Sliding Wear Characteristics of Ni–Cr–Fe Overlay Weld Alloy with Dispersed NbC Particles

Tomoki Tomita**, Yasuyuki Takatani**, Genzo Hashizume** and Yoshio Harada***

Carbide dispersed overlay weld alloys with the Ni–Cr–Fe matrix phase containing various amounts of NbC particles were prepared by a plasma powder welding process. Effects of the dispersion of NbC particles on wear characteristics of the alloys were investigated at sliding speeds of 0.12 to 4.39 m/s under the unlubricated condition, using Ogoshi wear tester. The wear resistance of the alloys containing NbC particles less than 10 vol% was not remarkably improved. But it was found that the wear rate of the alloys with NbC contents more than 25 vol% was about 1/10~1/100 times that of the NbC-free alloys and the wear loss of counter material was also very small. Especially the wear rate of the alloy with 30 vol% NbC was smaller than that of Stellite No. 6 alloy at any sliding speeds in the range of measurement.

It is considered that these excellent characteristics of wear resistance of the alloys were due to the following phenomena caused by dispersed NbC particles. Thus, at the high sliding speed (above 3.53 m/s) the coefficient of friction could be decreased with the result that the unmelted NbC particles became the true contact surface for counter material. On the other hand, at the intermediate and low sliding speed (below 3.53 m/s) the unmelted NbC particles prevented the plastic flow of the matrix phase and the adhesion could be depressed by fine NbC powder made from the pulverized unmelted NbC particles.

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Keywords: plasma powder welding process, carbide dispersed overlay weld alloy, sliding wear characteristic, adhesion, wear rate, plastic flow, niobium carbide

I. Introduction

In order to develop a material having corrosion resistance and wear resistance, the Ni–Cr–Fe overlay weld alloys containing various carbide particles were prepared on the mild steel by plasma powder welding process. When NbC particles having about 100 μm diameter were used, most of the NbC particles were dispersed nearly uniformly as unmelted ones in the matrix alloy. However part of NbC particles were melted and during solidification process primary NbC and eutectic NbC appeared (Fig. 1). While consequently the mean hardness of overlay weld alloys increased, the micro-hardness of matrix alloy, Ni–Cr–Fe solid solution, did not increase, because niobium and carbon were little dissolved into the alloy.

On the other hand, fine carbide particles have often been used to improve wear resistance because of the dispersive hardening of matrix alloy and preventing counter material from adhesion. In contrast, wear properties of soft materials with dispersed coarse carbide particles, such as present overlay weld alloy, have been little investigated. In this study, Ni–Cr–Fe overlay weld alloys with various amounts of NbC particles were prepared by plasma powder welding process and sliding wear tests were performed against hardened steel. Effects of the dispersion of NbC particles on the wear behavior of Ni–Cr–Fe matrix alloy, soft and adhesive material, have been examined by the measurement of wear rate and the observation of wear morphologies.

II. Experimtal Procedure

1. Preparation of overlay weld alloys

Ni–50 mass% Cr alloy powder and NbC powder (purity: 99.9%) have been used as starting materials. The both particle size were 60~150 μm. These powders were mixed up to 60 vol% at the mixing ratio of NbC. Using these mixed powders, the Ni–Cr–Fe overlay weld alloys with dispersed NbC particles were formed to 4 mm thickness on mild steel (SS41, 150 mm × 150 mm × 25 mm). Table 1 shows the welding conditions and Table 2 shows the chemical compositions of matrix alloys and the dilution ratios of overlay weld alloys. While the Fe content increased with the increase of mixing ratio of NbC, the matrix alloys have kept the γ-phase (Ni–Cr–Fe solid solution). In order to examine the effect of the matrix compositions on the wear properties, a specimen (No. 7) was also prepared using stainless steel powder (SUS309L) instead of Ni–50 mass% Cr alloy powder.

Figure 2 shows the relationships between volume fractions of various NbC particles and the mixing ratio of NbC. The total volume fraction of NbC particles contained in the overlay weld alloy proved to be 1/2 times those of NbC particles in the mixed powder because the matrix alloys were diluted by Fe invaded from melted mild steel. Then NbC contents were represented by the mixing ratio
Fig. 1 Microstructures of NbC dispersed overlay weld alloy (Specimen No. 4, 40 vol% NbC). A: Unmelted NbC, B: Primary NbC, C: Eutectic NbC.

<table>
<thead>
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<th>Equipment</th>
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<tr>
<td>Arc current</td>
<td>180 A</td>
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<tr>
<td>Traveling speed</td>
<td>(1.33 \times 10^{-3}) m/s</td>
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<tr>
<td>Torch oscillation</td>
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<tr>
<td></td>
<td>Width 2.3 (\times 10^{-3}) m</td>
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<tr>
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<tr>
<td>Carrier gas</td>
<td>He, 9 (\times 10^{-4}) m/s</td>
</tr>
<tr>
<td>Shield gas</td>
<td>Ar, 3 (\times 10^{-4}) m/s</td>
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Table 1 Condition of plasma powder welding process.

