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Improved Wear Resistance of Low Carbon Steel with Plasma Melt Injection of WC Particles

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Surface of a low carbon steel Q235 substrate was melted by a plasma torch, and tungsten carbide (WC) particles were injected into the melt pool. WC reinforced surface metal matrix composite (MMC) was synthesized. Dry sliding wear behavior of the surface MMC was studied and compared with the substrate. The results show that dry sliding wear resistance of low carbon steel can be greatly improved by plasma melt injection of WC particles. Hardness of the surface MMC is much higher than that of the substrate. The high hardness lowers the adhesion and abrasion of the surface MMC, and also the friction coefficient of it. The oxides formed in the sliding process also help to lower the friction coefficient. In this way, the dry sliding wear resistance of the surface MMC is greatly improved.

Keywords carbon/alloy steels, metal matrix composites, surface engineering

1. Introduction

Tungsten carbide (WC) is very hard and wear-resistant. Many efforts have been made to incorporate WC particles in metal matrix composite (MMC) coatings to improve the wear resistance of industrial parts (Ref 1-4). The composite coatings reinforced by WC particles can be produced by laser cladding, plasma arc cladding, hardfacing, thermal spray, etc. These composite coatings have been used in many severe wear conditions. While the composite coatings produced by thermal spray are prone to spallation when subjected to high stress or shocking, the composite coatings produced by cladding and hardfacing suffer from carbide dissolution and cracking (Ref 5, 6). To overcome this problem, Veerling et al. proposed a laser melt injection (LMI) process (Ref 7). In the LMI process, the substrate is melted by a defocused laser beam and a melt pool forms. The carbide particles are injected into the tail of the melt pool. Carbide dissolution is minimized by avoiding direct interaction of the carbide particles with the laser beam. To lower the equipment investment, we proposed a plasma melt injection (PMI) process (Ref 8). A transferred plasma arc was used as the heat source to melt the substrate. WC-Co particles were injected into the tail of the melt pool produced by the plasma arc. In this way, surface MMC has been produced on low carbon steel. To estimate the wear resistance of the surface MMC produced by PMI of WC particles, dry sliding wear test was performed with a ball-on-disk setup. Tribological properties of the surface MMC are compared to those of the low carbon steel substrate in this paper.

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2. Experiments

A schematic diagram of the PMI process is shown in Fig. 1. A 5 kW transferred plasma arc was employed for melting. The substrate was melted several hundreds μm and an elliptical melt pool formed when the plasma arc moved forward. A TWIN 10C powder feeder from Plasma Technik was used for particle injection. WC particles were injected by argon stream into the melt pool right after the plasma arc to avoid extra heating in the plasma arc. Parameters of the PMI process are shown in Table 1.

The particles injected were WC-17wt.%Co, manufactured by Sulzer Plasma Technik. The size of the WC particles ranged from 25 to 45 μm. The substrate was Q235 low carbon steel sheet of $200 \times 40 \times 4$ mm^3. The substrate was grit-blasted before using.

The substrate was melted 10 mm from one edge, and the WC particles were injected with parameters shown in Table 1.

The specimens were sectioned 100 mm away from the starting point, mounted, ground mechanically, and polished with diamond paste. The polished specimens were then etched with ferric chloride solution ($FeCl_3$:HCl:H_2O = 5:15:85). The microstructures of the SMMCs were observed using model S4700 scanning electron microscope (SEM).

Sliding wear test was performed on the surface MMC. A sample for the wear test was cut from the substrate by spark erosion with dimensions of $8 \times 8 \times 4$ mm^3. The MMC layer turned out to be about 0.5 mm thick, from image of its cross section. A layer of about 0.1 mm was removed from the top surface to get a flat plate for wear test. To evaluate the wear resistance of the whole MMC layer, 0.15 mm thick MMC layer was removed. In this way, the middle part was exposed for wear test. Then another 0.15 mm thick MMC layer was removed. The bottom part of the MMC layer was exposed for wear test. The wear test was performed using a CJS111A tester with

