Failure Analysis of Cr_7C_3 Coating for Helicopter Transmission System

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Abstract. The Cr_7C_3 coatings used in a helicopter transmission system was peel off in service life. In this paper, the causes of the crack are analyzed by experiments. The results show that peeling mode is contact fatigue flaking. The reason for the peeling is that there are many crack sources in the coatings. In addition, the contact between the surface asperities makes the coating surface and the near surface subjected to shear force. At the same time, under the action of high-pressure oil wave and alternating stress, the cracks extend in the direction of 45 degrees through the surface. Finally, under the effect of the surface shearing force, the coatings begin to peel off.

1. Introduction

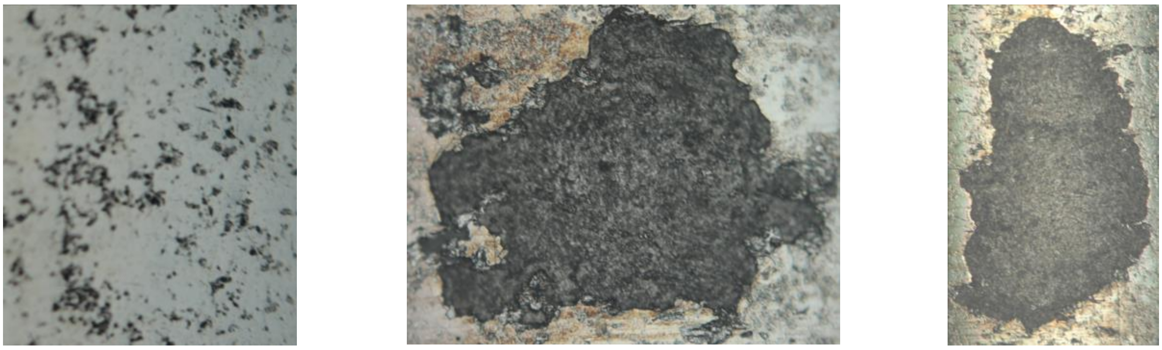
Overrunning clutch is one of the essential components in the helicopter transmission system. It is a critical element to ensure the correct combination and disengaged of the main reducer from the engine. An overrunning clutch is composed of wedges, a retainer and a spring. Its function is to unilaterally transfer the torque from the engine output shaft to the main reducer input shaft. Using chemical vapor deposition (CVD) method to plate Cr_7C_3 coating on the surface of wedges aims to reduce the wear of wedges. According to the stress analysis, it can concluded that the wedges are subjected to normal pressure and tangential sliding friction, which keep varying during the whole process of helicopter flight. In other words, the wedges are subjected to alternating normal pressure and tangential sliding friction.

During the helicopter flight, it is found that the actual service lifetime of the coating is much shorter than the designed ones. This paper studies the reasons of coating peeling by experiment methods.

2. Physical and Chemical Testing

2.1 Macroscopic Morphology of Spalled Coatings

The dismantling analysis of the failed clutch shows that nearly half of the wedges lose efficacy for peeling in different degrees. There are three types of failure: pitting, partial peeling and whole layer peeling, as shown in Fig.1.

