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Effect of tempering treatment upon the residual stress of bimetallic roll

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Abstract. Bimetallic rolls are widely used in steel rolling industries because of the excellent hardness, wear resistance, and high temperature properties. However, thermal stress is produced by heating-cooling thermal cycles, which is a great challenge for their practical application. Indeed, if severe thermal tensile stress is introduced into these rolls, it can assist the thermal cracks to propagate, even lead to the overall failure of rolls. In this paper, we investigated the effect of tempering treatment on the residual stress after the bimetallic rolls were subjected to quenching. Compared with the non-uniform heating-quenching process, the tempering process makes the maximum stress at the core decreased by 15% (from 275 MPa to 234 MPa) with considering martensite transformation but decreased by 26% (from 275 MPa to 201 MPa) without considering martensite transformation. For tempering process after uniform heating quenching, the maximum stress at the core decreases by 24% from 357 MPa to 273 MPa with considering martensite transformation but decreases by 30% from 357 MPa to 246 MPa without considering martensite transformation. And compared with the non-uniform heating-quenching process, the double tempering process makes the maximum stress at the core decreased by 8% (from 275 MPa to 253 MPa) with considering martensite transformation but decreased by 27% (from 275 MPa to 200 MPa) without considering martensite transformation.

1. Introduction

Work rolls are used in the roughing stands of hot strip mill to reduce the steel thickness. They have to meet the requirements of hardness, wear resistance at the surface, and toughness at the center [1-3]. Traditional single material roll cannot satisfy these conflicting properties at the same time. Many studies were done to improve roll performance in the past decades. The bimetallic roll is one of the most important development to resolve this problem [4,5]. High speed steel (HSS) is widely used in the bimetallic roll as shell material. The HSS roll is characterized by excellent hardness, good wear resistance as the shell material and significant toughness of core material [6-9]. As shown in figure 1, the bimetallic roll is manufactured by centrifugal casting method, using HSS as the shell material and the ductile casting iron (DCI) as the core material. During heat treatment, residual stress is inevitably introduced due to temperature gradient and phase transformation [4,10,11]. The residual stress is self-equilibrating within the roll, independent of the any external loads. In addition, thermal stress is

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produced by heating-cooling thermal cycles during subsequent hot rolling process [12,13]. If severe thermal tensile stress is added under the rolling trouble, the thermal crack starts to propagate. Therefore, suitable compressive stresses are necessary for preventing the thermal crack extension.

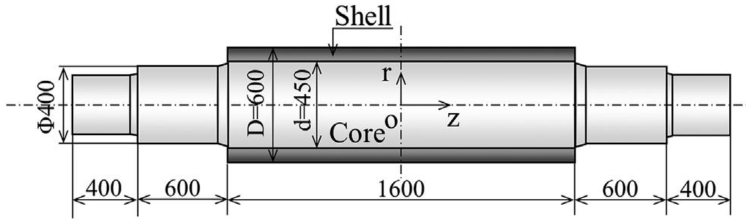


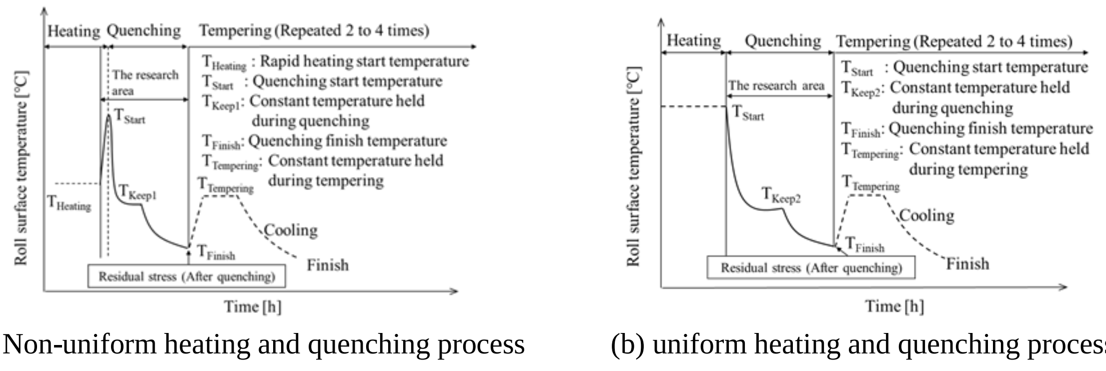
Figure 1. Schematic diagram of the HSS bimetallic roll (mm).

