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# Three-body Impact Corrosion-Abrasion: Studying for Low Carbon High Alloy Liner in Ore Grinder

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**The impact-corrosion-abrasion resistance of the low carbon high alloy steel, which can be used for mill lining under impact-corrosion-abrasion condition, are tested in laboratory by means of a new kind of experimental facility. The industrial trial run in the same condition has also been completed. The results show that the new alloy containing 0.2 wt.% carbon, 9 wt.% chromium, and 2 wt.% nickel is consisted of lath martensite entirely, and is more than two times superior to Mn13 cast steel in impact-corrosion-abrasion resistance. Spelling is the leading wear mechanism in impact-corrosion-abrasion condition for this alloy, which is lighter than that of high manganese steels because of its better hardness-toughness match.**

**Keywords** corrosion wear, high alloy steel, impact wear, lining board, wet grinder

## 1. Introduction

When several factors such as impact, corrosion, and abrasion occur at the same time, such as in the ore grinding process, the wear processes and mechanism are complex. In fact, the wear extent in this condition is not the simple accumulation of those caused by impact, abrasion, and corrosion, respectively (Ref 1-3). The mass loss is caused by the combined action of impact, abrasion, and corrosion whose interactions are not well-determined (Ref 4-8).

The lining boards are often used in wet grinder. The grinding balls in grinder are usually large diameter steel balls with large weight, which impact the liner in wet grinder continuously. The grinded materials are often various iron ore or copper ore with high hardness and abrade the liner strongly. The ore pulp is acidic or basic and can corrode the lining board. So the liner of wet grinder must have excellent toughness, corrosion resistance, and wearability. In fact, the wear rate of alloy in wet slurry is several times as that in dry abrasives (Ref 9). Presently, the materials used in this occasion are usually the high manganese steels, which have high toughness, high impact toughness, and high corrosion resistance, but bad wearing resistance in this condition. Other materials used to replace the high manganese steels, such as the medium carbon alloy steels, the high chromium cast irons, etc., have short operation life similar to the high manganese steels. The low carbon high alloy steels containing a larger percentage of chromium and nickel can obtain both good corrosion resistance because of the effect of chromium and nickel and high toughness because of its low carbon content. The impact-corrosion-abrasion properties of this alloy in wet grinder are studied in this article.

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## 2. Test Methods

### 2.1 Materials

The alloys, which contain 0.15-0.3 wt.% carbon, 7-10 wt.% chromium, and 1.5-2 wt.% nickel, were investigated. The samples were all held at the heat-treatment temperatures of 1050 °C for half an hour before being quenched in oil tempered at 250 °C. At the same time, the high manganese steels, which contain 1.2 wt.% carbon, 1.3 wt.% manganese, and are widely used as lining board, were investigated for comparison.

### 2.2 Industrial Trial Run

Industrial trial run were proceeded in a $\Phi 2.7 \times 3.6$ m ball grinder with 20.6 rpm rotary speed, 35 t/h output, and 40% maximum charge amount. The mill balls were made of cast iron, whose biggest diameter was 100 mm before testing. The grinded materials were ore slurry consisting of iron ore (Hardness: $f = 17$, green diameter is about 5-30 mm) and 30% water. Around 80% of the ore particles poured into the grinder were less than 30 mm in diameter. The pH value was 5 and temperature was between 15 and 25 °C. The volume loss was tested after 4320 h milling and about 80,000 tons of iron ore being milled.

### 2.3 Laboratory Tests

Many methods such as acoustic emission (AE) have been used for studying the corrosion-abrasion process by ejecting the hard particles onto the target material (Ref 10-13). But it has not been used for studying on the three-body impact-corrosion-abrasion properties of the wet mill liner successfully. For individual impacts, the AE is only correlated to the kinetic energy of the particles other than the mechanical damage itself. In this article, an improved device is used tentatively.

