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Research on Gradient Temperature Rolling Process and Deformation Uniformity of 10Ni5CrMoV Heavy Plate

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To improve the heterogeneous deformation in the rolling process of 10Ni5CrMoV heavy plate, both uniform temperature rolling (UTR) and graded temperature rolling (GTR) are investigated through numerical simulation and verification experiments. These methods are effective in enhancing microstructure and deformation uniformity of 10Ni5CrMoV steel. The strengthening mechanism of high permeability rolling process on the rolling deformation of 10Ni5CrMoV heavy steel is clarified. The results show that compared with the uniform temperature rolling process (UTR), different gradient temperature rolling processes (GTR) cause the deformation area to gradually expand toward the core, significantly increasing the deformation of the core. The reduction rate of the first pass gradient temperature rolling processes (FGTR) is about 2.3% higher than that of uniform temperature rolling, and that of continuous gradient temperature rolling (CGTR) is about 5.3%. As the same time, the microstructure difference between the core and surface is reduced, which is conducive to improving the uniformity of microstructure and properties. Furthermore, the microstructure of the core in the rolled material is uniformly refined, with the original austenite grain size decreasing from 30-40 μm to 10-20 μm.

Keywords: 10Ni5CrMoV steel, Heterogeneous deformation, Gradient temperature rolling, Finite element analogy, Heavy plate, Uniform temperature rolling

1 Introduction

10Ni5CrMoV steel is renowned for its combination of high strength, excellent toughness, outstanding welding performance, and exceptional corrosion resistance. Since its successful development in the 1990s, it has become the main structural material for Chinese ships and marine engineering, as well as being widely used in industries such as pressure vessels and high-pressure pipelines [1-2]. However, the core of large-section castings often has defects such as shrinkage, porosity, and segregation. During conventional hot rolling processes, deformation is limited in penetrating the core, making it challenging to eliminate these defects, leading to poor uniformity in the finished plate structure. This renders is difficult to meet the stringent quality requirements of engineering applications involving heavy plates [3-4]. Gradient temperature rolling (also referred to as differential temperature rolling) creates a substantial temperature gradient from the surface to the core of the steel billet through controlled cooling. The lower the surface temperature, the higher the deformation resistance, while the higher the core temperature, the lower the deformation resistance. This promotes deep deformation penetration, thereby enhancing the quality of the rolled product [5-7]. Wang et al. [8] and Rawles et al. [9] have shown that gradient temperature rolling increases strain in the center, refines the grain structure, and improves the uniformity of both the microstructure and properties of extra-heavy plates. Zhang et al. [10] and Bian et al. [11] indicates that differential temperature rolling also contributes to enhanced strength, toughness, and resistance to laminar tearing. Ning et al. [12] and Yan [13] assert that gradient temperature rolling facilitates crack healing and the elimination of internal defects. On the other hand, as the cooling rate increases during differential temperature rolling, the strength of the rolled steel improves, while its toughness tends to decrease [14-21]. Therefore, the differential temperature rolling process for high-strength heavy plates requires further investigation and optimization to fully leverage its advantages.

Gradient temperature rolling represents a promising approach to enhance the deformation of the core in heavy plates. However, the research on the multi-pass continuous gradient temperature rolling process is limited. This study takes 10Ni5CrMoV steel as the subject material and adopts a combined methodology of finite element analysis and laboratory experiments. The coupling process of gradient temperature rolling is investigated to achieve a specific temperature gradient condition on the surface of medium-heavy plates through controlled cooling, distinguishing it from conventional methods that require temperature reversal. Subsequently, the deformation behavior and micro structural changes of the steel plate, from the surface to the core, under various uniform and differential temperature processes, are systematically compared and analyzed. This work aims to provide comprehensively understand the differential temperature process and its industrial applications potential in medium-heavy plate rolling, offering valuable insights for optimizing the rolling process in industrial environments.

2 Material and Research Method

2.1 Rolling experiment

The experimental material 10Ni5CrMoV is a C-Si-Mn-Ni-Cr-Cu-V composition system to ensure high strength plasticity, good low-temperature toughness, weld ability, and formability. The 350 mm thickness cast billet produced on an industrial production line is rolled to a thickness of 120mm, and then processed into sample sizes H120 × W120 × L200 mm. A 10 mm × 10 mm × 120 mm nickel square is embedded on the surface of the 10Ni5CrMoV substrate at 5mm, 1/4H, and 1/2H positions, respectively, and then welded at the edges to form a composite slab (Fig.1).

