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Wear Resistance of a Cr_3C_2-NiCr Detonation Spray Coating

Jun Wang, Baode Sun, Qixin Guo, Mitsuhiro Nishio, and Hiroshi Ogawa

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Coatings can be applied to surfaces to improve the surface characteristics over those of the bulk properties and are widely used in tribological applications either to reduce wear and/or to modify friction during contact. One of the foremost coating methods for combating wear is thermal spraying. To prolong the life of steel slab continuous casting rolls, Cr_3C_2-NiCr detonation spray coating was processed on the roll surface in a steelmaking plant in China. This article studies the mechanical properties and wear resistance of this coating. The abrasive and dry frictional wear testing were performed using a pin-on-disk tester. Experimental results show that the wear resistance of the coated samples, i.e., coating reduces the risk of seizure compared to uncoated samples, is much better than those of the uncoated steel at room and elevated temperatures with any load and sliding velocity. The coating wear mechanisms under different test conditions are discussed.

Keywords Cr_3C_2-NiCr, detonation spray coating, roll, wear resistance

1. Introduction

The environment of slab continuous casting rolls is characterized by high temperature and heavy load conditions together with thermal fatigue and wear, which always damage the roll surface and remove the rolls from operation.

It is accepted that coatings can improve the surface characteristics over those of the substrate bulk properties and are widely used in tribological applications either to reduce wear or to modify friction during contact. However, most of the diffusion coatings are either too thin or not hard enough for rolls. Casehardened coatings are not sufficiently corrosion resistant and lose their effectiveness at high temperatures. The gas detonation spray coating process is well known for providing premium quality coatings with low porosity and high adhesion to protect the matrix from corrosion and wear.[1-4] It is extensively used in the aircraft and automobile industries. Because of its high thermal stability, Cr_3C_2-NiCr coatings are often employed at high temperatures.[5,6] These kinds of coatings, consisting of hard phases of carbides and a tough matrix phase of metal, is one of the most promising materials and one of the most extensively researched coatings. Despite its widespread industrial use, the wear behavior and the mechanisms by which such coatings wear is not clear. Thus, most of such wear coating applications and developments are based on empiricism. Therefore, it is necessary to fully evaluate the properties of this kind of coating made by detonation spraying, especially the wear resistance as coating on rolls.

Jun Wang, Venture Business Laboratory, Saga University, Japan; **Jun Wang** and **Baode Sun,** School of Materials Science and Engineering, Shanghai Jiao Tong University, China; and **Qixin Guo, Mitsuhiro Nishio,** and **Hiroshi Ogawa,** Faculty of Science and Engineering, Saga University, Japan. Contact e-mail: wang@vbl.saga.u.ac.jp.

2. Experimental

2.1 Materials

Commercially available $75Cr_3C_2$-25NiCr (wt.%) powder, containing the designed component ratio, was used in this study. The powder was formed as homogeneous, agglomerated, and sintered particles with a nominal diameter of 50 μm.

The substrate for coating was high-temperature structural steel, DIN 12CrMo44, of which the rolls were made.

2.2 Equipment

The GEMEMOH detonation spray system (Ukraine) was used for this study. Oxygen and acetylene are fed through a mixer into the combustion chamber. Simultaneously, powders are injected by compressed air from a feeder to the gun. Then an explosion is triggered in the combustion chamber by a spark plug. The combustion leads to a detonation effect, forming a high-pressure ultrasonic wave that propagates the hot gas stream and accelerates the powder particles. The particle speed is typically 600 m/s and the particle/gas temperature is in excess of 3273 K during process.

2.3 Procedure Details

The first focus of this investigation was to evaluate the basic properties of the coatings obtained, such as the microstructure and oxidation resistance. The microstructure of the coating was analyzed with a model MEF4M metalloscope (Leica, Germany). An isothermal oxidation test was used to determine the oxidation resistance. Surface preparation consisted of polishing by abrading with SiC papers down to 600 grit in succession followed by drying in acetone. Tests were carried out in an electric muffle furnace at 1023 and 1123 K in air.

