

## RESIDUAL STRESS GENERATION MECHANISM FOR HOT STRIP COMPOSITE ROLLS DURING QUENCHING PROCESS

Kejun Hu<sup>1</sup>, Yoshikazu Sano<sup>1\*</sup>, Nao-Aki Noda<sup>1</sup>, Katsma Ono<sup>1</sup> and Chengwei Wu<sup>2</sup>

<sup>1</sup> Department of Mechanical Engineering, Kyushu Institute of Technology, Kitakyushu, Japan

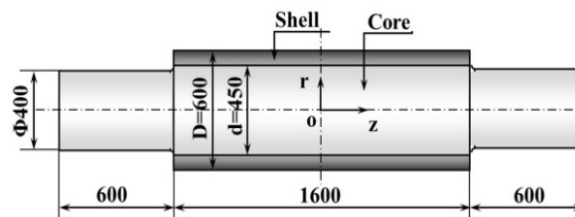
<sup>2</sup>State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian, China

**Abstract:** Composite rolls are widely used in hot rolling mill because of the excellent hardness, wear resistance and high temperature properties. During hot rolling process, composite rolls are subjected to heating-cooling thermal cycles from the hot strip contact and water cooling. The thermal stress is added to already existing residual stress. The thermal fatigue cracking appears at roll surface, and the fracture is possible happen in roll centre when the tensile stress exceeds the centre strength. Therefore, residual stress plays an important role in composite roll. In this paper, FEM (finite element method) simulation is performed to investigate the generation mechanism of the residual stress during quenching process. It should be noted that a large number of experimental data of the core and shell materials are utilized for the wide range of temperature considering the quenching process. The results verify that initially the tensile stress appears on the roll surface but finally the compressive stress occurs.

**Keywords:** Composite roll; Residual stress; Quenching; FEM.

### 1 INTRODUCTION

Composite roll is composed of high speed steel as shell material, and ductile iron as core material, as shown in Fig.1. This composite roll is characterized of excellent hardness, wear resistance and high-temperature property on the surface, as well as high strength, high toughness in the centre [1]. In addition, composite roll meets the requirements of better product quality, higher productivity and lower production cost for hot steel rolling industry. However, it's difficult for conventional single material roll to meet these several requirements at the same time. In this way, the composite roll is widely used for hot strip rolling mill. The residual stresses are always introduced into the composite roll affected by temperature gradient and phase transformation during the heat treatment process. During hot rolling process, thermal stresses are caused by cyclic temperature variation due to hot strip contact and water cooling [2]. As a result, the produced thermal stresses add already existing residual stresses at the roll, resulting in thermal fatigue cracking on roll surface and fracture in roll centre. Hence, residual stress plays an important role in composite rolls services life.



**Fig. 1** A schematic diagram of the composite roll (unit: mm)

In previous studies, the residual stress has been evaluated experimentally with a large amount of cost because non-destructive measurement is not possible for large-scale rolls [3]. Meanwhile, a large number of material property data are necessary to calculate the residual stress for composite rolls, which are often difficult to be obtained since the wide ranges of temperature during quenching process. In the past decades, few studies were available for residual stress of composite roll during quenching process. Therefore, the investigation and understanding of stress during heat treatment process is important to improve the quality and reliability for the composite roll. In this study, the numerical simulation using finite element method (FEM) software MSC.Marc2012 is applied to reveal the residual stress during quenching process.

## 2 GENERATION MECHANISM OF RESIDUAL STRESS FOR SINGLE MATERIAL ROLL

In the first place, by taking an example of single material roll, the residual stress generation mechanism will be considered. Fig.2 shows the simplified single material roll considered in this study. An axisymmetric FEM model is performed, ignoring the phase transformation.

It is known that the axial residual stress  $\sigma_z$  is the most important stress causing roll fracture and spalling during the manufacturing and using process. Therefore, the  $\sigma_z$  residual stress distributions are mainly discussed in this paper. Fig.3 shows the residual stresses  $\sigma_z$  distribution after quenching process. As shown in Fig.3, the compressive stresses appear on the surface, while the tensile stresses appear in the centre. It is seen that  $\sigma_z$  ranges between -115MPa and 101MPa. Both the maximum compressive stress and maximum tensile stress at the central cross section where  $z=0$ .

