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Investigation of the Effects of Cooling and Lubricating Strategies on Tribological Characteristics in Machining of Hybrid Composites

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Abstract: Engineering materials are expected to contain physical and mechanical properties to meet the requirements and to improve the functionality according to their application area. In this direction, hybrid composites stand as an excellent option to fulfill these requests thanks to their production procedure. Despite the powder metallurgy method that allows for manufacturing products with high accuracy, machining operations are still required to obtain a final product. On the other hand, such materials are characterized with uncertainties in the structure and extremely hard reinforcement particles that aggravate the machinability. One of the prominent solutions for better machinability of composites is to use evolutionary cooling and lubricating strategies. This study focuses on the determination of tribological behavior of Cu-based, B-Ti-SiC_P reinforced, about 5% wt. hybrid composites under milling of several environments, such as dry, minimum quantity lubrication (MQL)-assisted and cryogenic LN_2-assisted. Comprehensive evaluation was carried out by considering tool wear, temperature, energy, surface roughness, surface texture and chips morphology as the machinability characteristics. The findings of this experimental research showed that cryogenic cooling improves the tribological conditions by reducing the cutting temperatures, flank wear tendency and required cutting energy. On the other hand, MQL based lubricating strategy provided the best tool wear index and surface characteristics, i.e., surface roughness and surface topography, which is related to spectacular ability in developing the friction conditions in the deformation zones. Therefore, this paper offers a novel milling strategy for Cu-based hybrid composites with the help of environmentally-friendly techniques.

Keywords: hybrid composites; tribological performance; MQL; cryogenic cooling; milling; machining

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1. Introduction

Copper (Cu) is a chiefly preferred metallic material for various industrial applications such as electrical packaging, electrodes, conduct cables and different electrical devices thanks to its highly malleable, ductile behavior with excellent thermal and electrical conductivity characteristics [1]. Nevertheless, deficient mechanical and tribological performance at elevated temperatures restricts the widespread utilization of this material system [2]. To augment its usability in different areas and enhance overall properties, various studies have been performed employing diverse approaches, and the new generation of metal matrix composites, or so-called "hybrid composites", have been discovered by researchers [3]. This group of Cu-based systems can be produced by different fabrication methods such as stir casting, thermal spray, deposition techniques, powder metallurgy, melting and consolidation [4,5]. Among them, powder metallurgical (PM) routes have been considered as the most appropriate approach for achieving uniform dispersion of reinforcements with nano scale dimension and improved solid solubility limit of alloying elements within the matrix [6,7]. A fine microstructure with the uniformly dispersed reinforcements throughout the Cu matrix enhances the overall properties such as hardness, corrosion resistance and resultant mechanical and tribological performance [8,9]. However, the primary factor inhibiting the wide-range usage of Cu-based hybrid composites is the poor machinability characteristics of them due to differences and mismatches in behavior of hard reinforcement and soft matrix phases under the different machining operations [10]. Cu matrix hybrid composites are usually preferred in advanced electric industries, where improved surface aspects are needed [11]. A remarkable heat generation is formed because of severe plastic deformation in the cutting region and friction at the interfaces of tool and workpiece material during the milling operation of Cu-based composites due to differences between soft matrix and hard reinforcement materials [12]. These circumstances result in tool wear causing insufficient surface integrity and lack of dimensional accuracy in the different industrial applications [13]. Thus, a remarkable attention is required to supply optimal surface quality during the machining operations, since the surface integrity directly or indirectly effects the resultant machine product performance, such as strength, hardness, fatigue, corrosion and wear resistance, together with production costs [14]. In this context, different cooling and lubricating agents are chiefly used in milling operation to discharge the chips from the exterior region, cool the tool-workpiece interfaces and decrease the detrimental influences of heat and friction formation between the cutting tool and composite material [15]. Such effects develop service lives of tool and cutting conditions as a whole, providing improved surface quality of the machined surface. Today's cooling and lubricating technologies, such as minimum quantity lubrication (MQL), pressure-assisted wet cutting, cryogenic cooling and their different combinations, also exhibit outstanding enhancement on the machinability performance, even milling the extremely hard material systems [16]. Although there is serious curiosity about the effectuation of these revolutionary methods on the processing quality of Cu-based composites, little research has been performed in the literature due to the outlined difficulties.

As an option to conventional machining operations, MQL technique alters the pressurized oil towards mist forming [17]. This approach not only provides little consumption of the lubricants but also reduces the cutting temperatures influentially by means of intimately reorganized nozzle and pressured oils [18]. Considering their functions, the MQL process consumes a minimal level of cutting fluids (50–500 mL/h) and it is regarded as near-dry machining thanks to this phenomenon [19]. Thus, reducing fluid consumption makes the MQL systems environmentally friendly, more economical and more harmless to human health [20]. As a matter of fact, one of the oldest and simplest methods, dry cutting, is a significantly unproductive method as compared to different cooling and lubricating strategies in assisted machining operations, since it results in undesirable surface quality and reduced tool life [21]. To eliminate or minimize the overheating, different inert gases such as O_2, H_2, N_2 and He are mainly considered as cryogenic mediums in liquid forms [22]. Among them, N_2 is a peerless option thanks to its abundance in the open atmosphere and its health and environmentally friendly nature [13]. Based on the above discourses, newly emerged different MQL and cryogenic approaches are spectacular methods due to their sustainable, productive and eco-friendly aspects. Considering open literature, while various properties of different cooling and lubricating strategies on the machining of metals (i.e., Ti, Ni and Fe) and its alloys have been thoroughly examined, the hybrid composites, specifically Cu-based ones, have received cursory attention.

A comprehensive literature survey [23–26] shows that many attempts have been made by diverse researchers in the context of improvement in machining and tribological performance of composite material systems under several cutting environments with a different machining operation, such as turning, milling and grinding. For instance, James and Annamalai [27] examined that the influence of dry and MQL cutting environments on the surface quality, cutting force and tool life of AA6061/ZrO_2 composites during turning operation. Their results revealed that the proportional relationship was observed between MQL condition with surface smoothness and tool wear due to minimized adhesive and abrasive wear mechanisms, but there was no discernible effect on the cutting forces. Niu et al. [15] compared the machining performance of SiC_p/Al composites in terms of surface quality and cutting forces under the dry and cryogenic systems during the milling. They reported that a cryogenic coolant was beneficial for improved surface quality and reduced cutting forces. In another notable study, Khanna et al. [28] compared the liquid Co_2 and N_2 assisted cryogenic and dry conditions during the turning of casted Mg-based composites. One vital observation from their study was that the surface roughness was remarkably reduced in a dry environment, approximately 40% comparing cryogenics. Such an observation was ascribed to homogenous development and breaking of the build-up edge at the cutting zone in dry condition.

Apart from machining of metal-based composites, various researchers investigated the machining performance of polymer matrix composites under different cutting strategies. For example, Giasin et al. [29] assessed the drilling performance of S2/FM94 polymer composites under a cryogenic environment. They reported that the fluid mediums in cryogenic conditions were the most influential parameters on the delamination behavior and hardness increment. Lavorel et al. [30] determined the impact of the cryogenic N2 jet cutting process on the fiber reinforced bio-composites. Their outcomes showed that the pressure and traversal speed of the coolant were the most effective factors on the mechanical performance and thermal stress distribution. Koklu et al. [31] evaluated the impact of cryogenic media while comparing it with the dry environment in drilling of glass fiber composites. Enhanced surface properties and fewer damage zones in hole diameter were achieved by a cryogenically cooled condition. On the basis of a comprehensive literature survey and previously published studies listed in Table 1, it was observed that a large extent of studies focused on cutting performance of the aluminum matrix composites or fiber reinforced polymer matrix composites under the diverse cooling and lubricating environments. In this regard, this study is original and novel since it addresses the machining performance of Cu-based hybrid composites under dry, cryogenic fluid and MQL conditions.

