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High Speed Steel Type Cold Rolling Mill Roll by Continuous Pouring Process for Cladding

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Abstract

Because strip rolling work is performed through the roll, the quality of a roll which contacts a product directly influences product quality and productivity. The improvement in roll performance has been intensely needed. The authors developed the high speed steel roll manufactured by the CPC process (Continuous Pouring process for Cladding) in order to provide a fast improvement in a life of roll. The feature and the obtained result of the new roll are summarized as follows. (1) It has a fine casting microstructure with the hard eutectic carbide; (2) High hardness over 800HV, the stable structure at high temperature and low residual stress are achieved because of the application of progressive low frequency induction hardening process and high temperature tempering. As a result, the resistance to roll marks and cracking in incident is improved; (3) When rolling operation is presented, the developed roll maintains the initial surface roughness much longer and holds the stable friction coefficient within a roll bite. The rolling campaigns have been greatly improved 3 to 5 times comparing to the conventional 5 mass% chromium forged steel roll; and (4) Wear loss of a roll is also very small and the width inversion (schedule-free) operation in using oil lubricants is attained. Thus, this roll demonstrates a high performance in wear resistance, small fall of surface roughness, and the resistance to incident, and eases the restrictions conditions of a roll reason sharply in a cold rolling field. In addition to the improvement in productivity, a flexible rolling operation, the simplification and laborsaving of roll management, and the increase in efficiency of a physical distribution are expected.

1. Introduction

Steel rolling technologies have developed in response to strict quality requirements such as ultra-thin gauge products, improved dimensional accuracy and better surface quality and, at the same time, in pursuit of economical operation. Since the second half of the 1970s, in particular, various high performance rolling mills have been developed, and their introduction brought about drastic advancements in product quality and operation performance. In parallel to the above, in view of the facts that the rolls directly contact rolled products and that their quality directly influences the quality of the products and the ease of rolling operation, demands for improved performance of

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rolls have become louder and louder.

In 1988, the authors developed a composite high speed steel roll for hot rolling[1,2], wherein high-carbon high speed steel (HSS) material was cast around a steel-base core through the continuous pouring process for cladding (CPC). The developed roll exhibited excellent wear resistance, about 5 times that of conventional rolls, and, as a result, it came to be widely used as the work rolls of finish mill stands of hot strip mills. The developed roll significantly relaxed the rolling operation restrictions for roll reasons and, as a result, made schedule-free rolling and other operation improvements practicable. Futhermore, it greatly contributed to quality enhancement of rolled products.

For the work rolls of cold rolling mills, on the other hand, because of homogeneous metallographic structure and extremely high hardness required of them, 5 mass % Cr (hereinafter written simply as 5% Cr) forged steel rolls manufactured by the electro-slag remelting (ESR) process have generally been used . Like in the field of hot rolling, the demand for a longer service life of a cold work roll is very strong and to meet demand, the HSS roll manufactured by the ESR process with alloying elements added to the 5% Cr steel material and other new rolls were proposed, but no substantial improvement in cold rolling operation has been realized.

In view of the situation, the authors tackled the task of developing an HSS roll for cold rolling by the CPC process for the purpose of achieving a drastic improvement in the service life of the roll for cold rolling, and the roll thus developed has come to be used in commercial production. This paper reports the basic development concept of the roll, the characteristics of the developed roll and the results of its application to commercial production.

2. Requirements for Work Roll for Cold Rolling

New cold rolling processes and new types of cold rolling mill were developed and as a result of these changes in the field of cold rolling technologies, the quality requirements for work rolls have also changed.

