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Tribological Behavior of Austenitic Stainless Steel and Vanadium Carbide Coated by TRD Process

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Abstract

In forming austenitic stainless steel sheet, galling is the major cause of tool steels failure. Coating on tool surface is an effective way to lessen galling tendency. In this paper, vanadium carbide coating by TRD process was conducted on tool steel and intentionally tempered in air to produce thicker vanadium oxide on vanadium carbide surface. Ring-on-disc wear test was conducted by sliding with austenitic stainless steel ring to investigate tribological behavior. Weight of ring was measured before and after wear tests. Chemical composition of ring surface was cross-section analyzed by EPMA. Surface of the disc was analyzed by XPS.

Wear test results show that weight loss of stainless steel increases with increasing normal load from 120 N till 320 N. EPMA analysis results of cross-section of stainless steel ring show that ring surface contains more Cr content than Fe content in surface oxide in specimen with 120 N load while more Fe content than Cr content is shown in that with 320 N load. XPS analysis of disc surface shows V_2O_5 and VO_2 on VC coating surface before wear test. Both Cr rich oxide on stainless steel surface and vanadium penta-oxide are thought to contribute to less adhesion of stainless steel on VC coated disc.

Keywords: Austenitic stainless steel, Adhesion, Vanadium carbide, TRD process

Introduction

In forming austenitic stainless steel sheet, galling is the major cause of tool steels failure.(1-3) Coating on tool surface is an effective way to lessen galling tendency. Substrate surface roughness is reported to be benefit for coatings layer to resist galling.(4-8) Smoother substrate roughness provides smoother surface roughness of hard coating. Furthermore, surface roughness of coating layer is also advantage to resist galling. Polishing of coating surface is recommended for more efficiency of coating layer.

Vanadium oxide which formed at high temperature on vanadium nitride layer plays a role as lubricant(9-10) during sliding which resulted in less adhesive wear. Previous work[11] indicated that chromium oxide contributed to less adhesion of stainless steel on VC coating surface. In this paper, vanadium carbide coating by TRD process was conducted on tool steel and intentionally tempered in air to produce thicker vanadium oxide on vanadium carbide surface. Wear test was performed by sliding with austenitic stainless steel ring to investigate tribological behavior especially galling tendency which stainless steel was stick on coating layer.

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Materials and Experimental Procedures

DC53 steel with diameter of 46 mm and thickness of 5 mm was used as disc in a ring-on-disc wear test by Friction and Wear Tester EFM III-1010 type. Ring is 304 austenitic stainless steel with outer diameter of 25.6 mm and inner diameter of 20.0 mm. Vanadium carbide was coated on the disc by TRD process in which vanadium oxide and boron carbide were dissolved in molten borax to coat vanadium carbide about 8 µm in thickness. Coating temperature is 1000°C with immersing time of 6.25 hours. After coating and quenching in oil, discs were tempered twice at temperature of 520°C for 2 hours in the furnace without controlled atmosphere to produce vanadium oxide. Disc surface was ground and polished till surface roughness Ra less than 0.032 µm before coating. After coating vanadium carbide coating layer was polished until surface roughness about 0.15 µm. Wear test was conducted with sliding distance of 2000 m. Sliding velocity was 1.432 m/s and normal load was varied from 120 N till 320 N. Since weight loss of disc is very low, only weight loss of ring was measured and reported in all wear tests. Wear track of disc was investigated by SEM. Chemical composition of ring surface was cross-section analyzed by Electron Probe Micro-analyzer (EPMA). Surface of the disc was analyzed by X-ray Photoelectron Spectroscopy (XPS).

Results and Discussions

In discs with controlled atmosphere during tempering, resulting in thinner vanadium oxide on the surface in previous work,[11] weight loss of stainless steel not only increases with sliding velocity from 0.716 m/s to 2.148 m/s, but also increases with increasing sliding distance especially at distance of 2000 m. In case of varying normal load, weight loss of stainless steel increases gradually between normal load from 120 N till 220 N and then increases abruptly at normal load of 320 N as shown in Figure 1. Figure 1 also shows relation of weight loss of austenitic stainless steel ring and normal load of present work. In discs without controlled atmosphere during tempering which thicker vanadium oxide is expected to form on coating surface, weight loss of stainless steel increases with increasing normal load from 120 N till 320 N. At normal load of 320 N, average weight loss of ring is about 28.9 mg which is much lower than that with thinner vanadium oxide in previous work. It is thought that vanadium oxide on the coating surface might contribute to lower weight loss of stainless steel ring.

