Application of a High Chromium Steel to Roughing Work Rolls for Hot Strip Mills

Hisashi HIRAOKA, Yoshihiro KATAOKA,¹⁾ Kouji YUDA,²⁾ Kazuyuki TANIGUCHI, Mikio SASADA and Itaru HISHINUMA³⁾

Iron & Steel Research Laboratories, Kawasaki Steel Corporation, Kawasaki-cho, Chuo-ku, Chiba, Chiba-ken, 260 Japan.

1) Iron & Steel Research Laboratories, Kawasaki Steel Corporation, Kawasaki-cho, Handa, Aichi-ken, 475 Japan.

2) Chita Works, Kawasaki Steel Corporation, Kawasaki-cho, Handa, Aichi-ken, 475 Japan.

3) Mizushima Works, Kawasaki Steel Corporation, Kawasaki-dori, Mizushima, Kurashiki, Okayama-ken, 712 Japan.

(Received on April 20, 1992; accepted in final form on July 17, 1992)

High-chromium (Hi-Cr) iron rolls have good wear resistance, but have certain disadvantages in their application to roughing mills. The influence of C and Cr contents on material and mechanical properties were examined.

The dendritic structure of the material changes with C and Cr contents, with the structure of lower C and Cr steel being larger than that of higher C and Cr iron. Hot hardness and wear resistance do not depend on C and Cr contents, while the mechanical wear of these materials decreases with increasing hardness. The thermal shock resistance decreases with decreasing Cr content.

Using Hi-Cr steel rolls instead of Hi-Cr iron rolls in a hot strip roughing mill, accidental slippage was prevented by their rougher surface and better performance obtained by increasing hardness.

KEY WORDS: work roll; high chromium steel; high chromium iron; hot strip mill.

1. Introduction

Many materials for work rolls have been modified in hot strip mills to satisfy the requirements for better surface quality and reduced cost of hot-rolled sheet. High-chromium (Hi-Cr) iron rolls (2.6–2.8% C, 16–18% Cr) were first applied to the former stands of finishing trains about ten years ago in Japan. This iron demonstrated strong resistance to wear and the surface deterioration of the work rolls, and rolls made of this material have been more widely used than conventional Adamite steel rolls. Hi-Cr iron rolls have recently been applied to the second part of the stands in roughing mills. While wear resistance has doubled, the frequency of accidental slippage occurring between the work rolls and sheet has also increased. This may be due to the increasing hardness and carbide quantity of these iron rolls compared to Adamite steel rolls.

Hi-Cr steel (0.7–1.4% C, 8–14% Cr) rolls have been used in the second part of roughing at the majority of hot strip mills in North America and Europe, and the advantage of these Hi-Cr steel rolls have been reported.^{1–4)} However, the data concerning the properties of Hi-Cr steel rolls were inadequate to prove their applicability to roughing mills. Even Hi-Cr iron roll was not viewed as advantageous in Japan during the 1970's when it was the major material used for former stands of finishing mills in Europe. The material of a work roll has to be selected according to the rolling

conditions and mill configuration. Generally, the wear resistance of rolls are closely related with the volume fraction of carbide. The wear resistance of Hi-Cr steel is uncertain, the volume fraction of carbide being less than that of Hi-Cr iron.

Carbon and chromium are the most effective elements forming the carbide which contribute to the wear resistance of Hi-Cr steel and iron rolls. Depending on the proportion of chromium content to carbon content, three types of carbides are formed: M_3C , M_7C_3 and $M_{23}C_6$. Carbides of the M_7C_3 type are considered the most preferable of these for rolls, and Hi-Cr iron rolls with a chromium–carbon ratio of 7:1 have been applied to mills.

The influence of the carbon and chromium contents is examined, and the optimum chemical composition is proposed for roughing mills. The results of the application of Hi-Cr steel rolls to a roughing mill are also discussed.

2. Experimental Procedure

2.1. Materials

The materials were melted in a high-frequency induction furnace and poured into sand molds, in which a chiller was set at the bottom. The weight of each ingot was about 20 kg and the shape was a “Y” block of 30 mm thickness.

Table 1 shows the chemical composition range of the

Table 1. Chemical composition range of the specimens.

