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INFLUENCE OF BOTH RAKE AND FLANK FACES METAL WORKING FLUID (MWF) STRATEGIES ON MACHINABILITY OF Ti-6Al-4V ALLOY

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Abstract
This study mainly focuses to investigate the machining performances of variety of metal working fluid (MWF) strategies such as cryogenic (CO_2), minimum quantity lubrication (MQL) and emulsion, into rake and flank face application during the face milling of titanium (Ti-6Al-4V grade 5) alloy. Modified CoroMill600 milling cutter with internal channels to inserts rake face and flank face delivery, and PVD coated inserts are used for the study. This novel approach of rake face and flank face delivery of MWF's has been evaluated on machinability of the process, in terms of surface integrity, cutting forces and chip microstructure analysis. The results show that cryogenic CO_2 machining has improved surface roughness (up to 34% and 38% for Ra and Rz respectively). Additional results show that efficient cooling at liquid CO_2 condition reduces the friction between workpiece and tool, confirmed by observing chip microstructure. However, the cutting force has been found to increase as a result of higher shear resistance of the material at liquid CO_2 machining, with evidences from the chip microstructure analysis. Up to 9% increase in hardness of the machined surface is observed at cryogenic environment compared to non-machined, indicates the cold strength hardening of the material. The overall results imply that the cryogenic CO_2 offer best surface roughness and improved friction between tool and workpiece. Even though further studies are needed for the better understanding the results in terms of hardness of the machined workpiece via optimized cryogenic flow.

Keywords:
Cryogenic machining; Rake and flank application; CO_2; Ti-6Al-4V; Machinability; Surface integrity; Chip microstructure

1 INTRODUCTION

Ti-6Al-4V grade 5 alloy is one of the most attractive and commonly used super alloy for aerospace industry, particularly in airframe structural components and jet engines due to its outstanding strength to weight ratio [ASM Handbook 1990] and its ability to maintain the strength and toughness even at high temperature with its superior low density nature [Caggiano et al. 2017]. Ti-6Al-4V grade 5 (α-β alloy) is first studied in 1954 and currently it uses around 60 % of the total titanium production [Ezugwu et al. 2017]. However, Ti-6Al-4V alloy is coming under the group of difficult to cut materials because of its characteristics such as (a) low thermal conductivity which leads to higher temperature zones between tool-workpiece and tool-chip interfaces, (b) the formation of adiabatic shear bands causing high dynamic loads and vibrations of cutting tool (c) higher possibilities of chemical wear formation due to chemical reactivity of Ti alloys with many of the cutting tool materials [Ugarte et al. 2012].

Conventional emulsion based cutting fluids have been widely used for machining of Ti-6Al-4V alloys to overcome the difficulties while machining and significant improvements in machining of super alloys in terms of enhanced machinability and tool wear progression has also been reported [Pramanik et al 2015; Iturbe et al. 2016; Ezugwu et al. 2017]. However, the conventional cutting fluids cause 7 % to 17% of total production cost including the risk of recyclability and also for the critical health and environmental issues etc. [Pereira et al. 2016]. Here comes the importance of finding a better alternative for conventional cutting fluids and numerous studies have claimed that cryogenic machining is one of the best alternative solution in terms of process sustainability, safety, cleanliness, and eco friendliness [Iturbe et al. 2016; Ezugwu et al. 2017; Tapoglou et al. 2017; Hong et al. 2001].