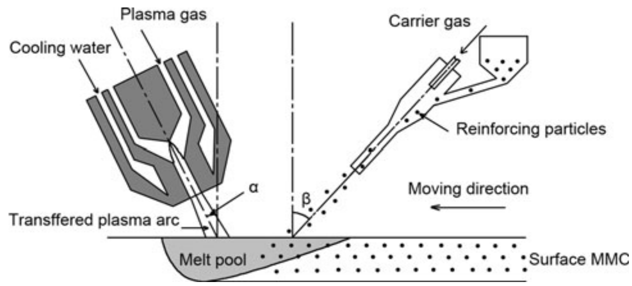

Fig. 1 Schematic diagram of PMI process

Table 1 Parameters of plasma melt injection process

Current, A	75
Distance between nozzle and substrate, mm	18
Angle between plasma torch and normal to the substrate surface α, °	−45
Angle between particle stream and normal to the substrate surface β, °	45
Moving velocity of plasma torch, mm/s	5
Diameter of injection nozzle, mm	1.8
Particle feeding rate, mg/s	300

ball-on-disk setup. The specimen was fixed on a rotating disk. A Ø 6 mm SiC ball was pressed against the surface of the specimen under a normal force of 50 g. The rotational speed of the disk was 300 rpm, and radius of the wear track was 2 mm. The wear test was performed without lubrication and at room temperature. The friction force was measured continuously for 15 min of wear testing, and the friction coefficient was calculated using the friction force divided by the normal force. The wear behavior of the surface MMC was compared with that of the untreated substrate. The specimens were weighed before and after every 30 min during the wear test with a Sartorius BS224S electronic balance. The sensitivity of the balance is 0.1 mg. The worn surfaces of the MMC layer and the substrate were observed using model S4700 SEM, and the composition was determined by energy dispersive spectroscopy (EDS).

3. Results and Discussion

A typical microstructure of the surface MMC is shown in Fig. 2. Several phases can be identified in the surface MMC layer (Ref 8). The white small blocks are unmelted WC particles. The white bars are M_6C (Fe_3W_3C and/or Co_3W_3C) type carbides. The gray phase and the needle-like phase are both iron-based.

The hardness of different locations in the cross section of the surface MMC and the Q235 substrate is shown in Fig. 3. Hardness of the middle part is the highest (Hv1369.3). Hardness of all the three parts is more than Hv1000 and much higher than that of the Q235 substrate (Hv234.0). The substrate is locally heated by the plasma arc in the PMI process, and a melt pool forms under the arc. When the plasma arc moves forward, the melt pool begins to solidify and leaves a tail behind it. The WC particles are injected into the tail of the melt pool. The melt pool solidifies soon after injection of the WC particles and traps them. The WC particles are heated only by the liquid metal, and the heating time is short, so dissolution of the carbide particles can be minimized. The unmelted WC particles found in the surface MMC layer prove this (Fig. 2). Some of the WC particles dissolve in the liquid metal. M_6C type carbides precipitate first in the cooling process. The M_6C type carbides are fine (less than 20 μm, as shown in Fig. 2), because the cooling rate of the PMI process is very fast. Then, the liquid metal left solidifies as the

