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Sustainable Machining of Metal Matrix Composites Using Liquid Nitrogen

Sravan Kumar Josyula[a], Suresh Kumar Reddy Narala[b]*, E.Guru Charan[a], H. A. Kishawy[b]

[a]BITS Pilani Hyderabad Campus, Hyderabad, 500078, India
[b]University of Ontario Institute of Technology, Oshawa, L1H 7K4, Canada

* Corresponding author. Tel.: +9140-66303565; fax: +9140-66303998. *E-mail address:* nskreddy@hyderbad.bits-pilani.ac.in

Abstract

Machining of composite materials is difficult due to the high abrasiveness of reinforcing constituents. This creates friction between work piece-tool-chip interfaces resulting in high temperatures. The risk of developing elevated temperatures can be controlled by coolants, however, they are known to cause environmental problems. In the interest of ecological and environmental safety the global focus is towards achieving sustainable manufacturing. In the present study, a pressurized liquid nitrogen (LN_2) feeding system is developed to supply LN_2 over the tool edge-work piece interface. Comparative experiments are carried out during cutting of Al-5%TiC_P under cryogenically chilled air (CCA), LN_2, wet and dry conditions. It is found that LN_2 reduces surface roughness, tool wear and cutting temperatures. Further, there is a reduction in built up edge formation. LN_2 assisted machining has shown to improve machinability of composites while achieving sustainable manufacturing.

Keywords:

1. Introduction

Metal matrix composites (MMC) play a vital role in modern material science in all types of engineering and structural applications. Striving continuously to improve production methods and finding alternative materials are the best solution to meet the requirements of MMC in aerospace, marine, defense, automotive and medical fields. Aluminum metal matrix composites (AMC) have greater advantages in a wide number of specific fields because of its superior properties, especially high specific modulus (modulus per unit weight) and specific strength (strength per unit weight) [1].

Several ceramic reinforcements are identified for AMCs, but titanium carbide (TiC) has gained attention due to its high hardness, high specific strength, stiffness, wear resistance and dimensional stability [2]. Discontinuously TiC particulate reinforced aluminum composites (DRAC)-(Al-TiC_P) composite usually are produced close to the final dimension in different manufacturing methods but in most engineering applications, the need for machining cannot be completely eliminated to get the final dimensions. The existence of hard particles in soft metal matrix increases the mechanical characteristics of these MMCs and thus influences machinability using conventional methods such as turning, drilling, milling and sawing [3].

The machining of DRAC presents significant challenges to industries due to the high abrasiveness of the reinforcing particles and the anisotropic & non homogenous structure. Premature failure of tool is reported as the major problem in machining of DRAC [4]. This creates friction between workpiece-cutting tool-chip interfaces leading to high temperature. This can cause poor surface finish, higher cutting forces and built up edge on the cutting tool.

Conventional coolants have been used as supplementary choice in order to overcome these problems. However, incompatibilities have been reported in relation to conventional coolants in machining of composite materials. Hung et al., [5] studied the effect of cutting fluid on the machinability of AMC reinforced with SiC or Al_2O_3 particles, observed that cutting fluid had no significant effect on machining performance in terms of tool life, surface finish and cutting forces. Comparative studies for dry and wet turning of DRAC were investigated by Kannan et al. [6]. They reported that small differences were observed between the cutting forces in dry and

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wet cutting conditions. This result was attributed to the rapid abrasion of the cutting tool (coated tungsten carbide) by the particles even under wet cutting conditions suggesting the incapability of the cutting fluid to create any protective film which would reduce the frictional conditions on the tool flank face. Due to effective cooling, prominent results were witnessed at higher cutting speeds (240 m/min) in terms of cutting forces and reduced tool flank wear. Under wet cutting conditions, surface quality was found to have deteriorated by using coolant. Also the micro-hardness of the machined surface increased. In another study Shetty et al., [7] examined the machining performance of DRAC under steam, oil oblique water emulsion and dry conditions. It was inferred that high pressure steam improves the turning performance of DRAC composites in terms of cutting force and cutting temperature reductions. From these studies it can be clearly understood that conventional coolants fail to provide desirable cutting temperature in the cutting zone.