In the cold rolling process in the first half of the 1970's, continuous tandem cold rolling came into being and many integrated lines linking tandem cold rolling with pickling and/or continuous annealing have since been built to enhance productivity and production yield[3]. As the integrated lines became a common practice, the occurrence of roll bruises such as top marks and end marks and the frequency of rolling accidents such as strip breakage were remarkably reduced. Advancements in lubrication technology, on the other hand, decreased the occurrence of roll marks of strip surfaces caused by foreign objects falling between a roll and a rolled material. Owing to these changes, the frequency of so-called unscheduled roll changes in the middle of a sequential rolling schedule was drastically decreased and, accordingly, rolling tonnage of a roll campaign became to be determined rather by surface roughening and the wear of surface finish of rolls than the roll bruises. Thus, the ability to withstand a long time continuous rolling by the enhancement of wear resistance (the ability to retain initial surface roughness) came to be required of a rolling roll.

Recently the quality requirements for a cold work roll have become still more demanding, as heavy reduction rolling and high-speed rolling have come to be widely practiced for further improving productivity. Apart from these, diversification of user needs has accelerated the trend of small lot production of widely varied products and as a result, schedule-free cold rolling has come to be considered as a possible solution, as was the case in hot rolling.

3. Basic Development Concept and Quality Design

Aiming mainly at improving the ability to retain initial surface roughness, the authors proceeded with the development of a new high performance roll for cold rolling through the combination of the HSS material excellent in wear resistance and the CPC process, which makes the most of the excellent characteristics of the material by forming a fine casting structure. **Table 1** outlines the basic design of the new roll in comparison with a conventional roll. The material characteristics and manufacturing process of the new roll are explained specifically below.

3.1 Material Characteristics[4]

For the purpose of improving wear resistance, a multi-component alloy containing Cr, Mo and V, a kind of the so-called HSS material, was selected, making use of the MC and M_6C type hard carbides in the alloy. In order that the new roll had an improved ability to retain surface roughness as its most conspicuous characteristic, the hard carbides were made to crystallize at the boundaries of fine grains of the alloy's casting structure. For securing dent resistance of the roll so as to obtain good product surface quality, a target hardness was set in terms of Vickers hardness, which is an indicator of the resistance against dents, at 800 HV or higher, the level equivalent to the conventional 5% Cr forged steel rolls. Further, in order to suppress the occurrence of cracks of the roll caused by temper softening due to local heating (to 573K or so)[5] on the occasions of slippage during rolling, high temperature tempering at 773K or higher was applied for stabilizing the structure.

3.2 Application of CPC Process

The CPC process, which is practically free from restrictions on the addition of alloying elements and capable of achieving a high solidification and cooling rate, thus obtaining a fine casting structure in the casting of HSS materials, it was selected and on this basis, the new roll was designed as a composite roll. The outline of the CPC process is illustrated in **Fig. 1**. By the process, a composite roll is manufactured by: pouring molten steel of the material of an outer shell into a gap between a core set vertically and a water-cooled mold set co-axially to the core; having the molten steel weld to the core and solidify continuously; and drawing the core downwards intermittently and the outer shell thus formed . This process has the following four advantages:

1) An outer shell having high contents of alloying elements can be obtained easily without segregation.
2) A high solidification and cooling rate 3 to 5 times that of the ESR process is achieved and as a result, the obtained casting structure is fine and highly homogeneous from the outer surface to the depth corresponding to the scrap diameter.
3) The coarse dendritic wear pattern running in the axial direction as

Table 1 Basic development design of HSS roll by CPC for cold rolling

Kind of roll		HSS roll by CPC	5% Cr forged steel roll
Shell material		1%C-Cr, Mo, V	1%C-5%Cr
Structure	Carbides	M_6C, MC	M_7C
	Matrix	Martensite	Martensite
Hardness		800 HV (HS 90) ≦	800 HV (HS 95) ≦
Crystal grain size		≦ 100 μm	Approx. 400 μm
Manufacturing process		CPC	ESR + forging
Solidification rate		15 - 25 mm/min	3 - 5 mm/min
Heat treatment	Quenching	Progressive low frequency induction heating	Progressive low frequency induction heating
	Tempering	773K ≦	≦ 473K

