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ORIGINAL ARTICLE

Tool wear in Ti-6Al-4V alloy turning under oils on water cooling comparing with cryogenic air mixed with minimal quantity lubrication

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Abstract Wet cutting is the most common cooling method used during the cutting of titanium alloys. However, this method is associated with high costs, pollution, and hazards to operators. Minimal quantity lubrication (MQL) is an effective environmentally friendly cooling method, but is not suitable for difficult-to-machine materials because of its low heat transfer capacity. Using cryogenic air mixed with MQL (CAMQL) for cooling has better heat transfer, but high equipment costs and noise pollution limit its industrial application. This paper proposes the use of oils on water (OoW) as a cooling method for the turning of Ti-6Al-4V alloy and aims at exploring the effect of OoW cooling. Both external oils on water (EOoW) and internal oils on water (IOoW) methods are considered. The effects of EOoW spraying location and the amount of water required for IOoW are compared with respect to chip morphology, cutting temperatures, cutting forces, surface roughness, and tool wear. The use of CAMQL at different air temperatures is compared with wet and dry cutting. The results show that the chips created by OoW and CAMQL are continuous spirals. Compared with CAMQL, use of IOoW cooling with an appropriate amount of water or EOoW cooling from a proper location yields lower surface roughness and slower flank wear rate, and bare areas on the cutting tool substrate were absent because of better lubrication. The properties of the lubricants have an influence on IOoW and CAMQ L, but not on EOoW. A suitable cutting tool coating should be selected to ensure the best cutting performance under these cooling methods.

Keywords Lubrication mechanism · Ti-6Al-4V · External oils on water (EOoW) · Internal oils on water (IOoW) · Cryogenic air mixed with minimal quantity lubrication (CAMQL) · Tool wear

Nomenclature

MQL	Minimal quantity lubrication
CAMQL	Cryogenic air mixed with MQL
OoW	Oils on water
EOoW	External oils on water
$EOoW_r$	Spray to rake face in EOoW
$EOoW_f$	Spray to flank face in EOoW
$EOoW_{rf}$	Spray to rake and flank faces in EOoW
IOoW	Internal oils on water
F_x	Cutting force in the feed direction (N)
F_y	Cutting force in the radial direction (N)
F_z	Main force (N)
V_B	Width of flank wear (mm)
n	Spindle rotate speed (r/min)
v_c	Cutting speed (m/min)
f	Feed per revolution (mm/r)
a_p	Depth of cut (mm)

1 Introduction

Titanium alloys are widely used in the aerospace, automotive, chemical, and biomedical industries [1] owing to their excellent mechanical and physical properties (e.g., excellent corrosion resistance, low density or high strength-to-weight ratios, and good high-temperature properties). However, problems

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such as fast tool wear, poor surface quality, and machining deformation [2] are encountered during the machining of titanium alloys because of their low thermal conductivity, low modulus of elasticity, and high chemical activity [3, 4]. Cooling during the machining process is required to improve cutting of titanium alloys. Wet cutting is the most common cooling method, but this has high cost and pollution, and presents hazards to operators [5–7]. Many near-dry cutting methods have been proposed to minimize or eliminate the use of cutting fluids, including cryogenic cooling (such as liquid nitrogen (LN_2) cooling) [8–15], water vapor cooling [16–19], and minimal quantity lubrication (MQL) [20–23].

The application of LN_2 at −196 °C to the cutting zone during the machining process, known as liquid nitrogen cooling [14], is effective in reducing the cutting temperature and maintaining the temperature of cutting tool. Nitrogen evaporates harmlessly into the air, and no residual oil is left on the chip, but this is an energy-dissipating technique. Moreover, Dhar et al. [15] confirmed that the benefit of LN_2 cooling dominates at lower cutting velocity because of more effective penetration at the interface. Godlevski [16] proposed a new green cutting technique, using water vapor as the coolant and lubricant. Water vapor enters the cutting zone in the gas phase, which is helpful in improving the penetrability. Han et al. [17] observed a 10 % reduction in cutting force when turning 45# steel with water vapor cooling compared with that using a cutting fluid. However, this method lacks lubricating ability, because water, as the main medium, is used mainly for cooling. Compared with other green cooling methods, MQL is most commonly used because of its simple equipment, low cost, and good cutting performance for some materials. Traditional MQL technology contains a very small amount of lubricating oil (10 to 200 mL/h), which is directed to the cutting zone by compressed air. Owning to its high penetrability, this method has been approved to have great performance in many practical machining operations, including turning [2, 20, 21], milling [23, 24], drilling [25–27], and grinding [28–30]. The major limitation of MQL is its low heat transfer, especially in cutting operations that experience thermal problems. High temperatures in the cutting zone contribute to the evaporation of the lubricant and the loss of lubrication function, so traditional MQL cannot be used in machining difficult-to-machine materials [31, 32].

To solve the issue of MQL heat transfer, some researchers have proposed the use of cryogenic air mixed with minimal quantity lubrication (CAMQL) cooling. CAMQL has relatively good cutting performance for difficult-to-machine materials, such as Inconel 718 [33] and Ti-6Al-4V [34]. The MQL in CAMQL cooling functions as a lubricant, while the cryogenic air is used to increase the heat transfer, which lowers the cutting temperature and maintains the strength of the oil film, leading to better lubrication. CAMQL is an energy-saving technology, and the gas temperature is not as cold as LN_2 cooling, which changes the properties of titanium alloys. Nevertheless, CAMQL has high equipment costs and creates noise pollution. The lubricant can also freeze inside the nozzle during the machining process.

In machining of aluminum alloys, Itoigawa et al. [32] proposed a new cooling method known as oil film on water droplet (OoW), which uses MQL for lubrication and the phase transformation of water droplets to improve heat transfer. These researchers conducted friction tests between a PCD tool and an aluminum disk and suggested that this method had good lubrication performance depending on the chilling effect of water to sustain the film strength. Better cutting performance was also achieved in machining aluminum alloys using OoW than by traditional MQL.

The effectiveness of OoW for some hard-to-machine materials, such as titanium alloys and hardened steel [35], and the characteristics of tool wear and surface roughness using OoW have, however, received little attention to date.

In this paper, the cutting performance during the turning of Ti-6Al-4V alloy using OoW cooling is studied. There are two different ways of spraying: from the interior of the cutting tool (internal OoW (IOoW)) or from the outside of the cutting tool (external OoW (EOoW)). The effects of spraying location (rake face, flank face, rake and flank faces) and lubricants on EOoW and the quantity of water and lubricants on IOoW were studied. The results are compared with those achieved using CAMQL, wet cutting, and dry cutting. Cutting tools with different coating films were used to study the influence of coatings on the cooling methods.

2 Experiment

Ti-6Al-4V alloy bars (manufactured by Baoti Group®), with a length of 200 mm and a diameter of 50 mm, were used to carry out turning experiments on a CAK3675V CNC lathe. The coated carbide inserts (WNMG080812-MF5) and tool holder (MWLNR2525m08) manufactured by Seco were used. The rake and flank angles of the inserts in the turning process were 5 and 6°, respectively. The cutting parameters selected were cutting speeds of 70, 90, and 110 m/min; a depth of cut of 1.0 mm; and a feed rate of 0.25 mm/r.

To study the cutting performance of different lubricants and cemented carbide cutting tool with different coating films, two lubricants and three coated carbide inserts were used, shown in Tables 1 and 2, respectively.

Schematics of the EOoW, IOoW, and CAMQL cooling conditions are shown in Table 3. In the EOoW experiments, microlubricant and a small amount of water were transported by the external MQL equipment to a cold air gun, atomized, mixed, and then sprayed onto the cutting zone by compressed

Table 1 Properties of lubricants

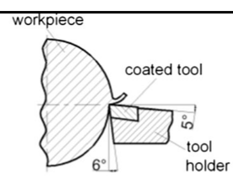
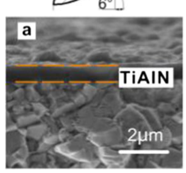
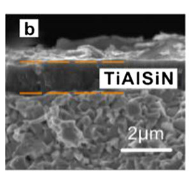
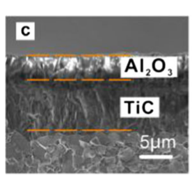
Type of oils	Main composition	Viscosity (40 °C) [cSt]	Flash point [°C]	Lubricity	Cooling ability	Producer
2000-10	Fatty alcohol	15	165	Moderate	High	DG Armorine Energy-Efficient and Eco-Friendly Tech Co., Ltd, China
2000-30	Synthetic ester	30	290	High	Moderate	

air, as shown in the equipment schematic of Table 3 (b). As shown in the equipment schematic of Table 3 (c), in IOoW, the lubricant was atomized inside the IOoW equipment and mixed with a moderate amount of water droplets. The mixed fluid was then introduced into the modified cutting bar and simultaneously sprayed towards the rake and flank faces. Under the CAMQL condition (in the equipment schematic of Table 3 (d)), cryogenic air, generated by cryogenic equipment, was mixed with the oil mist coming from the IOoW equipment, and sprayed onto the cutting zone. All green cooling equipments mentioned above are produced by DG Armorine Energy-Efficient and Eco-Friendly Tech Co., Ltd, China.

