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Effect of water oil mist spray (WOMS) cooling on drilling of Ti6Al4V alloy using Ester oil based cutting fluid

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Abstract

This paper explains environment friendly water oil mist spray (WOMS) cooling method which is used to obtain lower cutting temperature and higher lubrication at tool chip interface during Ti6Al4V twist drilling process. WOMS is Ester oil based minimum quantity lubrication (MQL) technique but different than neat oil or straight oil based MQL techniques due to combined application of water and oil. Drilling experiments at maximum cutting speed of 50 m/min and 167mm^3/s material removal rate (MRR), using a 8mm diameter TiAlN coated solid carbide twist drill are conducted under dry machining and WOMS cooling environment. The effect of WOMS are mainly discussed with different cutting parameters, twist drill geometry and compared with dry cutting conditions. A comprehensive evaluation on the cooling effects of WOMS was carried out by spray characterization and subsequent drilling tests. This work is focused on the combined study of tool wear evolution, drill geometry, quality of machined holes under WOMS cooling environment. Drilling under WOMS condition observed 66% higher tool life than dry cutting environment. Experimental results indicated that drilling under WOMS cooling had better cooling effects, higher tool life, optimum cutting parameters.

Keywords: WOMS cooling; twist drilling; Ti6Al4V; tool geometry; tool life, tool wear

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1. Introduction

Titanium alloy is one of the popularly used materials in aerospace industry in view of its unique properties such as high strength-weight ratio, low density, corrosion resistance, and hot hardness. Apart from these uncommon properties, it has reputation for poor machinability due to its low thermal conductivity, modulus of elasticity and high chemical reactivity [1]. During machining of Ti6Al4V, lot of heat generation takes place and major portion of the heat is transferred to the cutting edge. High tool-work interface temperature and friction are the two major issues in machining this alloy. Low cutting speeds of the order of 30-40 m/min are generally used in machining titanium alloy due to significant reduction in tool life at slight increase in cutting speeds. Cutting tool geometry, tool coatings, cutting fluid are some of the key parameters to improve Ti machining performance. Apart from these difficulties, and due to increased awareness of environment, health and safety (EHS) guidelines, industry has been making efforts to adopt either to eliminate or reduce cutting fluid consumption globally by implementing different initiative methods like green machining, near-dry machining, minimal quantity of lubrication (MQL), Nitrogen cooling, etc.

The primary objective of supplying coolant under high pressure to the cutting zone is to reduce tool-work piece and tool-chip interface temperature which results in increased tool life. The secondary objective is to reduce friction at the tool-work interface. It is found that application of highly pressurized cutting fluid during machining for aerospace material like Ti6Al4V results into longer tool life. Cutting fluid reduces not only temperature and friction but also reduces cutting forces and welding of chips to cutting tool that are commonly found in Ti6Al4V machining [1]. Several researchers worked on the application of cutting fluids in various forms of machining. The cutting fluids could be in the form of liquid, gas, gaseous-fluid or solid. While both the purposes are important for a cutting fluid; for machining a work material with poor thermal conductivity, extraction of localized heat is much more important. Several studies have been conducted as discussed in the following sections. Several strategies have been tested for coolant applications which include identifying most relevant combination of coolant and lubricant. Various coolants used include compressed air, cold water, liquid nitrogen, carbon dioxide snow, etc., and several lubricants like straight oils and neat oils have also been characterized. Recently, the use of combination of above techniques has been undertaken, some typical combinations include high pressure cooling with neat oil, cold water mist jet, nitrogen-oil mist, compressed cold nitrogen gas-oil mist, carbon dioxide-snow, etc. These strategies have been evaluated to identify effect of cutting fluids on cutting forces, chip morphology and tool wear.

