IOP Conf. Series: Materials Science and Engineering **281** (2017) 012059 doi:10.1088/1757-899X/281/1/012059

Tribological Behavior of Coating Cr Layer on 40Cr after Surface Electron Beam Pretreatment

J J Hu[a*], J Wang[b], P Jiang, H B Xu, H Li and T F Hou

Chongqing University of Technology, Banan, Chongqing400054, China

Email:[a] 5671538@qq.com,[b]w1181748426@163.com

Abstract. In this study,the friction and wear behavior of PVD coatings which were treated by 5 different processes,based on gear material-40Cr. Analyzing the effects of treating the gear material with electron beam in combination with magnetron sputtering on it,for dry friction and wear properties.The result showed that the electron beam pretreated substrate was useful to improve the tribological performance of coating material.Furthermore, the surface roughness of coating ,the bonding force between substrate and coating as well as the load are the main factors affecting the tribological performance of this coating. Most importantly, the contribution of plowing effect on friction coefficient should be considered when the surface roughness is high.

1. Introduction

Gear transmission as the largest proportion of transmission form in the mechanical products has complex stress situation and a diversity of failure forms. Statistics showed that the gear transmission failure caused by the damage of the gear surface has been up to 74%[1,2]. This suggests that improving the gear surface performance is an effective way to improve the performance and service life of gear transmission.

Electron beam material surface modification can make the material surface cool after rapid melting by it , so it can change material's structure, improve its surface hardness and so on[3,4]. In this paper, the friction coefficient, the three-dimensional topography of worn surface, SEM and local area EDS analysis of worn surface will be used for exploring the effects of electron beam pretreatment on the tribological performance of PVD coating and discussing the wear mechanisms[5-7].

2. Material and experimental

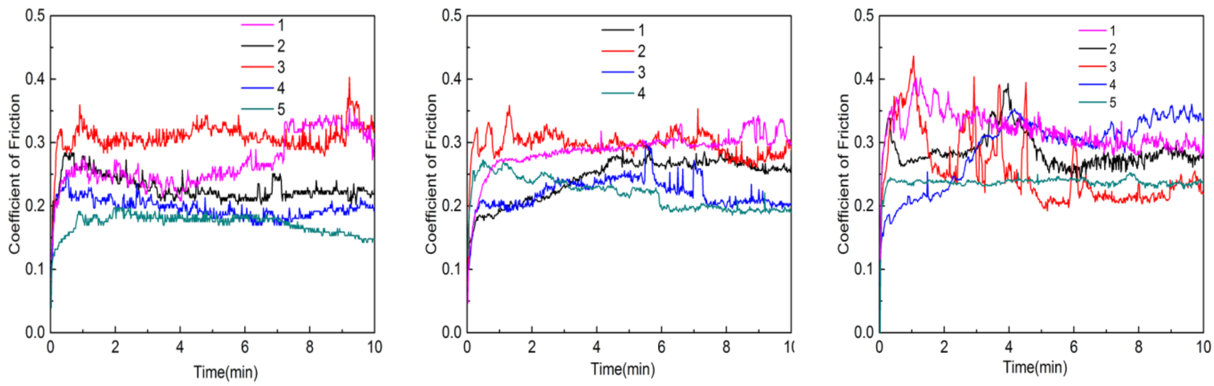
The common gear material—40Cr(C 0.39 %,Si 0.23%,Mn 0.70%,Cr 0.80%,Ni≤0.30%） was used in this experiment. There are five samples, after them have been modulated, sample 1 sputtered 2 μm Cr coating,and others treated by electron beam irradiation at the same voltage(27kV)while different times(sample 2,3,4 and 5 are 5times,15times,25times,35times respectively)then sputtered 2 μm Cr coating on their surface.The reciprocating dry sliding tests were carried out on a ball-on-flat tribometer (MFT-R4000), which has been described in detail in the literature[8] The friction pair is a Al_2O_3 ceramic ball (hardness: 1900 HV) with 4mm in diameter.

The Carle Zeiss vertical metallographic microscope Axio Imager (A10), super depth filed microscopy (Kean VR-3000) and scanning electron microscope (S-3700N) was used to observe the morphology of the wear tracks. Ambios profiler was used to measure their cross-sectional contour and wear volume. The energy dispersive spectrometer (EDS) in combination with the SEM morphology were also used to analyze the composition of worn surfaces and wear debris.