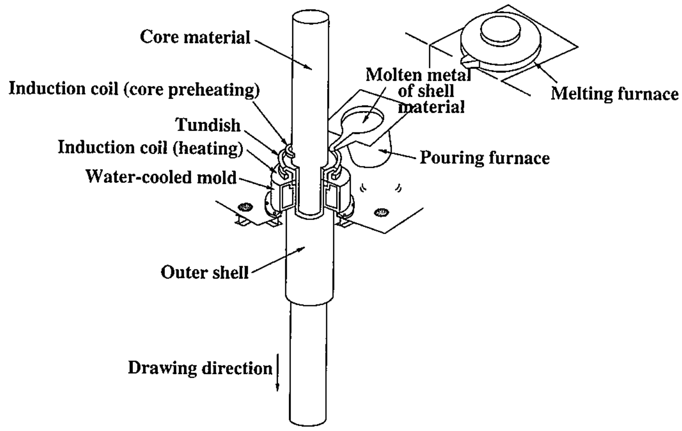


Fig. 1 Schematic illustration of continuous pouring process for cladding (CPC Process)

seen with the rolls manufactured through the ESR process is not formed, because the solidification of a cast material proceeds in the radial direction (substantially in right angles to the roll surface).

4) Thanks to the combination of a steel-base core having high toughness and rigidity with the HSS material of the outer shell, the forging process for enhancing strength can be eliminated, thus the fine casting structure is preserved without being disturbed by the forging.

4. Development of Roll Manufacturing Technology and Roll Quality

Rolls for actual use having a diameter of 583 mm (a scrap diameter of 483 mm), a barrel length of 1,422 mm and a total length of 3,365 mm were manufactured by the CPC process. The structural characteristics of the HSS material of the outer shell of the developed roll are shown in **Fig. 2** in comparison with those of the conventional 5% Cr forged steel roll and HSS roll, both manufactured by the ESR process. In the casting structure of the developed roll, hard eutectic carbides (whitish strings in the photo) are distributed at the boundaries of fine crystal grains 100 μm or less in size, and granular MC type carbides are dispersed in the crystal grains. In contrast, in the roll made of the same HSS material but by the conventional ESR process , its crystal grain size is as large as 400 μm or so, and coarse eutectic carbides are observed, and the metallographic structure is stretched by forging.

Thanks to the high alloying, the percentage area of carbides, which enhance wear resistance (the ability to retain surface roughness), was increased to 5% in the developed roll, significantly greater than that in conventional rolls. Coarse carbides, which deteriorate grindability, were not observed in the new roll, either. As a result, the developed roll is excellent in both wear resistance and grindability. The residual stress at the surface of the new roll is 300 to 600 N/mm² in compression, which is considerably lower than 900 N/mm² or so of the 5% Cr forged steel roll. The new roll is expected to be excellent also in spalling resistance.

Fig. 3 shows the hardness distribution of the developed roll at a cross section. A target hardness of 800 HV or higher was obtained in the entire outer shell to the depth of 50 mm. Another feature seen in the new roll is that there is no drop in hardness at reduced diameters as is the case with conventional rolls, and stable hardness is maintained to the scrap diameter, therefore the roll is expected to maintain its initial performance until it is ground to the scrap diameter. For reference, the above hardness corresponds to HS 90 in Shore hardness. Compared with HS 95 of the conventional 5% Cr forged steel roll, the above value of the new roll is apparently low, but the value of Shore hardness is influenced by the residual stress at the surface of the roll[6], and the apparently lower Shore hardness value of the new roll reflects its lower residual stress.

Table 2 shows the mechanical and thermal characteristics of the developed roll. Since the Young's modulus and thermal expansion coefficient of the new roll are substantially the same as those of the conventional 5% Cr forged steel roll, the crown and other roll profile conditions and operation conditions for the new roll need not be changed from those of the conventional rolls. **Fig. 4** shows the de-

