A Method of Using Continuous Surface Magnetization and Friction Coefficient Variations for Monitoring the Tribological Properties of CrO₂/SS400 Steel for the Flexible Gas Seal

Yuh-Ping Chang, Huann-Ming Chou, Meng-Jie Lin and Zi-Wei Huang
Department of Mechanical Engineering, Kun Shan University, Tainan, Taiwan, ROC

ABSTRACT
The experimental results demonstrate that the dynamic variations in surface magnetization and friction coefficient showed great potential for determining the onset of CrO₂ film fracture. It is also shown that the CrO₂ film resulted in low friction and low surface magnetization during the friction process, and is wear-resistant. Therefore, this study is novel and practical for the industry.

CrO₂/SS400 sample demonstrates no rutting wear, high wear resistance, low friction coefficient, and low magnetization.

1. Foreword
The rapid growth of contemporary industry has increased the demand for longer service life and better precision and reliability for all the parts of any piece of equipment. This is reflected in the large volume of research into wear damage. Dry friction, and wear due to friction which is the primary type of damage encountered in the drive elements of precision machinery, wind turbines, aerospace mechanics, and power facilities. In addition to adhesion between drive elements, mechanical vibration and that caused by noise also contribute to the accelerated generation and expansion of fatigue cracks, reduced product life, and even total system failure and severe industrial safety issues. Research on wear resistance is critical to industry.

Research into the enhancement and improvement in lubrication, material properties, and surface
coatings [14–19] are all widely used approaches to the problem. Hard ceramic surface coatings have been used [20–23] and reduce component friction and wear.

However, with its greater hardness, very good chemical stability, and lower friction coefficient, a CrO₂ layer [24,25] beats its ceramic material rivals in protecting drive elements from damage by friction. In most application CrO₂ is employed in grinding silicon nitride or chip for its chemical stability. This is not the case with railway, bridge, pylon, and scores of electronic equipment.[26–28] This paper concentrates on the friction between a CrO₂ layer and SS400 steel to measure changes in friction coefficient and surface magnetism under conditions of dry friction and severe wear. Scanning electron microscopy (SEM) was used for qualitative evaluation of wear in a study of the antifriction properties of CrO₂ film on a flexible air seal sheet. The results of this study may be valuable in the design of film coatings for products subject to dry friction.

2. Experimental apparatus and procedures

2.1. Experimental apparatus

The experiments were conducted on a pin/disk friction tester with the measuring systems as shown in Figure 1 to investigate the tribological properties of CrO₂/SS400 steel. The disk surface is set vertical to the ground to simplify wear mechanisms. The stationary pin specimen is placed on a rest, connected to the load cell and supported by the roller bearings. A load, vertical to the disk surface, is applied to the pin specimen using the level rule. This setup enables the accurate measurement of the friction coefficient between the specimens.

2.2. Test specimens

The thickness of the CrO₂ coating is approximately 1 mm. The disk specimen is made of SS400 steel. They are shown in Figure 2 and their material properties are given in Table 1. The pin and disk specimens were sequentially polished by 600–2000 grade of emery papers to a surface roughness, Ra, in the range 0.05–0.1 µm before each surface finishing.

2.3. Experimental procedure

The experimental parameters are shown in Table 2. Prior to each friction test, the specimens are cleaned with acetone in an ultrasonic cleaner and securely locked in position in the tester. As the output electric potential from the Gauss meter during the rotating friction process is in the order of mV, a DC isolated amplifier is used at a gain of 50. The response time of the measuring system is less than 1 ms with the accuracy of 0.1% full scale.

3. Experimental results and discussion

3.1. Responses of surface magnetization and friction coefficient

Figure 3 shows the typical responses of surface magnetization and friction coefficient with sliding distance produced by CrO₂/SS400 steel under a normal load of 60 N and a sliding speed of 200 mm/s. It is seen from this figure that the average friction coefficient was between 0 and 0.12 and the surface magnetic field was close to 0 G. A closer look suggests the following: the friction coefficient was practically constant between 0 and 0.1,

Table 1. Material properties of SS400 steel.

| SS400 wt(%) | C | Si | M | P | S |
|-------------|---|----|---|---|---|
|             | 0.050 | 0.050 |

Table 2. Experimental parameters.

| Pin       | SCM420 | ϕ5 mm |
|-----------|--------|-------|
| Disk      | SS400  | ϕ80 mm |
| Temperature | 25 ± 3 °C |
| Film thickness | CrO₂, t = 1 mm |
| Load      | 60, 80, 100, 150 (N) |
| Speed     | 200 (mm/s) |
| Lubrication | Dry friction |
Figure 2. The size and shape of the specimen.

Figure 3. Surface magnetization and friction coefficient responses for CrO₂/SS400 steel under a normal load of 60 N and a sliding speed of 200 mm/s.

