacji stali AISI4135 w próbie skręcania. Ciągłe próby skręcania wykonano w celu wyznaczenia krytycznych odkształceń dla dynamicznej rekrystalizacji (DRX). Czasy do 50% rekrystalizacji SRX i MDRX zostały wyznaczone w dwustopniowych próbach skręcania. Dodatkowo, zmiany wielkości ziarna austenitu (AGS) spowodowane rekrystalizacją były mierzone na mikroskopie optycznym. Stosując opracowany model ewolucji mikrostruktury, wyznaczona została wielkość ziarna austenitu przy walcowaniu na gorąco prętów ze stali AISI4135. Wyznaczone wartości AGS zostały porównane z wynikami otrzymanymi z dostępnego w literaturze modelu i z wynikami doświadczeń, które posłużyły do weryfikacji modelu. Następnie określono wpływ takich parametrów jak czas przerwy, temperatura i prędkość walcowania na rozkład AGS przy walcowaniu w układzie przepustów kwadrat-romb. Wyniki numerycznej symulacji ułatwiły zrozumienie wpływu warunków procesu na rozwój mikrostruktury i bardziej dokładne sterowanie procesem stało się możliwe.

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