Table 1. Previously published studies regarding the effect of different environments on the machining performance of composites during milling operation.

Material Systems	Machining Process	Cutting Environments	Cutting Fluids	Observed Results	References
TiB_2/Al7075	Milling	Dry, Cryo, MQL and CMQL	Water-based oil, and CO_2	Abrasive and adhesive wear ↓, 200% improved tool life as compared to dry	[32]
SiC_p/Al	Milling	Dry and MQL	-	Flank wear ↓	[33]
SiC_p/A356	Milling	Dry, flood and MQL	Bio-lubricant	Tool wear ↓, no discernible differences in R_a	[34]
CFRP	Milling	Dry and Cryo	LN_2	Surface roughness ↓, delamination factor ↓, cutting forces ↑	[35]
CFRP	Milling	Dry, MQL and Cryo	Synthetic-based oil, LN_2 and CO_2	Machining time ↓, Surface roughness ↓, Tool life ↑	[36]
CFRP	Milling	Dry and MQL	Oil-based fluid	Tool wear ↓, Surface quality ↑ Reduced burr formation compared with dry	[37]

The present study is focused on determining the surface integrity and resultant tribological performance of Ti, B and SiC_p reinforced Cu matrix hybrid composites during milling operation in comparison with under the dry, MQL and LN_2 assisted cryogenic environments. In this framework, cutting speed and feed rate were ascribed as two inputs to examine the machinability characteristics of composites under different machining operations. In the second step for investigations, machined composites were thoroughly characterized in terms of surface aspects, tool wear, chip shapes and cutting performance (i.e., temperature, and energy). Although various attempts have been made by numerous studies for machining performance of steels, Ti, Ni and its alloys employing several cooling strategies in the open literature; the milling performance of the new generation of Cu-based hybrid composites under the MQL and cryogenic environments is novel. In the present study, explanatory information about the two-legged experimental setup will be described thoroughly in the materials and methods section. In this context, the production phase of hybrid composites comprising the powder preparation and subsequent consolidation process will be explained in detail. Finally, comprehensive analysis of milling procedure and physical conditions for cooling and lubricating and assessment of whole measurement techniques for machinability properties will be elucidated. After the experimental work completed, analysis and evaluation of the machinability indicators were performed including tool wear, cutting temperature, surface characteristics, energy consumption and chips morphology. Observed critical outcomes were discussed within the framework of the structure–performance relationship with the help of experimental quantitation.

2. Materials and Methods

2.1. Production and Characterization of Hybrid Composites

Cu matrix powders (99.90 ≤ purity and 44 μm ≥ particle size), commercially purchased from Ege Nanotek Co. Ltd. (Ankara, Turkey), were used as the matrix phase. Ti powders (99.90 ≤ purity and 44 μm ≥ particle size), B powders (99.90 ≤ purity and 1.8 μm ≥ particle size) and SiC_p powders (99.90 ≤ purity and 45–75 μm particle size) supplied from Nanokar Co. Ltd., (Ankara, Turkey) were employed as reinforcements to fabricate Cu-based hybrid composites. More detailed information about the powder morphologies and shapes was reported in our previously published papers [38,39]. Prior to consolidation and sintering steps, the produced powders were kept in the drying oven at 100 °C for 2 h to minimize the impact of extraneous effects such as contamination and moisture. To produce composites with desired chemical composition, the matrix and reinforcement powders were weighted by the "Precisa-XB 220A" model precise scale, having a precision of 0.001 g according to predetermined weight fractions based on our earlier published data [38]. Subsequently, weighted powders were mixed by tubular mixer(Elazığ, Turkey) at 40 rev/min for 4 h to provide a homogeneous structure throughout the mixed powders, according to German's rule of mixture [40]. The compaction procedure of mixed powders was conducted utilizing a uniaxial hydraulic cold press(Konya, Turkey) with the help of synchronic motion of the punches, and 40 × 15 × 10 mm rectangular samples were successfully produced. To avoid powders smearing between the male and female dies, outer surfaces of these molds were cursorily subjected to graphite powders by virtue of their lubricating and thinning influence to improve surface integrity. The compacted specimens were sintered at 1000 °C for 100 min under the constant heating rate of 10 °C/min, introducing high purity Ar atmosphere to prevent oxidation and other potential risks such as gas adsorption on the interior and exterior region of powders. The protecting Ar atmosphere's flow rate was settled as 2 L/min during sintering process for avoiding other undesirable circumstances. The abovementioned preparation parameters of powders and composites were chosen utilizing our previously reported data [2,39], literature survey [41,42] and prior knowledge. The microstructural evolution of sintered products was determined by scanning electron microscopy (SEM, JEOL JSM 6510, Tokyo, Japan). For microstructure observations, produced composites were metallographically grounded using 200 up to 2000 mesh SiC papers, and they were polished by diamond paste

(Ra = 1 μm). To reveal grains and grain boundaries between the matrix and reinforcement phases, polished samples were etched by mixed reagent (25 mL HCl, 1–2 g $FeCl_3$, 100 mL H_2O) for 20 s.

An energy-dispersive X-ray spectroscopy (EDS) module (Shanghai, China) within the SEM instrument was executed to identify content of constituents and their dispersion behavior. The bulk densities of sintered composites were determined by a precise scale utilizing Archimedes' principle [43], their theoretical densities were assessed by the basic rule of mixture equation [40] and the theoretical density values of Cu, Ti, B and SiC were 8.96, 4.50, 2.08 and 3.21 gr/cm^3, respectively. Then, the bulk densities of composites were divided by theoretical densities for calculation of relative density results. To obtain high preciseness and reproducibility in measured data, at least three identical samples were analyzed from each group. Furthermore, five different measurements were performed on each set and the arithmetic average of measured results was given with their standard deviations to achieve true statistical sampling.

2.2. Machine Tool and Cutting Tool Properties

In the present study, machining experiments were performed on MCV-860 model CNC milling machine (Taichung, Taiwan) supplied by Dahlil Company. Successfully produced hybrid composites were centralized to the clamp of the machine tool for each test. The employed cutting tool tips (AlTiN PVD coated) were acquired by Iscar Company (Kocaeli, Turkey), and they coded and standardized as HM90 APKT 100,316 PDR and ISO 13399, respectively.

Twelve different experiments were conducted in this study and, for each set, distinct cutting tool tips were utilized. Cutting inserts were fastened to the 403 BT 40 ER32 × 70 standard cutting tool holders (Gisstec, Germany), produced by Mas Company. The experimental setups consisting of different machining parameters are represented in Table 2. The zig-zag model was selected for all cutting operations to supply tool path strategy, and depth of material removal rate was maintained as a constant ($a_p = 2 \times 0.75$ mm and $a_e = 6$ mm) during the milling process.

Table 2. Machining parameters performed during the milling operation.

Cutting Parameters	1st Level	2nd Level	3rd Level
Cutting speed (m/min)	200	300	–
Feed rate (mm/rev)	0.2	0.3	–
Environment	Dry	MQL	Cryo

2.3. Machinability Experiments

Before starting tests, a thin (≈0.2 mm) layer was removed from the raw surface of the composites to preserve the workpiece and cutting inserts from agglomerated hard particles and spatter. Besides, numerous trials were performed before the real experiments for regulating chip morphology and cutting mechanism together with chatter vibrations. The operator knowledge was employed in this stage of the experiments, which is so crucial to prevent dust chip shapes and extreme chatter impact. It was also aimed to preserve the cutting tool and workpiece parts from extreme loads generated by rigid and hard particles. In this regard, all experiments including two feed rates and cutting speeds and three machining conditions were repeated three times. Such a machining operation was performed to supply reproducibility of the predetermined cutting environments, and it was noticed that error of experiments for all responsive case was smaller than 5%. After taking into account all these considerations, before terminating the final decision regarding the cutting parameters, as previously listed in Table 2, ISO standard was followed. Furthermore, the tool maker's knowledge and recommendations were carefully considered.