Figure 4. Surface magnetization and friction coefficient responses for CrO₂/SS400 steel under a normal load of 80 N and a sliding speed of 200 mm/s.
The results of CrO₂/SS400 steel friction experiments under a normal load of 100 N and a sliding speed of 200 mm/s are shown in Figure 5. It can be seen from this figure that the average friction coefficient lies around 0.33 and the surface magnetic field varies over a range of from 0 to 10 G. A closer look suggests the following: to start with the friction coefficient rises fast from 0 to around 0.35 over a distance of from 60 to 170 m during which it remains stable. After 170 m, the coefficient shows a considerable degree of fluctuation. The surface magnetic field is very low and hardly changes up to 170 m after which it rises rapidly and may reach 10 G by 240 m after which it remains very high.

Under a load of 150 N the typical results for the same pair of samples, CrO₂/SS400 steel, at a sliding speed of 200 mm/s are shown in Figure 6. The average friction coefficient is steady at about 0.25, while the surface magnetic field varies over a range of from 0 to 40 G. A closer look suggests the following: to start with the friction coefficient rises fast from 0 to around 0.25 and remains steady at this level throughout the experiment. The surface magnetic field varies within a range from 0 to 40 G during the experiment. The strength of the surface magnetic field was zero all the way and magnetization was therefore negligible.

The typical responses of surface magnetization and the friction coefficient with sliding distance produced by CrO₂/SS400 steel under a normal load of 80 N and a sliding speed of 200 mm/s are shown in Figure 4. It is seen from this figure that the average friction coefficient lies between 0.35 and 0.45, and the surface magnetic field varies between 0 and 10 G. A closer look suggests the following: in the initial stages, the friction coefficient rises fast from 0 to around 0.3 over a distance of from 10 to 30 m. After a rapid initial rise the friction coefficient then remains constant at around 0.4. On the other hand, the strength of the surface magnetic field stays under 10 G for some time, but when the friction distance goes above 80 m it starts to rise and by the time the distance reaches 300 m the field may have reached a strength of 10 G.
Figure 7. The comparisons of surface magnetization and friction coefficient responses for the four material pairs of 60 N and a sliding speed of 200 mm/s. (a) CrO₂/SS400, (b) Fe/Fe, (c) Fe/Sn-film/Fe, (d) Fe/Sn-Al₂O₃ film/Fe.
the friction test. It then soars to around 18 G when the friction distance hit 30 m and may reach as high as 40 G at a distance of 260–280 m.

Figure 7 shows the comparisons of surface magnetization and friction coefficient responses for four different material pairs of at 60 N and 200 mm/s. It can be seen that the average friction coefficients of CrO$_2$/SS400 steel lie within a range 0–0.12, while the surface magnetic field remains at 0 G. A closer look suggests the friction coefficient remains flat within a range of 0–0.1 throughout the experiment period while the surface magnetic field stays at around 0 G, with almost no fluctuation whatsoever. With a dynamic friction coefficient that varies over a range of only 0.01–0.12, CrO$_2$/SS400 outperforms

| CrO$_2$ | X500 | X1000 |
|--------|------|-------|
| 60N    | ![Image](image1) | ![Image](image2) |
|        | ![Image](image3) | ![Image](image4) |

*Figure 8. Representative SEM images of CrO$_2$/SS400 steel under a constant load of 60 N and sliding speed of 200 mm/s.*

| CrO$_2$ | X500 | X1000 |
|--------|------|-------|
| 80N    | ![Image](image5) | ![Image](image6) |
|        | ![Image](image7) | ![Image](image8) |

*Figure 9. Representative SEM images of CrO$_2$/SS400 steel under a constant load of 80 N and sliding speed of 200 mm/s.*
3.2. SEM images of friction wear

SEM images of CrO₂/SS400 steel samples under the different loads and a sliding speed of 200 mm/s are shown in Figures 8–11. It is abundantly clear from the images that the other three specimens in this regard by 10- to 100-fold against Fe/Fe, five-fold against Fe/Sn-film/Fe, and is more than three-fold better than Fe/Sn–Al₂O₃ film/Fe and also surpasses all three cases with respect to surface magnetic field.
added 1 μm Al₂O₃ ceramic particles which behave as rollers that prevent the formation of ruts. The CrO₂/SS400 and Fe/Sn–Al₂O₃ film/Fe samples may share very similar friction resistant properties.

4. Conclusions

The feasibility of using continuous surface magnetization and friction coefficient variations for the evaluation of the tribological properties of CrO₂/SS400 steel was investigated under dry friction condition. From the experimental results and SEM observations of the extent and nature of the wear, the following conclusions have been drawn:

1. The dynamic variations in surface magnetization and friction coefficient showed great potential for determining the onset of CrO₂ film fracture.
2. The low friction coefficient of CrO₂, (0–0.1) proves the low susceptibility of CrO₂.
3. Almost no rutting wear in the CrO₂/SS400 steel sample demonstrates high wear resistance.
4. Surface magnetization stays close to 0 G suggesting low magnetization of CrO₂.
Acknowledgments

The authors would like to express their sincere appreciation for the two grants of financial support from the Taiwan Ministry of Science and Technology.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was financially supported by the Taiwan Ministry of Science and Technology [MOST 105-2622-E-150-001-CC2], [MOST 104-2221-E-168-019].

