



Tribological and machining characteristics of milling SiCp/Al MMC composites under sustainable cooling conditions

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Abstract

SiC particle-based aluminum matrix (SiCp/Al 20%) is characterized by poor surface quality, high cutting forces, and accelerated tool wear during machining. Environmentally friendly cooling/lubrication (CO₂ snow, MQL) can advance the machinability of such composites even at high material removal rates. In this experimental study, milling of SiCp/Al was performed by implementing MQL and CO₂ at different cutting speeds and feed per tooth and compared the effect of these lubri-cooling against dry cutting. The experimental results showed the minimum cutting forces, surface roughness, and tool life under MQL followed by CO₂ and dry cutting. The microscopic analysis depicted adhesion and abrasion as prevalent wear mechanisms. The EDS analysis (line, point, mapping) revealed relatively less adhesion of aluminum (Al) and silicon (Si) chemical elements under cryogenic compared to dry cutting on tool major cutting edge. Besides, the chip analysis under MQL machining showed discontinuous and serrated-type chips.

Keywords Cryogenic · MQL · Tool wear · Surface roughness · Tribology

1 Introduction

SiCp/Al metal matrix composites are latest materials that possess high precision materials owing to excellent physical and mechanical characteristics. SiCp/Al composites have emerged to meet the needs of modern times of heavy-duty industrial applications [1, 2]. To overcome the shortcomings of a single material, SiCp/Al showed excellent strength, specific modulus, dimensional stability, contains low cost, and ease in availability.

SiCp/Al composites have several applications in aerospace, military, medical equipment, laser electronics, sports equipment, high-tech fields, ultra-precision fields and other machining and precision fields [3, 4]. It is known from metal cutting process literature that the machining research on the influencing factors of SiCp/Al composites so far has been mainly reflected owing to content of SiC-reinforced elements; it is because of discontinuous dispersal of SiC-reinforced grains in the matrix. SiCp/Al composites material itself has high brittleness and low toughness. In many studies using SiC particles, it has been reported that mechanical and tribological performances significantly increased [5, 6]. Sap et al. [7] stated that wear rate of copper composites generated by mixing Mo-SiC particles to Cu raised. The complexity of the microstructure determines the difference between its cutting mechanism and general metal processing, and the shear slip of the material during cutting displacement and deformation can easily cause. The dislocation slip and stress concentration of SiC grains and the matrix can cause appearance of micro-cracks, chipping, particle chipping, fracture, and particle spalling at the machined surface [8, 9]. SiC is the most commonly used reinforcing particle in Aluminum composite materials, due to its affordable cost and superior properties [10]. However, these phenomena also cause wear of the tool and fluctuation in cutting forces and deteriorate surface roughness which makes the SiCp/Al cutting process extremely difficult for

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machining and hard to obtain the proper dimensional stability of the component. Different research work mentioned the frequently influencing factors on SiCp/Al composites machining process have so far been mainly reflected as important parameters namely machining environments, depth of cut, feed rate, cutting speed, and volume percentage of SiC-reinforced particles [11, 12]. Silicon-reinforced particles have greatly improved the hardness of the SiCp/Al composite, which behaves as an abrasive particle [13], which severely reduces the tool life due to accelerated tool wear and increases cutting costs and the material characteristics have a vital role in the machining process. PCD tools are considered the most ideal cutting tools for processing Silicon particle-reinforced metal matrix composites. It is relatively better regarding hardness, strength, and tool life; however, they are costly compared to other tools such as cemented carbide WC, PCBN, etc. The surface microstructure is relatively good [14, 15] and after several tests, the particle-reinforced composite induces cutting tools and wear forms. Among the numerous types of wear, abrasive wear and bond wear are typical wear forms associated with the metal matrix composite materials, with crater wear and cutting edges. Cutting tool wear phenomena such as small chipping edges and scratches left on the rake surface by produced chips, which are presented in the research results in [16], and [17], are due to the hardened SiC reinforcement. Internal components of particle-reinforced composite determine non-general nature of their processing mechanisms [18]. The particle volume, size, and reinforcing phase are the most important influencing aspects in the cutting process [19].

In cutting SiCp/Al MMCs using carbide K10 cutters, the reinforcing phase of high-volume fraction in the composite led to high cutting forces. It is a fact that as the content is greater, the axial component of force becomes larger than the cutting force component, thus the higher the content of the reinforcing particles made larger the difference. The larger axial component will cause a serious “give-away” phenomenon, resulting in difficulty in cutting material, and the machining accuracy is difficult to promise [20]. Furthermore, to experience the machining process at different factors affecting the cutting forces, the experiments were performed for difficult-to-cut composite material. A comparative study of cutting SiCp/Al composite using CVD coated and uncoated carbide inserts was carried out to find a relationship between cutting forces, cutting length, and cutting speed. It was concluded that cutting speed did not significantly affect the cutting forces however, the increase of cutting distance raised all three components of cutting forces [21]. The feed force and radial force are close to or even greater than the cutting force component, especially at 0° rake angle and the relief angle equal to or greater than 11° and the cutting speed is high. This tendency becomes significant, and as the length of cut increases further, the difference also rises. The Al_2O_3 p/Al composite with 10%, 15%, and 20% of weight percentages showed an increase in three components of cutting forces with the increase of cutting

distance in machining [22]. The PCD tool does not appear to have a cutting depth component larger than the main cutting force. In another study, PCD tools were used to machine SiC particles reinforced aluminum-based composites [17]. Tool wear includes adhesive wear and macro and micro-fractures caused by internal defects in diamond particles. The tool wear mechanism includes adhesion, abrasive, chemical, and diffusion wear. An increase in tool flank wear was examined due to reinforcement particles hardness [23]. In the milling of titanium-based MMCs, the surface integrity is found significant improvement with an increasing flow rate of coolant along with pressure. Further, it is also seen in the milling process of titanium that the liquid carbon dioxide reduces crack propagation and chipping [24]. Furthermore, Iqbal et al. studied the machining process from the perspective of increasing tool life than emulsion cooling. The influence on tool life shows positive signs, cutting parameters, micro-lubrication, and work material's state, which were evaluated and analyzed in the sustainable milling process [25] (Fig. 1).

It was obvious from the results of the cutting process that the MQL technique was the most influential parameter along with material characteristics concerning the sustainable processes, such as process cost tool life. Sartori et al. in their experimental report show that the MQL combined with a CO_2 and LN_2 could improve the process of the lubrication and cooling effect in the cutting process which can lower the crater wear mechanism [26]. MQL and dry milling machining environment were employed during the cutting process of Inconel 718, which shows significant improvement in the



Fig. 1 Sustainable machining pillars

cutting process with MQL than under dry conditions. It is seen from the results that the milling performance increased with improving surface micro-hardness, roughness, forces, and cutting temperature [27]. The machinability of composites always remained the focus of the researcher to better understand and analyze the machining characteristics of such materials. The machinability of composites adopted several techniques to overcome the machining issues such technique includes the cutting conditions including cutting fluids and cooling/lubrication methods to improve the machinability [28]. The cutting fluids and coolants/lubricants have the ability to cool workpiece interface to allow the removal of excessive heat and ease to material removal process with increasing life of the cutting tool and prosper surface finish [29, 30]. Besides, the process should be sustainable. Heat reduction in the cutting process with the cooling/lubrication allows the cutting tool to maintain tool sharpness which helps in smooth material removal process and excellent surface quality; ultimately, it improves the overall machining operation in difficult-to-cut materials [31].

This research study adopts the application of MQL, CO₂ snow, and dry machining environment on SiCp/Al metal matrix composite materials together to compare their machinability effects. The study focuses on understanding the tool wear mechanism, chip formation, morphology, cutting forces, surface finish, and surface texture tribological aspects under sustainable lubri-cooling strategies. The sections of the paper are organized as follows: materials and methods, experimental approach lubri-cooling milling process of SiCp/Al 20% is interpreted in Sect. 2. Tool wear mechanism was observed using SEM and EDS, (point EDS, line EDS, and mapping) and tool life, morphology of chips, cutting forces examination, surface roughness evaluations, and surface texture are given in Sect. 3.

2 Materials and methods

2.1 Workpiece and cutting insert

The silicon particle-reinforced metal matrix composite SiCp/Al material with 20% volume fractions of SiCp is machined using face milling. The workpiece is taken in the shape of a rectangular bar (40 mm × 50 mm × 107 mm), respectively. The machining experiments were performed on high-speed machining center (UCP 710, Mikron), with a spindle power of 16 kW and a maximum spindle speed of 18,000 rpm. Figure 2 illustrates the microstructure of the SiCp/Al 20% MMCs with SiC particle size of 10 μm.