A thermocouple is embedded at the core of the nickel square, and its placement is shown in Fig.1. The 120 mm thick sample is loaded into a heating furnace at a low temperature of T<600 °C, with a heating rate of less than 10 °C/min. The heating temperature is TA=1200 °C, and evenly heated for 40 minutes. Then it is rolled into a thickness of 50 mm through 5 passes, as shown in Table 1 and Table 2.

After rolling, the thickness of each nickel square was measured before and after rolling using a steel ruler and a profilometer. To calculate the strain distribution and changes along the thickness direction of the slab under traditional uniform temperature rolling (UTR), the first pass gradient temperature rolling (FGTR) and the continuous gradient temperature rolling (CGTR) conditions methodology are adopted. The temperature variations during the rolling processes of UTR, FGTR, and CGTR are shown in Fig. 2. After distinct rolling processes, the temperature changes at the surface are shownin Fig. 2(a). In addition, the temperature gradient between the outer and inner regions during different rolling passes is shown in Fig. 2(b).

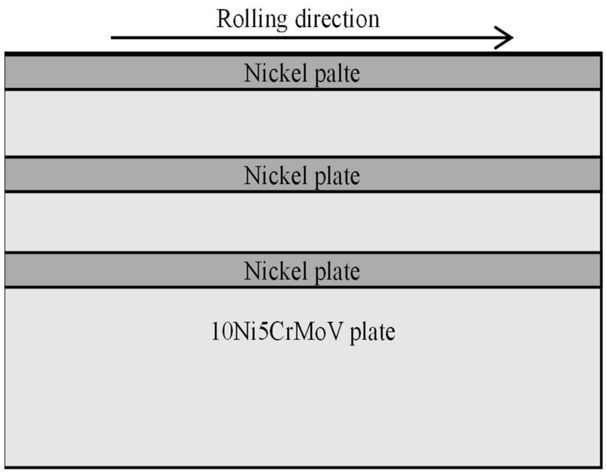


Fig. 1 *Schematic diagram of test billet*

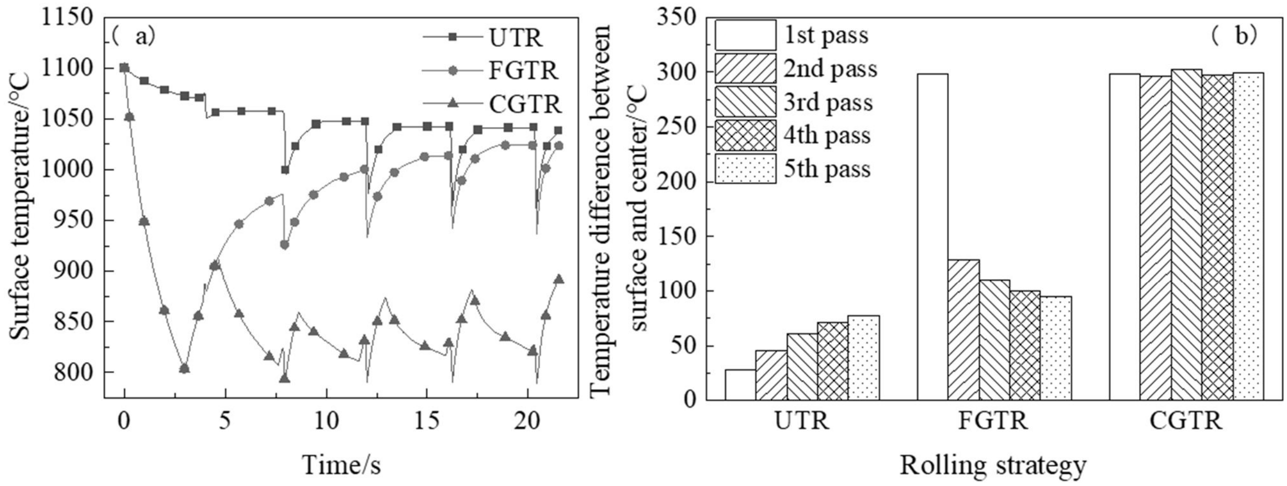
The Charpy impact tests were tested under -80 °C using ZBC2752-d-D, and the microstructure was observed under Leica microscope and FEI Quanta 650 FEG. The impact fracture surface was analyzed by SEM using Sigm300 scanning electron microscope, and EBSD test was conducted using Oxford X-Max50 energy spectrum.