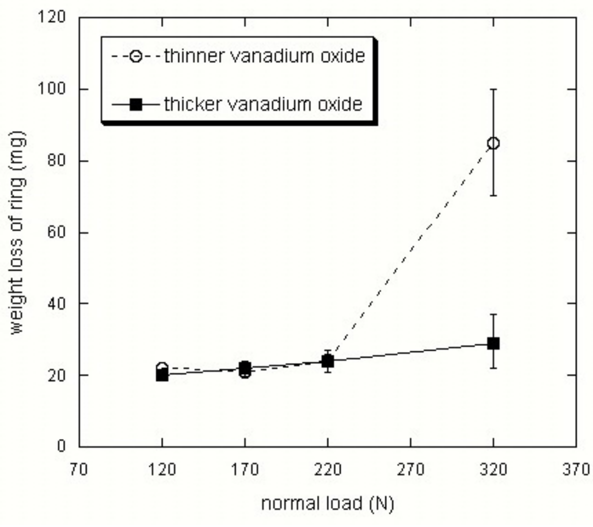
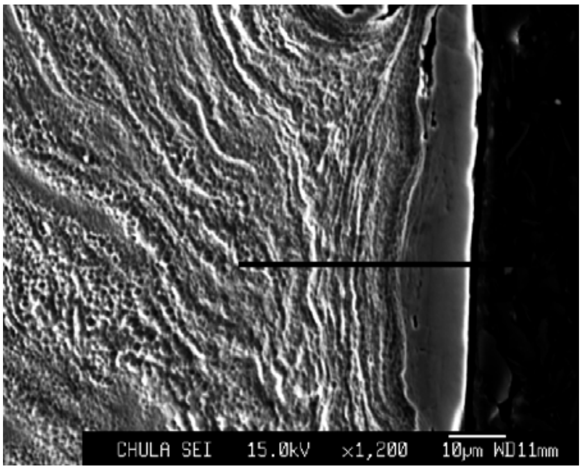
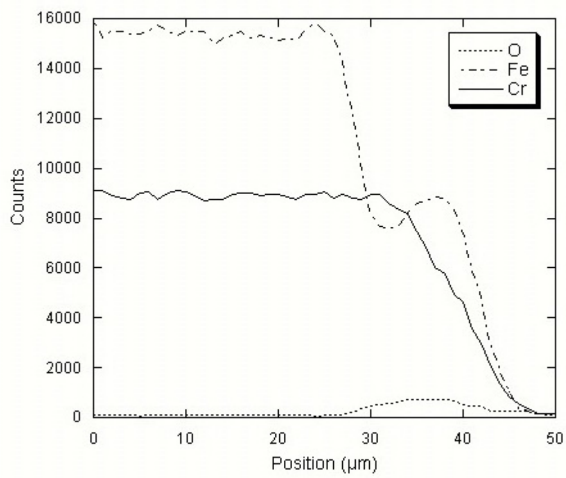


Figure 1. Relation of weight loss of stainless steel ring and normal load

Figure 2 shows EPMA analysis result of cross-section of stainless steel ring which was tested at normal load of 320 N. The stainless steel ring with low weight loss of 37.2 mg shows thick layer on surface after testing for 2000 m. This surface layer was analyzed by EPMA and shows that the layer contains Cr, Fe and O with thickness about 15 µm. The outer part of this layer contains Fe more than Cr while the inner part contains Cr a little more than Fe as shown in Figure 2 (b). This mixed oxide layer might be prone to stick to counter material.

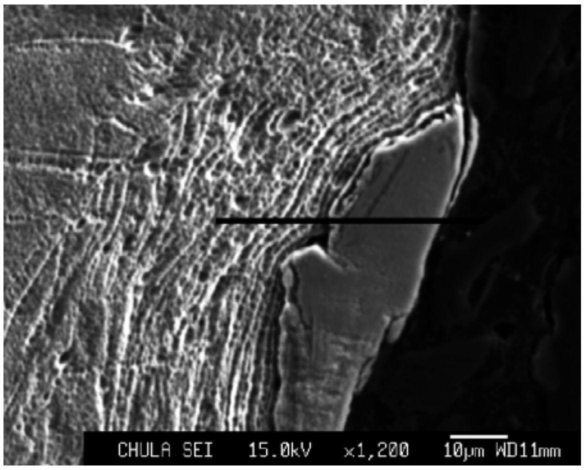


(a)