The secondary focus of this study was to evaluate the wear behavior of the coatings obtained. The abrasive and dry frictional wear tests were performed on a pin-on-disk tester. To simulate the working conditions of the roller, quenched GCr15 steel with a hardness of HRC63 and a surface roughness of R_a =

0.4 μm was used as the disk. The Φ6 × 12 mm block specimens coated with Cr_3C_2-NiCr were pressed against a rotating disk under a certain load. The locus of the pin was a circle with diameter of 25 mm. Specimens were cleaned ultrasonically in an alcohol bath after they were polished, and were weighed before being tested. The wear rate was determined by wear mass loss, which was measured by weighing the samples before and after each of the wear tests and dividing by the sliding distance. The wear test was performed under the following conditions: two loads of 9.8 and 98 N, which are equal to the pressure on a pin of 0.35 and 3.47 MPa, respectively, and two rotational speeds of 50 and 500 rpm, which are equal to two sliding velocities of 0.13 and 1.3 ms^{-1}, respectively, at the contact surface of samples. The wear surface was analyzed using a X-650 scanning electron microscope (SEM) (Hitachi, Japan).

2.3.1 Basic Properties of the Coatings. The primary properties and the thicknesses of coatings are listed in Table 1. The shear strength of the coating was determined according to the national standard of China GB/T113222-91. The values compare well with those reported in literature for this coating.[7]

As seen in Fig. 1, the polished and unetched cross section of the coating is composed of plate-like lamella oriented parallel to the substrate. In the image, the light areas indicate the metallic binding matrix, whereas the gray stringers between the lamella indicate the presence of either the chrome carbides (Cr_3C_2) or the oxides (Cr_2O_3) formed as a result of oxidation occurring during particle exposures to the high temperature of the spraying process. In the coating, the carbides appear to be well dispersed and well bonded within the structure. Pores appear black in the micrograph.

Figure 2 represents the isothermal oxidation kinetics of the uncoated and coated specimens at different temperatures for 70 h. DIN 12CrMo44 was used as both the uncoated specimen and

Table 1 Characteristics of the Detonation Spray Coatings

Average Thickness, μm	Hardness, HR15N	Porosity, %	Shear Strength, MPa
300 ± 10.5	70 ± 2.5	1.9 ± 0.11	41.7 ± 0.35