Global focus is towards achieving sustainable manufacturing, in the interest of ecological and environmental safety. Liquid nitrogen (LN_2) is an ecofriendly coolant and lubricant used for the desirable control of cutting temperature and enhancement of the tool life [8]. It also reduces power consumption and friction force, improves dimensional accuracy, surface quality, chip breakability and chip removal for precision machining [9]. Further, it reduces manufacturing cost and manufacturing time by providing machining with higher cutting speeds [10]. Different cryogenic machining strategies such as 1) Cryogenic pre-cooling the workpiece/tool 2) Indirect cryogenic cooling 3) Cryogenic spraying and jet cooling (by delivering the cryogen to the tool-chip or tool/work interfaces) have been applied to the cutting operations.

In all of the three strategies, the cooling effect is observed to be the cryogenic spray and jet cooling strategies, however have shown both cooling effect as well as lubrication effect. Studies by Hong et al., [11] studies reveal that LN_2 possesses lubrication effect. A fluid cushion was formed by LN_2 at the tool-chip interface and provided a lubrication effect by absorbing heat and evaporating quickly. Thus the feed force decreased at cold temperatures because of the lower friction between the chip and tool face. This lower friction can be achieved by reducing the cutting temperature and micro scale hydrostatic effect. In order to maximize the hydrostatic effect LN_2 should be applied as close as possible to the contact area with high pressure [12].

Singh et al., [13] used cryogenic spray method for improving the grindability of ceramic matrix composites. It was observed that that there is an improvement in surface quality of the ground surface with cryogenic cooling because of lubrication effect of cryogenic mist at grinding zone under high pressure application of the cryogen. It was also stated that specific grinding energy was reduced by cryogenic cooling, depending on the reduction in cutting forces.

In the past few decades, numerous studies have been carried out on cryogenic machining. However, machinability studies in cryogenic machining of MMCs are very limited. Further effective supply of liquid nitrogen into the chip-tool interface has shown to improve the machining performance. The main objective of this study is to develop a supply system to apply LN_2 exactly on the machining interface based upon a new concept of having a high lubricity despite of penetration of LN_2. In this research work, turning experiments on Al-5%TiC_P composites are carried out under LN_2 as coolant and lubricant. Tool wear and surface roughness are the two important performance characteristics considered in this work. Comparative studies are carried out to analyze the effectiveness of LN_2 with dry, wet and cryogenically chilled air (CCA). The experimental results indicate that the new method can be applied to industry for improving operation environment and lowering manufacturing costs.

2. Experimentation

Machining studies were carried out on Al-5%TiC_P composite fabricated by stir casting process under inert atmosphere. The chemical composition of matrix material, reinforcement properties are given in Table 1. 5% TiC particles were preheated at 300°C and introduced into molten metal in the form of capsules during mechanical stirring. A blanket of argon gas was maintained to prevent reaction of molten aluminum with atmosphere. After addition of TiC particles, a 15 min nonstop stirring produced a homogenous mixture. This mixture of molten metal was poured into a mold to form test material in bars. These bars were fully heat treated to the T71 condition before carrying out the cutting experiments.