Rough turning with flood and high pressure cooling is carried out by diluting a high-lubricity emulsion coolant with 6% water concentration [2]. This improves tool life at 7MPa coolant pressure against conventional machining. Further, a high pressure cooling was carried out with use of neat oil and jet application parameters like coolant pressure, angle of impingement of jet, spot distance and nozzle diameter were analysed to study their effect on tool wear and chip morphology [3]. The observed results present further improvement in tool life which was twice as that of cryogenic cooling. However, typically broken chips were observed at such high jet momentum. Also applying coolant at flank face did not show any improvement in tool wear rate and tool damage. Cryogenic cooling includes use of safe, clean, non-toxic coolants like liquid nitrogen which is one of costliest cooling techniques. Also, it was reported that feed and depth of cut influence more on tool wear and cutting forces in the presence of cryogenic cooling [4,5]. However, such high cooling did not affect the friction coefficient in some cases, while in some cases this coefficient is increased. Recently, mist-based cooling techniques have been identified as the most effective lubrication and cooling strategy, which provide improved cutting fluid properties.

Cold water mist jet covers heat convection of three phases including cold air, droplet and even ice particles. The reports reveal that the spray characteristics like particle size and impingement velocity play an important role in enhancing lubricating and cooling properties of mist jet [6]. The work also reveals that by conducting spray characterization experiments, a significant reduction in cutting temperature was observed. At particular jet velocity, the enhanced heat transfer and lubrication are evident. Cold water mist jet has been identified as an effective eco-friendly cooling method. With identification of mist-based cooling as an important technique, several other combinations were tried including nitrogen-oil mist cooling and compressed cold nitrogen-oil mist based cooling.

N. K. Dhar [7] used vegetable oil as MQL lubricant during turning AISI 9310 alloy steel. His experimental results and observations conclude that the vegetable oil based MQL drastically improves surface finish and reduces tool wear. A detailed study has been carried by them for spray characterization, flow pressure, nozzle diameter, and droplet diameter that reduce tool wear during turning of alloy steel. Rahim and Sasahara [8] evaluated impact of palm oil and ester oil based MQL on drilling of Ti6Al4V using TiAlN coated carbide drills at cutting speed of 60m/min and federate of 0.1mm/rev. Drilling under palm oil based MQL shows lower cutting forces than flood cooling. The palm based MQL have higher viscosity than ester oil, but tool life of the drill under palm oil based MQL, ester oil based MQL and flood cooling was 314 seconds approximately in each case [8]. This shows that the flood condition can be replaced by palm oil or ester oil based MQL, but at the same time it is observed that the condition based on these coolants results into alleviating pollution. At higher cutting speeds, burning at the tool-chip interface takes place. Rodrigo and Walter [9] evaluated the generation of temperature with external MQL, internal MQL while drilling of Ti6Al4V using uncoated and coated carbide drills. The results reveal that internal MQL exhibited the lowest temperature in comparison to external MQL at 30-50m/min cutting speed.

The above literature gives a detail overview of MQL and other near dry cooling and their impact on Ti alloy machining, tool wear mechanisms, tool failure modes and impact of different cooling techniques to reduce tool wear. But no literature is available which says about simultaneous reduction of temperature and friction. In Ti6Al4V machining, small changes in cutting speed results into major change in temperature at tool chip interface due to low thermal conductivity. In such cases, it is difficult to control temperature by controlling friction. To reduce cutting temperature in Titanium machining, new dual cooling approach is introduced with the help of WOMS cooling technique. The present work is an attempt to investigate tool wear during Ti6Al4V drilling under near dry cutting technique like WOMS and validate its results with drilling under dry cutting environment. However, in WOMS cooling, spray characterization plays a vital role due to differences in viscosity of water and Ester oil.

This article highlights the effect of different drill geometry to optimize the performance of Ti6Al4V drilling. Presently, cutting edge preparation is becoming a popular method to improve tool life. Fernando and Rodrigo [10] evaluated effect of cutting edge preparation on the surface integrity after dry drilling of die steel, AISI P20. The authors observed that higher roughness values during drilling with the help of sharpened drill with cutting edge radius. The work concluded with various cutting edge preparations in the form of cutting edge radius influencing the cutting force and tool life improvement. Moises and Milton[11] studied the influence of twist drill main cutting edge preparation in drilling of SAE 4144M hardened and tempered steel with simply sharpened, 40μm rounding and 40μm×0.12 × 15º chamfered HSS twist drill. The work attempted by preparing twist drill cutting edge chamfer and rounding shows 8 times higher tool life than twist drill without edge preparation. Wyen and Wegener [12] had done extensive research on the influence of cutting edge radius from 10μm to 50μm on cutting forces in turning of Ti alloy. The results also reveal that the cutting edge radius is directly proportional to friction coefficient. Denkena and Biermann [13] had done detailed study of cutting edge preparation methods and characterization of cutting edge radius with respect to tool wear, cutting forces during machining of low alloyed steel.

