Development of Cold Rolling Mill Rolls of High Speed Steel Type by Using Continuous Pouring Process for Cladding

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The quality of work rolls that come into direct contact with the steel product has a direct effect on product quality and mill operation. A forged steel with a chromium content of 5 mass% has been conventionally used to meet the requirement of metallurgical structure homogeneity and high hardness for work rolls in cold rolling. Rolls having improved performance are strongly demanded. The authors develop the rolls of high speed steel type by using a continuous pouring process for cladding (CPC process). The characteristics and benefits of the new rolls are summarized as follows. (1) Precipitated hard carbides are utilized to attain a fine cast structure. (2) Low-frequency progressive induction hardening and high-temperature tempering are employed to provide a high hardness of HV 800 or more, a stable structure at elevated temperatures and low residual stress. As a result, the new rolls are improved in dent resistance and crack resistance. (3) When used in rolling operation, the new rolls retain a stable friction coefficient in the roll bite and allow continuous rolling of a large tonnage since their surface roughness decrease is small. (4) The wear of the new rolls is extremely small. A schedule-free rolling operation can be done when the work rolls are lubricated with rolling oil. In this way, high speed steel rolls manufactured by the CPC process exhibit high wear resistance, surface roughness retentivity and crack resistance.

KEY WORDS: rolling mill roll; cold rolling; tool steel; wear; CPC.

1. Introduction

In recent years, steel-rolling technology has been developed to improve the quality of rolled products and pursue the economical operation of rolling mills. In the latter half of the 1970’s, high-performance mills were developed and introduced to achieve remarkable results. The quality of the work rolls that come into direct contact with the steel product has a direct effect on the steel product quality and mill operation. For this reason, rolls having improved performance are strongly demanded. A new type of roll manufactured by a continuous pouring process for cladding (hereafter referred to as CPC process) was developed. Made of a high-carbon high speed steel type material (HSS material) and provided with wear resistance about five times that of conventional rolls, the new rolls are extensively used at the finishing stands of hot strip mills. As a result, the rolls significantly improved the quality of rolled products and enabled the constraints imposed by work rolls in the rolling operation to be relaxed. Today, HSS rolls are produced by various processes including the CPC process, and are supplied for use in various rolling mills.

Forged steel rolls with a chromium content of 5 mass% (%) are used to meet the metallurgical structure homogeneity and extremely high hardness requirements of work rolls in cold rolling. The authors have developed medium-carbon HSS rolls by using the CPC process (CPC rolls) for the purpose of achieving a dramatic improvement in the life of rolls in cold rolling as well. This paper describes the basic concepts, manufacture and application results of the CPC rolls.

2. Needs and Recent Trends for Work Rolls of Cold Rolling Mills

The quality requirements of work rolls in cold rolling have changed with the introduction of continuous lines and new type of rolling mills. Figure 1 shows the change of work roll in contrast with the technical trends in cold rolling.

The continuous tandem cold mill was developed in the early 1970’s, followed by the introduction of continuous processing lines integrated with pickling or continuous annealing lines. As a result, the productivity and product yield increased, tail-out roll defects decreased, and rolled steel quality was improved. When defects like roll marks or heat streaks occur, the resultant damage increases at an emergency stop or strip breakage. It is thus demanded all the
more to keep continuous lines operating in a steady and stable state. The widespread use of continuous processing lines reduced the roll changes necessitated by strip marks of head and tail ends, and made rolled tonnage dependent on roll surface roughening texture or roll surface roughness loss. At the same time, a continuous casting was introduced and a steel material was changed to aluminum-killed steel, then the wear of work rolls increased. A new type of rolling mill, such as 6-high mill, was introduced and the diameter of rolls became smaller, and thus roll service conditions became severer.