2.4. Cooling and Lubricating Strategies

In these experiments, two diverse approaches for lubricating and cooling fluids were used for comparison purposes with dry conditions: (i) synthetic based MQL and (ii) LN_2 assisted cryogenics. The preparation phases of the liquids and ancillary equipment for delivering these fluids are described in detail in the following sentences with the help of an extensive literature survey. The KY 200 numbered synthetic based MQL lubricant oil was purchased from Kar-Tes Company (Konya, Turkey). To penetrate of the lubricant towards cutting zone, Werte brand oil unit (Konya, Turkey) was utilized. The system specifications were arranged as follows: nozzle diameter = 3 mm, flow rate = 50 mL/h, pressure = 6 bar, nozzle distance from cutting tool tip = 100 mm, nozzle angle = 45° during MQL assisted spraying process. The N_2 in the liquid form was chosen as a cryogenic agent due to its high preference. A YDS 10 coded N_2 tank, produced by MC-BIO firm (Konya, Turkey), was employed to supply liquid flow. Operational circumstances of the used coolant were specified as follows: nozzle diameter = 3 mm, flow rate = 20 L/h, pressure = 6 bar, nozzle distance from cutting tool tip = 20 mm, nozzle angle = 30°.

2.5. Devices for Measurement of Machining Variables and Graphical Abstract

In the present study, surface quality, tool wear and cutting parameters (i.e., temperature and energy) and resultant chip shapes were regarded as outputs. A 3200 coded surface analyzer (Beijing, China) produced by TIME Company (Beijing, China) was employed for surface roughness measurements. The most preferred surface roughness parameter (R_a), average surface roughness values, was selected for the assessment of surface smoothness. At least five measurements were taken from each specimen's different regions in accordance with ISO 4287 criteria. After, the lowest and highest values were cancelled to provide accurate statistical sampling. All surface measurements were made immediately after the cutting experiments to eliminate the effect of any oxidation and contamination. A Nikon Eclipse, MA 100N brand optical microscope (Düsseldorf, Germany) was used to monitor the surface development in different cutting environments. After, the procured images were processed with ImageJ (Maryland, USA) image processing software with an interactive 3D surface plot module to assess surface topography under different cutting conditions. On the other hand, different chip types resulting from different cutting strategies were collected during experiments and then analyzed by digital camera (Wetzlar, Germany) in macroscopic view. SEM analyses were also performed to monitor tool wear changes in terms of rake and flank face. Prior to SEM observations, one of the three identical cutting tool tips used in repetitive experiments was chosen and it was analyzed with the help of light microscope. To measure developing temperature changes in the cutting zone with respect to different cutting environments, an 871 coded Testo brand thermal camera (Düsseldorf, Germany) was utilized. Considering recommendations and knowledge of the producer to supply more correct and prompt measurements, the emissivity of the camera was settled as 0.5. This instrument is capable of determining temperature increases up to 650 °C. As for assessment of power and energy consumption, Hioki Corp. brand power analyzer instrument (Hioki, Japan) was used. During these measurements, the cables connected to the main phase of the machine tool, which allowed to follow the current drawn, were utilized. Meanwhile, an entire process was followed according to the power requirement, and accordingly, the energy consumption, which developed over time, was evaluated.

3. Results

3.1. Microstructural Analysis of Sintered Cu-Based Hybbrid Composites

Figure 1 shows the SEM image of hybrid composites indicating matrix and different reinforcement phases and their location in the structure. Figure 2 illustrates the black and white SEM image and corresponding EDX results which were taken from different points in the composite system. Considering EDX analyses of these areas, the spectrums 1 and 2 show the SiC_p and Ti reinforcements, respectively. Spectrum 3, which was taken from matrix and reinforcement regions, shows the main Cu matrix and different reinforcement phases. The EDX spectra of B element was discernible due to its quite small particle size, and the uniform distribution of reinforcements within the structure resulted from followed mixing protocol.

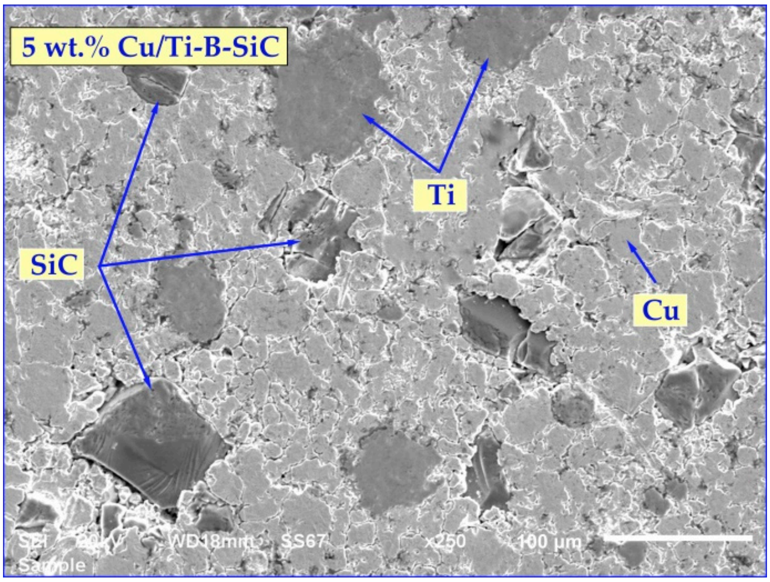
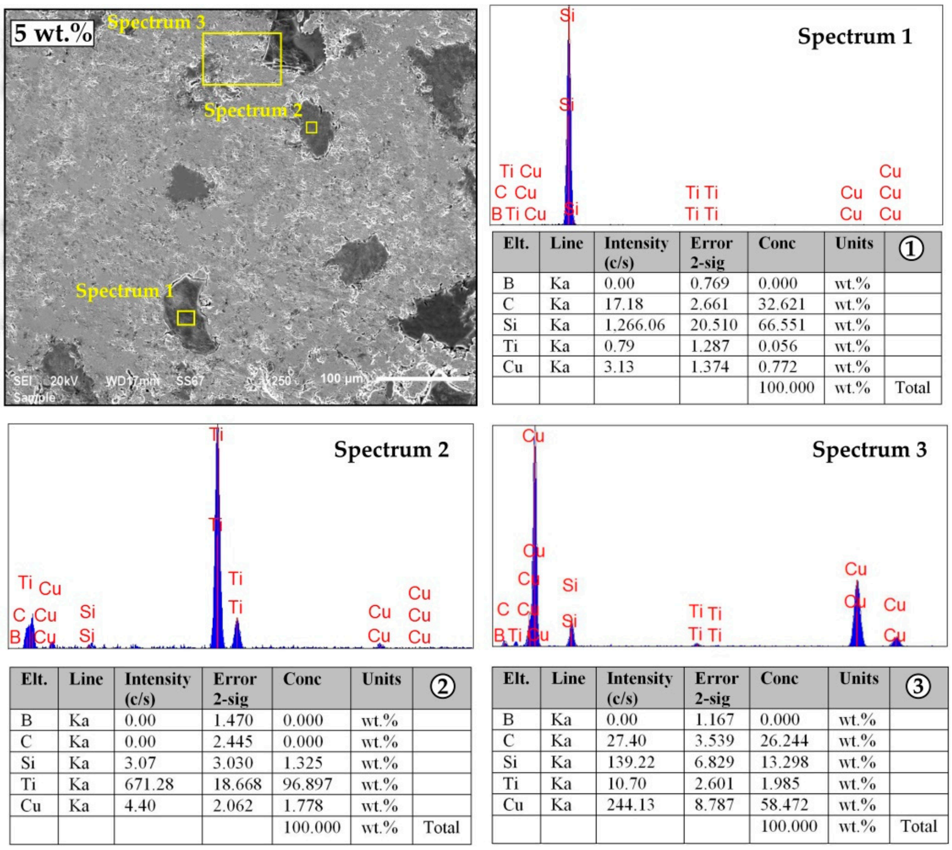


Figure 1. Microstructure of the hybrid composite materials.



Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units	①
B	Ka	0.00	0.769	0.000	wt.%	
C	Ka	17.18	2.661	32.621	wt.%	
Si	Ka	1,266.06	20.510	66.551	wt.%	
Ti	Ka	0.79	1.287	0.056	wt.%	
Cu	Ka	3.13	1.374	0.772	wt.%	
				100.000	wt.%	Total

Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units	②
B	Ka	0.00	1.470	0.000	wt.%	
C	Ka	0.00	2.445	0.000	wt.%	
Si	Ka	3.07	3.030	1.325	wt.%	
Ti	Ka	671.28	18.668	96.897	wt.%	
Cu	Ka	4.40	2.062	1.778	wt.%	
				100.000	wt.%	Total

Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units	③
B	Ka	0.00	1.167	0.000	wt.%	
C	Ka	27.40	3.539	26.244	wt.%	
Si	Ka	139.22	6.829	13.298	wt.%	
Ti	Ka	10.70	2.601	1.985	wt.%	
Cu	Ka	244.13	8.787	58.472	wt.%	
				100.000	wt.%	Total

Figure 2. EDX results of the taken from the composites.

3.2. Tool Wear Mechanism and Flank Wear

Machining of the composites mostly distinguishes from the conventional types of materials due to the randomly dispersed hard particles in the soft matrix [44,45]. This can be understood as a result of the natural progression of the production process, and it plays a vital role in the stability of the cutting [46]. The cutting zone is already suitable for the high temperatures and cutting forces as a result of the excessive plastic deformation rate [47]. Ambiguous structural integrity of the composites may lead to versatility in such machining variables [48]. Therefore, homogeneous distributions of the reinforcements in the main structure have great importance in the composite machining field [49]. In the course of this study, different behavior during milling operation can be observed as a consequence of relatively high density of the test specimens. In total, it is expected that the reinforcements in the body may cause damage to the cutting mechanism. Considering the full structure of the composites, not only do the hard additives affect the operation but the soft matrix also changes the cutting dynamics [39]. In both cases, ideal conditions gradually disappear, and several wear mechanisms may appear on the cutting tool according to the encountering medium. There are four basic wear mechanisms that may develop during machining of composites [50], that can be sorted as; (i) abrasive wear mechanism resulting from the addition of hard particles, and it is usually responsible for progressive flank wear, (ii) the existence of adhesion mechanism in the soft materials and elevated temperatures that trigger the build-up-edge formation, (iii) diffusion wear mechanism developing on the rake face of the insert causing crater wear and (iv) an oxidation wear mechanism may develop on the back region of the main cutting edge and cause notch wear.

From the abovementioned theoretical infrastructure, it can be said that flank wear and build-up-edge mechanisms were observed as the governing wear types during milling of the hybrid composite materials. Figure 3 represents the flank wear changes comparing the effect of cooling conditions along with cutting speed-feed rate combinations. In addition, Figures 4 and 5 show the wear conditions at clearance and rake faces, respectively. Flank wear is one of the most important and addressed tool wear types since it can be used as a tool life criterion. Moreover, this situation was guaranteed by the standard that makes it a perfect way to measure the cutting performance [51]. As mentioned before, hard particles intensify the frictional conditions between cutting tool and workpiece, and they play the leading role in progressive flank wear. There are two types of flank wear development: (i) the wear land may progress with variable depths from the main edge to downwards through the cutting edge and (ii) propagation of the wear land is stable throughout the cutting edge. Since the wear land on the clearance face increases in two dimensions, a determination of the flank wear level was conducted according to the maximum flank wear rule [52]. The obtained values in Figure 3 can be checked from images shown in Figure 4. According to the measured flank wear values, changing of the feed rate has no importance and shows a regular effect, especially at low cutting speed, for all cooling conditions. Maximum change in flank wear reaches 8% variation at dry milling while operating with different feed rates. Seemingly, flank wear shows an increasing behavior with higher cutting speeds ranges between 8% and 14% at cryogenic condition, 10% and 16% at MQL medium and 6% and 15% under dry milling respectively. This is attributed to the increasing plastic deformation rate and reaches to the maximum value under dry condition. When looking to the impact of lubri-cooling, interesting results are seen. A critical cutting speed level was detected between 200 m/min and 300 m/min, that makes N_2 more effective than pressurized mist oil. It is thought that at low cutting speed, the oil pressurized with the help of air can penetrate to the deformation zones more effectively than cryogenics. Somehow, exceeding this value makes it easier for the LN_2 to enter these regions, which can be attributed to the gaseous form of cryogenic coolant. It is true that both lubri-cooling strategies provide better results at low cutting speed and, with the increase in the cutting speed cryogenic environment, protect the tool edge powerfully. It was mentioned by the authors [13] that cutting fluids are capable of reducing chatter tendency, cutting forces and friction coefficient. Moreover, the successes of the lubricants used were explained by the authors [53] in that high-pressurized aerosols transferred to the cutting zone have the ability to decrease the thermal shocks, overdose tool wear and frictional force. In sum, improvement in the tool life can be reached up to the ranges of 7%–20% and 7%–13% when comparing dry environment with cryogenic medium and MQL assisted milling, respectively. Cryogenic cooling and a small quantity of lubricating were found as successful for obtaining good flank wear results.

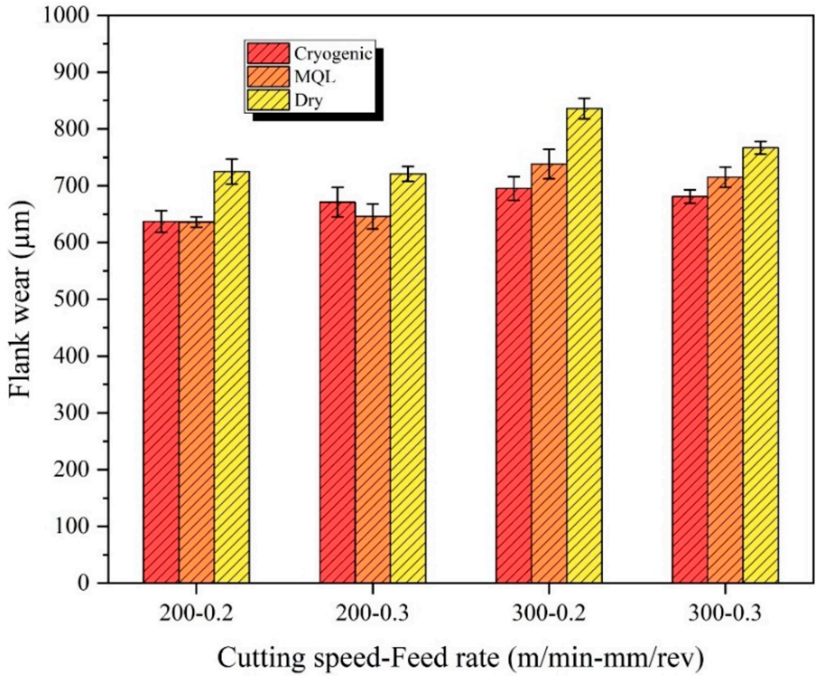


Figure 3. Impact of cooling and lubricating effect on flank wear.