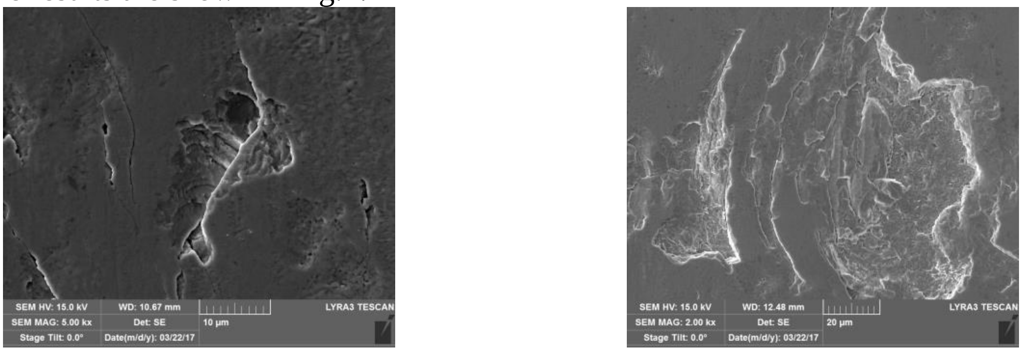


(a) Pitting (b) Partial peeling (c) Whole layer peeling

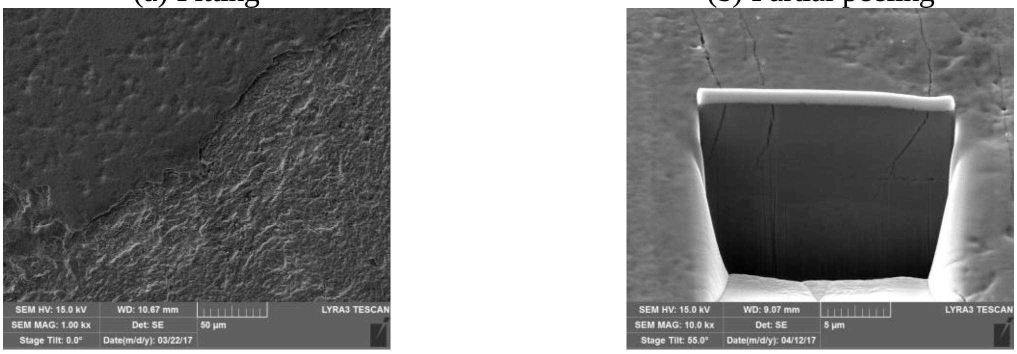
Figure 1. Macrographs of three failure modes of wedges (Magnification: 20 times).

2.2 Microstructure of the Spalled Coatings

Three kinds of failure surfaces were observed by focused ion beam scanning electron microscope (SEM). The results are shown in Fig.2.



(a) Pitting (b) Partial peeling



(c) Whole layer peeling (d) Focused ion beam morphology

Figure 2. SEM morphology of Cr7C3 coatings.

Figure 2 shows that there are many cracks near the pitting, and obvious cracks inside the pitting. The edge of partial peeling pit is characterized by typical arc fatigue cracks. There are cracks in the edge and interior of the peeling pit. The edge of the whole layer peeling pit are the arc fatigue peeling characteristics, too. Microscopic morphology reveals that the coatings peeling mode is contact fatigue flaking.

The result of Stripping off the coating on the surface by focused ion beam (FIB) is shown in Fig.2 (d). According to the analysis of Fig.2 (d), it can be found that the angle between the crack and the surface is about 45 degrees, which indicates that the crack is propagate under the leading of the shear stress. Moreover, some cracks do not reach the substrate, which indicates that the cracks extend from the surface of the coating.

2.3 Chemical Composition

Qualitative and semi-quantitative energy spectrum analysis were performed on the surface of unused wedges by focused ion beam SEM. The result is shown in Fig.3. The surface of the coatings contain a large amount of iron, while the designed coatings contain only Cr and C elements.

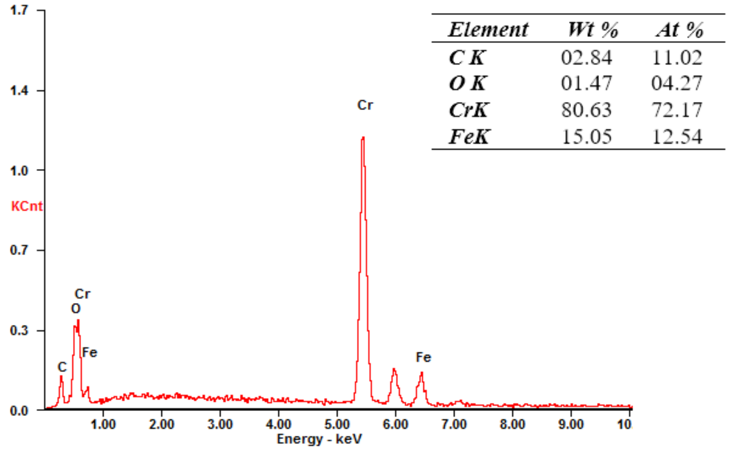


Figure 3. ED’s spectrum of the surface of Cr7C3 coating.

