Numerical simulation of dynamic recrystallization behavior of 316L stainless steel under flexible rolling state

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With the rapid development of continuous rolling technology, the rigid connection of production equipment-techniques often results in roll wear and frequent shutdowns for roll replacement, which restricts the development of its technical advantages. In this paper, ASTM-316L is used as the experimental steel, based on the numerical simulation technology to carry out the numerical simulation and process optimization research of online roll changing of flexible rolling, comprehensive material high-temperature plastic flow behavior, coupling recrystallization kinetic model embedded in Deform-3D software, to establish a multi-field coupled collaborative control model of online roll changing of flexible rolling, simulating the impact of online roll change on the strip DRX behavior. The results show that the reduction rate of the online roll change, the roll exit speed, the roll input speed, and the deformation temperature have essential effects on the microstructure uniformity of the strip along the thickness direction. Smaller reduction rate, faster roll exit speed, slower roll input speed, and lower deformation temperature are all beneficial to reduce the gradient of DRX volume fraction in the core and surface of the strip and avoid stress concentration and instability. The roll diameter has little effect on the DRX volume fraction gradient at the core and surface of the strip. Therefore, it is necessary to control the online roll changing process of flexible rolling according to the actual rolling process, considering the load of the rolling mill and the mass of the rolls. The research on the recrystallization behavior of online roll changing in this paper can provide a theoretical basis for designing and optimizing the microstructure control of flexible rolling.

KEYWORDS: FLEXIBLE ROLLING, ONLINE ROLL CHANGE, DYNAMIC RECRYSTALLIZATION, NUMERICAL SIMULATION

INTRODUCTION

With the development of traditional rolling in the direction of short process and near-net shape, high-efficiency continuous rolling technology has been increasingly applied in recent years [1-3]. Due to the long rolling kilometers in the continuous rolling process, this leads to serious roll wear. When the roll is worn, it needs to stop rolling to replace the roll, which affects the product yield and production efficiency. For this reason, some researchers have put forward the concept of flexible rolling, which realizes continuous rolling through online roll change, and fully releases the equipment unit's process potential [4,5]. Dynamic recrystallization behavior during rolling plays an important role in optimizing rolling mill load and improving the organizational properties of the product [6-8]. In recent years, many scholars have conducted research in this area. Wang et al. investigated the dynamic and static recrystallization behavior of 15V38 alloy bar rolling process, constructed a dynamic model

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based on physical simulation and embedded it into the simulation system, simulated the effect of deformation volume and distortion temperature on recrystallization behavior during steady-state rolling of the bar, and obtained that the dynamic recrystallization volume fraction increased with increasing distortion temperature [9,10]. Duan et al. studied the dynamic recrystallization behavior of 34CrNiMo6 high-strength steel under uniaxial compression based on physical and numerical simulations and showed that the recrystallization behavior of the experimental steel under uniaxial compression could be accurately predicted by embedding the established recrystallization model into the simulation system [11]. Dong et al. constructed recrystallization models based on physical simulations and embedded them in simulation software to simulate sub-dynamic and static recrystallization behavior under various deformation conditions. The results show that accurate construction of simulation model boundary conditions is a prerequisite for obtaining good prediction results [12-14]. Gu simulated the dynamic recrystallization behavior of 38MnVS6 steel during compression. The results show that the non-uniformity of dynamic recrystallization is related to the machining state of the workpiece and that the dynamic recrystallization volume fraction decreases with increasing deformation temperature and decreasing strain rate. The experimental results agree with the simulation results and can be used to predict the dynamic recrystallization behavior of 38MnVS6 steel during compression [15]. Although there has been some research into the numerical simulation of dynamic recrystallization, these studies have all been based on a stable rolling condition, that is, the roll gap does not change. However, there is a process of roll exit and input in the online roll change of flexible rolling. During this process, the key process parameters of DRX change drastically, heat transfer occurs between the strip and the surrounding environment and the roll, and both the volume work generated by the plastic deformation of the strip and the frictional heat generated by the friction of the roll will cause the temperature of the strip to increase, the lifting of the roll makes the deformation of the strip in the rolling direction change continuously, and the material flow behavior changes accordingly. Compared with traditional rolling, online roll change of flexible rolling is a more complex and highly nonlinear irreversible change process. Therefore, the study of the mapping relationship between the variation of DRX and the heat deformation process parameters is the theoretical basis for regulating of the recrystallization behavior of flexible rolling online roll change. In this paper, Deform-3D simulation is used to simulate the effects of reduction rate, roll exit speed, roll input speed, deformation temperature, and roll diameter on DRX under the online roll change state of experimental steel flexible rolling to provide theoretical support for forecasting and optimizing the strip flexible rolling online roll change forming process.