Table 2 Chemical composition (mass%) of matrix alloys and dilution ratio (%) of overlay weld alloys.

<table>
<thead>
<tr>
<th>No.</th>
<th>Mixing ratio of NbC (vol%)</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Dilution ratio</th>
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<td>62.1</td>
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<td>17.3</td>
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<tr>
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<tr>
<td>7</td>
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<td>14.1</td>
<td>17.9</td>
<td>68.0</td>
<td>53</td>
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</table>

Fig. 2 Relationships between the contents of various NbC particles and the mixing ratio of NbC. A: Unmelted NbC, B: Primary NbC, C: Eutectic NbC.

of NbC (vol% NbC) in the mixed powder in the later section of the paper. The micro-hardness of the matrix alloys were \(H\), 200 ~ 250.

2. Wear test

The Ogoshi wear tester has been used to investigate the sliding wear properties. The wear rates have been measured at sliding speeds of 0.12 m/s to 4.39 m/s, a sliding distance of 200 m and a final load of 125 N under the unlubricated condition. The results were compared with that of stellite No. 6 alloy (\(H\), 450). The surface of the specimen was polished to make roughness 0.1 ~ 0.3 \(\mu m\) at the center line average. The counter material, hardened bearing steel (SUJ2, \(H\), 750), was polished under a constant condition and dewaxed using acetone before each wear test.

After wear tests, the worn surface and wear debris gathered around the specimen were examined using optical microscopy, SEM, EDX analysis and X-ray diffraction (CuK\(\alpha\), 40 kV, 200 mA). The plastic flow were also observed at the cross-sections under the wear impressions using SEM. The wear loss of counter materials was estimated by measuring their weight changes.

III. Results and Discussion

1. The wear characteristics of NbC-free alloys

In order to examine wear characteristics of the matrix alloy, wear tests of NbC-free overlay weld alloys having different chemical compositions (No. 1 and No. 7) were carried out. Figure 3 shows the relationships between wear rates and sliding speeds. In spite of different compositions, the wear rates of both alloys tend to be nearly equal at any sliding speeds. At low sliding speed (A), the wear rate remained very small. With the increase of sliding speed (A to B), the wear rate remarkably increased. At the higher sliding speed (B to C), the wear rate decreased after having a small peak. With the further increase of the sliding speed (C to D), a large increase of the wear rate was obtained after passing through a minimum value. Beyond the sliding speed (D) no significant increase was obtained.
in Fig. 5, the worn surface became uneven and a little plastic deformations were observed below the worn surface. Very fine wear debris were obtained and found to consist of γ-Fe₂O₃, γ-Fe and a little α-Fe₂O₃ by using X-ray diffraction. By means of EDX analysis, Fe contents in the wear debris proved to be much more than those in the matrix alloy. Most of the wear debris must have been produced from the counter material. Thus it was considered that an oxidative wear²⁹, having very small wear rate, must have happened because at low sliding speed adsorption of atmospheric gas was sufficient to oxidize fine iron fragments made from the counter material³⁰.

At sliding speeds of B to C (0.62 m/s), even worn surfaces, having metallic luster, were obtained. The depth of plastic flow layer was about 60 μm (Fig. 5(a)). It was estimated that a large shearing stress was applied to deep places of matrix alloy by severe adhesion. Thin flake-like sheets, about 300 μm length, were obtained as the wear debris and found to consist of γ-Fe and a little α-Fe by using X-ray diffraction. The fine fragments torn off from plastic flow layer must have been adhered to each other, grown up and fallen off as large metal sheets³⁰, because the adsorption of atmospheric gas became unsufficient to oxidize them with the increase of sliding speed³⁰. Although large increase of wear rate should be expected at the sliding speeds of B to C, the wear rate decreased, because the true contact pressure was decreased with the result that friction surface was flattened due to softening of the matrix alloy with increasing surface temperature by friction.

At the sliding speeds of C to D (2.38 m/s), the worn surfaces were also even and metallic luster remained. However, partially melted portions (marked by † in Fig.

Fig. 3 Effect of the matrix composition on wear rate at the various sliding speeds.