**Table 1 Composition, structure and properties of experimental materials**

| | Chemical composition, % | | | | | | Alloy characterization | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Alloy | C | Cr | Ni | Mn | S | P | %Martensite | %Austernite | Densite, g/cm$^3$ | Hardness, HRC | Impact toughness, J/cm$^2$ |
| 1 | 0.15 | 9 | 2 | ... | <0.035 | <0.035 | 99 | <1 | 7.48 | 50 | 62 |
| 2 | 0.20 | 9 | 2 | ... | <0.035 | <0.035 | 99 | <1 | 7.64 | 53 | 59 |
| 3 | 0.25 | 9 | 2 | ... | <0.035 | <0.035 | 99 | <1 | 7.57 | 55 | 56 |
| 4 | 0.20 | 6 | <1 | ... | <0.035 | <0.035 | 99 | <1 | 7.57 | 52 | 60 |
| 5 | 1.20 | ... | ... | 13 | <0.035 | <0.035 | ... | 100 | 7.45 | <21 | >147 |

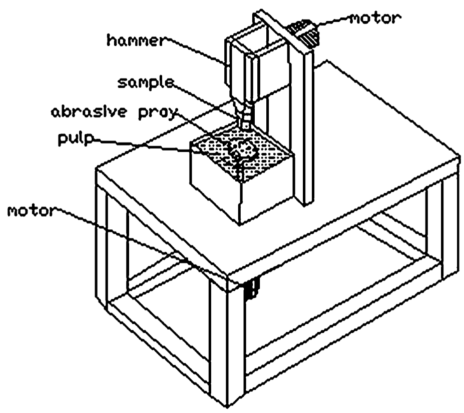


**Fig. 1** Schematic diagram of the laboratory wear test apparatus

An impact-erosion-abrasion test consists of a series of "wear cycle," and each cycle involves an impact between the specimen and the grinded materials with the rotation of the abraser-charging tray, on which the grinded ore are poured down. The abraser-charging tray is fixed and immersed in a container filled by corrodent. In this test, impacts are direct, i.e., the specimens themselves are fixed on the hammer to impact the ore.

The schematic of test apparatus is shown in Fig. 1. The samples are $10\times10\times30$ mm cuboids. A motor located below the corrosive container rotates the abraser-charging tray and the grinded ore. Another motor located on the right side of the device provides the up-and-down movement of the samples with the rotation of an eccentric wheel, which makes the samples impact the grinded ore particles continuously. The hammer weighs 10 kg and the height the hammer dropping can be adjusted, which determines the impact energy loaded on the specimen.

Before laboratory test, the specimens were cleaned with acetone in supersonic cleaner followed by drying. The slurry, whose pH value was 5, was the mixture of iron ore particles with 5 mm diameter and water, in which there was 40% particles by weight. The iron ore particles moved with the rotation of abraser-charging tray. The impact energy was 2.6 J.

The specimens were cleaned with acetone in supersonic cleaner after impact-corrosion wear followed by drying and weighting the mass loss.

## 3. Results and Discussion

### 3.1 Component and Microstructure Design of Lining Board Alloy

It has been suggested in many studies that lining board in wet grinder has longer operation life when its impact toughness is more than 50 J/cm$^2$ and its hardness is more than 45 HRC (Ref 14-16). So the new alloy is designed to be martensitic cast steel with more than 50 J/cm$^2$ impact toughness and 45 HRC hardness, whose microstructure is shown in Fig. 1 and properties are listed in Table 1. The carbon content in the new alloys is 0.15-0.30%, which gives them suitable match of hardness and toughness. Chromium can improve the hardenability and corrosion resistance of alloy, nickel can improve the toughness and can improve the corrosion resistance together with chromium.

### 3.2 Industrial Trial Run

The volume loss and wear rate in industrial TR of the low carbon high alloy steels and the high manganese steels, whose composition are the same as those listed in Table 1, are shown in Table 2.

The results show that the average wear rate of alloy 2 is 0.4385 cm$^3$/h and volume loss of it is 21.96% after 4320 h milling, which is lower than all other tested alloys and is less than half of that of high manganese steels in the same condition. When milling for 5040 h and producing 9.3 tons milled ore, the volume loss of material 2 is 27.50%. Since having higher toughness, the alloy 2 is not easy to break during milling and its wear process is uniform. So the service life and ore-milling capacity of the lining boards made of alloy 2 can be presented as

$$F = \frac{R - R_1}{R_1 - R_2} \cdot (t_1 - t_2) + t_1$$

$$W = \frac{R - R_1}{R_1 - R_2} \cdot (W_1 - W_2) + W_1$$

where, $t_1$, $t_2$ are the milling time; $R_1$, $R_2$ are the percentage of volume loss corresponding to $t_1$, $t_2$, respectively; $W_1$, $W_2$ are the ore milling output corresponding to $t_1$, $t_2$, respectively; $F$ is the calculated operating life of the lining board; $R$ is the percentage of volume loss when the lining boards retired; $W$ is the ore milling output when the lining boards retired.