Under the EOoW conditions, the effects of three different spraying locations (rake face, flank face, and rake and flank faces) were studied. In the IOoW experiments, the effects of small (1.2 L/h) and large (2.4 L/h) amounts of water were studied. In the CAMQL experiments, two different cryogenic air temperatures, −16 and −26 °C, were studied. The other cooling conditions, including spray angles et al., are also listed in Table 3.

During the experiments, the cutting forces in three directions (feed force F_x, radial force F_y, and main force F_z) were measured using an online force measurement system, which included a piezo-electric three-component dynamometer (Kistler 9257B, Kistler Instrument®), a multichannel charge amplifier (Kistler 5080A1030001, Kistler Instrument®), and a personal computer (PC)-based data acquisition system (Dynaware). Thermal infrared equipment (TVS-500EX, NEC®) and online data monitoring and acquisition software (AVIO®) were used to measure the cutting temperature. The surface roughness was measured using a portable roughness meter (TR200). The width of flank wear, V_B, was measured using an OLYMPUS SZ61 microscope after each predetermined cutting action. In addition, the tool surfaces were observed using a Supra 40 scanning electron microscope (SEM) with energy-dispersive spectroscopy (EDS) (Zeiss Group®) to analyze and illustrate the modes of tool wear at the end of the full cut. Experimental setup of cutting force and cutting temperature test systems is shown in Fig. 1.

Table 2 Cutting inserts with three different coating films

WNMG080412-MF5 coated cemented carbide Seco Tools, Sweden		
1. TS2500: PVD coating TiAlN		
2. TH1000: CVD coating TiAlSiN		
3. TP2500: PVD coating Al_2O_3/TiC		

3 Results and discussion

3.1 EOoW and IOoW

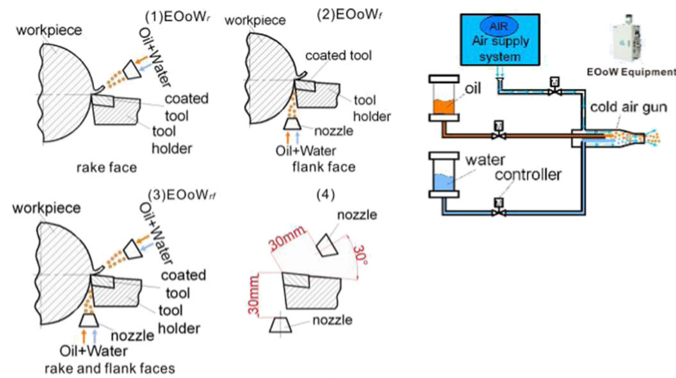
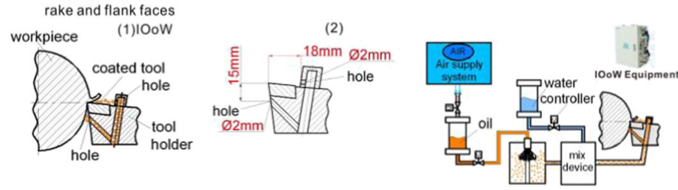
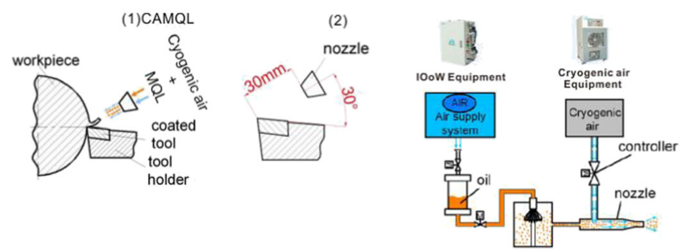
3.1.1 EOoW

Effect of spray location on cutting performance The effects of different spraying locations (rake face, flank face, and rake and flank faces) and the lubrication properties on EOoW performance were studied. The effect of lubrication at the three different spraying locations is shown in Table 4.

As Fig. 2 shows, the chip morphology obtained under all of these EOoW cooling conditions was continuous spirals. Compared with $EOoW_r$ (Fig. 2a) and $EOoW_{rf}$ (Fig. 2c), however, the chips produced by $EOoW_f$ (Fig. 2b) were shorter because of the single air-spraying direction (down to up), which broke the chips more easily.

Figure 3 compares cutting temperatures, cutting forces, surface roughness, and flank wear rate under $EOoW_r$, $EOoW_f$, and $EOoW_{rf}$ conditions (referring to Table 3). $EOoW_r$ and $EOoW_{rf}$ gave almost the same cutting temperature, while $EOoW_f$ was about 80 °C higher (Fig. 3a). $EOoW_{rf}$ had the

Table 3 Cooling conditions for wet cutting, EOoW, IOoW, and CAMQL

	Cooling	Conditions	Equipment schematic
(a)	Wet cutting		Semi-synthetic coolant
(b)	EOoW	water: 150 mL/h air temperature: 11°C water temperature: 20°C Injection location: rake face, flank face, rake and flank face	
(c)	IOoW	air: 30°C, water: 30°C Water supply: 1.2 L/h and 2.4 L/h	
(d)	CAMQL	Air temperature: -16°C and -26 °C	
		Air pressure: 0.3 MPa; MQL oil supply: 20 mL/h	

lowest F_x, EOoW$_f$ was the second lowest, and EOoW$_f$ had the lowest F_z (Fig. 3b).

EOoW$_{rf}$ conditions gave the lowest feed force F_x and flank wear rate, but the highest surface roughness. EOoW$_f$ conditions gave the highest feed force F_x but the lowest roughness (Fig. 3c). A 20 % reduction in surface roughness for EOoW$_f$ was obtained compared with wet cutting. For EOoW, the surface roughness was determined not only by the feed force F_x and flank wear alone but also by chip formation and the shearing of material [36]. As Fig. 2 shows, the chips formed during EOoW$_f$ were much shorter than those of EOoW$_r$ and EOoW$_{rf}$ because of the air-spraying direction from down to up. This may contribute to lower surface roughness. Under EOoW$_{rf}$ conditions, two air streams were sprayed along the rake and flank faces, and met near the cutting zone, resulting in the chips more easily staying in the rake face. As the enlarged drawing of the rake face in Fig. 4c shows, some chips were bonded to the cutting edge of the rake face. This may increase surface roughness under EOoW$_{rf}$ cooling.

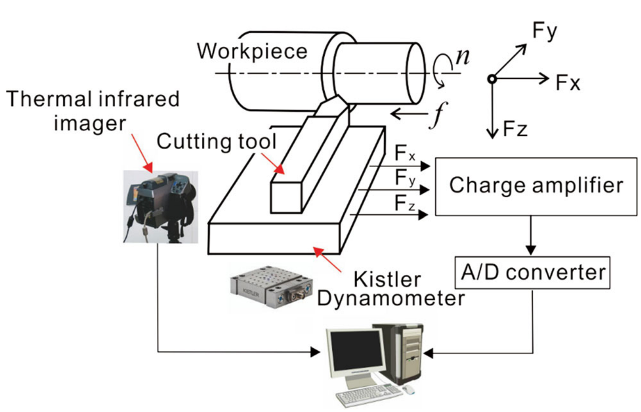
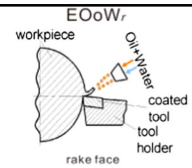


Fig. 1 Experimental setup of cutting force and cutting temperature test system

Figure 3d shows that the flank wear rate for EOoW$_{rf}$ cooling was the slowest of the three locations. This was because of good lubrication of the flank face and fast heat transfer on the rake face when simultaneously spraying to both faces. The flank wear rate for EOoW$_f$ cooling was lower than using the EOoW$_r$ conditions before and at the cutting distance of 120 m, and increased when the cutting distance exceeded

Table 4 The effect of lubrication at three different spraying locations

			
Rake face	Cooling and lubrication by cryogenic air and the penetration of oils directly	Cooling and lubrication by the penetration a few oils indirectly	Both cooling and lubrication by cryogenic air and the penetration of oils directly
Flank face	Lubrication by the penetration of a few oils indirectly	Cooling and lubrication by cryogenic air and the penetration of oils directly	

180 m. At the beginning of the cutting process, the flank face was lubricated directly to reduce flank wear under EOoW$_f$ conditions, but the oil film quickly lost its lubricating effect because of the higher cutting temperature, which led to severe friction on the flank face. Although the flank face was lubricated indirectly by oil penetration under EOoW$_r$ conditions, the strength of the oil film was maintained because of the almost 80 °C lower cutting temperature (Fig. 3a), leading to better reduction of flank wear.

