Tribological and dry drilling performance of WS₂/Cr-AlCrN coatings

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Abstract

Dry drilling gives a higher request to the anti-friction property of cutting tools. However, most tool coatings commonly have less lubricant effect. In present paper, WS₂/Cr layer was deposited on AlCrN layer by a radio frequency magnetron sputtering system, forming the WS₂/Cr-AlCrN lubricant-hard coatings. Its microstructure was studied using scanning electric microscope (SEM) and X-ray diffraction (XRD). Dry sliding tests were carried out against Ti6Al4V balls to evaluate the lubricant effect of the lubricant-hard coatings with different Cr contents in WS₂/Cr layer. Dry drilling performance of WS₂/Cr-AlCrN coating was also studied compared with uncoated and AlCrN coated tool in dry drilling of Ti6Al4V and 7075Al. It is found that as Cr contents increased, WS₂/Cr became denser but the crystallinity decreased. The coating with Cr content of ~9.8 at.% had the best lubricant effect with the lowest friction coefficient and the narrowest wear track. Dry drilling tests show that WS₂/Cr-AlCrN coated tool had the longest tool life and produced the lowest surface roughness. The high wear resistance of AlCrN layer was mainly played near cutting edge. While the anti-friction role of the lubricant layer was mainly played on drill flute, resulting in less material adhesion and improved chip removal.

Keywords : Dry drilling, Lubricant coating, Hard coating, Friction, Adhesion

1. Introduction

In aircraft assembling, cutting fluids are forbidden from being used in order to avoid contaminating components and workplace, so holes on titanium alloys and aluminum alloys are drilled without any cutting fluid. However, dry drilling process generates severe friction on tool-chip and leads to serious adhesion, high cutting temperature and chip removal problems (Fernandes et al., 2018). The harsh conditions consequently exacerbate tool degradation, which is disadvantageous to aircraft assembling efficiency.

Coating is an effective way to increase tool life. The most used tool coatings are transition metal carbides/nitrides with high hardness and excellent thermal stability, such as TiN, CrN, TiAlN, AlCrN, TiAlSiN, etc. They can increase tool wear resistance by several times (Ravi et al., 2017; Liu et al., 2018; Su et al., 2017). However, those hard coatings sometimes increase workpiece material adhesion on tool surface (Li, S. et al., 2018), leading to chip removal difficulties in dry drilling process. Therefore, increasing lubrication in dry drilling is an effective way to further improve tool performance.

WS₂ has superior lubricity (Xu et al., 2014; Scharf et al., 2006), thereby attracts growing attention as a kind of antifriction coating (Lian et al., 2018; Li, X. et al., 2018; Deepthi et al., 2018; Li et al., 2014), but WS₂ coating is not durable due to extremely low hardness. Therefore, doped WS₂ coatings were developed to improve their wear resistance, including WS₂/Cr (Deepthi et al., 2010), WS₂/Ni (Xu et al., 2017; Roy et al., 2017), WS₂/Cu (Xu et al., 2014), WS₂/Ag (Quan et al., 2017), WS₂/Ti (Banerjee and Chattopadhyay, 2014), WS₂/C (Cao et al., 2017), etc. Those works have proved that the proper content of doped element largely increased coating hardness and thermal stability as well as wear life, but the protective effect of doped WS₂ coatings is still far less than that of carbides/nitrides hard coatings.

Some researchers proposed a kind of lubricant-hard multi-layer coating, including a lubricant layer and a wear-resistant layer, such as MoST-TiCN (Fox et al., 2017), WC/C-TiAlN (Derflinger et al., 1999) and WS₂-TiSiN (Li et al., 2014; Li et al., 2015). These studies showed that the lubricant-hard coatings can combine the low friction coefficient of lubricant layer and the high wear resistance of hard layer and improve cutting performances. Nevertheless, the performance of lubricant-hard coatings in dry drilling of titanium alloys and aluminum alloys are rarely assessed.