References

[1] Hutchings IM. Tribology: friction and wear of engineering materials. Boca Raton, FL: CRC Press; 1992. p. 73–92, 226, 227.
[2] Rabinowicz E. Friction and wear of materials. 2nd ed. New York: Wiley – Interscience; 1995. p. 34–43, 82–88, 242, 243.
[3] Masuko M, Shibatsuji M, Yokomizo M, et al. On the effort to discriminate the principal function of tribofilm on friction under the boundary lubrication condition. Tribol. Int. 2011;44:702–710.
[4] Marui E, Endo H. Significance of contact resistance in boundary lubrication. Wear. 1992;156:49–55.
[5] Kato S, Marui E, Kobayashi A, et al. The influence of lubricants on static friction characteristics under boundary lubrication. J. Tribol. 1985;107:188–194.
[6] Kato S, Marui E, Hashimoto M. Fundamental study on normal load dependency of friction characteristics under boundary lubrication. Tribol. Trans. 1998;41:341–349.
[7] Yang TS. Investigation of the strain distribution with lubrication during the deep drawing process. Tribol. Int. 2010;43:1104–1112.
[8] Carlson MF, Narasimha Rao BV, Thomas G. The effect of austenitizing temperature upon the microstructure and mechanical properties of experimental Fe/Cr/C steels. Metall. Trans. A. 1979;10A:1273–1284.
[9] Chai HF, Laird C. Mechanisms of cyclic softening and cyclic creep in low carbon steel. Mater. Sci. Eng. 1987;93:159–174.
[10] Thelning KE. Steel and its heat treatment: Bofors Handbook. Sweden: Smedjebacken-Boxholm Stål AB; 1975. p. 246.
[11] Nasreldin AM, Ghoneim MM, Hammad FH, et al. Effect of tempering on the toughness of a Cr-Mo bainitic steel. J. Mater. Eng. Perform. 1993;2:413–419.
[12] Sweeney TP Jr. Deep cryogenics: the great cold debate. Heat Treat. 1986;18:28–32.
[13] Collins DN. Deep cryogenic treatment of tool steels: a review. Heat Treat. Met. 1996;2:40–42.
[14] Butilenko AK, Vovk AY, Khan HR. Structural and electrical properties of cathodic sputtered thin chromium films. Surf. Coat. Technol. 1998;107:197–199.
[15] Viswanathan M, Ramachandran EG. Electrocodeposited composites of graphite, molybdenum disulfide and tungsten disulfide with copper for tribological applications. Met. Finish. 1980;78:55–60.
[16] Katsuhiro K, Masashi A. The frictional properties of a spray-bonded MoS2/Sb2O3 film under the fretting in vacuum. Lubr. Eng. 1995;51:943–949.
[17] Wang DF, Kato K. Coating hardness effect on the critical number of friction cycles for wear particle generation in carbon nitride coatings. Diamond Relat. Mater. 2002;11:1817–1830.
[18] Wang DF, Kato K. Coating thickness effects on initial wear of nitrogen-doped amorphous carbon in nano-scale sliding contact: part I – in situ examination. Tribol. Int. 2003;36:649–658.
[19] Wang DF, Hu N, Kato K. Coating thickness effect on initial wear of nitrogen-doped amorphous carbon in nano-scale sliding contact: part II – theoretical modeling. Tribol. Int. 2003;36:659–665.
[20] Wilson S, Alpas AT. TiN coating wear mechanisms in dry sliding contact against high speed steel. Surf. Coat. Technol. 1998;108–109:369–376.
[21] Hwang BJ, Hwang CS. Mechanism of codeposition of silicon carbide with electrolytic cobalt. J. Electrochem. Soc. 1993;140:979–984.
[22] Chen M, Kato K, Adachi K. Friction and wear of self-mated SiC and Si3N4 sliding in water. Wear. 2001;250:246–255.
[23] Hamdy MM, Waterhouse RB. The fretting fatigue behaviour of the titanium alloy IMI 829 at temperatures up to 600°C. Fatigue Fract. Eng. Mater. Struct. 1982;5:267–274.
[24] Quinn TFJ. The role of oxide films in the friction and wear behavior of metals. Tribology series 7. Amsterdam: Elsevier; 1982. p. 579–597.
[25] Chang YP, Hung YY, Chu LM, et al. The surface magnetization approach on assessing tribological properties of steels with different TiN coatings. Proc. Inst. Mech. Eng. J. J. Eng. Tribol. JET502. 2009;223:715–722.
[26] Chang YP, Yur JP, Chu LM, et al. Effects of friction on tribo-magnetization mechanisms for self-mated iron pairs under dry friction condition. Proc. Inst. Mech. Eng. J. J. Eng. Tribol. JET501. 2009;223:859–869.
[27] Chang YP, Horng JH, Yur JP, et al. The surface magnetization approach on assessing the tribological properties of iron sliding against iron coated with pure tin and with a tin composite. Proc. Inst. Mech. Eng. J. J. Eng. Tribol. 2011;225:1199–1208.