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Tool Wear Performance in Face Milling Inconel 182 using Minimum Quantity Lubrication with Different Nozzle Positions

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Minimum quantity lubrication (MQL) is one of the promising Green Manufacturing Technology to meet the challenge of machining difficult-to-cut material Inconel 182 which is deposited by Shield Metal Arc Welding (SMAW). Unlike the flood lubrication, in MQL, only a small amount of non-toxic biodegradable oil are directly sprayed to the cutting zone by compressed air, which can reduce friction coefficient and temperature. Wear performance of uncoated tool inserts and Physical Vapor Deposition (PVD) coated tool inserts are evaluated by comparison during up and down face milling Inconel 182 with different MQL nozzle positions. Results indicate that uncoated tool inserts are not suitable for face milling Inconel 182 in all lubrication conditions due to the severe flank wear and the catastrophic breakage. On the contrary, PVD coated tool inserts have longer tool life compared to uncoated ones in all lubrication conditions. MQL nozzle positioned at tool cut into workpiece and positioned at tool cut out of workpiece in down milling as well as MQL nozzle positioned at tool cut out of workpiece in up milling can effectively prolong tool life of PVD coated tool inserts, which can be selected as the optimal lubrication solution for face milling Inconel 182.

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1. Introduction

Nickel-based alloys are well known as popular material, widely used in aerospace industry, nuclear power plants, chemical and petrochemical industries due to its superior advantages of high resistance to thermal fatigue, thermal shock, creep, and erosion.[1,2] They are also difficult-to-cut materials with some disadvantages such as strong adhesion, severe work hardening, low thermal conductivity, and the tendency to weld onto tool material to form Built-Up-Edge (BUE). Such disadvantages will cause severe thermo-mechanical contacts in the cutting zone, leading to severe tool surface damages such as crater, notching and even catastrophic breakage.[3-5]

Among nickel based alloys, Inconel 182 has been extensively used as weld metal in light-water-reactor structural components in the past few decades. Major concern has been focused on the microstructural and compositional features of Inconel 182 weldment as well as its corresponding intergranular cracking or intergranular stress corrosion cracking properties by many scientific researchers.[6-10] On the contrary, few literatures has reported its machinability, thus, it is still a challenge of machining Inconel 182, especially in aggressive dry cutting condition due to its strong adhesion property. In dry cutting condition, the cutting temperature is typically high, for this reason, cutting zone should be well lubricated by applying cutting fluids. However, the use of cutting fluids in conventional machining processes has been questioned recently due to the environmental contaminants and the high cost of lubricant consumption. As reported by Wu et al.[11] the maintenance and disposal cost of cutting fluids ranged from 7-17% of the total machining cost, which forced engineers and researchers to looking for environmental friendly solution to reduce the use of lubricants in manufacturing industry.

Minimum quantity lubrication (MQL), widely used in turning, drilling and milling process, is one of the promising Green Manufacturing Technology to meet the challenge of machining Inconel 182 economically and ecologically.[12-14] Unlike the flood lubrication, in MQL, a very small amount lubricant flow is used. In this case, non-toxic MQL biodegradable oil are directly sprayed to the cutting area by compressed air, which can reduce friction coefficient and cutting temperature.

Milling is intermitted cutting process, the tool inserts periodically cut into material and then cut out. In each revolution of milling tool, it can be divided into two cycles, active cycle and inactive cycle. When MQL is applied, tool inserts are exposed to oil mist in inactive cycle, therefore wetting the tool surfaces. This is followed by the next period, called active cycle. In this period, inserts have been already lubricant and covered with molecular oil film, once entering into the workpiece, the molecular oil film will prevent inserts from severe impact and friction.[15]

In order to improve productivity in manufacture industry, large diameter milling cutters are usually adopted, in this case, inappropriate MQL nozzle position cannot effectively deliver oil to the cutting zone because they maybe hinder by milling cutter.[16] Thus, MQL nozzle position will directly determine the lubrication effect, which attracts a lot of attention. Yan et al. studied the influence of MQL parameters on tool wear and surface roughness in milling forged steel. The results showed that nozzle-feed position at 120, the elevation angle at 60 and the distance from nozzle to the cutting zone at 20 mm prolonged tool life and reduced surface roughness values.[17] López de Lacalle et al. investigated the influence of the position of the injection nozzle in relation to the feed direction at 45 and 135 through computational fluid dynamics simulation and experiment in high speed milling. It was found that the cutting fluid cannot completely penetrate into tool edge at the position angle of 45, because turbulences originated in the proximity of tool prevented MQL oil drops going to the cutting zone, however, the 135 position effectively allowed MQL oil penetrated into inner zone of tool edge.[18] Tawakoli et al. studied the influence of oil flow rate, air pressure, MQL nozzle position and distance from the wheel-workpiece contact zone on grinding forces and surface roughness. It was found that the MQL nozzle location was an important factor regarding the effective application of MQL. MQL nozzle positioned angularly toward the wheel can be the most effectively position for oil mist penetrated the boundary layer flow around the grinding wheel.[19] Liu et al. focused on the effect of air pressure, oil quantity and nozzle position on cutting forces and cutting temperatures during end milling Ti-6Al-4V. It was found that MQL spraying distance of approximate 25 mm, spraying air pressure of 0.6 MPa, spaying angle of 135, and oil supply rate of 10 ml/h were the optimal parameters.[20] Cai. et al. discussed the MQL oil supply rate in high speed end milling of Ti-6Al-4V. The results indicate that higher oil supply rate can effectively reduce cutting force, surface roughness and length of tool chipping edge. As the MQL oil supply rate increasing from 2 ml/h to 14 ml/h, tool wear types transformed from diffusive wear to uniform flank wear.[21]