As far as roll materials are concerned, a forged steel containing about 1% C and 1.8% Cr was initially the basic composition. The chromium content was increased to 3% and then 5% in the late 1970's. Until about 1980, technology developments centered on the manufacture of rolls of a thicker hardened depth by adding alloy elements that improve hardenability. As a result, the effective use of diameter of rolls increased to approximate 4 inches (about 100 mm). At present, there is a strong demand for higher wear resistance. To meet this demand, some steels contain an increased amount of carbon or alloying elements to improve their wear resistance. These steels are called die steels or semi-HSS steels, and are used only in limited applications.9–11)

As regards the manufacture of rolls, the cleanliness of steel ingots was considerably improved by such processes as vacuum degassing, ladle refining, ladle degassing and electro-slag re-melting (ESR process). The rotary casting process was tried for dendrite size reduction and internal homogenization. The process of building up an ESR shell while rotating the roll (rotational bimetallic ESR process) enables high-alloy HSS composite rolls to be manufactured,12) but has not enjoyed wide acceptance. In terms of heat treatment, the low-frequency induction hardening process increased the hardness and the hardened depth of rolls as noted above.

3. Basic Development Concept and Quality Design of CPC Rolls

The greatest factor for hampering cold rolling operation is the decrease in friction in the roll bite, which destabilizes the rolling operation and frequently necessitates roll changes. This phenomenon is related to the decrease in surface roughness of rolls. It is generally referred to as surface roughness retentivity or wear-resistance in a broader sense of the term. The authors aim at the development of high-performance rolls by the combination of HSS material featuring excellent wear resistance with the CPC process that makes good use of the characteristics and the fine cast structure of medium-carbon HSS material. The development undertakes to achieve the following two items:

1. To achieve long-time optimum friction conditions in the roll bite, thus eliminating the most important operation-inhibiting factor in cold rolling.
2. To take advantage of cast rolls that are strengthened, and practically to apply high-performance rolls to cold rolling.

Table 1 compares the basic design data of the new CPC
rolls with those of conventional rolls. The material properties and manufacture of the CPC rolls are described below.

### 3.1. Material Properties

Hard MC-type and M₆C-type carbides are utilized in a multi-component alloy with chromium, molybdenum and vanadium added, what is called an HSS material, for higher wear resistance. With the improvement in surface roughness retentivity as its major characteristic, these hard carbides are precipitated at the grain boundaries and matrices of the dense cast structure. Vickers hardness of 800 or more is obtained to ensure the desired surface quality of rolled products. To prevent cracks from originating in temper softening attendant on local heating during an in-service slip accident, the structure is also designed to be stable and free from a drop in hardness at elevated temperatures.

### 3.2. Manufacture

The CPC process is adopted to manufacture the new composite roll. With the CPC process, alloy additions are not limited substantially in the casting of HSS materials, the solidification and cooling rates are high, and a fine cast structure is obtained with solidification progressing from the surface toward the center or in the radial direction of the roll. The CPC process is schematically depicted in Fig. 2. The molten shell metal is poured into the gap between the vertically arranged core and the water-cooled mold arranged concentrically with the core. The shell is progressively solidified to be tightly bonded with the core and is intermittently withdrawn downward to form the composite roll. The CPC process features the following three main characteristics:

1. The alloy content of the shell can be easily increased without segregation.
2. The solidification and cooling rates are high, and a fine cast structure is obtained.
3. The core can be made of strong, tough and rigid steel.

The solidification pattern of the CPC process is schematically illustrated compared with that of the ESR process, the most popular manufacture process for work rolls, in Fig. 3. The CPC process features three to five times higher solidification and cooling rates than the ESR process, and thus produces a finer cast structure. With the ESR process, the solidification front moves in the axial direction of the roll or upward in Fig. 3, and the dendrites grow large. When the roll is put to use, these grown dendrites appear on the surface of the roll and decrease the surface roughening retentivity. With the CPC process, the solidification front moves in the radial direction of the roll or in the radial direction in Fig. 3. No grown dendrite structure appears in the roll surface, and a fine cast structure develops to improve the surface roughening retentivity of the roll. The progressive induction heat hardening process that provides high-temperature heating and high-rate cooling is adopted as a heat treatment method to obtain high hardness. Tempering is performed at a temperature above 773 K to ensure micro-structural stability.

