TUNGSTEN CONTAINING HYDROGENATED DLC COATINGS ON GREASE LUBRICATED HARMONIC DRIVE GEAR FOR SPACE APPLICATION

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ABSTRACT

Harmonic Drive gears are commonly used in space mechanisms. The performance degradation and even failure of grease-lubricated-type HD gear may be mainly caused by the wear of flexspline, circular spline, especially the interface between the wave generator and flexspline. Tungsten containing hydrogenated DLC (W-C:H) coatings have the potential to improve the wear resistance and working life of HD gears. In this paper, the tribological behaviors of W-C:H coatings deposited with different C_2H_2 flow were assessed. Coating composition was optimized based on ball-on-disc tribotester under grease lubrication in vacuum environment. The results show that the coatings exhibited a very low friction coefficient of 0.08 and good wear resistance. New in this work is that optimized coating was applied to existing grease lubricated HD gears for space application verification. Two HD gears have been carried out life test in space simulator. The result show that the coated grease lubricated HD gears can work more than 5,000 hours, which was beyond twice times that of original ones. The improved life owing to the W-C:H coating using was a statistically significant result.

1. INTRODUCTION

The combination of low mass, small volume and high drive ratio make harmonic drive gears one of the most important moving parts in space mechanisms since its coming out . Lubrication is a critical aspect for proper, effective performance. Applications for different conditions, there are solid-lubricated-type and grease-lubricated-type HD gears. The wear of gear pair, especially the interface on the flexspline which contacted to the wave generator could lead to bad performance and even failure [1-5]. Recently, due to their excellent properties, such as high hardness, high elastic modulus, low friction coefficient, good chemical inertness and low surface roughness, tungsten containing hydrogenated DLC (W-C:H) coating bring the chance to improve the wear resistance and life of HD gears.

In recent years, a lot of researches are being carried out on the structure, mechanical and tribological properties of W-C:H coatings with or without lubrication in air , little was done in vacuum, especially their applications on space moving mechanical parts [6-11].

In this study, the performances of three formula W-C:H coatings deposited by unbalanced magnetron sputtering (UBM) system with different C_2H_2 flow were assessed by ball-on-disc tribotester, accompanied with PFPE(perfluoroalkylether)grease lubrication in vacuum. The best performing coating was applied to existing grease lubricated harmonic drive gears and was subjected to life test in space simulator.

2. EXPERIMENTAL

2.1. Coating deposition

Tungsten-containing hydrogenated diamond like carbon coatings (W-C:H) were deposited by unbalanced magnetron sputtering (UBM) system (HAUZER, HTC750) using tungsten carbide targets in Ar/ C_2H_2 atmosphere at a deposited temperature of ~200℃. Three formulations of the W-C:H coatings have been evaluated. All coatings were deposited on 30CrMnSi steel substrates at a process pressure of 1.33 Pa, WC target power of 8 kW, bias voltage of -100V, with different flow of C_2H_2 parameters (from 10sccm to 45sccm). Prior to W-C:H coating deposition, the samples were plasma cleaned and Cr-based interlayer was applied to ensure coating adhesion.

2.2. Coating characterization

The coatings were characterized by thickness, hardness, elastic modulus and adhesion to the substrate. A CSM calotest was used to measure the coating's thickness. The hardness and elastic modulus were got by using CSM nano-hardness tester under depth control model with Berkovich indenter. Hardness and elastic modulus were determined from the load-displacement curves and calculated by the Oliver and Pharr method [12]. Penetration depth was limited to 100 nm to minimize the substrate contribution. The adhesion of the coating to the substrate was assessed by scratch testing, using a CSM nano-scratch tester. In this test the diamond stylus (R=2 μm) is drawn across the surface of the sample under a increased normal load of 30 mN/mm until cracking or spalling event occurred . The normal load at the broken

'14th European Space Mechanisms & Tribology Symposium – ESMATS 2011'
Constance, Germany, 28–30 September 2011

point is defined as the critical normal load Lc. The failure point was checked by inspection the scratch track under an optical microscope.