Figure 4 shows morphologies of the worn surfaces and wear debris of the NbC-free alloy (No. 7) and Fig. 5(a) and (b) show its cross-sections under wear impressions. At a low sliding speed (0.12 m/s), which is not indicated

Fig. 4 Morphologies of worn surface (upper) and wear debris (under) obtained from NbC-free overlay weld alloy (Specimen No. 7).
4) were observed at several places of the worn surface. The wear debris were nearly equivalent to those produced at B to C, except that a little Fe₂O₃ was contained. The depth of plastic flow layer was smaller than those at B to C. These facts mean that at higher sliding speeds the matrix alloy tend to flow only just below the surface due to softening caused by the increase of surface temperature by friction. Thus it was considered that the wear rate was once again increased on account of such severe adhesion accompanied by the partially fusion.

Since a large wear loss of counter materials was expected at such a high sliding speed, their weight changes were measured. The results are shown as curve (A) in Fig. 6. The weight of counter materials rapidly decreased at above the sliding speed where a minimum value of wear rate was attained. A maximum value of weight loss has been obtained at about 2.38 m/s. With the further increase of sliding speed, the weight loss was rapidly reduced and at above 3.53 m/s the weight gain started. It was thought that such weight gain has been obtained by the transferred melted parts to the surface of counter material. Therefore a melting wear must have happened at above 3.53 m/s with the further increase of surface temperature by friction.

2. The wear characteristics of alloys with dispersed NbC particles

(1) Curves of wear rate vs sliding speed

The relationships between wear rate and sliding speed are shown in Fig. 7 for various NbC contents. As a comparison the results of Stellite No. 6 alloy and NbC-free alloy (No. 7) are also presented. The changes of wear rate at below 40 vol% NbC had a different tendency from those at above 40 vol% NbC. The wear rate of the alloys at below 20 vol% NbC was similar to that of NbC-free
alloy shown by chained line in Fig. 7. They were increased step by step after rapid increase at low sliding speed. In contrast, the wear rate of alloys at above 50 vol% NbC decreased to 1/10 ~ 1/100 times that of NbC-free alloys and a maximum and a minimum value appeared at about 0.9 and 1.6 m/s, respectively. Especially the wear rate of the alloy containing 60 vol% NbC, having very excellent wear resistance, was smaller than that of stellite No. 6 alloy at any sliding speed in the range of measurement.

With the increase of the mixing ratio of NbC, the chemical compositions of the matrix alloys were varied as shown in Table 2. However, as mentioned above, two NbC-free alloys having different compositions exhibited the same wear characteristics. Thus the change in wear rate with the increase of the mixing ratio of NbC must have depended on the dispersion of NbC particles.

In order to clarify this reason, the wear behavior of NbC particles in the frictional process were examined about the following two cases, at below 20 vol% NbC and at above 50 vol% NbC.

(2) The wear characteristics of alloys at below 20 vol% NbC

Although the wear debris made from alloys at below 20 vol% NbC contained small amounts of NbC, the morphologies were the same as the case of NbC-free alloys. It was suggested that the wear mechanism of these alloys was similar to that of NbC-free alloys. In order to examine this reason, the cross sections below the wear impression were observed using SEM and the result was shown in Fig. 5(c). The depth of plastic flow layer, about 40 μm, was nearly equal to those of NbC-free alloys. The crystallized NbC particles, white ones in Fig. 5(c), have been little broken and moved along the plastic flow layer. It was considered that the contribution of crystallized NbC particles to the flow resistance of matrix alloy must have been very small. Since, as previously mentioned, the contribution of unmelted NbC particles to the flow resistance of matrix alloy became very small below 40 vol% NbC, a large plastic flow of the matrix alloy would occur below 20 vol% NbC. Therefore wear behavior of these alloys would be the same as those of NbC-free alloys, because the NbC particles exposed to the worn surface might have been covered with the plastic flow layer.

(3) The wear characteristics of alloys at above 50 vol% NbC

The morphologies of wear debris produced at various sliding speed are shown in Fig. 8. The wear debris obtained at 0.12 m/s, dark brown and very fine particles, were found to consist of α-Fe₂O₃, NbC and a little γ-Fe by using X-ray diffraction. It was thought that at above 50 vol% NbC an oxidative wear has taken place as well as at below 20 vol% NbC, because adsorption of atmospheric gas was sufficient to oxidize fine iron fragments at low sliding speed. But it was suggested that at above 50 vol% NbC a steady state wear must have been more rapidly reached than at below 20 vol% NbC, because the iron oxides were different from those of NbC-free alloys.

In contrast, between two sliding speeds attaining a maximum value and a minimum value of wear rate (1.14 m/s), the mixture of thin flake-like sheets and fine
particles has been obtained. At above the sliding speed where a minimum value of wear rate was attained (2.38 m/s, 4.39 m/s), thin flake-like sheets, about 50 μm length, have been mainly produced. In both cases, these wear debris were found to consist of γ-Fe, α-Fe and NbC by using X-ray diffraction. It was considered that the adhered fragments would grow up and fall off as thin flake-like sheets, because adsorption of atmospheric gas became insufficient to oxidize them with the increase of sliding speed.