Tab. 1 *Pass schedule*

Rolling pass	1st pass	2nd pass	3rd pass	4th pass	5th pass
Roll gap/mm	102	86	72	60	50
Reduction/mm	18	16	14	12	10
Percentage reduction/%	15.00	15.69	16.28	16.67	16.67

Tab. 2 *Rolling process*

Process	Rolling speed/m·s^{-1}	Type of colling	1st pass/°C	2nd pass/°C	3rd pass/°C	4th pass/°C	5th pass/°C
UTR	1	Air colling	1073	1055	1040	1029	1022
FGTR	1	Water colling 3 s before 1st pass	802	972	990	1000	1005
CGTR	1	Water colling 3 s before each pass	800	804	798	803	802

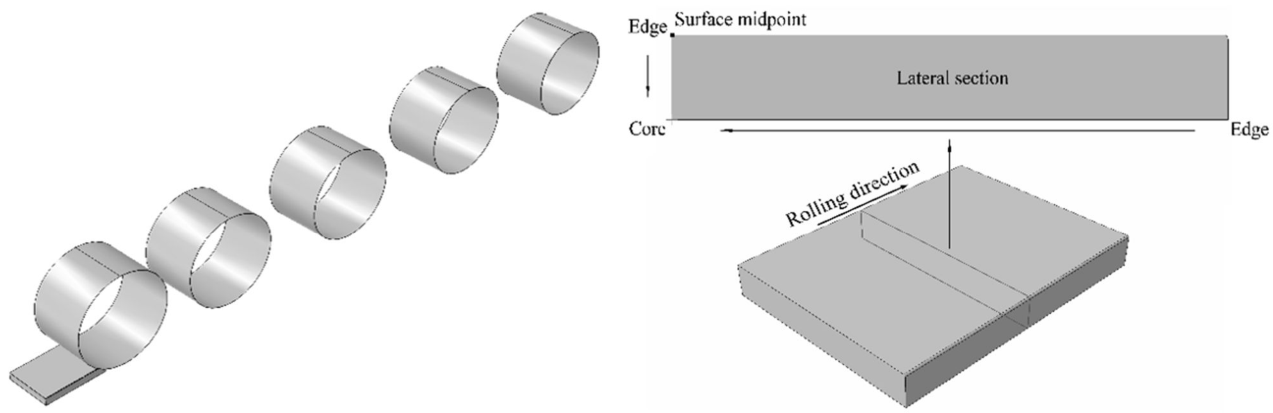


(a) Surface temperature curve (b) Temperature difference between surface and core

***Fig. 2** Surface temperature variation in rolling process and temperature difference between surface and core before every pass of the slab*

2.2 Finite Element Model

Fig. 3 shows the temperature field and surface temperature difference before rolling under different rolling processes. The roll diameter of the rolling mill is 750 mm; the roll width is 1000 mm, and the cross-sectional size of the billet is 750 mm (W) × 120 mm (H) (Fig. 3(a)). According to the rolling regulations (Table 1), a 1/4 model of five passes of rolling was established using finite element software Abaqus, as shown in Fig. 3(b). The temperature and strain fields of the cross-section of the rolled piece were used to analyze the temperature change and deformation laws. Neglecting the deformation of the rolling mill, the surface radiation coefficient of the rolled piece is taken as 0.85; the convective heat transfer coefficients of the rolled piece surface during air cooling and are water cooling taken as 20 $W \cdot m^{-2} \cdot K^{-1}$ and 1000~2000 $W \cdot m^{-2} \cdot K^{-1}$, respectively; the contact heat transfer coefficient between the rolled piece and the rolling mill is taken as 8000 $W \cdot m^{-2} \cdot K^{-1}$, and the plastic work heat conversion coefficient is 0.9. The frictional heat is evenly distributed to the rolling mill and the rolled piece.