One of the most used numerical modelling techniques is finite element method, which can be used for many engineering applications conveniently [14-19]. In the previous studies [14-16], different quenching methods were discussed through FEM simulations to produce suitable surface compressive residual stresses and to reduce the center tensile residual stress. However, since the tempering process after quenching was not been considered yet, the tempering effect will be discussed after uniform heating quenching and after non-uniform heating quenching on the basis of FEM simulations.

2. Tempering effect to reduce residual stress

2.1. Quenching and tempering heat treatment

Figure 2(a) illustrates the non-uniform heating quenching process in comparison with figure 2(b), which illustrates the uniform heating quenching process. In the uniform heating process, the whole roll is heated up to the higher temperature equaling to T_{Start} before the quenching process. In the non-uniform heating process, the whole roll is heated up to the uniform lower temperature of T_{Heat} and kept at T_{Heat} for some hours, then rapidly heated up to T_{Start} as the non-uniform heating before quenching. This rapid heating provides temperature difference between the roll surface and roll center. The quenching processes after non-uniform heating and uniform heating are similar, but the keeping temperature T_{Keep1} in figure 2(a) > T_{Keep2} in figure 2(b). The quenching process after the non-uniform heating quenching can be described in the following way: the roll is put out from the heating furnace and cooled down rapidly from T_{Start} by using the spray cooling. After rapid cooling, the roll is maintained for several hours when the surface temperature drops to T_{Keep1}. Here, keeping T_{Keep1} is beneficial to relax the excessive thermal stresses caused by rapid surface cooling. After keeping T_{Keep1}, the roll is put out from the furnace and slowly cooled down in air until to T_{Finish}. In this paper, one or two tempering processes will be assumed to clarify the effect of transformation after uniform heating and non-uniform heating.



(a) Non-uniform heating and quenching process (b) uniform heating and quenching process

Figure 2. Heating and quenching processes of HSS bimetallic roll.

Figure 3 shows the thermal expansion rate used in tempering analysis. The temperature is normalized by the quenching temperature T_{Start}°C. After quenching, the temperature is raised from T_{Finish}°C and held at tempering temperature $T_{Tempering}$, and cooled down. During the cooling down process, martensitic transformation occurs from retained austenite. Although stress reduction may appear by keeping tempering temperature $T_{Tempering}$, martensitic expansion may elliminate this effect. Figure 3 is obtained by using the specimen with dimensions of 8 mm width × 17 mm length × 8 mm thickness, which was cut out from HSS roll. The results obtained from the solid line in figure 3 is denoted as martensite transformation 100%. If the compressive residual stress of 300 to 500 MPa existing in the outer layer of the actual roll is considered, the martensitic transformation may be suppressed. By considering this surface residual effect, in this study, an extreme case will be considered for martensite transformation 0% obtained from the dotted line data shown in figure 3.

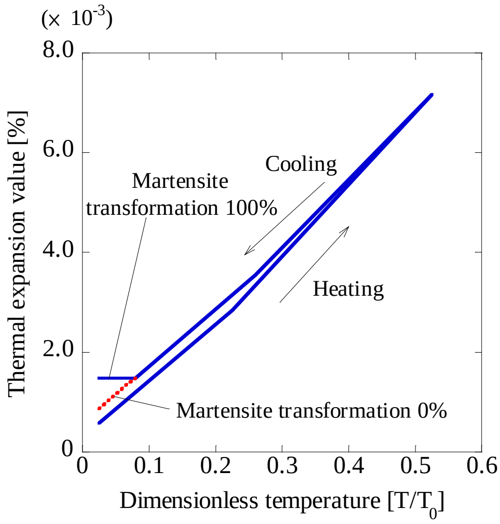


Figure 3. Dilatometric curves during tempering process ($T_0 = T_{Start}$).

2.2. Creep analysis

In the creep analysis, the transient creep strain should be considered as well as the steady creep strain. Among several equations available for creep analysis, the time hardening law, sometimes called power law, is used to express the core material which has low strength under high temperature. The core creep can be given by equation (1).

$$\varepsilon^c = \mathrm{A}\sigma^{\mathrm{m}} t^{\mathrm{n}} \quad (1)$$

Where ε^c is the transient strain, σ is stress, t is time, A, m, and n are temperature dependent material constants. This time hardening formulation is used to predict the creep behavior under a variable stress history. In order to determine constants A, m, and n, the creep tests are performed.