However, few literature has reported the influence of MQL nozzle positions on face milling difficult-to-cut material Inconel 182 with large diameter milling cutter. The aim of the present work is to evaluate the wear performance of uncoated tool inserts and PVD coated tool inserts in face milling (up or down milling) Inconel 182 with large diameter milling cutter under different lubrication conditions: (i) drying cutting; (ii) MQL nozzle positioned at tool cut into workpiece; (iii) MQL nozzle positioned at tool cut out of workpiece. Their flank wear rate, tool failure modes and wear mechanism were investigated correspondingly.

Table 1 Welding Details

Deposited material	Inconel 182 (ENiCrFe-3)
Preheat (K)	400
Electrode diameter (mm)	3.2
Arc Current (A)	145
Arc Voltage (V)	17
Traveling speed (mm/s)	1.4
Total deposited weld depth (mm)	13

2. Experiment

2.1 Tool preparation

Indexable milling cutter R390-050Q22-17M with 4 flutes supplied by Sandvik CoroMill was employed in the experiments. Uncoated and TiAlN/TiN PVD coated inserts GC1030 R390-17 04 08M from Sandvik Coromant were also employed. Only one insert was mounted on the R390 milling cutter and diameter of the milling cutter was 50 mm.

2.2 Workpiece preparation

The workpiece were solution annealed mould steel G17CrMo9-10, prepared in the dimensions of 80 mm × 40 mm × 40 mm rectangular blocks. Its chemical compositions are up to 90% Fe, 2.3% Cr, 1.1% Mo and small amount of C, Mn, Si, Cu and Ti. The deposited weld metal Inconel 182, which contains 60% Ni, 15% Cr, 12% Fe, 7.6% Mn, 1% Si, 1% Ti and small amount of Nb, Ta and Cu, was cladded on the base material G17CrMo9-10 by Shield Metal Arc Welding (SMAW). Argon gas was continuously supplied as the shielding gas during the weld process to prevent oxidation. Stress relief was performed to eliminate the residual stress generated in SMAW process. Detail welding conditions employed are listed in Table 1.

2.3 Experiment condition

Two types of face milling experiments, i.e., up milling and down milling were conducted on a 5-axis CNC vertical machining center DMU 70V with a maximum spindle speed of 12000 rpm, equipped an external Accu-Lube type MQL system. In this system, non-toxic biodegradable oil and the compressed air can be mixed or separated in a special nozzle to spray the micro oil mists to the cutting zone. The schematic diagram of different MQL nozzle positions including positioned at tool cut into workpiece or positioned at tool cut out of workpiece in face milling and their corresponding spraying angles are illustrated in Fig. 1. MQL parameters including air flowrate, compressed air pressure, oil quantity, elevation angle and MQL spraying distance adopted in this test are listed in Table 2 in detail.

The cutting speed of 160 m/min (spindle speed of 1019 rpm), feed per tooth of 0.2 mm/tooth, the axial depth of cut of 1 mm and radial depth of cut of 40 mm are selected according to the previously milling parameters testing which is not presented in this paper. Workpiece surfaces were face milled to get rid of original skin layer containing some voids and cracks in Inconel 182 before the real milling testing.

Tool wear and their microstructures were observed and measured by optical microscope Keyence VHX-500FE and HITACHI S-4800 scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS). All images have the same magnification level of 30X and use the same light source and microscope settings. Either

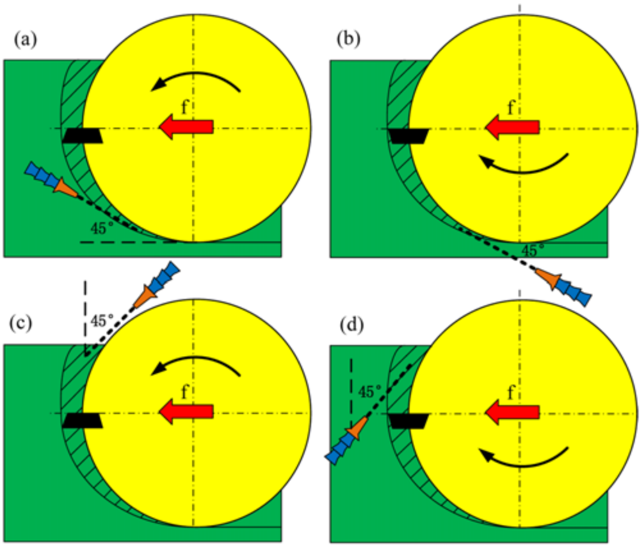

Fig. 1 MQL nozzle positions: (a) positioned at tool cut out of workpiece in down milling; (b) positioned at tool cut into workpiece in up milling; (c) positioned at tool cut into workpiece in down milling; (b) positioned at tool cut out of workpiece in up milling

