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The Effect of Direct Rolling of Without-heating process on the Microstructure and Properties of a 400 MPa Rebar

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Abstract. In this study, the mechanical properties and phase composition of HRB400 rebars produced via a novel direct rolling of without-heating (DROW) process and the traditional hot rolling (THR) process were compared experimentally, and the effect of the temperature gradient on the phase distribution in the rebar was investigated by combining phase transformation dynamics with the finite element method. Compared with the THR process, the grains of the produced rebar were more refined when using the DROW process, and the average yield strength and tensile strength increased by 17 and 5 MPa, respectively. Moreover, by adopting the DROW process, the volume fraction of pearlite could be increased, thereby inhibiting the growth of ferrite. The DROW process was demonstrated to not only reduce the energy consumption, but also enhance the mechanical properties of the rebar.

1. Introduction

With the development of modern materials science and technology and the change of market demand, the requirements for the microstructure and the mechanical properties of rebars have continuously improved. Paul et al. [1] studied and compared the fatigue performance of microalloyed and thermo-mechanically treated (TMT) rebars, and discovered that the microalloyed rebar possessed a uniform ferrite-pearlite microstructure, which contributed to their improved anti-fatigue performance. Mukherjee et al. [2] predicted the rim hardness limit of tempered martensite in a TMT rebar. Zaky et al. [3] discovered that the temper-softened bainite phase was generated in a BST500S rebar microalloyed with V/Nb when the bar was first hot-rolled, then water-quenched to 600 °C and then cooled in air, thereby ensuring the desired mechanical properties. Chen et al. [4] studied the anti-corrosion properties of 400 MPa graded rebar, and Wei et al. [5,6] investigated the effect of a novel chemical reagent on the anti-corrosion properties of rebar after a quenching treatment. Furthermore, You et al. [7] explored a kind of novel glass fiber rebar composite with a tensile strength of up to 900 MPa.

In addition, many research groups adopted numerical computation methods to study the performance of rebar. For instance, Paul et al. [8] utilized the finite element method (FEM) to investigate the generation and expansion of fatigue cracks, whereas German et al. [9] employed the FEM to study the effect of the rebar's corrosion on the concrete cover. Rocha et al. [10,11] studied the fatigue behavior of rebar utilizing the Navarro-De Los Rios model and predicted the crack initiation stages including the growth stage of short cracks and the expansion stage of long cracks.

At present, studies on the enhancement of the anti-corrosion properties, fatigue life and mechanical properties of rebar mainly focus on the adjustment of the microalloying components, the rolling control and the cooling control, etc. In contrast, only a few studies focus on improving the existing process for the production of hot-rolled rebars. The direct rolling of without-heating (DROW) is a



novel process for fabricating bars and rods. It is based on an optimization of the continuous casting process parameters to significantly increase the temperature of the casting billet after it is transported out of the continuous caster, and then directly transporting the casting billet to the rollers, thereby eliminating the heating process and saving energy. Compared with the traditional hot rolling (THR) process, this novel process endowed the casting billet with a lower surface temperature and a higher core temperature. In order to understand the effect of the temperature distribution on the microstructure and mechanical properties of the final products, we studied the variation of the temperature in the rolled-piece and the variation of the microstructure and mechanical properties of the products during the DROW process employing the FEM and field measurements.

2. Experimental and Simulation Procedure

2.1. Rebar Fabrication

For this study, rebars were fabricated using the DROW process and the THR process, respectively, and figure 1 shows a schematic illustration of production line setup for the rolling of the rebar. The dimensions of the casting billet were $150\text{mm} \times 150\text{mm} \times 10000\text{mm}$, and the casting billet was rolled to obtain a rebar with a diameter of 32mm after 12 passes. For the THR process, the casting billet was first transported into the heating furnace for the heating process, and was then transported to the rolling mill for rolling. For the DROW process, the overall temperature of the casting billet was significantly higher when it was transported out of the continuous caster due to an optimization of the continuous casting parameters. Thus, the casting billet could be directly transported to the rolling mill for the rolling process and did not require a heating step.

Portable IR thermometers were used to measure the temperatures before the rolling process, and the fixed thermometers on the back of the last stand of the finishing mill were used to measure the finish rolling temperature (as showed in figure 1).