Effect of spray location on tool wear Figure 4 shows the rake and flank face wear morphologies under EOoW$_r$ (Fig. 4a), EOoW$_f$ (Fig. 4b), and EOoW$_{rf}$ (Fig. 4c) conditions. Adhesive wear was the main wear form on the rake face for EOoW cooling. EOoW$_f$ experienced large bulk chips in the rake face due to severe adhesive wear; however, this was absent in samples from the other two spraying locations.

Besides severe adhesive wear on the flank face, there were bare areas on the cutting tool substrates in the EOoW$_r$ and EOoW$_f$ experiments, marked as A in the enlarged drawing in Fig. 4a, b, which had undergone a dynamic adhesion–peeling–adhesion process, leading to the loss of cobalt from the cutting tool material. The tungsten component of the cutting tool material was more easily eroded by the flowing chips, resulting in bareness of the cutting tool substrate (zone A). The occurrence of zone A contributed to the lack of lubrication and severe friction on the flank face. This area was absent from EOoW$_{rf}$ samples due to the better lubrication in flank face under this conditions.

The spraying location used during EOoW cooling has a significant influence on the cutting performance and tool wear during the machining of Ti-6Al-4V. The EOoW$_f$ conditions gave the lowest surface roughness but the fastest flank wear rate, while EOoW$_{rf}$ gave the opposite results. Furthermore, the EOoW$_{rf}$ conditions did not give rise to bare areas because of the better lubrication than that occurred during the EOoW$_r$ and EOoW$_f$ experiments (see zone A in Fig. 4a, b).

Effect of lubricants on surface roughness and tool wear The influence of lubricants on the surface roughness under EOoW$_r$ conditions and flank wear under EOoW$_{rf}$ cooling is shown in Fig. 5. The results for the two lubricants are very similar, which suggests that the properties of the lubricants have little influence on EOoW cooling.

In conclusion, the chips produced by EOoW$_f$ cooling are much shorter than those by EOoW$_r$ because of the single air-spraying direction, which breaks the chips more easily. Of the three spraying locations, EOoW$_f$ gave the lowest surface roughness and EOoW$_{rf}$ gave the slowest flank wear rate. The bare area of the cutting tool substrate (zone A) was only

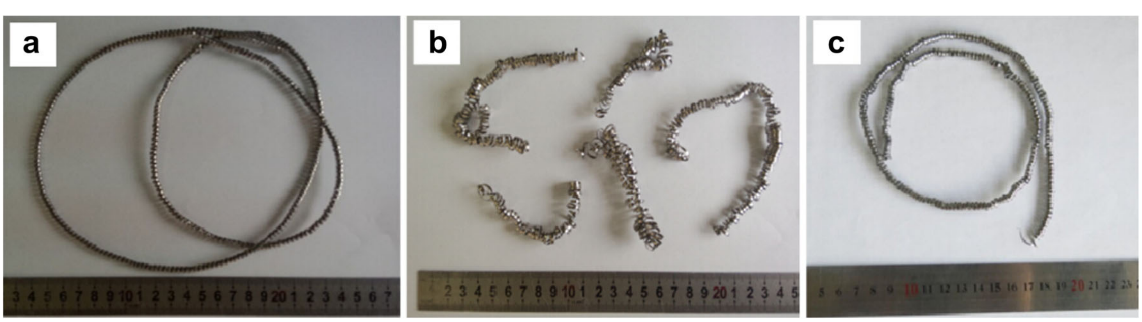


Fig. 2 Chip morphology obtained under **a** EOoW$_r$, **b** EOoW$_f$, and **c** EOoW$_{rf}$ conditions (v_c=90 m/min, f=0.25 mm/r, a_p=1 mm; cutting distance, 120 m)

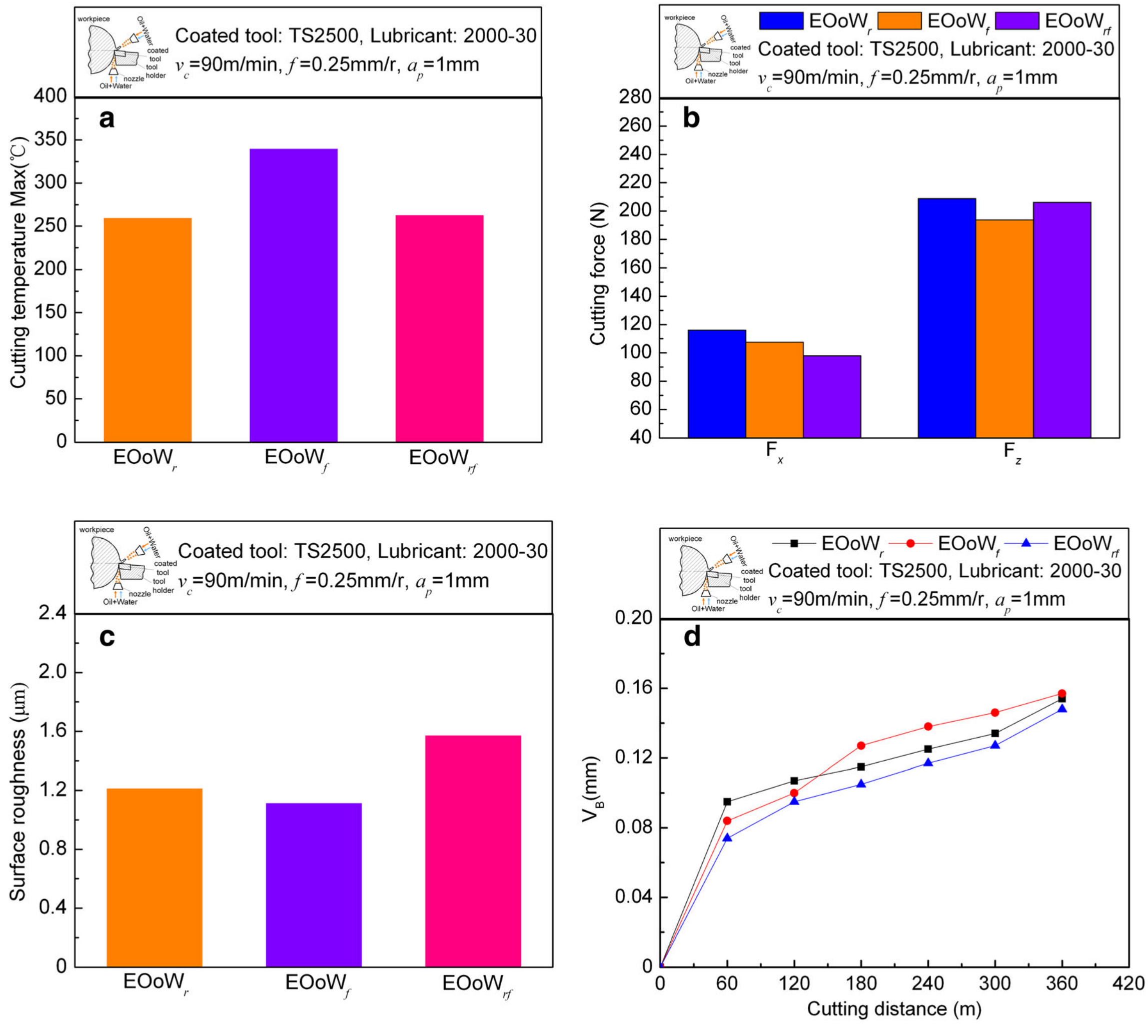


Fig. 3 Comparisons of cutting performance of Ti alloy under EOoW$_r$, EOoW$_f$, and EOoW$_{rf}$ conditions. **a** Cutting temperature, **b** cutting force, **c** surface roughness, and **d** flank wear, V_B