Machining of titanium and its alloys at cryogenic environment lead to both efficient cooling and enhanced chemical stability at tool workpiece interface, which significantly increases the productivity [Hong et al. 2001; Sun et al. 2015]. Cryogenic CO_2 and N_2 are the most commonly used cryogens for most of the machining applications. The application methodology and the physics are different for both cryogens. Cryogenic CO_2 needs standard high-pressure equipment to deliver the high pressure (≈ 57 bar) CO_2 gas to application zone and the Joule Thomson effect is the physics behind the cooling. In the case of liquid nitrogen (LN_2), special vacuum insulated feeding system and tubes use to carry the low temperature liquid nitrogen (-210°C) to application zone and the boiling of LN_2 above -196°C leads efficient cooling effect [Blau et al. 2015]. Several studies have claimed that improvements in tool wear and machinability of super alloys at cryogenic CO_2 milling machining [Sadik et al. 2016; Sadik et al. 2017] and LN_2 turning process [Hardt et al. 2018]. Cryogenic cooling reports significant improvements in surface roughness and at the same time increase in hardness of the machined Ti-6Al-4V alloys compared to other MWF strategies [Rotella et al. 2014]. Considering the application methodology, only few studies are reported for cryogenic milling with internal spindle cryogenic application, among them most of the studies are focused on CO_2 as cryogen [Tapoglou et al. 2017; Sadik et al. 2017; Sadik et al. 2016]. Several studies are available with technical precise application of cryogens to inserts rake and flank faces are focused in LN_2 turning process [Hardt et al. 2018; Bermingham et al. 2011]. A number of researchers have investigated the effects of cryogenic delivery methods and its influences on machining of Ti-6Al-4V alloys [Sadik et al. 2016; Bermingham et al. 2011]. The rake and flank delivery of the liquid nitrogen reports decrease in cutting force compared to LN_2 rake only application during turning of Ti-6Al-4V alloy, due to reduced friction by additional lubrication effects of LN_2 which forms cushion of gas between contacting surfaces [Bermingham et al. 2011]. LN_2 flank application leads to increase in the hardness and affects layer thickness when turning of Ti-6Al-4V alloy workpiece surface compared to rake and flank LN_2 application as a result of higher flow rate of the LN_2 [Hardt et al. 2018; Bermingham et al. 2011]. The micro-nozzle placed between the tool rake and chip breaker; and a secondary nozzle to flank have reported more economical LN_2 machining with less negative impacts on the increase in cutting force [Hong et al. 2001].

Extreme low temperature machining environment at cryogenic machining have reported for increase in hardness and strength of the workpiece surface [Hong et al. 2001; Park et al. 2017]. US national bureau of standards have also mentioned the same conclusions of cryogenic hardening of Ti-6Al-4V alloys in cryogenic material, based on the studies at temperature range from - 100° C to - 200° C [Park et al. 2017]. It has been reported that the hardness of workpiece surface increases from ≈ 33.5 HRc (room temperature) to ≈ 38.5 HRc (at ≈ -78°C) and ≈ 42 HRc (at ≈ -200°C) along with the proportional increase in strength of the material [Hong et al. 2001; Park et al. 2017]. This leads in the increase of cutting force at cryogenic environment compared to conventional emulsion machining [Park et al. 2017]. Preheated workpiece can reduce the increase in cutting force up to 65% in LN_2 milling of Ti-6Al-4V alloy [Lee et al. 2015]. A reduction in the coefficient of friction is observed at cryogenic machining of LN_2 in Ti alloys compared to the dry and emulsion machining conditions [Jawahir et al. 2016; Hong et al. 2006] where the coefficient of friction between tool and workpiece strongly depends on the positions of the nozzles and delivery pressure of LN_2 jet [Hong et al. 2006]. The phases of the cryogenic medium are also playing an important role to define the friction coefficient where the liquid phase nitrogen shows lower coefficient of friction than the gas phase nitrogen machining [Courbon et al. 2013]. There are no reports with investigation of coefficient of friction at cryogenic CO_2 milling of Ti alloys, so further studies are needed on the same fields to understand the frictional behavior at cryogenic CO_2 environment while milling of Ti-6Al-4V alloy.

There are investigations on the chip macro and microstructure comparison for the different MWF strategies. Chip morphology analysis has been considered as the methodology to understand the physical or thermal phenomenon happening on the machining [Pramanik et al. 2015; Sima et al. 2010; Velasquez et al. 2007]. It mainly focuses on the analysis of shear-band width, chip segment spacing and secondary deformation zone width. The low thermal conductivity nature of Ti-6Al-4V alloy while machining brings out adiabatic shear bands, which negatively impacts the stability of machining and surface integrity of machined product [Pramanik et al. 2015]. Saw-tooth or serrated chip as the results of localized thermal softening zone (isolated adiabatic shear zones) has been widely reported in all most all chip morphology studies [Aramcharoen 2016; Kent et al. 2018; Pramanik et al. 2015; Sima et al. 2010; Velasquez et al. 2007]. Investigations on the secondary deformation zone can provide clear evidence of adhesion of the tool and chip or workpiece at respective machining environments and cutting conditions [Aramcharoen 2016; Kent et al. 2018; Pramanik et al. 2015].

According to the state of art, the delivery optimization of CO_2 on insert seems to be a vital condition to improve the tool wear and the quality of performance. This innovative cutting mechanism of inserts rake face and flank face delivery of different MWF strategies could be a better option to improve the machinability of the Ti-6Al-4V alloy. The term machinability defines the ease and / or difficult of a material to be machined and the defined criteria to evaluate the machinability are tool life, wear mechanism, cutting forces, surface integrity, cutting temperature and chip formation etc.[Ezugwu et al. 1999]. So, this innovative cutting mechanism of inserts flank face and rake face delivery of different MWF strategies has been evaluated on machinability of Ti-6Al-4V workpiece in terms of cutting forces, surface integrity of workpiece and chip microstructural studies.