MATERIALS AND METHODS

Experimental details

In this paper, ASTM-316L hot-rolled strip steel is selected to simulate the flexible rolling process. Before constructing the simulation model, it is necessary to obtain the high-temperature flow behavior of the material and establish the dynamic recrystallization dynamics model of the experimental steel. The material flow behavior analysis and dynamic recrystallization dynamics model have been given in the author's previous article [16]. The established model was embedded into the Deform simulation software to simulate the dynamic recrystallization behavior of the flexible rolled strip.

Simulation details

The established DRX kinetic model was embedded into DEFORM-3D software to simulate the DRX behavior of the hot rolling process of strip. During the online roll changing process of flexible rolling, the stress state of the strip under the action of external forces such as tension, rolling force, and friction is complex. In the process of high-temperature plastic deformation, the strip is subjected to the interaction of deformation temperature, strain, and strain rate, resulting in dramatic changes in the internal microstructure of the material. Therefore, it is necessary to establish an accurate finite element model to reveal the variation regulation of the strain field during the online roll change of flexible rolling, the high-temperature plastic flow behavior of metal materials, and the DRX situation. Considering the accuracy and efficiency of the model calculation, the following assumptions are made in this paper in the establishment of the geometric model of online roll change for flexible rolling:

(1) As the rolling process studied in this paper is a symmetrical rolling process, the upper and lower rolls have the same diameter and rotational speed and are arranged symmetrically. In order to reduce the number of meshes to improve the efficiency of the model calculation,

a 1/4 geometric model of online roll changing for flexible rolling of strips was established with the transverse and longitudinal center planes of the strips as the symmetrical planes.

(2) In actual production, the elastic deformation of the roll is smaller than the plastic deformation of the strip, and the rigidity and stability are higher, so the roll is set as a rigid body in the simulation model.

(3) Flexible rolling can be arranged in two modes of "5+1" and "5-1", and the online roll change process of flexible rolling is completed through coordination and adaptation between different stands. In order to improve the efficiency of simulation analysis and calculation and simulate the production and operation process of the strip wedge region after the roll is lifted, a two-stand arrangement is used to establish a simulation model of online roll change of flexible rolling, which simulates the geometric shape and microstructure variation law of the strip after the roll of the previous stand is lifted.

Based on the above assumptions, the geometric model of online roll changing for flexible strip rolling is established, as shown in Fig. 1. The mesh cell type is hexahedral, the material is the experimental steel selected in this paper, and the relevant theoretical model is imported to simulate the microstructure evolution of experimental steel during online roll change of flexible rolling. The relevant process parameters of the finite element model are based on the existing rolling mill in the laboratory, as shown in Table 1. After the simulation is completed, the results are extracted for the surface and core of the wedge region of the strip along the rolling direction.

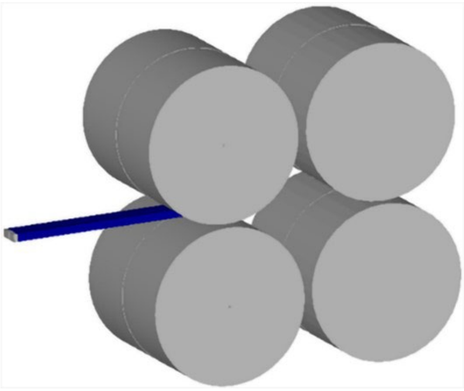

Fig. 1 - Finite element model for online roll change process.

Tab.1 - Composizione chimica degli acciai analizzati / Chemical composition of the studied steels.