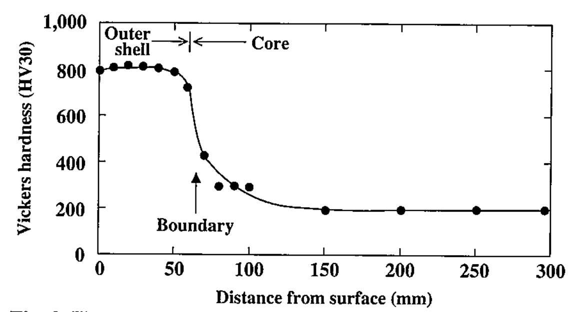


Fig. 3 Hardness distribution at cross section of developed roll

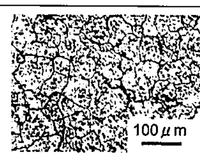
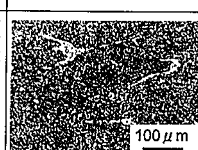
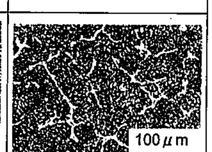
Material	5% Cr steel	High speed steel	
Manufacturing process (casting/forging)	Electro-slag remelting + forging	Electro-slag remelting + forging	Continuous pouring process for cladding (CPC) (Developed roll)
Basic chemical composition (mass%)	1%C-5%Cr	1%C-5%Cr-2%Mo-V,W	1%C-5%Cr-4%Mo-V
Microscopic structure	 100μm	 100μm	 100μm
Type of carbide and percentage area	M_3C 0.5%	M_7C_3, MC 1%	M_6C, MC 5%
Hardness	HS95(800HV)≤	HS95(800HV)≤	HS90(800HV)≤
Residual stress at surface	700-1,000N/mm²	700-1,000N/mm²	300-600N/mm²

Fig. 2 Comparison of shell materials of developed roll (HSS roll by CPC) and conventional rolls

Table 2 Mechanical and thermal characteristics of developed roll

	5% Cr forged steel	HSS by CPC	
		Outer shell: HSS	Core: SCM440
Compression strength(N/mm^2)	3,000	3,500	-
Tensile strength(N/mm^2)	920	1,150	690
K_{IC}($N/mm^{3/2}$)	600	800	-
Young's modulus (N/mm^2)	214,000	215,000	213,000
Rolling fatigue strength(N/mm^2)	2,300	2,600	-
Thermal expansion coefficient at 375K(/K)	11.3×10^{-6}	14.3×10^{-6}	13.9×10^{-6}

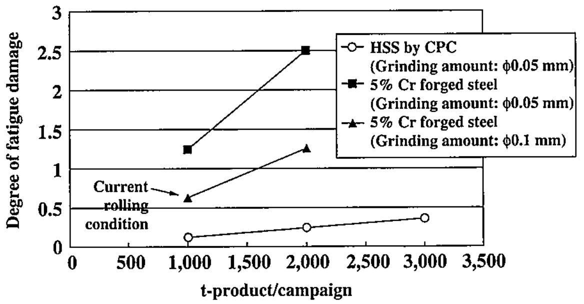


Fig. 4 Comparison of degree of fatigue damage between HSS roll by CPC and 5% Cr forged steel roll

gree of fatigue damage of the new roll calculated on the basis of the rolling conditions at No. 2 stand of 1TCM of Hirohata Works. When the degree of fatigue damage exceeding 1, fatigue fractures are likely to occur. Since the conventional 5% Cr forged steel rolls are used near a degree of fatigue damage of 1 under the present rolling conditions, it is difficult to achieve a significant improvement in t-product/mm (an increase in t-product/campaign or a remarkable decrease in the amount of grinding). On the other hand, it is clear in the figure that the developed roll is excellent in fatigue resistance and capable of well withstanding long rolling campaigns. Thus, the new roll is expected to be applicable to high rolling load mills using small diameter work rolls, in which accumulated fatigue of rolls easily causes problems.

5. Performance Evaluation of Developed Roll Material[4)]

For investigating whether the HSS cast material was applicable to the rolls for cold rolling, the fundamental tribological characteristics of the material were evaluated using a high-speed rolling wear tester, focusing especially on wear resistance. In addition, the wear condition of the cast HSS material after the wear test was investigated by SEM observation. The generally used 5% Cr forged steel material and the developed HSS material were tested, and two kinds of surface finishing, equivalent to the bright and scratch finishing of rolls, were applied to both the materials.