Table 1. Work material details

Titanium carbide (*TiC*):	***Source:*** Himedia labs Pvt Ltd ***Density:*** 4900 Kgm^{-3} ***Average particle size:*** -325 mesh size (40microns)
Aluminium (*Al*):	Commercially pure aluminum composition (by weight %) Si, 0.15; Fe, 0.15; Cu, 0.021; Ti, 0.053; Mg, 0.92; Mn, 0.044; Zn, 0.072; Cr, 0.005; Al remaining
Workpiece material:	Al-5%TiC_P composite
Manufacturing method:	Stir casting (argon gas as blanket)
Dimension of work piece:	30 mm diameter×150 mm length

2.1. Liquid nitrogen supply system

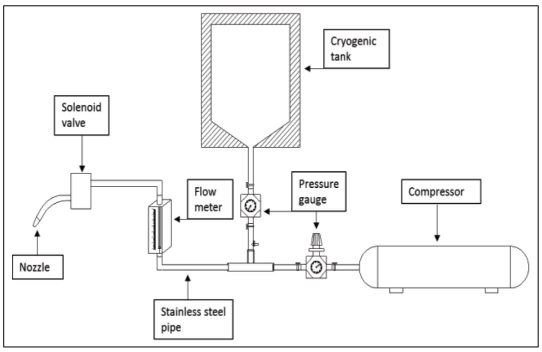

Fig. 1. Schematic view of LN_2 supply system

LN_2 supply system was developed in which the jet flow parameters (pressure and flow rate) and cooling distance were adjustable. A schematic design of LN_2 supply system is shown in Fig.1. The experimental setup consists of cryogenic tank, compressor, a servo valve, pneumatic pressure gauge, solenoid valve, and a specially designed L shaped nozzle (shown in fig.2), LN_2 pressure regulator, and rotameter for LN_2 flow rate measurement.

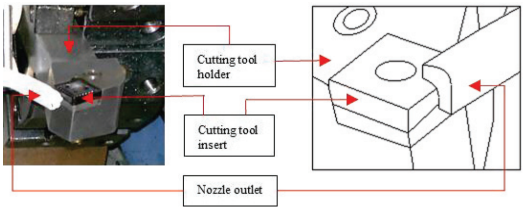

Fig. 2. Photographic and schematic arrangement of nozzle outlet on the insert.

Table 2. Details of cutting tool & Machining condition

Tool geometry	
Tool holder and its common angles	P type tool holder in k20 grade (20×20×125); Inclination angle: -6^0, orthogonal rake angle: -6^0, orthogonal clearance angle: 6^0
approach angles ψ (degree)	90^0
Cutting insert	PVD Coated carbide insert of CNMG1204 in grade of KCU10
Rake angles γ (*degree*)	0, 4, 8, 12, 16
Nose radius r_e (*mm*)	0.4
Process parameters	
Cutting speed v_s (*m/min*)	250
Feed rate f (*mm/rev*)	0.3
Depth of cut a_p (*mm*)	0.5
Environment	Dry, Wet, CCA, & LN_2
Coolant distance (*mm*)	10

2.2 Cutting experiments

Turning experiments were performed on Al-5%TiC_P composite using coated carbide insert. The selected machining parameters, and ISO codes of cutting insert and tool holder are shown in Table 2. Machining process were carried out on PTC 200 lathe under dry, wet, CCA and LN_2 conditions. LN_2 was supplied on the rake face of the tool tip at 2 bar pressure and 0.2 lit/min flow rate. Machinability characteristics of tool work material was judged by work surface integrity and tool performance.

In the present work, surface roughness was studied to analyses the surface integrity of the machined surface. At the same time, flank wear was measured to analyses and study the performance of tool. Machining test was carried at the condition as mentioned in Table 2 for a period of 2 min and all the trials were repeated thrice at each condition in order to keep experimental error at a minimum. The average of three measurements was used to represent the performance of machining. The surface roughness was measured immediately after the turning process at five different locations on the workpiece by using a Surface Profilometer (Taylor Hobson Surtronic S25). Microstructure was analyzed by means of metallurgical microscope on a section perpendicular to the surface of work piece to observe the topography of the machined surface. The flank wear was measured using tool makers microscope (Olympus STM6). The temperature under all machining conditions around the chip at the cutting zone was monitored using thermal IR imaging camera which was positioned 350mm from the top of the cutting tool.