	C	Si	Mn	P	S	Ni	Cr	Mo
Max.	2.8	1.1	0.8	0.02	0.013	1.3	22.0	2.0
Min.	0.8	0.9	0.6	0.01	0.005	1.0	6.9	1.8

Fig. 1. C and Cr contents of specimens in the Fe-C-Cr phase diagram at room temperature. Compositions can be classified into three groups: Cr/C=7, 11 and 15.

Fig. 2. Schematic diagram of the thermal shock testing apparatus.

Hi-Cr iron and steel used, while the contents of carbon and chromium are shown by a phase diagram in **Fig. 1**. The compositions of these materials can be classified into three groups by the chromium-carbon ratio: Cr/C=7, 11 and 15.

After heat-treating the ingots, test blocks were cut out at a position which is 30 mm from the chiller for microscopic observation.

2.2. Mechanical Properties

A hot hardness test, wear test and thermal shock test were conducted. The test specimen for hot hardness was $35 \times 35 \times 35 \text{ mm}^3$. Rockwell hardness HRC was measured from room temperature to 1023 K with the increment of 50 or 100 K.

The wear was measured with an Ohgoshi wear testing machine (modified Spindel⁵⁾ type) without lubrication. Specimens were $50 \times 20 \times 10 \text{ mm}^3$, and the rotary disk in a tool steel was 30 mm in diameter and 3 mm in thickness. The slipping rate was from 0.1 to 4.3 m/s, and slipping distance and final load were 600 m and 130 N, re-

Fig. 3. Optical microstructures of typical Hi-Cr iron and steel.

spectively.

Figure 2 shows a schematic diagram of the thermal shock testing machine.⁶⁾ The size of each specimen is $55 \times 40 \times 15 \text{ mm}^3$ and the rotary disk made of tool steel is 350 mm in diameter and 30 mm in thickness. Each specimen was pressed on the rotary disk under a load of 1 500 N for 15 sec. The contact face was then quenched by water immediately after the specimen was separated from the rotary disk, and several cracks were induced by the thermal shock. After tests each specimen was cut parallel to the slipping direction at the widest crack, and the depth and interval of cracking were measured in the cross section.

3. Results and Discussion

3.1. Microstructure and Dendritic Structure

The volume fraction of eutectic carbide decreases with decreasing carbon and chromium contents. **Figure 3** shows typical examples of the microstructure of Hi-Cr iron (2.6% C, 18% Cr) and steel (1% C, 11% Cr), eutectic carbide appearing as white rods or particles in the micrographs. The volume fractions of eutectic carbide in the Hi-Cr steel and iron are 5 and 25%, respectively, and the dendritic structure becomes larger with decreasing carbon and chromium. **Figure 4** shows examples of the dendritic structure observed in a composition series with a chromium-carbon ratio of seven.

(a) 1.1% C-7% Cr (b) 1.5% C-10% Cr
(c) 1.9% C-13% Cr (d) 2.8% C-18% Cr

Fig. 4. Effects of C and Cr contents on the dendritic structures for a Cr/C ratio of 7.

While secondary dendrite arm spacing (d_2) had a strong correlation with the contents of carbon and chromium, parameter L indicated stronger correlation with d_2 than the multiple correlation of carbon and chromium. Parameter L is defined by the carbon and chromium contents as Eq. (1) and represents the fraction of eutectic area in the microstructure.

$$L = 15.5 \times \%C + \%Cr \dots\dots\dots(1)$$

The secondary arm spacing was inversely proportional to L as shown in Fig. 5, L decreasing as d_2 increases. With decreasing carbon and chromium contents, d_2 increases. For instance, the dendrite arm spacing of Hi-Cr steel (1% C, 11% Cr) was about twice larger than that

Fig. 5. Relationship between d_2 and parameter L . d_2 was measured from the micrographs.

Fig. 6. Hot hardness at elevated temperature. The material compositions were 1.0% C-10% Cr (Hi-Cr steel) and 2.7% C-18% Cr (Hi-Cr iron).

Fig. 7. Examples of indentations observed after the wear test.

of Hi-Cr iron (2.7% C, 18% Cr). Microscopical wear is more marked in the primary crystal area than in the eutectic area, and a large dendritic structure may be

Fig. 8. Relationship between wear and slip rate. Cr/C ratio is 11.

Fig. 9. Relationship between wear and hardness for several slip rates (S.R.).

advantageous for preventing accidental slippage with its rough surface induced by the microscopical wear.

