Research on dynamic wear behavior at elevated temperature of HVOF sprayed nanostructured WC-17Co coating

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Abstract. Nanostructured WC-17Co coatings have been prepared by means of High Velocity Oxy-fuel (HVOF) technique. The wear resistance at the elevated temperature (500°C) of nanostructured coatings was compared using GCr15 steel as counterpart in sliding wear tests. The results show that when at the temperature of 500°C, the wear failure mechanism turns from plastic deformation to fracture resulted from crack propagation and adhesive wear. With the wear going, abrasive wear dominate in the coating, then turns into adhesive wear with changes of microscope.

1. Introduction
Many engineering components are subjected to elevated temperature in tribological conditions during service. High contact surface temperatures also arise due to the generation of friction heating, particularly for large sliding speeds and contact loads. Under these extreme environments, the wear resistance strongly diminishes, which may lead to the rapid failure of the coating [1, 2]. Thus, it starts to be a priority to know the tribological behavior of hard coatings with temperature.

WC-Co materials have been widely applied in cutting tools and wear resistant components for its high hardness, strength and wear resistance.

Yang et al. [4] researched the sliding wear behavior of HVOF sprayed WC-12%Co coatings at elevated temperatures. Previous work [5] researched the wear behavior of nanostructured and ultra-fine HVOF Spraying WC-17Co coatings at 600°C. The results show that the wear resistance and the fracture toughness of the nanostructured coatings at elevated temperature are better than that of the ultra-fine coatings. Ref [6] investigated the friction and wear behavior at 600°C of plasma sprayed nanostructured WC-Co coatings.

A lot of researches have carried out on HVOF spraying nanostructured WC-Co coatings. However, the dynamic wear failure mechanism at high temperature of HVOF spraying nanostructured coating is little understood. In the present study, nanostructured WC-17Co coatings have been prepared by means of High Velocity Oxy-fuel (HVOF) technique. The dynamic wear failure mechanism at
elevated temperature of HVOF spraying nanostructured WC-17Co coating was studied using the high temperature sliding wear tester.

2. Experimental detail
One commercial nano powder was used as feedstock in the present study. The powder was agglomerated into sprayable sizes. The powder was obtained from Inframat Ltd., Famington, USA. The powder characteristics are shown in Table 1.

| Feedstock powder | Feedstock size/μm | WC grain size |
|------------------|-------------------|--------------|
| Nanostructured WC-17Co | 5-45 | 50-500nm |

The Q235 was used as substrate. The HVOF spraying system was D-3000 (Zhengzhou Dayang Thermal Spraying Co. Ltd.). Airplane kerosene was used as a fuel. The optimized HVOF parameters are summarized in Table 2.

| Sliding wear WC-17Co | Oxygen (m³/h) | Fuel (m³/h) | Ar (m³/h) | Powder-feed rate (g/min) |
|---------------------|--------------|-------------|-----------|------------------------|
| Nanostructured WC-17Co | 35 | 25 | 0.7 | 1.0 |

Sliding wear test was carried out using MMU-5G sliding tester (Yihua Tester Co. Ltd., Jinan, China), which described in Ref [6]. Sliding wear tests were performed using GCr15 steel as the counterpart, at sliding speed of 200r/min. And wear circumstance temperature is 500℃, under constant load of 200N. Weight losses of the specimens were measured using an electronic balance with an accuracy of ±0.1mg. The worn traces were observed with SEM.

3. Results and discussion
The worn trace after different wearing time all consist of bright region (A) and dark region (B). EDS analysis indicates that there is more element Fe in region B than in region A except the worn trace after 40min wearing, which illustrates that adhesion wear is more severe in region B.

It can be seen from Figure 1 (a) that after wearing 20min, the wear of the coating is slight. From Figure 1 (b), magnification of region A, it can be found that the morphology is similar to the coating before wearing. WC particles distribute uniformly and dispersive in the Co matrix. Figure 1 (c) is magnification of distinct B in Figure 1 (a), from where it can clearly be seen traces of plastic deformation, which could be rational since the local flash temperature at the rubbing interface might be sufficiently high to soften the asperities in contact and cause deformation of the asperities under initial high contact stress [7].