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**Table 1.** Basic design of high speed steel roll manufactured by CPC process (CPC roll) for cold rolling.

| Roll type | CPC roll | Conventional |
|-----------|----------|--------------|
| Shell material (mass%) | 1%Cr, Mo, V | 1%Cr-5%Cr |
| Structure | Carbide M₆C | Matrix Martensite |
| Hardness | HV800 (HS90) | HV800 (HS95) |
| Grain size | ≤100 µm | About 400 µm |
| Manufacture process | CPC-Casting | ESR-Forging |
| Solidification rate | 15~25 mm/min | 3~5 mm/min |
| Heat treatment | Quench Induction heat | Induction heat |
| | Temper | 773K ≤ | 473K |

Note: ESR: Electro-slag re-melting, CPC: Continuous pouring process for cladding.

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**Fig. 2.** Schematic drawing of continuous pouring process for cladding (CPC process).

**Fig. 3.** Sectional drawings near solidifying region of continuous pouring process for cladding and electro-slag re-melting process.
4. Manufacturing Technology for CPC Rolls

The practical rolls with a diameter of 583 mm (minimum available diameter of 483 mm), barrel length of 1,420 mm and overall length of 3,365 mm are manufactured by the CPC process. The macrostructure of the body section of the CPC roll is shown in Fig. 4. In Fig. 5, the microstructure of the shell of the CPC roll is shown in comparison with the microstructures of a conventional 5% Cr forged steel roll and an HSS roll manufactured by the conventional ESR process. The cast structure of the CPC roll is such that hard eutectic $\text{M}_6\text{C}$ type carbides (visible as white ribbons in the micrograph) are distributed at the boundaries of 100 $\mu$m or finer grains and that nodular MC-type carbides are dispersed within the grains. This is in sharp contrast with the microstructure of the HSS roll manufactured by the ESR process that is elongated by the forging operation and exhibits large grains of about 400 $\mu$m and coarse eutectic carbide. Figure 6 shows the hardness distribution on the cut section of the CPC roll. The target hardness of at least HV 800 is achieved throughout the shell. The residual stress of the roll surface is a compressive stress of 700 MPa or less and is lower than that of the conventional rolls. Figure 7 shows the sectional stress distribution measured by the disk method in which the roll is machined to small cubic elements through thin disk and the residual stress is estimated with its released strains. Figure 8 compares the elevated-temperature hardness of the CPC roll to that of the 5% Cr forged steel roll. The 5% Cr forged steel roll is generally tempered at a temperature below 473 K, since its hardness

| Material          | 5 mass% Cr | High speed steel |
|-------------------|------------|------------------|
| Casting           | Electro-slag remelting (ESR) | Electro-slag remelting (ESR) | Continuous pouring process for cladding (CPC) |
| Forging           | Forging    | Forging          | No-forging |
| Microphotograph   | ![Microphotograph](image) | ![Microphotograph](image) | ![Microphotograph](image) |
| Carbide (Fraction%) | $\text{M}_6\text{C}$ type (0.5%) | $\text{M}_7\text{C}_3$, MC type (1%) | $\text{M}_6\text{C}$, MC type (5%) |

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**Fig. 4.** Sectional macrostructure of high speed steel roll manufactured by CPC process.

**Fig. 5.** Microstructures of high speed steel roll manufactured by CPC process and conventional rolls.

**Fig. 6.** Hardness distribution at cross section of high speed steel roll manufactured by CPC process (roll diameter 580 mm).

**Fig. 7.** Residual stress distributions at cross section of high speed steel roll manufactured by CPC process (roll diameter 580 mm).

**Fig. 8.** Hardness at elevated temperature of high speed steel roll manufactured by CPC process (CPC roll) and conventional roll.
begins to decrease as temperature exceeds 473 K. The CPC roll is tempered above 773 K, since it retains its high hardness at higher temperatures.