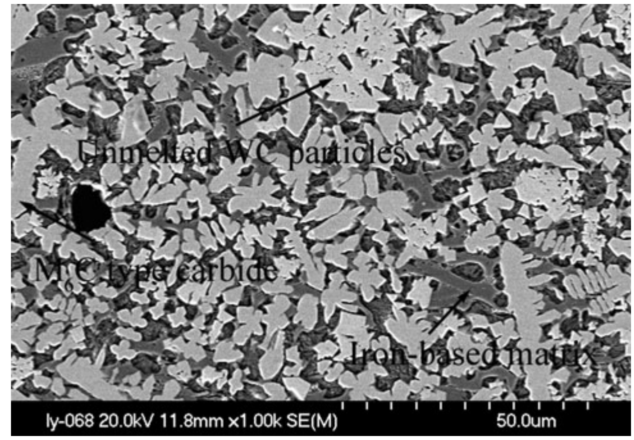

Fig. 2 Microstructure of the surface MMC produced by PMI of WC-Co particles

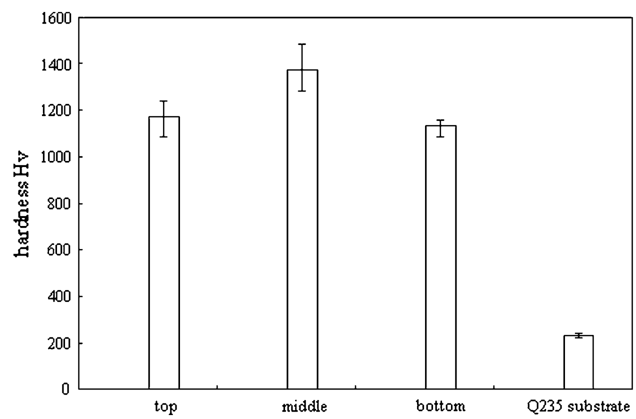

Fig. 3 Hardness of the surface MMC and the Q235 substrate

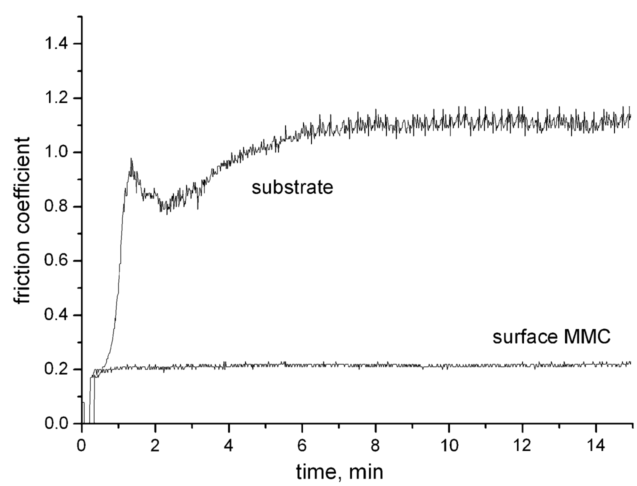

Fig. 4 Friction coefficients of the surface MMC and the substrate vs. sliding time