Fig. 5 shows the relation between the mass lost by wear and the number of revolutions, and **Fig. 6** the relation between the ratio of retained surface roughness (where the initial surface roughness is 100%) and the number of revolutions. It was confirmed in the test results that the cast HSS was superior to the 5% Cr forged steel in the ratio of retained surface roughness (the ability to keep initial surface roughness), and that the former was superior to the latter also in wear resistance (the indicator of both the change in mass and the

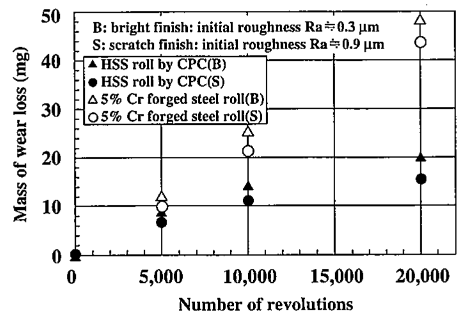


Fig. 5 Amount of wear loss at cold rolling wear test

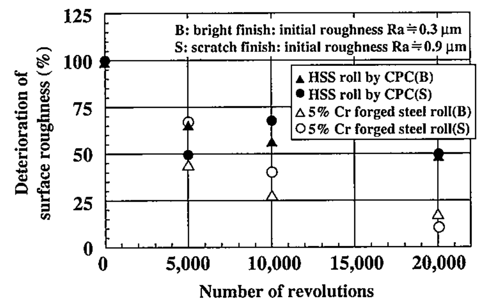
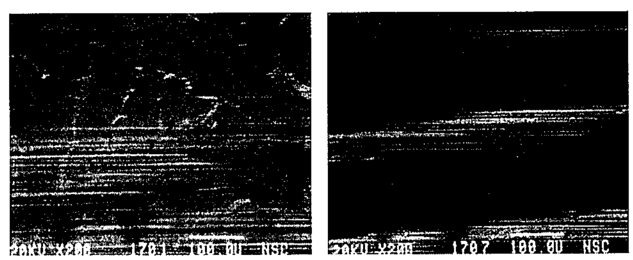


Fig. 6 Deterioration of surface roughness at cold rolling wear test



(a) High speed steel (b) 5% Cr steel

Fig. 7 SEM micrographs of test piece surfaces after cold rolling wear test

ratio of retained surface roughness) in both the cases of the bright and scratch surface finishing.

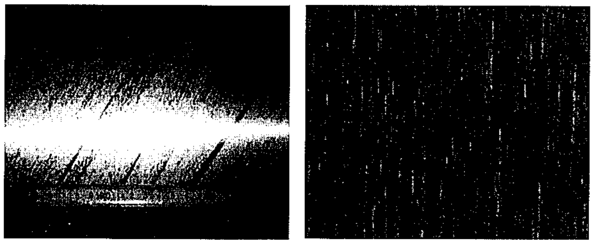
Fig. 7 shows examples of the wear of contact surfaces after 20,000 revolutions. Whereas the linear irregularities (grinding asperity) on the surface of the 5% Cr forged steel gradually disappeared and flattened as its surface roughness decreased, the number of linear irregularities of the cast HSS disappearing after the same number of revolutions was smaller than that of the 5% Cr forged steel. Furthermore, new depressions were formed at the portions where the linear irregularities were flattened. It is suspected that the new depressions of the cast HSS material were formed by the carbides falling off the surface and that the phenomenon contributes to the property of the developed material to keep the ratio of retained surface roughness at a high level.

6. Results of Application to Commercial Production

The rolling performance and surface roughness retaining ability of the developed roll were investigated through the use in commercial rolling operation at 1TCM (a 5-stand tandem mill for tinplates) of Hirohata Works, in comparison with the conventional 5% Cr forged steel roll.