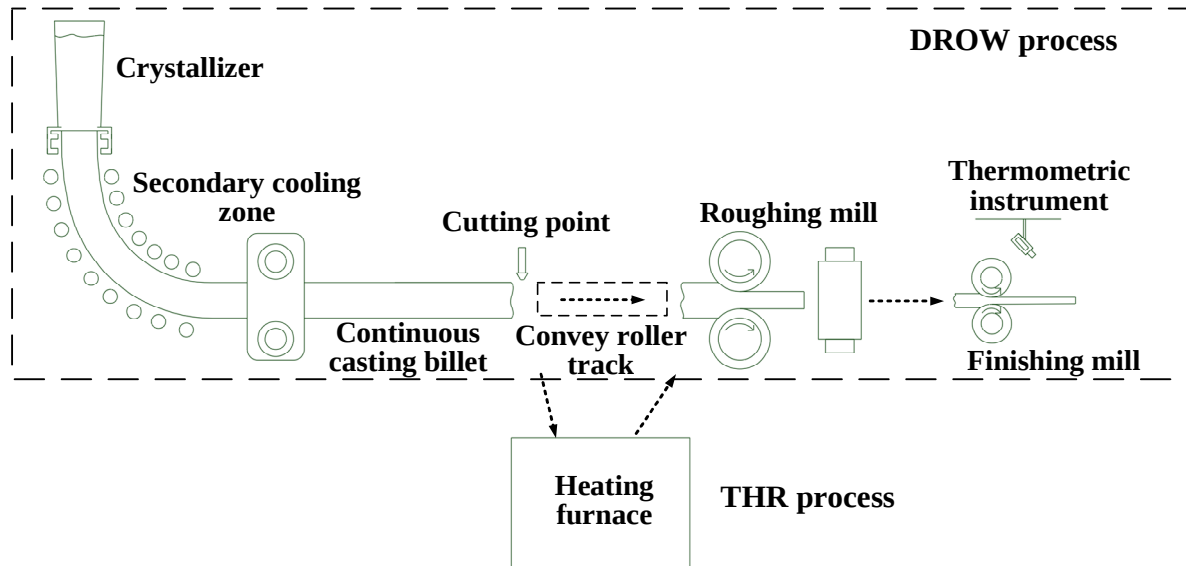


Figure 1. Schematic illustration of the production line setup for the rolling of the rebars.

2.2. Material and Experimental Procedure

The experimental specimens were derived from commercial HRB400 rebar, and the chemical composition is provided in table 1.

Table 1. Chemical composition of the rebar (in wt%).

C	Si	Mn	P	S	V	Others
0.23	0.42	1.32	0.021	0.020	0.025	Trace residual Cr, Ni, Cu, etc.

After the rebar samples were produced using the DROW process and the THR process, respectively, the corresponding microstructure morphology of the samples was observed using a metalloscope, and the mechanical properties were investigated using a tensile testing machine.

The thermal simulation experiments for the DROW process and the THR process were carried out using a Gleeble-3500 thermal simulator. First, the specimen was heated to 1200 °C at a heating rate of 20 °C/s, and then held at this temperature for 5 min. Afterwards, the specimen was cooled down to the deformation temperature of 880 °C (970°C) at a cooling rate of 10 °C/s, and then left at this temperature for 1 min. The specimens were compressed by 70% at a deformation rate of 10 s⁻¹. Finally, the specimens were cooled down to room temperature at a cooling rate of 0.1, 0.5, 1, 2, 5, 10, 20 and 30 °C/s, respectively. The dynamic CCT curves were obtained utilizing the thermal dilation method and the metallographic method.

2.3. Simulation of the Thermal Deformation Process

The material phase transformation was investigated by FEM. Considering the geometric symmetry of the casting billet. A quarterly geometric model was adopted for the analysis.

2.3.1. Heat transfer equation. The equation describing the temperature of the rolled-pieces during hot rolling process can be written as follows:

$$\rho c \dot{T} = \nabla \cdot (k \nabla T) + \sigma_{ij} \dot{\epsilon}_{ij}^p + \sum L_{AB} \dot{\xi}_{AB} + \dot{Q} \quad (1)$$

where, ρ , c , k and Q denote the density, specific heat, thermal conductivity and the heat provided by the external heat source. L_{AB} is the latent heat of phase transformation from phase A to phase B, $\dot{\xi}_{AB}$ is the derivative of the volume fraction transforming from phase A to phase B, $\dot{\xi}_{AB}$, with respect to time, also referred to as the transformation rate, and σ_{ij} and $\dot{\epsilon}_{ij}^p$ are the stress and the plastic strain tensor, respectively. Finally, $\sigma_{ij} \dot{\epsilon}_{ij}^p$ and $\sum L_{ab} \dot{\xi}_{ab}$ are the heat resulting from plastic deformation and the heat variation resulting from phase transformation.