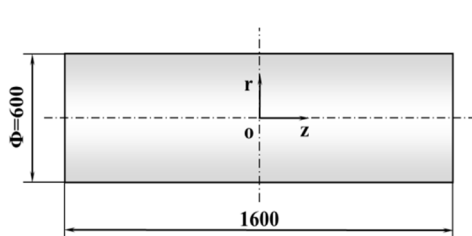


Fig. 2 Model of the single material roll (unit: mm)

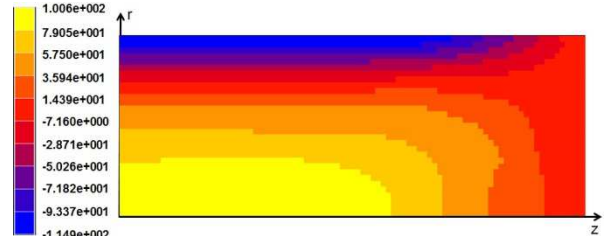
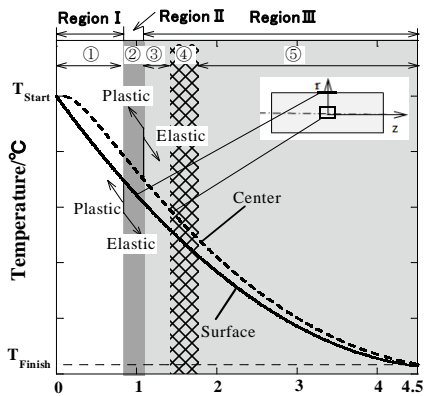
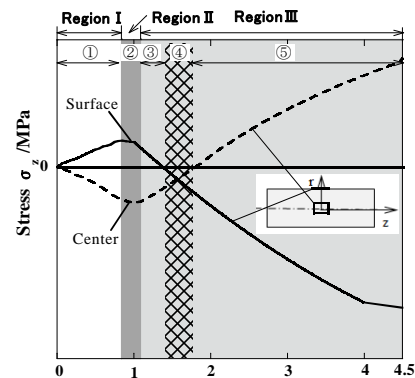


Fig. 3  $\sigma_z$  of the single material roll after quenching

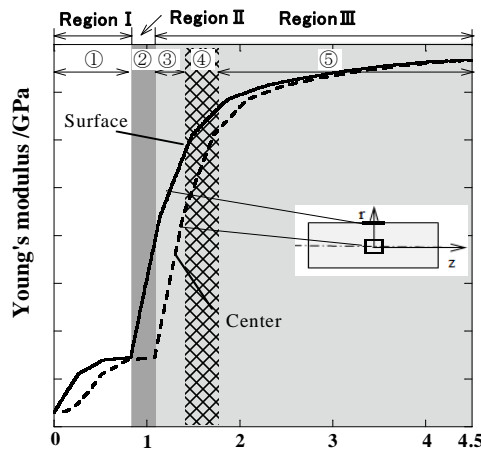
Fig.4 shows the variation of temperature, residual stress and Young's modulus for the single material roll during quenching process. As is shown in Fig.4, the solid lines represent roll surface and the dotted lines represent roll centre, respectively. Fig.4 (a) shows the temperature history during quenching process. It should be noted that these smooth temperature variation curves are different from the real temperature variation of quenching process, which are simply used to simulate the cooling trend of roll during quenching process. Fig.4 (b) shows the  $\sigma_z$  obtained by the simulation and Fig.4 (c) demonstrates the variations of Young's modulus with the time.



(a) Temperature



(b)  $\sigma_z$  residual stress



(c) Young's modulus

Fig. 4 Residual stress generation mechanism of single material roll

The quenching process can be divided into Region I, Region II and Region III based on the material state (plastic, elastic-plastic and elastic). Furthermore, these three regions can be separated five regions named as I-V, which are based on the deformation state and stress state (tensile or compressive). The generation mechanism of residual stress of single material roll during quenching process can be summarized as following.