(a) Rolling model (b) Lateral section

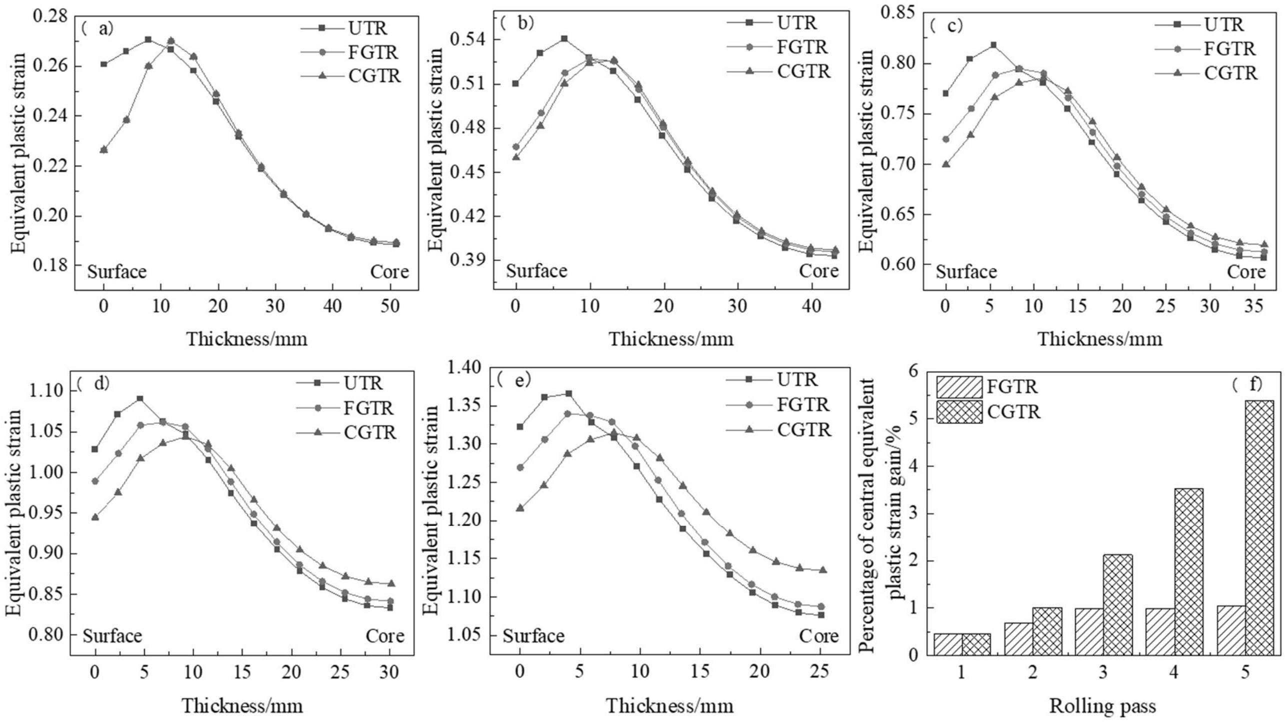
***Fig. 3** 1/4 rolling model and lateral section position*

3 Results and Analysis

3.1 Influence of different gradient temperature rolling processes on surface to core deformation

The distribution of equivalent strain along the thickness direction (from the surface to the core) after each pass under different rolling processes is shown in Fig. 4. Compared with uniform temperature rolling, under differential temperature process, the equivalent plastic strain in the core increased by only 0.0046 after the first pass. After two passes, the equivalent plastic strain in the core increased by 0.0067 and 0.0101, respectively under the first pass differential temperature process and continuous differential temperature process [22]. The continuous differential temperature process begins to have a significant effect on promoting core deformation.

After five passes of rolling, as shown in Fig. 4(f), the core equivalent strain under the first pass of differential temperature process increased by 1.04% compared to uniform temperature rolling. However, the core equivalent strain under the continuous differential temperature process increased by 5.40% compared to uniform temperature rolling. During the continuous differential temperature rolling process, deformation is more likely to penetrate into the core. This is because the cooling between passes in the continuous differential temperature rolling process maintains a large temperature gradient in the thickness direction of the rolled piece, which is more conducive to promoting deformation in the core.