2.3. Ball-on-disc tribological testing

Tribological testing was carried out using a self-made vacuum tribometer instrument in a ball-on-disc configuration. AISI 52100 steel ball (Φ8 mm,Ra=0.02 μm) was used as the counterpart. Before testing, a thin layer of Brycote601 PFPE grease was uniformly smeared on the coated disc .Then the instrument was pumped down. When the pressure in the chamber was below 1×10^{-3} Pa , the disc was run at a normal contact load of 5 N and a sliding speed of 1.25 m/s, the radius of the wear scar on the disc was set to 12 mm. The test run at room temperature for 3×10^{5} laps. Resistance to motion of the stationary steel ball was measured by strain gauge and the real-time friction coefficients were calculated and drawn by the software. After test, the wear scars on both disc and ball were inspected using an optical microscopy.

2.4. Vacuum life testing of harmonic drive gear

Two harmonic drive gears , type HD60 with a reduction ratio of 100 and lubricating with PFPE grease (Braycote 601) were provided for testing. The surface of flexspline and Circular spline were all coated with optimized W-C:H coating. The movement conditions of the HD gears in the life test are showed in Tab. 1. It was decided that the test pieces were taken out from the vacuum simulator when the test was proceeded at 1000 h, 2000 h, 3000 h, 3500 h, 4000 h, 4500 h and 5000 h. The main performances such as transmission accuracy, backlash and efficiency of the gears would be assessed using a special measurement system .

The simple principle of performances test is showed in Fig.1. For transmission accuracy test,The input angular (ω_i) and output angular (ω_o) were measured at rated output torque and input speed. The transmission accuracy is defined as the difference between ω_o and ω_i divided by the reduction ratio. When test the backlash, the input axis will be fixed. The output angular was measured when output load torque change with four stages(first load from 0 N·m to 20N·m; then unload from 20N·m to 0N·m; and then load from 0 N·m to -20N·m; last unload from -20N·m to 0N·m). For efficiency test, the angle encoder at input side will be replaced by torque sensor. The performance test conditions are showed in Tab. 2.

Table 1 Life test condition

Test	Item and condition
Life test	Swing range: 0~165° Inertia load: 0.14kg·m^2 Output speed: 0.75°/s Temperature: room temperature(20~25℃) Pressure: <1×10^{-3} Pa

Table 2 Performance test condition

Test	Item and condition
Performance test	Output load torque: 20N·m Input speed: 100 r/min Temperature: room temperature(20~25℃)

Table 3
Properties of the different W-C:H formulas coatings

Coating formulas	Thickness (μm)	Hardness (GPa)	E-modulus (GPa)	Critical load (mN)
A	1.2	13.1	102.9	79
B	1.1	11.5	98.3	85
C	1.3	9.2	89.0	92