Table 2 MQL parameters in face milling Inconel 182

Air flowrate (litres/min)	125
Compressed air pressures (MPa)	0.7
Oil quantity (millilitres/hour)	16
Elevation angle (°)	30
Spray angle (°)	45
MQL spray distance to cutting zone (mm)	25

maximum flank wear VB reached 0.3 mm or catastrophic failure happened can be the tool rejection criteria. As we all known, tool reaching its end of life is quite unpredictable, and when it reaches tool rejection criteria, in most cases, it is not possible for the scientific researcher to stop experiment exactly.[22] So tool flank wear were measured at intervals after tool moving a complete cutting pass.

3. Result and Discussion

3.1 Microstructures of Inconel 182

As shown in Fig. 2, the microstructures of Inconel 182 deposited by SMAW are fully austenitic with a dendritic morphology, which due to the fact that it hasn't undergone allotropic transformation during welding.[23] It shows recrystallized features with extensive grain boundary migration (MGB) where the recrystallized grain boundaries cut across the solidification substructures.[6] During the solidification phase of the welding, re-distribution of the solutes occurs, as a result, many types of precipitates have distributed on the dendritic grain boundaries during the cooling phase after solidification. Two kinds of them are studied and discussed in this article, one is SiC and TiC hard particles, and the other is small round intergranular precipitates consisted of Cr and C as a major metallic element and small amounts of Fe, and Mn.[1,10] The Cr carbides precipitated around grain boundaries in Inconel 182 depend on the heat treatments of the material and the environmental temperature

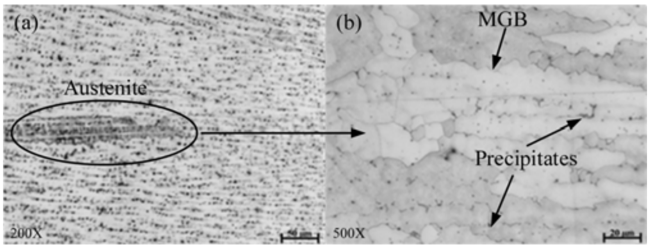

Fig. 2 Microstructure of deposited Inconel 182

during the milling process. However, the Cr carbide precipitation will scratch the surface layer of tool inserts and score on the worn tool surface, therefore, it is detrimental for milling Inconel 182.

3.2 Flank wear

Tool flank wear evolution of uncoated tool inserts and PVD coated tool inserts with metal removal volume in up and down milling in different lubrication conditions can been seen in Fig. 3 and Fig. 4, respectively. For up milling, it can be noticed that uncoated tool inserts wear so rapidly that they have not undergone normal wear stage, directly entering into severe wear state even with MQL. Their flank wear are far beyond the tool rejection criterion, reaching approximate VB = 0.9 mm after only 6.4 cm^3 (two cutting passes) in both dry and MQL cutting conditions. This phenomenon can be attributed to poor impact resistance of uncoated tool inserts and they are prone to suffer severe wear in high temperature or powerful pressure environment even with the help of MQL. However, PVD coated tool inserts have experienced initial wear, normal wear and severe wear stages, their flank wear gradually increase with the increase of the metal removal volume during up milling in all the lubrication conditions investigated. The flank wear of PVD coated tool insert in dry milling condition is approximate 0.66 mm, indicating the insert is rejected after removing volume of 12.8 cm^3. A huge decrease can be clearly observed that flank wear of PVD coated tool inserts in MQL condition are approximate 0.12 mm, showing a significant improvement of tool life when MQL is applied. In general, a thin film of molecular layer created by MQL biodegradable oil can effectively access and remain at the tool-workpiece interface, which promotes boundary lubrication, reducing friction and lower the temperature in the cutting zone. So PVD coated tool inserts' life under MQL have been significantly improved compared to it in dry cutting condition, and the lubrication efficiency of MQL nozzle positioned at tool cut out of workpiece is better than it positioned at tool cut into workpiece.

For down milling, the same conclusion can be drawn that uncoated tool inserts are still not suitable for milling Inconel 182 because of abnormal severe tool wear even with MQL. However, when MQL nozzle positioned at tool cut into workpiece, it is obvious from Fig. 4 that flank wear of uncoated tool insert decreases a lot to 0.08 mm after removing volume of 6.4 cm^3, illustrating that tool surface can be effectively protected by MQL film to prevent suffering severe impact when tool insert cutting into workpiece at the initial period during down milling process. By comparison, PVD coated tool inserts have a similar flank wear evolution, which have experienced initial wear, normal wear and severe wear stages in all lubrication condition investigated. Tool flank wear of PVD coated tool inserts in MQL