The above literature gives an overview of edge preparation techniques and characterization, but there is a necessity to compare two different edge preparation techniques specifically for Ti6Al4V drilling. This work presented in this paper, shows the influence of rounded and chamfered cutting edges under dry cutting and WOMS cooling on the performance of Ti6Al4V drilling.

2. Experimental setup and spray characterization

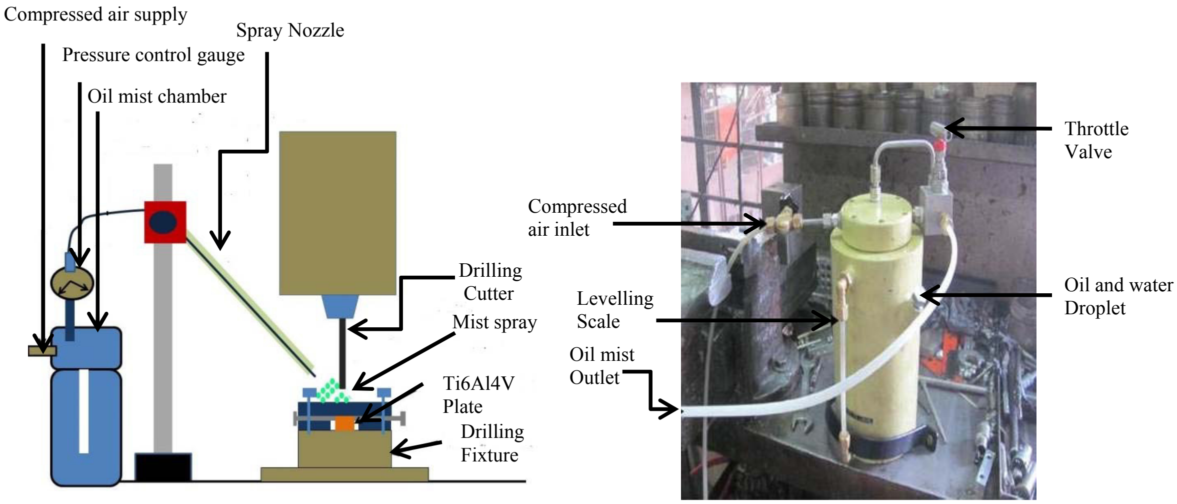
2.1. Experimental details

The drilling experiments were carried on a vertical CNC machining centre (Harding VMC 600II) with 20kW of power having a maximum rotational speed of 15,000 rpm. The work piece considered is Ti6Al4V plate of size 25×150×18 mm^3 and a 8mm diameter solid carbide twist drill with TiAlN coating is used. The drill considered has different point angle and cutting edge geometry and experiments are conducted under WOMS cooling and dry cutting conditions as mentioned in Table 1. Section 2 gives the WOMS cooling and its spray characterization setup. Figure 1 (a) shows the schematic of the experimental process.

Table 1 Details of Drill Geometry

Drill type	Drill Diameter (mm)	Flute Length (mm)	Overall Length (mm)	Point angle (degree)	Chamfer radius(µm)	chamfer distance (µm) and angle (degree)
I	8	50	100	130°	Radius40µm	-
II	8	50	100	130°	-	Chamfer 20µm x15°
III	8	50	100	140°	Radius40µm	-
IV	8	50	100	140°	-	Chamfer 20µm x15°