2. EXPERIMENTAL DETAILS

The machining experiments in this study are performed by face milling process on Ti-6Al-4V grade 5 alloy for different MWF strategies. The α/β Ti-6Al-4V alloy in forged and annealed condition was used as work material, in the form of rectangular block with dimensions of 250 mm x 190 mm x 70 mm. Tab.1 shows the chemical composition of work material in mass percentage. All milling tests are conducted on Hermle C40U machining center with modified CoroMill 600 cutter (diameter 63 mm) equipped with 2 PVD coated inserts (600-1252E-ML 1030). The inserts were placed on the cutter with an arc of engagement of 180°. The CoroMill cutter has modified internal channels. The effective exit channel diameter is 0.8 mm to rake and 0.8 mm to flank faces (see tab. 2).

Tab. 1: Chemical composition of the work-piece Ti-6Al-4V alloy in mass %.

Element	Al	V	Fe	N	C	H	O
Mass %	6	4	0.19	<0.01	0.02	0.01	0.18

Tab. 2: Details of rake and flank face MWF delivery channel exits based on NF-E-66-502 standard frame.

	Distance from the cutting edge	Inclination on standard PR-PP-PF reference plane
Rake face delivery channel exit	8.5 mm	20 degrees inclined to (-) PP direction
Flank face delivery channel exit	6 mm	10 degrees inclined to (-) PR direction

The test was performed by two phases (i) Measuring the maximum cutting forces based on a full factorial design of experiment with varying cutting speed and feed per tooth as shown in tab. 3. (ii) analyzing the surface roughness and surface hardness of the machined surface for cutting speed V_c = 90 m/min, feed per tooth f_z = 0.17 mm/tooth. Depth of cut a_p = 2 mm and width of cut ae = 15 mm were kept as constant for all tests. The cutting data has been selected in reference with the Sandvik Coromant recommendations.

Tab. 3: Experimental design order for cutting force measurements.

Exp No	Run Order	Vc (m/min)	Feed (mm/tooth)
1	2	50	0.05
2	8	100	0.05
3	4	50	0.15
4	7	100	0.15
5	9	50	0.1
6	5	100	0.1
7	11	75	0.05
8	10	75	0.15
9	6	75	0.1
10	1	75	0.1
11	3	75	0.1

MQL oil VP15009 (based on synthetic polyol esters optimized for titanium machining) from Blaser Swisslube was used with SKF mono-channel MQL generator, for internal spindle flow with outlet pressure of 2 bars and flow rate of 73 ml/ hr. ChilAir E13120 model cryogenic system was used for the supply of CO_2 at 50 bars through internal channels of spindle. The CO_2 consumption was 0.6 kg/ min per insert. The conventional flood emulsion (IGOL USINOV 2475) flow supply pressure was also set as constant at 50 bars. External jets of emulsion focused to machining zone settled in addition with internal rake and flank delivery strategy, to ensure the reachability of emulsion flow to machining zone. Fig. 1 illustrates the experimental setup.

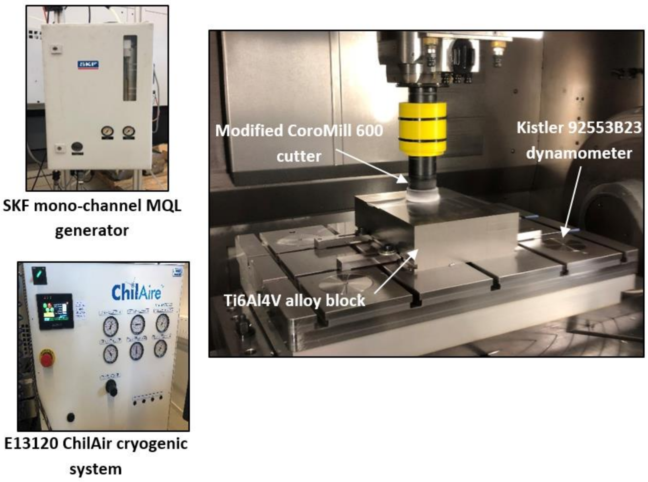

Fig. 1: Experiment set up with modified CoroMill600 milling cutter.

Keyence VHX 5000 digital microscope was used for chip microstructural studies. Proceq Equotip 3 portable hardness tester and Vickers hardness tester (crayford kent) were selected for hardness studies. The surface roughness was analyzed by Mahr MarSurf perthometer.