Changing wear texture on the flank faces of cutting tools is seen in Figures 4 and 5. The magnification of the figures was arranged as 100× to compare the worn surfaces fairly. All SEM images, both for rake and flank faces, belong to the operational conditions of 200 m/min and 0.2 mm/rev. It should be noted that feed rate and cutting speed had no comparable and visible impact on the wear mechanisms. The influences on the flank wear were described previously and other wear types showed no distinct differences. However, with the change in cooling strategy, material adhesion that causes build-up-edge formation is seen under cryogenic and dry environments. It is thought that the low hardness of the composite materials leads to adherence of the soft matrix on the cutting tool, mostly due to the insufficient lubri-cooling effect. The dry medium is already thirsty for the material adhesion owing to the lack of the tribological performance improvements existing on other environments [32]. Despite the fact that liquid nitrogen was found to be successful in protecting the cutting tool from abrasion wear as well as mist oil, it is insufficient in preventing build-up-edge formation. The penetration of the mist oil sent by the MQL nozzle is effective with the help of the pressured air, which reveals a hybrid cooling and lubricating effect. Therefore, pulverized oil droplets create a strong bonding surface between the back face of the chip and cutting tool providing better plastic flow [54]. Application of the MQL method with all cutting parameters did not cause such adhesion or other wear mechanisms. The abrasion marks can be clearly seen under the MQL environment that composes the flank wear area. Plus, the flank wear area of cryogenic and dry medium is demonstrated along with abrasive wear marks. As seen in Figure 5, the MQL strategy provides impressive results with no build-up-edge formation and protected cutting tool geometry.

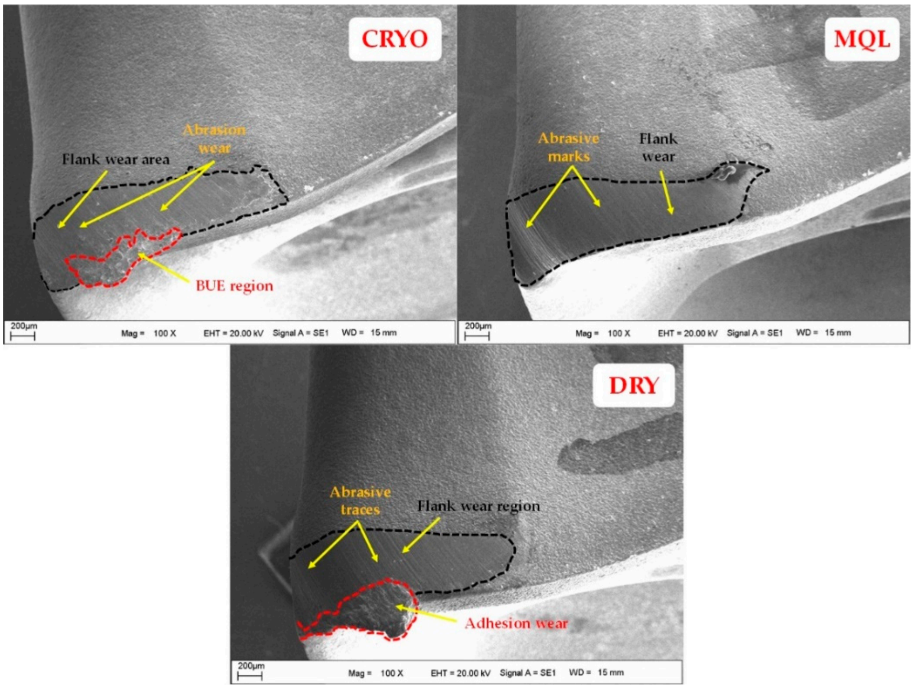


Figure 4. Impact of cooling and lubricating on microstructures of flank faces of tool wear.

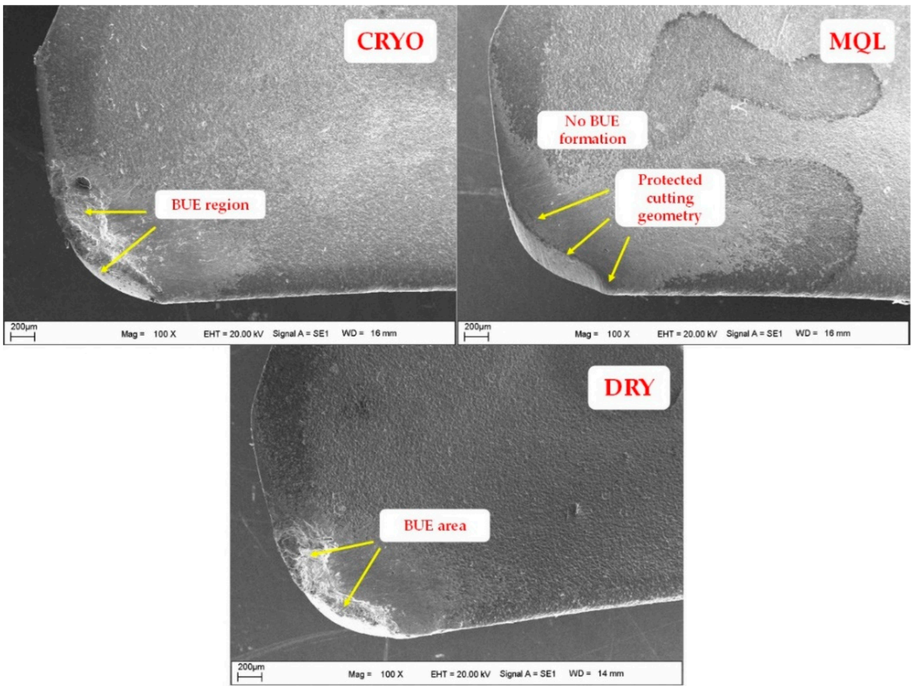


Figure 5. Impact of cooling and lubricating on microstructures of rake faces of tool wear.

3.3. Surface Roughness and Surface Topography

Surface integrity of an engineering product reflects the quality of manufacturing processes and can be represented by several indicators such as surface roughness, surface topography and microstructural images [55]. Surface condition of a material has importance in identifying the contact region and pressure, adhesion behavior, friction and wear conditions, especially on the shop-floor of industries [56]. Surface roughness is one of the most addressed surface quality measurement tools that is based on the calculation of height of the peaks and valley of the valleys [57,58]. Among surface roughness parameters, arithmetic mean value (Ra) is the widely preferred one that allows for the calculation of the average value of an equal number of peaks and valleys [59]. Many operational variables affecting the surface quality of the machined part have an active role in milling [60]. That is why some factors disturbing the cutting stability and reducing the surface quality should disappear [61]. Recently, cooling and lubricating methods have widened as per their positive effect on cutting performance [21]. From the above-given information, this study is desired to produce the best surface condition under different environments. Figure 6 presents the surface roughness results of different cutting parameters and mediums. Clearly, dry milling creates the worst surface roughness values that range between 3.79 µm and 4.851 µm at all feed rate/cutting speed combinations. The absence of supportive lubricants for better friction conditions in dry cutting reduces the surface roughness [62]. In addition, it is thought that distortion of the cutting geometry because of build-up-edge on the rake face leads to this outcome. The same situation can be mentioned for the cryogenic assisted milling that worsens the surface quality. Surface roughness results belonging to liquid nitrogen assisted machining vary between 3.215 µm and 4.623 µm, which is better than but remarkably close to the dry medium. The results of the near-dry machining are promising for the industries. This can be explained by MQL being a hybrid method, including pressured air and oil droplets, which provides a thin film between the chip–tool interfaces, causing the following physical impacts: (i) lubricating the contact faces makes for easier chip flow and produces better surface roughness and (ii) quick elimination of the heat from the cutting area lowers the uninvited thermal effects related with material structures [63,64]. According to the results achieved, MQL is the best option for milling of hybrid composites by a long margin due to the fact that the product quality comes first in manufacturing processes. This is in line with the tool wear index and doubles the success of this method. The best surface roughness was achieved by the MQL method and improvements were obtained that reached up to 891% and 814% compared with dry and LN_2 methods. This is a critical discovery in surface quality improvement of machining of hybrid composites.