In Region I, at the beginning of the cooling, the surface temperature drops faster than the centre temperature, leading to the temperature gradient. Afterwards, the roll surface is stretched in the axial direction and result in tensile stress due to the rapid cooling. In order to balance the stresses in the roll interior, the compressive stress is produced in roll centre. With the increase the temperature gradient, the tensile stress on roll surface and the compressive stress in roll centre increase as well continuously.

In Region II, due to the continuous cooling, the roll surface turns to be elastic with the increase of Young's modulus, at the same time, the roll centre is still plastic under the high temperature environments. In this period, the thermal contraction in the centre is restricted because of elastic state on roll surface, resulting in the thermal contraction rate in the centre slowing down. However, the thermal contraction rate in the centre is faster than the rate on the surface, causing the thermal strain differences to decrease. Finally, both surface and centre stresses reach peak values.

In Region III, the thermal contraction rate in roll centre is higher than the rate on roll surface, which cause both surface and centre stresses to decrease, owing to the decrease of thermal contraction difference is shown in the Fig. 4(a). As the cooling continues, the surface thermal contraction is approximately equal to the centre thermal contraction, then the stresses state are interchanged from tension to compression and from compression to tension is shown in Fig. 4(b). According to region I and II in Fig. 4(a), the temperature changes in roll centre is larger than the one on roll surface because the temperature in the centre is higher. Therefore, the centre contraction is larger than the surface thermal contraction, resulting in the tensile stress in roll centre increases and compressive stress increases on roll surface. As is shown in Fig.4(c), since Young's modulus increases in in region III and II, the compressive stresses on roll surface increases and tensile stress in roll centre increases at the same time. Eventually, compressive stresses are obtained on the surface and tensile stresses are left in the centre.

### 3 QUENCHING ANALYSIS OF COMPOSITE ROLL

The composite rolls are manufactured by centrifugal casting method, using high speed steel as outer layer and the ductile iron as inner layer and roll neck, as is shown in Fig.1. The chemical compositions of high speed steel and ductile iron are presented in Table 1, and the material properties at room temperature are given in Table 2.

**Table 1** Chemical compositions of high speed steel and ductile iron for composite roll, wt- %

	C	Si	Mn	Ni	Cr	Mo	Co	V	W	Mg	P	S
HSS	1-3	<2	<1.5	<5	2 - 7	<10	<10	3 - 10	<20	<10		
DCI	2.5-4	1.5-3.1		0.4 - 5	0.01-1.5	0.1-1				0.02-0.08	<0.1	<0.1

**Table 2** Mechanical property for shell and core at room temperature

Property	Shell	Core
Yield stress /MPa	1282	415
Young's modulus /GPa	233	173
Poisson's ratio	0.3	0.3
Density /kg·m <sup>-3</sup>	7.6	7.3
Thermal expansion coefficient /K <sup>-1</sup>	12.6×10 <sup>-6</sup>	13.0×10 <sup>-6</sup>
Thermal conductivity W(m·K) <sup>-1</sup>	20.2	23.4
Specific heat /J(kg·K) <sup>-1</sup>	0.46	0.46

The heat treatment process of composite roll is given in Fig.5, which includes heating, quenching and tempering. In Fig.5, the whole roll is heated to a uniform temperature of  $T_{Start}$  and kept at  $T_{Start}$  for some hours, then dropped rapidly to  $T_{Keep1}$ . Afterwards, the roll is maintained at  $T_{Keep1}$  for several hours, which helps to decrease excessive thermal stresses caused by rapid cooling of surface temperature. After maintained treatment at  $T_{Keep1}$ , the roll is transferred into furnace and cooled until temperature drops to  $T_{Finish}$ . In this study, only the quenching process is investigated and the tempering process will be studied in the future. To analyse composite roll, the half model is applied to as is shown in Fig.6.