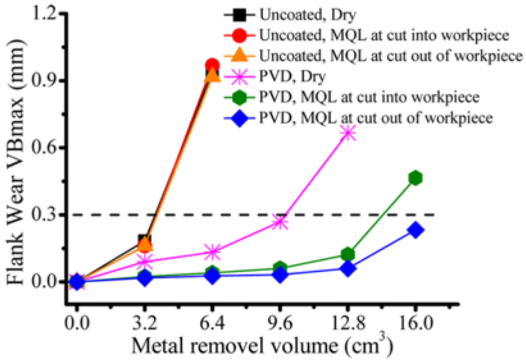

Fig. 3 Tool flank wear in up milling Inconel 182 under different lubrication conditions

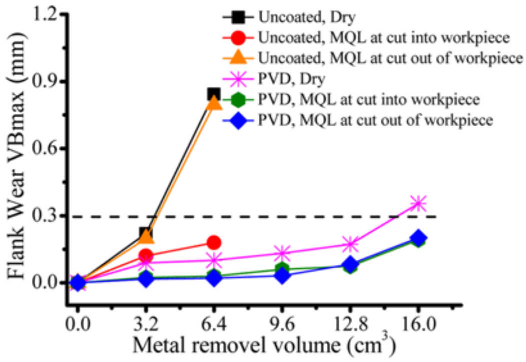

Fig. 4 Tool flank wear in down milling Inconel 182 under different lubrication conditions

condition are near 0.07 mm at feed length after removing volume of 12.8 cm^3, lower than that in dry cutting condition 0.17 mm. Furthermore, although MQL can effectively improve tool life compared to dry milling condition, the lubrication efficiency of MQL nozzle positioned at tool cut into workpiece or cut out of workpiece is slight.

It can be concluded that uncoated tool inserts are not suitable for milling Inconel 182 due to its severe tool flank wear regardless of the lubrication conditions. For PVD coated tool inserts, MQL can effectively reduce tool flank wear in both up and down milling process, however, MQL nozzle positioned at both tool cut into workpiece and tool cut out of workpiece in down milling as well as positioned at tool cut out of workpiece in up milling can be selected as the optimal lubrication method for milling Inconel 182.

3.3 Wear morphology and failure modes

Flank wear morphology of worn uncoated tool inserts after removing volume of 6.4 cm^3 in different lubrication conditions are illustrated in Fig. 5. For up milling, it can be observed that uncoated tool inserts exhibit severe damage and catastrophic breakage in all lubrication conditions. As strong adhesive property of Inconel 182, BUE can be easily formed on tool surface when inserts squeezing and scratching workpiece at initial period of up milling. With tool insert gradually cuts in, cutting load increases, and BUE on tool surface will be hit and torn off, causing severe damage and catastrophic failure of cutting tool. However, in down milling, severe groove wear is the dominate failure mode in both dry cutting condition and MQL nozzle positioned at tool cut out of workpiece while the uniform flank wear is the failure mode of uncoated tool insert when MQL nozzle positioned at tool cut into the workpiece.

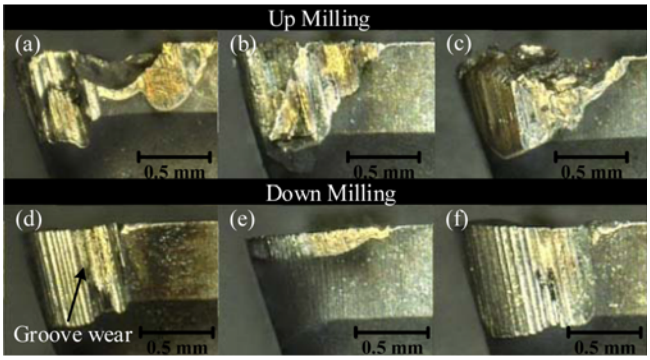

Fig. 5 Flank of worn uncoated tool inserts after removing volume of 6.4 cm^3 in different lubrication conditions (a) (d), Dry; (b) (e), MQL nozzle positioned at tool cut into workpiece; (c) (f), MQL nozzle positioned at tool cut out of workpiece

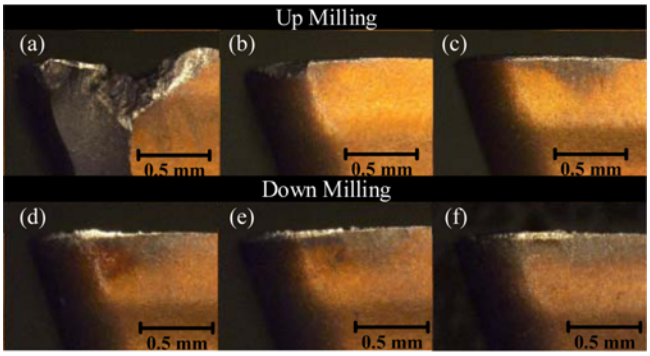

Fig. 6 Flank of worn PVD coated tool inserts after removing volume of 12.8 cm^3 in different lubrication conditions (a) (d), Dry; (b) (e), MQL nozzle positioned at tool cut into workpiece; (c) (f), MQL nozzle positioned at tool cut out of workpiece

Flank wear morphology of worn PVD coated tool inserts after removing volume of 12.8 cm^3 in different lubrication conditions are illustrated in Fig. 6. By comparison of wear morphology of uncoated tool inserts after removing volume of 6.4 cm^3, wear morphology of PVD coated tool inserts have significant improved in both up and down milling even after removing volume of 12.8 cm^3. It is notable that PVD coated tool insert in up milling without MQL still exhibit severe damage and catastrophic breakage and the maximum flank wear is 0.66 mm after removing volume of 12.8 cm^3 according to flank wear curve in Fig. 3, indicating that the BUE is still formed and peeled off during up milling process.