3. RESULTS AND DISCUSSIONS

3.1 Cutting forces

Cutting force is a significant indicator for the productivity and quality of the machining process since energy consumption in a machining is associated with both cutting force and friction. The cutting forces were measured based on a full factorial design of experiment with respect to the varying cutting speed and feed per tooth (table 3). The forces were analyzed in the fixed frame of reference of the dynamometer table. The maximum cutting force (F_c) was selected for the studies. The results for the experimental matrix in table 3 and the complementary results are presented in the form of contour plots shown in fig 2. The contours indicate the relation of cutting force (F_c) as a function of cutting speed and feed per tooth for emulsion, liquid CO_2 and MQL conditions. The results show a similar trend of cutting force evolution for liquid CO_2 and MQL with respect to feed and cutting speed compared to the emulsion condition. A nonlinear and proportional increment on F_c is observed with respect to the increase in feed for all the three MWF strategies. But in case of cutting speed, first an increment is observed till a particular range of cutting speed and then slightly slope turns to decrement for both MQL and liquid CO_2. Whereas the order has changed from decrement to increment in emulsion machining. This turning point of cutting speed is different for all the three MWF strategies. An average of 20 % increase in cutting force was observed on cutting force contour of liquid CO_2 condition compared to emulsion strategy. In place, average of 11 % decrease in cutting force was recorded on MQL cutting force contours compared to emulsion condition. The increase in cutting force for liquid CO_2 is probably due to the increases of hardness of Ti-6Al-4V at cryogenic environment as a result of cold strength hardening, which coincides with the literature studies.

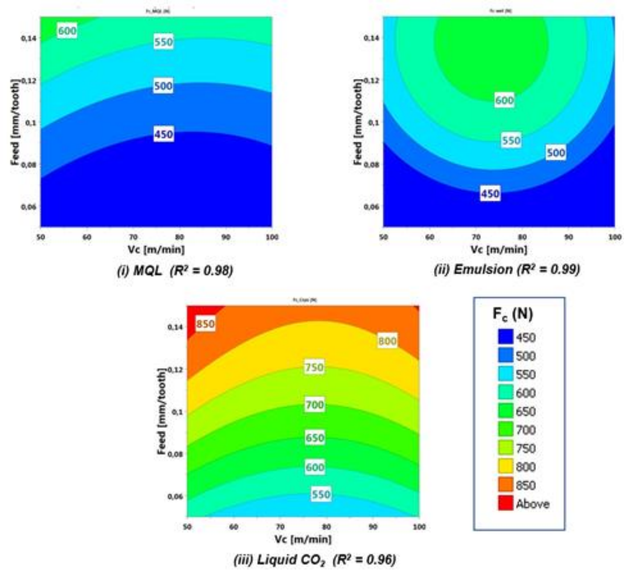

Fig. 2: Cutting force F_c as a function of cutting speed and feed per tooth for MQL, emulsion and liquid CO_2 conditions.

The hardness of machined workpiece surface has been studied to understand the effects of cold strength hardening of machined workpiece surface for different MWF strategies, especially at cryogenic environment. The Chip microstructure was also examined, since the spacing between shear bands in chip microstructure is a clear indicator of shear resistance of the machining material [Cedergren et al. 2013; Joshi et al. 2014; Wan et al. 2012]. Observed results are added in section 3.2 and 3.4.

The benefits of F_c contours for emulsion, MQL and liquid CO_2 conditions as a function of cutting data helps to find the appropriate cutting parameters window to achieve the complete benefits of the cryogenic machining.

3.2 Hardness HV

The surface hardness values are analyzed for machined Ti-6Al-4V alloys in Vickers scale for all the three MWF strategies. To understand the influence of cryogenic environment on the hardness of machined workpiece; hardness is measured at two different conditions for liquid CO_2 machining (i) immediately after the liquid CO_2 machining passes and (ii) once after reached the cryogenic machined workpiece surface into room temperature. For each condition, ten repetitions are made and fig 3 shows the average of corresponding measured hardness values in Vickers scale.

The results show 9% increase in hardness value for liquid CO_2 machining at measurements immediately after the machining compared to unmachined sample. This result concludes the cryogenic hardening of the Ti-6Al-4V alloy at liquid CO_2 machining environment. The liquid CO_2, (at room temperature), MQL and emulsion machining observed 3 - 5% increases in the hardness of the machined surface at room temperature, as a result of work hardening at machining temperature. But the error bar range shows comparable values among these three conditions with unmachined sample hardness. so, the hardness of machined Ti-6Al-4V alloy for given cutting parameters condition is comparable for all the three metal working fluid strategies at room temperature. Only the Ti-6Al-4V alloy at cryogenic environment causes the cold strength hardening effects which leads higher F_c while machining.