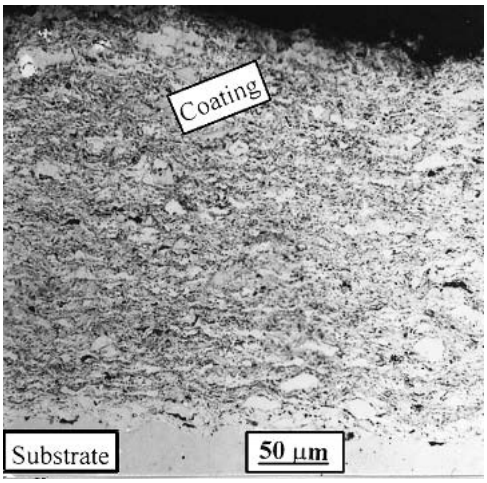

Fig. 1 Cross section of the detonation-sprayed Cr_3C_2-NiCr coating

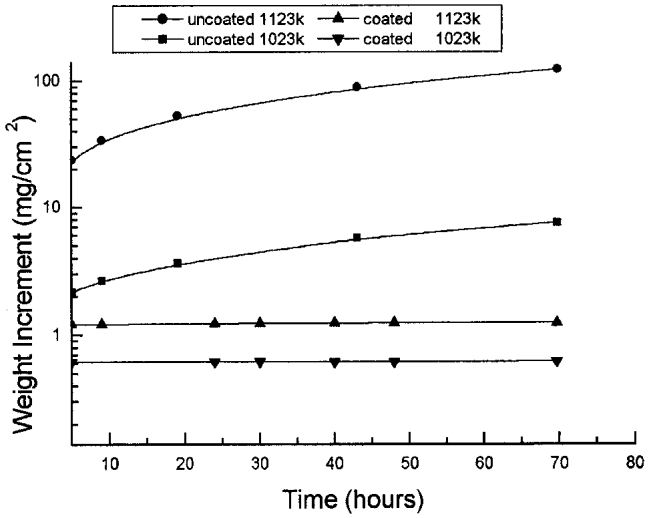

Fig. 2 Oxidation kinetics of coated and uncoated specimens

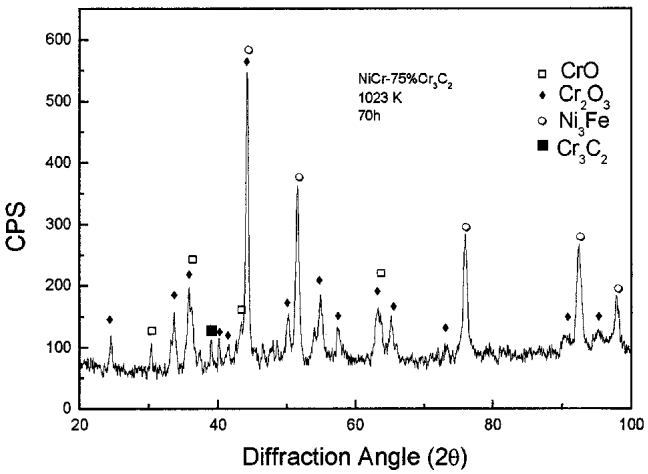

Fig. 3 X-ray analysis result of the coating after oxidation test

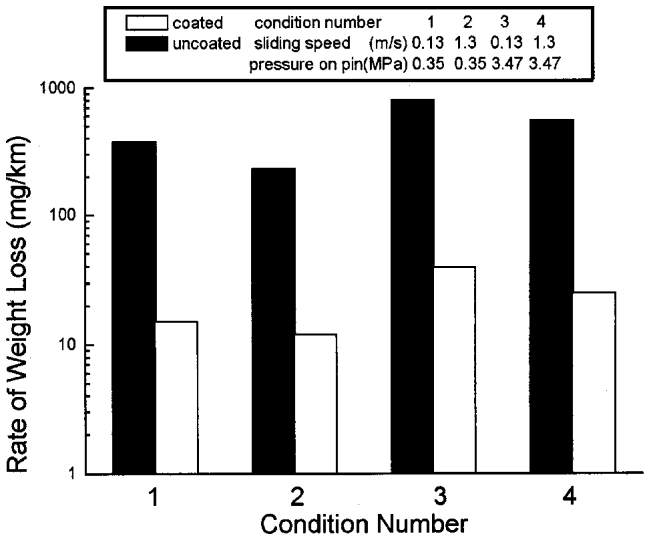

Fig. 4 Abrasive wear rate of samples; the experimental scatter never exceeded 10%

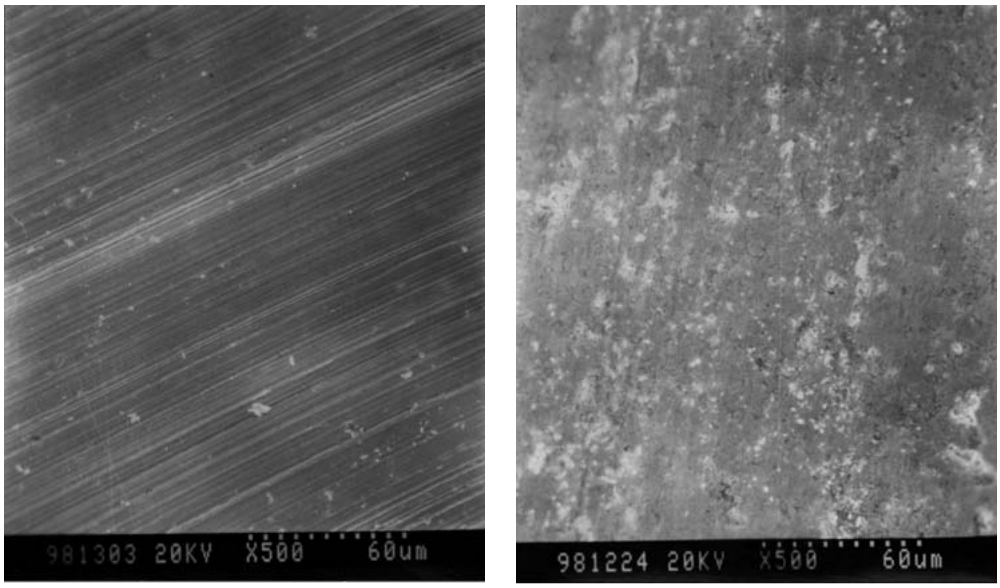

Fig. 5 Abrasive wear surface of samples **(a)** uncoated sample **(b)** coated sample

the substrate of the coated specimen. It is obvious that the coated specimens exhibit remarkable improvement in high-temperature corrosion resistance compared to the uncoated specimens. The total weight gain of the coated specimens is about 10 times less than that of the uncoated specimens after 70 h of oxidation at 1023 K and 100 times less at 1123 K. No visible change appears on the surface of the coating after testing. On the contrary, very thick oxide scales with severe spallation are observed on the uncoated specimens by naked eyes.

The x-ray diffraction (XRD) analysis result (Fig. 3) shows that the surface of the coating has become Cr_2O_3 and the surface of the uncoated specimens has become Fe_2O_3 because of selective oxidation. The corrosion resistance of the coating is attributed to its high Cr content. The dense coating protects the substrate from the inward permeation of oxygen. The selective oxidation of chromium improves the high-temperature corrosion resistance of the coated steel.

