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Effect of Rolling Reduction Rate on the Microstructure of Hot Rolling Stainless Steel Clad Plate

Herong Jin[1, 2, a], Lei Zhang[3, b] and Yali Yi[3, c]

[1]Key Laboratory of Advanced Forging & Stamping Technology and Science of Ministry of National Education, Yanshan University, Qinhuangdao, 066004, China
[2]Parallel Robot and Mechatronic System Laboratory of Hebei Province, Yanshan University, Qinhuangdao, 066004, China
[3]School of Mechanical Engineering, Yanshan University, Qinhuangdao, 066004, China

[a]ysujhr@ysu.edu.cn, [b]1044797918@qq.com, [c]yiyali@ysu.edu.cn

Abstract. The macro-scale and meso-scale simulation models of stainless steel clad plate were established by DEFORM-3D. The multi-scale coupling simulations of clad plate with different rolling parameters were carried out. The seven pass hot rolling process of stainless steel clad plate was simulated by numerical simulation. By contrasting the vertical stress and the deformation resistance of cladding layer, the rolling reduction rate satisfying interface bonding was obtained. The grain distribution at the center of the substrate layer was analyzed and reasonable hot rolling reduction rates were selected considering their effects on the recrystallization volume percent and the grain size. The results show that the grain size decreases with the increase of reduction rate. However, too much reduction rate will decrease the rate of recrystallization volume percent and the refining effect of grain is not obvious. To ensure uniform grain size distribution, it is most reasonable to set the rolling temperature to 1150℃ and the reduction rate to 50%.

1. Introduction

Stainless steel clad plate has the advantages of high temperature strength, oxidation resistance and corrosion resistance and is widely used in high-end industries [1]. Since the microstructure of the plate after rolling dramatically affects the performance of the product, study on the microstructure evolution during hot rolling is of very importance to predict the mechanical properties of the hot-rolled products and set optimum technological parameters [2].

With the development of computer technology, the numerical simulation has been recognized as one of the most effective approaches to obtain the distribution of stress and strain of specimen during thermal deformation. The stress field, strain field and temperature field in the process of material processing can be obtained by numerical simulation, so that the processing parameters can be optimized [3]. Wang et al. combined the rigid-thermoviscoplastic finite element method with dynamic recrystallization, static recrystallization, and grain growth models to investigate the microstructural evolutions during the hot finishing rolling process [4]. Qin et al. established a three-dimensional thermo elastoplastic model by using finite element method, and simulated the multi-pass hot rolling process [5]. Chen et al. studied the dynamic recrystallization behavior of 42CrMo steel by hot compression test, and discussed the effects of deformation temperature, strain rate, and initial austenite grain size on the dynamic recrystallization behavior [6]. Jia et al. obtained the distribution of the rolling force and changes of austenite grain size and recrystallization volume fraction in different rolling pass by finite element method [7]. Most of these researches simply analyze the relationship between rolling process and microstructure evolution. However, there are few researches on controlling rolling process parameters according to microstructural evolution.

In this work, the dynamic recrystallization model of stainless steel clad plate during hot-rolling process is established. The influence of rolling temperature and rolling reduction rate on the microstructure evolution law is analyzed using elastoplastic finite element method to obtain the reasonable reduction rate.

2. Finite element modeling

In this section, the simulation of hot rolling process of stainless steel clad plate is carried out by using DEFORM-3D finite element software. To avoid the lateral bending and warping at the boundary, which is caused by different performance indexes of substrate and cladding material, the four-layer symmetrical rolling of bimetal clad plate is adopted. Polish at symmetrical interfaces and apply stripping agent between the two cladding layers. Hot-rolled bonding is carried out by using a two high reversing mill, the rolling principle is shown in Fig. 1