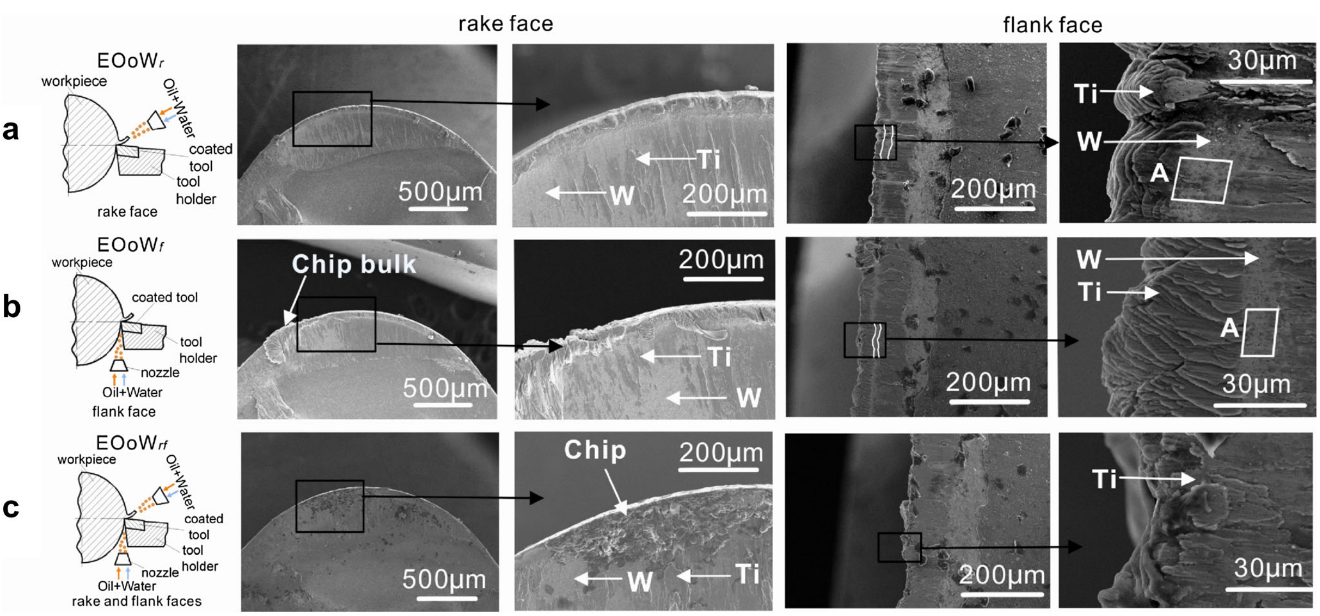


Fig. 4 Flank wear morphology under EOoW$_r$, EOoW$_f$, and EOoW$_{rf}$ conditions (v_c=90 m/min, f=0.25 mm/r, a_p=1 mm; cutting distance, 360 m)

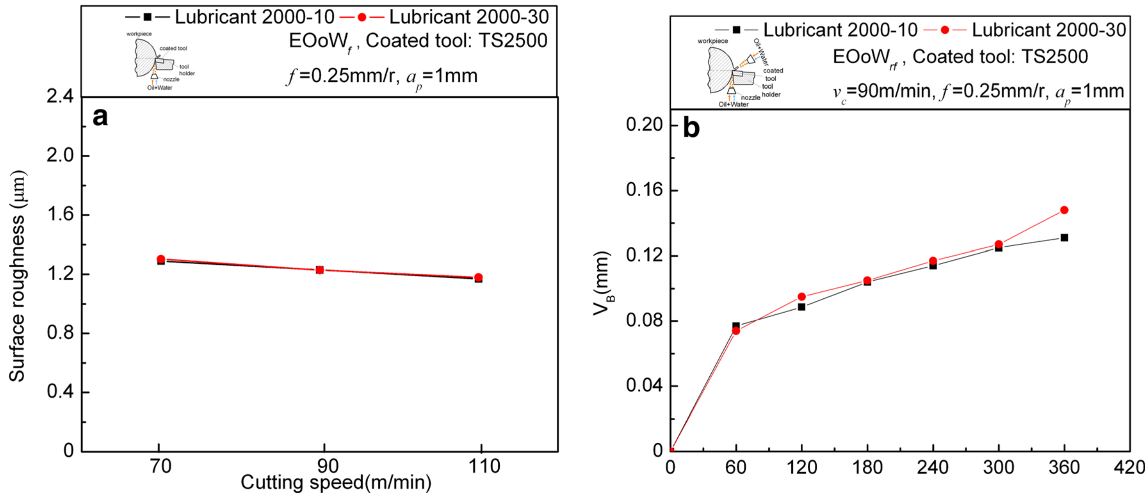


Fig. 5 Influence of lubricants on **a** surface roughness and **b** flank wear V_B under EOoW cooling conditions

absent from EOoW$_{rf}$ because of the better lubrication. Lubricants have no influence on the surface roughness and flank wear rate in EOoW.

3.1.2 IOoW

Effect of water amount on the cutting performance Figure 6 shows the chip morphology created under IOoW cooling conditions using different amounts of water. The continuous spiral chip shapes of IOoW (1.2 and 2.4 L/h water) were similar to those obtained from the EOoW$_r$ and EOoW$_{rf}$ conditions. The amount of water used during IOoW cooling had no influence on the formation of chips during the turning of Ti-6Al-4V.

As shown in Fig. 7a, IOoW with a larger amount of water has better ability to reduce the cutting temperature. IOoW (1.2 L/h water) has a lower feed force F_x, but higher main force F_z (Fig. 7b). The surface roughness created by IOoW with 1.2 L/h water was lower than that by IOoW with 2.4 L/h water (Fig. 7c). Meanwhile, the feed force Fx of IOoW with 1.2 L/h water was also slightly lower than that of IOoW with 2.4 L/h water because of the better lubrication at the tool and workpiece interface. Figure 7d also shows that the flank wear rate of IOoW with a smaller amount of water was much slower than that with a large amount of water, again indicating better lubrication on the flank face under IOoW conditions with 1.2 L/h water.

Effect of amount of water on tool wear Figure 8 shows the rake and flank wear morphologies under IOoW (1.2 and 2.4 L/h water) conditions. As the enlarged drawing of the rake face in Fig. 8a, b shows large bulk chips only bonded on the rake face under IOoW (2.4 L/h water) conditions, because of poor lubrication at the rake face and chip interface, even though the cutting temperature was lower in this case (Fig. 7a). Concerning the flank wear morphology, a bare area was created on the cutting tool substrate (zone A) under IOoW (2.4 L/h water) conditions (see the enlarged drawing of the flank face in Fig. 8b). Similar to zones A seen for EOoW$_r$ and EOoW$_f$ cooling, this area undergoes an adhesion–peeling–adhesion process, and parts of the cutting tool material are removed. This effect was absent from IOoW (1.2 L/h water) samples, as seen in the enlarged drawing of the flank face in Fig. 8a, because of much better lubrication, attributed to the oil film between the interface of the flank face and workpiece under IOoW conditions using a small amount of water.

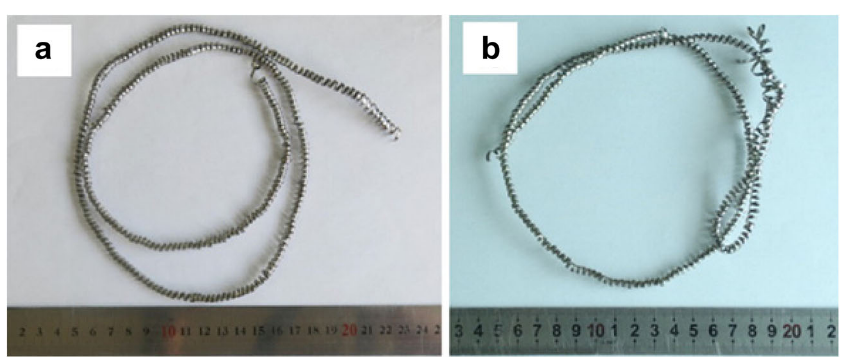


Fig. 6 Chip morphology under **a** IOoW with 1.2 L/h water and **b** IOoW with 2.4 L/h water conditions (v_c=90 m/min, f= 0.25 mm/r, a_p=1 mm; cutting distance, 120 m)