3. The experimental results

3.1. The Coefficient of Friction

The friction behavior of PVD coatings on 40Cr with various normal loads are illustrated in Figure 1. In general, the friction coefficient increased during the early stage of the test and then rapidly climbed to a relatively stable stage value and fluctuated around this stage at different degrees. After experiencing certain cycles, it began to decline obviously but eventually approached to a stable value. This suggests that the wear of the coating got into a dynamic equilibrium. The pictures reveal that the friction coefficient in relatively stable stage experiences more and more serious fluctuation with the increasing load except for the sample 5, moreover, this trend in sample 1 is most obvious. The mean stable friction coefficient of all samples increased with increasing load except for the sample 3,and it approximately increased with the increasing pre-irradiated times ,in general(as shown in Figure 2). This reveals that the load is not the only factor affecting the coating’s friction coefficient, and the friction coefficient of the samples which were pretreated by electron beam were not constantly increasing with the increasing load.



(a) load 5N (b) load10N (c) load 15N

Figure 1 Effect of applied load on the friction coefficient

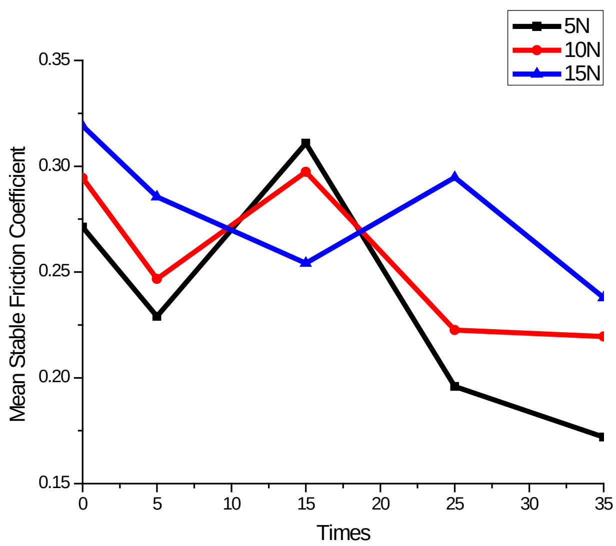
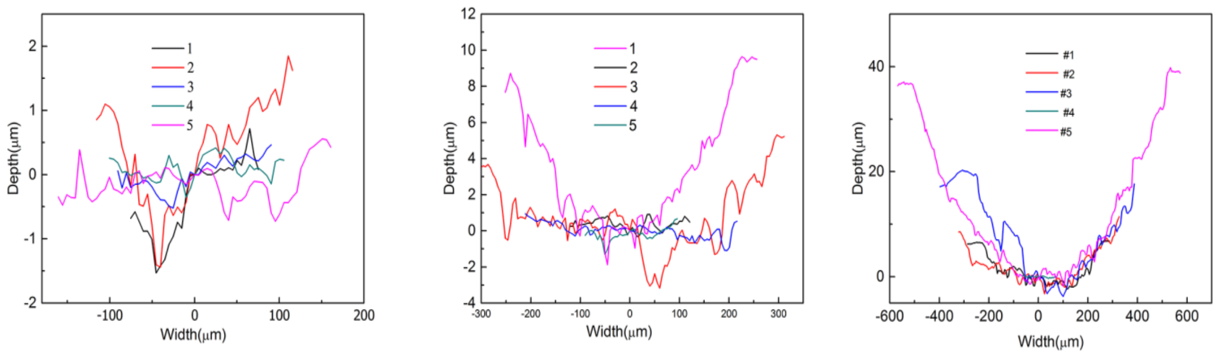


Figure 2 Mean stable friction coefficient at different load

IOP Conf. Series: Materials Science and Engineering **281** (2017) 012059 doi:10.1088/1757-899X/281/1/012059

3.2. Three Dimensional Morphology

The three-dimensional morphology of the wear tracks (as shown in Figure 3) indicates that all samples wear tracks morphologies had different shape and fluctuation degree, and although the width and depth of them changed a lot, that of sample 5 remained basically unchanged. The results suggest that the wear of samples gradually extended to the substrate from coating with the increase in the load except for the sample 5. Moreover, the morphology of wear tracks of samples 1, 3 and 4 are experienced a greater change and less stable wear than other 2 samples at various normal loads.