Tables 1 and 2 show the chemical composition and material characteristics of SiCp/Al 20%, respectively.

The milling machining experimental setup using the lubri-cooling sustainable process for SiCp/Al 20% MMCs, respectively. PCD cutting tool inserts APGT-1135-R0.8

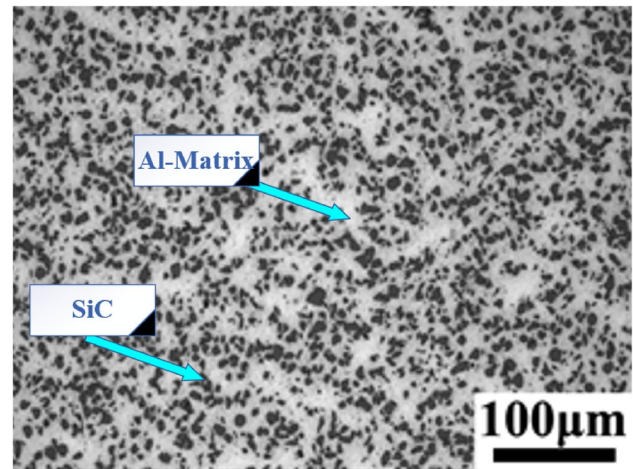


Fig. 2 Microstructure of the SiCp/Al 20% MMCs

are used in this study, nose radius of 0.8 mm, 11° of relief angle, with a tool holder 300R-C20-21-250-2 T and two numbers of flutes. The experiments were performed continuously until the tool flank wear of PCD cutting insert reaches 0.3 mm. Flank wear (VB) of PCD cutting tool was set according to the ISO 3685 (ISO, 1993) standard [32, 33].

2.2 Cutting environments

In the face milling of SiCp/Al, three cutting environments (CO₂ snow, MQL, dry cutting) were employed. The CO₂ snow was compressed in the cylinder, with a temperature of −56 °C and pressure of 5.5 MPa. The compressed CO₂ was sprayed at constant flow rate of 0.2 kg/min along with the 0.5 mm diameter nozzle at a distance of 25 mm far from the cutting zone. For MQL, a biodegradable Blasocut oil (Vascomill MMS FA-1) oil was sprayed at the face of the tool-chip interface through the nozzle. The nozzle has a diameter of 2 mm at a pressure of 6 bar at the flow rate of 2.5 ml/min. MQL nozzle is fixed at the 25 mm distance from the tool-chip interface.

2.3 Cutting conditions and performance measurement setup

In the machining process, the influences of machining parameters with different machining environments such as dry, MQL, and CO₂ snow were employed to take the machining characteristics. The dry cutting environments are a traditional approach used with the adopted cutting parameters to understand the machinability of materials. This study adopted the dry cutting environment for comparing the results of composite machining with the lubri-cooling environment approaches during the cutting process. The levels of variable predictors are provided in Table 3.

Table 1 Chemical composition of SiCp/Al 20%

Element	Si	C	O	Fe	Mn	Cu	Mg	K	S	Al
Percentage	18.1%	19.9%	5.9%	6.6%	0.4%	1.3%	0.4%	1.1%	0.2%	Balance

Table 2 Material properties of SiCp/Al 20%

SiCp, Vol%	Yield strength, MPa	Young's modulus, GPa	Thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$	Thermal expansion coefficient, $10^{-6}/^{\circ}C$	Mass density, g/cm^3
20%	170	115	175	14.5	2.86

The flank and rake wear were measured using an optical microscope fitted on a camera. The surface roughness was determined by MahrSurf M 300 C Germany. The surface roughness was measured for every three passes with the roughness measurements instrument, which uses the 2-micron stylus to get the arithmetic mean height for $R_a(\mu m)$ of the machined workpiece as per the ISO-11562 standard. The Kistler piezoelectric dynamometer 9265B was measured for the cutting forces in the milling of SiCp/Al. The dynamometer measure the range between 0 and 30 kN in the z-direction and x, y-direction range from 0 to 15 kN for the cutting operation, which is obtained from the Switzerland Kistler AG, Bern with force plate of the 9443B. This study focuses on the experimental investigation of machining hard-to-cut materials such SiCp/Al with the approach of lubri-cooling environments and they are compared with the dry cutting process there are three different approaches used as dry, MQL, and CO_2 , as shown in Fig. 3.

3 Results and discussion

3.1 Surface roughness

Surface quality of machined part can be characterized by numerous indicators, i.e., surface roughness, surface topography, surface texture, residual stress, micro-hardness, etc. [34]. Among them, average surface roughness (R_a) is an

excellent tool to quantify the highness of each point in handled and referenced line. Surface roughness works with the principle of 2D image creation based on profiling the peaks and valleys on the measured line. This will provide knowledge about corrosion resistance, strength, and contact conditions, etc. Surface roughness is not only affected by chip formation, tool wear textures, cutting forces, chatter tendency, and also affected by the variety of materials, tool geometry, and basic cutting mechanism [35]. Therefore, it can be easily said that surface finish is the most addressed evaluative factor of surface roughness in all types of machining operations [36]. Since surface quality depends on the deviations through the baseline, calculations of the roughness index can be carried out in different ways. For average surface roughness, R_a determines an origin point and randomly selects ten irregularities irrespective of looking if they are peaks or valleys. Then, the calculation is done by summation of these values and later dividing it by the number of points. Ten points of the height of irregularities are called as R_z representing the sum of these heights subtracting valley points from peak points and giving an average value. Previously, researchers reported that surface roughness is highly affected by feed rate and tool radius [37]. In addition, cutting speed was also detected as a contributing factor to the roughness index [38]. Figure 4 presents changes in surface roughness values of R_a and R_z according to the varied feed rate, cutting speed, and cooling conditions. Accordingly, MQL produces the best surface roughness values in almost all results

Table 3 Cutting parameters and levels

Parameters	Levels
Composite	SiCp/Al 20%
Milling insert	PCD cutting inserts (APGT-1135-R0.8) Walter Inc
Cutting speed	160 m/min, 200 m/min
Feed per tooth	0.06 mm/z, 0.12 mm/z, 0.24 mm/z
Axial depth of cut	1 mm
Radial width of cut	8 mm
MQL cooling conditions	Temperature = 20 °C, pressure = 6 bar, flow rate = 2.5 ml/min, nozzle diameter = 2 mm
CO_2 cooling conditions	Temperature = -56 °C, pressure = 5.5 MPa, flow rate = 0.2 kg/min, nozzle diameter = 0.5 mm

