

FEM Analysis of Stress on Roll Surface Black Oxide Layers Exfoliation in Hot Strip Rolling

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To understand the mechanism of formation and exfoliation, black oxide layers were investigated, and the effects of stress on the exfoliation were analyzed by finite element method (FEM). The roll surface on which black oxide layers form is composed mainly of Fe_3O_4, which is caused by the oxidation of the roll material itself. Cracks form and are easily propagated along M_3C- and M_7C_3-type carbides, which leads to further cracking along M_3C and M_7C_3 carbides as a result of contact stress fatigue produced by cyclic mechanical stresses that normally occur during the rolling process. Thermal fatigue of the roll surface is produced by the thermal cycles created alternately by contact with the hot strip and the cooling water on the roll. The generation and propagation of cracks in the black oxide layers during rolling is promoted by circumference compressive stress at roll surface. Under this stress, the exfoliation of the black oxide layers happens on the roll surface.

Keywords black oxide layers, FEM, hot strip rolling, roll, stress

1. Introduction

During hot strip rolling, contact between the steel strip and the work roll results in the formation of a thin, adherent oxide layer on the surface of the work roll, a surface that is referred to in the general literature as a black oxide layer.[1] The formation and exfoliation mechanisms of black oxide layers are of the utmost importance because the structural integrity of the roll surface and, more importantly, the quality of the steel strips are conditioned by the contact between the steel strip, through the scale formed on its surface, and the work roll, through the black oxide layers. Other work and references have discussed previously the mechanisms of black oxide layer formation and exfoliation on the work roll surface.[2–7] The effects of stress on the roll surface of black oxide layer exfoliation are not well understood.

Based on these general considerations, the formation of the black oxide layers on the roll surface and the effects of stress on the black oxide layer exfoliation by finite element method (FEM) were investigated. The purpose of the present study was to examine further the effects of stress on the mechanism of oxide exfoliation on high chromium iron roll, which will be beneficial in improving the surface quality of strip steels generated by the black oxide layers on the roll surface in hot strip rolling.

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2. Experiment of the Black Oxide Layer Formation

2.1 Experimental Materials

The specimens (20 mm × 30 mm × 30 mm) used in the present study were taken from the high chromium cast iron work rolls and SPHC (Japanese steel grade, 3.0 mm × 50 mm × 20 mm) strip steel from slabs rolled in 2050 mm of Shanghai Baosteel hot mill. The chemical composition of the work roll and slab are given in Table 1. The tensile strength of the work roll was 470 MPa; the hardness is given in Table 2.

2.2 Experimental Method

An Oxford ISIS energy dispersive X-ray (EDX) spectrometer was used to measure the chemical composition of the black oxide layers on the roll. The appearance and cracking characteristics of black oxide layers were observed with an optical AHM-I-HL microscope and a Cambridge S360 scanning electron microscope (SEM). An MHT-1 microhardness tester was used to measure the hardness of the carbides in the black oxide layers. The composition of the slab surface oxidation was analyzed with a Cambridge S360 energy spectrum.

2.3 Experimental Results

The black oxide layers formed and the exfoliation of work roll surface are shown in Fig. 1. The photograph was taken from the F2 finishing work roll of a 2050 mm Shanghai Baosteel hot strip mill. Figure 2 shows the phase composition of the oxide layers obtained by means of Oxford ISIS SEM. It can be seen that many cracks were formed in the surface of the roll, particularly during exfoliation. To elucidate the composition and oxide type, microhardness testing was used. The morphology of the microstructure, microhardness values, and carbide types are given in Table 3.

It is clear that the main composition of the layers was Fe_3O_4. To verify this conclusion, the layers and matrix were analyzed by means of Oxford ISIS EDX spectrometer. The

Table 1 Chemical Composition of the High Cr Rolls and Slab Investigated, wt.%

Material	C	Si	Mn	P	S	Ni	Cr	Mo	Other
Roll	2.70	0.56	1.01	0.036	0.008	1.32	17.60	1.21	...
Slab	0.16	0.077	0.710	0.024	0.010	...	...	...	0.019