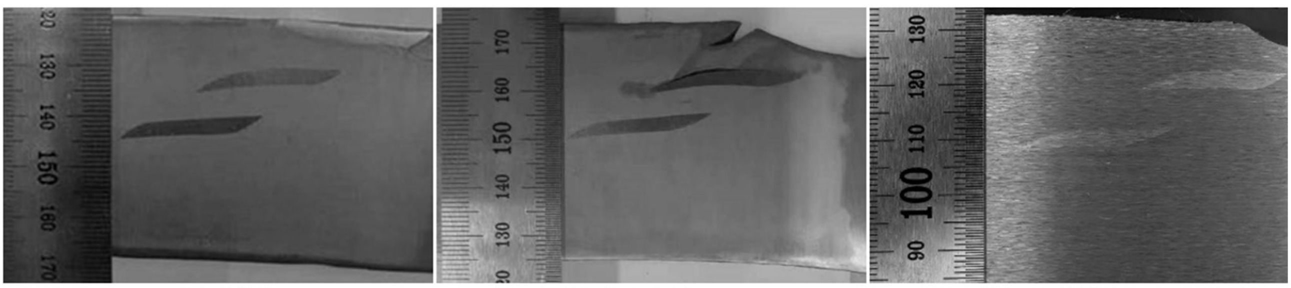


(a) 1st pass (b) 2nd pass (c) 3rd pass (d) 4th pass (e) 5th pass (f) Comparison of central equivalent plastic strain of UTR with GTR

Fig. 4 *Comparison of strain distribution along thickness direction at each pass of different rolling process*

3.2 Verification of the deformation shadow from surface to core using different GTR processes

The heavy plate rolled by different processes is horizontally cut open, and the cross-sectional morphology is observed after acid washing. The compression rate of Ni plate at different positions is measured and counted. The statistical results of macroscopic morphology are shown in Fig. 5. Fig. 6 shows that the deformation and infiltration of the CGTR core are improved by about 5% compared to the UTR process, and the deformation area expands towards the core. Under the gradient temperature rolling processes, the deformation of the core is significantly increased [23]. The core reduction rate of FGTR is about 2.3% higher than that of UTR. The core reduction rate of CGTR is about 5.3% higher than that of UTR, which is consistent with the simulation results. The CGTR is more conducive to the penetration of deformation into the core.



(a) UTR (b) FGTR (c) CGTR

Fig. 5 *Macro cross-sectional morphology of the composite plate*

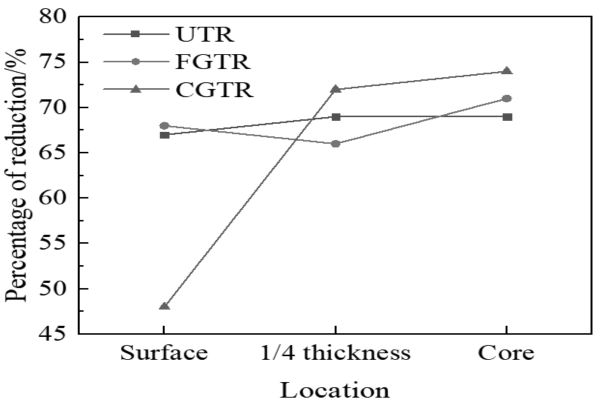


Fig. 6 *The influence of different rolling processes on the deformation rate at different positions of the cross-section*

3.3 Effects of different gradient temperature rolling processes on surface to core microstructure

The microstructure morphology obtained by different gradient temperature rolling processes in the core are analyzed by experimental methods of SEM and EBSD. As shown in Fig.7, the microstructure at different positions after rolling using the uniform temperature process (UTR) and continuous differential temperature process (CGTR) is mainly composed of granular bainite. After continuous differential temperature rolling, the grain size at a quarter and core of the rolled piece is significantly refined, and the microstructure is more uniform.