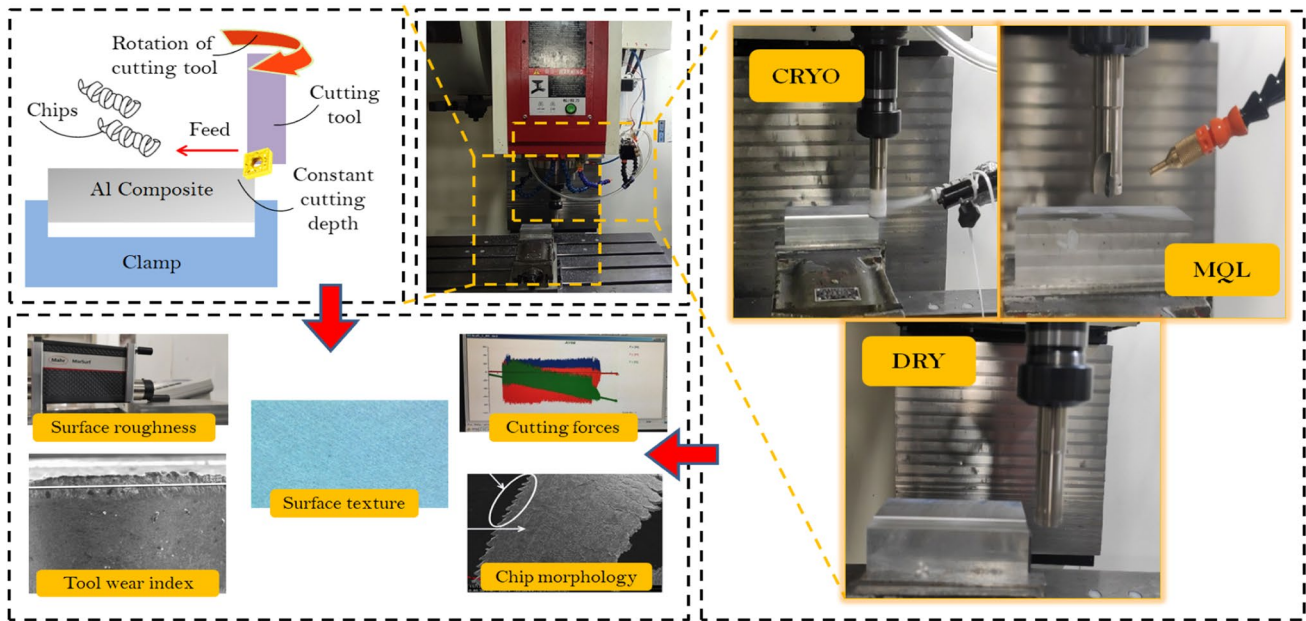


Fig. 3 Experimental setup presenting cooling modes and response measurements

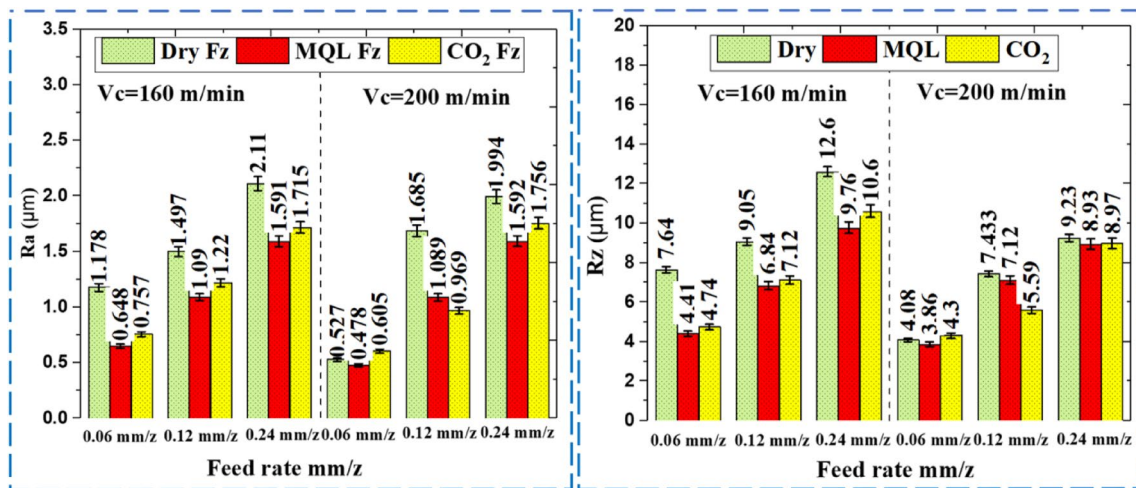


Fig. 4 Surface roughness variations as per cooling environments

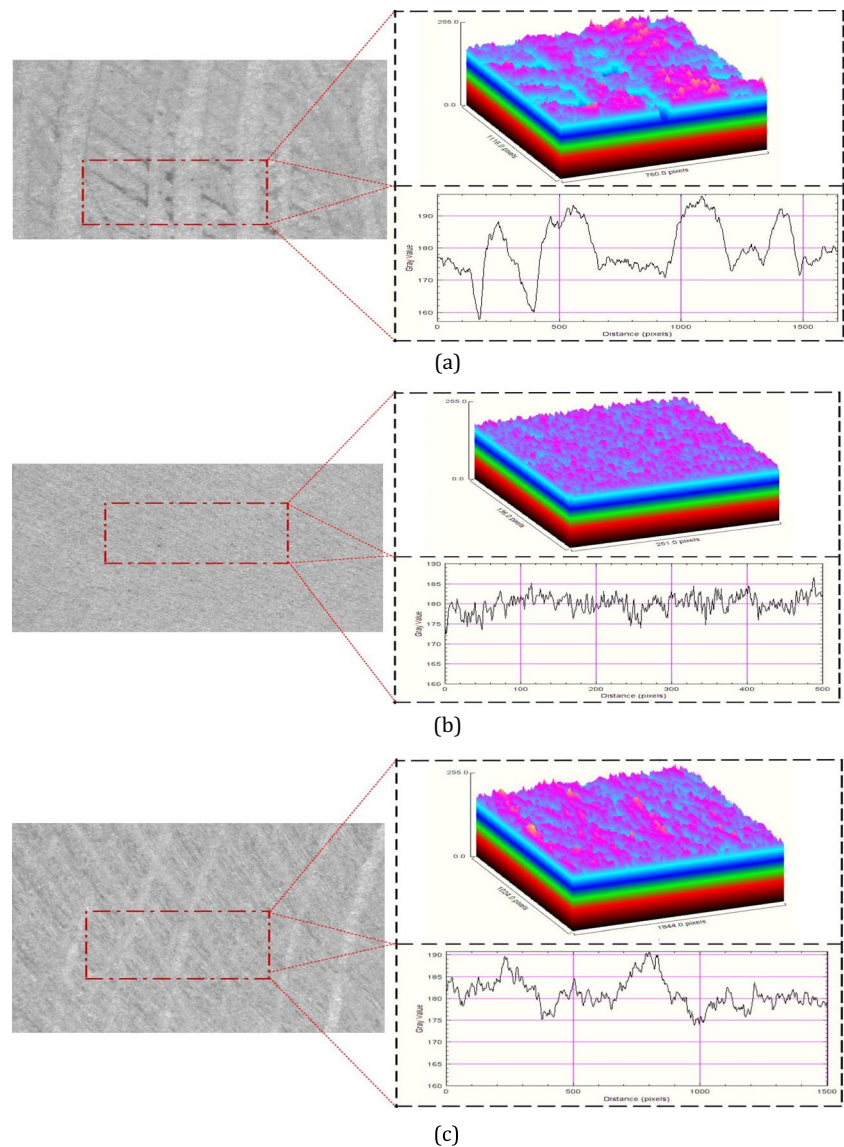
except for some conditions (0.12 mm/rev and 200 m/min). There is an improvement that reaches up to 45% at 0.06 mm/rev, 160 m/min and under MQL assistance than dry cutting. On the other hand, cryogenic cooling provides good results under certain conditions (0.12 mm/rev) that enable to obtain impressive improvements (about 42%). The best roughness values were obtained by the MQL strategy (Ra=0.478 µm and Rz=3.86 µm). In this direction, it is plausible to note that lubri-cooling has a strong impact on the surface quality improvement in the machinability of composites while near-dry machining such as MQL stands as the best option.

The effect of cooling and lubricating mechanism will be discussed in the surface texture topic.

3.2 Surface texture and topography

Considering the machine elements with all surfaces and geometrical details as a whole, engineers aim to manufacture a fully developed product with numerous aspects. The surface integrity of any product is a key factor affecting the tribological interactions, especially under operating conditions [39]. Such interactions play a role in the performance indicators

Fig. 5 The surface textures variations according to different environments. **a** Dry. **b** MQL. **c** CO₂ snow



that may impact the functionality of the final product which can be characterized by wear/friction behavior, adhesion tendency, longevity, etc. In addition to that, the surface integrity of the machined part shows variations depending on various parameters including their mono and multiple effects [40]. Surface integrity can be characterized in terms of roughness, topography, texture, etc. Therefore, further investigation of machinability is required for SiCp/Al particle-reinforced composites to evaluate their surface quality with different machining approaches. Figure 5 presents the surface textures of the milled surfaces under different cooling/lubricating strategies adopted during cutting process to enhance the surface integrity of SiCp/Al component. Besides, there are surface topographies roughness profiles taken from the machine surfaces of the workpiece. Surface topography presents the peaks and valleys throughout the SiCp/Al surface. As seen, a dry cutting environment produces irregular

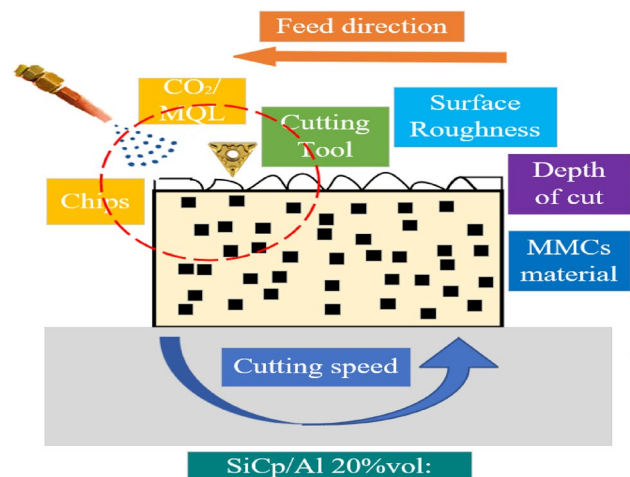


Fig. 6 The holistic view of machining of SiCp/Al with different cutting parameters and cutting environments