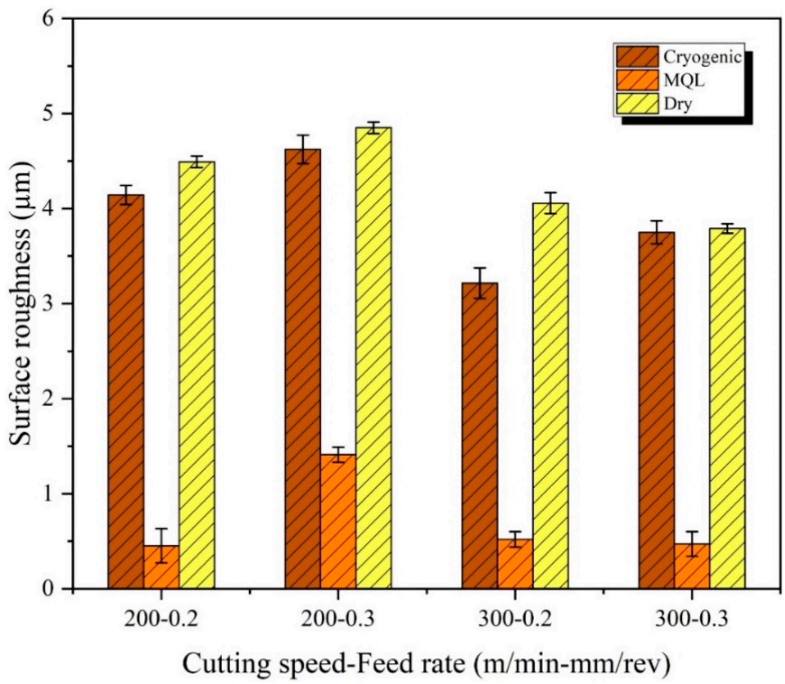


Figure 6. Impact of cooling and lubricating on surface roughness.

Considering that the surface characteristics of a product can be described by a range of factors, there is a need to investigate such properties as much as possible. In spite of the fact that surface roughness is a determiner of surface condition, 3D profiling provides an idea of the complete structure [65]. Surface topography describes the general view of the surface texture which will be necessitated on the shop-floor of industrial companies. Moreover, this allows for the determination of the functional properties such as wear/friction, corrosion resistance, adhesion behavior, etc. [66]. Therefore, 3D topographies taken from the machined parts are depicted separately with real surfaces and a colored map. The area with dimensions of 2.8 × 1.6 mm from the surface was chosen to evaluate the surface morphologies. To maintain consistency, the samples were chosen from the experiments operated under 200 m/min and 0.2 mm/rev, which is the same with tool wear SEM photos. As seen, mist oil sent to the cutting zone produces the best surface conditions, including small variations. The MQL strategy enables for smooth cutting for the cutting insert, protecting the stability by improving tribological performance [67]. Improvement in tribological conditions is based on the protection ability of the greasing mechanism of the surface and cutting tool from adhesion mechanism [68]. It is thought that penetration of the oil vapor was successfully carried out in the current study. As a result, consecutive feed marks are created, which can be clearly seen in the colored map. On the other hand, poverty of the lubricating effect and irregular particle distribution in the material aggravates chip formation under dry milling [69]. Therefore, chips were ruptured instead of cutting from the body, which led to vacancies, as seen in Figure 7. Consequently, surface integrity responds these anomalies with fluctuations and uncertainties on the structure.

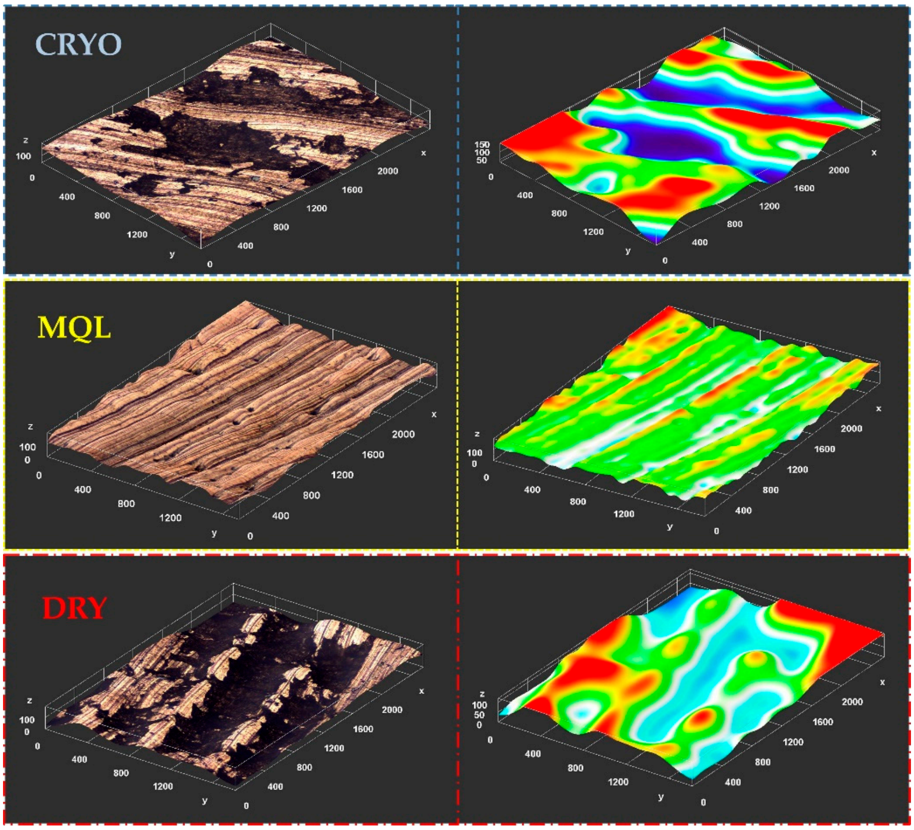


Figure 7. Impact of cooling and lubricating on surface texture.

The cryogenic environment also had low surface quality, as represented by the physical view of the captured image and color map. The main reason for this is that sub-zero cooling affects the main matrix and additive particles differently, as per they include particular material constituents owing to different hardness levels [70]. Moreover, sub-zero cooling of cryogenic nitrogen causes work hardening, that makes chip removing difficult and results in poor surface integrity [71]. Structural integrity of composite materials, especially those produced by the powder metallurgy method, can be influenced by various parameters simultaneously, such as sinterability, packability, hardness, density, sintering temperature, pressure, production method and, perhaps the most importantly, interfacial bonding characteristics of material constituents [72]. Interfacial bonding mechanisms can be achieved by different methods, such as chemical reactions, diffusions, adhesion and mechanical interlocking [73]. The last one is frequently observed by different researchers with production of Cu or other different base metal matrix composite systems fabricated by powder metallurgical routes. To supply uniform stress transformation throughout the material system, a strong interfacial bonding characteristic is required. However, in addition to abovementioned irregularities or other metallurgical defects, different environment conditions also manipulate this interfacial interaction. In machining operations, when the tool tip comes across to the material's surface, two dominant mechanisms co-exist; the cooling and heating effect try to conquer the environment and this leads to thermal shrinkage between matrix and reinforcement phases. Moreover, the cryogenic coolant creates cavities between the matrix and reinforcement due to thermal mismatch behavior between ductile Cu matrix and hard ceramic particles. As can be seen in the last section in the study, larger chips prove the above explained events and the influence of the cryogenic environment. Lastly, it is proven here that surface roughness and surface topography results are in agreement, to a great extent.