The morphologies of the worn surface produced at various sliding speeds are shown in Fig. 9. At below sliding speeds where a maximum value was attained (0.12 m/s), the worn surfaces became uneven as well as in the case of NbC-free alloys. Between two sliding speeds attaining a maximum and a minimum value of wear rate (1.14 m/s), smooth worn surfaces having metallic luster were obtained. At above the sliding speed where a minimum value of wear rate (2.38 m/s), smooth worn surfaces having metallic luster were also obtained. But the exfoliated portions appeared at several places of the worn surface (A in Fig. 9(c)). At above 3.53 m/s circular spots, about 50 μm diameter, appeared (B in Fig. 9(d)) and were found to be niobium-rich areas by EDX analysis (Fig. 9(f)). These spots proved to be unmelted NbC particles exposed to the worn surface by means of the observation of cross sections (Fig. 10(a)), because the plastic flow layer became as thin as about 5 μm with the increase of sliding speed. Although these unmelted NbC particles contained many micro-cracks, any shearing deformation couldn’t be found out. At above 3.53 m/s, the weight change of counter material was nearly equal to zero (C in Fig. 6). Thus it was considered that at the high sliding speed the unmelted NbC particles exposed to the worn surface could prevent adhesion and reduce the coefficient of friction by becoming a true contact surface against the counter material, because the matrix alloy would flow only just below the surface with a large increase of the surface temperature by friction.

Below 3.53 m/s, with the decrease of sliding speed, the depth of the plastic flow layer increased and a peak value, about 20 μm, was obtained at nearly 1.14 m/s (Fig. 10(b)). This fact means that at lower sliding speed the shearing stress was applied into deeper places of the matrix alloy because of the decreased surface temperature by friction. However the depth of plastic flow layer was not as large as that of NbC-free alloy due to the great contribution of unmelted NbC particles to the flow resistance of the matrix alloy at above 40 vol% NbC. Crystallized NbC particles have been little broken and moved along plastic flow layer under the wear impression (Fig. 10(b)). In contrast, unmelted NbC particles below the worn surface were sheared in the sliding direction (B in Fig. 10) and covered with a plastic flow layer. While it was expected that the wear rate should become large because adhesion to the counter material would be more easily carried out, no large wear loss occurred below 3.53 m/s. The reason for this was discussed by the observation of the worn surface as follows. Under the wear impression, the small NbC particles made from fractured unmelted NbC particle seemed to move along the plastic flow layer and reach just below the surface (C in Fig. 10). By means of EDX analysis (Fig. 9(e)), it was found that niobium were distributed at a long-extended area along the sliding direction on the worn surface. These results mean that the small NbC particles might be pushed out and more finely pulverized on the friction surface. Therefore it was considered that no large wear rate could

![Figure 9](image-url)  
**Fig. 9** Morphologies of worn surface and their X-ray images obtained from NbC dispersed overlay weld alloy (Specimen No. 6). (a) 0.12 m/s, (b) 1.14 m/s, (c) 2.38 m/s, (d) 4.39 m/s, (e) Nb Lα image of (c), (f) Nb Lα image of (d).
occur such as NbC-free alloys because these fine NbC particles on the surface must have depressed adhesion. Thus one of the reason that a maximum and a minimum value of wear rate have been obtained, would be due to the change of amounts of these fine NbC particles on the friction surface with the increase of sliding speeds.

IV. Conclusion

The Ni–Cr–Fe overlay weld alloys with dispersed NbC particles were prepared by a plasma powder welding process and the effects of dispersion of NbC particles on wear characteristics of the alloys were investigated. The results obtained are as follows:

1. The wear resistance of the alloys containing NbC particles less than 10 vol% (the mixing ratio of NbC, 20 vol%) was nearly equal to that of NbC-free alloys and little improved.

2. It was found that the wear rate of the alloys with NbC contents more than 25 vol% (the mixing ratio of NbC, 50 vol%) was about 1/10-1/100 times that of the NbC-free alloys and the wear loss of counter material was very small. Especially the wear resistance of the alloy with 30 vol% NbC (the mixing ratio of NbC, 60 vol%) was superior to that of Stellite No. 6 alloy at any sliding speeds in the range of measurement.

3. It was considered that these excellent characteristics of wear resistance of the alloys were obtained due to the following phenomena caused by dispersed NbC particles. At the high sliding speed (above 3.53 m/s), the coefficient of friction could be decreased with the result that the unmelted NbC particles became the true contact surface for counter material.

On the other hand, at intermediate and low sliding speeds (below 3.53 m/s) unmelted NbC particles prevented matrix alloy from plastic flow and adhesion could be depressed by fine NbC particles made from pulverized unmelted NbC particles.

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REFERENCES