Simulation Parameters	Numerical Value (Unit)
Strip temperature	950°C, 1050°C, 1150°C
Strip thickness	10mm
Roll temperature	25°C
Ambient temperature	20°C
Thermal conductivity of strip and roll	4/N/s^{-1}/mm^{-1}/°C
Heat transfer coefficient between strip and air	0.02/N/s^{-1}/mm^{-1}/°C
The friction coefficient between strip and roll	0.3
Roll diameter	180mm, 200mm,220mm
Rolling speed	50mm/s
Roll lift and input speed	1.5mm/s, 2mm/s, 2.5mm/s
Reduction rate	30%, 50%, 60%
Strip mesh divisions	17100

RESULTS AND DISCUSSION

Effects of deformation degree on DRX behavior

In actual production, the roll diameter, contact friction coefficient, and strip thickness cannot be changed by active adjustment, while the roll reduction rate can be adjusted according to the production schedule during the rolling process, which leads to the effect of the roll uplift and exit from rolling on the plastic deformation of the strip under various reduction ratios.

Fig. 2 a), b), and c) are the nephogram of the strain distribution in the thickness direction of the rolling strip when the rolls are lifted and withdrawn at various reduction rates. The wedge-shaped transition region is extended with the increase of the reduction rate, and the strip is non-uniformly deformed along the thickness direction. Fig. 2 d) shows the tracking curves of the core and surface strains of the strips at various reduction rates when the rolls are lifted and withdrawn from the rolling process. With the increase of the reduction rate, the deformation gradually penetrates into the core of the strip, and the maximum strain appears in the near-surface area of the strip.

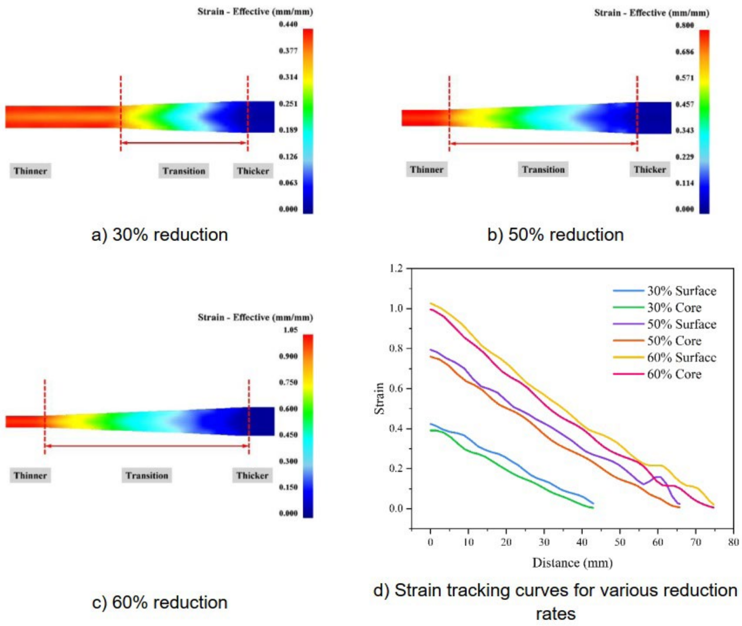

Fig.2 - Strain contour of the strip along the thickness direction.

Fig. 3 a), b), and c) are the nephogram of the DRX distribution in the thickness direction of the strip after the rolls with various reduction rates are raised and withdrawn from rolling. The volume fraction of DRX is different at various reduction rates, and the DRX distribution characteristics are the same as the strain distribution nephogram. The volume fraction of DRX at the core of the strip increases significantly after the roll is lifted and withdrawn from rolling under the high reduction ratio, indicating that the DRX behavior of the core of the strip is promoted under the high reduction ratio. Fig. 3 d) shows the DRX tracking curves for the core and surface of the strips at various reduction rates when the rolls are raised and withdrawn from the rolling process. As the reduction rate increases, the volume fraction gradient of the recrystallization of the core and surface increases, increasing the non-uniform distribution of grain size in the thickness direction of the strip, bringing a negative impact on the mechanical properties of the strip such as strength and plasticity. Therefore, it is preferable to transition from the high reduction rate mode to the low reduction rate mode during the online roll changing process of flexible rolling, which is conducive to the uniform transition of the deformation in the strip thickness direction and can reduce the DRX volume fraction gradient in the thickness direction of the strip. It is beneficial to the uniform distribution of the structure, and it can also reduce the load of the rolling mill.

