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INVESTIGATION THE EFFECTS OF SUSTAINABLE COOLING/LUBRICATION CONDITIONS ON THE MACHINABILITY OF Al-3Gr BASED HYBRID COMPOSITES

SÜRDÜRÜLEBİLİR SOĞUTMA/YAĞLAMA KOŞULLARININ Al-3Gr ESASLI HİBRİT KOMPOZİTLERİN İŞLENEBİLİRLİĞİ ÜZERİNDEKİ ETKİLERİNİN ARAŞTIRILMASI

Üsame Ali USCA[1] (ORCID: 0000-0001-5160-5526)
Ünal DEĞİRMENCİ[2] (ORCID: 0000-0003-1480-2488)
Serhat ŞAP[3*] (ORCID: 0000-0001-5177-4952)

[1] Department of Mechanical Engineering, Bingöl University, Bingöl, Türkiye
[2] Department of Machinery and Metal Technologies, Bingöl University, Bingöl, Türkiye
[3*] Department of Electricity and Energy, Bingöl University, Bingöl, Türkiye

*Sorumlu Yazar / Corresponding Author: Serhat ŞAP, ssap@bingol.edu.tr

ABSTRACT

The main purpose of this research is to meticulously evaluate various derivatives resulting from recently developed Al-3Gr-based hybrid composites and to complete the deficiencies for industrial applications, especially focusing on processability. Assessments were conducted using a computer numerical control (CNC) milling apparatus, involving a spectrum of cutting parameters: varying cutting speeds (150-225-300 m/min), feed rates (0.15-0.225-0.3 mm/rev), and diverse cooling/lubrication conditions (dry-minimum quantity lubrication-liquid nitrogen). The experimental framework was meticulously structured based on the Taguchi L_{18} orthogonal array, which was further validated through a comprehensive analysis of variance (ANOVA) at a 95% confidence level. Throughout the experimentation, crucial machinability parameters such as cutting temperature, flank wear, and surface roughness were meticulously scrutinized. The optimized test outcomes, demonstrating an impressive precision level of 97%, revealed a reduction in machinability by approximately 18%, accompanied by a noteworthy decrease in cutting temperature by 16%, flank wear values by 16%, and surface roughness by 25%. Overall, the findings elucidate that the cooling/lubrication conditions significantly dictated the machinability parameters during the experimental trials. The empirical evidence extracted from these experiments emphatically suggests the potential utilization of the novel Al-3Gr composites, signifying a promising avenue for their widespread integration within industrial domains.

Keywords: Al-3Gr composites, milling, cooling/lubrication, design of experiments, machinability

ÖZET

Bu araştırmanın temel amacı, son dönemde geliştirilen Al-3Gr bazlı hibrit kompozitlerden elde edilen çeşitli türevleri titizlikle değerlendirmek ve özellikle işlenebilirlik konusuna odaklanarak endüstriyel uygulamalara yönelik eksiklikleri tamamlamaktır. Değerlendirmeler, çeşitli kesme parametrelerini içeren bir bilgisayar sayısal kontrol (CNC) frezeleme aparatı kullanılarak gerçekleştirildi: değişen kesme hızları (150-225-300 m/dak), ilerleme hızları (0,15-0,225-0,300 mm/dev) ve çeşitli kesme parametreleri soğutma/yağlama koşulları (kuru-minimum miktarda yağlama-sıvı nitrojen). Deneysel çerçeve, % 95 güven seviyesinde kapsamlı bir varyans analizi (ANOVA) yoluyla daha da doğrulanan Taguchi L_{18} ortogonal dizisine dayalı olarak titizlikle yapılandırılmıştır. Deney boyunca kesme sıcaklığı, yan aşınma ve yüzey pürüzlülüğü gibi önemli işlenebilirlik parametreleri titizlikle incelendi. % 97'lik etkileyici bir hassasiyet düzeyi sergileyen optimize edilmiş test sonuçları, işlenebilirlikte yaklaşık % 18'lik bir azalmanın yanı sıra kesme sıcaklığında % 16, yan aşınma değerlerinde %16 ve yüzey pürüzlülüğünde % 25 oranında

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kayda değer bir azalma olduğunu ortaya çıkardı. Genel olarak bulgular, soğutma/yağlama koşullarının deneysel denemeler sırasında işlenebilirlik parametrelerini önemli ölçüde belirlediğini ortaya koyuyor. Bu deneylerden elde edilen ampirik kanıtlar, yeni Al-3Gr kompozitlerinin potansiyel kullanımını açıkça ortaya koymakta ve bunların endüstriyel alanlarda yaygın entegrasyonu için umut verici bir yol olduğunu göstermektedir.