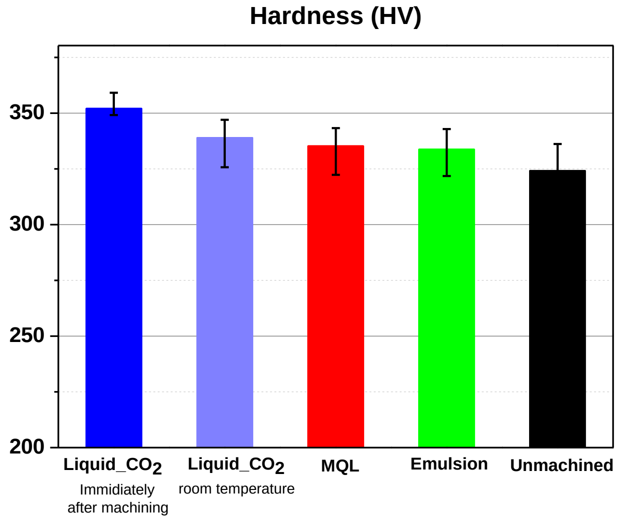

Fig. 3: Hardness HV induced in Ti6Al4V workpiece surface during face milling of different cooling/lubrication

(Vc = 90 m/min, fz = 0.17 mm/tooth, ap = 2 mm, ae = 15 mm, z = 2 mm).

3.3 Surface roughness

The surface roughness of machined Ti-6Al-4V workpiece was measured by Mahr MarSurf PS10 perthometer. Both R_a (arithmetical mean roughness) and R_z (mean roughness) parameters were selected for the studies based on literature. New inserts with controlled edge radius were used for all the three machining conditions. The roughness was measured from three different areas on machined workpiece according to the fig. 4. Measurements were performed in each spot with a repetition of 3 times in the direction of feed, on a length of 4 mm according to the ISO 4288, ASME B46 1 standards.

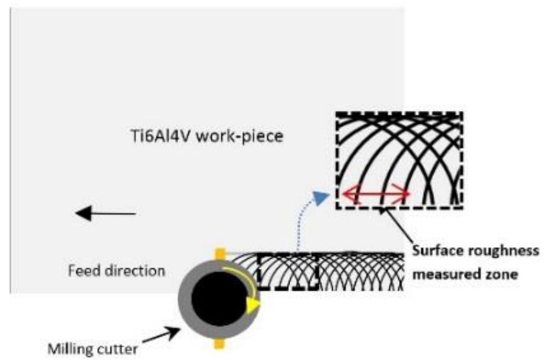

Fig. 4: Surface roughness measured methodology.

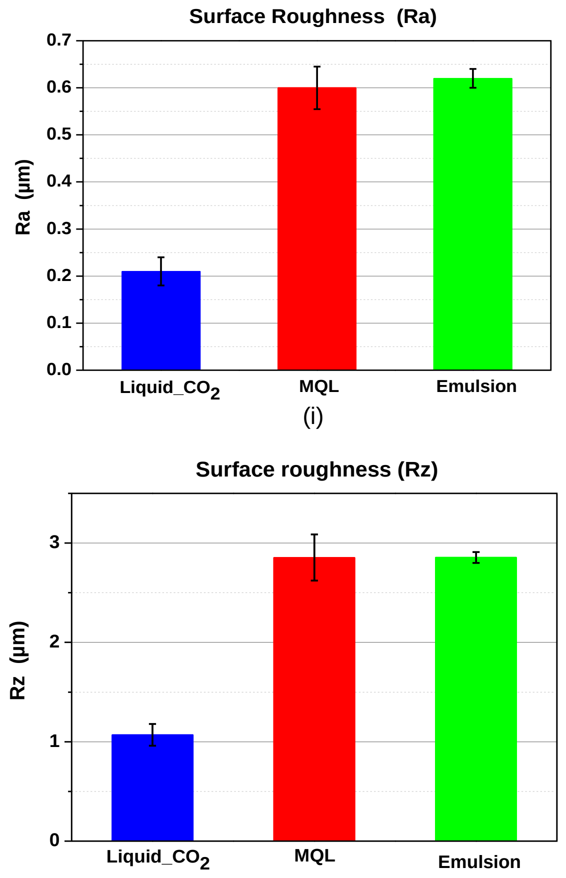

Fig. 5: Surface roughness (i) R_a and (ii) R_z for face milling of Ti-6Al-4V alloy for different MWF strategies,

(Vc = 90 m/min, fz = 0.17 mm/tooth, ap = 2 mm, ae = 15 mm, z = 2 mm).