3.4. Cutting Temperatures

High cutting temperatures are one of the problematic issues of machining processes, owing to the negative activity on the material properties [74]. This can be listed as the adverse effect on the morphology of the machined surface, i.e., residual stresses, poor mechanical properties of the part depend on overheating level and acceleration of tool wear mechanisms with higher material diffusion [75]. Therefore, excessive heat needs to be transferred from the environment for achieving the desired energy flow [76]. It is expected from the machining operations that the surplus heat should be removed from the area by chip removing. In the course of this study, since the main matrix Cu is characterized with high thermal conductivity, quick transmission of the heat to the cutting tool and workpiece is accepted as a normal situation. However, interactions between material pairs such as cutting tool–composite and cutting tool–chip make it difficult to achieve the desired temperature distribution [77]. To overcome this challenge, cooling and lubricating organizers have been used commonly in the field [78]. One of the primary goals of this study is to determine the ability to control the temperatures via modern cooling techniques during milling of hybrid composites. Thus, to make a comparative analysis between different environments, a bar graph was used in Figure 8. Seemingly, cutting speed has a remarkable effect on the temperature variation, especially at higher feed rates, but shows a changeable trend according to the cutting environment (the impact reaches up to 17% in all cutting mediums). Feed rate, on the other hand, had a regular impact on the cutting temperature, reducing it with higher parameter levels. This effect increases up to 29%–31% for all cutting mediums, executing the operation with high cutting speed. The comment can be made here: the increase in feed rate reduces the contact time between the cutting tool and composite material. Effective cutting of the material is possible with eliminating the restricting force during the contacted periods. When looking to the cutting mediums, cryogenic nitrogen dominates the results with reducing the temperatures' minimum values in the study, i.e., 46.6 °C and 54.7 °C. The main reason is that the extremely cold nitrogen gas easily decreases the temperature in the environment [79]. In addition, this ability makes it easier to remove the heat around the cutting area, creating a liquid/gaseous buffer between the chip and insert interfaces [80]. It is understood that dry cutting is unable to remove the heat, and the additional effect of hard ceramics in the composites makes the tribological conditions more harsh [81]. The MQL strategy was also found to be effective, especially considering the success in reducing tool wear and improving the surface characteristics. However, it can be said that the fast evaporation of the oil droplets may result from the lack of cooling effect, which mainly results in lubrication. In sum, cryogenic cooling reduces the temperatures in the range of 12–47% and 5–49% compared to dry and MQL strategies.

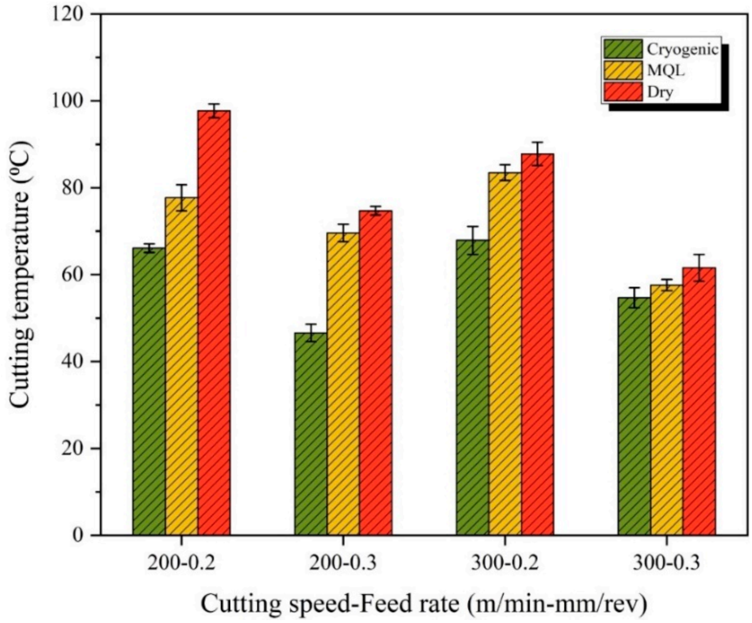


Figure 8. Impact of cooling and lubricating on cutting temperatures.

3.5. Cutting Energy

Cutting energy consumption composes one of the main aims of an industrial company, and share of it demonstrates an increasing trend day-by-day. The reason is that power generation and transportation are highly costly matters. Machine tools are responsible for the huge part (accordingly 30% of total depletion) of the energy consumption in the manufacturing sector [82]. From this point of view, improvements, even at a small scale, will make a considerable contribution in terms of total costs [38]. The potential in the cutting energy reduction with machining operations takes the attention not only for the technological aspect, but also for its importance in the sustainability issue. Since the extreme consumption of cutting energy is related with the carbon emission, minimization of this variable is accepted as an environmentally-friendly approach. In addition, basic cutting parameters such as cutting speed and feed rate also play a dramatic role on total energy depletion. Based on this information, this study purposes to calculate and to find the optimum conditions for minimum energy consumption during milling of the hybrid composites. Figure 9 presents the consumed energy results with different parameter combinations and under various cooling conditions. When calculating the total cutting energy, actual cutting time was utilized. The findings from this study show that cryogenic nitrogen assisted machining is the best choice for reduction in the energy consumption. On the other hand, calculations in the MQL method are very close to the cryogenic results. Therefore, it can be said that near-dry lubrication and sub-zero cooling are effective methods when compared to dry milling. It is thought that both mist oil and LN_2 snow are successful in reducing the friction between the cutting tool and workpiece, with their high accessibility to the cutting zone. The best two findings for minimum energy demand in milling of hybrid composites were found as 5.01 kJ and 5.36 kJ under cryogenic assisted and MQL assisted machining, respectively. This situation directly affects the required cutting forces and reduces the cutting power and energy. In another perspective, better tribological medium protects the cutting tool and its sharpness improves the cutting ability. It is useful to mention that both mist cryogens and oil particles allow for the reducing of machining vibrations, cutting force components, coefficient of friction, cutting power and, indirectly, the cutting energy [83–85]. Despite the fact that dry cutting is ineffective for consumed energy reduction under operating all cutting parameters, it can provide close results as good as with other approaches, i.e., 200 m/min and 0.2 mm/rev. In sum, improvement can be attained by organizing the cooling environment that reaches up to 25% and 17% with using cryogenics and MQL approaches. A general trend can be seen for the cutting speed and feed rate, in that they play an increasing and decreasing role on energy consumption, respectively. It is understood that the higher level of cutting speed increases the plastic deformation, which requires more energy during cutting. Cutting speed change has an important variation on the energy consumption, that ranges from 3% to 31% and reaches the maximum under dry condition. On the other hand, it is logical that an increase in the feed rate directly decreases the total cutting time and required energy. Change in feed rate also plays a significant role that can reduce the energy consumption down to the 20% ratio.