5. Performance Evaluation of CPC Rolls

To determine whether or not cast HSS material is applicable to cold rolling mill rolls, its basic tribological properties, especially wear resistance, were evaluated and studied in the laboratory.

Using a high-speed rotating wear testing machine as an experimental apparatus, a wear resistance experiment was conducted under the conditions shown in Table 2, and the wear phenomena were observed by scanning electron microscopy (SEM). The roll materials used in the experiment were 5% Cr forged steel and the newly developed cast HSS material. The experiments were done with setting two levels of initial surface roughness for each material.

Figure 9 shows the relationship between the wear loss and the number of revolutions. The relationship between the surface roughness retentivity and the number of revolutions is given in Fig. 10. The cast HSS material is superior to the 5% Cr forged steel in surface roughness retentivity (ability to retain the initial surface roughness). When the initial surface roughness is equivalent to bright finish (small roughness) or scratch finish (comparatively large roughness), the wear resistance (index for evaluating both the mass change and surface roughness retentivity) of the cast HSS material is higher than that of the 5% Cr forged steel.

Figure 11 shows a typical wear appearance of friction surfaces after 20,000 revolutions. The conventional 5% Cr forged steel decreases in the number of streaks (grinding marks) with decreasing surface roughness and increasing flatness. The cast HSS material also decreases in the number of streaks with decreasing surface roughness, but the amount of decrease is small, and new depressions are formed where the surface is flattened. The depressions in the surface of the cast HSS material are considered to have resulted from the loss of carbides. These depressions are believed to contribute to the desired surface roughness retentivity.

6. Results of Application to Actual Rolling Operation

The CPC process made the new composite rolls with a shell of HSS material containing chromium, molybdenum and vanadium. The CPC rolls were used in the five-stand tandem cold mill shown in Table 3, mainly for tinplate production, and were investigated for operability and surface roughness retentivity. The CPC rolls were ground with a ceramic type wheel and were applied to actual rolling, and

![Fig. 9. Amount of wear of roll materials in tribological experiment.](image)

![Fig. 10. Roughness of surface of roll materials in tribological experiment.](image)

![Fig. 11. Secondary electron images of surface of roll materials after experiment.](image)
they were evaluated against conventional 5% Cr forged steel rolls.

Figure 12 shows the change in the forward slip ratio with CPC rolls at the No. 1 stand. Figure 13 shows the change in the inter-stand tension between the No. 2 and No. 3 stands at the No. 3 stand. The forward slip ratio and inter-stand tension are used as indexes for evaluating the surface roughness retentivity. When the surface roughness decreases and the friction in the roll bite drops below the optimum value, the forward slip and the inter-stand tension decrease and slip between strip and roll occurs.

On the No. 1 stand, the forward slip ratio of conventional 5% Cr forged steel rolls steeply declined with the progress of rolling. The rolls needed to be changed when the rolled tonnage reached 600 t. When the rolled tonnage reached 2500 t, on the other hand, the CPC rolls still retained their high forward slip and were capable of stable rolling. As shown in Fig. 12 their forward slip ratio dropped twice at about 1000 and 1900 t rolled during the rolling operation, but the reason for this was the influence of the decline in the surface roughness of the 5% Cr forged steel rolls used on the succeeding No. 2 stand. Then the forward slip ratio returned to normal when the rolls on No. 2 stand were changed. As shown in Fig. 13 the inter-stand tension between the No. 2 and No. 3 stands sharply declined with the progress of rolling with the conventional 5% Cr forged steel rolls in the No. 3 stand to such a degree that the rolls had to be changed at an early time. When the rolled tonnage reached 1700 t, the CPC rolls still assured a high inter-stand tension and were capable of stable rolling.