In order to further analyze the peeling reasons, the qualitative analysis of the phase for unused wedges surface is made by high power X-ray diffractometer (XRD). The result is shown in Fig.4. There is $(Cr,Fe)_7C_3$ in the coating. This is due to the formation of a complex six-dimensional lattice structure of Cr_7C_3, which can dissolve Fe atoms, in the process of chemical vapor deposition (CVD).

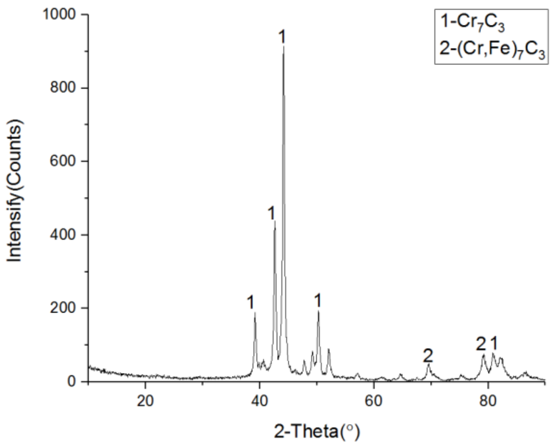


Figure 4. XRD diffraction pattern of the surface of Cr7C3 coating.

As shown in Table 1, comparing the mechanical properties of Cr_7C_3 and $(Cr,Fe)_7C_3$, brings out that the hardness of $(Cr,Fe)_7C_3$ is lower than that of Cr_7C_3. This leads $(Cr,Fe)_7C_3$ to be the weak phase in the coating. Because of the existence of the weak phase, the stress distribution in the coating is uneven, and the positions of high stress will become crack sources.

Table 1. Mechanical properties of Cr7C3 and (Cr,Fe)7C3 [1].

Carbide	Density (g/cm^3)	Micro Hardness (HV)
Cr7C3	6.92	1882
(Cr,Fe)7C3	7.67	1500-1800

2.4 Nano Hardness Measurement

The Nano hardness of the cross section of the wedge was measured by Nano-indenter after mosaic, grinding and polishing. The magnitude of the load is 20mN, and the loading rate is $40\,mN/min$. Five points are selected for measurement as shown in Fig.5.

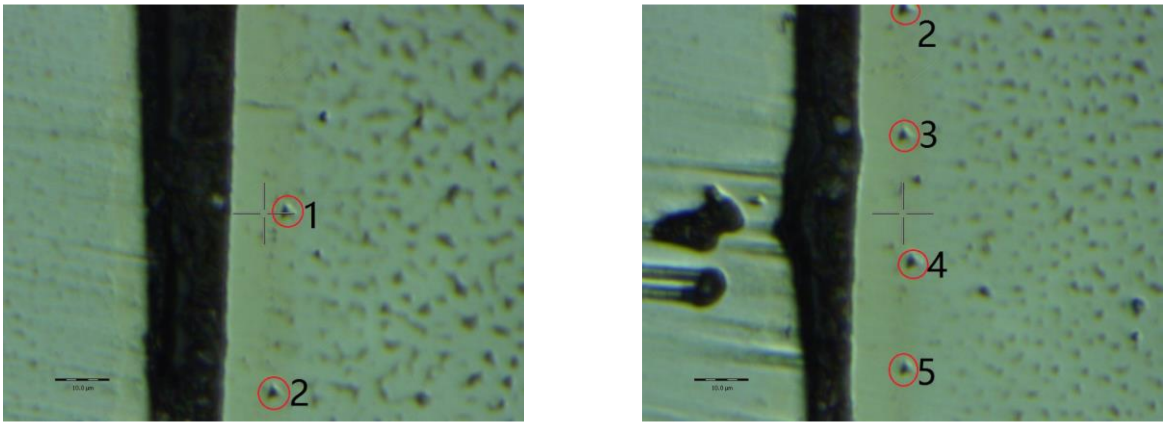


Figure 5. The location of Nano hardness test points.