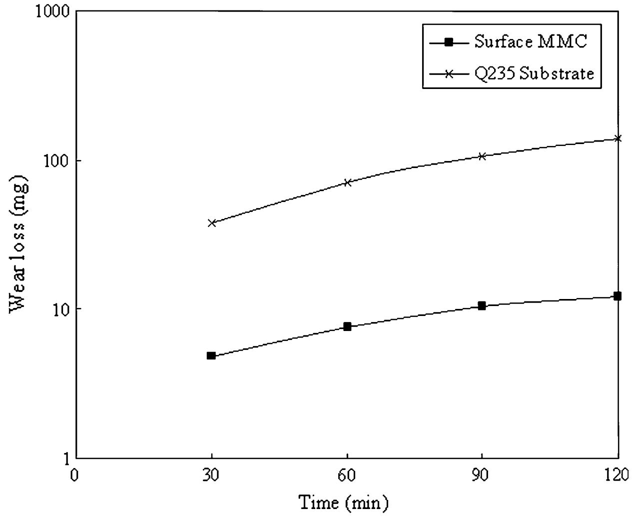

Fig. 5 Wear loss of the surface MMC and the substrate vs. time

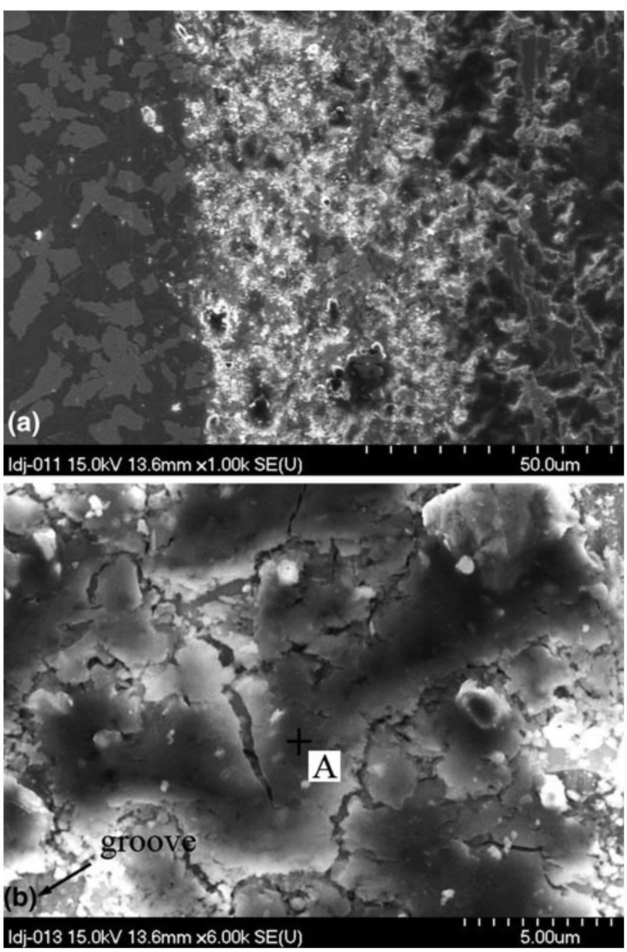

Fig. 6 Worn surface of the surface MMC. (a) Overview of the wear track and (b) debris on the worn surface of the surface MMC

iron-based matrix. The iron-based matrix is rich in tungsten and carbon. Fine carbides dispersed in the matrix make the hardness of the surface MMC very high.

Friction coefficients of the surface MMC and the substrate versus sliding time are shown in Fig. 4. After a short incubation period, the friction coefficient of the surface MMC becomes constant. The coefficient of friction of the surface MMC is about 0.2 in the whole process.

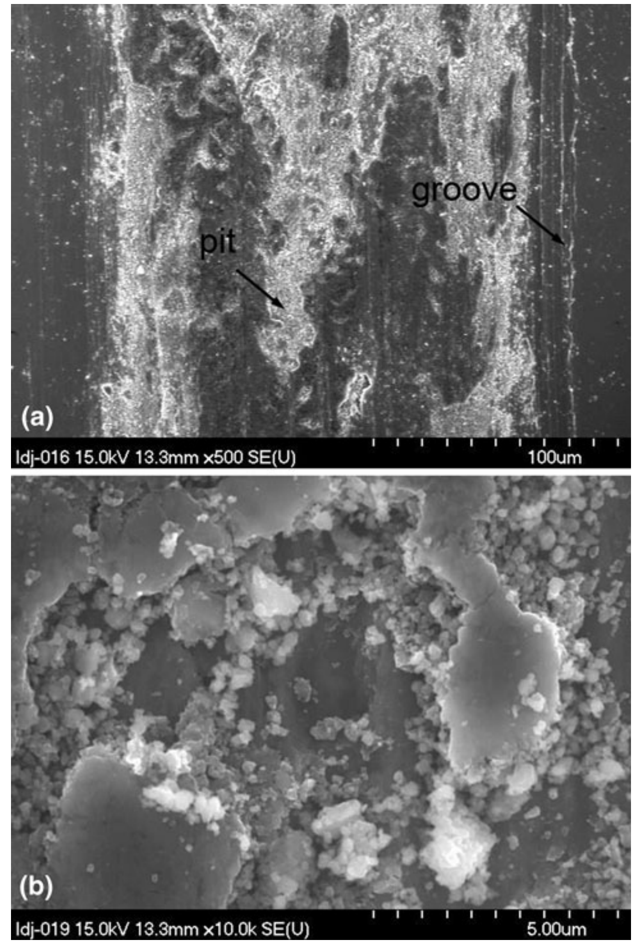

Fig. 7 Worn surface of the Q235 steel. (a) Overview of the wear track and (b) debris on the worn surface of the Q235 steel

The coefficient of friction of the Q235 substrate increases to about 1.0 a short time after the incubation period, and then decreases to about 0.8. Then, the friction coefficient increases continuously to about 1.1 after a long transition period. The friction coefficient of the surface MMC is significantly lower than that of the substrate.

The wear loss of the surface MMC and the substrate versus time is shown in Fig. 5. The wear loss of the surface MMC is about 2-4 mg/h, much lower than that of the substrate, which is about 60-80 mg/h.