3. Results and discussion

In this research work, comparative studies on tool life and surface roughness were carried out under LN_2, CCA, wet and dry cutting conditions. In this section, the effect of cutting environments on surface roughness, tool life, and cutting temperature is discussed. Further, detailed explanation about microscopic observations performed on flank wear are presented to understand the wear mechanism of cutting environments.

3.1 Surface roughness

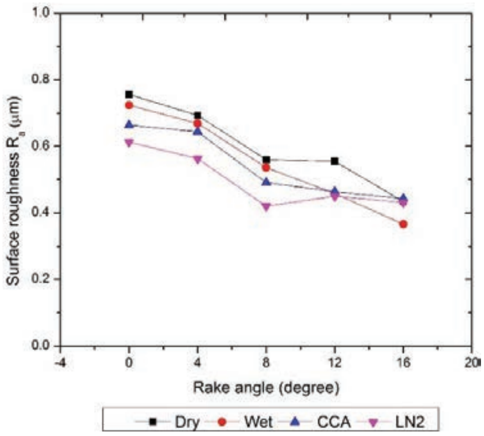

Fig. 3. Surface roughness measured during machining Al-5%TiC_P at various environments.

The variation in average surface roughness (R_a) as a function of rake angle during turning of Al-5%TiC_P is shown in Fig. 3. It is observed that as rake angle increases surface roughness value increases due to increase in contact area between tool and work piece. Also, it can be seen that under LN_2 lubrication the surface roughness values dropped down significantly by a range of 21-33%, 18-27% and 8-17% in comparison with dry, wet, and CCA at different rake angles. This variation is observed due to supply of LN_2 at high pressure by the nozzle into the cutting zone. The pressurized LN_2 penetrates effectively into tool-workpiece interface and forms micro hydrostatic lubrication effect [11], thereby remarkably reducing the surface roughness.

The typical surface topography of machined MMCs through microscopic images under dry, wet and cryogenic environment respectively are shown in Fig. 4. Micro-cracks and voids are observed around the TiC particles due to strain hardening of material and pull-out of TiC particles are formed due to in cohesion between the matrix and reinforcement particles. These intermittent particles are dragged or rolled along the cutting zone causing scratches and grooves thereby significantly affecting the quality as well as the rate of production [14]. This could be the reason why more grooves result upon dry machining when compared with CCA and LN_2. LN_2 condition gives more cleaned surface than CCA. This supports the surface roughness value discussed earlier

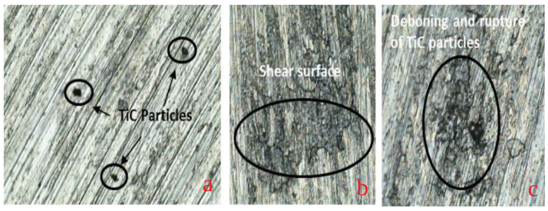

Fig. 4. Microscopic images of surface topography of machined composite at 0º rake angle under dry, wet and cryogenic condition.

3.2 Tool wear

During machining of MMCs, tool wear is not only intensive but also irregular due to the presence of hard reinforced particles in the matrix this further causes premature failure of tool. The primary wear mechanism of the tools was abrasion wear of the tool face by the reinforcement particles, with the greatest wear on the flank face of the tool. Two body and three-body abrasion causes flank wear between the tool and work piece [17]. This occurs due to softening of matrix and easy removal of particles at high cutting temperature. Therefore, change in contact area and proper lubrication strategies will directly influence cutting temperature and frictional generated. This study is an attempt to investigate the effect of LN_2 cutting fluid on flank wear while turning of Al-5%TiC_P composite.