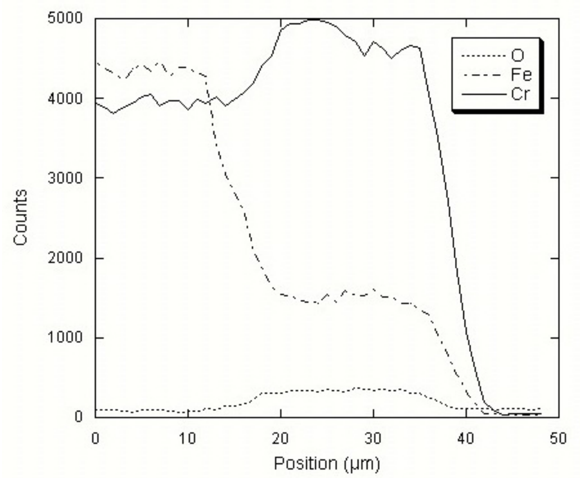


(b)

Figure 2. SEM image (a) and EPMA line scan (b) of specimen tested at 320 N normal load



(a)



(b)

Figure 3. SEM image (a) and EPMA line scan (b) of specimen tested at 120 N normal load

The ring with low weight loss of 18.8 mg which was tested at normal load of 120 N shows the layer on the ring surface with thickness about 20 µm in Figure 3 (a). EPMA line scan shows that the layer contain Cr, Fe and O; nevertheless, there is higher Cr content than Fe content while the inner matrix shows higher Fe content than Cr content as shown in Figure 3 (b). Though there is not layer on some places of the ring, this higher Cr content might not adhere to counter material, consequently contribute to lower weight loss.

Figure 4 shows XPS spectrum after sputtering for 600 seconds of disc which was coated with vanadium carbide and tempered in air. Before wear testing, the peaks of $V2p_{3/2}$ at 517.8 eV and $V2p_{1/2}$ at 524.5 eV are identified as V_2O_5. Peak of $V2p_{3/2}$ at 516.7 eV and $V2p_{1/2}$ at 522.2 eV are identified as VO_2 in agreement with the work of Manisha.[12] The surfaces containing vanadium oxides, confirmed that thicker vanadium oxide was formed on vanadium carbide surface during tempering without controlling atmosphere at temperature of 520°C. Figure 5 shows XPS spectrum after sputtering for 600 seconds of disc after wear testing. The peaks of $V2p_{3/2}$ at 517.3 eV and $V2p_{1/2}$ at 524.8 eV are identified as V_2O_5.

Considering stainless steel ring, before wear testing, no oxide layer was detected with EPMA and Fe content in stainless steel was more than Cr content. After wear testing for 2000 m, there is layer near surface with thickness about 20 μm in the specimen tested at normal load of 120 N. Cr content in this layer is more than Fe content and oxygen is also detected. It is thought that this layer is (Cr,Fe) oxide and is developed during sliding. The temperature during sliding increases as high as 400°C at sliding distance about 800 m in the specimen with 320 N normal load. Oxide layer forms intentionally at temperature lower than 500°C showed Fe content is higher than Cr content at the surface of stainless steel.[(13)] So (Cr,Fe) oxide layer formed under normal load during sliding is different from that heated in air. Oxide layer is found intermittently along the circumference of stainless steel ring. The Cr rich oxide might be less sticky against VC coating surface.

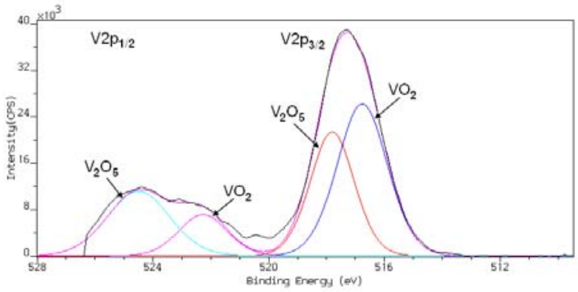


Figure 4. XPS spectra of V2p3/2 - V2p1/2 of vanadium oxides on disc surface before wear test

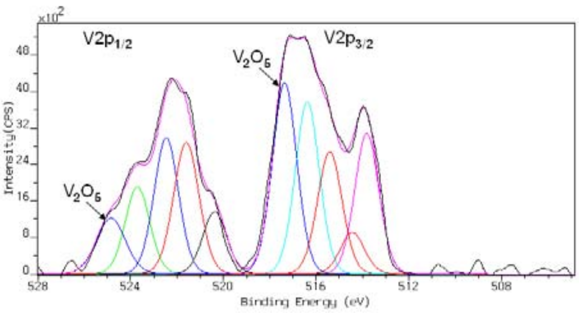


Figure 5. XPS spectra of V2p3/2 - V2p1/2 of vanadium oxides on disc surface after wear test

Considering VC coated DC53 disc, there is vanadium oxide especially V_2O_5 and VO_2. By calculation of area under XPS spectrum, both oxides content is about 50% by mass. The melting point of V_2O_5 is about 680°C while that of VO_2 is about 1545°C. During sliding, V_2O_5 could act as liquid lubricant in case that the temperature of V_2O_5 increases locally to it's melting point.