2.3.2. Boundary conditions. The contact heat transfer between the rolled-piece and the rolls was calculated using the following equation:

$$q = h_c (T_b - T_r) \quad (2)$$

where q is the heat flux density, h_c is the contact heat transfer coefficient, and T_b and T_r are the surface temperature of the rolled-piece and the rolls, respectively.

The heat transfer between the rolled-piece and air can be divided into convective heat transfer and radiation heat transfer:

$$\begin{cases} q = h_a (T_b - T_a) \\ q = \varepsilon \sigma (T_b^4 - T_a^4) \end{cases} \quad (3)$$

where h_a is the convective heat transfer coefficient, and ε , σ and T_a denote the emissivity, the Stefan-Boltzmann constant and the environment temperature, respectively.

2.3.3. Phase transformation model. When computing the phase transformation via continuous cooling transformation curves, there is a linear relationship between the transformed phase volume and the temperature difference:

$$V = V_0 \frac{T_s - T_i}{T_s - T_f} \quad (4)$$

where T_s , T_i and T_f are the starting temperature, the actual cooling temperature and the final temperature during the phase transformation process, respectively. V_0 is the maximum transformed phase volume fraction for a given cooling rate, and V is the instantaneously transformed volume fraction of a specific phase structure.

2.3.4. *Simulation parameters.* The relevant computational parameters are listed in table 2.

Table 2. Parameters required for the simulation of the rolling process.

Physical property	Unit	Value
Ambient temperature	°C	25
Emissivity	—	0.85
Contact heat transfer coefficient	W/(m ² ·K)	5500
Thermal conductivity	W/(m·K)	32
Convective heat transfer coefficient	W/(m ² ·K)	30

3. Results and Discussion

3.1. Analysis of the Temperature of Rolled-Piece

Before rolling process, since the temperature difference between the surface and the core of rolled-piece is different in the two rolling processes. However, the difference gradually decreases during the rolling process as revealed by the FEM results. Table 3 shows, at the head region of rolled-piece, the simulated temperature before rolling and after finishing rolling for the two different rolling processes.

Table 3. Comparison of the temperature in the DROW and the THR process.

Rolling process	Head region of rolled-piece	Surface temperature (°C)	Core temperature (°C)
DROW	Before the start of rolling	947	1027
	After the final rolling	892	925
THR	Before the start of rolling	1043	1090
	After the final rolling	975	1014

In the THR process, the surface and core temperatures of head region of rolled-piece before rolling are 1043 and 1090 °C, respectively, corresponding to a difference of 47 °C. When rolled-piece had moved to the exit of the final rolling mill, the difference between the surface and core temperature of head region of rolled-piece had dropped to 39°C.

In the DROW process, the surface and core temperatures of head region of rolled-piece are 947 and 1027 °C, respectively, corresponding to a temperature difference of 80 °C; by the time the rolled-piece arrived at the exit of the final rolling mill, the temperature difference had dropped to 33 °C. Thus, during the rolling process, the temperature gradient between the surface and the core of rolled-piece more rapidly decreases in the DROW process.

The experimental results and the calculated temperatures of the rebar head surface before and after the rolling process are compared and listed in Table 4. In comparison, the computational results obtained for the temperature are in better agreement with the experimental values.

Table 4. Comparison of the experimentally and the calculated temperatures.

Rolling process	Head surface position of rolled-piece	Experimental temperature (°C)	Calculated temperature (°C)
DROW	Before the start of rolling	951	947
	After the final rolling	880	892
THR	Before the start of rolling	1048	1043
	After the final rolling	971	975

3.2. Analysis of the Phase Transformation

Figure 2 compares the experimentally obtained dynamic CCT curves for the two different rolling processes, and it can be seen that the phase transformation curves are lower for higher holding temperatures. In figure 2, Ac1 is 718 °C, and Ac3 is 820 °C.