(a) load of 5N (b) load of 10N (c) load of 15N

Figure 3 The three-dimensional morphology of worn samples

3.3 The Fracture Morphology of Worn Surfaces

As we can see from the SEM micrograph of fracture morphology (as shown in Figure 4), five main types of wear morphologies were observed on the worn surfaces of all samples at various normal load. They were sheet spalling and delamination, continuous ploughing grooving, sheet pit, crack, sheet and filamentous shallow traces. At the different load situations,it's easily found that sample 5 had the highest degree of wear, and it always kept the simple ploughing lines morphology ,while others not only were worn severely but also had a very complex morphology.

4. Analyses and discussion

4.1. The Wear Mechanism

In order to more clearly clarify the wear mechanism of the five sample groups more clearly, the energy spectrum was used to analyze the oxygen content value in the representative worn areas of each

sample at different load situations, and the results are shown in Table1. It indicates that wear tracks of of each sample have oxide under all load situations.The dominate wear mechanism of coating in which the substrate hadn't pretreated was oxidation wear and fatigue wear.

The binding force of coating improved after the substrate had been treated by electron beam, the coating was too hard to chipped off under the repeated stress. With the increase of binding force, the spalling speed of coating was reduced,mainly abrasive wear was observed.

Therefore, it can be concluded that the main wear form for samples which were modified by electron beam pretreatment and PVD coating composite process is the abrasive wear. However,the bonding force between the coating and the substrate is the main factor which decides the wear mechanism of coating at a higher load. When the binding force is lower, oxidation wear is more likely to be observed.