If the lining boards are scrapped after 60% volume loss, $R$, $R_1$, $R_2$, $f_1$, $f_2$, $W_1$, $W_2$ can be 60, 27.50, 21.75, 5040, 4320, 93,000, 79,950, respectively. Then the service life of alloy 2 calculated is 9251 h or 12.85 months. The ore milling output ($W$) is 169,572 tons.

The high manganese steel liners have usually 4320 h operation life and 79,950 tons average ore milling output. The result shows that alloy 2 is much superior to the high manganese steels when used as mill liners (Fig. 2).

**Table 2 Wear rate of two kinds of steel in industrial TR after 4320 h milling**

| Alloy | Number of liner | Average volume before test, $cm^3$ | Average volume after 4320 h milling, $cm^3$ | Volume loss, $cm^3$ | Rate of volume loss, % | Wear rate, $cm^3/h$ |
|---|---|---|---|---|---|---|
| 1 | 12 | 8891.71 | 5486.63 | 3405.08 | 38.29 | 0.7882 |
| 2 | 12 | 8625.65 | 6731.37 | 1894.28 | 21.96 | 0.4385 |
| 3 | 12 | 8767.50 | 6228.53 | 2538.97 | 28.96 | 0.5877 |
| 4 | 12 | 8821.66 | 5036.98 | 3784.68 | 42.90 | 0.8761 |
| 5 | 12 | 8927.52 | 4555.04 | 4372.48 | 48.90 | 1.0121 |