In this paper, a WS₂/Cr layer was deposited on AlCrN layer, forming the lubricant-hard coating. The Cr content of WS₂/Cr was optimized based on the tribological performance against Ti6Al4V ball. The cutting performances of WS₂/Cr-AlCrN coatings in dry drilling of Ti6Al4V and 7075Al were investigated based on tool wear, cutting chips and hole surface roughness. The mechanisms of performance improvement using WS₂/Cr-AlCrN coated drill were discussed.

2. Experimental details

2.1 Preparation and characterization of coatings

Due to the advanced preparation technologies of hard coatings, hard layer of the lubricant-hard coatings was deposited by Oerlikon Balzers Co. Ltd. AlCrN-based coating (BALINIT-ALDURA, hereinafter, AlCrN) was selected as the hard layer material as a result of high hardness and high-temperature resistance and wide application for cutting tools. The properties of the AlCrN coating were listed in Table 1. Then a WS₂/Cr layer was deposited on the AlCrN layer by a hybrid system with arc ion plating (AIP) and radio frequency magnetron sputtering (RFMS). In depositing WS₂/Cr layer, the samples were placed on a rotational holder after cleaned ultrasonically in ethanol and acetone progressively. The chamber was evacuated to lower than 1.0×10^{-2} Pa. Then the samples were bombarded by Ar⁺ ions to clean the surface for 15 minutes under the bias voltage of -800V and Ar atmosphere of 2.5 Pa. An AIP target of Cr (99.99%) was used to deposit a Cr interlayer firstly, then two targets of Cr (99.99%) and WS₂ (99.99%) were sputtered to deposit WS₂/Cr layer. The deposition details were listed in Table 2. WS₂/Cr-AlCrN coatings with WS₂/Cr layers deposited at Cr target power of 0W, 32W, 55W, 66W and 84W were prepared, which were abbreviated to L0H, L32H, L55H, L66H and L84H, respectively.

Table 1 Specifications of AlCrN-based coating.

Properties	AlCrN-based coating (BALINIT-ALDURA)
Micro-hardness	~3300 Hv
Thickness	2~4 μm
Structure	Multi-structure with a TiAlN interlayer between the AlCrN layer and substrate.

Table 2 The deposition parameters of WS₂/Cr lubricant layer.

Deposition parameters	L0H coating	L32H coating	L55H coating	L66H coating	L84H coating
Sputtering power of Cr target	0W	32W	55W	66W	84W
Sputtering power of WS ₂ target			150W		
Deposition pressure			0.5Pa		
Deposition temperature			250°C		
Bias voltage			-100V		
Deposition time			120min		

Table 3 Cutting parameters.

Parameter	Drilling of Ti6Al4V	Drilling of 7075Al
Spindle speed	2120 r/min	4240 r/min
Feedrate	0.08 mm/r	0.08 mm/r
Drilling depth	15mm	15mm
Hole diameter	6 mm	6 mm

A scanning electron microscope (SEM, FEI Quanta 250FEG) was used to observe coating morphology. The

chemical composition and crystalline structure of coatings were analyzed by an energy dispersive spectrometer (EDS, equipped together with the SEM device) and X-ray diffraction (XRD). Coating hardness was measured by a MH-6 hardness tester with a Vickers indenter at the load of 50g, and five indentations were carried out for each sample. Adhesive strength was evaluated by an MFT-3000 scratch tester with a loading speed of 100N/min and a scratching length of 5 mm.

2.2 Friction and wear test

Dry friction tests were carried out by a ball-on-disk multi-functional friction tester (MMW-1) in ambient air. Coatings used in friction tests were deposited on cemented carbides disks (WC/Co). The ball was made of titanium alloy (Ti6Al4V) with a diameter of 10 mm and was fixed on a holder while the disk was spinning with a speed of 276 r/min. The sliding velocity was kept at 40 m/min. A normal load of 20N was applied. Each test lasted for 30 min. The friction coefficient was recorded by the tester computer. Wear morphologies were observed by a VHX-5000 optical microscope and SEM.