Table 2 Hardness of Roll

Specimen	Hardness (HS)
1	69
2	69
3	70
4	70

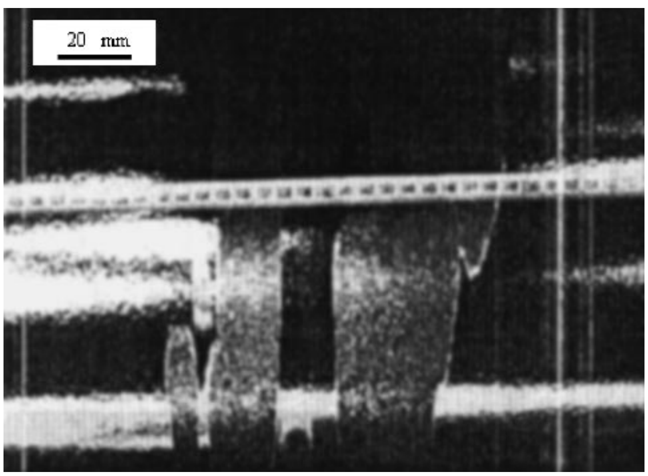


Fig. 1 Black oxide layer exfoliation on the roll

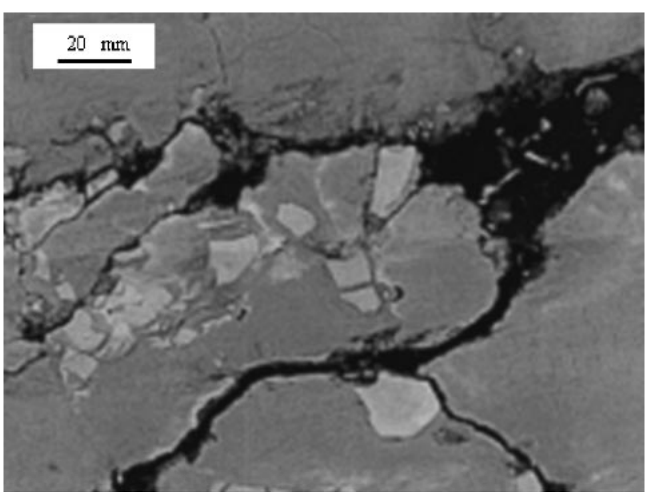
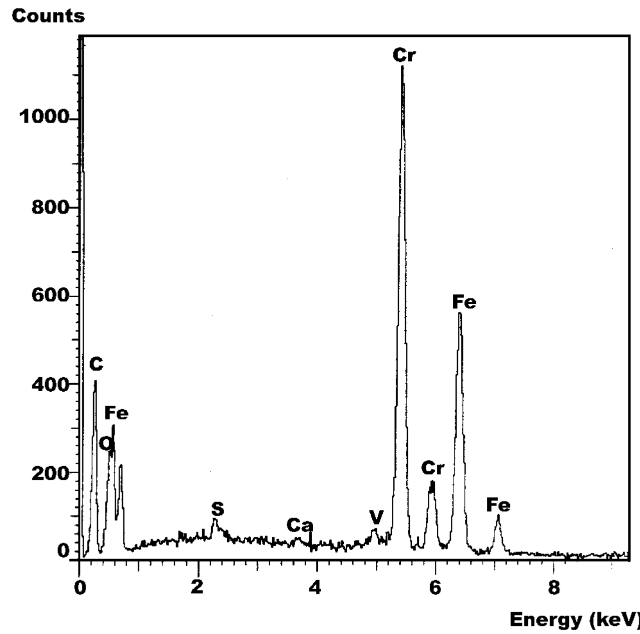


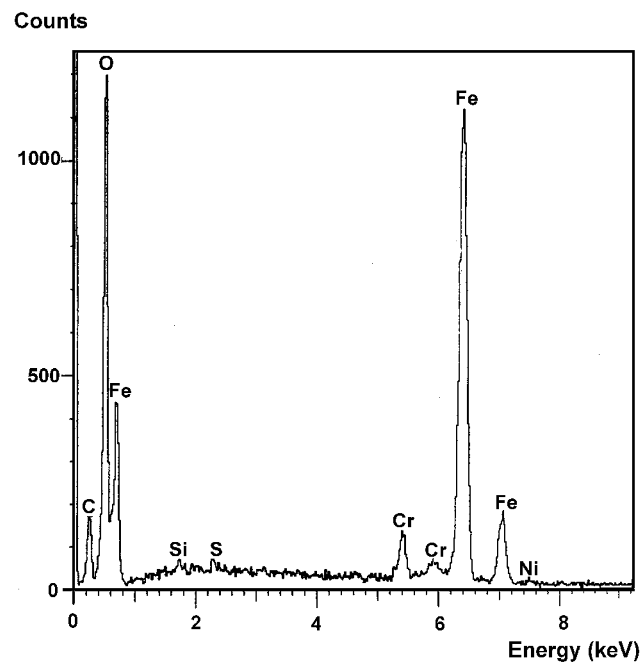
Fig. 2 Micrograph showing phase composition of oxide layers

Table 3 Morphology, Microhardness, and Carbide Type of Oxide Layers: M = (Fe, Cr, Mo, W, . . .)