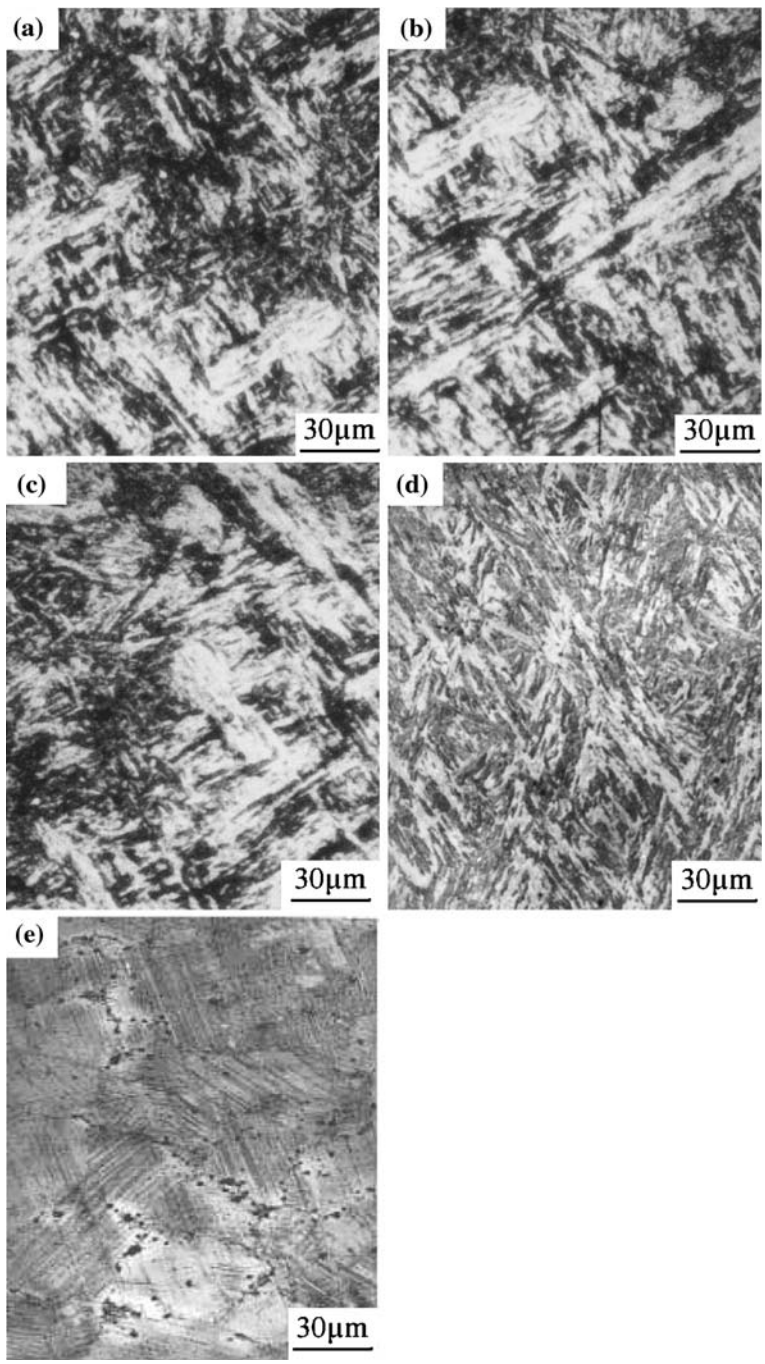


**Fig. 2** Microstructure of two kinds of alloys after quenching and tempering; (a) material 1, (b) material 2, (c) material 3, (d) material 4, (e) material 5

### 3.3 Laboratory Tests

**3.3.1 Compatibility between Laboratory Test and Industrial TR.** Table 3 lists the average volume loss of the low carbon high alloy steel and the high manganese steel in laboratory test. For the low carbon high alloy steel (whose number are 1, 2, 3, 4, respectively) and the high manganese steel (whose number is 5), the ratio of volume loss in laboratory test and in industrial TR after 4320 h milling were measured respectively and are shown in Fig. 3. Those reveal that the volume loss in laboratory test after 48,000 cycles and 72,000 cycles' impact-abrasion is coincident very well to the results in industrial TR. It is revealed that the volume loss in laboratory test for 24,000 cycles is not coincident very well to that in industrial test, whose reason may be that the steady state had not been reached under laboratory condition before 24,000 cycles. So the laboratory test can be used to simulate the industrial TR after 48,000 cycles.

**3.3.2 Comparison of Impact-Corrosion-Wear Properties between Test Materials in Laboratory.** Figure 4 shows the volume loss's evolution of material 2, 4, 5 in laboratory test. The result shows that the volume loss of these three kinds of samples are approaching before 24,000 cycles' wearing, but the wear rate of the low carbon high alloy steel which contains 9% of chromium and 2% of nickel is much lower than that of the high manganese steel after 24,000 cycles. The wear extent of the former increases slowly and uniformly in this stage, and that of the later increases significantly, i.e., the wearability of the low carbon high alloy steel is better than that of the high manganese steel in laboratory test. Material 4, a low carbon high alloy steel which contains 6% of chromium and less than 1% nickel, is abraded heavier than material 2 and slighter than high manganese steels.

**3.3.3 Effect of Carbon Content on Impact-Corrosion-Wear Properties of the New Alloy.** Figure 5 shows that materials 1 and 3 have lower impact-corrosion-abrasion resistance than material 2, i.e., the low carbon high alloy steel containing 0.2% carbon has been abraded in a lower rate in the stable wear stage, although the wear extent of this alloy is higher than that of material 3 containing 0.25% of carbon before 24,000 cycles.

### 3.4 Wear Mechanism of New Alloys

The wear surface's morphology of the low carbon high alloy steels and the high manganese steels are shown in Fig. 6 and 7.

Before 24,000 cycles, a large amount of furrows and extruded ridges occur on the wear surface of the high manganese steel because of its lower hardness, which are produced by plowing and extrusion deformation led by the hard abrasive particles. There are some small shallow corrosion pits existing on the wear surface of the high manganese steel, which do not exist in the low carbon high alloy steel. Extrusion