6.1 Grindability

Ceramic grinding wheels were used for grinding the tested rolls. **Fig. 8** shows the surface textures of ground rolls. A good surface



(a) Chalk test result (b) Enlarged image of ground texture

Fig. 8 Ground texture of HSS roll by CPC

texture usable at the rear stands of a tandem mill was obtained. A technology has already been established for finishing the developed roll by automatic grinding within the same time as it takes for finishing the conventional 5% Cr forged steel roll. The surfaces of the developed rolls used in No. 1 stand were finished to an initial roughness of Ra 1.2 μm by shot blasting. The shot blasting was done under the same condition as that for the conventional 5% Cr forged steel roll, and the same surface quality was obtained. The surfaces of the developed rolls used in No. 3 stand were finished to an initial roughness of Ra 0.5 μm by grinding.

For reference, electric discharge texturing for dull treatment was also tested and it was confirmed that the developed roll could be treated by the method under the same condition as applied to the 5% Cr forged steel roll.

6.2 Results of Rolling Tests[4)]

6.2.1 Ability to Retain Surface Roughness

In the test at the commercial rolling mill, the developed HSS roll by CPC was set, in a pair, in either No. 1 or No. 3 stand.

The rolling performance of the developed roll was evaluated in terms of the ability to retain surface roughness; when the roll was tested at No. 1 stand, the forward slip ratio at the stand was used as the indicator of the ability to retain surface roughness, and, when it was tested at No. 3 stand, the inter-stand tension between Nos. 2 and 3 stands as the indicator of the same. The results are shown in **Figs. 9 and 10**, respectively.

When the conventional roll was used at No. 1 stand, the forward slip ratio at the stand fell quickly as rolling tonnage increased and the work rolls had to be changed after rolling 600 t. With the developed HSS rolls, in contrast, the forward slip ratio remained high even after rolling 2,400 t, and the rolling operation remained stable. It has to be noted that the falls in the forward slip ratio seen in Fig. 9 at accumulated tonnages of 1,000 and 1,700 t, approximately, were caused by the deterioration of surface roughness of 5% Cr forged steel rolls used at No. 2 stand, behind No. 1 stand where the developed rolls were tested, and the forward slip ratio recovered after the conventional rolls were replaced with newly ground rolls. At No. 3 stand, likewise, when the conventional rolls were used, the inter-stand tension between Nos. 2 and 3 stands fell quickly as rolling tonnage increased and the rolls had to be changed after rolling a small tonnage; when the developed rolls were tested, the inter-stand tension remained sufficiently high even after rolling 1,700 t and the rolling operation remained stable.

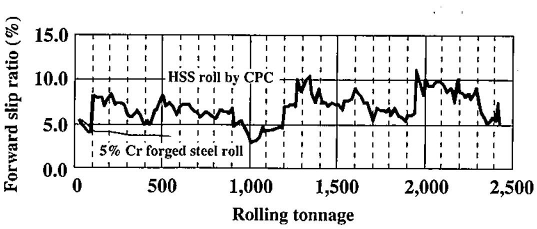


Fig. 9 Change of forward slip ratio at No. 1 stand

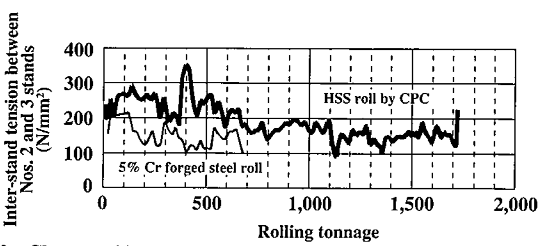


Fig. 10 Change of inter-stand tension between Nos. 2 and 3 stands with rolls tested at No. 3 stand

Fig. 11 shows the change of surface roughness of rolls before and after the use at No. 1 stand. The developed roll showed only a little deterioration of surface roughness after rolling a large tonnage, and the roughness converged on a certain level. It is suspected that the above result was brought about by the fine casting structure having the carbides at crystal grain boundaries working effectively for maintaining the surface roughness. Further, it was confirmed through microscopic observation of the roll surface texture after rolling that the surface roughness initially given to the developed rolls was maintained without significant deterioration through rolling of a large tonnage, as seen in **Fig. 12**.