As tool flank is the non-contacted surface, the actual wear state of tool inserts cannot be only estimated by tool flank wear. Wear morphology of rake face of worn uncoated tool inserts after removing volume of 6.4 cm^3 and worn PVD coated tool inserts after removing volume of 12.8 cm^3 in different lubrication conditions are shown in Fig. 7 and Fig. 8, respectively.

For up milling, it is obvious that both uncoated tool inserts and PVD

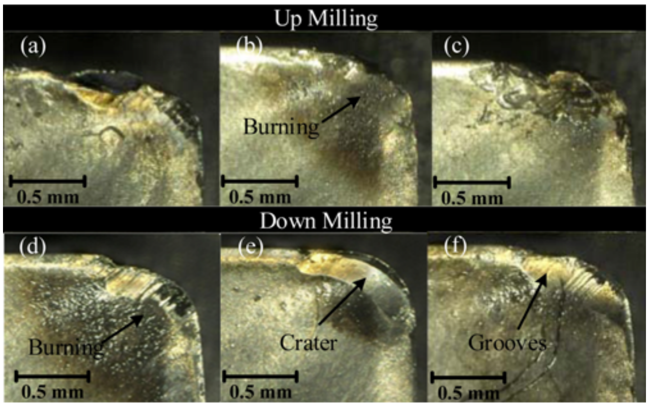

Fig. 7 Rake faces of worn uncoated tool inserts after removing volume of 6.4 cm^3 in different lubrication conditions (a) (d), Dry; (b) (e), MQL nozzle positioned at tool cut into workpiece; (c) (f), MQL nozzle positioned at tool cut out of workpiece

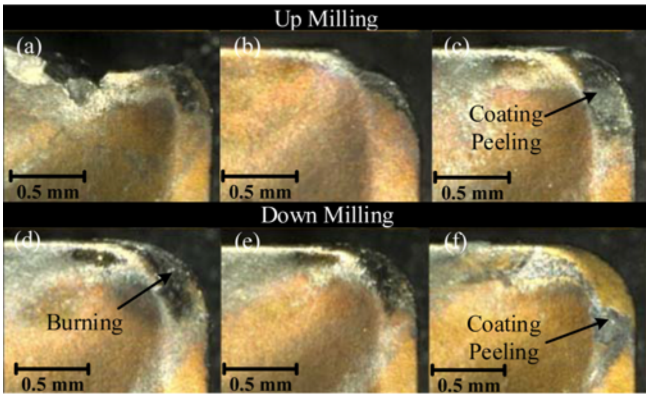

Fig. 8 Rake faces of worn PVD coated tool inserts after removing volume of 12.8 cm^3 in different lubrication conditions (a) (d), Dry; (b) (e), MQL nozzle positioned at tool cut into workpiece; (c) (f), MQL nozzle positioned at tool cut out of workpiece

coated tool inserts exhibit catastrophic tool breakage on tool cutting edge in dry cutting condition. Wear performance of uncoated tool inserts have no significant improvement when MQL is applied. On the contrary, instead of catastrophic tool breakage, notching is the failure mode of PVD coated tool insert when MQL nozzle positioned at tool cut into workpiece. Furthermore, if MQL nozzle positioned at tool cut out of workpiece, PVD coated tool insert presents tiny burning and coating peeling. Due to the low friction coefficient and high impact resistance of TiAlN/TiN coating, PVD coated tool insert exhibits excellent wear resistance with the help of MQL nozzle positioned at tool cut out of workpiece.

For down milling, due to lack of coating protection, uncoated tool inserts suffer severe impact at the initial period of down milling process even with the help of MQL, result in crater on rake face. Crater wear is mainly induced by chip scratching the insert surface. Attributing to high temperature and high pressure in cutting zone, crater wear is also induced by chemical diffusion between the chip and inserts.[2] MQL cannot reduce cutting temperature of uncoated tool inserts in down milling Inconel 182, and the failure modes of uncoated tool inserts in