Morphology	Load, g	Microhardness	Carbide Type
Big block shaped	50	927	M_3C
Block shaped	100	1288	M_7C_3
Rosette (graphite)	50	178	Ferrite (Matrix)
Big gray block shaped	50	450	Fe_3O_4

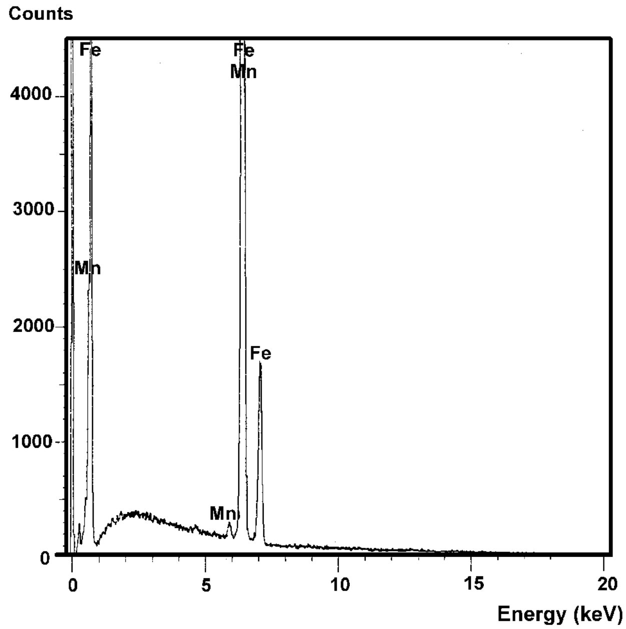


(a)

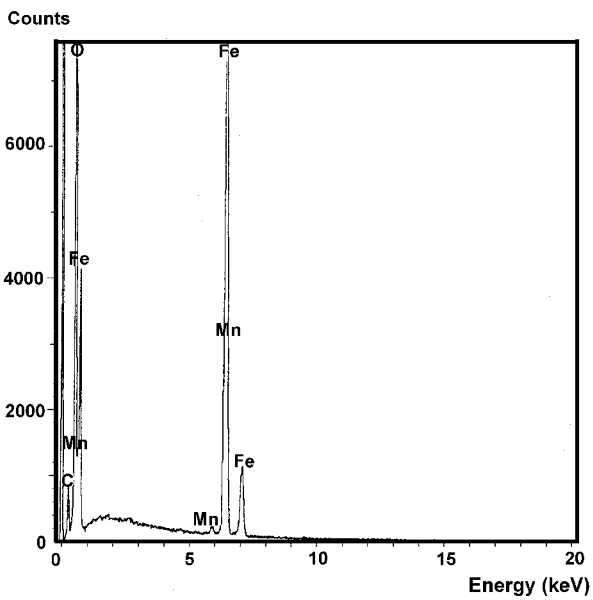


(b)

Fig. 3 Energy dispersive spectrogram of **(a)** oxide layers on the roll surface and **(b)** roll matrix



(a)



(b)

Fig. 4 Energy dispersive spectrogram of **(a)** slab matrix and **(b)** slab surface

energy spectrogram of the roll surface oxidelayers and roll matrix are shown in Fig. 3(a) and 3(b), respectively.

To distinguish the oxide layers of the slab and the black oxide layers of the roll surface, the slab oxide layers were investigated. The composition of the slab oxide layers consisted mainly of Fe_2O_3, which was detected by means of Cambridge S360 EDX spectrometer. The energy spectrograms of the slab matrix and the slab surface are shown in Fig. 4(a) and Fig. 4(b), respectively.