6.2.2 Accident Resistance

While it is true that the occurrence of accidents has been drastically reduced thanks to the enhancement of operation technologies, accident resistance is still one of the most important properties required of a rolling roll, because the large grinding amount required for recovering the damage inflicted by an accident greatly increases roll consumption. **Fig. 13** shows the grinding amounts after rolling accidents during commercial operation. As seen in the figure, the grinding amounts of the HSS roll by CPC after rolling accidents are

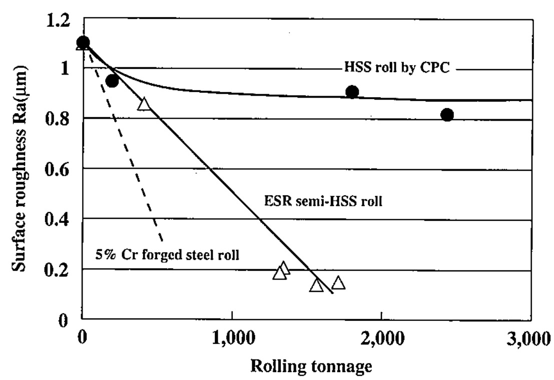
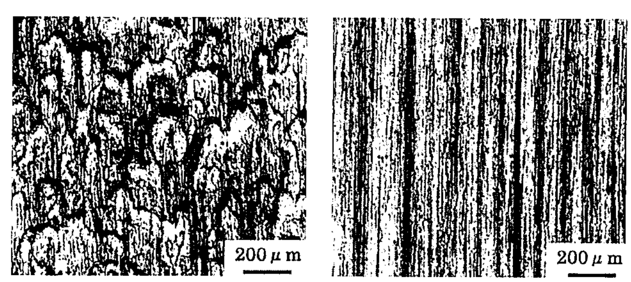


Fig. 11 Change of roll surface roughness with rolls tested at No. 1 stand



(a) Surface texture of dull-finished developed roll, after rolling 2,400 t at No. 1 stand

(b) Surface texture of scratch-finished developed roll, after rolling 1,700 t at No. 3 stand

Fig. 12 Comparison of roll surface textures after rolling

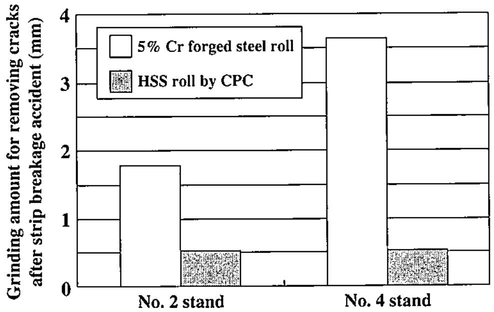


Fig. 13 Average grinding amount for removing cracks after strip breakage accident

extremely small. No significant change in structure was observed after etching of the developed roll, which attested that the accident resistance of the developed roll was significantly improved by applying high temperature tempering for stabilizing the structure. Note that the cracks of the developed roll can be detected by ultrasonic testing (surface wave technique) and thus the same crack control as that for the conventional 5% Cr forged steel rolls is enough also for the developed roll.

6.2.3 Width Inversion Rolling Test

It is the normal practice of cold rolling to schedule rolling sequence from wider strips to narrower ones and strictly abide by the sequence, because wear and the deterioration of surface roughness occur locally at the portions of rolls corresponding to strip edges, and the damaged roll surface condition is transferred to rolled strips, deteriorating their surface quality. This rolling schedule, however, has made it difficult to improve productivity. In view of the situation, a test of width inversion rolling to roll wider strips after narrower strips was carried out using the developed rolls excellent in wear resistance. The developed rolls were set at No. 3 stand of the tandem cold mill and used for rolling following the width sequence shown in **Fig. 14** including inversion in strip width. In the test, the work rolls of all the other stands were changed before width inversion. As a result, good surface quality of the rolled strips was secured when the developed roll was used.