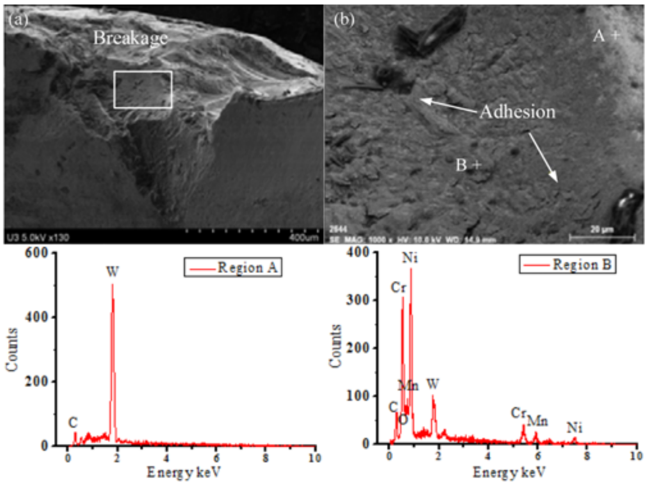

Fig. 9 SEM and EDS images of worn tool without MQL in up milling

different lubrication conditions are chipping, burning, grooves and crater.[22] However, crater disappear on rake face of PVD coated tool inserts. Instead, burning or coating peeling can be the dominate failure modes. Burning and coating peeling area of PVD coated tool inserts in dry cutting condition and MQL nozzle positioned at tool cut into workpiece are similar, on the contrary, there is no burning but only coating peeling on rake face when MQL nozzle positioned at tool cut out of workpiece. Furthermore, it should be noticed that there is no coating peeling on insert nose, illustrating that insert nose is well protected by MQL oil mists.

3.4 Wear mechanism

From above discussion, a conclusion can be drawn that it is unnecessary to further study the wear mechanism of uncoated tool inserts because catastrophic failure have already happened even at initial period in all lubrication conditions when face milling Inconel 182. In this section, wear mechanism of PVD coated tool inserts in different lubrication conditions are discussed in detail.

In up milling, catastrophic tool breakage dominates the cutting edge and the nose in dry cutting condition, as illustrated in Fig. 9. In most cases, strong adhesion and high cutting temperature are the main causes that lead to severe tool wear and catastrophic failure. From the SEM and EDS images, it is found that only tool substrate elements W and C exist in region A, demonstrating that coating has been worn and the tungsten carbide (WC) substrate is exposed to adhesion, which will lead to further catastrophic breakage. A different spectrum in region B indicates that except for tool substrate elements W and C, the Ni, Cr and Mn from Inconel 182 have diffused and adhered to the surface of breakage tool because the temperature of cutting zone is relative higher. The existence of O element also demonstrates that oxidative wear happened. Thus, up milling without MQL provides an ideal environment for adhesion, diffusion and oxidation.[21]

When MQL nozzle positioned at tool cut into workpiece, lubricating film layer adheres to tool surface to provide sufficient protection for cutting edge, reducing the cutting temperature. As shown in Fig. 10, coating and substrate material are lost in tool nose. No catastrophic tool breakage happened according to SEM image, instead, grooves and notch wear are observed. The high-speed mists sprayed by MQL nozzle will

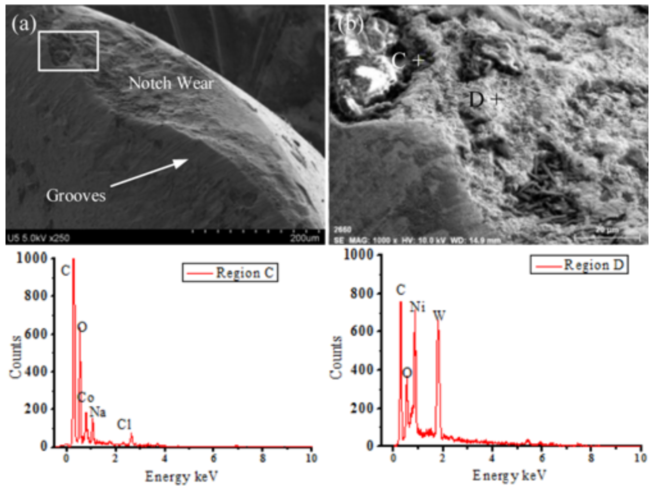

Fig. 10 SEM and EDS images of worn tool in up milling when MQL nozzle positioned at tool cut into workpiece

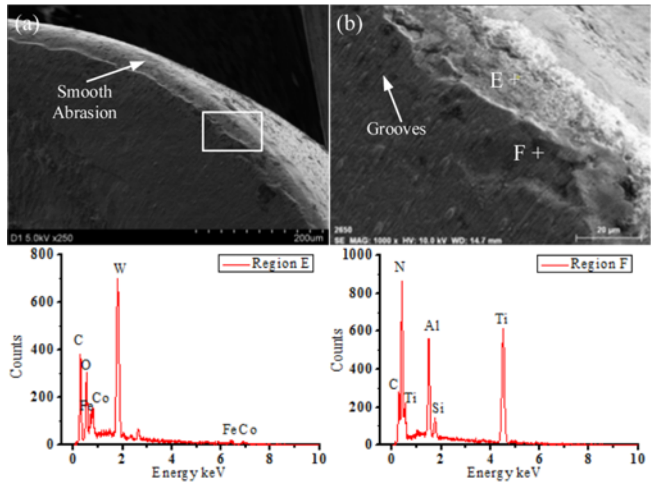

Fig. 11 SEM and EDS images of worn tool in up milling when MQL nozzle positioned at tool cut out of workpiece

greatly increase the oxygen content in cutting zone, and these oxygen can easily combine with carbide insert composition Co to form cobalt oxides at certain temperature. The existence of O and Co elements in region C demonstrates oxidation wear happened. As shown in region D, except for W, O and C elements, Ni is observed at tool surface, illustrating adhesion happened. Therefore, it can be concluded that oxidative wear and adhesive wear are the wear mechanism of up milling Inconel 182 using PVD coated tool insert when MQL nozzle positioned at tool cut into workpiece.