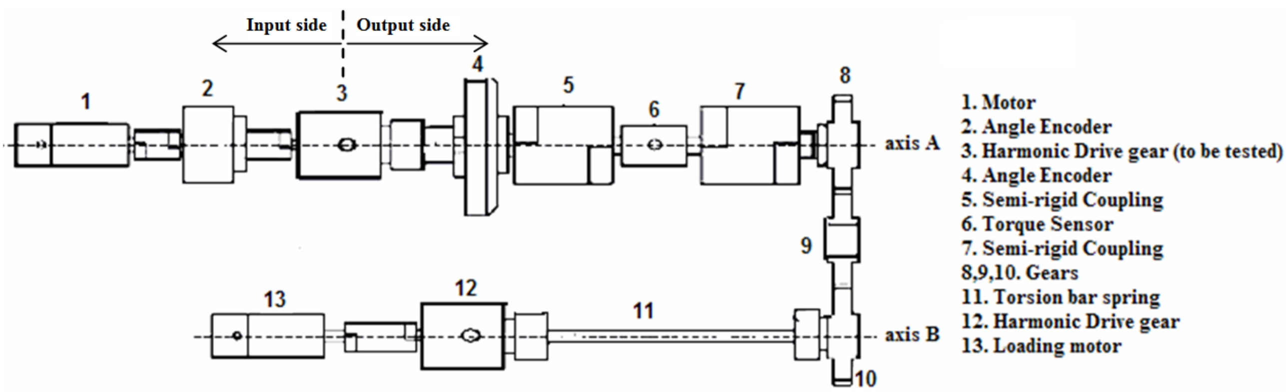
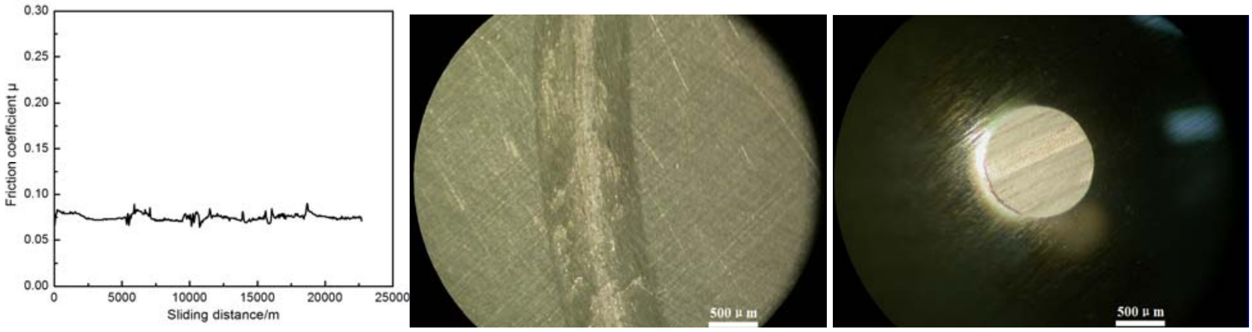
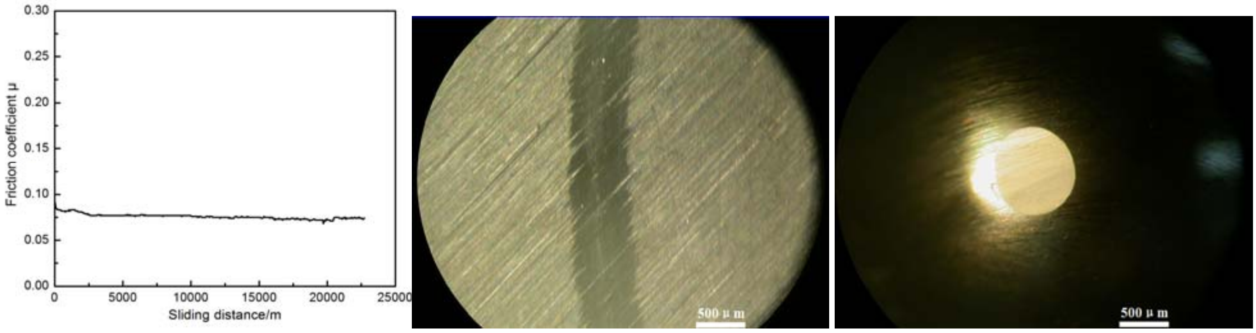


Figure 1 diagram of performance test



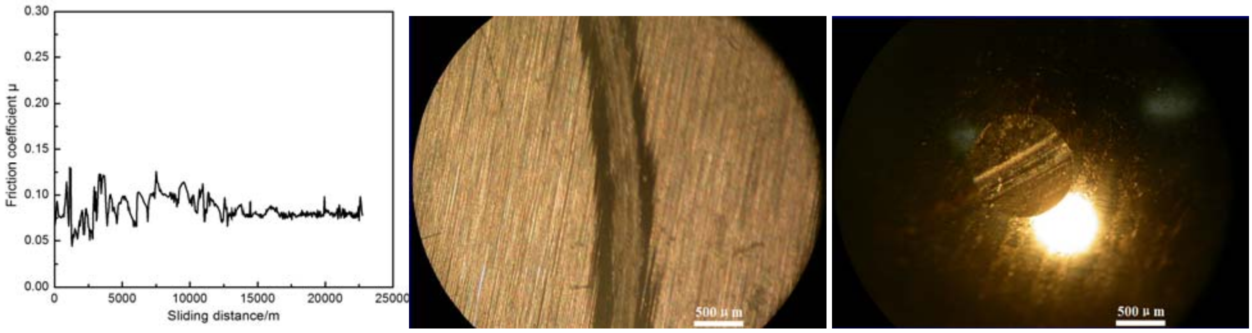
(a) (b) (c)