Figure 1 (d) is the worn trace of coating undergoing 40min wearing. From the EDS result, it can be concluded that severe adhesion wear occurs. Once adhesive between counterpart materials takes place, the adhesive force actually acts as a strain stress perpendicular to the lamellar direction. The adhesive force probably caused micro-cracking and fracturing along the inter-lamellar contact and resulted in flake off of flat plate-like lamella [8]. Figure 1 (e) is the magnified image of distinct A of Figure 1 (d). Oxide of Fe forms a tribofilm covering the coating. WC particles began to become broken. Because Co-based begins to melt and lost, the WC particles fracture in the process of wearing at high temperature. And the WC particles act as abrasive involved in the process of wear and being grounded. Figure 1 (f) is a magnified image of region B of Figure 1 (d). Cracks are clearly seen in the worn trace and fracture has occurred in some parts of the worn trace.

It can be seen from Figure 1 (g) that furrows form after 60min wearing. Figure 1 (h) indicates that the oxides formed in the surface detached from the coating, exposing a fresh surface. From Figure 1 (i) it can be found the cracks propagate, forming net-like shape. The contact points bear two kinds of load in the process of wearing: mechanical load and thermal load. Rapid increase of heat load leads to over-temperature in local surface of counterpart, resulting in larger temperature gradient within the objects, causing thermal stress. Under the dual roles of thermal stress and mechanical stress, surface and internal fracture by duplicating fever. Plastic deformation occurs with wearing. When deformation accumulates to a certain amount, cracks occur under the cyclic stress in the contact area. The expansion of cracks causes spalling in the region of cracking [9].

Furrows are visible in Figure 1 (j). And so are traces of adhesive wear. Figure 1 (k) is the enlarged image of region A in Figure 1 (j). It can be seen that WC particles has been broken and bonded.
together, losing the original morphology of WC particles, which illustrates that the coating morphology has already begun to change with wearing. From Figure 1 (k) it can be found the region of plastic deformation becomes smooth. The particles in Figure 1 (h) tear off down and become abrasive. In the grinding tablets wear process, the abrasive edges and corners will penetrate the material surface in the role of force, while pierce the material surface in the role of tangential force, resulting in furrows. The existence of particles will reduce the penetrated depth into the matrix and prevent further abrasive plowing, thus improving the wear resistance of materials. But after hard particles falling, they not only lose the role of anti-wear, but also become abrasive themselves, further exacerbate wearing and reduce the wear resistance of composite materials significantly. Usually rigid particles are uprooted under the impact instead of being refined gradually.

From Figure 1 (m) it can see that the coating experienced severe adhesive wear. Figure 1 (n) is the enlarged image of region A in Figure 1 (m). It can be found that the original morphology of WC can not be seen. The particles are connected together, which may due to extremely high flash point temperature. In the process of grinding, only a part of protruding particles bear pressure. The stress is so large and the flash point temperature is so high that may result in the melting of Co-phase, WC particles flow in the melting Co phase, and bond together under the role of friction force, forming the topography of Figure 1 (n). Figure 1 (o) is the enlarged image of region B in Figure 1 (m). It can be seen clear traces of plastic deformation and fracture of the coating.

From the analysis above, it can be concluded that plastic deformation occurs at the beginning. When plastic deformation accumulates to a certain degree, cracks occur under the dual roles of thermal stress and mechanical stress. The expansion of cracks causes delaminating in the region of cracking.

A part of the abrasives produced by spalling of coating are taken out of the worn surface, and some remain in the coating acting as abrasives participating wearing. The abrasives cut the coating, forming furrow morphology. The occurrence of abrasive wear deteriorates the wear process. With the processing of wearing, the transfer of materials has taken place between the coating and the counterpart and morphology of the coating changed dramatically.

4. Conclusions
(1) The worn trace after different wearing time all consist of two distinct regions. The dark region experiences severe adhesion wear.
(2) The wear mechanism is different after different wearing time.
(3) The wear failure mechanism of the coating turns from plastic deformation to fracture resulted from crack propagation and adhesive wear. With the wear going, abrasive wear dominate in the coating, then turns into adhesive wear again with changes of microscope.

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