There is almost no obvious adhesion on tool edge when MQL nozzle positioned at tool cut out of workpiece. As shown in SEM images in Fig. 11, smooth abrasive wear evenly distributes along the whole cutting edge during the up milling process. Abrasive wear is caused by the rubbing action between the cutting tool edge and the workpiece. Barshilia et al. found that TiAlN/TiN coating starts to oxidation at about 800.[24] As the temperature continues to rise, Al (or Ti) in the coating material and O in the air will form a dense Al_2O_3 (or a small amount of TiO2) top thin layer covering the coating surface. It increases the oxidation resistance of coating and also reduce the diffusion wear. When the temperature is above 1100, coating bond strength and hot hardness pronounced decrease, Al_2O_3 top thin layer will peel off and the remains will decompose to AlN particles instead of chemical dissolution during metal cutting process.[25] Besides coating elements Ti, Al and N, the existence of small amounts of Si and C which precipitated from Inconel materials in region F will form SiC or TiC hard particles in high temperature or high pressure environment, they are just like many grinding marks, deeply scratching the surface layer of inserts and scoring on the worn tool surface.[26,27] As a consequence, several grooves appear on the coating surface and abrasive wear happened.[28] In addition, the existence O element in region E indicates the occurrence of oxidative wear. Thus, smooth abrasive wear and oxidation wear are found to be the main wear mechanism, demonstrating that MQL nozzle positioned at tool cut out of workpiece during up milling process can effectively reduce cutting temperature and protect insert from adhesion.

Fig. 12 are the SEM and EDS images of worn PVD coated tool insert without MQL during down milling process. It can be observed that wear performance of PVD coated tool insert in down milling without

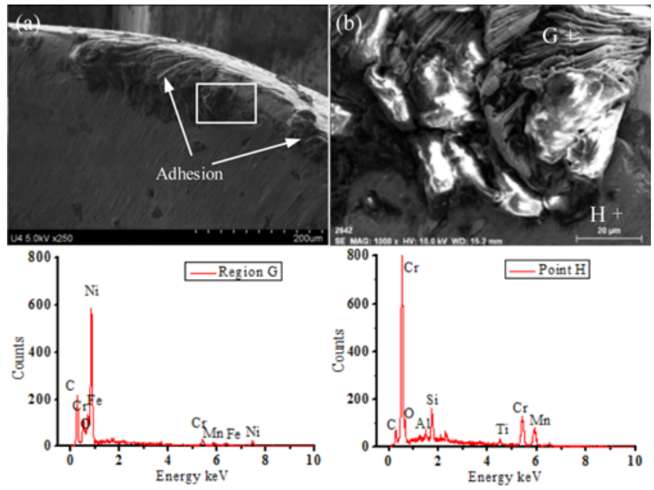

Fig. 12 SEM and EDS images of worn tool without MQL in down milling

MQL is better than those in up milling because no catastrophic tool breakage happened. Instead, cutting edge has been welded with some adhering residual chips of the Inconel 182 (BUE). The BUE occurs aggressively because higher stress and higher temperature acts on the cutting edge, as shown in region G by EDS image. It is also observed from region H that coating (Ti, Al) is covered by high content of Cr, Si element, which precipitated from Inconel 182 at relative low temperature, then, it adheres to the tool cutting edge to form carbides. The adhered Cr carbides and SiC hard particles will scratched the tool surface and induce abrasive wear. Therefore, adhesive wear, abrasive wear as well as oxidation wear are found to be the main wear types of down milling Inconel 182 using PVD coated tool inserts without MQL.

When MQL nozzle positioned at tool cut into workpiece, the cutting zone is sufficient lubricated and the temperature decreases, as a consequence, adhesive wear is relieved. As shown in Fig. 13, uniform abrasive wear is found along the tool cutting edge. Although there is no BUE along the cutting edge, adhesion are also found both at tool rake face and flank. EDS image in region J (Ni, Cr, Fe, Mn and C) shows

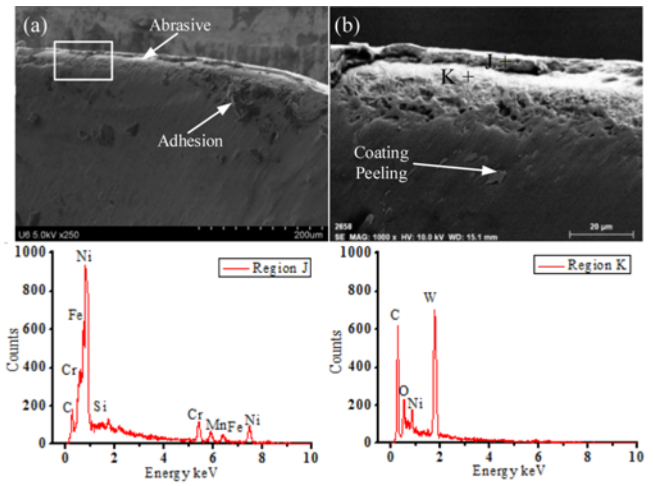

Fig. 13 SEM and EDS images of worn tool in down milling when MQL nozzle positioned at tool cut into workpiece