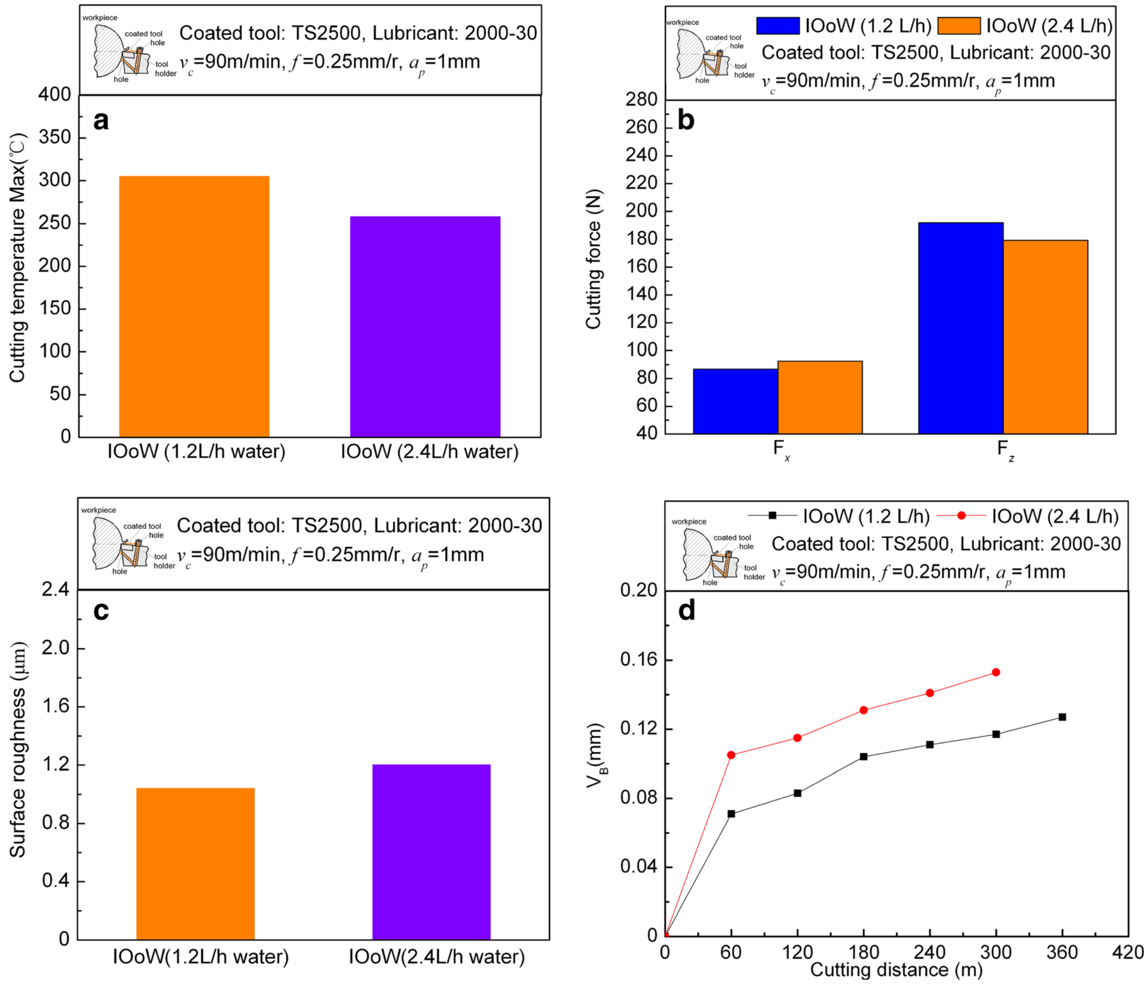


Fig. 7 Comparisons of cutting performance of Ti alloy under IOoW with 1.2 L/h water and IOoW with 2.4 L/h water conditions. **a** Cutting temperature, **b** cutting force, **c** surface roughness, and **d** flank wear V_B

Effect of lubricants on surface roughness and tool wear The surface roughness obtained under three different cutting speeds (70, 90, and 110 m/min) was lower, and the flank wear rate was slower when using lubricant 2000-30 for IOoW cooling, as shown in Fig. 9. These results indicate that the lubricant properties have a significant influence on surface roughness and flank wear under IOoW cooling conditions.

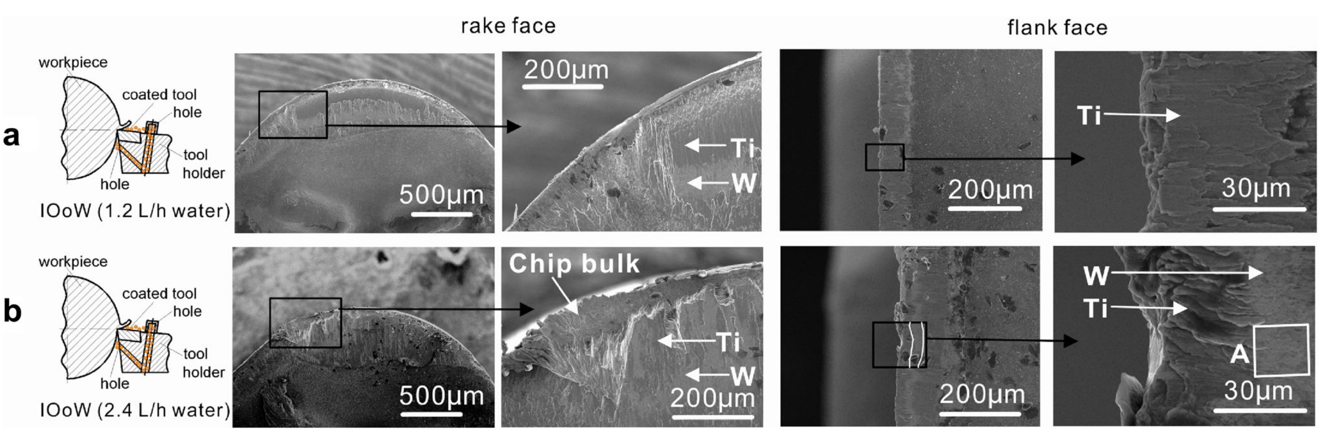


Fig. 8 Flank wear morphology under **a** IOoW with 1.2 L/h water and **b** IOoW with 2.4 L/h water conditions (v_c=90 m/min, f=0.25 mm/r, a_p=1 mm; cutting distance, 360 m)

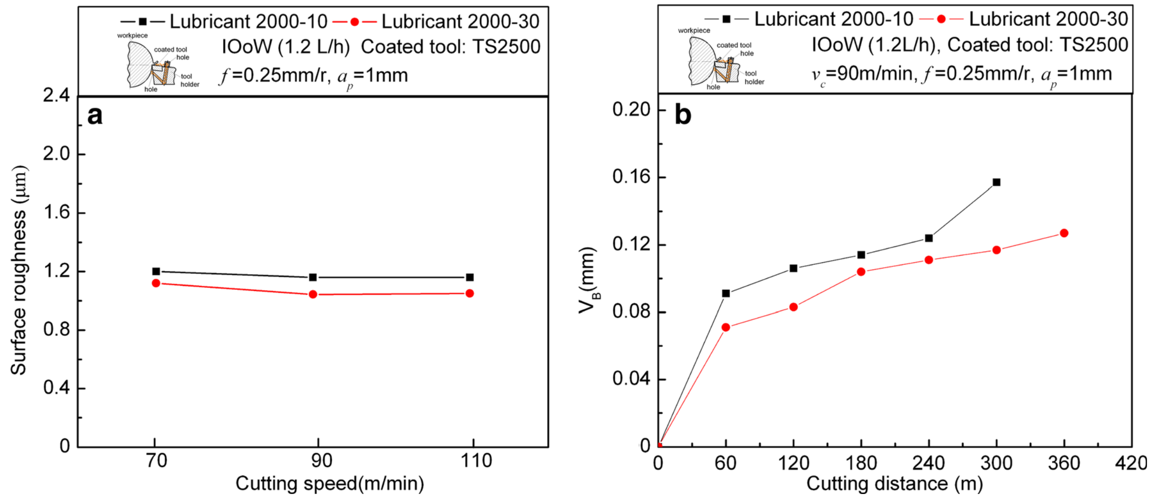


Fig. 9 Influence of lubricants on **a** surface roughness and **b** flank wear, V_B, under IOoW conditions

In conclusion, the chip morphology produced by IOoW cooling with different amounts of water is continuous spirals. IOoW cooling with a lower amount of water gave better lubrication, the surface roughness was lower, and the flank wear rate was slower compared with IOoW cooling using a larger amount of water. The bulk chips and bare areas on the cutting tool substrate (zone A) were both absent under IOoW (1.2 L/h water) cooling conditions. The lubricant properties have a significant influence on surface roughness and tool wear in IOoW cooling.

3.2 Comparison of CAMQL with wet cutting and dry cutting

3.2.1 Cutting performance

CAMQL (−16 and −26 °C) was compared with wet and dry cutting with respect to cutting temperature, cutting forces, surface roughness, tool wear, and chip morphology. The different lubricants were also compared to understand their effect on CAMQL.

Figure 10 shows that the dry-cut chips formed tangled spirals, while CAMQL and wet cutting gave long continuous spiral chips. This means that CAMQL cooling has little influence on chip morphology compared with wet cutting.