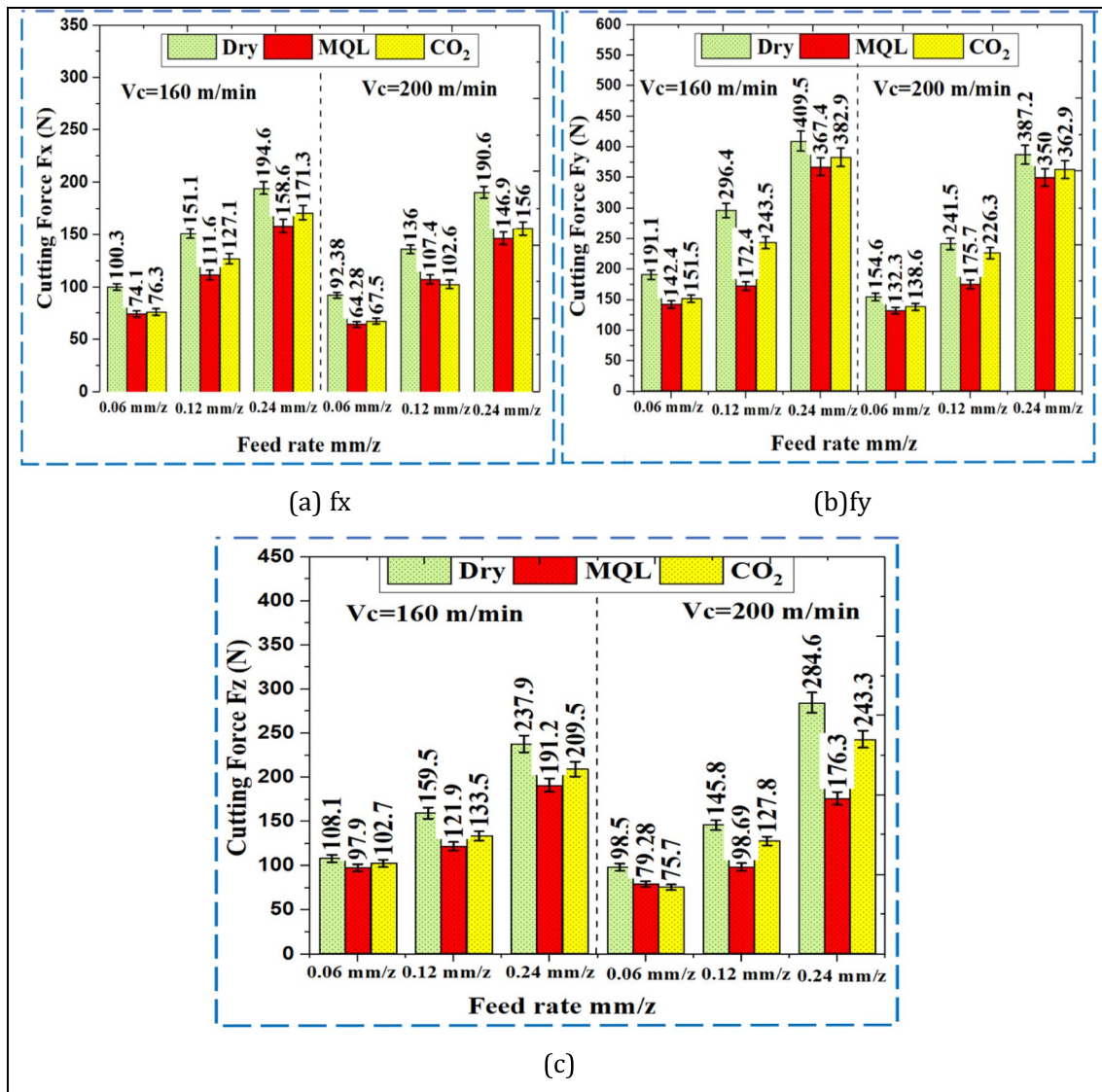


Fig. 7 Cutting forces variations according to different environments

surface traces and relatively high peaks and valleys (Fig. 5a). This phenomenon may occur due to the lack of the lubricator under dry cutting and allowed relatively continuous chip that touched the machined surface and reduce the surface quality [41]. It is believed that uncurled chip shape under dry milling process adversely affects the surface integrity generating tearing on the component surface. The same results were found by the authors in [42]. Moreover, the roughness profile demonstrates larger variations compared to MQL and cryogenic environments. In the MQL environment, feed marks and feed direction can be clearly observed in smaller contexts; thus, it can be said a very smooth surface is obtained by the MQL process. Thus, pulverized mist oil provided the best surface condition for Al-based composites for milling process owing to penetration of oil between tool-workpiece,

hence obtaining a reduction in surface damage [37]. MQL strategy produces the best surface topography as seen on the right side in Fig. 5b. Relatively lower peaks and valleys were observed under MQL than cryogenic environment. It was addressed before those cryogenics have an impressive effect on the material behavior that varies from the ductile structure to the fragile [43]. This procedure can be related to superior lubrication capability of MQL and results in superior surface quality than cryogenic as shown in Fig. 5c.

3.3 Cutting force components

Cutting forces during cutting process have a distinctive role in determining the mechanical loads that comes to the insert which influences the machining performance, tool wear

characteristics, and tool life eventually. Regulating cutting force through the operation is a highly difficult case mostly due to the momentary changes in tool-workpiece contact conditions and dynamic structure of cutting. On the other hand, triggering events such as chatter mechanism, progressive tool wear, and material dependent variations have a dramatic impact on the cutting forces [44, 45]. Therefore, an imperative to detect the cutting force components for each mechanical machining processes to achieve the desired results from the cutting tool and to provide geometric tolerances and functional properties from the part. The prominent determinatives of the cutting forces are fundamental machining conditions such as cutting depth, cutting speed, feed rate, and cutting condition (Fig. 6).

Since the hardness determines the difficulty in exposing plastic deformation, tool geometry parameters, coating, and base material of cutting tool have importance on cutting force deviations [46]. In the context of this study, composites have a special structure that makes them interesting when investigating their behavior during exposed excessive plastic deformations. Thus, meeting the expectations depend on obtaining the ideal machining environment, and cutting forces stand at the core of such demands. Eliminating the unexpected changes and protecting the cutting stability can be done by using modern cooling and lubricating techniques according to recent advances. This purpose of this study is to reduce the cutting force components in the milling of the composite materials using effective lubri-cooling strategies. Figure 7 displays the 3 components of forces and their variations with varying cutting speeds and feed rate as well. According to these results, MQL machining seems like the most powerful way of lowering the cutting forces for composites considering the general trend except for some dispensations. After that, cryogenic cooling comes in second place and dry milling shows the lowest performance comparing

to MQL and cryogenic cooling showing the agreement with other machining characteristics. The smallest force components were achieved by lubricating and cooling facilities (64.28 N, 132.3 N, and 75.7 N) at a low feed rate and high cutting speed. This proves improvements in the tribological conditions at the deformation zones of cutting areas between cutting tool and chip. Oil droplets of the MQL strategy increase greasiness and chip flow becomes much easier compared with dry conditions [47, 48]. In a similar way, the efficient penetration ability of gaseous carbon dioxide helps for reducing friction and better results for cutting forces can be obtained [49]. Dry milling produces the highest values such as 194.6 N, 409.5 N, and 284.6 N at determined cutting parameters as a result of severe chip tearing and breaking mechanism. Such a situation develops mostly due to insufficient oiling and chilling at the medium [50]. As seen in the graphs of Fig. 13, an increase in feed rate makes a dramatic impact on increasing all force components. This is a widely seen case revealed as a result of elevated material removal rates. On the other hand, a higher level of cutting speed paves the way for plastic deformation. In this situation, the better cutting ability is obtained and this directly provides a reduction of cutting force components.

4 Tool life and tool wear mechanism

The composite materials indicate extraordinary mechanical, physical, and tribological behavior compared to metals and alloys that come from their production process [51]. Such properties are tended to change especially under intense plastic deformation conditions. The unique production procedure of composites led to random dispersion of the hard additives in the soft matrix [52]. That is why the characterization of the composites is a challenging issue as per some dependencies such as production method, process parameters, and the extent of the reinforcements [53]. In the course of the nature of machining process, the cutting zone temperature increases because of tool-chip interaction, due to that the cutting tool reaches excessive deformation rates due to effect of high temperatures and cutting forces [51]. This impact may intensify according to some irregularities in the material microstructure due to the unstable cutting conditions. In this perspective, total relative density is of great importance and heavily depends on the uniformity of the added particles, their bonding types, and the structural integrity of the ultimate product. Accumulated soft matrix elements or hard ceramics may disturb and give damage the stability of the cutting mechanism [54].