Figure 14 shows the change in the surface roughness of the rolls on the No. 1 stand. The surface roughness of the CPC rolls decreases a little after rolling a large tonnage and keeps a certain value. This is probably because their metallurgical structure is fine and the cast structure containing carbides at the grain boundaries effectively works to retain the initial surface roughness.

In cold rolling, the work rolls wear and decrease in surface roughness locally at the strip edges. This local wear and reduced surface roughness are transferred to the strip being rolled, and deteriorate the surface quality of the product. For this reason, the rolling order of strip products in width is strictly controlled from wider strip to narrower strip. This often restricts the operation in cold rolling. The CPC rolls with excellent wear resistance were used in the No. 3 stand with oil lubrication to roll wider strip after narrower strip as shown in Fig. 15. The CPC rolls succeeded in
this rolling without any surface quality problem. The surface appearance of one of the CPC rolls and a micrograph of the contact portion with the strip edge are shown in Fig. 16. The CPC roll exhibits some strip edge marks formed after the switch from narrow strip to wide strip, but no strip edge marks at all before the narrow-to-wide strip switch. This means that the CPC rolls are damaged little on the surface where they come into contact with the strip edges. Minute deposits are seen in the micrograph of the contact portion with strip edge. They are similar to the deposits with oil streaking.

The depth of cracks caused by rolling accidents is shown in Table 4. Cracks of the CPC rolls are shallow and the crack resistance is improved.

Table 4. Crack depth caused in roll surface due to rolling accident of high speed steel roll manufactured by CPC process (CPC roll) and conventional roll.

| Roll type | CPC roll | Conventional 5mass%Cr roll |
|-----------|----------|-----------------------------|
| No.1 stand| 0.52mm   | 1.78mm                      |
| No.4 stand| 0.54mm   | 3.63mm                      |

Note) Values show average diameters of shaving off for crack removal.

Fig. 16. Surface texture and micrograph of contact portion with strip edge after rolling of high speed steel roll manufactured by CPC process (CPC roll).

Fig. 17. Benefits expected from introduction of high speed steel roll manufactured by CPC process (CPC roll).

7. Future Outlook

The laboratory tribological property evaluation and actual rolling operation test confirmed that the new CPC rolls have significantly high wear resistance and surface roughness retentivity. They are also improved in crack resistance by a stable microstructure at elevated temperatures and reduced residual stress. The benefits expected from the introduction of the CPC rolls in cold rolling are summarized in Fig. 17. The new rolls eliminate the greatest operational constraints, or roll wear and reduction in the friction coefficient in the roll bite. The alleviation of roll damage has enabled the rolling of strip products in increasing order of width, which in turn has enabled:

1. Long-time continuous rolling
2. Schedule-free rolling

The resultant reduction in the number of roll changes is expected to simplify roll management, achieve labor reductions and increase the flexibility of rolling operations.

8. Conclusions

The CPC process makes it possible to manufacture composite rolls with a shell of an HSS material for cold rolling. The following findings are obtained:

1. The CPC rolls exhibit the cast structure in which nodular MC-type carbides are dispersed intragranularly and eutectic M₆C-type carbides are distributed at the boundaries of 100 μm or finer grains.

2. Low-frequency progressive induction heat hardening provides the CPC rolls with a Vickers hardness of 800 or more and high enough dent resistance.

3. Tempering at a high temperature of 773 K or more provides a stable structure at elevated temperatures, and restricts the residual surface stress to the compressive stress of 700 MPa or less. As a result, the CPC rolls are improved in crack resistance against a rolling accident like slip.
When the CPC rolls are used in actual rolling operations, the reduction in their surface roughness is small and the surface roughness keeps a certain value owing to their dense cast structure.

The CPC rolls retain a stable friction coefficient in the roll bite and allow the continuous rolling of a large tonnage between roll changes.

The CPC rolls have extremely small wear. A schedule-free rolling operation can be done when the work rolls are lubricated with rolling oil.

The CPC rolls exhibit good wear resistance, surface roughness retentivity and crack resistance, and expect to ease the roll-imposed constraints in cold rolling.

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