2.3. Creep test

The creep testing was conducted by using a miniature creep rupture testing machine based on JISZ2271. The specimens were prepared from core material as shown in figure 4(a). Those specimens were, respectively, heated up to the testing temperatures, T_{Keep1} and T_{Keep2}, and kept at theses temperatures during the testing process. Then, the creep tests were carried out by applying constant loads 100 and 130 MPa. The strain changes were recorded with time. From the strain–time curves obtained, the creep equations can be written as shown in equations (2) and (3).

$$\varepsilon^c = 2.25 \times 10^{-13} \sigma^{3.44} t^{0.672} (T_{keep1}) \quad (2)$$

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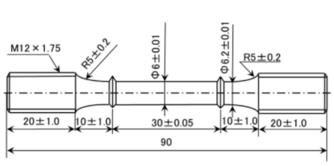
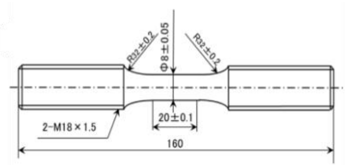
$$\varepsilon^{c} = 8.38 \times 10^{-19} \sigma^{5.71} t^{0.514} (T_{keep2}) \tag{3}$$



(a) Specimen of the creep test (mm)



(b) specimen of the stress relaxation test (mm)

Figure 4. Specimens of the creep test and stress relaxation test.

2.4. Stress relaxation test

To confirm the validity of equations (2) and (3), the following stress relaxation testing was conducted. The specimens were prepared from the core material as shown in figure 4(b). Those specimens were, respectively, heated up to the testing temperature, T_{Keep1} and T_{Keep2}, and kept at theses temperatures during the testing process. Then, the stress relaxation tests were carried out under the constant strain when the primary stress is 130 MPa. The time and stress changes were recorded as shown in figure 5.

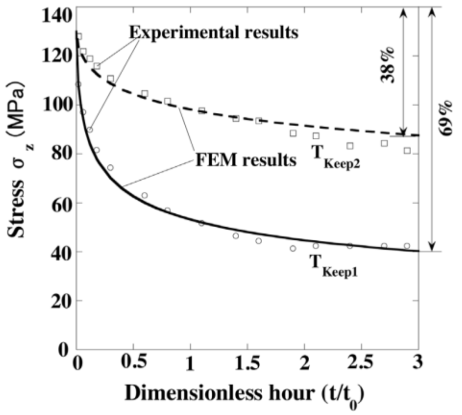


Figure 5. Comparison between FEM simulation results and experimental results for stress relaxation at T_{Keep1} and T_{Keep2}.

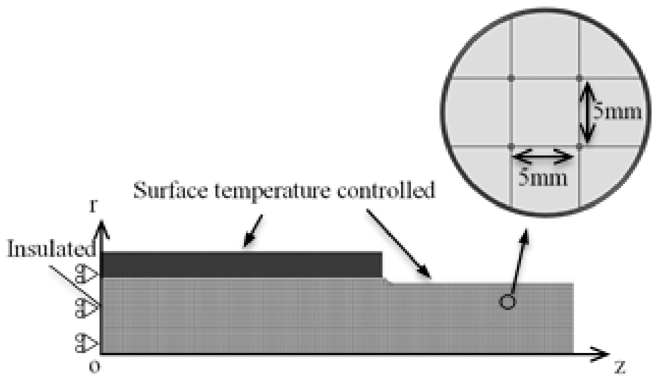


Figure 6. Analytical model and boundary condition for bimetallic roll whose mesh size is 5×5 mm for both inner and core material.

2.5. Results and discussion for creep

The model used for the FEM simulations is shown in figure 6, and the mechanical properties as shown in table 1.

Table 1. Mechanical properties of shell and core at room temperature.

Property	Shell	Core
0.2% proof stress (MPa)	(1270)*1	410
Young's modulus (GPa)	228	168
Poisson's ratio	0.3	0.28
Density (kg/m^3)	7600	7300
Thermal expansion coefficient (/K)	12.6×10^{-6}	13.0×10^{-6}
Thermal conductivity [W/(m·K)]	20.2	23.4
Specific heat [J/(kg·K)]	0.46	0.42
Shore hardness, Hs	85	50

Table 2. Comparison of keeping process between non-uniformheating quenching and uniform heating quenching.