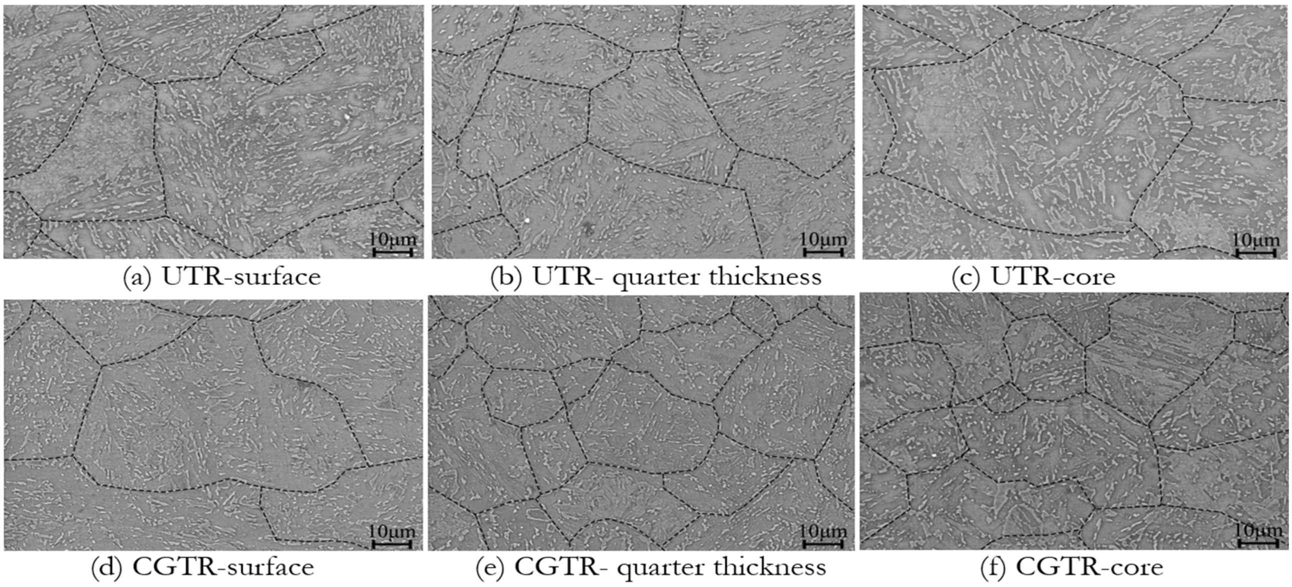


Fig. 7 *SEM Microstructure at different thickness location after UTR and CGTR*

Fig. 8 shows the calculated distribution of primary austenite grain boundaries and various grain boundary density statistics. According to the statistics of the original austenite grain size in Fig. 8(a) and Fig. 8(b), the average original austenite grain size of UTR-core steel and CGTR-core steel are 41.1 ± 6.6 μm and 20.9 ± 3.4 μm, respectively [24]. Compared with the UTR process, the CGTR process significantly reduces the size of the original austenite grains, and the refinement of the original austenite grains is beneficial for increasing the packet density and block grain boundaries in marten site. From Fig. 8(c), it can be seen that compared with the UTR process, the CGTR process cannot significantly increase the density of the central block grain boundaries and sub- block grain boundaries, but significantly increase the density of the high pack grain boundaries and low pack grain boundaries. Compared with UTR-core steel, the high-density grain boundary density of CGTR-core steel increased from 0.075 μm^{-1} to 0.104 μm^{-1}, and the low-density grain boundary density increased from 0.037 μm^{-1} to 0.055 μm^{-1}.