2.3.2 Wear Resistance Test

Abrasion Test. Abrasive wear testing was done with 300 grit Al_2O_3 paper adhered on the disk. The sliding distance of each test was 30 m. The abrasive wear rate is shown in Fig. 4. The wear rate values of the uncoated specimens are always much higher than that of the coated specimens under any test condition. Furthermore, the wear rates of coated and uncoated specimens all increase with the increment of the pressure on the pin.

The wear mechanisms of the coated specimens are mild abrasion and strain fatigue. There are microcutting traces on the surface, as seen in Fig. 5(a). At the same time, there exists a plastically deformed very thin layer on the coating surface, which has a weak bond to the base coating and is liable to be removed by friction. The forming and removing of the thin plastic layer behave as a strain fatigue mechanism of wear. It can be seen that the mechanism of the uncoated specimen is obviously severe abrasion. There are many wide and deep plowing grooves on the surface, as seen in Fig. 5(b).

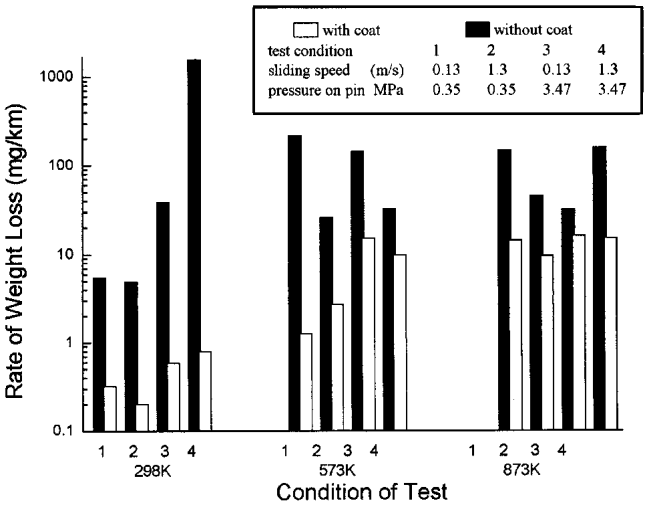

Fig. 6 Dry wear rate of samples; the experimental scatter never exceeded 15%

Dry Frictional Wear Test. Although the environment temperatures were different from the abrasion test, the dry frictional wear test conditions are the same as for the abrasion test. The dry frictional wear tests were performed at room and elevated temperature, i.e., 298, 573, and 873 K. The sliding distance of each test was 1 km. The wear rates of the coated and uncoated samples under different test conditions are shown in Fig. 6.

Results showed that:

- The wear resistance of the coated samples without the risk of seizure was much better than that of the uncoated at any temperature, load, and sliding velocity.
- The wear rates of the coated samples increased with the increment of the environment temperature as well as load.

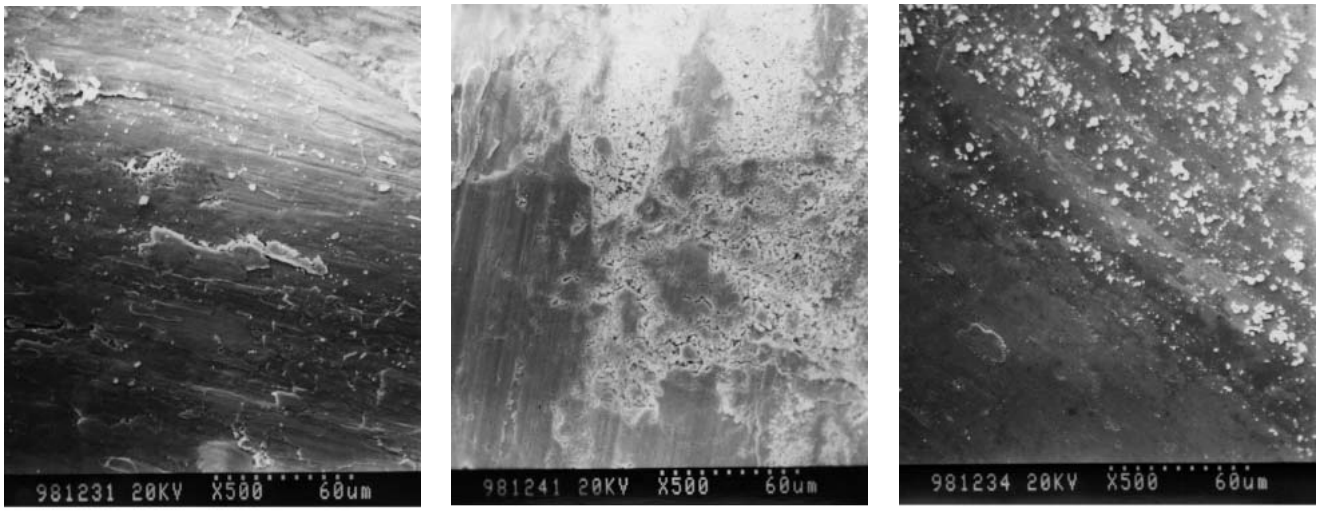

Fig. 7 Dry frictional wear surface of coated specimens **(a)** 298K **(b)** 573K **(c)** 873K