Figure 6 shows the worn surface of the surface MMC after dry sliding against the SiC ball under 50 g normal pressure for 2 h. The morphology of the worn surface of the reference substrate Q235 steel with the same wear conditions is shown in Fig. 7. The wear track on the surface MMC is very smooth. No grooves can be found even when the magnification ratio is 1000 (Fig. 6a).

While deep grooves along the sliding direction can be easily found on the worn surface of the reference substrate Q235 steel sample when the magnification is only 500 (Fig. 7a). Removing of material by adhesion is also very obvious. The hardness of the Q235 steel is only Hv234.0. When the SiC ball slides against the surface of the Q235 steel sample, substantial plastic deformation and micro-cutting occur on it. The adhesion

Table 2 EDS analysis of point A in Fig. 6(b), wt.%

Element:	Fe	Co	W	O
Content	63.4	7.7	20.7	8.2

between the SiC ball and the Q235 steel is also very serious because SiC can be wetted by Fe very easily. While the hardness of the surface MMC is much higher. The hardness of the surface MMC prevents occurrence of great plastic deformation and micro-cutting when the surface MMC is under the same wear condition with the Q235 steel. The high hardness of the surface MMC also minimizes material removal by adhesion between the wearing parts. The large amount of tungsten carbides existing in the surface MMC also helps to minimize the adhesion between the SiC ball and the surface MMC. So the friction coefficient of the surface MMC is much lower than that of the Q235 steel. Greater fluctuation of the friction coefficient of the Q235 steel also suggests severe adhesion between the Q235 steel and the SiC ball.

Typical debris on the worn surface of the surface MMC are shown in Fig. 6(b). EDS analysis of the debris shows that there is oxygen element in it, as shown in Table 2. These oxides that are formed in the sliding process also help lowering the friction coefficient. Very shallow grooves can be found in the highly magnified SEM image, as shown in Fig. 6(b).

4. Conclusion

Dry sliding wear resistance of low carbon steel Q235 can be greatly improved by PMI of WC particles. The hardness of the surface MMC is over Hv1000, much higher than that of the substrate. The high hardness lowers the adhesion and abrasion of the surface MMC, and also the friction coefficient of it. The oxides formed in the sliding process also help to lower the friction coefficient. In this way, the dry sliding wear resistance of the surface MMC is greatly improved.

References

1. L. St-Georges, Development and Characterization of Composite Ni–Cr + WC Laser Cladding, *Wear*, 2007, **263**, p 562–566
2. Y.Y. Liu, J. Yu, H. Huang, B.H. Xu, X.L. Liu, Y. Gao, and X.L. Dong, Synthesis and Tribological Behavior of Electroless Ni–P–WC Nanocomposite Coatings, *Surf. Coat. Technol.*, 2007, **201**, p 7246–7251
3. Z. Li, Y. Jiang, R. Zhou, D. Lu, and R. Zhou, Dry Three-Body Abrasive Wear Behavior of WC Reinforced Iron Matrix Surface Composites Produced by V-EPC Infiltration Casting Process, *Wear*, 2007, **262**, p 649–654
4. P.K. Deshpande and R.Y. Lin, Wear Resistance of WC Particle Reinforced Copper Matrix Composites and the Effect of Porosity, *Mater. Sci. Eng A*, 2006, **418**, p 137–145
5. K.A. Chiang and Y.C. Chen, Microstructural Characterization and Microscopy Analysis of Laser Cladding Stellite12 and Tungsten Carbide, *J. Mater. Process. Technol.*, 2007, **182**, p 297–302
6. C. Navas, R. Colaço, J. de Damborenea, and R. Vilar, Abrasive Wear Behaviour of Laser Clad and Flame Sprayed-Melted NiCrBSi Coatings, *Surf. Coat. Technol.*, 2006, **200**, p 6854–6862
7. Y.T. Pei, V. Ocelik, and J.T.M. De Hosson, SiCp/Ti-6Al-4V Functionally Graded Materials Produced by Laser Melt Injection, *Acta Mater.*, 2002, **50**, p 2035–2051
8. M. Zhao, A. Liu, M. Guo, D. Liu, Z. Wang, and C. Wang, WC Reinforced Surface Metal Matrix Composite Produced by Plasma Melt Injection, *Surf. Coat. Technol.*, 2006, **201**, p 1655–1659