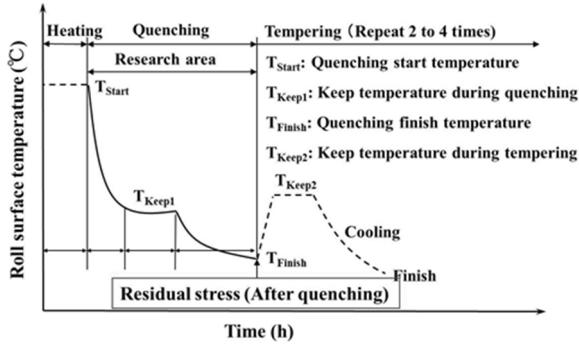


Fig.5 Heat treatment processes for composite roll

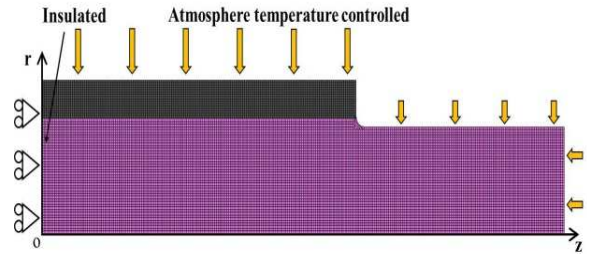


Fig.6 FEM model of composite roll

#### 4 RESULTS AND DISCUSSION OF COMPOSITE ROLL

Fig.7 shows the stress history of composite roll during quenching process. In Region I, the roll is cooled from the uniform temperature  $T_{Start}$ , in the meantime the surface tensile stress increases continuously because of rapid cooling on the roll surface. In Region II, in respect of temperature of  $T_{EP}$ , roll surface changes into elastic-plastic from plastic while roll centre is still in elastic. Meanwhile, stress on roll surface moves from tension to compression. After that, thermal contraction in roll centre becomes larger than the one on the surface, resulting in the decrease of compressive stress in the centre. Accordingly, tensile stress on surface has a peak value then reverses to compression. As cooling continues to the temperature  $T_{Pearlite}$ , pearlite transformation starts from the place that near the interface and expands to the centre. Due to the pearlite transformation, the compressive stress in the centre is reversed to tensile stress rapidly, and jumped back to compressive stress after reaching the peak.

In Region III, owing to the high temperature in the roll centre, the roll centre is further contracted, which leads to stresses state interchanged from tension to compression on roll surface and from compression to tension in roll centre. Until cooling to the  $T_{Keep1}$ , both surface and centre stresses increase continuously. When keeping at  $T_{Keep1}$ , the thermal contraction difference decreases due to the temperature gradient decreasing, contributing to the decrease of stress both surface and centre. At the temperature of  $T_{Bainite}$ , bainite transformation occurs on surface, causing volumetric expansion, and surface compressive stress increases as followed. To balance the surface compressive stresses in the roll interior, the centre tensile stress also increases. After the bainite phase transformation, the centre thermal contraction becomes larger than surface thermal contraction and the Young's modulus increases with decreasing of temperature. Eventually, both surface and centre residual stresses increase continuously.

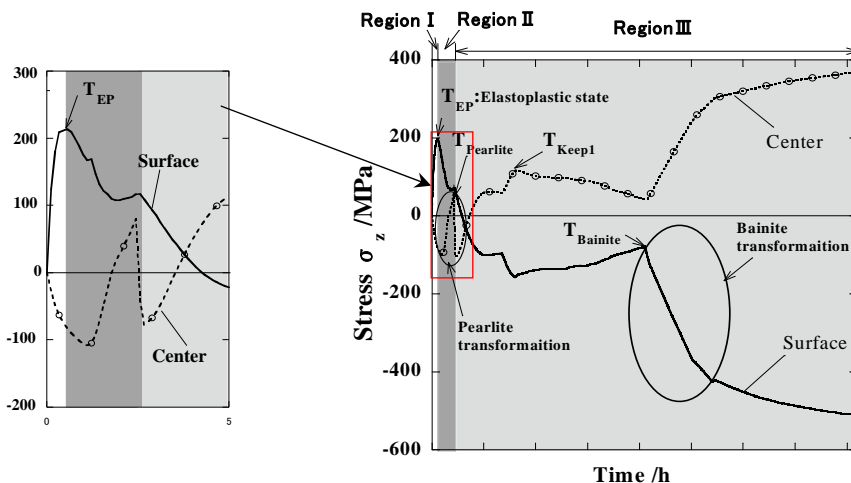
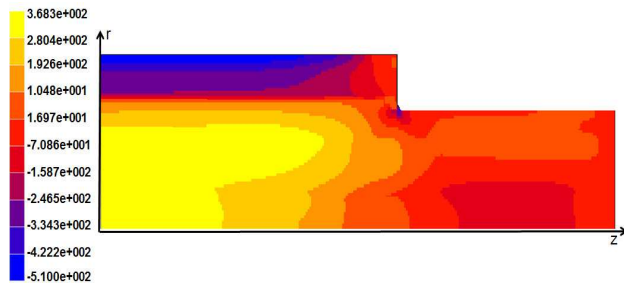
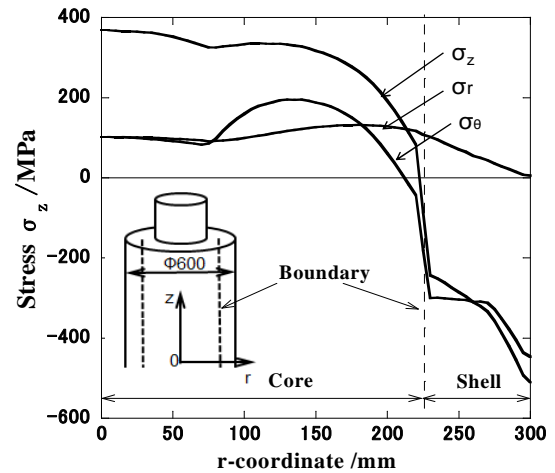