Figure 11 compares cutting temperatures, cutting forces, surface roughness, and flank wear V_B under CAMQL (−16 and −26 °C) with wet cutting and dry cutting. As Fig. 11a shows, the dry cutting temperature is 100 to 150 °C higher than that of CAMQL at both cryogenic temperatures tested. CAMQL (−26 °C) has a lower cutting temperature because of the colder cryogenic air. The wet cutting temperature could not be measured using the thermal infrared equipment because the cutting zone was covered by a large amount of cutting fluid and the equipment can only measure the surface temperature. CAMQL can reduce the cutting force to a certain extent compared with dry and wet cutting, and CAMQL at −16 °C is more effective than at −26 °C in reducing the cutting force (Fig. 11b) because colder cryogenic air maintains the strength and hardness of the titanium alloy to a greater extent. CAMQL has the ability to reduce surface roughness compared with dry and wet cutting, as shown in Fig. 11c. A 14 % reduction in surface roughness of CAMQL (−16 °C) was measured compared with wet cutting. The surface roughness of CAMQL at −16 °C decreased slightly compared with that at −26 °C, corresponding to the change in feed force F_x, which was also slightly lower at −16 °C. As Fig. 11d shows, CAMQL has the ability to reduce the flank wear rate compared with wet and dry cutting because of the small oil droplets penetrating into the cutting zone and producing an oil film, which leads to better lubrication. Cryogenic air not only lowers the cutting

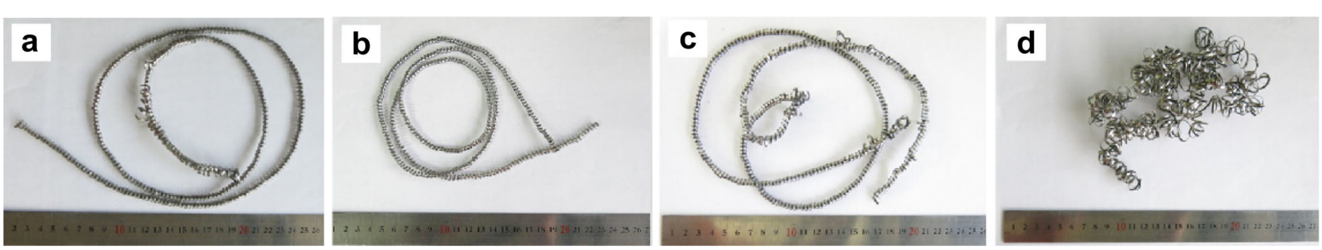


Fig. 10 Chip morphology under cooling conditions for **a** CAMQL at −16 °C, **b** CAMQL at −26 °C, **c** wet cutting, and **d** dry cutting (v_c=90 m/min, f= 0.25 mm/r, a_p=1 mm; cutting distance, 120 m)

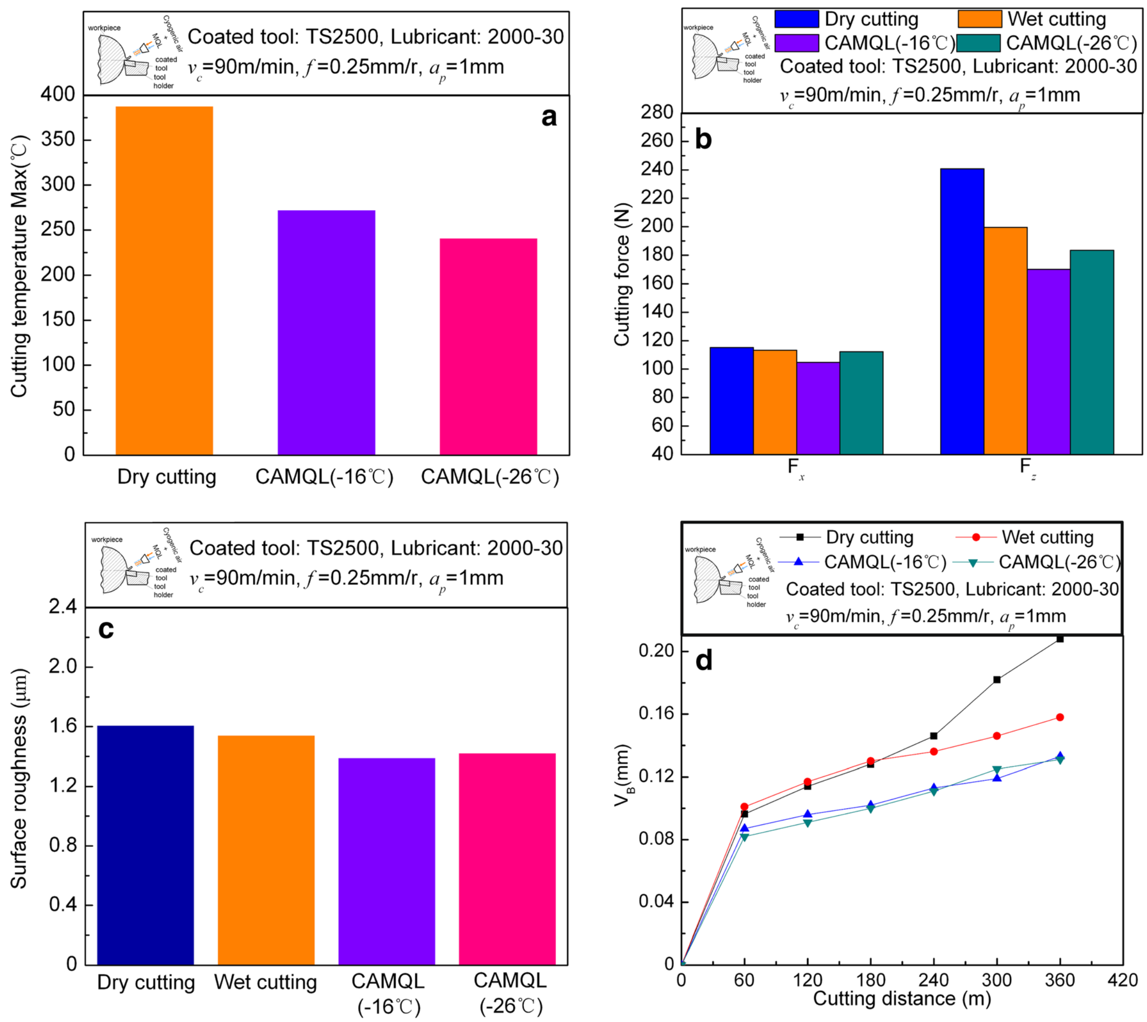


Fig. 11 Comparisons of cutting performance under dry, wet, and CAMQL (−16 and −26 °C) conditions. **a** Cutting temperature, **b** cutting force, **c** surface roughness, and **d** flank wear V_B

temperature but also maintains the strength of the oil film on the surface between the cutting tool and the workpiece.

3.2.2 Tool wear

Figure 12 compares the wear morphologies of the rake and flank faces under CAMQL cooling and wet and dry cutting. Tool breakage of the rake faces only occurred under wet cutting, resulting from interrupted cooling, as shown in Fig. 12c. The vapor membrane, which forms at a certain height in the vertical direction of the tool surface, leads to film boiling during the cutting process using traditional cutting fluid. By preventing the cutting heat from leaving and the cutting fluid from entering the cutting zone, film boiling decreases the heat coefficient and results in poorer cooling. This interrupted cooling phenomenon leads to thermal shock on the cutting tool and influences the surface quality. Some reports have attributed flaking of the rake surface that occurs near the end of the crater wear region during wet cutting of titanium alloy to a high thermal gradient at the end of the crater contact [36], as shown in the enlarged drawing of the rake face in Fig. 12c. CAMQL cooling did not show large area breakage and flaking, which indicated better continuous cooling and a less intensive heat impact, attributed to excellent penetrability (Fig. 12a, b). Small bulk chips appeared in the rake face under CAMQL at −16 °C conditions (Fig. 12a), while these were absent from the −26 °C samples (Fig. 12b) because of the lower cutting temperature (Fig. 11a).

The rake face of the cutting tool showed relatively large bare areas of substrate following dry cutting (Fig. 12d). The cutting tool suffered severe adhesion wear under the high pressures and temperatures of this condition. Titanium alloy bonding to the rake and flank faces usually undergoes a dynamic adhesion–peeling–