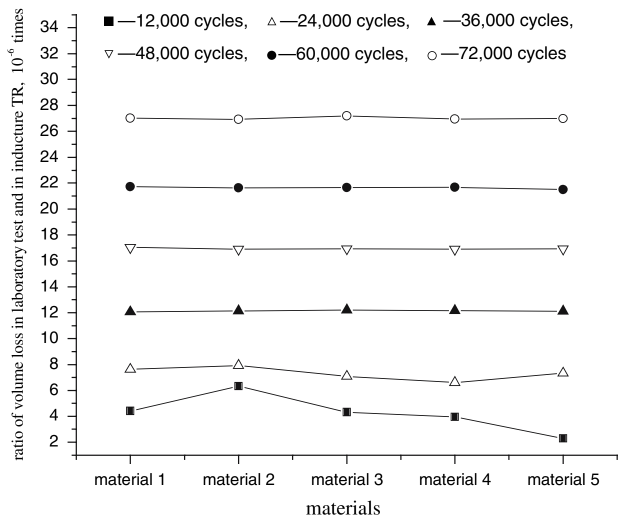


**Fig. 3** Comparison between industrial TR and laboratory test after various cycles

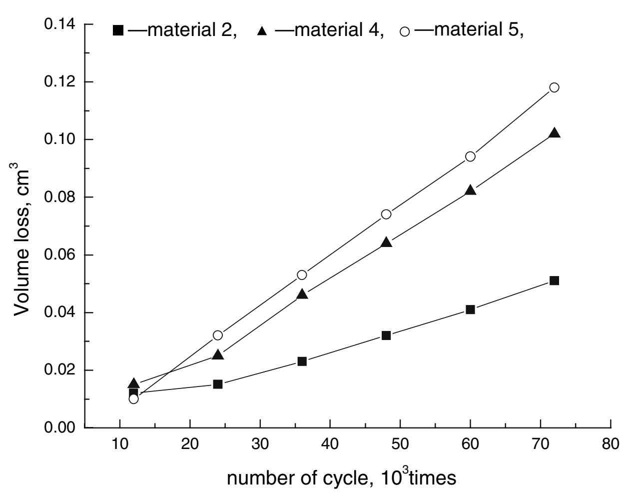


**Fig. 4** Volume loss of new alloys and high manganese steel in laboratory test

**Table 3 Volume loss of samples after impact-corrosion-abrasion tests in laboratory**

| | Number of impact cycles, ×$10^3$ times | | | | | |
|---|---|---|---|---|---|---|
| | 12 | 24 | 36 | 48 | 60 | 72 |
| Alloy | Volume loss, $cm^3$ | | | | | |
| 1 | 0.015 | 0.026 | 0.041 | 0.058 | 0.074 | 0.092 |
| 2 | 0.012 | 0.015 | 0.023 | 0.032 | 0.041 | 0.051 |
| 3 | 0.011 | 0.018 | 0.031 | 0.043 | 0.055 | 0.069 |
| 4 | 0.015 | 0.025 | 0.046 | 0.064 | 0.082 | 0.102 |
| 5 | 0.010 | 0.032 | 0.053 | 0.074 | 0.094 | 0.118 |

deformation and some ridges are formed because of stronger impact. The reason why wear rate of the high manganese steel is higher than that of material 2 in this stage may be that the surface materials are easily to be removed by plowing because of their lower hardness.

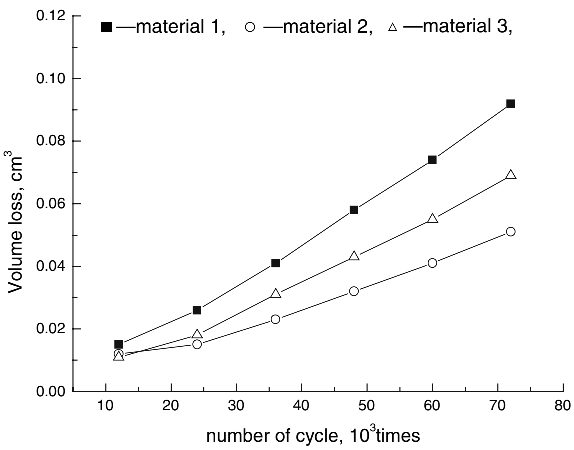


**Fig. 5** Influence of carbon content on impact-corrosion-abrasion resistance of new alloy

After 96,000 impact cycles, some deep spalling pits occur on the wear surface as shown in Fig. 7(a). Those spalling pits occur only at the ridge created earlier and are small in size. According to the theory of corrosion-abrasive (Ref 17), the corrodent in the experiment condition can accelerate the crack generation and growth. The work-hardening area can store large amounts of distortion energy, which can reduce the corrosion resistance of alloy. Besides initiating in the subsurface stratum of ridges, the crack can also initiate from the surface corrosion pits. After the cracks generate on the wear surface, the corrodent can permeate into the crack and accelerate the crack growth (Ref 18). But since the low carbon high alloy steel has higher hardness than high manganese steel, the peeling can only occur in small area, i.e., in the ribs. So, the wear rate is lower.