In present work, ester oil and water combination is used for mist formation. Selection of oil mist fluid depends on performance of spray cooling in terms of reduction of friction and temperature at tool-chip interface. Pressure flow, viscosity and velocity of spray coolant are the key attributes which impact the friction and temperature. These attributes depend mainly on percentage of oil in WOMS cooling mixture. To mix exact proportion of oil in water oil fluid, a customized fixture is developed. The design of mixing chamber includes high pressure mixing of oil and water inside the chamber. Pressurized air at 0.6MPa enters the chamber causing a violent mixing of two liquids. The chamber contains a capillary at the centre. The pressurized air drives the oil-water composition to enter into the capillary. The capillary is then connected to a nozzle of small diameter. Mixing chamber specifications include filter regulator, flow control valve-air, flow control valve-oil, level gauge, mixing chamber and nozzle with delivery nylon pipe. Figure 1 (b) shows the fabricated mixing chamber with required details.

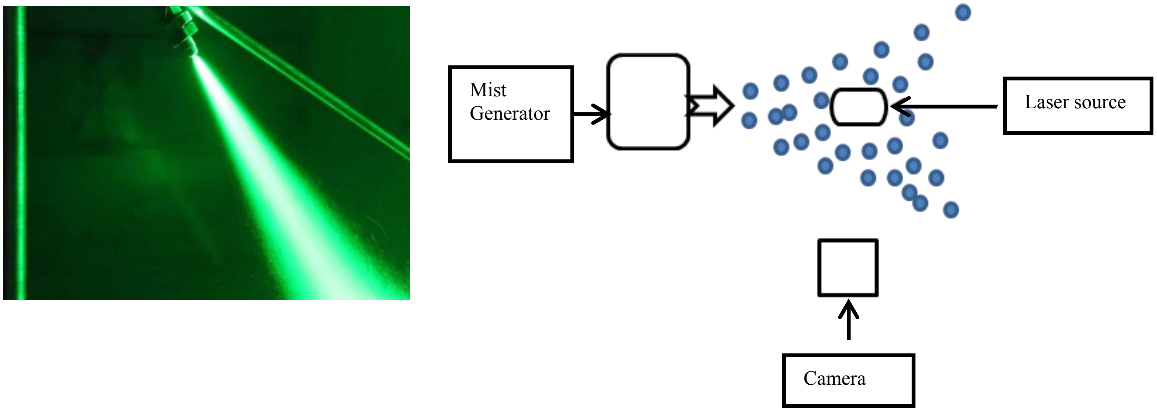


(a) Schematic of drilling with WOMS cooling (b) Fabricated mixing chamber

Fig.1Schematic of WOMS cooling system and actual details water oil mixture chamber

2.2. Droplet size measurement of oil-mist spray

Diameter of impinging droplets determine the behaviour of mist, a large droplet fails to effectively penetrate into interfacial region while a very small droplet becomes inefficient in removing heat. Characterization of droplet diameter is measured by using PDIA (particle droplet image analyzer) instrument. PDIA is basically a simple instrument in which one camera and laser are used to take images of oil mist spray. In current experiments, a laser source placed under spray and a high resolution DSLR camera (12 MP) that is used to capture images of spray. Spray samples include 20% mist and 40% mist precisely sheared and sprayed at 0.6MPa pressure. The spray region is kept in a dark space with only laser source to enhance visibility of droplets. The spray is then passed from an area covered by the laser which undergoes diffraction. This diffraction gives us volume occupied by every droplet passing through laser and can be used to calculate diameters of droplets. It gives a normal distribution curve of droplet diameter versus number of droplet passing through nozzle. To adjust the angle, height and flow direction of nozzle, a small stand is designed as shown in Fig.2 (a). A high definition digital camera is kept perpendicular to WOMS nozzle and laser beam is adjusted in horizontal direction but parallel to WOMS nozzle and perpendicular to camera. Figure 2 (b) shows schematic of WOMS cooling stand. Images recorded are then processed in image processing toolbox of Matlab software.