Fig.5 shows corresponding bar diagram of average surface roughness comparison for different MWF strategies. The lowest surface roughness values R_a of 0.21 μm and R_z of 1.07 μm are measured for the liquid CO_2. Both MQL and emulsion are recorded same average roughness values, where Ra = 0.60 μm and Rz = 2.9 μm. The efficient cooling of liquid CO_2 with precise rake and flank application strategy results improved surface roughness by 34% on R_a and 38% on R_z compared to the MQL and emulsion MWF strategies. Chip microstructure has been studied to understand the real phenomenon behind this, since the secondary deformation zone in chip microstructure provides a clear evidence of the frictional behavior between cutting tool and workpiece at machining zone [Aramcharoen 2016; Kent et al. 2018; Pramanik et al. 2015]. Observations are included in section 3.4.

3.4 Chip microstructure

Chip microstructures were studied to understand the effects of different MWF startegies on machinability of Ti-6Al-4V alloy workpiece. The machined chips were collected with a controled tool wear (v_b) less than 0.1 mm. Collected chips were mounted, polished and etched to analyse the chip microstructures. In total of 3 chips, each with 5 different spots were analysed. So total of 15 measurments were taken for statistical study.

For all the three cutting fluid strategies, the overall shape of the chips are similar with the segmented and serrated form of chips (see fig 6). It shows the inhomogenous deformations of the Ti-6Al-4V alloys due to its low thermal conductivity nature and related high temperature accumulations at machining zone. The localized thermal softening as a result of adiabatic thermal zones in Ti-6Al-4V alloy at machining zones, reduces the material strain hardening capacity locally and leads shear instability in narrow zones through out the chip [Pramanik et al. 2015]. In this formed shear band area, the shear strain and plastic deformation are much larger than the area of segments in between these shear bands [Pramanik et al. 2015]. Particularly the chip microsctructure from liquid CO_2, shows more predominat fractures in between the chip segments. This is caused by the normal load and not because of the results of thermoplastic strain from high temperature [Aramcharoen 2016].