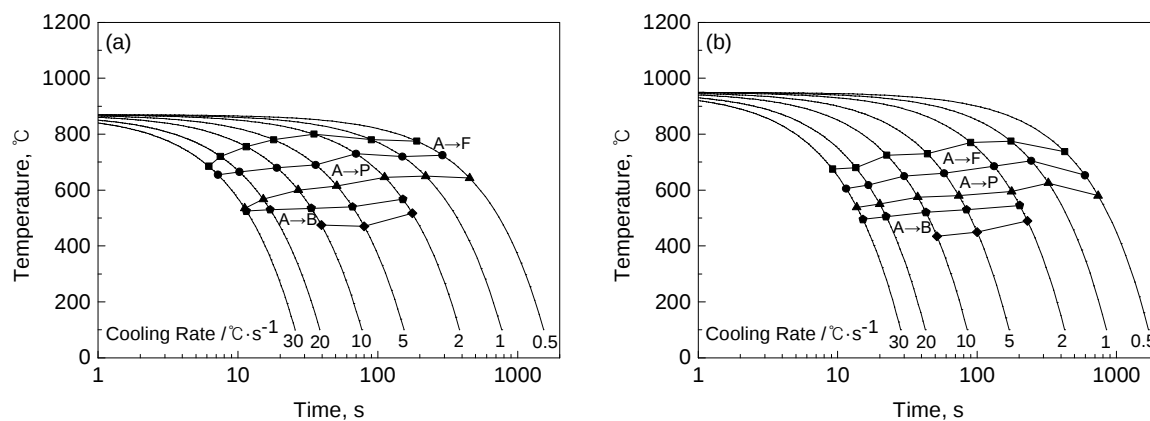


Figure 2. Dynamic CCT curves for the two different rolling processes:
(a) DROW process; (b) THR process

Figure 3 compares the morphology of the grains of the rebar for the two different rolling processes.

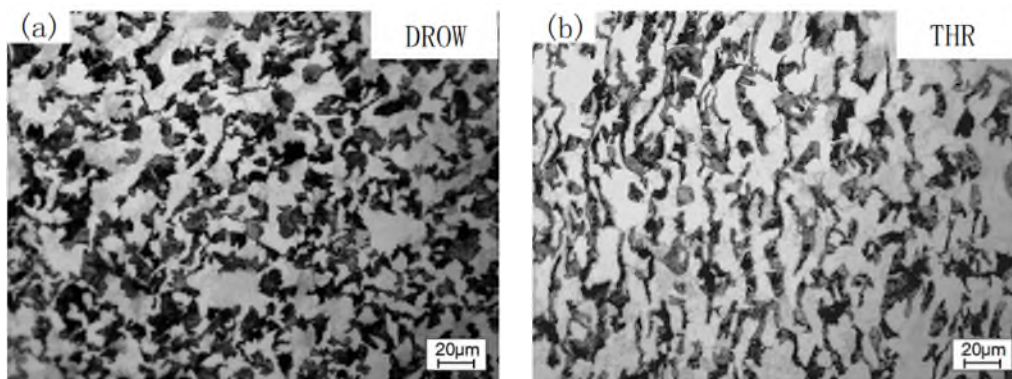


Figure 3. Grain morphology obtained for the rebar after the two different rolling processes:
(a) DROW process; (b) THR process

Because the temperature of rolled-piece is lower in the DROW process than in the THR process, the grains of the rebar are more refined.

Based on the CCT curves shown in figure 2 and the equations (1)-(4), the volume fractions of the different phases in the radial direction of the rebar at room temperature were simulated using the FEM, and the results were compared with experimental data. Figure 4 shows the phase distribution and the volume fraction of the cross-section of the rebar.

The results show that the volume fraction calculated for ferrite, pearlite and bainite show little variation along the radial direction. Compared with the THR process, in the DROW process, the ferrite content decreased by 6.42%, the pearlite content increased by 6.44% while the bainite content decreased by 0.02%.

The experimental and calculated volume fraction of each phase are compared in Table 5 for rebar fabricated via the DROW process, and the calculated values are in good agreement with the experimental data.