2.3 Dry drilling test

Drilling tests were carried out on a DMC75V linear five-axis machining center to evaluate the coated drills performance. Ti6Al4V plate and 7075 aluminum alloy (7075Al) plate with a same thickness of 20 mm were used as the workpiece materials. 15 mm deep blind holes with a diameter of 6 mm were drilled without any cutting fluid. The cutting parameters were listed in Table 3. The roughness of hole side surface was measured by a Time (type TR200) roughness tester. According to the cutting characteristics of Ti6Al4V, the failure criterion for drills in drilling of Ti6Al4V was the occurrence of cutting sparks. While in drilling of 7075Al, cutting test was stopped when tool flutes was completely clogged up by cutting chips. The worn surfaces of drills were studied using VHX-5000 microscope and SEM.

3. Results and discussion

3.1 Microstructure and mechanical properties of WS_2 /Cr-AlCrN coatings

Figure 1 shows the cross-sectional images of the AlCrN coating and the lubricant-hard coating of L55H. The lubricant layer had a looser structure than AlCrN layer. The thicknesses of both layers were in the range of 1.9~2.6 μ m. Figure 2 shows that with Cr target power increasing, Cr content increased from ~4 at.% to ~21 at.%, and the microstructure became denser. The appearance of O may be caused by the absorption of H_2O and O_2 when exposed to the atmosphere after deposition. Noticeably, O content decreased with the increase of Cr content, which was resulted from the dense microstructure at high Cr content. Figure 3(a) shows the XRD spectra of these samples. WS_2 (104) was the dominated crystal orientation of WS_2 /Cr layer. WS_2 (002) also appeared but with a poor crystallinity (broad diffraction peak). WS_2 (104) peak almost disappeared in L84H coating, indicating that overhigh Cr content largely reduced the crystallinity of WS_2 . Figure 3(b) shows the hardness and adhesive strength of lubricant-hard coatings. When Cr target power was over 66W coating hardness significantly increased, while the adhesive strength shows no obvious change.

Fig. 1 Cross-sectional pictures of (a) AlCrN coating; (b) WS_2 /Cr-AlCrN coating (L55H).

Fig. 2 (a) the chemical composition of WS₂/Cr layer; (b)-(f) the surface morphologies of lubricant-hard coatings prepared at different Cr power in WS₂/Cr deposition.

Fig. 3 (a) XRD spectra and (b) hardness and adhesive strength of different lubricant-hard coatings.

3.2 Tribological performance

Figure 4 shows the friction coefficients of different coatings sliding against Ti6Al4V balls. The sliding process can be divided into two stages for each WS₂/Cr-AlCrN coating: the first stage with coefficients lower than 0.2 and the second stage with larger and fluctuant coefficients. The distinct difference between the two stages indicates that the lubricant layer was worn out. The average friction coefficients were shown in Fig. 5. The friction coefficients of all WS₂/Cr-AlCrN coatings had been consistently lower than that of AlCrN coating, showing that the lubricant layer still had residual antifriction effect even after being worn out. But in the second stage, there was an optimal Cr content of ~9.8 at.% where the friction coefficient was the lowest. The change rule of the average friction coefficient illustrates that the lubricant effect depended on the anti-friction function in the second stage more than that in the first stage.

Fig. 4 Friction coefficients of different coatings against Ti6Al4V balls, (a) AlCrN , (b) L0H , (c) L32H, (d) L55H, (e) L66H and (f) L84H.

Fig. 5 The average friction coefficient in different stages.

Figure 6 shows the wear morphologies of these coatings after 30 min dry sliding against Ti6Al4V ball. The order of wear track width was consistent with the friction coefficients. From the EDS analysis (see Fig. 7), in the middle of wear track, lots of titanium alloy materials adhered, and only on L55H coating a small amount of S was detected while no WS_2 was found on other lubricant-hard coatings. It directly proves that WS_2/Cr layer had been worn out. Nonetheless, there were still lots of S on the edge of wear track. It is the reason for the lower friction coefficients of lubricant-hard coatings than that of AlCrN coating even at the end of test (see Fig. 4). In view of the friction coefficient and wear track width as well as the amount of residual S in the wear track, L55H coating had the most durable lubricant effect.