Figure 2 Vacuum tribological test results of W-C:H coating formulas A under PFPE grease lubrication, (a) friction coefficient versus sliding distance, (b) wear track on disc(4.5×), (c) wear scar on steel (4.5×)



(a) (b) (c)

Figure 3 Vacuum tribological test results of W-C:H coating formulas B under PFPE grease lubrication, (a) friction coefficient versus sliding distance, (b) wear track on disc(4.5×), (c) wear scar on steel (4.5×)



(a) (b) (c)

Figure 4 Vacuum tribological test results of W-C:H coating formulas C under PFPE grease lubrication, (a) friction coefficient versus sliding distance, (b) wear track on disc(4.5×), (c) wear scar on steel (4.5×)

3. RESULTS AND DISCUSSION

3.1. Coating quality assessment

Tab. 3 shows the quality control results for the different coating formulas. The thickness of the coatings is 1.2±0.1μm. It can also be found that all of the coatings have a good adhesion to the substrate. From formula A to C, the critical normal load is 79 mN, 85 mN, and 92 mN respectively. It can be seen that the adhesion of W-C:H coatings increases with the increasing of C_2H_2 flow. This behaviors can be explained by the ideas of C. Strondl that the compressive stress of the coating will decrease when we increase the C_2H_2 flow during deposition[13], and the higher the compressive stress, the easier the coating spalling when scratching.

In Tab. 3, changed hardness and elastic modulus can be seen at different coating formulas. The hardness of Formula A, B and C is 13.1 GPa, 11.4 GPa, and 9.2 GPa respectively and their corresponding elastic modulus is 102.9 GPa ,98.3 and 89.0 GPa. It can also be seen that with the increasing of the C_2H_2 flow, the hardness and elastic modulus of the coatings will decrease. During deposition, a very soft a-C:H matrix and a hard WC phase will compose the coating, higher C_2H_2 flow will decrease the ratio of the hard WC phase and then reduce the hardness.

3.2. Ball-on-disc tribological results

The vacuum tribological test behaviors of different formula coatings are shown in Fig.2, Fig.3 and Fig.4. It can be seen that the formula B got the best results which revealed the most smooth friction coefficient and the least wear on disc and ball. Under PFPE grease lubrication in vacuum, the friction coefficient of this coating changed between a very small range from 0.07 to 0.09. Compared , Formula A got a better tribological performance than C, and their friction coefficient is between 0.06 ~ 0.10and 0.05~0.13 respectively. The fluctuation of the friction coefficient could be related to a periodical removal and recovery of a transfer layer built up on the surface of the ball, the grease distribution in the contact region or the debris produced during the rubbing. Microscopic inspection of the wear track and wear scar after the tests showed relatively low amounts of debris, suggesting that fluctuations are probably not mainly arose from them. It might be associated with the establishment of continuous, sufficient and uniform grease on the contact area which requires further study.

3.3. HD gears Life test results

Fig.5 shows the evolution of transmission accuracy versus cumulative working life of two HD gears. The first 3500 h, the transmission accuracy of the tested HD gears decreased relatively slow, the change range of HD gears 1 and 2 is 0.008° to 0.017° and 0.009° to 0.016° respectively. After 3500 h , the decline tendency becomes quickly, the transmission accuracy of them reduced from 0.017° to 0.025° and 0.016° to 0.021° respectively.