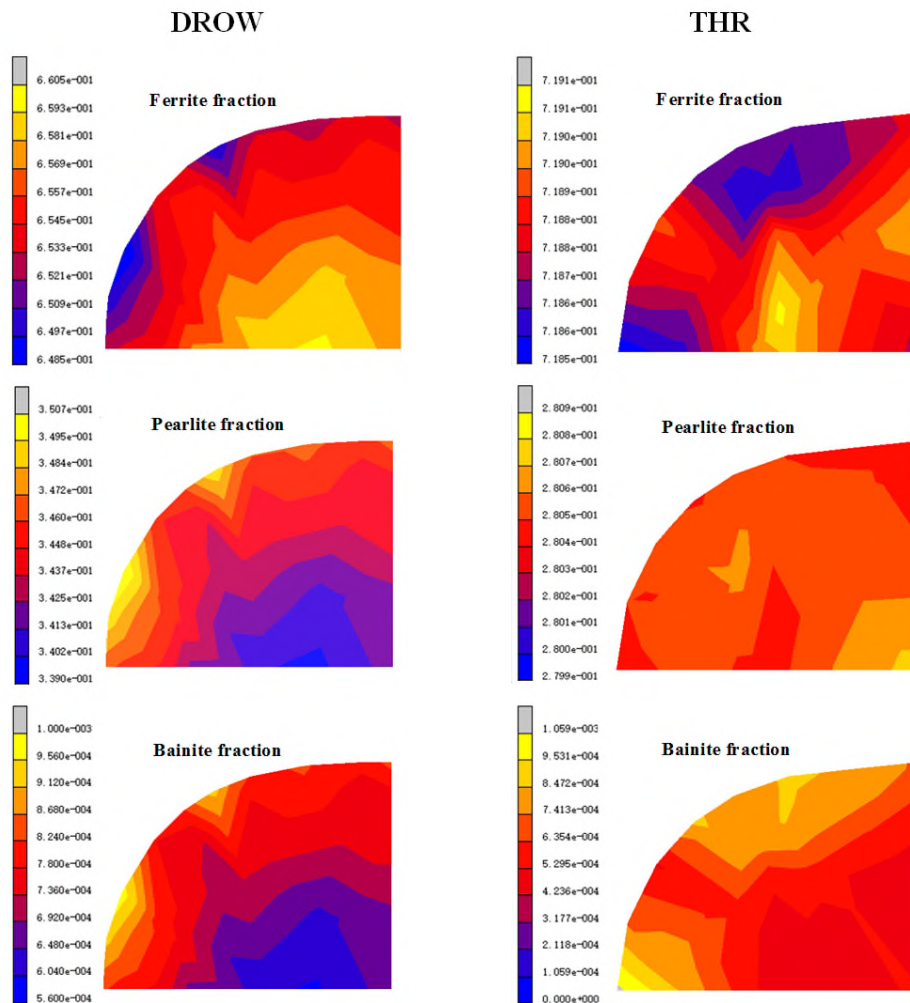


Figure 4. Volume fraction of each phase found in the rebar.

Table 5. Comparison of the experimental and calculated volume percentages for each phase.

	Experimental value (vol%)	Calculated value (vol%)
Ferrite	63.23	65.45
Pearlite	36.59	34.47
Bainite	0.18	0.08

3.3. Experimental Comparison of the Mechanical Properties of the Rebars

The experimental results obtained for the mechanical properties of the rebars fabricated via the DROW and the THR process, respectively, are compared in Table 6.

Table 6. Mechanical properties of the rebars fabricated via the two different rolling processes.

	Average yield strength (MPa)	Average tensile strength (MPa)
DROW	449	612
THR	432	607

The average yield strength and tensile strength of rebar produced via the DROW process showed the enhancement, and they were found to be improved by 17 and 5 MPa, respectively, compared with the average yield strength and tensile strength of the rebar produced via the THR process.

4. Conclusions

(1) When changing to the DROW process, the pearlite content increased by 6.44%, and the ferrite content decreased by 6.42%. In addition, compared with the THR process, the DROW process did not have a negative effect on the uniformity of the cross-sectional phase distribution.

(2) The temperature of rolled-piece is lower in the DROW process than in the THR process, the grains of rebar are more refined, and the average yield strength and tensile strength increased by 17 and 5 MPa, respectively.

(3) The rebars produced by the DROW process can improve mechanical properties without requiring a heating furnace. Thereby reducing production costs and increasing productivity.

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