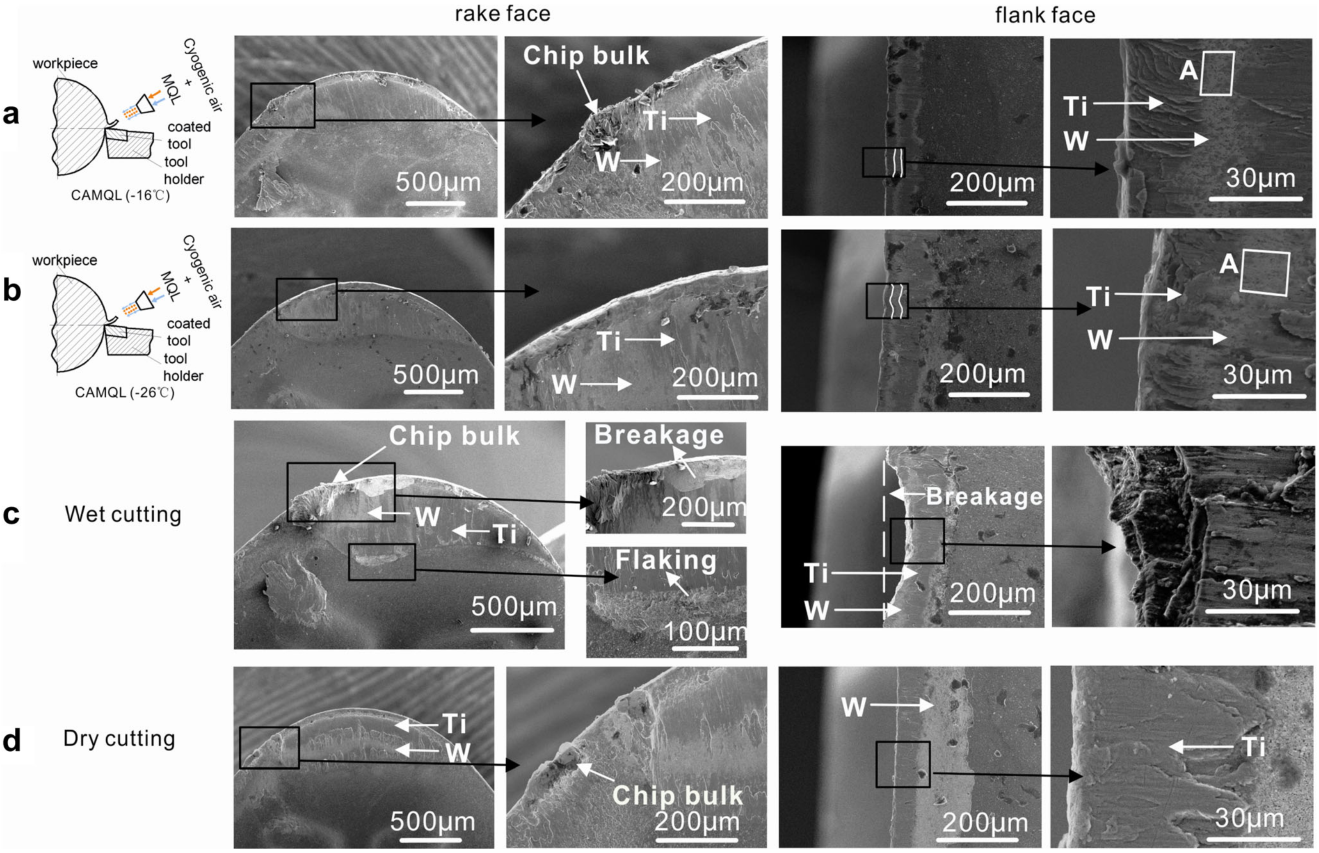


Fig. 12 Rake wear morphology of cutting tool under **a** CAMQL at −16 °C, **b** CAMQL at −26 °C, **c** wet cutting, and **d** dry cutting conditions (v_c=90 m/min, f=0.25 mm/r, a_p=1 mm; cutting distance, 360 m)

adhesion process, so some of the cutting tool material was periodically removed, thereby accelerating the tool wear.

On the flank face, besides severe adhesive wear under CAMQL conditions, a bare area (zone A) appeared, marked as A in the enlarged drawing of the flank face in Fig. 12a,b, which undergoes dynamic adhesion–peeling–adhesion, causing bare regions on the cutting tool substrate. The occurrence of this zone contributes to the lack of lubrication and severe friction on the flank face. In wet cutting, shown for the flank

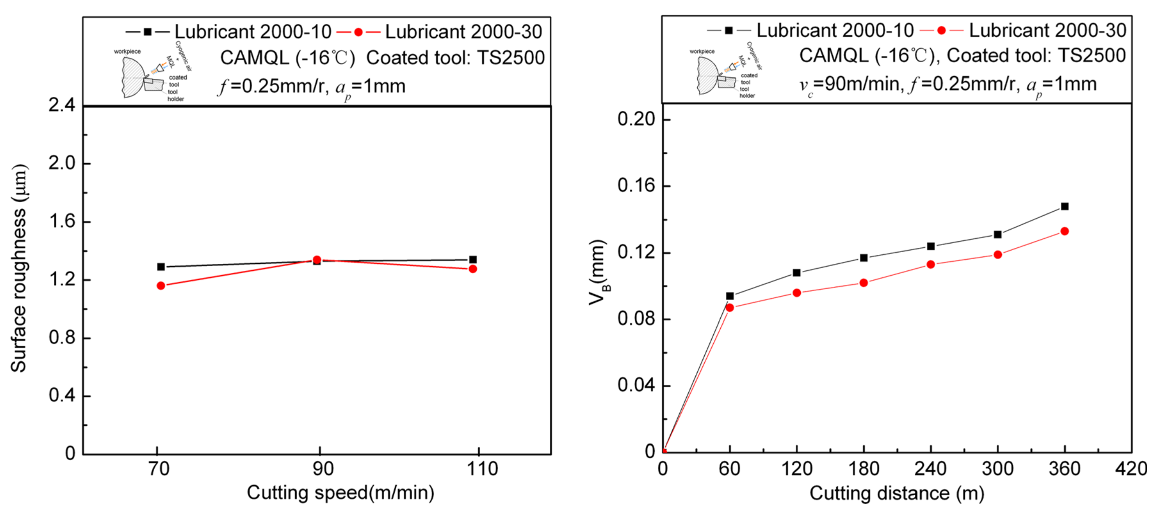


Fig. 13 Influence of lubricants on **a** surface roughness and **b** flank wear V_B under CAMQL at −16 °C air

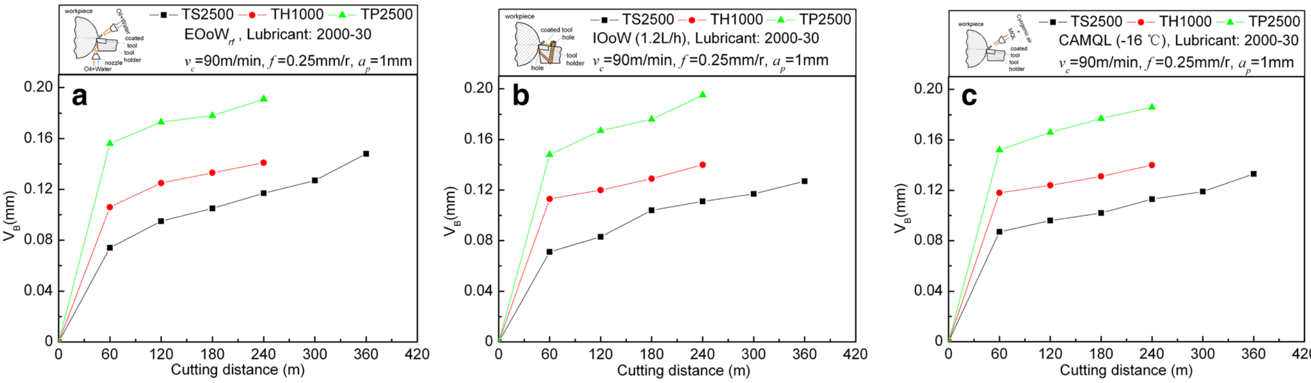


Fig. 14 Flank wear, V_B, of different coated tools under **a** EOoW, **b** IOoW, and **c** CAMQL conditions

face of Fig. 12c, the breakage of flank wear was caused by the heat impact mentioned above. On the flank face of Fig. 12d, apart from the bonding of titanium alloys under dry cutting conditions, a large flaking area resulted from the high cutting temperature (Fig. 11a).

3.2.3 Effect of lubricants on surface roughness and tool wear

As Fig. 13 shows, comparing with the lubricant 2000-10, the surface roughness was slightly lower and the flank wear rate was slower when using the lubricant 2000-30 under CAMQL (−16 °C) conditions, indicating that the lubricant properties have an obvious effect on the cutting performance in the turning of titanium alloy under CAMQL cooling conditions. In terms of energy saving and cutting performance, cooling by CAMQL at −16 °C using the lubricant 2000-30 gave better results than that by CAMQL at −26 °C, wet cutting, or dry cutting. The results of CAMQL (−16 °C) were used to compare with those of OoW.

In conclusion, the chip morphology obtained with CAMQ L cooling was similar to that with wet cutting. The surface roughness of CAMQL at −16 °C was slightly lower than that at −26 °C, and both cryogenic temperatures gave almost the same flank wear rate. CAMQL is better for lowering surface roughness and reducing flank wear rate than both wet cutting and dry cutting. Unlike wet cutting, the cutting tool had no breakage under CAMQL conditions because of better continuous cooling and a less intensive heat impact attributed to excellent penetrability. The bare area on the cutting tool substrate (zone A) in CAMQL cooling resulted from adhesive wear.