Fig. 6 Morphologies of the wear track of different coatings after 30 min sliding against Ti6Al4V ball, (a)-(b) AICrN coating, (c)-(d) L0H, (e)-(f) L32H, (g)-(h) L55H, (i)-(j) L66H and (k)-(l) L84H.

Fig. 7 The corresponding EDS analysis result of each marked zones in Fig. 6.

3.3 Dry drilling tests

Based on the best anti-friction performance of L55H coating in sliding wear tests, L55H coated drills were selected in dry drilling tests. As comparisons, uncoated drills and AICrN coated drills were also used. Figure 8 shows the shape of cutting chip. In drilling of Ti6Al4V, blocky-ribbon chips formed when drilling of the 16th hole using

uncoated drill. Meanwhile, the chips produced by both coated tools were in folded-ribbon shape. In drilling of 7075Al, uncoated and AlCrN coated tools produced blocky chips and it seems AlCrN coated drill had a worse degree after only four hole drilling, while the chips produced by L55H coated drill were still chipped. The blocky chips in drilling process usually indicate the severe difficulty in chip removal. The lubricant effect of L55H coating resulted in less material adhering on drill flute surface and thereby increased chip removal ability.

Fig. 8 Chip appearances in drilling of Ti6Al4V and 7075Al.

Figure 9 shows the tool life of different drills. In drilling of Ti6Al4V, L55H coated tool produced 22% more holes than AlCrN coated tool and 175% more holes than uncoated tools. While in drilling of 7075Al, tool life decreased largely compared to that in drilling of Ti6Al4V. This abnormal phenomenon is mainly due to the high cutting speed used in drilling of 7075Al without any coolant. A lower speed may improve chip removal condition and increase tool life. In spite of that, the different behaviors of these tools still can reflect coating performances. AlCrN coated tool was clogged up only after drilling of 6 holes on 7075Al plate, 57% less than uncoated tool. While L55H coated tool produced 71% more than uncoated tool. AlCrN largely increased tool wear resistance in drilling of Ti6Al4V but had a negative influence on chip removal in drilling of 7075Al. L55H tool, combining the high wear resistance of AlCrN and the good lubrication of WS_2/Cr , had better performances in drilling of both the materials.

Fig. 9 Tool life of different coated tools in drilling of Ti6Al4V and 7075Al.

Figure 10 shows the hole side surface roughness of Ra. Generally, L55H produced the lowest surface roughness. The differences in the roughness produced by different tools in drilling of 7075Al are obviously larger than those in drilling of Ti6Al4V. The surface roughness machined by AlCrN coated tool is very similar to that machined by L55H tool in drilling of Ti6Al4V, showing that the machined quality is mainly related to tool wear resistance. But in drilling of 7075Al, AlCrN coated tool produced the roughest surface.

Fig. 10 Surface roughness Ra of hole side wall produced by different coated tools in drilling of (a) Ti6Al4V and (b) 7075Al.

3.4 Discussion

3.4.1 Tribological performances

In friction tests, the tribological performances of lubricant-hard coatings with different Cr content in WS_2 /Cr layer varied a lot. It is mainly ascribed to the anti-friction property and the durability of lubricant layer. The anti-friction effect of WS_2 /Cr is basically determined by the hexagonal crystal of WS_2 (Scharf et al., 2006; Lian et al., 2018). WS_2 /Cr layer with low Cr content has good crystallinity but low wear resistance and less sustainable lubrication, so L0H and L32H coatings has lower friction coefficients in the first stage but higher friction coefficients in the whole friction test (see Fig. 4 and Fig. 5). However, overhigh Cr content brings more adverse effects for coating lubrication, resulting in the highest friction coefficient of L84H. An appropriate Cr content can effectively combined the anti-friction function and relatively high wear resistance, showing the longest lubricant effect (L55H coating).