As a result, there are several wear mechanisms having the potential to be placed on the cutting tool edge and surfaces such as adhesive, abrasive, fatigue, oxidation, and diffusion. When looking at resultant wear textures on the cutting

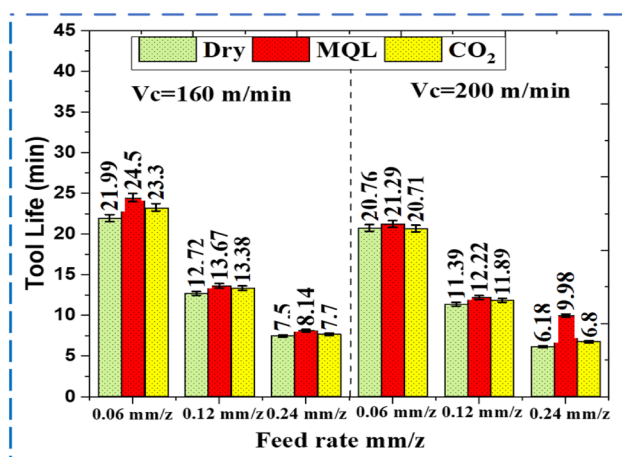
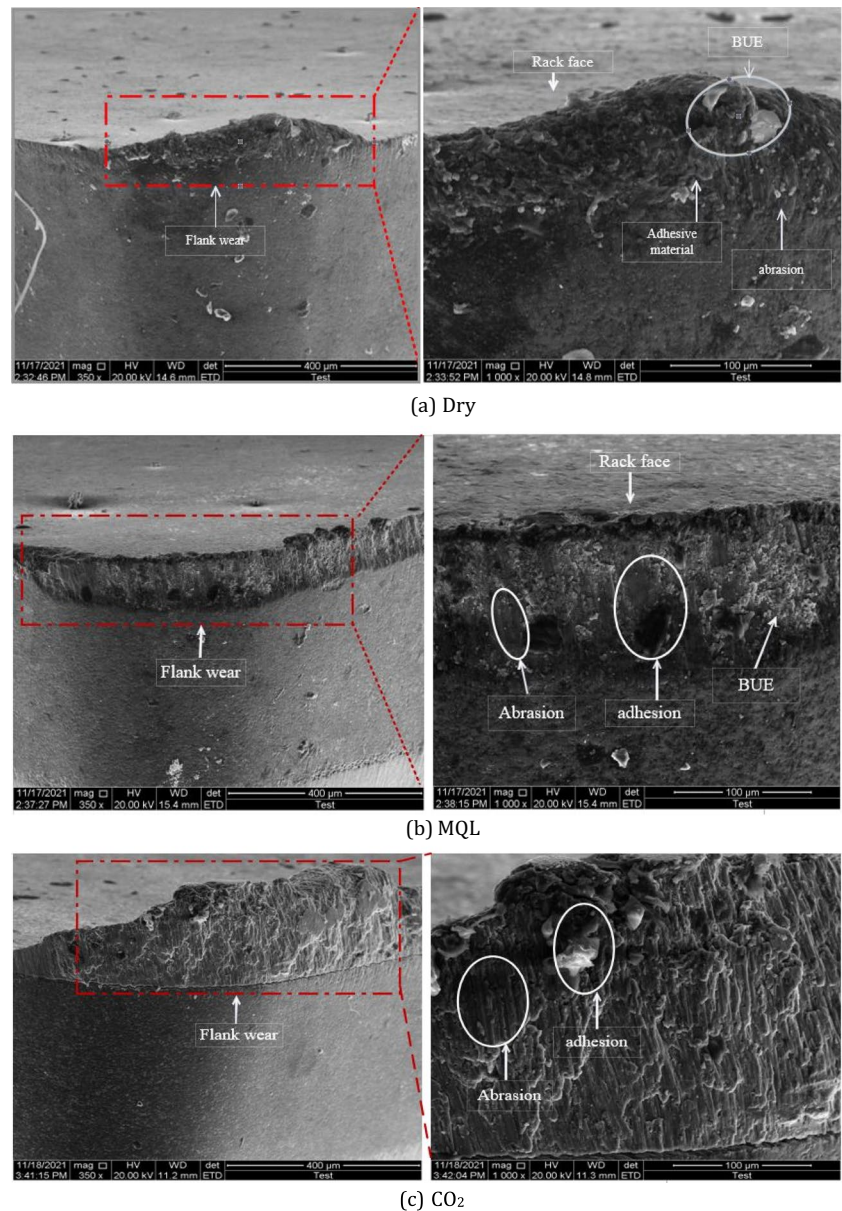


Fig. 8 Tool life at different cutting parameters and cutting conditions

Fig. 9 Flank wear of PCD tool under different cutting environments

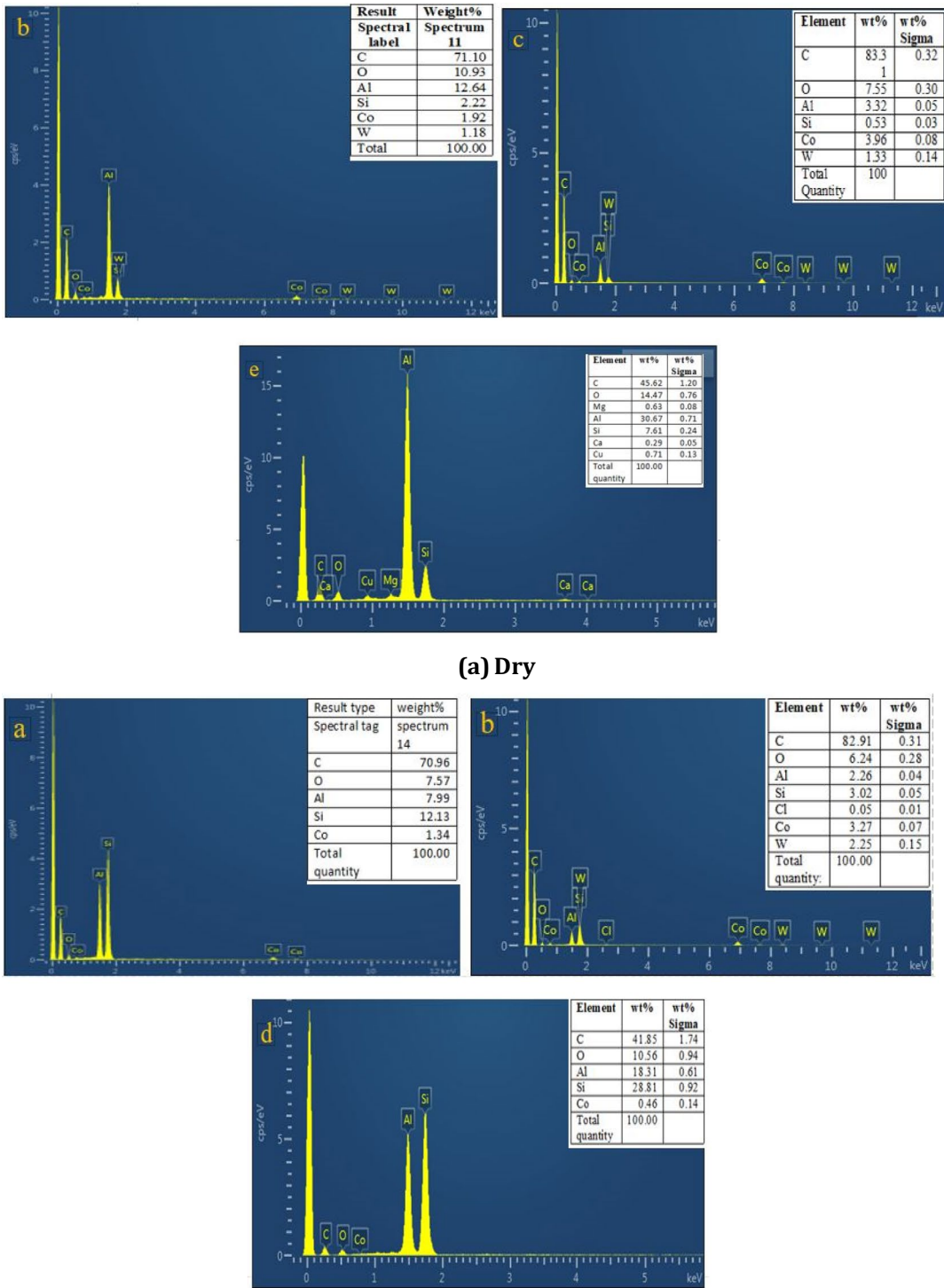


insert during milling of the SiCp/Al composites, two major wear mechanisms were observed: (i) abrasive wear mechanism that develops owing to the entity of the extremely hard ceramic particles, and (ii) adhesive wear mechanism that rises because of the adherence of the soft matrix material creating build-up-edge formation.