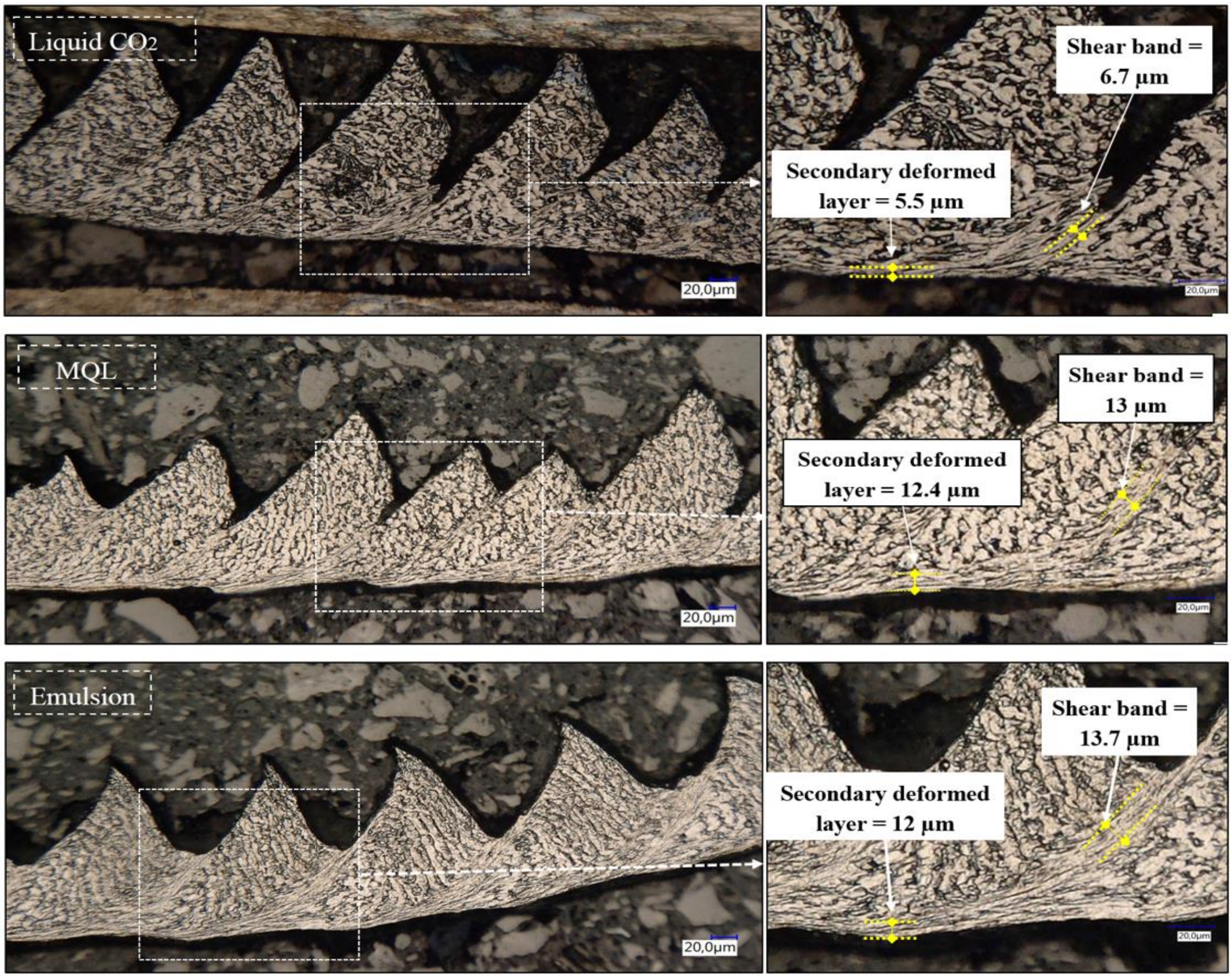

Fig. 6: Chip morphology studies for different MWF strategies (V_c = 90 m/min, fz = 0.17 mm/tooth, ap = 2mm, ae = 15mm, z = 2mm).

The width of the shear bands, secondary deformation zone and spacing between shear bands were analysed under Keyence microscope with 500 X and 1000 X magnifications. Measurements were taken under 1000 X magnification and 1.5 µm is the instrumental error for corresponding magnification.

Shear band width indicates the heat accumulation zone at shear planes or plastic deformation zone width while machining. The secondary deformation zone and its width shows the evidence of friction between tool and chip or adhesion of the tool and workpiece at machining zone for corresponding machining environment [Aramcharoen 2016; Kent et al. 2018; Pramanik et al. 2015; Velasquez et al. 2007]. The spacing between the shear bands indicates the segmentation frequency of the chips and it causes variations in shear localization at deformation zone during machining [Cedergren et al. 2013; Wan et al. 2012]. The spacing between shear bands is inversely proportional to the shear resistance of the material in orthogonal cutting [Joshi et al. 2014].

From the analysis, cryogenic assisted machining is observed narrow shear bands (narrow plastic deformation region) with 6.7 ± 1.5 µm width, which shows the efficient cooling and less heat accumulation at shear bands during cryogenic environment. For same cutting parameteric condition, emulsion and MQL strategies are reported thicker shear bands with $13.7^{+2}_{-1.5}$ µm and $13^{+4.85}_{-2}$ µm width respectively. The low thermal conductivity nature of Ti-6Al-4V alloy leads to localized adiabatic thermal bands with accumulated cutting temperature in shear zones, which further leads to deformation of the grains within shear bands [Aramcharoen 2016; Pramanik et al. 2015]. This elongation is noticable in shear band and surrounded zones for both MQL and emulsion chips. The error bar range in bar diagram of shear band width is higher for MQL due to the lack of cooling or nonuniform shear band formation.

The secondary deformation zone in chip is the zone where chip surface come along with the contact length of the tool rake face. So the thicker secondary deformation zone indicates the higher heat and higher friction between tool-chip interface [Aramcharoen 2016; Kent et al. 2018; Pramanik et al. 2015; Velasquez et al. 2007]. Both MQL and emulsion condition chips show higher secondary deformation layer ($12.4^{+3.4}_{-0,8}$ µm and $12^{+1.7}_{-1,4}$ µm respectively) compared to liquid CO_2 condition (5.5 ± 1 µm). It shows the reduced friction between tool and chip interface or tool and workpiece interface at cryogenic machining environment for liquid CO_2 supply, with rake face and flank face application methodology.

The measured result of spacing between shear bands shows a clear evidence for the cutting force variation in different MWF strategies, since it is indicating the shear resistance of the material. The liquid CO_2 has measured the lowest spacing between shear bands (90^{+15}_{-12} μm) compared to the emulsion condition (113^{+16}_{-19} μm). Whereas MQL condition shows 103^{+27}_{-38} μm spacing between shear bands with wider error bar. It links the cutting force pattern variation in MQL machining and also the observed lower average cutting forces in observed cutting force contour compared to emulsion strategy. So, the cryogenic hardening of the Ti-6Al-4V alloy machining leads higher shear resistance and which demands higher cutting forces while machining.