In accordance with previous work,[8,9] it is concluded that the oxide layers on the roll surface in the early stands are

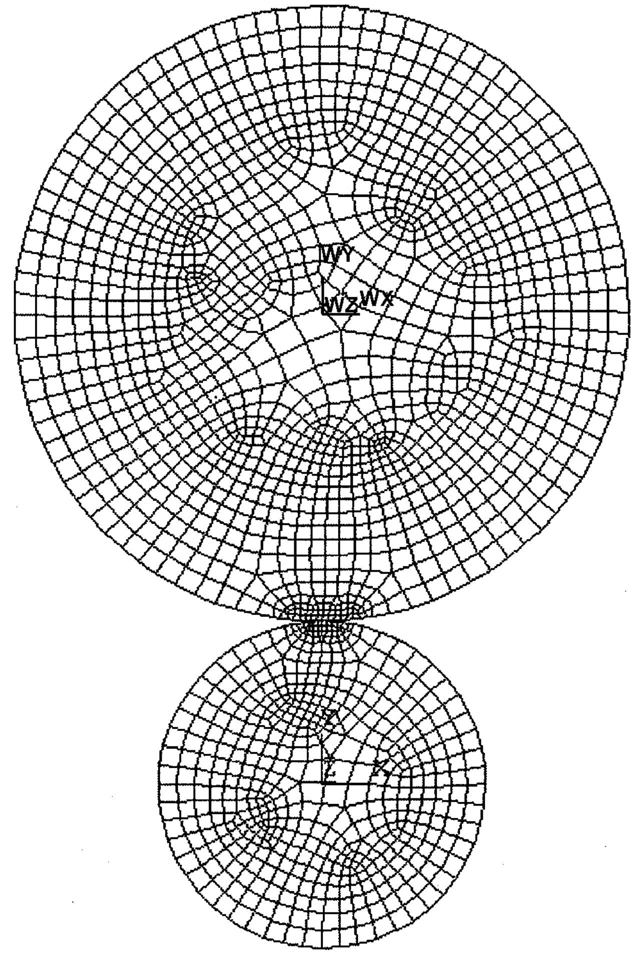


Fig. 5 FEM mesh of the work roll and the backup roll

caused by oxidation of the roll material itself, owing to the high chromium content. This oxidation takes place in the roll bite and may be affected primarily by the following: 1) roll material, 2) the grade of steel, 3) the temperature of the steel, 4) contact time, 5) rolling loads, 6) friction between the roll and strip surface, and 7) cooling of the roll surface.

3. Stress Analysis of Black Oxide Layer Exfoliation

3.1 Analytical Conditions

In this work, ANSYS5.5 software was used to analysis the stress effecting the black oxide layer exfoliation on the surface of work roll. The model that was used in this analysis is shown in Fig. 5. The element type is Structural Solid PLANE 42, and its element number is 2728. The elements of contact parts between the backup roll and the work roll were divided into small segments to increase analytical accuracy. The model investigated is a backup F2 finishing work roll and backup roll of a 2050-mm Shanghai Baosteel hot strip mill. The rotation velocity of work roll was 48r/m and rolling pressure is 11200kN. The material rolled was SPHC steel. The thickness of the strip entry was 24 mm and the exit entry 14 mm. The analytical conditions are shown in Table 4.

3.2 Analytical Results and Discussion

The program was developed by the authors using APDL language to analyze the contact stress field between the work and the backup roll. In this article, Hertz stress and shear stress were discussed. Figure 6 shows the Hertz stress distribution. It is clear that if two mill rolls are pressed together with their axes parallel under a uniform specific contact force, there is a complex system of stresses both at the region of contact as well as throughout the cross-section of the rolls. At the region of contact, local elastic flattening takes place, over which a semi-elliptical distribution of contact compressive stress exists. On the surface of the roll, the maximum and the minimum stress values are 412 Mpa and 31.3 Mpa, respectively.

Figure 7 shows the principal types of shear stress. The major shear stresses occur along the line connecting the roll centers and are oriented at 45 degrees to this line. They vary from 0 at the point of contact, increase to a maximium value, and attenuate again with increasing depth below the roll surface. As the two rolls rotate, the stresses at this point increase from 0 to a maximum value of 223 Mpa and decrease to 0 again as the point passes under the contact line.