Figure 8 presents the tool life under varying cutting speed, feed, and cutting modes. From the figure, the maximum tool life of 24.5 min was achieved under MQL followed by 23.3 min under CO₂ and minimum of 21.9 min under dry machining at minimum cutting speeds and feed per tooth. Similarly, at high cutting levels of cutting parameters, the tool life was decreased due to accelerated tool wear. However, at extreme cutting speeds and feed, MQL was dominant because of higher tool life comparing to dry

machining and CO₂. Tool life at highest cutting speed and feed was 9.9 min under MQL followed by 6.8 min under CO₂ and minimum under dry conditions was 6.1 min. An improvement was reached up about 5% and 11% for tool life while practicing the MQL method compared to CO₂ and dry environments, respectively. In the concept of the presented study, bonding between the particles and structural integrity are affected unavoidably by the randomly dispersed abrasive particles during cutting process. Intrinsically complex machining operations already have harsh impact on the machining characteristics [56]. In addition to that, indigenously developed composite samples possess hard-to-cut SiC particles that will influence the cutting performance.

Within the various types of cutting tool wear, one of the most crucial parameters affecting the cutting performance

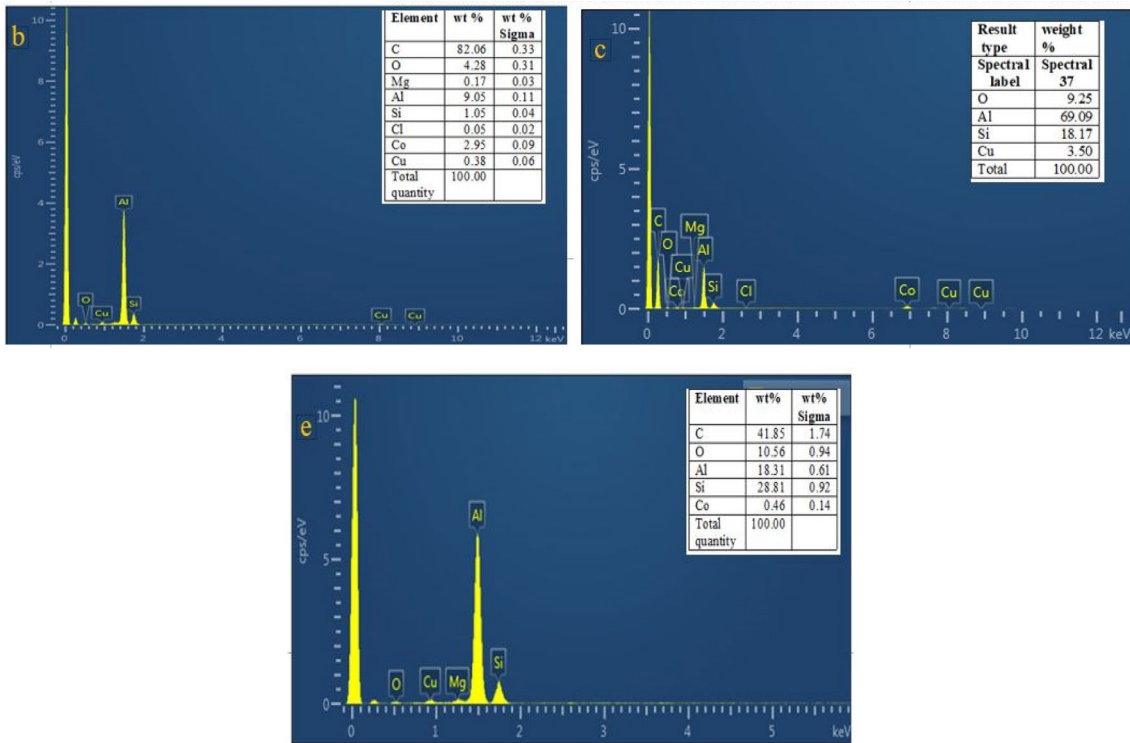


5. MQL

Fig. 10 Point EDS analysis under different cutting environments

and tool life is content of SiC-reinforced particles in SiCp/Al [56]. Abrasive nature of SiC reinforced particles in SiCp/Al exaggerated different types of wear progresses on the main

cutting edge in both horizontal and vertical directions by creating abrasion routes and leading to material loss from cutting tool. Strong contact conditions of tool edge and work



6. CO₂

Fig. 10 (continued)

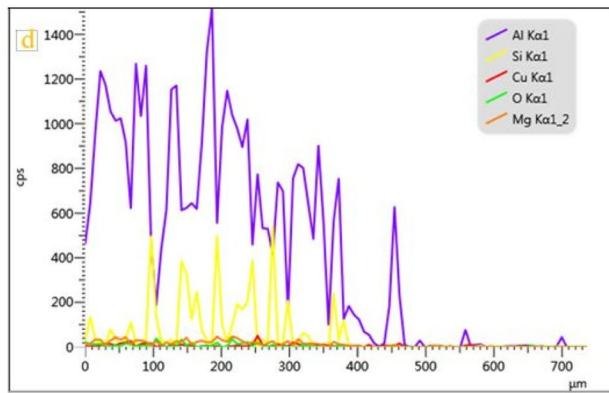
material cause a high friction coefficient and cutting tool begins to lose its cutting ability.

4.1 SEM analysis of tool flank wear under different cutting environments

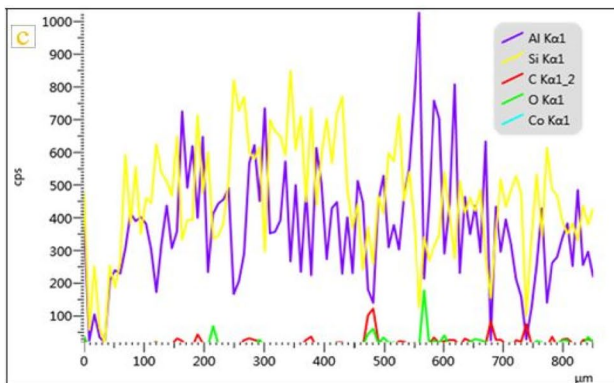
Figure 9a displays the condition of the cutting edge after milling experiments in a dry milling environment. Dry milling is found to be less effective during milling SiCp/Al compared to the lubri-cooling cutting strategy while considering tool life in the progression of this study. As a result, severe adhesion and abrasion was the dominant phenomenon on tool main cutting edge. Seemingly, irrespective of all milling parameters, the absence of cooling and lubricating is not useful for the longer tool life in the milling of composites. Despite its simplicity and being unnecessary of equipment of other lubricating facilities, poverty of lubri-cooling affects badly the tribological aspects. Drought at the cutting zone causes poor frictional conditions between tool-chip interfaces, an increase in cutting forces, gradual reduction of the machining ability of tool, and decreased surface quality [59]. All these developments emerge in a sequence while the operation continues, and it may intensify with the complex mechanism of cutting and interactions between parameters. When looking at the SEM images of the dry cutting environment,

adhered material on the cutting insert and build-up-edge formation on the rake face can be seen.

Figure 9b shows the SEM of cutting tool under MQL environment. As seen, the MQL assistance in the machining of composites can successfully dispel the material adhesion from the rake face. When compared with the CO₂ strategy, the mist oil spraying method is highly effective to avoid build-up-edge formation. The observation clearly shows that flank wear occurs on the cutting edge expressing its major wear mechanisms of abrasion and adhesion. This situation demonstrates that MQL-assisted milling supports the ideal cutting geometry providing the best tool life at selected cutting parameters. The increasing levels of feed rate and cutting speed dramatically reduce the tool life which attributed to the elevated material removal rate [43]. Seemingly, homogeneously distributed oil droplets have improved the tribological conditions with supreme penetration ability even into the extremely small zones [58]. Therefore, tool-chip interface can be lubricated in a perfect way that also decreases the coefficient of friction and required forces directly. Figure 9c represents developed wear on the cutting edge while applying CO₂ cooling. Seemingly, the governing tool wear mechanism is adhesion wear and followed by partial abrasive wear at certain zones of the tool edge.