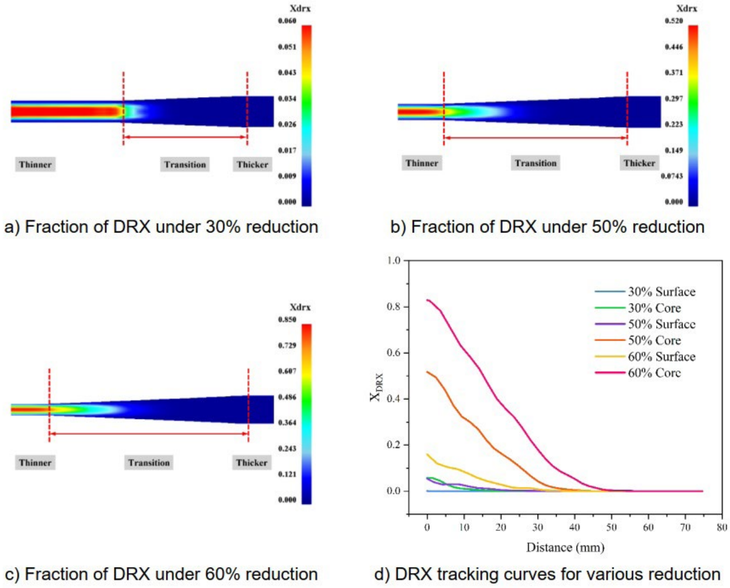

Fig.3 - Volume fraction of DRX of the strip after the upper roller raised and the lower roller lowered.

Effects of roll exit speed on DRX behavior

Fig. 4 a), b), and c) are the cloud diagram of DRX distribution in the strip thickness direction with various roll exit speeds (the upper roller raised speed, the lower roller lowered speed). When the roll exit speed is slow, the separation between the roll and the strip takes a long time to complete, resulting in a longer wedge transition region of the strip, and the strip has adequate time for the DRX process. The lower roll exit speed can also enhance the deformation of the strip surface, which increases the DRX degree of the strip surface to a certain extent. Fig. 4 d) shows the DRX tracking curves for the core and surface of the strip at various roll exit speeds. When the roll exit speed is slow, the gradient of DRX volume fraction on the core and surface in the thickness transition region changes significantly. When the roll exit speed is fast, the rapid withdrawal of the roll makes the roll and the strip quickly separate, and the wedge-shaped transition region is formed quickly, which suppresses the DRX volume fraction gradient on the core and surface in the thickness direction. To avoid stress concentration and instability during the online roll change of flexible rolling, it is preferable to perform online roll change of flexible rolling at a faster roll exit speed.

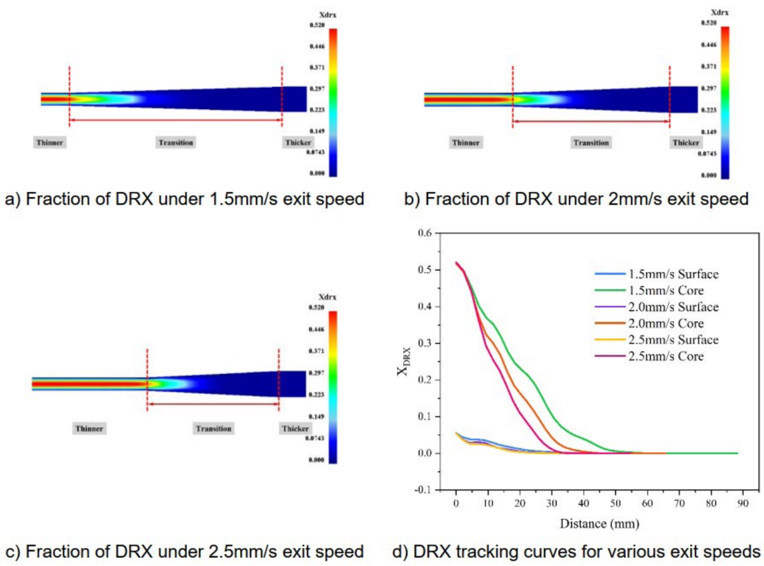

Fig.4 - Effect of roll exit speed on DRX volume fraction after the upper roller raised and the lower roller lowered

Effects of roll input speed on DRX behavior

Fig. 5 a), b), and c) are the cloud diagram of DRX distribution in the thickness direction of the strip at various roll input speeds (the upper roller lowered speed, the lower roller raised speed). When the roll input speed is faster, the wedge-shaped transition region of the strip along the rolling direction is shorter. Fig. 5 d) is the DRX tracking curve of the strip core and surface at various roll input speeds, which is opposite to the roll exit speed. When the roll input speed is fast, the roll and the strip contact quickly and reach the target position in a short time, forming a wedge-shaped transition region quickly, which increases the DRX volume fraction gradient on the core and surface in the thickness direction of the strip. Therefore, it is preferable that the online roll change of the flexible rolling is carried out in the mode of slower roll input speed.