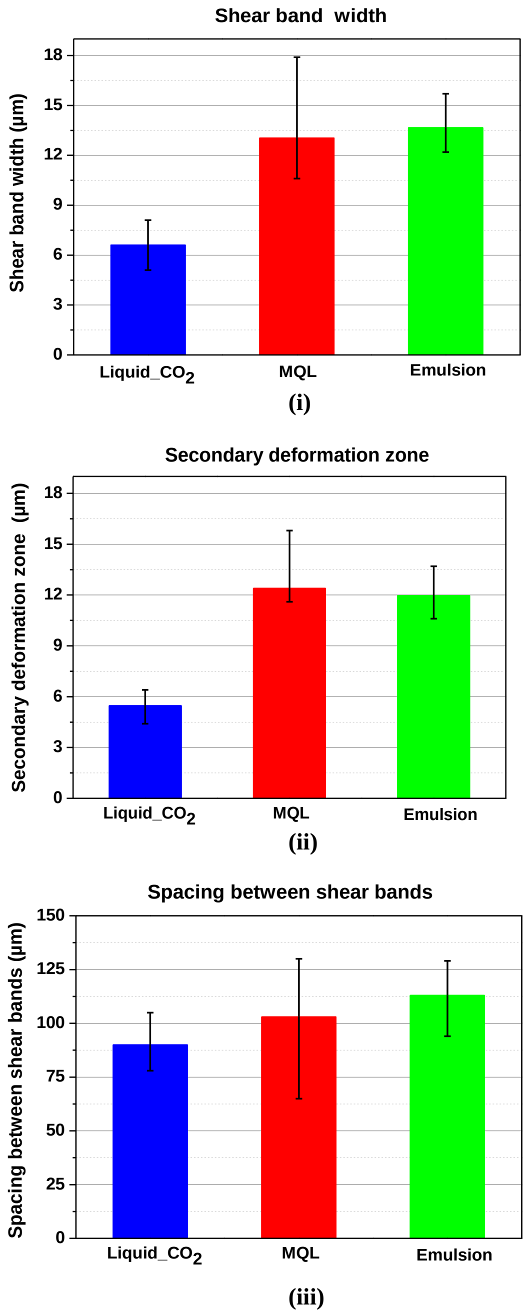

Fig. 7: Chip morphology analysis results (i) shear band width, (ii) Secondary deformation zone, (iii) Spacing between shear bands (Vc = 90 m/min, fz = 0.17 mm/tooth, ap = 2mm, ae = 15mm, z = 2mm).

The above results clearly propose the efficient cooling and less localized thermal softening at liquid CO_2. This further decreases the adhesion of the tool-chip interface or tool-workpeice at machining zone during the machining of Ti-6Al-4V alloy under liquid CO_2 environment; compared to MQL and emulsion conditions. Chip microstructure studies conclude that the cryogenic CO_2 application to both rake and flank faces provides efficient cooling with reduced temperature at shear bands, and also reduces the adhesion and friction between workpiece and tool. This results in the improvement of surface roughness of Ti-6Al-4V alloy for cryogenc machining.

4. CONCLUSIONS

The innovative cutting mechanism of delivery of MWF's (metal working fluids) to inserts rake face and flank face was investigated in face milling of Ti-6Al-4V alloy. The MWF strategies such as MQL, liquid CO_2, emulsion were tested with modified milling tool via internal MWF flow. This novel milling tool design strategy was evaluated in machinability of the process, in terms of the cutting forces, surface integrity of workpiece and chip microstructural studies. The following conclusions can be obtained from this study:

- Liquid CO_2 machining of Ti-6Al-4V workpiece causes increases in cutting forces compared to MQL and emulsion strategies, as a result of increase in shear resistance of material at deformation zone. The less spacing between shear bands in chip microstructure for liquid CO_2 machining is the clear evidence for the same.
- The cryogenic machining environment leads to cold strength hardening of the Ti-6Al-4V workpiece surface. 9% increase in hardness of the machined surface at cryogenic environment illustrates the same as observed in literature. But hardness of the machined Ti-6Al-4V alloy is all most same for all the three MWF strategies (emulsion, MQL and liquid CO_2) at room temperature.
- The reduced or less localized thermal softening observed for liquid CO_2 machining of Ti-6Al-4V alloy. It shows decrease in the friction between tool-workpiece and tool-chip interface at liquid CO_2 condition.
- The decrease in adhesion between workpiece and tool at machining zone for cryogenic machining leads to improves in surface roughness parameters. In terms of both Ra (34 %) and Rz (38%) at beginning of machining, compared to MQL and emulsion strategies.

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