Table 4 Analytical Conditions

Items	Work Roll	Backup Roll
Roll material	High chromium iron	Forged steel
Young's modules (Pa)	3×10^{11}	2.8×11^{11}
Density (N/mm^3)	7850	7800
Poisson's ratio	0.3	0.3
Diameter (mm)	825	1450
Friction coefficient	0.3	0.3

In hot strip rolling, the roll surface is exposed to very severe and complex friction conditions that are related to the temperature, stress, the materials, and the atmosphere; therefore, a great variety of tribological phenomena can appear. Contact stresses and thermal stresses are the main factors affecting the exfoliation of black oxide layers from the roll surface. Contact stresses occur in the roll's surface, and thermal stresses are created by temperature gradients during rolling in a mill stand. First, as a result of thermal expansion, additional compressive stress occurs on the roll surface, which originally was exposed to considerable pressure, followed by a chilling effect caused by the cooling water, such that compressive stress creates the formation of microscopic hot cracks. For an initial stretch of time, the roll surface stays smooth because of the abrasion occurring in the working roll gap and between the backup and the work rolls. Then, fatiguing of the roll surface layers occurs as a result of the cyclic mechanical stresses that normally occur during the rolling process and thermal fatigue of the roll surface as a result of the thermal cycles created alternately by contact with hot strip and cooling water of the roll. As the exposure to thermo-