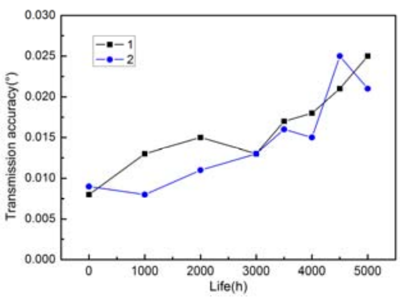


Figure 5 Transmission accuracy versus life time for two HD gears 1and 2 at output load torque of 20N·m.

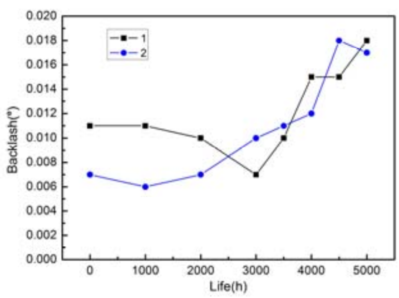


Figure 6 Backlash versus life time for two HD gears 1and 2 at output load torque of 20N·m.

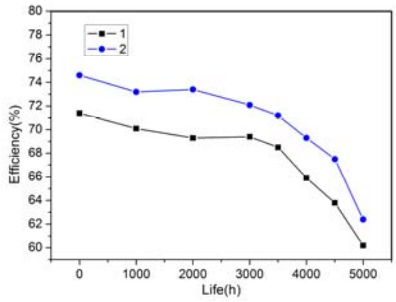


Figure 7 Efficiency versus life time for two HD gears 1 and 2 at output load torque of 20N·m.

Fig.6 shows the evolution of backlash versus cumulative life of two HD gears. The evolution is similar to that of transmission accuracy. The backlash of two test pieces grew slowly from begin to 3500 h, and rapidly increased afterwards. When the working life reached 5000 hours, the corresponding backlash of HD gears is about 0.018° .

Fig.7 shows the evolution of efficiency versus cumulative life of two HD gears. Similarly, the efficiency decreased slowly from 71.4% to 68.5% and 74.6%° to 71.2% of two HD gears respectively at the first 3500 h and then rapidly reduced to about 60% after that time.

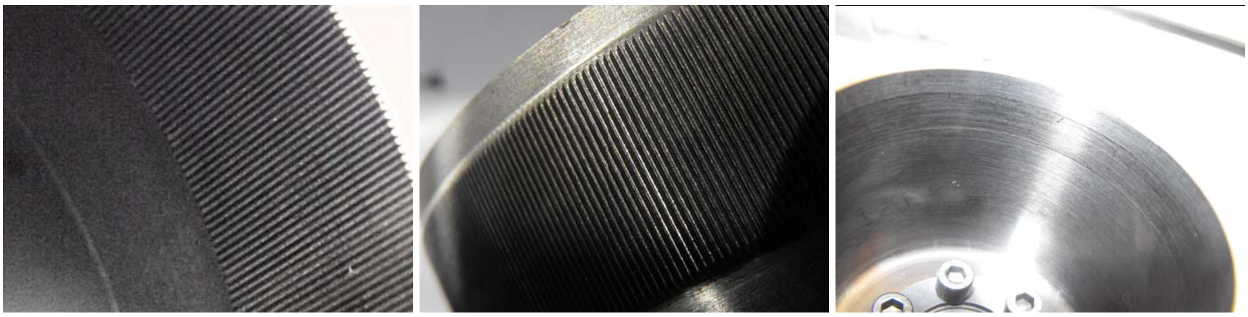

(a) (b) (c)

Figure 8 Condition of rubbing surface after life test (gear 1):(a) circular spline teeth, (b) flexspline teeth, and (c) flexspline inner surface