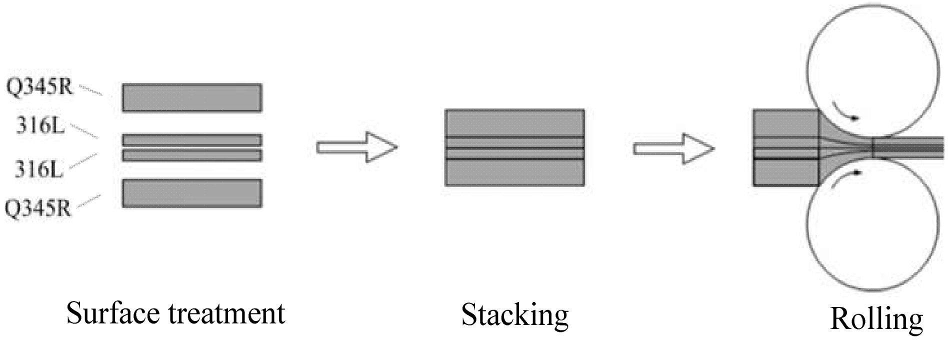


Fig. 1 Rolling principle diagram of stainless steel clad plate

Define the contact between the work roll and the work piece, and between the substrate and the cladding layer. The Coulomb's Friction model is applied to simulate the contact between the roller and the rolled piece, and the friction coefficient is considered as 0.2. The friction type between the substrate and cladding layer is considered as shear friction with the friction coefficient 0.5. The contact heat transfer coefficient of the piece and roller surface is set as 40 KW/(m^2·℃), the convective heat transfer coefficient between the free surface of low alloy steel and external environment was taken as 0.011 KW/(m^2·℃), and the radiative heat transfer coefficient was set to be 18 KW/(m^2·℃). The initial thickness ratio of the substrate and the cladding layer is 1: 9. The single-roller reduction during seven-pass hot roll bonding process is 12.5, 12.5, 12.5, 12.5, 10, 10, and 5mm, respectively.

3. Dynamic recrystallization molding

The dynamic recrystallization occurs within the metallic material, based on the JMAK dynamic theory, the relationship between dynamic recrystallization volume fraction X_d and strain ε can be established:

$$X_d = 1 - \exp\left[-\beta_d \left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_p} \right)^{k_d} \right] \tag{1}$$

Where ε_p denotes the peak strain; k_d and β_d are metal material parameters.

During the dynamic recrystallization of the microstructure of the material, the grains near grain boundary exhibit re-nucleation, growth and change of grain size. Therefore, through the comparisons of microstructure morphology change and original microstructure, dynamic recrystallization volume fraction can be approximately determined. However, in the process of metallographic observation of the microstructure, there will be considerable errors due to some man-made factors.

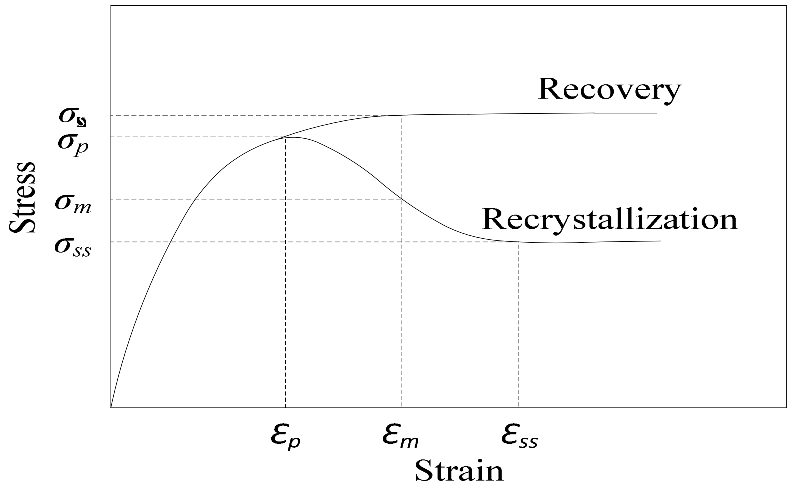


Fig. 2 Dynamic recrystallization volume fraction during hot rolling

To avoid that, by analyzing the variation trend of stress-strain curves and its causes in Fig. 2, the dynamic recrystallization volume fraction can be computed through the following equation:

$$X_d = \frac{\sigma_s - \sigma_m}{\sigma_s - \sigma_{ss}} \times 100\% \tag{2}$$

Where σ_s is the steady-state stress of dynamic recovery curve; σ_{ss} is the steady-state stress of dynamic recrystallization curve; σ_m is the stress corresponding to deformation ε_m of dynamic recrystallization curve.

4. Analysis and discussions

The macroscopic and mesoscopic methods are adopted to simulate the changes of microstructure of the clad plate before, during and after deformation. As demonstrated in Fig.3, when the clad plate enters the rolling deformation zone, it is subjected to greater rolling force. The deformed grains are