(a)Laser image of WOMS stand (b) Schematic of PDIA setup

Fig.2 WOMS cooling stand and PDIA set up for droplet measurement

2.3. Viscosity measurement

A Rheometer is used for measuring the viscosity of different oil mist samples. The MCR301 rheometer is equipped with tool master system for online measurement of viscosity has a maximum torque rotation of 0.2pa-s. A sample is taken into a 5ml beaker and placed under a stirrer. The sample is stirred at a constant shear rate with a frequency of 1500 per seconds. The interfacial liquid between stirrer and beaker undergoes shearing and its viscosity is calculated. The shear stress or resistance of sample against the flow is measured and subsequently shear viscosity is evaluated. A sample shearing time undertaken is 20 minutes and online recordings of shear viscosity values are studied. Viscosity results obtained by rheometer are mentioned in Table 2.

Table 2 PDIA results for droplet diameter for sample I and II

Sr.no.	Oil: water ratio	Diameter of particle of minimum diameter	Diameter of particle with maximum quantity	Viscosity
Sample I	2:3	19.24µm	20µm	0.009 pa-s
Sample II	1:4	28.53µm	25µm	0.015 pa-s

Mist samples are studied within Newtonian range with variation in shear viscosity with shear stresses almost negligible. Shear stresses increase temperature of liquid till the shear viscosity reaches a constant value within the working range. Here temperature dependence of shear viscosity is neglected. Shear viscosity of sample I is lower than sample II due to low oil concentration in the mist.

2.4. Spray Characterization results

On literature review [4, 5, 6, 7], sample I and II were found to be the most suitable oil mist spray combination for the required cooling and lubrication based on viscosity and droplet size. Minimum droplet diameter of sample I is

19.24µm and least viscosity is 0.09pa-s. Viscosity and droplet size results obtained by rheometer and PDIA respectively are mentioned in Table 2 and it shows that viscosity of sample I is lower than sample II. Sample I is selected as a final oil mist combination due to its minimum droplet diameter and lower viscosity.

3. Results and discussions

3.1. Tool life analysis

Table 3 Tool life under different cutting conditions

Exp. No.	Drill type (Point Angle Cutting Edge Geometry)	Tool life under dry cutting conditions		Tool life under oil mist cooling condition in terms of no. of holes		Max. flank wear (mm)		Increase in tool life in percentage
		No. of drilled holes	Drilling distance (mm)	No. of drilled holes	Drilling distance (mm)	Dry drilling	Oil mist cooling	
1	I	6	120	6	120	0.40	0.30	0.00
2	II	6	120	8	160	0.21	0.20	33.33
3	II	6	120	10	200	0.39	0.22	66.67
4	IV	6	120	7	140	0.32	0.30	16.67
5	II	5	100	5	100	0.36	0.28	0.00
6	IV	4	80	6	120	0.39	0.24	50.00
7	I	4	80	5	100	0.42	0.31	25.00
8	III	6	120	8	160	0.28	0.36	33.33
Total		43	860	55	1100			27.90

The work presented in this paper is focused on the evolution of tool wear during drilling of Ti6Al4V alloy. To understand the various wear patterns, experiments were conducted at dry cutting and oil mist cooling conditions as per design of experiments. In the present experimental set, to drill one complete hole 18mm depth, a minimum 20mm deep drilling need to be performed. Therefore, tool life of drilling cutter is measured in terms of number of holes or drilling length in the multiples of 20mm. The tool wear is measured with the help of a tool maker's microscope. Table 3 presents a comparative analysis of the tool life under the specified machining conditions. In the present work, 43 holes are drilled under dry cutting environment and 55 holes are drilled under WOMS cooling conditions. Overall, there is a 27% increase in tool life after completion of 8 experiments under the specified conditions. As per results mentioned in Table 3, there is very less impact of point angle on tool wear and subsequent cutting forces. The results from Table 3, it is clear that that out of 16 primary experiments, drilling with twist drill with cutting edge chamfering shows best cutting performance in the form of highest tool life. Exp. No. 1 shows that twist drilling with cutting edge rounding results into poor tool life. Table 4 and 5 shows that cutting edge rounding increases higher friction after tertiary wear zone during Exp.1.