3.3 Flank wear rates of different coated tools under EOoW, IOoW, and CAMQL cooling conditions

To study the influence of cutting tools with different coatings on EOoW, IOoW, and CAMQL cooling, three kinds of coated tools, TS2500 (TiAlN PVD coating), TH1000 (TiAlSiN CVD coating), and TP2500 (Al_2O_3/TiC PVD coating), were tested. The flank wear rates of these coated tools under EOoW, IOoW, and CAMQL cooling conditions are compared in Fig. 14. The same sequence of flank wear rates for different coated tools is observed for all cooling methods, indicating that suitably coated cutting tools should be selected for the

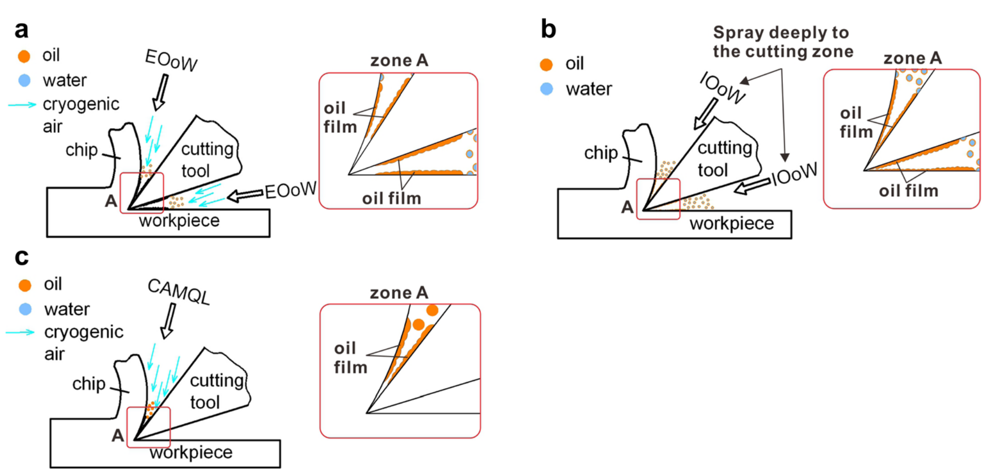


Fig. 15 Schematics of **a** EOoW, **b** IOoW, and **c** CAMQL working processes

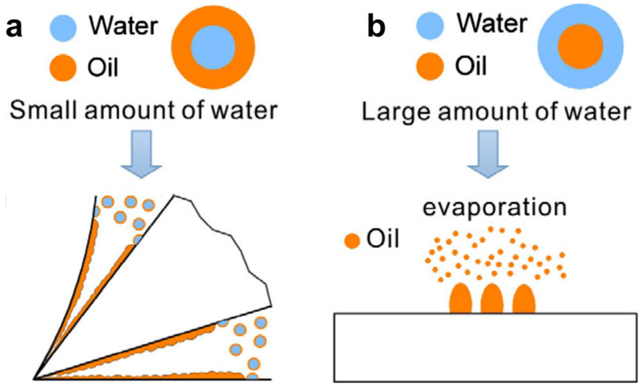


Fig. 16 Water and oil combinations

turning of Ti-6Al-4V to achieve the best cutting performance under these employed cooling methods.

3.4 Comparison of EOoW, IOoW, and CAMQL

3.4.1 Lubrication mechanism of EOoW, IOoW, and CAMQL

Figure 15 shows schematics of the EOoW, IOoW, and CAMQ L working processes. In EOoW, cryogenic air and water are used for heat transfer, and oils for lubricating. In IOoW, water and oils play roles in heat transfer and lubricating, respectively. Cryogenic air and oils play roles in heat transfer and lubricating, respectively, in CAMQL. Cryogenic air at less than 0 °C contributes to maintaining the strength of the oil film, as well as the strength and hardness of the titanium alloy. Unlike CAMQL and EOoW, the IOoW media can spray deeply into the cutting zone, as shown in zone A of Fig. 15, allowing more oils to penetrate to the cutting zone, which strengthens the oil film compared with CAMQL and EOoW when the same amount of oil is used. This is the main reason why IOoW has better cutting performance than CAMQL and EOoW.

Depending on the form of the water and oil, lubrication in IOoW differs with different amounts of water, as shown in Fig. 16. When a small amount of water is used, the mixture takes the form of oils on water; when using large amounts of water, this reverses to water on oils. The oil in the oils on water system bonds to cutting tool and workpiece surfaces, then penetrates deeply into the cutting zone and forms an oil film, which contributes to good lubrication. Oils in the water on oil system evaporate quickly, as soon as the water evaporates, instead of penetrating into the cutting zone and forming an oil film.

3.4.2 Comparison of OoW with other cooling methods

Comparisons of EOoW, IOoW, and CAMQL on surface roughness and flank wear rates are shown in Fig. 17. The sequence of surface roughness increased from IOoW (1.2 L/h water), to $EOoW_f$, to CAMQL (−16 °C). The flank wear rates for IOoW (1.2 L/h water) and CAMQL (−16 °C) were similar, and both were slightly slower than that for $EOoW_{rf}$ once the cutting distance exceeded 180 m. Overall, IOoW (1.2 L/h water) had the best performance in lowering surface roughness and reducing flank wear during the turning of Ti-6Al-4V.

Compared to other kinds of green methods used in the turning of titanium alloys by other researchers, the OoW cooling method shows superiority. An et al. [37] conducted the experimental study in the turning of titanium alloy with cold water mist jet (CWMJ) cooling. Their results show that tool life was improved, but the surface roughness was higher with CWMJ as compared to that with flood cooling. In titanium alloy turning under both LN_2 cooling and wet conditions, the flaking of the rake surface just at the end of the crater wear

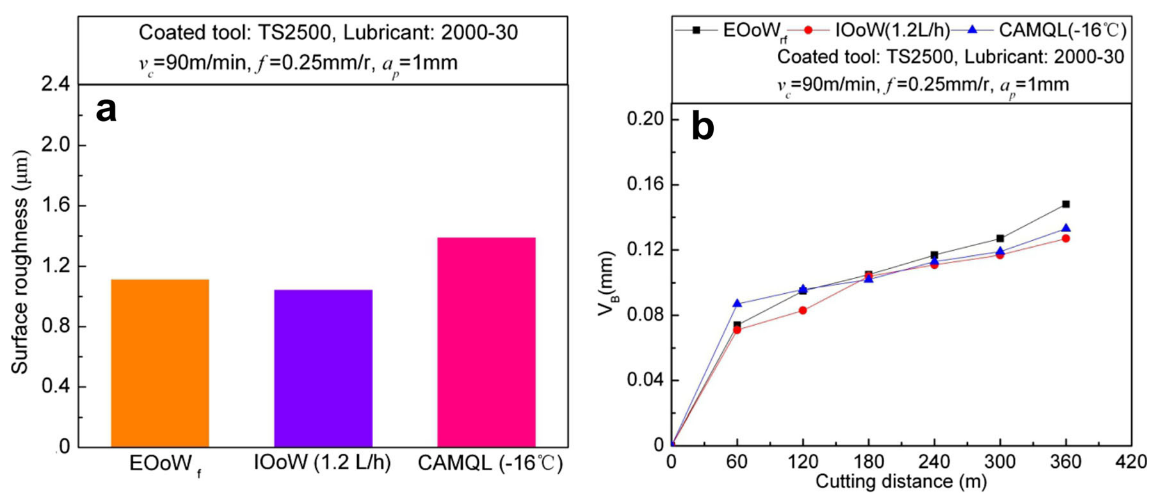


Fig. 17 Comparisons of EOoW, IOoW, and CAMQL on **a** surface roughness and **b** flank wear V_B

region was attributed to heat impact [36]. Such flaking is absent in OoW cooling (Figs. 4 and 8), which indicates good continuous cooling of this method.

4 Conclusions

The cooling methods EOoW, IOoW, CAMQL, wet cutting, and dry cutting were studied with respect to cutting performance and tool wear for the turning of Ti-6Al-4V. Conclusions drawn from this study are as follows:

1. Chip morphologies created by OoW and CAMQL conditions are continuous spirals. The chips resulting from $EOoW_f$ conditions are much shorter than those from $EOoW_r$ because the single air-spraying direction breaks the chips more easily.
2. Compared with that of CAMQL, IOoW (1.2 L/h water) cooling gave both lower surface roughness and slower flank wear rate, while the $EOoW_f$ (spray to flank face) and $EOoW_{rf}$ (spray to rake and flank faces) gave lower surface roughness and slower flank wear rate, respectively. The $EOoW_{rf}$ and IOoW (1.2 L/h water) were the only conditions that avoided creating a bare area on the cutting tool substrate because of the better lubrication.
3. IOoW and CAMQL performed better in lowering surface roughness and reducing flank wear when using lubricant 2000-30. The lubricant properties have no influence on EOoW.
4. The flank wear rates of cutting tools with different coating films show the same trends under EOoW, IOoW, and CAMQL cooling conditions, indicating that a suitably coated cutting tool is required to achieve the best cutting performance.
5. IOoW with a lower quantity of water gave the best performance in lowering surface roughness and reducing flank wear during the turning of Ti-6Al-4V. The IOoW media sprays deeply into the cutting zone, enabling better oil penetration to the cutting zone. With a small amount of water, oils in the form of oils on water bond to the surfaces of the cutting tool and workpiece, then penetrate deeply into the cutting zone and form oil film.
6. Further research should focus on simulating the working mechanism of the oil and water particles when using OoW. Different cutting speeds, feed rates, and depths of cut can be tested to analyze the influence of these cutting parameters on the wear rate and surface roughness under OoW and CAMQL cooling.

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