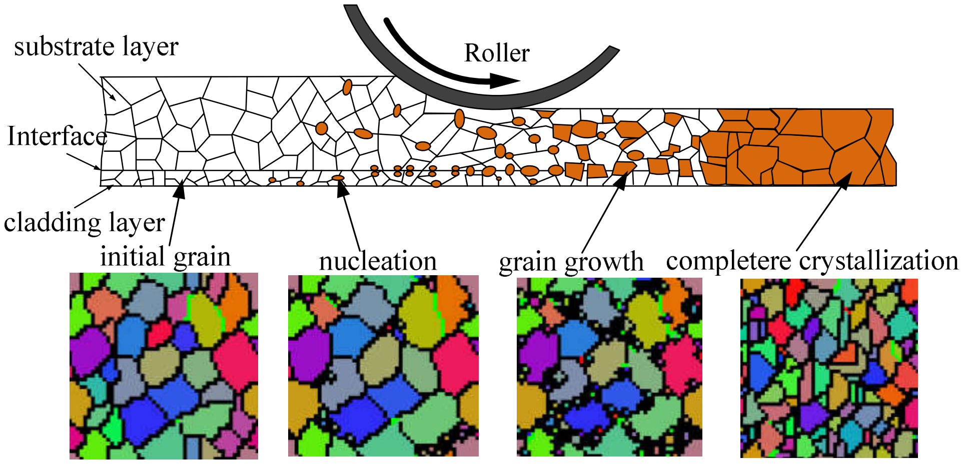


Fig. 3 The evolution of grain during hot rolling

Elongated and the dislocations between grains increase gradually, this is due to the large rolling reduction rate. When the dislocation energy reaches a certain level, recrystallization occurs inside the material to form new crystal nucleus at the grain boundary. As the rolling process going, the number of nascent nucleus gradually increases and expands along the grain boundaries. After the clad plate is separated from the roll, the grain growth increases and the average grain size becomes finer at high temperature. The dislocation energy in the material can be released and the dislocation density decreases.

5. Analysis of process parameters on the bonding

In the process of rolling, the vertical stress of the clad 316L at the interface is larger than its deformation resistance to ensure the effective bonding of double metal interfaces. When the temperature is 950, 1050, 1150 and 1250℃, the deformation resistance of the layers is 108, 81, 67 and 58MPa, respectively. As shown in Fig. 4, 8 nodes are selected from the symmetrical surface to the outer side in the rolling deformation zone.

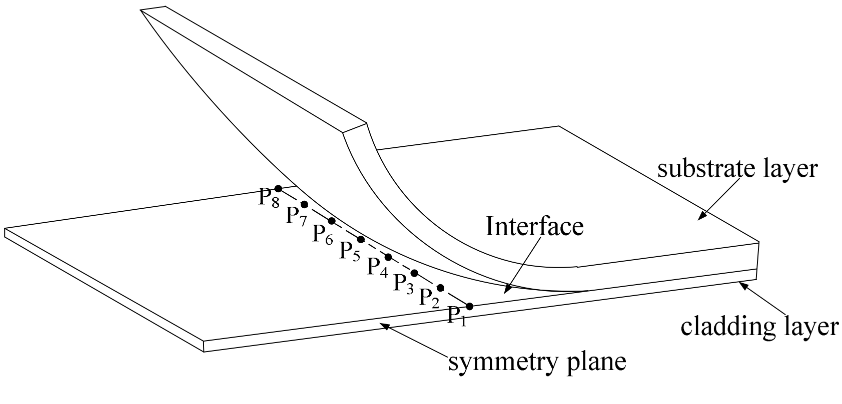


Fig. 4 Sketch map of node selection

Extract the corresponding vertical stress of cladding layer node and calculate its average value, and then compare it with its deformation resistance, as shown in Fig. 5. The minimum pass number and reduction to realize the bonding at the temperature of 950℃ is 6 and 70%, respectively. When the temperature is 1050℃, it needs to be effectively combined after 5 pass and with the reduction rate of 60%. At the temperature of 1150℃ and 1250℃, the minimum pass number and reduction to realize the bonding is 4 and 50%. In order to study the effect of reduction rate on grain size, considering the range of the reduction ratio and the effective combination of the interface, the rolling temperature of 1150℃ is chosen for the further research.