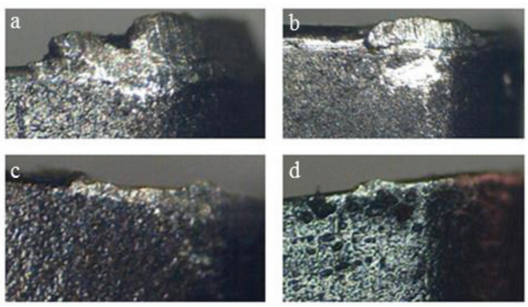

Fig. 5. Microscopic observations of flack wear and BUE cutting tool after machining of Al-5%TiC_P at 8º rake angle. (a) Dry (b) Wet (c) CCA (d) LN_2

Fig. 5 shows the microscopic view of flank wear while machining of DRAC under dry, wet, and CCA and LN_2 conditions. The worn tool surface is almost similar in dry & wet condition with two body wear mechanism. But to some extent the three body abrasion has been reduced during turning under CCA and LN_2 conditions. This can be explained in terms of the absence of cracks and pits that the particulates indent on the cutting tool surface. This can be attributed to the effective application of the cutting fluid which helps in flushing away the chips and abrasive powder formed as a result of broken particulates. This also prevents the re-cutting of the abrasive chips by the tool. Further, it is also observed that the built up

The variation in average flank wear (V_b) as a function rake angle during turning of Al-5%TiC_P is shown in Fig. 6. It is observed that as rake angle increases, flank wear value increases due to variation in contact area between workpiece-tool interfaces. Under LN_2 lubrication conditions the maximum wear values reduced by about 28-48%, 15-47% and 12-42% when comparing with dry, wet cutting, and CCA at various rake angles. This is occurred due to significant reduction in temperature under CCA and LN_2 than dry and wet condition. Further, recent studies have revealed that LN_2 acts as lubricant under high pressure. This might be a reason for low flank wear in LN_2 than CCA condition. CCA provides the same cooling effect as LN_2 but the fluidization effect varies. Pressurized liquid state LN_2 breaches the space between tool and work piece due to its effective evaporation rate and creates a cushion effect which reduces wear. Similar trend has been seen in one of the previous work [12], where higher pressure LN_2, enters effectively into interface zone and results in relatively lower frictional forces, leading to lower cutting temperature.

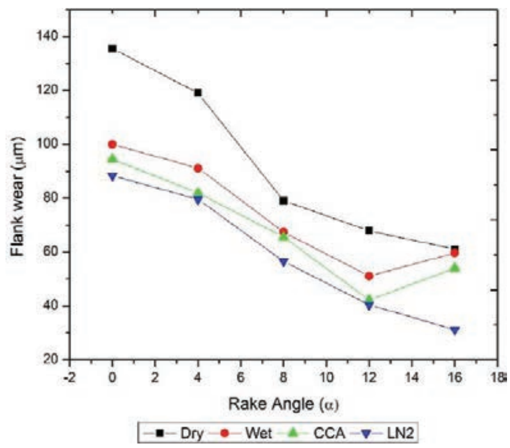

Fig. 6. Flank wear measured under various rake angle while turning under various lubrication strategies

3.3 Cutting temperature

The cutting temperature was measured using Thermal Infrared Camera (sensitivity < 0.05) this camera cannot measure the exact temperature of the cutting zone under the cutting fluid but only measure the surface temperature only. By considering only the surface temperature, Fig 7 shows the variation of surface temperature as a function of rake angle under dry, CCA and LN_2 conditions. In general, LN_2 mainly depends upon heat convention to reduce cutting temperature significantly. Further, LN_2 forms a fluidized cushion between the mating faces which helps to reduce the contact friction of tool chip interface with high efficiency lubrication action thereby producing a cooling effect [12]. As it is seen from Fig.8, when LN_2 is used as coolant and lubricant, the cutting temperature reduced by range of 70-76%, 39-45% and 23-27%, compared with dry, wet and CCA assisted machining at different rake angles. In Fig 8, sample thermal images have been depicted for 4 different conditions.