Figure 7(b) shows that large piece of peeling occur on the wearing surface of the high manganese steel after 96,000 cycles.

High manganese steels is a typical work-hardening alloy. Under the effect of impact and abrasion, large amounts of deformation can be generated, and high-density dislocation occurs at local area where small corrosion pits are ease to form because of the increased lattice distortion energy. High-density dislocation area and small corrosion pits are often the source of cracks.

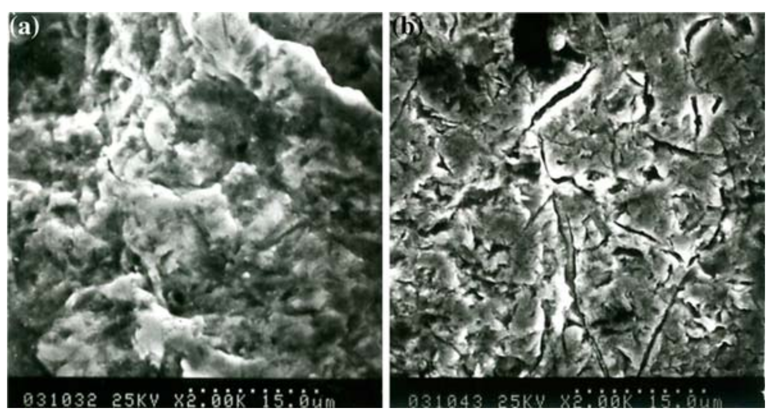


**Fig. 6** Morphology of wear surface after 24,000 cycles impacting; (a) low carbon high alloy steel (b) high manganese steel

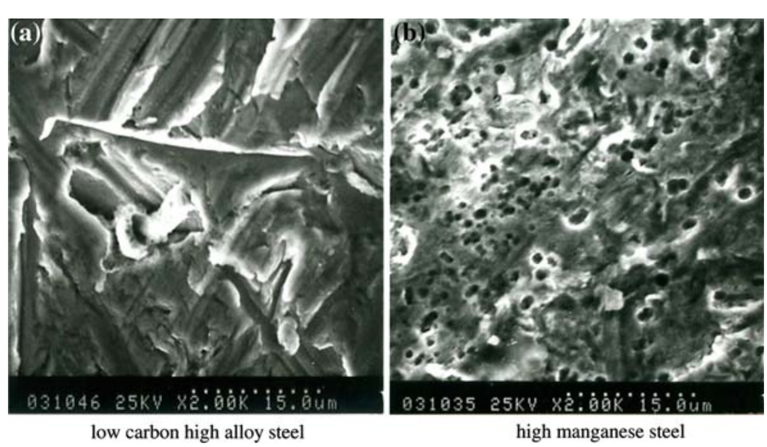


**Fig. 7** Morphology of wear surface after 96,000 cycles impacting; (a) low carbon high alloy steel (b) high manganese steel

In the previous research (Ref 18), the metallograph normal to the wear surface shows that a thicker severe deformed layer is created by deformation. The cracks initiate at the high-density dislocation area in subsurface stratum or small corrosion pits on wear surface and develop along the border of severe deformed layer and matrix to form large spall. In the process of creak forming and growing, corrodent has promoting action.

## 4. Conclusions

From laboratory tests and industrial TR, the conclusion can be got that the low carbon high alloy steel which contains 0.2 wt.% carbon, 9 wt.% chromium, 2 wt.% nickel with entirely matensite microstructure, 53 HRC, 56 J/cm$^2$ impact toughness is superior to other new alloys used for liner in wet grinder. Its wear rate is less than half of that of high manganese steel other in laboratory testing condition or in industrial trial run condition. The lining board made of this kind of alloy have 9251 h operating life and 169,572 tons milling output. Under impact-corrosion-abrasion condition, spelling is the primary wear mechanism for the low carbon high alloy steel. But since the new alloy is harder, tougher, and has higher corrosion resistance, the spalling pits on its wear surface are small and shallow after long-time wearing.

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