- The divergence of the wear rate under different conditions became less with the increment of the environment temperature for the uncoated specimens. The maximum difference of the wear rates changed from 1566.2 mg/km at room temperature to 125 mg/km at 873 K. However, the wear rate difference reached the maximum for the coated specimens when environment temperature was 573 K.
- At room temperature, the wear rates of the coated and uncoated samples both increased with the increment of load. The sliding velocity had little effect on the wear rate of the coated samples. High velocity, however, made the wear rate of the uncoated specimens increase more than one thousand times under heavy load.
- At medium temperature, i.e., 573 K, there was no great change for the coated specimens at any load and speed. But the effect of speed was more noticeable than that of load for the uncoated specimens.
- At high temperature, i.e., 873 K, the wear rates of the uncoated specimens were higher when load and speed were low or high simultaneously. Otherwise, the wear rates of the coated specimens were higher at high load.

The main reason that the wear resistance of the coated samples was much better than that of the uncoated is that there exist many carbides and few oxides in the dense coating, with good bonding to the substrate.

The typical wear surface micrograph of the uncoated samples shows plowing grooves and plastic deformation in addition to abrasion by oxide debris. The wear surfaces of the coatings can be divided into four regions: (1) a polished surface containing a very thin transferred layer of steel; (2) small islands of transferred layer; (3) a large transferred layer with several cracks; and (4) a small pit. Typically, the surfaces of the coated samples are covered with both large continuous and "island"-transferred layers. It is believed that the wear mechanism for Cr_3C_2-NiCr coating involves the fatigue-induced detachment of the transferred layer. The transferred layer serves to protect the unworn surface of the Cr_3C_2-NiCr, reducing the wear of both bodies. This type of transferred layer is known as an *island*. Its composition, mainly iron, is identified by energy-dispersive x-ray spectroscopy (EDX) analysis.

The wear rate depends upon the spalling of the transferred layer. Because of the properties of the counter body surface, the transferred layer and its oxide change with the test conditions, such as load, sliding velocity, and environment temperature, and the wear behavior varies with the test condition as shown in Fig. 6. Three typical worn features of the coated samples at different environment temperatures, such as 298, 673, and 873 K, are shown in Fig. 7. The pressure on pin and sliding speed were the same for these samples, i.e., 17.34 MPa and 1.3 m/s. At room temperature, the transferred layer from the counter body adheres to the coating surface, and acts as a lubricant between two bodies (Fig. 7a). At 573 K, however, the transferred layer becomes easily welded to the coating. Then it spalls from the surface with part of the coating, which increases the wear rate as in Fig. 7(b). However, at 873 K the environment temperature and the friction-induced temperature accelerated the oxidation of the transferred layer. Then the layer became granulated, as in Fig. 7(c).

2.3.3 Field Test. Five rolls were detonation sprayed with the $75Cr_3C_2$-25NiCr coating. The thickness of the coating was 0.29 to 0.30 mm. From July 1998 to September 2000, testing in service conditions was carried out in Bao Steel. It was reported by the on-site inspection after 3740 heats that there were many alligator cracks formed on the surfaces of the uncoated rolls, some of which had to be repaired. However, compared with the original surface, no changes after 12,000 heats were detected on the surfaces of the coated rolls, which continue to be used.

3. Conclusion

The following conclusions can be drawn from the above:

- The detonation-sprayed Cr_3C_2-NiCr coatings processed are dense, with good bonding to the substrate as well as high resistance to oxidation.

- The abrasive and dry frictional testing results showed that the resistance of the detonation-sprayed Cr_3C_2-NiCr coating is much better than that of the substrate material DIN 12CrMo44. The wear mechanism of the coating depends on the properties of the transferred layers, which vary with the wear conditions such as environment temperature, load, sliding velocity, and other factors.
- The reports of the in-service test from the steelmaking plant show that the use of the coating is an efficient means of prolonging the life of the conticaster rolls.

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