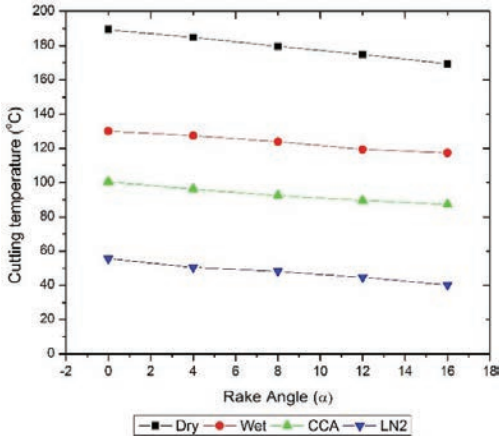

Fig. 7. Cutting temperature with respective rake angle while turning of Al-5%TiC$_P$ under different lubrication strategies.

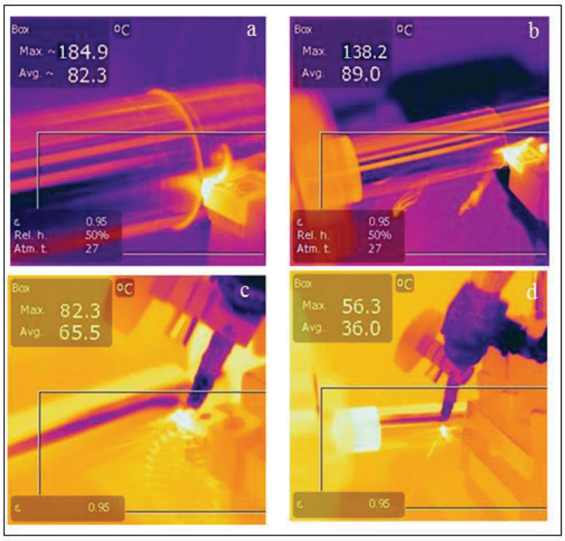

Fig. 8. Sample thermal image while turning of Al-5%TiC$_P$ under (a) Dry (b) Wet (c) CCA (d) LN$_2$.

3.4 Chip formation

The form of chip produced in a machining process is one of the most important parameter, not only influences the surface finish, but also the accuracy of workpiece and the tool life, thereby affecting productivity and product quality [18]. Hence, in metal cutting process, production of an acceptable form of chip is vital. According to ISO 3685 standard, chip shapes during a machining process can be classified into several types, which can be in either acceptable form or unacceptable form. Acceptable chip forms (short tubular, washer type, spiral and arc shape) can move easily from the machining zone and do not interfere with the machined surface quality. Contrarily, unacceptable chips (ribbon, tangled and needle type) can not only influence the quality of the machined surface but also tend to pose safety problems to the operator, as they tend to tangle around the tool and the workpiece. Figure 9 shows some of the chip shapes obtained during machining of composite under different cutting conditions. It is clear that the chip shapes formed during LN$_2$ assisted machining of Al-5%TiC$_P$ composite are in the form tubular and helical chips are formed.

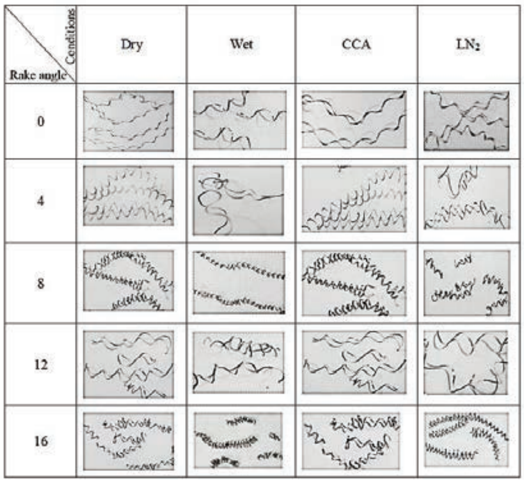

Fig. 9. Comparison of chip samples formed during machining of Al-5%TiC$_P$ at various environments.