Fig. 15 shows the appearance of the roll surface after the test and a micrograph of the roll surface portion corresponding to an edge of a rolled strip. While the mark of the edge of the strip after the width inversion (wider strip) is identifiable as such in the photo (a), the mark of an edge of the narrower strip (780 mm in width) before the width inversion is not, which fact demonstrates that the damage to the surface of the developed roll caused by the edge of a strip is very little. In the micrograph of the roll surface portion corresponding to a strip edge, a small amount of sticking material is observed, but this is only a trifle sticking material as seen in heat streaks and its influence on product quality is negligibly small. This result seems to point to a possibility of schedule-free rolling becoming a normal practice also in the field of cold rolling.

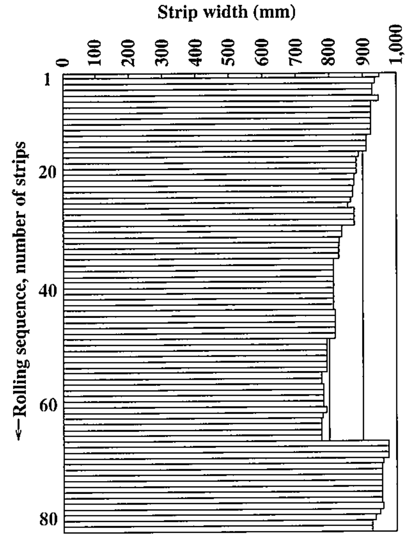
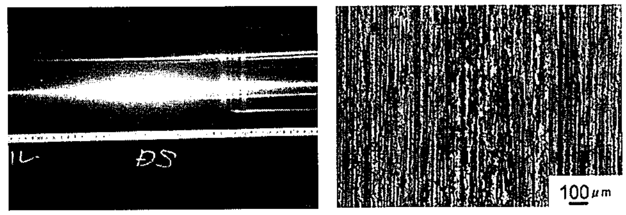


Fig. 14 Rolling sequence at width inversion rolling test



(a) Roll surface texture (b) Roll surface condition at edge-marked portion

Fig. 15 Roll surface texture after width inversion rolling test

7. Summary

A high performance composite roll for cold rolling has been developed, wherein an outer shell of an HSS material is formed through the CPC process. Because of the fine casting structure of the outer shell, in which a great amount of fine hard carbides are dispersed, the developed roll exhibited a very excellent ability to maintain surface roughness, 3 to 5 times that of a conventional 5% Cr forged steel roll, in the application to commercial rolling operation. It also proved successful in a test of width inversion rolling, making schedule-free rolling a probability in the field of cold rolling.

Additionally, the excellent ability of the developed roll to maintain initial surface roughness is expected to make a roll without Cr plating usable at the rolling stands where the use of Cr-plated rolls has been essential for securing wear resistance. Furthermore, since the great amount of dispersed carbides is expected to improve the friction pick-up resistance of the roll, the authors intend to test and evaluate the developed roll in high-speed, heavy reduction rolling and stainless steel rolling.

The application of the developed roll significantly relaxes the operation restrictions for roll reasons and as repercussion effects, it is expected to increase productivity, simplify roll management, save manpower, and make rolling operation flexible and materials handling effective.

References

1) Hashimoto, M. et al.: Nippon Steel Technical Report. 71, 48 (1991)
2) Tanaka, T. et al.: 39th MWSP Conf. Proc, ISS. 35, 435 (1998)
3) Kitahama, M.: Nishiyama Memorial Technical Lectures, Nos. 148-149, 1993, p.165
4) Hashimoto, M. et al.: CAMP-ISIJ. 13, 1065-1067 (2000)
5) Yarita, M. et al.: Tetsu-to-Hagané. 67(14), 2152 (1981)
6) Furukawa, M. et al.: Tetsu-to-Hagané. 65(4), 260 (1979)