The measurement result is shown in Table 2.

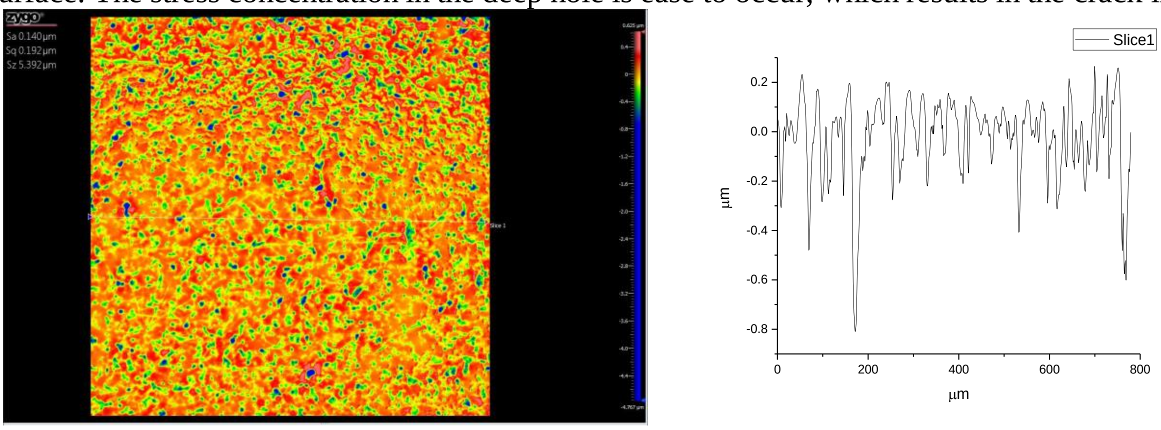
Table 2. Nano hardness test results of Cr7C3 coating.

Number of Test Points	1	2	3	4	5	Average Value
Vickers Hardness (HV)	1701	1906	2114	1726	1938	1877
Young Modulus (MPa)	18373	20589	22827	18641	20927	2071

The results show that the hardness of the coating is about 1877HV, which meets the design value of $1800 \pm 200\text{HV}$. However, the hardness values of these 5 points are different, and the standard deviation is 169HV, which shows that the uniformity of the coating is poor. Consider the result of X-ray diffraction, it can be inferred that the hardness of the region is lower when the $(Cr,Fe)_7C_3$ content is high in some regions.

2.5 Coating Surface Morphology

The surface of an unused wedge was measured by a three-dimensional white light interferometer. The result is shown in Fig.6. The surface roughness of the coating is $S_a = 0.14\mu\text{m}$, which meets the requirement of surface roughness of $0.3\mu\text{m}$. However, $S_z = 5.392\mu\text{m}$ cannot be ignored for the coating thickness of $6\text{-}10\mu\text{m}$, the data show that there are deep holes on the surface of the coating. It can be concluded from the two-dimensional topography that there are many deep holes on the coating surface. The stress concentration in the deep hole is ease to occur, which results in the crack initiation.



(a) 2D surface topography of Cr_7C_3 coating (b) Height variation curve of Cr_7C_3 coating

Figure 6. Coating surface morphology.

3. Spalling Reason Analysis

According to the stress analysis, the wedges is imposed to the normal pressure and tangential sliding friction. Nearly half of the wedges has different degrees of coating peeling, and there is no regularity between the coating positions of different wedges. The difference of the radius of wedges will result in different stress state of different wedges.