(a) Dry



(b) MQL

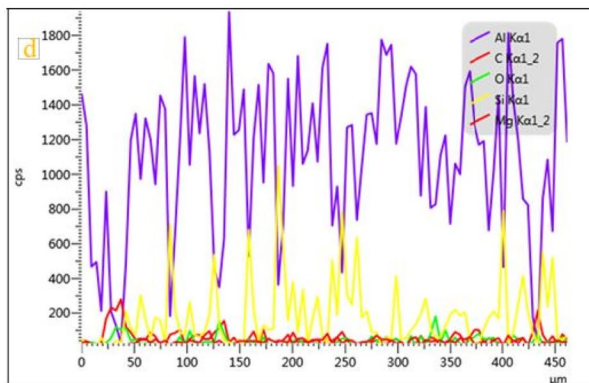
(c) CO₂

Fig. 11 Line EDS analysis under different cutting environments

4.2 EDS analysis of tool flank edge under different cutting environments

4.2.1 Point EDS analysis

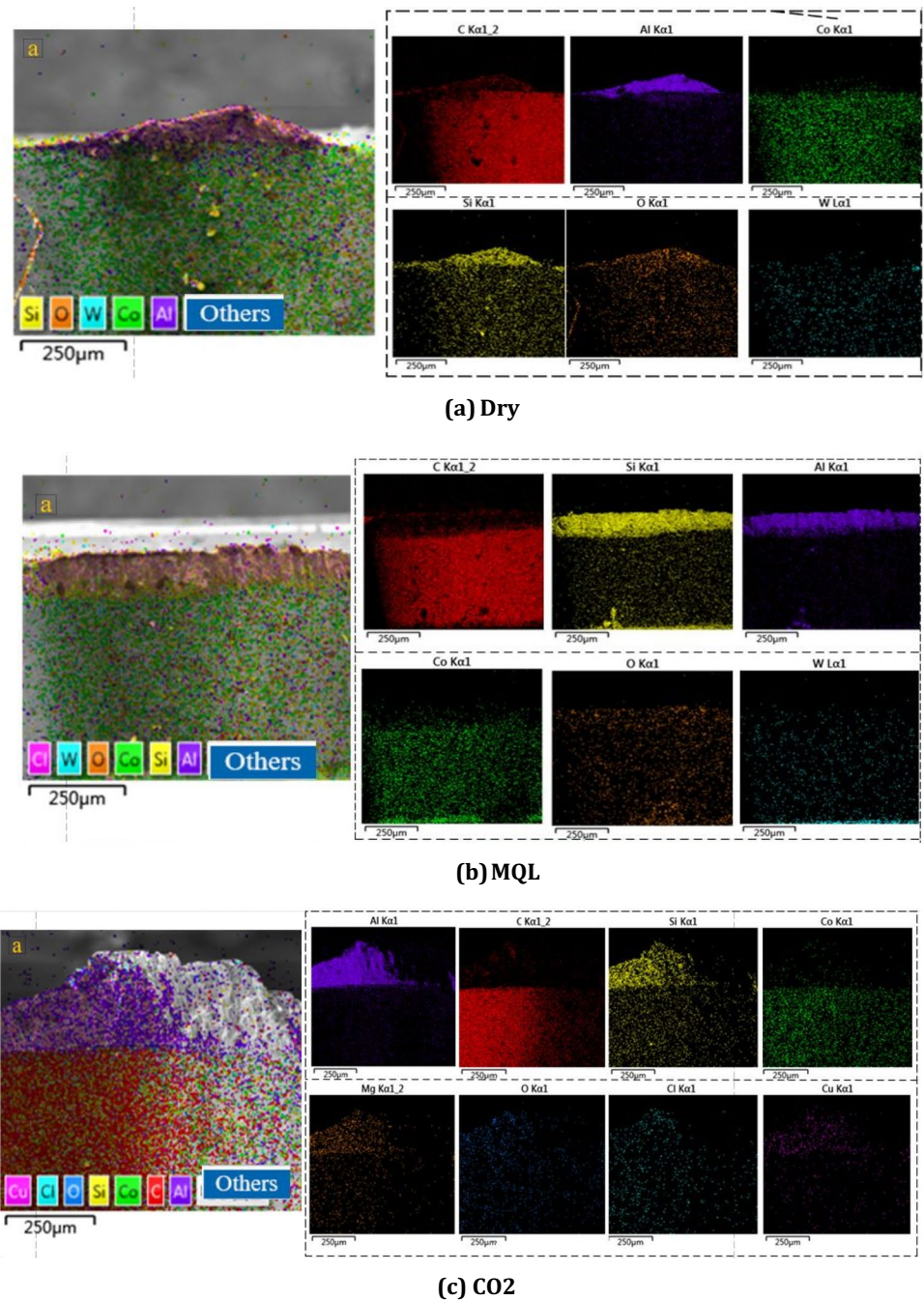
Figure 10 presents point EDS to quantify the adhesion of chemical elements of workpiece on the cutting tool edge. Cutting tool material and the elements that come from the composite samples can be separated as per

this analysis. Al and Si elements cover the adhered part of the image as can be seen according to the points EDS analysis. The content of Al and SiC elements are vary according to the adoption of cutting condition. The dry cutting conditions show that the amount of Al element is high compared to the MQL; however, CO₂ is higher than both dry and MQL conditions. Similarly, the content of SiC particles also found to be higher in CO₂ compared to both dry and MQL cutting conditions. Furthermore, comparing the dry and MQL, the MQL cutting condition shows higher amount of elements such Al and SiC on cutting tool flank comparing to the dry cutting condition. One conclusion can be reached at this point that the CO₂ snow is successful in reducing the flank wear on the clearance face mostly due to the developing build-up edge protecting the tooltip from silicon particles. When looking at the tool life results, cryogenic-assisted milling stands in second place after the MQL strategy. Despite extremely cold gaseous being able to eliminate the temperature around the machining zone, the flow zone at the chip-tool interface contributes hugely to the tool temperatures owing to the severe plastic deformation. Material behavior totally changes in this region resulting in high cutting temperatures and strain rates [57]. However, in the flow zone where the material acts like a viscous liquid, the cooling method even if the coolant exists at extremely low temperatures is unable to provide a good cutting mechanism for the tool. This comes from the softening of the Al-based composite with quite high-temperature gradients. With the intermittent cutting mechanism of milling, gradual coherence of the melted material builds this additional cutting edge which enables stability for the cutting operation due to the strong structure of the work-hardened build-up-edge.

4.2.2 Line EDS analysis

According to the analysis of cutting tool in Fig. 11, flank wear area is enveloped with composite material creating small build-up-edge formations. Line analysis verifies this claim in which SiC particles and Al matrix cover the worn area completely. Figure 11 shows (a) dry, (b) MQL, (c) CO₂ cutting conditions draw the lines which represent the elements stick to flank face of the cutting. It can be seen from the figure that the MQL cutting shows that the amount of Al and SiC element is lower compared to the dry cutting and CO₂ environments. However, the CO₂ cutting environment shows higher amount of Al and SiC element on tool flank compared to both dry and MQL conditions. Furthermore, comparing the dry and MQL, the MQL cutting condition shows higher amount of SiC elements on cutting tool flank compared to the dry cutting condition.

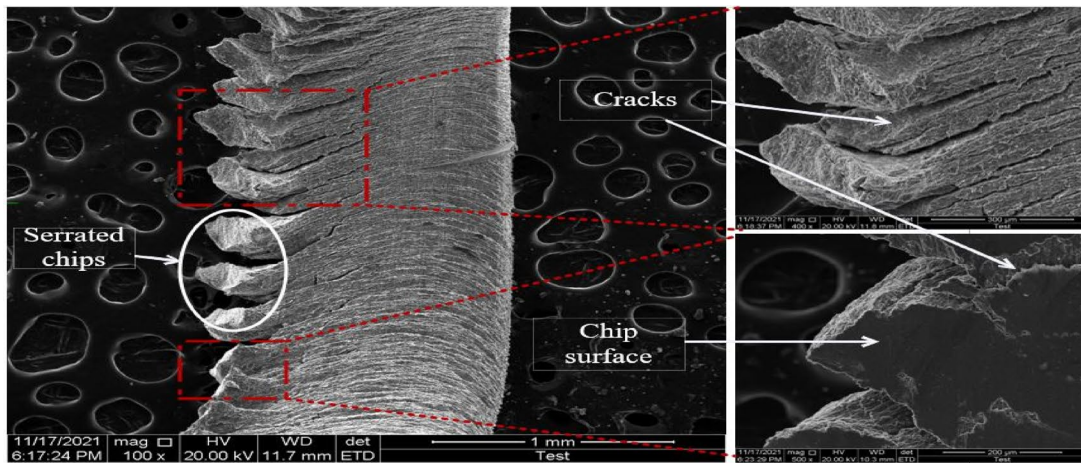
Fig. 12 EDS mapping analysis under different cutting environments