3.4.2 Drilling performance

From the results of cutting experiments, it can be found that the lubricant-hard coating played different roles in drilling of titanium alloys and aluminum alloys. In drilling of Ti6Al4V, AlCrN hard layer played a major role for the performance improvement. Figure 11 and Fig. 12 show the worn morphologies and the corresponding EDS results of different drills. It can be seen that near the cutting edge of L55H tool, WS_2 layer had been worn out after 4 holes drilling. Under the extremely high cutting press and temperature in drilling of Ti alloys (Ezugwu et al., 1997), WS_2 /Cr layer of low hardness was worn rapidly, so WS_2 /Cr layer in cutting regions was worn out completely after a short cutting length. In the rest of drilling process, only AlCrN layer worked. Therefore, the better performance of L55H coated tool is mainly resulted from the high wear-resistance of AlCrN layer. However, Figures 13(a) and (b) show that on the flute surface WS_2 /Cr still remained in the areas far away from cutting edge. Less adhesion on tool flute increased chip removal ability and consequently reduced the friction between cutting chips and hole side surface, which is beneficial for reducing surface roughness (as Fig. 10 shows). Furthermore, a lot of cutting heat transfers to cutting chips in metal drilling (Agapiou and DeVries, 1990a, 1990b), the good chip removal could therefore improve heat dissipation condition. That is probably a reason for the slightly longer life of L55H coated tool than AlCrN coated tool in drilling of Ti6Al4V.

While in drilling of 7075Al, the lubricant layer of L55H tool played a major role for the performance improvement. AlCrN coated tool even exhibited a worse performance than uncoated tool. Figure 11 shows that serious adhesion occurred for all tools and L55H tool seems had the least degree. Aluminum alloys commonly lead to little wear loss for cutting tool but serious material adhesion (Rashad and El-Hossainy, 2006), so in dry drilling of aluminum alloys, build-up edge and flute clogging easily occurred. WS_2 /Cr layer near the cutting edge seems to be out of function

quickly under the cutting press and friction of cutting chips. But on the flute, the press is much lower and the wear was also not concentrated, thereby lots of WS_2 still remained (see Fig. 13(c) and (d)). The durable anti-friction effect of WS_2/Cr layer on tool flute largely increased the chip removal ability of L55H tool and reduced the risk of flute clogging. In contrast, AlCrN coating cannot provide lubrication and even exacerbated the friction conditions, leading to a worse chip removal condition. Consequently, AlCrN coated tool produced the highest surface roughness and was clogged up after drilling of few holes.

Fig. 11 Wear morphologies on the rake face of different coated tools.

Fig. 12 The EDS analysis result of (a) Zone A, (b) Zone B, (c) Zone C, (d) Zone D, (e) Zone E and (f) Zone F in Fig. 11.

Fig. 13 Morphologies and the corresponding EDS analysis of the marked areas on the flute of L55H coated tools (a)-(b) after drilling 4 holes on Ti6Al4V plate and (c)-(d) after drilling 2 holes on 7075Al plate.

In summary, near cutting edges, due to the high cutting stress and cutting temperature, WS_2/Cr lubricant layer was worn out rapidly and the hard layer played the main protective role. While on tool flute, WS_2/Cr layer showed durable lubricant and anti-adhesion effects. Compared with hard coating, the lubricant-hard coating can play a more significant role in drilling of metals that commonly cause chip removal problems.

4. Conclusion

In this study, WS_2/Cr layer was deposited on AlCrN layer so as to form the WS_2/Cr -AlCrN lubricant-hard coatings. Its tribological and dry drilling performances were evaluated. The following conclusions can be drawn:

1. The increase of Cr content increased the density and the hardness of WS_2/Cr layer while reduced coating crystallinity. Excessive Cr content lead to an amorphous microstructure and was harmful for coating lubricant effect. WS_2/Cr layer with 9.8 at. % Cr had the best lubricant effect.
2. L55H coated tools had best cutting performance in dry drilling of Ti6Al4V and 7075Al. WS_2/Cr layer in cutting regions was worn out rapidly, but on the tool flute WS_2/Cr had a durable lubricant effect. It largely reduced the materials adhesion and improved chip removal ability.
3. The hard layer played the anti-wear role mainly in the region near cutting edge. While the anti-friction role of the lubricant layer was mainly played on drill flute, where stress and temperature were much lower than cutting region.

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