Cr_7C_3 coating contains $(Cr,Fe)_7C_3$. On one hand, it will lead to uneven coating, thus the stress concentration occurs, and the site of stress concentration provides the conditions for crack initiation [2]. On the other hand, the hardness of $(Cr,Fe)_7C_3$ is lower than Cr_7C_3, which makes the wear resistance and fatigue resistance of the coating decrease. Uneven distribution of the coating can be concluded from the standard deviation value, 169HV. From the two-dimensional topography of the coating surface, we conclude that there are many holes on the surface of the coating. Because of the existence of the deep holes, the high-pressure lubricating oil is easy to enter into the hole. The pressure of the high-pressure oil wave on the hole wall makes the deep hole become the crack source [3, 4].
The rough contact between the coating and the surface of the work piece and the micro sliding in the contact region make the coating prone to plastic deformation and micro shear. Therefore, it is necessary to study the lubrication state between the wedges and the inner and outer rings [5]. An empirical formula for calculating the oil film thickness, h_m, between wedges and the inner and outer rings is presented as follows:

$$h_m = 2.65\alpha^{0.54}\left(\eta_0 u\right)^{0.7} R^{0.43} E^{'-0.03} W^{-0.13} \tag{1}$$

In the formula, α is the pressure-viscosity coefficient of lubricating oil, and its value is $1.43\times10^{-8}\ \mathrm{m^2/N}$. η_0 is dynamic viscosity at atmospheric pressure, and its value is $0.00771\,\mathrm{N\cdot s/m^2}$. u is the average between the speeds of the wedges vs the inner and outer rings respectively at the contact zone. For outer ring contact area, u=67.8 m/s. For inner ring contact area, u=54.0 m/s. R is the equivalent radius of curvature. For outer ring contact, R=0.00455m. For inner ring contact area, R=0.00635m. E' is the equivalent elastic modulus, its value is E'=231.76GPa. W is the load on the unit contact length, its value is W=925925.926 N/m. For outer ring contact, the thickness of oil film is h_m=0.73496μm. For inner ring contact, the thickness of oil film is h_m=0.72332μm.
The oil film parameter, λ, is calculated as follows:

$$\lambda = \frac{h_m}{\sqrt{R_{a1}^2 + R_{a2}^2}} \tag{2}$$

In the formula, h_m is the oil film thickness? R_{a1} and R_{a2} are the root mean square values of the coating and the inner ring surface roughness, respectively. For inner ring contact, λ=1.87. For outer ring contact, λ=1.84. When $1<\lambda<3$, the coating surface is in the mixed lubrication state. Part of the friction surface is separated by lubricating oil film to bear part of the load. There will be part of the surface in the micro-convex body contact state [6]. The contact between the surface asperities makes the coating near the surface subjected to shear force.

Under the action of alternating stress and shear force, the crack begins to germinate. Lubricating oil in the contact stress generated by the high-pressure oil wave will enter the fatigue cracks. High-pressure lubricants will produce pressure on the fatigue crack wall, allowing the cracks to expand in depth. At the same time, the cracks under the action of shear stress will expand along the surface into the direction of 45 degrees to the substrate. When the cracks spread to the limit or two cracks intersect, the coating begins to peeling due to the coating subjected to shear force at the surface or near the surface. This is the pitting stripping process [7]. From the pitting SEM topography, it can be confirmed the crack initiation and expansion process. After pitting, the cracks will expand further to form partial spalling. Partial spalling SEM micrographs can be seen in the apparent arc fatigue spalling characteristics. After the coating is furthered peeled off to the substrate, the whole layer is peeled off. From the whole layer spalling SEM morphology, we can also see the obvious arc fatigue characteristics and fatigue crack.

4. Conclusion

The peel pattern of the coating is contact fatigue spalling. There is a large number of crack sources in the coating. During the contact process, the contact between the surface asperities makes the coating

surface and the near surface subject to the shear force. At the same time, under the influence of high-pressure oil waves and alternating stress, cracks extend through the surface in 45 degrees' direction to substrate. After the cracks spread to a certain extent, the coating begins to peel off under the influence of the surface shearing force.

The processing and assembly accuracy of the wedges have a great influence on the force loaded on the wedges. Therefore, it should be improved. The unevenness of the coating and holes are potential cracks source. The coating process should be improved to reduce the holes in the coating and improve the uniformity of the coating.

Acknowledgments

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