3.2. Hot Hardness

The hot hardness behavior of each material examined was nearly the same; typical examples of the hardness after heating from room temperature are shown in Fig. 6. Hot hardness can be seen nearly constant up to 673 K, with softening of the material beginning at about 773 K. Above 873 K, the hot hardness decreases linearly with

Fig. 10. Effect of parameter K (estimated volume fraction of carbide) on the wear at a high slip rate of 4.3 m/s.

increasing temperature.

The hot hardness of rolls is an important factor for hot rolling. Hi-Cr steel rolls seem to have the same characteristic softening as Hi-Cr iron rolls, even though the microstructure of the two differs.

3.3. Wear

As shown in Fig. 7, features of the indentations created by the wear test vary with the test conditions, the wear in the Ohgoshi test being defined as volume of the indentations. Figure 8 shows the variation of wear with slip rate, where each plot represents the average of three wear data. The mechanism for wear was mechanical abrasion at low slip rates (e.g., 0.1 and 0.3 m/s). Wear decreased with the oxide film formed on the contact surface at a medium slip rate (e.g., 0.6 m/s), and became large with melting at higher slip rates (e.g., 1.5 and 4.3 m/s).

The relationship between wear and hardness is shown in Fig. 9; in general, the two are closely related. However, the wear had no correlation with hardness at a high slip rate, e.g., 4.3 m/s. After several examinations, the wear at a high slip rate correlated with the volume fraction of carbide (K) as shown in Fig. 10, where the value for K was calculated numerically from Eq. (2) as proposed by Maratray *et al.*⁷⁾

$$K = 12.3 \times \%C + 0.55 \times \%Cr - 15.2 \quad \text{..... (2)}$$

Fig. 11. Effect of Cr content on D/W , the ratio of the average depth and interval of cracks after the thermal shock test.

The wear decreased with increasing carbide volume fraction at high slip rates; *i.e.*, under the condition of abrasion with melting.

On the other hand, the wear mechanism for a work roll during hot rolling is mechanical abrasion, so that the wear resistance of a Hi-Cr steel roll does not depend on the volume fraction of carbide, being predictable from its hardness as shown in Fig. 9, while the volume fraction of carbide in Hi-Cr steel is smaller than that in Hi-Cr iron (Fig. 3). Materials with a Cr/C ratio of 11 had good wear resistance (Fig. 9), except for the specimen with a high chromium content of 22%.

3.4. Thermal Shock Resistance

Many short cracks induced by thermal shock were observed in the cross section of specimens. The depth of most cracks in each specimen was influenced by the contact area between the specimen and rotating disk, which depends on the hardness and the volume fraction of carbide. In this investigation, the thermal shock resistance was evaluated by the ratio of the average depth to the average interval of cracks (D/W), which represents the material property for crack propagation. Figure 11 shows the influence of the chromium content on D/W . With increasing chromium content, the D/W decreases, and a small carbide fraction is advantageous to decrease D/W (K of less than 6 in Fig. 11).

It is apparent that the thermal shock is quite sensitive to the volume fraction of carbide, because carbide has low ductility. Furthermore, the influence of chromium content on the thermal shock resistance can be explained by its deformability at high temperature. The tensile strength at high temperature depends on the chromium content as shown in Fig. 12, and decreases with increasing chromium content at the relatively low temperature of 973 K, which may be considered as the effect of strengthening with carbide distribution. At rather high temperature (especially at 1273 K), however, the tensile strength becomes proportional to the chromium content.

Thermal shock resistance is one of the most essential factors for the mechanical properties of work rolls, because the deterioration of a roll surface is caused by small pits which are initiated by cracks. In roughing mills, large cracks and pits which were induced by thermal

Fig. 12. Relationship between the Cr content and tensile strength at high temperatures of 973, 1073, 1173 and 1273 K.

shock were observed on the surface of an Adamite steel roll (1.5–2% C, 1–2% Cr), demonstrating the importance of examining the thermal shock resistance of Hi-Cr steel rolls. High resistance to thermal shocks can be obtained with a high content of chromium. Compared with conventional Hi-Cr iron (2.7% C, 18% Cr), similar or better resistance to thermal shock can be expected in Hi-Cr steel, if the chromium content is kept above 10% (Fig. 11).