Figure 6 shows SEM image of stainless steel sticking on VC coating at normal load of 320 N while Figure 7 shows relation of friction coefficient and sliding distance with the same wear test condition. There is running-in period during sliding of VC coating disc and stainless steel ring at normal load of 320 N, which friction coefficient increases sharply at the beginning of the test, then decreases to about 0.30 with certain amount of sliding distance, and finally increases to nearly constant about 0.41. Fluctuation of friction coefficient means that stainless steel debris might be the case. When stainless steel including Cr-Fe oxide adhering to vanadium carbide of which the surface is vanadium oxide, vanadium penta-oxide might act as lubricant to sticking stainless steel which separates and becomes debris. This debris might scratch vanadium carbide and cause fluctuation of friction coefficient. At low normal load of 120 N, vanadium penta-oxide on vanadium carbide might be thick enough to prevent adhesion of stainless steel only after running - in period, during which certain amount of stainless steel adhere to vanadium carbide. Coincidentally, Cr-Fe oxide which developed on ring surface during sliding contains more Cr content than Fe content. This chromium rich oxide might not be prone to stick to the disc[13] resulting in lower weight loss of the ring. At high normal load of 320 N, after running-in period, vanadium penta-oxide might be available to act as lubricant so that friction coefficient decreases to about 0.30 and when vanadium penta-oxide is exhausted due to high normal load, more stainless steel adheres to the disc, giving rise to more weight loss of stainless steel ring.

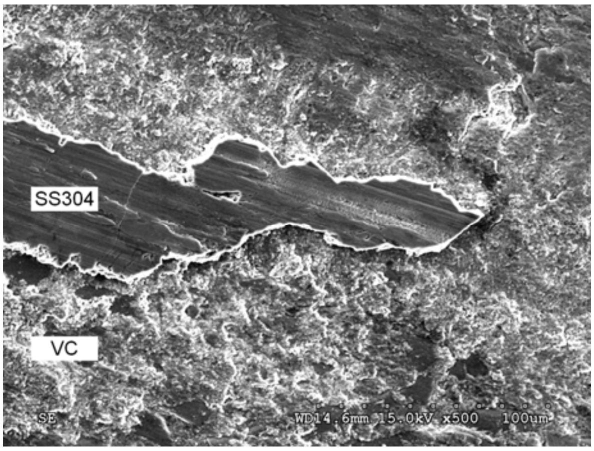


Figure 6. SEM image of stainless steel sticking on VC coating layer at 320 N normal load

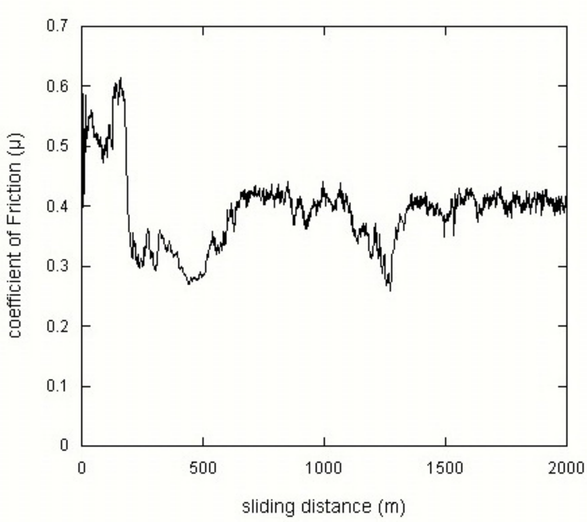


Figure 7. Relation of friction coefficient and sliding distance at 320 N normal load

Conclusions

Ring-on-disc wear tests between austenitic stainless steel ring and vanadium carbide coating disc between 120 N till 320 N of normal load were concluded as follows:

1. Weight loss of stainless steel ring increases with increasing normal load.
2. Both Cr rich oxide on surface of stainless steel and vanadium penta-oxide on vanadium carbide coating contribute to less adhesion of stainless steel.
3. Vanadium penta-oxide which is thick enough could decrease adhesion in some sliding conditions, namely low normal load.

Acknowledgement

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