3.2. Tool wear analysis

The flank wear measurement with tool maker's microscope is carried out after every 10 mm drilling distance until the maximum flank wear criteria is achieved. The details mentioned in Table 4 and Table 5 presents the overall variation of flank wear with cutting time, break in period (primary), steady state wear region (secondary) and failure region (tertiary) of all the drills used during dry drilling and under WOMS cooling conditions. Tool wear region is distinguished into primary, secondary and tertiary region on the basis of cutting time. In all experiments, Exp. 3 and Exp. 7 show the critical results in terms of highest tool life and poor tool life respectively. Apart from similarity in wear patterns it shows considerable variation in wear limit with respect to cutting time. Table 4 and Table 5 represents tool wear details in a phased manner where the drilling is performed at cutting speed of 40m/min and

50m/min respectively. From these tabular details, drilling results of Exp. 2 reveals least flank wear and Exp. 4 shows maximum flank wear in tertiary zone in dry drilling condition at lower cutting speed. Comparison of both experiments shows that during dry drilling, maximum point angle plays key role in minimizing flank wear. The major reason is that higher point results into higher cutting forces which result into less flank wear.

Least flank wear is observed in Exp. 3 as per results in Table 4 and Exp. 4 shows maximum flank wear in tertiary zone in oil mist cooling condition as per Table 4. Comparison of both experiments shows that cutting edge chamfering and cutting edge rounding is dominant factor in minimizing flank wear as tool with cutting edge rounding result into more friction at tool work piece interface.

Table 4 Tool wear zones during dry drilling cooling condition

Exp. No	Cooling condition	Speed (m/min)	Feed rate (mm/rev)	Drill type	Initial Wear (mm)	Intermediate wear (mm)	Final Wear (mm)
1	Dry	40	0.06	I	0.113	0.186	0.217
2	Dry	40	0.06	III	0.113	0.163	0.165
3	Dry	40	0.1	II	0.115	0.125	0.188
4	Dry	40	0.1	IV	0.156	0.16	0.238
5	Dry	50	0.06	II	0.170	0.175	0.217
6	Dry	50	0.06	IV	0.179	0.236	0.382
7	Dry	50	0.1	I	0.180	0.223	0.422
8	Dry	50	0.1	III	0.075	0.163	0.283

The details mentioned in Table 5, represent tool wear vs. cutting time for the Exp. 5-8 respectively in which drilling is performed at higher cutting speed (50m/min). Tabular results of Exp.5 shows least flank wear and Exp. 7, shows the maximum flank wear in tertiary zone in dry drilling condition. Comparison of these two experiments shows that during dry drilling at higher cutting speed, cutting edge rounding and higher feedrate plays key role in increasing flank wear. Higher cutting speed results in increasing temperature at the cutting edge due to its low thermal conductivity of Ti6Al4V. The rise in temperature, and increased contact area are due to cutting edge rounding which results into excessive friction at tool-work piece interface. This friction results into more abrasion and attrition flank wear.

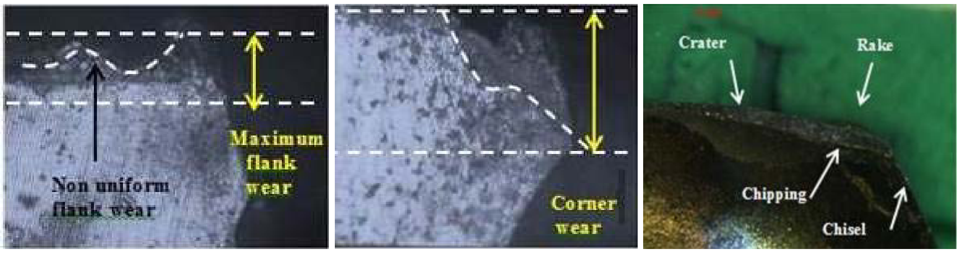
The least flank wear is observed in Exp. 5 and Exp. 6 shows maximum flank wear in tertiary zone in oil mist cooling conditions. The tool wear result of Exp. 5 and Exp. 6 shows that cutting edge rounding is again a dominant factor in increasing flank wear at higher cutting speeds. Apart from cooling effect in WOMS condition, due to high speed cutting, temperature rises rapidly at lower speed. Overall the process results into more abrasion, attrition of the tool wear.