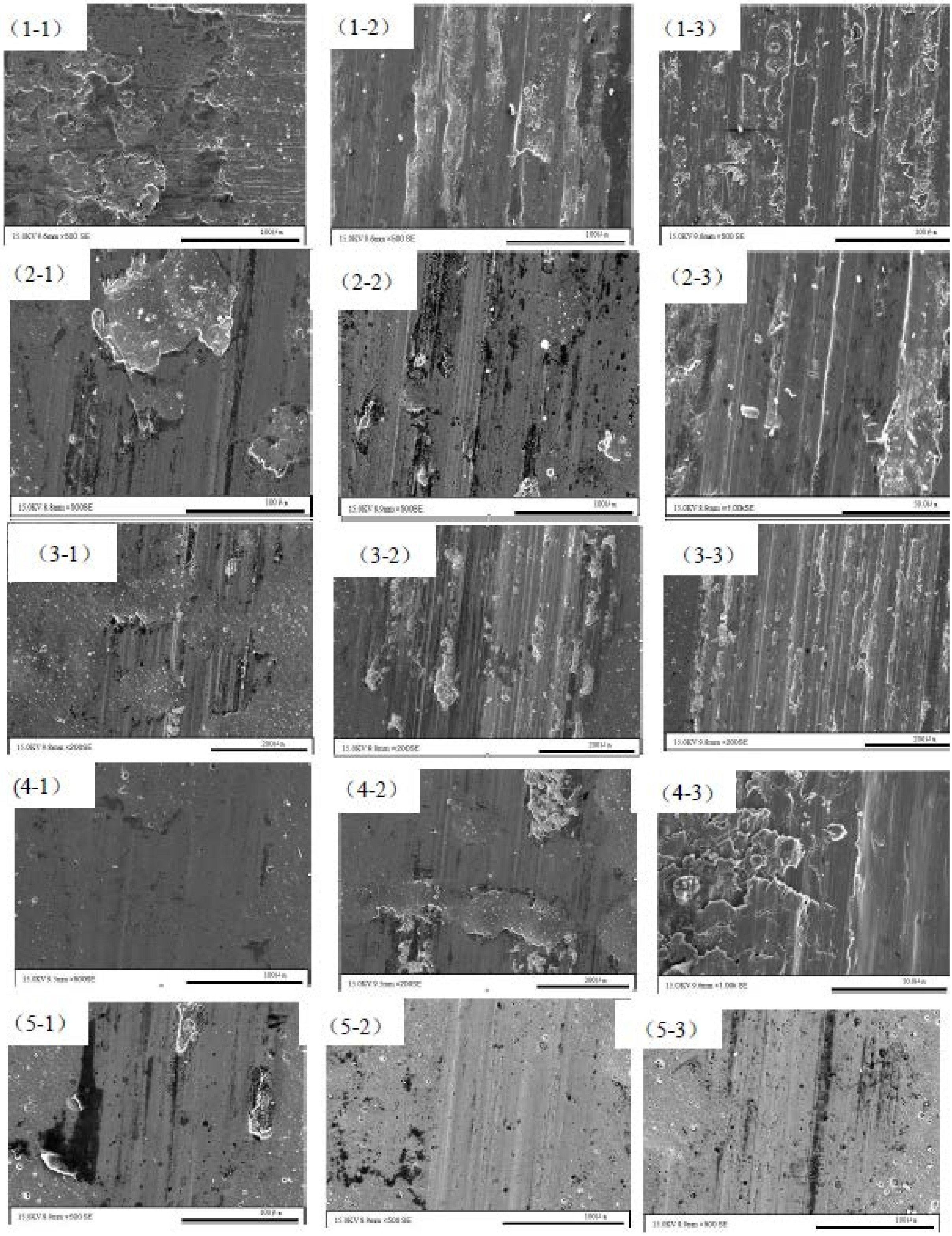


Figure 4 Representative SEM fractographs of worn surface for different samples (a)sample 1,(b)sample 2,(c) sample 3,(d)sample 4,(e)sample 5 under 5N,10N and 15N loads respectively

Table 1 Each sample's energy spectrum analysis of the oxygen content value on its representative areas at various loads (Wt %)

Load / Sample	5N	10N	15N
1	16.02	17.72	3.54
2	4.57	6.60	14.52
3	6.75	5.51	3.30
4	4.07	4.74	3.80
5	4.46	3.92	0.78

And with the gradually increase of binding force the fatigue wear and abrasive wear are also more susceptible to observed. However, the samples for which substrate were not pretreated by electron beam, fatigue wear and oxidation wear are observed at a lower load due to their poor bonding force.

4.2. Effects of Electron Beam Pretreatment on the Wear Resistance of the Coating

According to the research carried by Kenneth Holmberg [9], the coating-to-substrate hardness relationship, the thickness of the coating, the surface roughness and the contact debris are the four main factors affecting the macro wear mechanism of the coating.

In this study, however, the electron beam was used to pretreat substrate so these four factors mentioned above are also the main factors that affected the tribological properties of the coating. The hardnessincreased with the increasing irradiation time but the roughness increases first and then decreased with it on 27kV(as shown in Figure 5 and Figure 6). In addition, the bonding force between the substrateand the coating can also be improved by electron beam pretreatment. For example, the bonding force of 40Cr +Cr coating without electron beam pretreatment was about 12N,but it was improved afterthe electron beam pretreatement. Among them, the bonding force of samples 2 and 3 increased with 33.3% ,probably reaching 16N,and the bonding force of 4 and 5 increased with 41.7%, probably reaching 17N[10].

For the coating material itself, the bonding force between substrate and coating and the surface roughness determined by electron beam parameters have significant influence on friction coefficient of coating. So, in theory, the dry friction coefficient should decrease with the decrease of surface roughness under the elastic or elastic-plastic contact conditions [11].

So we can conclude that the bonding properties of coating and substrate are the main factors affecting the friction coefficient of the coating material when the binding force between coating and the substrate is poor, and under the same load, the bonding properties are poorer, the friction coefficient is higher. Furthermore, the roughness plays a key role when the roughness is too high. The friction coefficient increases with the increase of roughness in this situation. However, the friction coefficient of the same sample decreases with the increase of normal load. This is mainly because the high roughness surface is more likely to generate three body friction at a higher load.