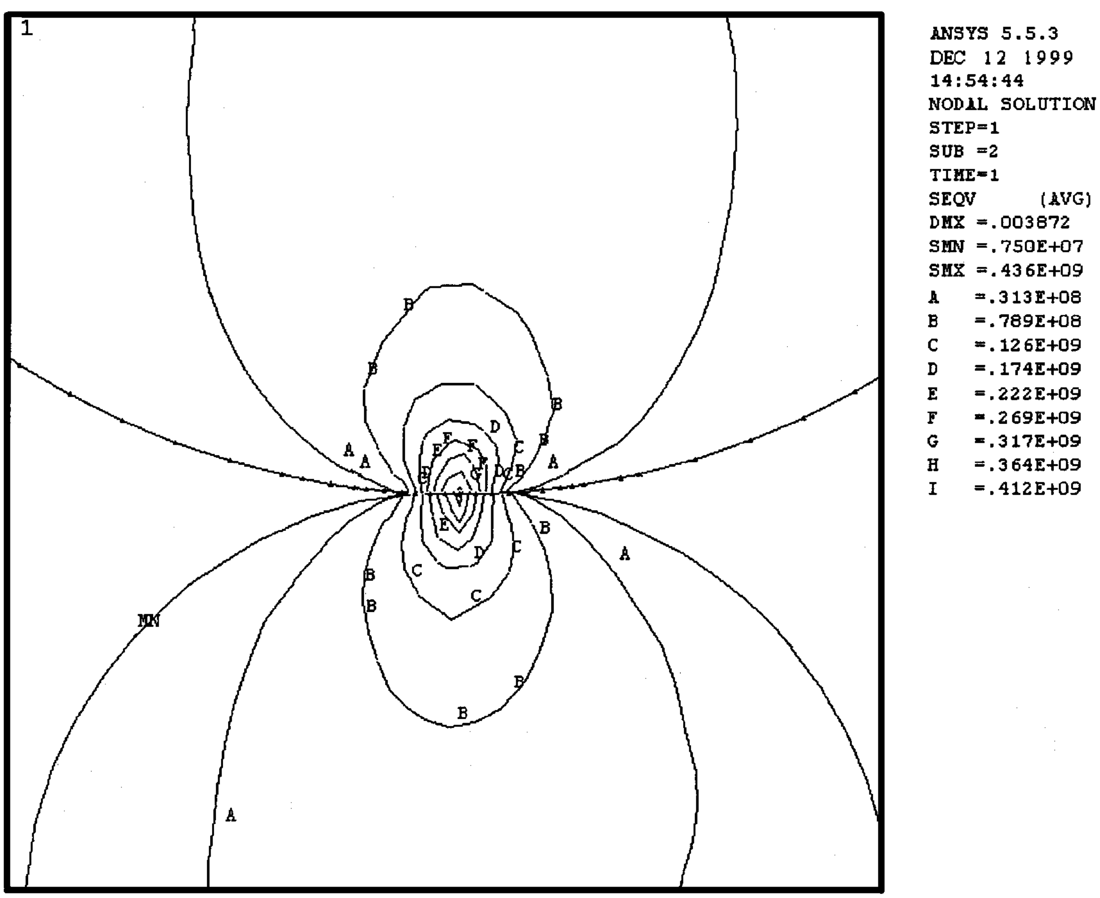


Fig. 6 Hertz stress between work roll and backup roll

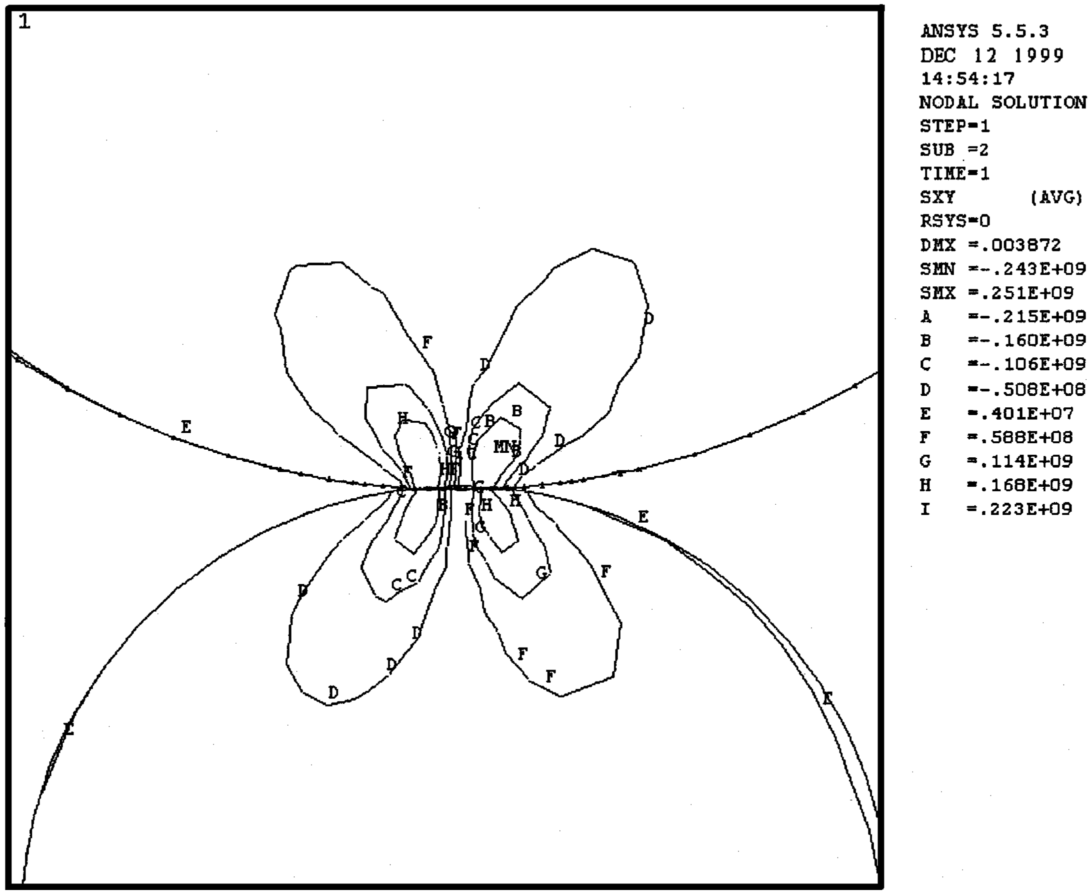


Fig. 7 Shear stress between work roll and backup roll

mechanical alternating stress continues, the cracks increase in size, and in addition to the hot cracks perpendicular to the roll surface, cracks parallel to it also appear. Thus, as warping and shear-induced displacement occur immediately beneath the surface, the roll surface develops a certain roughness, causing an oxide layer exfoliation to fall from the surface of a work roll.

4. Conclusions

The following conclusions can be drawn from the present investigation of formation and FEM analysis of stress on exfoliation of the black oxide layer on high chromium rolls in hot strip rolling. Black oxide layers on the roll surface are composed mainly of Fe_3O_4, which is caused by the oxidation of the roll material itself. The cracks are formed and are easily propagated along M_3C and M_7C_3 type carbides, which leads to further crack growth along M_3C and M_7C_3 carbides.

The generation and propagation of the crack for the black oxide layers during rolling is promoted by circumferential compressive stress at the roll's surface. Under this stress, the contact and thermal fatigue of the black oxide layers on the roll surface are produced by cyclic mechanical stresses and thermal cycles created alternately by contact with hot strip and cooling water of the roll. Exfoliation of the black oxide layers then occurs on the roll surface.

Acknowledgments

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