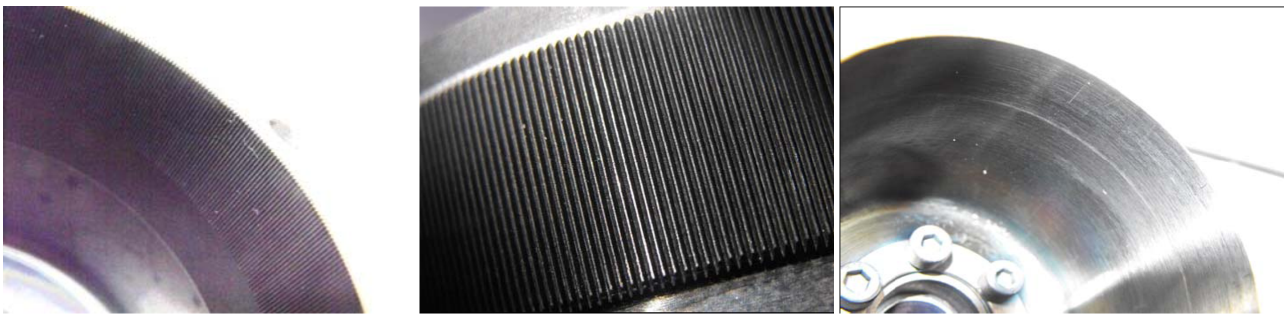

(a) (b) (c)

Figure 9 Condition of rubbing surface after life test (gear 2):(a) circular spline teeth, (b) flexspline teeth, and (c) flexspline inner surface

After life test, the surface of the gear pair and inner flexspline were checked and are shown in Fig.8 and Fig.9. There are no evident wear on both of the two HD gear pairs, only some slight wear scars were found at the interface of flexspline to wave generator, which is much better than that of the uncoated grease lubricated HD gear which underwent 2000 h life test (see Fig.10). From this point of view, W-C:H coating can effectively improve the wear resistance of HD gears. The coated grease lubricated HD gears can work more than 5,000 hours, increased at least one time of that of uncoated ones.

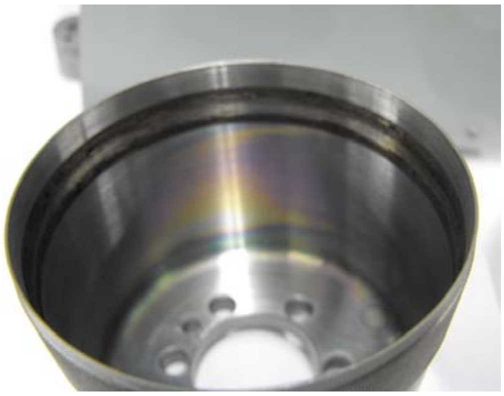


Figure 10 flexspline inner surface of uncoated grease lubricated HD gear

4. CONCLUSION

Through changing the C_2H_2 flow during coating deposition , Tungsten-containing hydrogenated diamond like carbon coatings with different properties such as hardness, elastic modulus and adhesion to the substrate will be got. In this study, the hardness of the coatings is between 9.2~13.1 GPa, corresponding elastic modulus increased from 89 to102.9 GPa , and their adhesion improved from 79 to 92mN.

Ball-on-disc tests have shown that the tribological performance of hydrogenated DLC coatings depends strongly on the deposition conditions. Coating formula B showed an excellent tribological performance in vacuum under PFPE grease lubrication, revealed the most smooth friction curve and the least wear on rubbing pair, and at the same time got a low average friction coefficient of 0.08 .

Life tests were conducted in vacuum simulator on two Harmonic Drive gears (type HD60) which were lubricated with formula B W-C:H coating and Braycote 601 grease. It was observed that the performances such as transmission accuracy, backlash and efficiency of two HD gears declined slowly at the first 3500 h, then deteriorated quickly during the last 1500h. Yet at the end of the test, two test pieces still remained relative good conditions (transmission accuracy $< 0.025°$, backlash$<0.020°$, efficiency$>60\%$). The working life of grease lubricated HD gears coated with W-C:H coating as the same time can reach more than 5,000 hours which was beyond twice times that of uncoated ones.

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