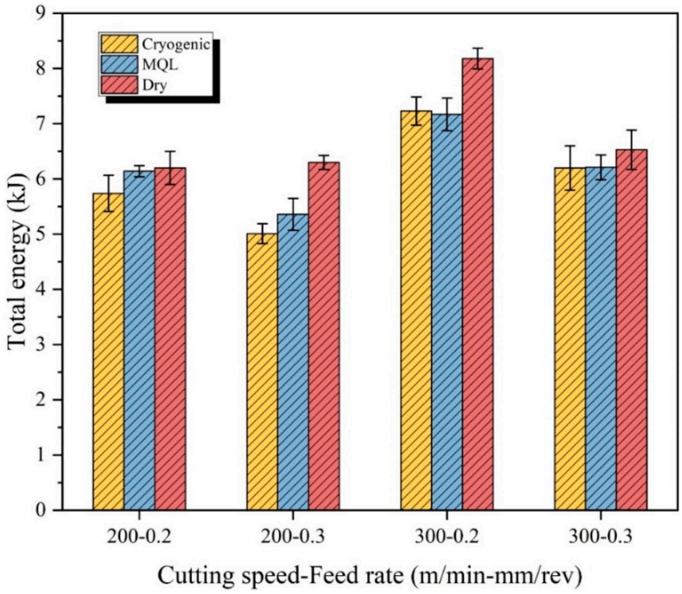


Figure 9. Impact of cooling and lubricating on cutting energy consumption.

3.6. Chips Characteristics

Chip morphology reflects the quality of machining operations in some way, since the distinct features such as color, shape and serrating's are important outcomes [86]. The major reason is that good surface morphology and tool wear texture are associated with desired chip shape. Another important issue concerning chip morphology is their ability to remove the existing heat around the cutting zone quickly [22]. Therefore, fast and effective chip removal guarantees the substantial elimination of thermally induced distortions on the surface and subsurface of cutting tools and workpiece. In addition, considering the machined part as a whole, regular chip formation is of great importance for obtaining entirely perfect surface integrity [87]. The machining environment includes numerous factors affecting the dynamics of the cutting operation naturally [88]. Some of them can be listed as: context and constitutive parameters of materials, operating parameters, chip removing mechanism, cutting geometry, cooling strategy, etc. Therefore, determination of the chip characteristics needs to be carried out for measuring the impact of these contributors. This study aims to discuss the impact of lubri-cooling on the chip characteristics. To make a comparative analysis, chip specimens were also selected from the experiments operated under 200 m/min cutting speed and 0.2 mm/rev feed rate, which is the same with surface topography and worn tool SEM. It should be noted here that cutting speed and feed rate have no visible effect on the chip morphology. There are slight differences between the chip's morphology received from different cutting mediums, as seen in Figure 10. It is thought that cutting mechanisms in milling and small cutting depth produce the same color chips for all experiments. In addition, relatively high cutting temperatures in a determined range lead to similar colored chips. As shown in Figure 10, cryogenic coolant-assisted and dry mediums seem close to each other as they contain similar dimensional chips. It can be concluded that sub-zero fluent cools the main matrix and reinforcement with different rates. During cutting of the composites and removal of the hard and soft parts of the material show a different separating mechanism that causes rupturing in general and cutting sometimes. Cooling and lubricating mechanisms of cryogenics and MQL oil provide a better tribological environment for chip breakability, which can be defined as the self-breakage [56]. This is a great chance for the cutting tool and the workpiece material because other types of chip breaking mechanisms occur as a result of crushing them. On the other hand, drought of the dry environment causes tearing but also cutting that reveals the large particles instead of metallic chips. These findings are in line with the previous ones, as represented in surface topographies. The MQL method was found to be the most successful method for creating desired chips for Cu based hybrid composites.

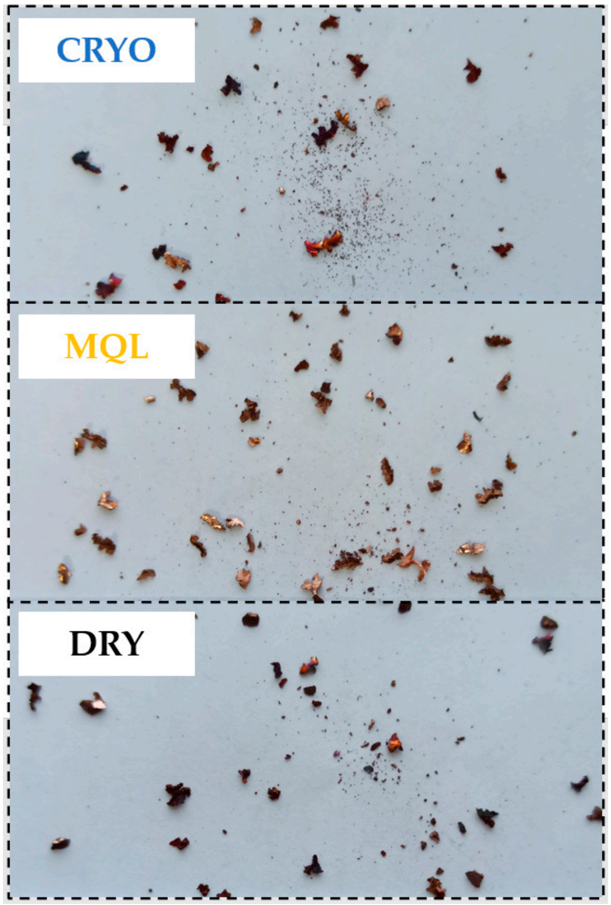


Figure 10. Chips characteristics under different cooling and lubricating conditions.

4. Conclusions

The following conclusions can be made from this comprehensive study:

- The MQL based lubricating strategy was found as the most effective approach in protecting the cutting tool from build-up-edge formation. One of the important effects of this result is the hybridized pressured air and greasing effect that enables it to protect the cutting tool from abrasive impacts, creating a thin film. On the other hand, flank wear development can be reduced with both oil mist and nitrogen assisted cooling. Sub-zero nitrogen can effectively infiltrate to the small spaces of the cutting zone by creating a cushion that results in better tribological environment for the cutting tool. Cryogenic cooling and MQL milling can increase the tool life about 20% and 13%, respectively, when compared with dry conditions during machining of the hybrid composites.
- Surface roughness and surface topography were obtained via using the MQL method as the most desired condition. However, the cryogenic environment and dry cutting affected the surface texture negatively. The dry medium suffers from the absence of

the lubri-cooling effect, which puts it in a disadvantageous position. On the other hand, work hardening of the workpiece exposed to cryogenic cooling produces poor surfaces. When compared with the MQL medium, dry and cryogenic environments were obtained with reduced surface roughness values that reached 891% and 814%.
- Cryogenic cooling was found as the most efficient way in reducing the cutting temperatures, followed by MQL and dry strategies, respectively. It is an expected result due to the very low temperatures of cryogenics, which cool the cutting environment completely. Despite its success in this area, surface quality dependent results are not satisfying for cryogenic cooling, which makes the MQL method sufficient.
- In calculation of the total energy consumption during milling of the hybrid composites, MQL and LN_2 based cooling provide close results. According to the different cutting parameters applied during operations, both methods may provide better results. It can be said that at higher cutting speed, MQL is effective, while at low cutting speed, cryogenic cooling demands lower energy. A general conclusion can be drawn here that, by their effective lubri-cooling influence, cutting fluids of MQL and cryogenic method improve the tribological performances of the cutting tool and reduce frictional forces and cutting forces eventually.
- Similarly with other findings, MQL creates the best chip morphology compared to other results. One of the deductions herein is the ability of tiny droplets to provide better shearing for the chips and improve breakability by protecting the cutting tool and workpiece material. This is an expected result due to the observations on the tool wear index and surface morphologies. In total, MQL approach was found as the most inflective way in improving the machinability performance of Cu based hybrid composites.

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