Fig. 7 Residual stress  $\sigma_z$  of composite roll during quenching process



**Fig. 8** Distribution of  $\sigma_z$  of composite roll after quenching process



**Fig. 9** Distribution of  $\sigma_z$ ,  $\sigma_\theta$  and  $\sigma_r$  at the central cross section

Fig.8 shows the distribution of  $\sigma_z$  after quenching process. According to the result, the compressive stresses appear on roll surface and the tensile stresses appear in roll centre, which is similar to the single material rolls. It can be found that the residual stresses are much large than the ones of single material roll. Fig.9 shows the distribution of  $\sigma_z$ ,  $\sigma_\theta$  and  $\sigma_r$  at central cross section where  $z=0$ . It can be seen that  $\sigma_z$  range from -510MPa to 368MPa,  $\sigma_\theta$  range from -446MPa to 102MPa,  $\sigma_r$  range from 5MPa to 102MPa. This residual stress distribution is similar to the results of alloy roll published by Y. Sano, T. Hattori and M. Haga [4]. However, the maximum tensile stress 368MPa in roll centre is still larger than the previous result and the maximum compressive stress 510MPa on roll surface tends to be larger as well. Differences in previous discussions are mainly resulted from the effect of tempering and the difference of core material.

## 5 CONCLUSIONS

In this paper, for composite rolls using for hot steel rolling mill, the residual stress distribution during quenching process has been investigated by FEM. The generation mechanisms of residual stress for single material roll and composite roll have been discussed. The results of current study can be summarized as follows.

- (1) Prediction of residual stress of composite roll during quenching is realized by FEM with low cost, high accuracy and efficiency compared to experimental measurement. The compressive stress appears at the shell while the tensile stress appears at the core.
- (2) The generation mechanism of residual stress during quenching process has been discussed and summarized, which is beneficial for understanding and controlling the residual stress.

Considering the effects of subsequent tempering and the difference of inner material, the simulation result of residual stress are large than the result of alloy roll published in previous. Therefore, the effect of tempering process should be discussed and investigated in the future studies.

## 6 REFERENCES

- [1] M. Shimizu, O. Shitamura, S. Matsuo, T. Kamata and Y. Kondo: 'Development of high performance new composite roll', *ISIJ International*, 1992, **32**, (11), 1244-1249.
- [2] D. Benasciutti, E. Brusa and G. Bazzaro: 'Finite elements prediction of thermal stresses in work roll of hot rolling mills', *Procedia Engineering*, 2010, **2** (1), 707-716.
- [3] P. J. Withers and H. K. D. H. Bhadeshia: 'Residual stress. Part 1—measurement techniques', *Material Science Technology*, 2001, **17**, (4), 355-365.
- [4] Y. Sano, T. Hattori and M. Haga: 'Characteristics of High-carbon High Speed Steel Rolls for Hot Strip Mill', *ISIJ International*, 1992, **32**, (11), 1194-1201.