The cutting of Al-5%TiC$_P$ composites result in different types of chip formation. When the tool cutting edge cuts only the matrix but not the reinforcement particles, plastic deformation occurs. If the shear deformation of the matrix is hindered by reinforcing particles, squeeze-break and collapse cutting will occur [19].

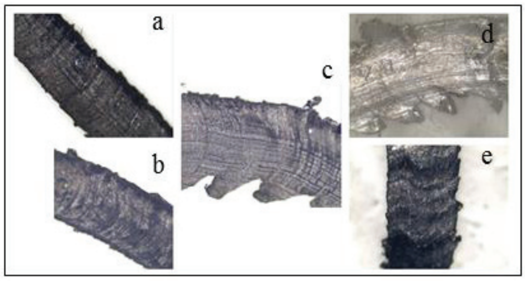

Fig. 10. Microscopic image of chip surface formed during machining of Al-5%TiC$_p$ under LN$_2$ condition at different rake angle. (a) 0^o (b) 4^o (c) 8^o (d) 12^o (e) 16^o.

It is observed that tubular type chips are formed at 8^o&16^o rake angles while washer type helical chips are found at 0^o& 12^o rake angles under all environments. In LN$_2$ condition, however, comparatively shorter chips are formed. At 4^o rake angle, snarled type of chips are formed which are tangled to the workpiece and cause surface damage. This observation provides the proof for sudden increase in surface roughness value in the earlier section. Microscopic observation of chip formed reveals that cracks and voids were frequently formed on outer surface of the chip. This is due to the matrix material undergoing shear by the movement of cutting. Once the material was sheared, the amalgamation of voids forms cracks and they propagate in a zig-zag manner along the shear plane throughout the thickness of the chip. Segmented chips are formed due to fracture. Propagation of fracture through the matrix material seems to develop along the stress concentration zone, i.e. at the boundary of the TiC particles with in the matrix. In comparison among various conditions, LN_2 chips found to be more brittle and chip break occurs more easily than other conditions (refer Fig. 10).

4. Conclusions

The performance of LN_2 assisted machining process during turning of Al-5%TiC_P composite has been demonstrated successfully. LN_2 machining endow machinability of MMC when compared with dry, wet and CCA. LN_2 assisted machining demonstrates the benefits in curtailing the heat generation at tool-workmaterial contacts. Further, it also improves the production of short chip of the same shape as other environments.

Average flank wear in LN_2 assisted machining reduced on average by 36%, 20% and 12% respectively for that of dry, wet and CCA. There was gradual reduction in BUE formation with LN_2 as coolant in turning of Al-5%TiC_P composites. This is because of the significantly lower temperature achieved by LN_2 which causes reduction in thermal softening of matrix. This in turn reduces the adhering tendency, makes BUE spare, decreases chip fracture and improves surface quality. Surface quality was improved by 17%, 10% and 8% respectively corresponding to dry, wet and CCA.

The results also suggest that the rake angle directly influences the temperature on the tool-chip interface which in turn effects the surface quality and tool life. It was observed that as rake angle increases cutting temperature decreases under all environments (dry, wet CCA and LN_2). Since the chip flow is directed by rake angle, using an optimum rake angle, all the following factors can be controlled i.e. flow of chip, tool tip temperature, tool life and surface quality of workpiece. Further, it is also concluded that optimum rake angle for machining of Al-5%TiC_P composite material is γ=80. It would be clearly viewed that rake angle of 80 gives better surface finish (R_a = 0.42 μm), lower tool wear (v_b= 56.618 μm) and a close observation on the chip flow shown that, it yields short and continuous tubular chip formation under LN_2 assisted machining.

LN_2 as a coolant and lubricant has the added advantages of being harmless and ecofriendly. No need for disposal and recycling makes it a lubricant of choice for machining processes. LN_2 provides the fundamental theory for green cutting and is the future of sustainable machining.

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