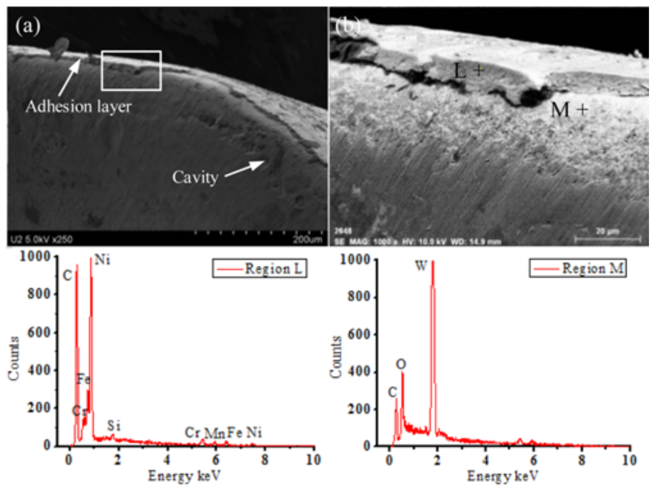

Fig. 14 SEM and EDS images of worn tool in down milling when MQL nozzle positioned at tool cut out of workpiece

that the adhesive layer on tool cutting edges are not TiAlN/TiN coating layer, Ni element from Inconel 182 has melt and adheres to tool flank, at whose temperature Cr carbides also precipitated. As shown in region K that besides carbide substrate elements W and C, there are a small amount of Ni and O elements, demonstrating that diffusive wear and oxidative wear happened. However, obvious coating peeling is found in the coating flaking zone. It is clearly notable that adhesive wear, uniform abrasive wear accompanied a little bit of oxidative wear and diffusive wear are the main wear types of PVD coated tools in down milling Inconel 182 when MQL nozzle positioned at tool cut into workpiece.

As shown in Fig. 14, when MQL nozzle positioned at tool cut out of workpiece, cutting zone is also sufficient lubricated. Compared the tool wear performance during down milling process when MQL nozzle positioned at tool cut out of workpiece, adhesive layer also can be found in tool flank. EDS from region L shows that the element spectrum of adhesive layer are similar (Ni, Cr, Fe, C, Si and Mn), Ni element from Inconel 182 has melt and adhered, hard particles such as SiC and Cr carbides also precipitated. However, adhesion on tool rake face and uniform abrasion disappears in region M. There are only W, C and O elements exist, demonstrating that tool substrate material are explored and oxidative wear happened. Thus, adhesion wear and oxidative wear are the main wear types in down milling Inconel 182 when MQL nozzle positioned at tool cut out of workpiece.

4. Conclusions

In this article, wear performance of uncoated tool inserts and PVD coated tool inserts in up and down face milling Inconel 182 deposited by SMAW under different lubrication conditions are investigated. Tool flank wear rate, wear morphology, failure modes and wear mechanism are detail discussed. The main obtained results are as follows:

Uncoated tool inserts are not suitable for face milling Inconel 182, because their flank wear in up or down milling process are far beyond the tool rejection criterion only after removing volume of 6.4 cm^3 in all lubrication conditions. Catastrophic tool breakage are the failure modes in up milling while crater and excessive uniform flank wear are the dominate failure modes in down milling.

PVD coated tool inserts have longer tool life compared to uncoated ones in all lubrication conditions. In up milling, catastrophic breakage, notching and coating peeling are the failure modes in drying cutting, MQL nozzle positioned at tool cut into workpiece and MQL nozzle positioned at tool cut out of workpiece, respectively. It is found that MQL can effectively prolong tool life of PVD coated tool inserts, but the lubrication efficiency of MQL nozzle positioned at tool cut out of workpiece is better than that at tool into of workpiece. However, in down milling, MQL can also effectively reduced tool wear of PVD coated tool inserts. Burning and coating peeling are the dominate failure modes, and the lubrication efficiency of MQL nozzle positioned at tool cut into workpiece or positioned at tool cut out of workpiece is slight.

Wear mechanism of PVD coated tool inserts in up or down milling in different lubrication conditions differ from one to another, they are mainly adhesive wear and abrasive wear, accompanied by diffusive wear and oxidative wear. Adhesive wear happened when the temperature is relative high, in this circumstance, chips can easily adhere to the cutting tool surface to form BUE due to strong adhesive property of Inconel 182. Abrasive wear can be attributed to the Cr and Si carbide precipitation around grain boundary of Inconel 182 at relative low temperature, scratching the surface layer of cutting tool inserts and scoring on the worn tool surface. Wear mechanism strongly depend on whether MQL nozzle positioned appropriately or not during both up and down milling process.

MQL nozzle positioned at both tool cut into workpiece and tool cut out of workpiece in down milling as well as MQL nozzle positioned at tool cut out of workpiece in up milling can be selected as the optimal lubrication methods for cutting deposited Inconel 182.

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