Table 5 Tool wear zones during oil mist cooling condition

Exp. No.	Cooling condition	Speed (m/min)	Feed rate (mm/rev)	Drill type	Initial Wear (mm)	Intermediate wear (mm)	Final Wear (mm)
1	oil mist	40	0.06	I	0.032	0.039	0.141
2	oil mist	40	0.06	III	0.031	0.035	0.160
3	oil mist	40	0.1	II	0.031	0.051	0.110
4	oil mist	40	0.1	IV	0.034	0.041	0.202
5	oil mist	50	0.06	II	0.041	0.051	0.108
6	oil mist	50	0.06	IV	0.062	0.062	0.243
7	oil mist	50	0.1	I	0.062	0.103	0.210
8	oil mist	50	0.1	III	0.040	0.041	0.183

3.3. Analysis of tool failure modes

Tool failure has been analyzed and differentiated into three different stages like primary wear (0-20mm drilling distance), secondary wear (21-50mm drilling distance) and tertiary wear (51-80mm drilling distance or flank wear limit or tool failure). Stereo and optical images gave microscopic analysis of tool wear. During primary wear zone, there is a uniform coating across the flank face of cutting lips and sharpness at the cutting edge. During dry drilling, microscopic inspection shows that chamfering of cutting edge started after 10 mm drilling distance and welding of chips or adhesion of work piece material started after 20 mm drilling distance. Small micro chipping also found on flank face of cutting edge. After primary wear zone or break in period, twist drill shows steady tool wear rate up to certain rate in every experiment. Micro-chipping on flank face or catastrophic failure takes place after the steady state wear zone. It increases the chamfering of cutting edge and adhesion or welding of chips.



(a) flank wear (b) corner wear (c) crater and chipping

Fig.3 Major wear during dry drilling

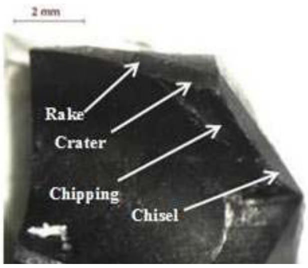


Fig.4 crater and chipping wear during drilling under WOMS cooling condition

Excessive adhesion results into weakening of cutting edge and leading to excessive flank wear and start formation of corner wear. Figure 3(a) and (b) shows excessive flank wear at one edge and corner wear on the other edge during dry drilling. In this case at 50m/min, weakening of cutting edge takes place resulting into breakage of the cutting tool. Apart from tool wear on the cutting edge, burning of chips was observed in both types of experiments under dry and WOMS cooling, but burning observations are very few during under WOMS environment. During dry conditions, extreme friction and high temperature at high cutting speeds results into burning of chips. Under oil mist cooling conditions, moderate friction and the presence of oil mist droplet at tool chip interface results into combustion of chips. Because of above reasons, in dry cutting, rake face wear are observed. Figure 3 (c) and Fig. 4 shows wear on rake face and wear on helix surface near chisel edge after drilling 4 holes in dry condition and after drilling 5 holes under WOMS cooling condition.

3.4. Conclusion and future scope

The WOMS cooling condition gives better results in terms of improvement in flank wear, increased tool life in drilling of Ti6Al4V as compared to dry drilling conditions. Uniform flank wear, micro-chipping, thermal cracking are the dominating tool failure modes for high speed drilling of Ti6Al4V alloy. However, thermal cracking has been observed to be severe under dry cutting conditions. In dry conditions, it is also observed that adhesion, abrasion, attrition and diffusion are dominant wear mechanisms, while in case of oil mist cooling conditions, the major wear mechanisms are adhesion and abrasion. Twist drill with cutting edge chamfering shows better performance in term of tool life.

This work is based on experimental results and mist spray characterization only and there is wide scope to validate above results by modelling and simulation of drilling process with FEM software tools with mathematical modelling techniques available. This work presents tool wear results of drilling under WOMS cooling conditions with ester oil based MQL in comparison with dry drilling, but there is a wide scope to use different oil combinations like palm oil, coconut oil, etc., to reduce friction and maintain minimum optimum temperature at tool-chip interface.

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