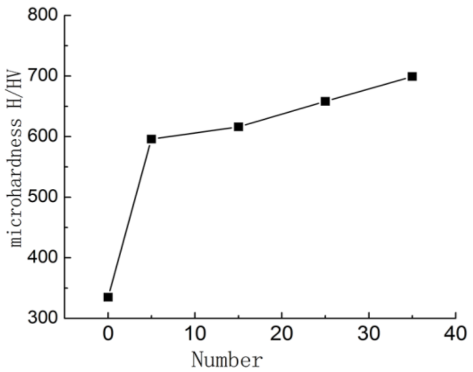


Figure 5. The hardness of pretreated substrates change with the irradiation times

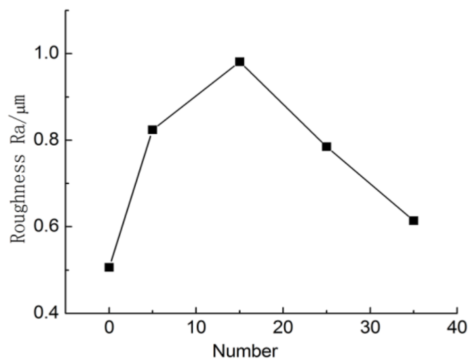


Figure 6. Roughness of samples change with irradiation times

5. Conclusions

Ball-on-flat reciprocating dry sliding wear tests with flats gear coating which was pretreated by electron beam and then sputtered Cr coating with PVD method was investigated against Al_2O_3 ceramic ball counterface at the normal load of 5N, 10N and 15 N. The main results can be summarized as following:

1) Generally speaking, the tribological properties of coating material could be improved by electron beam pretreated 40Cr substrate before it was sputtered to obtain Cr coating. And the sample 5 had the best tribological performance in this study.
2) At a lower load, the main wear mechanism was the abrasive wear. With the increase of load, oxidation wear was observed when the bonding force was poor while the fatigue and abrasive wear were observed when the bonding force was strong.
3) Besides the load, the bonding force between coating and substrate, and surface roughness are the main factors affecting the friction coefficient of the coating material. At the same load, bonding force played a dominant role and made the friction coefficient become larger when the bonding force was poor, however, the roughness played a dominant role and made the friction coefficient became larger when the roughness was too high.
4) The ploughing effect must be considered when the surface roughness is high and it can seriously affect the friction coefficient.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (51575073, 51501158 and 51275548), International Cooperation Special Project in Science and Technology of China (2015DFR70480), and Scientific and Technological Research Program of Chongqing (cstc2014gjhz70003 and cstc2017jcyjBX0031)

References

[1] Liu P D. Study on Failure Analysis and Failure Prevention of Gear. *Gansu Science and Technology* 2013; 02:28-31.
[2] Li R Z, Zhao Q H, *The Technical Information Publishing Division of Japan Society of Mechanical Engineers. Strength Design of Gear Data[M]*. Translate. Beijing: Machinery Industry Press 1984.
[3] Xu B S and Liu S C. Surface Engineering[M]. Beijing:Machinery Industry Press 2000.
[4] Li H. *Study on Process of Titanium Nitride Deposition onto Gears and Effects on Load-Carrying Ability of Gears[D]*. Chongqing University.2007.
[5] Dong C, Wu A, Hao S, Zou J, Liu Z, Zhong P, Zhang A, Xu T, Chen J, Xu J, Liu Q and Zhou Z. Surface treatment by high current pulsed electron beam[J]. *Surface and Coatings Technology* 2003,163-164:620-624.
[6] GaoY K. Use of low-energy, high-current electron beams for surface treatment of materials [J]. *Applied Surface Science* 2011;257(17):7455-7460.
[7] Guan Q F, Yang P L, Zou H and Zou G T Nanocrystalline and amorphous surface structure of 0.45%C steel produced by high current pulsed electron beam[J]. *Materials Science* 2006;41(2):479-483.
[8] Zhou F, Chen K M, Wang M L, Xu X J, Meng H, Yu M and Dai Z D. Friction and wear properties of CrN coatings sliding against Si3N4 balls in water and air[J]. *Wear* 2008;265(7-8)1029-1037.
[9] Holmberg K., Ronkainen H and Matthews A. Tribology of thin coatings[J]. *Ceramics International* 2000;26(7):787-795.
[10] Zhou Y. The study of technology and properties based on 40 Cr surface coating preparation by electron beam[D]. *Chongqing University of Technology* 2014.
[11] Liu Z L. Principles of Metal Tribology(The third edition)[M]. *Higher Education Press* 2009.