4. Application of Hi-Cr Steel to Roughing Work Rolls

Hi-Cr steel rolls with Hi-Cr steel shell and gray cast iron core were applied as a trial to the secondary stands (*i.e.*, from the 3rd to 5th stands) of the roughing mill in a hot strip mill, the chemical composition of Hi-Cr steel being determined from the results of this investigation. Using Hi-Cr steel rolls, the accidental slippage between the rolls and sheet was prevented, and the roll performance was better than that of Hi-Cr iron rolls.

The surface deterioration of rolls becomes worse with increasing of the amount of rolling. Figure 13 shows typical examples of the features of roll surfaces which were observed at the 3rd stand after rolling 60 000 t. While it is apparent that the Hi-Cr steel roll has a rougher surface than the Hi-Cr iron, small pits can be seen on the Hi-Cr iron roll, as shown by the arrows in Fig. 13, whereas none were observed on the Hi-Cr steel roll.

The roughness of the roll surface at the 5th stand after rolling 40 000 t is shown in Fig. 14, where the direction of measurement was perpendicular to the rolling direction. In the Hi-Cr steel, large cyclic peaks can be seen. On the contrary, the surface of the Hi-Cr iron is relatively smooth, the range between peak and trough being small. Stable rolling without slipping was produced by the rough surface of the Hi-Cr steel roll, the average roughness (R_a) of the Hi-Cr steel roll being twice that of the Hi-Cr iron roll. This difference may be related to

Fig. 13. Typical examples of roll surface features observed at the 3rd stand of a roughing mill after rolling about 60 000 t.

Fig. 14. Examples of roll surface roughness observed at the 5th stand of a roughing mill after rolling about 40 000 t. Roughness was measured perpendicular to the rolling direction.

Fig. 15. Comparison of roll profile with roll material after long-term operation. These data were measured from the same rolls as those in Fig. 14.

the dendritic structure, since the secondary arm spacing of Hi-Cr steel was nearly twice that of Hi-Cr iron.

In spite of its rough surface, the performance of the Hi-Cr steel roll was better than that of the Hi-Cr iron roll. Figure 15 shows roll wear profiles of the rolls in Fig. 14. In the case of the Hi-Cr steel roll, the maximum wear depth was reduced from 0.32 to 0.25 mm on the upper roll, and from 0.44 to 0.32 mm on the lower roll.

This difference in roll performance was caused by the hardness of the rolls. The maximum hardness of the Hi-Cr iron roll was HsD 70 to prevent slippage. On the other hand, the hardness of the Hi-Cr steel roll was about HsD 80, causing no slippage in normal operation. Consequently, the performance of the Hi-Cr steel roll was better than that of the Hi-Cr iron roll due to the

influence of the hardness on wear as described.

The average performance of the Hi-Cr steel roll on secondary stands of the roughing mills was from 60 000 to 80 000 t/mm (the weight of rolled products per unit diameter loss of a roll), where that of the Hi-Cr iron roll was from 40 000 to 60 000 t/mm.

5. Conclusion

The results can be summarized as follows:

- (1) The secondary dendrite arm spacing of Hi-Cr steel is larger than that of Hi-Cr iron, and inversely proportional to parameter L , the fraction of eutectic.
- (2) The wear of the Hi-Cr iron and steel depends on the wear mechanism. The governing factor is hardness for mechanical abrasion, and the volume fraction of carbide for abrasion with melting.
- (3) The thermal shock resistance is affected by the chromium content in Hi-Cr iron and steel materials. A chromium content above 10% is suggested for a Hi-Cr

steel roll.

- (4) Using the Hi-Cr steel roll instead of the Hi-Cr iron roll in the roughing at a hot strip mill, the roughness of roll surface became large. Then accidental slippage was prevented and the performance was improved with increasing hardness.

REFERENCES

- 1) J. Werquin and J. Bocquet: *Bull. Cercle Étud. Métaux*, **15** (1978) 5, 28.1.
- 2) D. J. Tarney and J. C. Wequin: *Work. Steel Process.*, **21** (1984), 181.
- 3) J. C. Werquin and J. C. Caillaud: *Mech. Work. Steel Process.*, **25** (1988), 311.
- 4) I. Sadler and T. P. Adams: *Mech. Work. Steel Process.*, **25** (1988), 295.
- 5) M. Spindel: *VDI*, **70** (1926), 415.
- 6) K. Sakabe and H. Tabe: *Tetsu-to-Hagané*, **57** (1971), 5, 836.
- 7) F. Maratray, A. Poulalion and P. Rabbe: *Bull. Cercle Étud. Métaux*, (1973), 11.