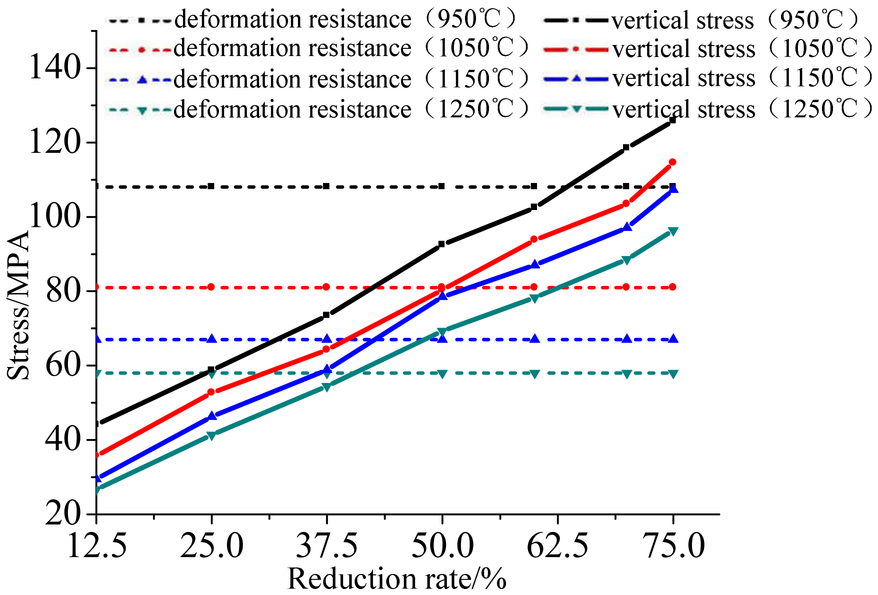
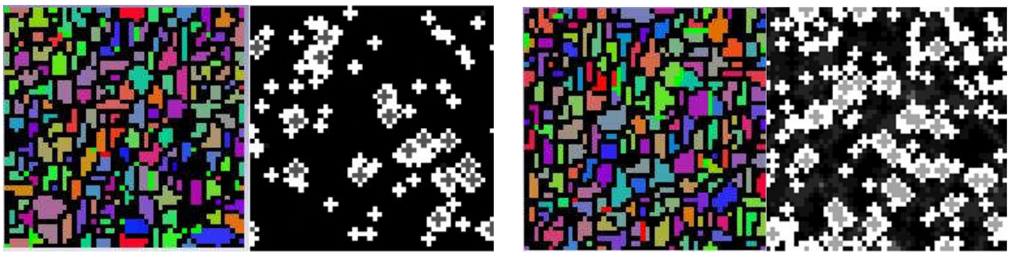


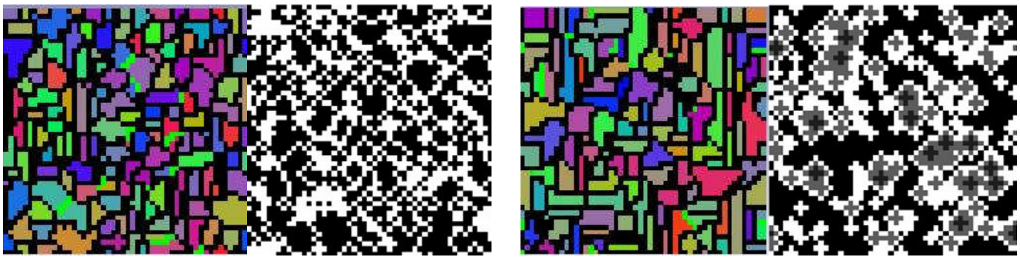
Fig. 5 Relationship between vertical stress and reduction rate at different temperatures

5.1. Effects of reduction rate on the dynamic recrystallization volume fraction

During the rolling process, the increase of the reduction rate will lead to the increase of dislocation density and dislocation energy. When the dislocation energy reaches the critical point, recrystallization is induced by the nucleation at the boundary and the grain size changes as well. Fig.6 demonstrates the microscopic grain, grain boundary and dislocation density at the center of the substrate layer under different reduction rates. As can be observed from Fig. 6(a), when the reduction rate is 37.5%, the deformation and the dislocation density are small, only a small part of recrystallization occurs. When the reduction rate increases to 50%, the dislocation density increases sharply and most of the microstructure in the simulated domain have been recrystallized. Recrystallized nuclei are almost everywhere throughout the simulation domain and the grain size is finer and more uniform, as illustrated in Fig. 6(b). From Fig. 6(c) it can be seen that with the increase of reduction rate to 60%, the dislocation density continues to increase, resulting in increased recrystallization. More recrystallized nuclei are found in the simulated region, which continuously expand around the microstructure under the action of the driving force to lead to the further decrease of average grain size. As shown in Fig. 6(d), when the reduction rate increases to 70%, the dislocation density continues to increase and the recrystallization has been completed basically. But the increase of volume fraction slows noticeably and the grain size is still decreasing.