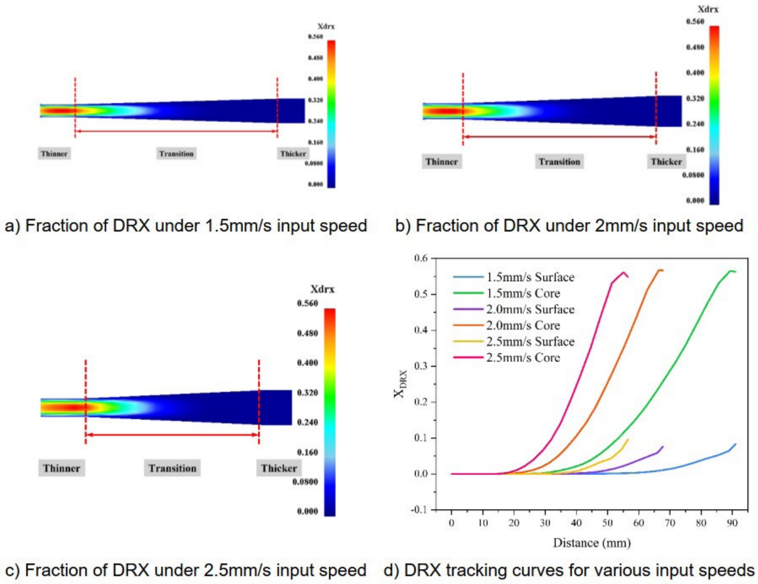

Fig.5 - Effect of roll input speed on DRX volume fraction after the upper roller lowered and the lower roller raised.

Effects of deformation temperature on DRX behavior

Fig. 6 a), b), and c) are the cloud diagram of DRX distribution in the thickness direction of the strip at various deformation temperatures. The volume fraction of DRX increases with the increase of the deformation temperature during the online roll change process of flexible rolling. From Fig. 6 d) DRX tracking curves of the core and surface of the rolled strip after the roll lifts at different deformation temperatures, it can be clearly seen that with the increase in deformation temperature, the DRX volume fraction on the strip surface increases significantly, and the DRX volume fraction gradient of the strip core and surface keeps increasing. For example, at the deformation temperature of 950°C, the volume fraction of DRX at the core and surface of the strip is 13.2% and 0% respectively, when the deformation temperature is increased from 950°C to 1150°C, the volume fraction of DRX increases to 91.2% and 29.1% respectively. This is due to the enhanced fluidity with increasing deformation temperature, which promotes DRX behavior. In addition, at higher deformation temperatures, the recrystallization region in the transition region is extended, the strip has a larger recrystallization gradient along the rolling direction, and the strip will have higher requirements for the high-temperature resistance of the flexible rolling online roll change equipment at higher deformation temperatures. In order to ensure the smooth transition of the strip during the roller raise and exit of the rolling process of flexible rolling, and green and low-carbon production, the online roll-changing of flexible rolling is preferably carried out in the mode of lower deformation temperature.

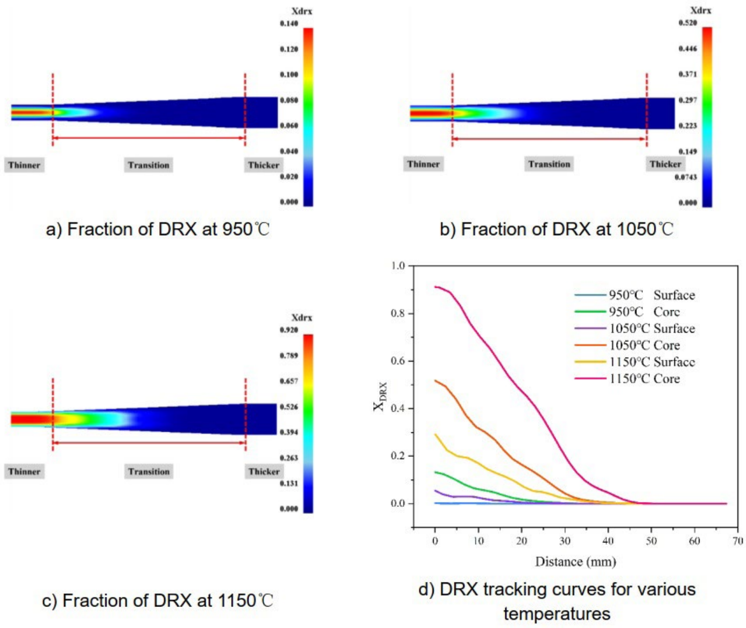

Fig.6 - Effect of deformation temperature on DRX volume fraction after the upper roller raised and the lower roller lowered.