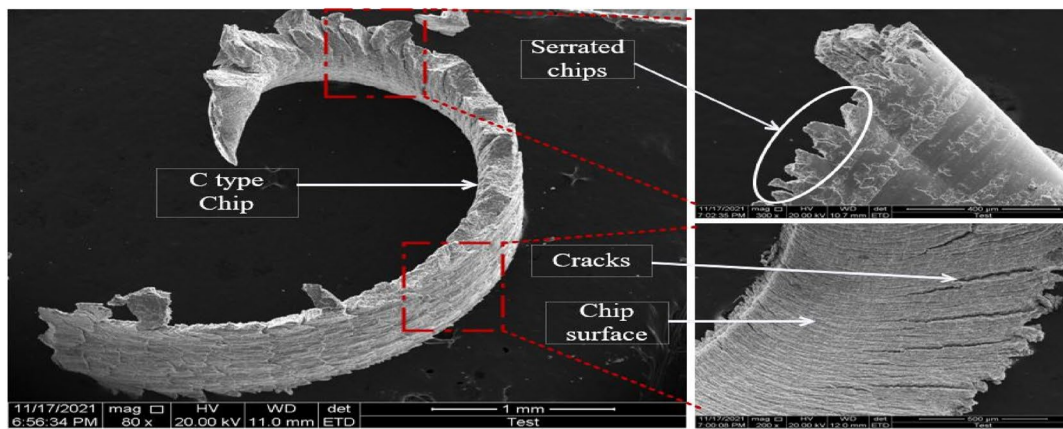
4.2.3 EDS mapping analysis

Figure 12 presents the EDS elemental mapping analysis to demonstrate the accumulated material belongs to the composites. The color of the different elements on the flank face of the cutting tool shows the dominance of the distinguish element, it means SiCp/Al workpiece leaving different elements on the cutting tool. the purple color is shown on the flank face of the cutting tool shows the Al and yellow color shows the SiC particles similarly, the

other colors representing the different elements which can be from workpiece, cutting tool or lubrication/cooling. Color combination of all cutting conditions shows their capability of machinability. Moreover, EDS elemental mapping analysis along with the line EDS and point EDS analysis proves the previous observations. In a word, it is noteworthy to mention that the MQL approach seems the best way in long cutting operations while milling the SiCp/Al-based composite materials considering tool wear mechanisms and tool life.



(a) Dry



(b) MQL

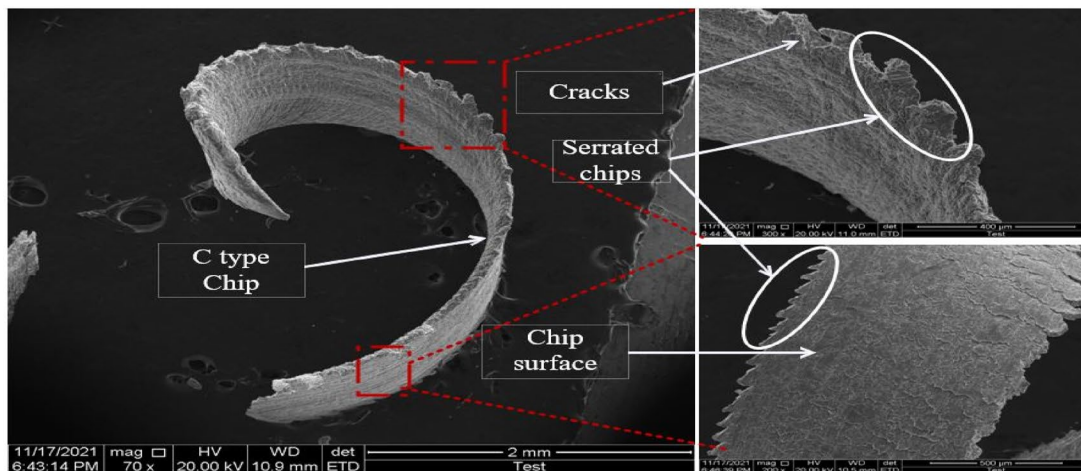
(c) CO₂

Fig. 13 Chip formation during milling SiCp/Al 20% under CO₂, MQL, and dry

4.3 Morphology of chip

Chip morphology is a complex and essential case since the collected metallic parts reflect the concealed details of the cutting mechanism such as thermal, mechanical, and chemical reactions between material and physical aspects namely the stability of the operation, material flow, and cutting tool performance [60]. On the other hand, cutting force deviations, tool and chip contact conditions, the surface texture of the machined workpiece, and the wear behavior of tool can be associated with chip morphology [61]. Chip morphology shows variations depending on the cutting parameters, machine tool mechanism, workpiece material, and tool geometry [62]. The requirement of removing chips comes from the desire to eliminate the heat from the cutting zone [63]. This will provide to protect against thermally induced surface distortions such as residual stresses and a number of wear mechanisms on a cutting tool such as adhesion and diffusion. According to the listed reasons, chip morphology was determined by the authors [64] as continuous chips, discontinuous chips, and saw-toothed chips. In the current paper, chip morphology under different cutting environments was discussed. A general view of the chip showing the geometrical type (left) and zoomed image indicating the serrations and surface view (right) are displayed in Fig. 13 for cryogenic-assisted, MQL-assisted, and dry machining conditions, respectively. There was no observable and considerable change between the chip morphology with varied cutting speed and feed rate. The prominent difference between chip morphology was obtained according to cooling and lubricating strategies. As a general strategy, classification of the chips can be done based on color, shape, and serration traces [65]. The evaluation was performed according to serration characteristics and dimensions of the segmented chips. In general view, the length of the chips is not as long as per the cutting mechanism of milling. In this direction, c-type chips were achieved under sub-zero-carbon dioxide and mist oil assistant machining.

It was indicated by the authors previously that arc-like chips are available to remove from the cutting zone enable good surface quality and are easy for cleaning [66]. This is beneficial due to the operator's health and machinability perspectives. However, straight chips were obtained during dry cutting conditions. All the chips collected from the experiments demonstrated serrated morphology. However, cryogenic CO₂ was found as successful in eliminating the cracks. Investigated chips under dry and MQL cutting conditions had large cracks between and under the serrations that develop owing to the intense friction between rake faces and chips. In addition, dry cutting is available to produce large serrations compared to MQL-assisted milling.

These observations and findings reveal that cooling and lubricating are very significant for better machinability of composites.

5 Conclusions

The milling process of SiCp/Al MMCs was conducted through PCD cutting tool and machining approaches based on the MQL, cryogenic cooling, and dry cutting process at different cutting parameters. The objective of this research work is to analyze and improve the machinability of difficult-to-cut materials SiCp/Al MMCs. The following conclusions can be obtained by milling of the Al-based and SiCp-reinforced composites at different cutting parameters:

- The prominent wear mechanisms of PCD cutting tools are observed as adhesion and abrasion during cutting of composites and play a role in developing flank wear and build-up-edge formations. A sub-zero cooling environment and dry cutting seem useful to generate build-up-edge on the tool rake face while MQL-assistance offers to keep the cutting tool from material adhesion. In total, near-dry machining is the best option for the longest tool life for improved machinability of composites. There can be an extending in tool life about 38% especially operating under high material removal rates.
- Since the chip morphology reflects the hidden sides of machining mechanism, determination of the chip characteristics reveals the positive and negative directions of the selected methodology. MQL- and CO₂-based milling have good potential in achieving desired chip shape that was serrated and c-type. These specifications were obtained through the lubri-cooling effect that improves the tribological conditions.
- Lower cutting force values were achieved under MQL condition and it reaches the lowest point at a low level of feed rate of 0.06 mm/rev and cutting speed of 200 m/min. This result proves the efficiency of cooling and lubricating mediums in developing the frictional conditions in the machining of composites.
- At the feed rate of 0.06 mm/rev, 160 m/min and MQL, surface roughness improvement can be reached about 45% compared with same conditions with a dry environment. Meanwhile, CO₂ regime is good at 0.12 mm/rev feed rate value and dramatic improvement of about 42% can be obtained. Ultimately, the most desired surface roughness values can be obtained under the MQL environment ($R_a = 0.478 \mu\text{m}$ and $R_z = 3.86 \mu\text{m}$). Surface textures are in agreement with surface roughness values.

In sum, MQL strategy seems like the most effective option in many aspects of composite machining. The cryogenic medium may also be beneficial under some conditions for determined machining characteristics that make it

conceivable for practical applications. The overall machining performance of MQL and CO₂ is better than the dry cutting process.

Author contribution Rashid Ali Laghari: methodology, validation, investigation, formal analysis, writing and editing. Muhammad Jamil: writing, methodology, and investigation. Ning He: resources and overseeing of analysis. Munish Kumar Gupta: review of experimental setup.

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Declarations

Conflict of interest The authors declare no competing interests.

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