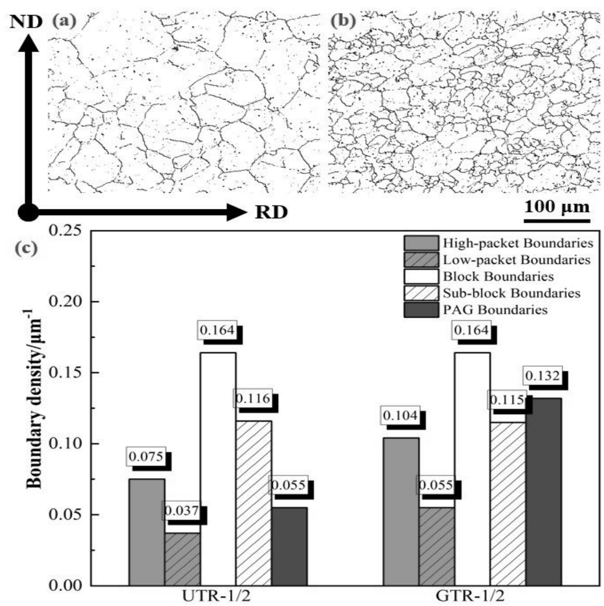
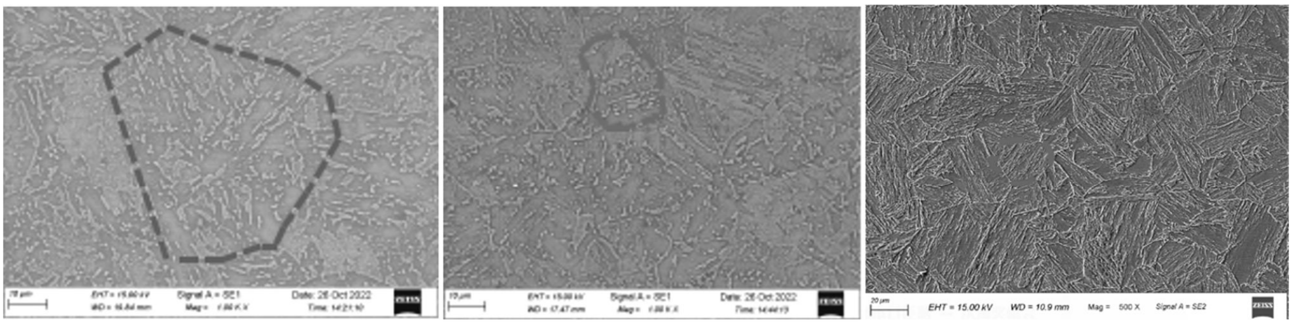


Fig. 8 *Calculated original austenite grain boundary distribution map and various grain boundary density statistical maps*

3.4 Effects of different Cooling and Heat Treatment Processes on Surface to Core Microstructure

Fig. 9 shows the deformation and infiltration of the CGTR core are improved compared to the UTR process, and the deformation area expands towards the core. At the same time, the microstructure of the core in the rolled and heat-treated states is uniformly refined, and the effect is significant. The original austenite grain size is refined from 30-40 μm to 10-20 μm.



(a) CGTR+air (b) CGTR+quenching (c) CGTR+quenching+tempering

Fig. 9 *Effect of different rolling process conditions on the microstructure of the core*

4 Conclusions

Using the CGTR method, the cooling between passes during continuous differential temperature rolling maintains the temperature distribution largely different in the thickness direction of the rolled piece. However, CGTR is more conducive to the penetration of deformation into the core. After CGTR, the original austenite grains, the grain size at a quarter and core are significantly refined with the more uniform microstructure. Even though CGTR process cannot increase the density of the central and sub block grain boundaries, but it is still promote the density of the high pack grain boundaries and low pack grain boundaries. The CGTR method not only expands the deformation area from the surface to core, but also uniform refined the core in the microstructures indicated that the method are suitable to be applied in practice.

- 1) The numerical simulation results show that when the total deformation of the five pass rolling is 58.3%, the equivalent strain at the core of the first pass differential temperature rolling process is increased by 1.04% compared to the uniform temperature rolling process. The equivalent strain at the core of the continuous differential temperature rolling process is increased by 5.40% compared to the uniform temperature rolling process. Due to the cooling between passes, the temperature distribution of the large temperature difference on the core surface of the rolled piece during the rolling process is ensused. Continuous differential temperature rolling is most conducive to the penetration of deformation into the core;
- 2) Compared with the uniform temperature rolling, the core reduction rate of the 10Ni5CrMoV heavy plate increased by 2.3% and 5.3% respectively under FGTR and CGTR. The continuous differential temperature rolling process is most conducive to core deformation;
- 3) The microstructure of the core in the rolled and heat-treated states is uniformly refined, and the original austenite grain size is refined from 30-40 μm to 10-20 μm.

Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgement

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