Effects of roll diameter on DRX behavior

Fig. 7 a), b), c), and d) are the DRX distribution cloud diagram and the DRX tracking curve of the core and surface in the thickness direction of the strip after the rolls with various diameters are raised and withdrawn from rolling. It can be seen that as the diameter of the roll increases, the length of the wedge transition region changes little, and the change of the DRX volume fraction gradient on the strip core and surface is not apparent. The volume fraction of DRX near the strip surface decreases slightly after the roll with a larger diameter is raised and withdrawn from rolling, and the effect of roll diameter on the DRX volume fraction gradient is not as pronounced as the reduction rate, roll exit speed, roll input speed and deformation temperature. Therefore, it is necessary to control the online roll change process of flexible rolling according to the actual rolling process, considering the load of the rolling mill and the mass of the rolls.

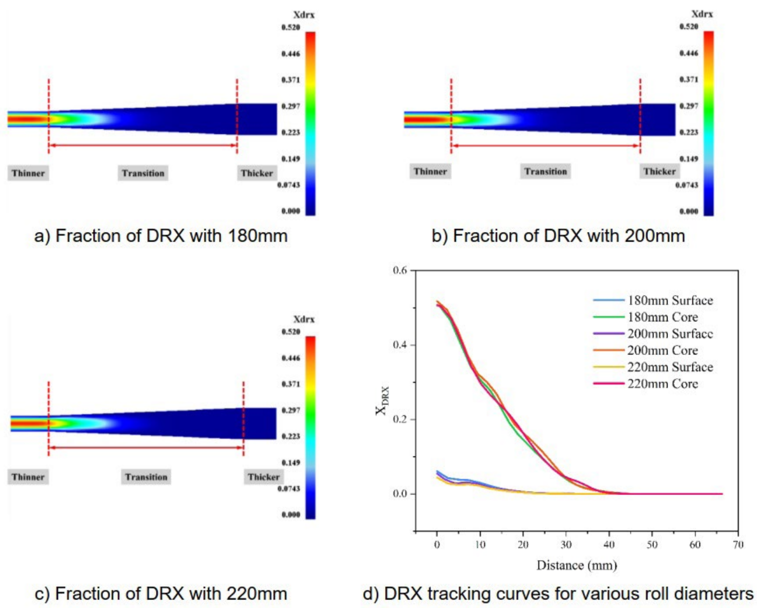

Fig.7 - Effect of roll diameter on DRX volume fraction after the upper roller raised and the lower roller lowered.

CONCLUSIONS

Based on the simulation, this paper studies the dynamic recrystallization behavior of online roll-changing in flexible strip rolling, and analyzes the effects of reduction rate, roll exit speed, roll input speed, deformation temperature, and roll diameter on the strip microstructure field. The main conclusions are as follows:

The low reduction rate mode is beneficial in reducing the gradient of the recrystallization volume fraction at the core and surface of the strip in the transition region. When the roll exit speed is fast, the rapid withdrawal of the roll makes the roll and the strip quickly separate and quickly form a wedge-shaped transition region, which suppresses the DRX volume fraction gradient on the core and surface in the thickness direction of the strip. When the roll input speed is fast, the roll and the strip contact quickly and reach the target position in a short time, forming a wedge-shaped transition region quickly, which increases the DRX volume fraction gradient on the core and surface in the thickness direction of the strip. Higher deformation temperatures increase material fluidity and promote DRX behavior, with a higher gradient in DRX volume fraction at the core and surface of the strip in the transition region. As the diameter of the roll increases, the length of the wedge transition region changes little, and the change of the DRX volume fraction gradient on the strip core and surface is not obvious. The effect of roll diameter on the DRX volume fraction gradient is not as pronounced as the reduction rate, roll exit speed, roll input speed, and deformation temperature.

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