(a) (b)



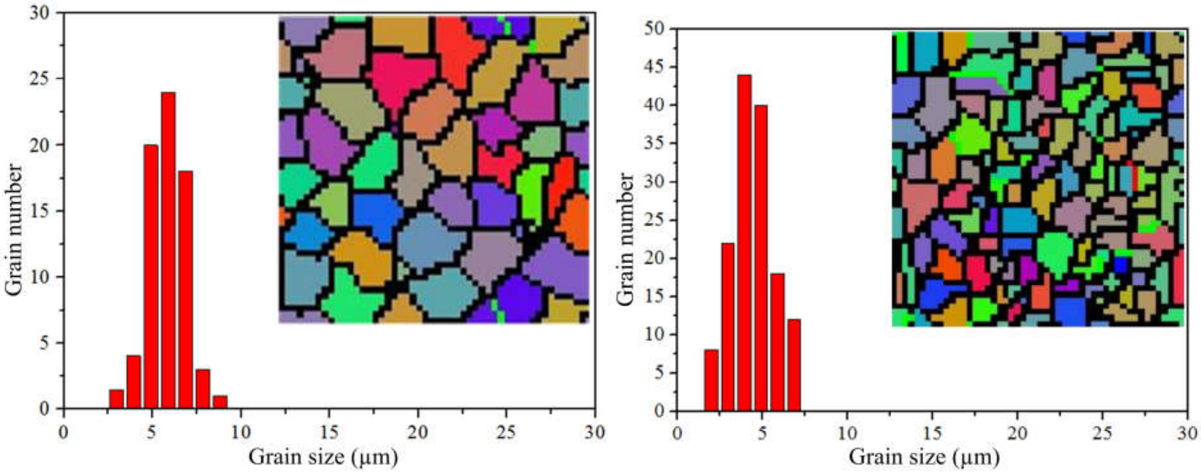
(c) (d)

Fig. 6 Grain size and dislocation density under four reduction rates: (a) 37.5%, (b) 50%, (c) 60%, (d) 70%

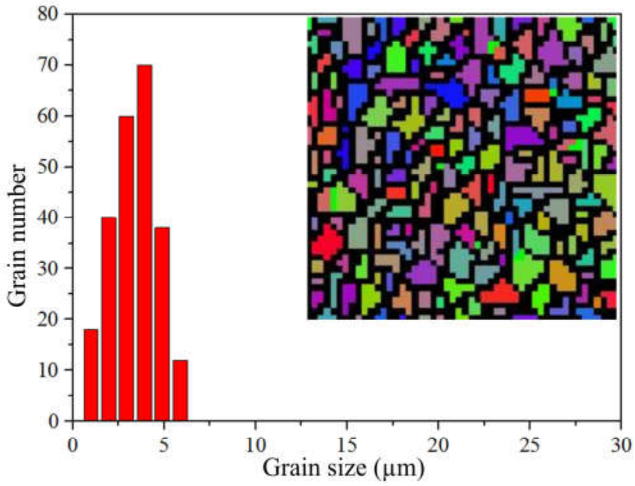
Before realizing the interface bond, the dynamic recrystallization volume fraction at the center point of substrate layer is about 50% at the reduction rate of 37.5%. When the reduction is 50%, the volume fraction is about 70%. As the reduction rate continues to increase, the volume fraction of dynamic recrystallization increases dramatically. When the reduction is 60%, the volume fraction is about 80%. However, the dynamic recrystallization volume fraction only increases about 5% when reduction rate increases to 70%.

5.2. Effects of reduction rate on the grain size

The grain distribution of the center of substrate layer after rolling under different reduction rates is illustrated in Fig. 7. It indicates that the grain size decreases gradually with the increase of reduction rate. When the reduction rate is 70%, the average grain size is 3.4μm. The grain is very small and uneven distributed, as shown in Fig. 7 (a). When the reduction rate is 60%, the average grain size is 4.5μm. The grain size distribution is improved, as shown in Fig. 7 (b). The average grain size is 6.8μm when the reduction rate is 50% and the grain size distribution is uniform, as shown in Fig. 7 (c).



(a) (b)



(c)

Fig. 7 Grain distribution of substrate layer under different rolling reductions: (a) 50%, (b) 60%, (c) 70%

6. Conclusion

The dislocation density and dislocation energy increase as the reduction rate increases. At the temperature of 1150℃, when the reduction rate is less than 50%, the dynamic recrystallization volume fraction increases rapidly to make grain nucleation faster and more evenly distributed; But when the reduction rate is greater than 50%, the volume fraction of dynamic recrystallization increases more slowly, the nucleation rate is slow, and the growth of recrystallization grain is not obvious.

The cladding and substrate layer of clad plate can be combined well when the temperature is 1150℃ and the reduction rate is 50%. The average size of grain is 6.8μm and the grain size distribution is uniform. The mechanical properties of the material can be improved to some extent.

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