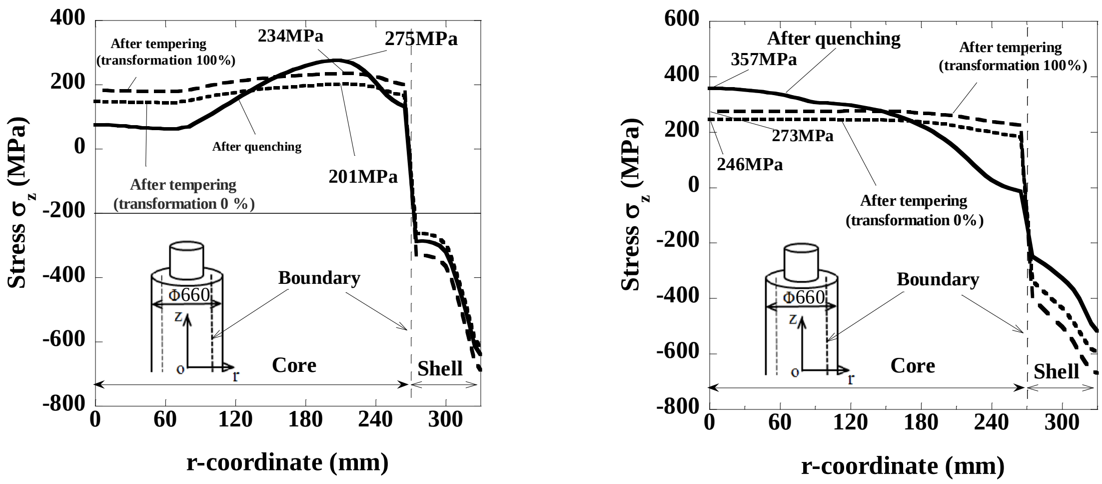
Heat treatment	Non-uniform	Uniform
Stress relaxation ratio [%]	69	38
Keeping temperature [ºC]	$T_{keep1} > T_{keep2}$	
σ_{eq} at keeping temperature [MPa]	136	103
Keeping time [h]	5.3	6

FEM simulations of stress relaxation were performed to verify equations (2) and (3) as shown in figure 5 in comparison with the experimental result at T_{Keep1} and T_{Keep2}. The results show that the stress decreases by 69% at T_{Keep1} and by 38% at T_{Keep2} as shown in table 2. It can be found that the stress relaxation ratio is larger at high temperature (T_{Keep1}) than relatively low temperature (T_{Keep2}). The FEM results are in good agreement with the experiment results. It is confirmed that equations (2) and (3) are useful for predicting the creep effect on the residual stress.

3. Residual stress after tempering

3.1. Effect of tempering process on residual stress

Figure 7 shows stress distribution σ_z along the central cross section where z = 0 after tempering process for non-uniform heating quenching and uniform heating quenching. It is shown that the tempering process effectively reduces the maximum tensile residual stress at the roll core and keeps large enough compressive residual stress at the roll surface. In addition, the stresses become uniformly distributed at the core after uniform heating quenching and also after non-uniform heating quenching.



(a) Tempering process after non-uniform heating quenching process

(b) Tempering after uniform heating quenching process

Figure 7. Effect of tempering process on the residual stress.

For tempering process after non-uniform heating quenching, the maximum stress at the core decreases by 15% from 275 MPa to 234 MPa for martensite transformation 100%, and decreases by 26% from 275 MPa to 201 MPa for martensite transformation 0%. For tempering process after uniform heating quenching, the maximum stress at the core decreases by 24% from 357 MPa to 273 MPa for martensite transformation 100%, and decreases by 30% from 357 MPa to 246 MPa for

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martensite transformation 0%.

4. Conclusion

In this paper, the numerical analysis method which can predict the residual stress reduction considering tempering process was established. The results of the current study can be summarized as follows:

- FEM simulations of stress relaxation were performed. As a result, it can be found that the stress relaxation ratio is larger at a high temperature than at a relatively low temperature.
- Compared with the non-uniform heating-quenching process, the tempering process makes the maximum stress at the core decreased by 15% (from 275 MPa to 234 MPa) with considering martensite transformation but decreased by 26% (from 275 MPa to 201 MPa) without considering martensite transformation.
- Compared with the uniform heating-quenching process, the tempering process makes the maximum stress at the core decreased by 24% (from 357 MPa to 273 MPa) with considering martensite transformation but decreased by 30% (from 357 MPa to 246 MPa) without considering martensite transformation.

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