Anahtar Kelimeler: Al-3Gr kompozitler, frezeleme, soğutma/yağlama, deney tasarımı, işlenebilirlik

GİRİŞ

The need for quality products can only be met by using new materials with more functional and advanced features. Today, composite materials with different main matrices meet this advanced material requirement rather than traditional materials. In this context, metal matrix composites (MMC) (Usca et al., 2022; Ramanathan et al., 2019; Taskin, et al., 2008) especially polymer (Tuloup et al., 2019; Benzait & Trabzon, 2018; Maiarù, D'Mello & Waas, 2018) and ceramic matrix composites (Yıldırım et al., 2019; Du et al., 2018) are widely studied by researchers in terms of their structural properties and their use in many fields (Usca et al., 2022; Oguntuyi et al., 2021; Sozhamannan et al., 2018). Among these structures, aluminum-based metal matrix composites (AMMC) significantly appeal to the aerospace, automobile, and defense industries due to their superior properties (Şap, 2023a; Taşkın & Çalıgülü, 2006). In this context, AMMCs with interesting properties were produced by adding ceramic and carbon-based reinforcements in various proportions to the main aluminum matrix, and many studies were carried out on their properties and application areas (Trinath et al., 2021; Ande et al., 2019; Sharma et al., 2019; Sozhamannan et al., 2018).

Studies on AMMCs have recently shifted from single-reinforced composite materials to hybrid composite structures with multiple reinforcements (Prasad et al., 2014). With more than one reinforcement added to the aluminum metal matrix composites, besides the good properties added by a single reinforcement, the adverse effects on the structure are eliminated with the second reinforcement. Thus, with hybrid reinforcement, it is possible to improve multiple properties of the matrix, not one-way (Kesarwani et al., 2020; Das et al., 2016; Suresh et al., 2014). Although hybrid AMMCs have interesting and superior properties in terms of mechanical, thermal, and electronic properties, their machinability becomes more difficult and complex due to their complex microstructure (Li & Laghari, 2019; Srivastava et al., 2018; Hakami et al., 2016; Gopalakannan & Senthilvelan, 2013). Numerous investigations within this domain have focused on delineating the output metrics encompassing tool life, tool wear, surface roughness, and cutting temperature after machining Metal Matrix Composites (MMCs). These studies meticulously designate feed rate, cutting speed, depth of cut, and cooling/lubrication conditions as pivotal input parameters for comprehensive analysis (S. Şap et al., 2022; Usca et al., 2022; Cai et al., 2021; Hakami et al., 2016). As an example of these studies, Ozben et al. (2008) investigated the effect of reinforcement ratio on the process parameters and mechanical properties by adding 5%, 10%, and 15% SiC_p' to the aluminum metal matrix. Empirical findings from experiments indicate a direct correlation between the augmentation of reinforcement ratio and enhanced mechanical characteristics, specifically elevating toughness, tensile strength, and hardness. However, this elevation concurrently induces heightened surface roughness and tool wear during machining operations, influenced notably by spindle speed and feed rate adjustments. Similarly, an independent study highlighted the substantial impact of SiC reinforcement volume ratio on tool wear, demonstrating a consistent escalation in wear as the percentage of reinforcement increased (Muthukrishnan & Davim, 2011). As the SiC ratio in the structure increases, it is stated that the particles with high kinetic energy will increase the wear by hitting the tool tip surface due to the increase in the contact surface between the SiC particles and the cutting edge (Bhushan, 2013). In another study, it was stated that SiCp-reinforced aluminum composites should be processed at higher cutting speeds to obtain better-machined surface quality (Muthukrishnan et al., 2008).

To obtain a good machined surface quality, it is important to use a good coolant as well as to determine the optimum cutting parameters (Jadhav & Mohanty, 2022). Although some dry machining studies are in the literature, high cutting forces and high temperatures in dry machining limit the application area (Zou et al., 2021). For this reason, cutting fluid is often needed. Cutting fluids serve a dual purpose in machining processes, functioning not solely as coolants but also as agents facilitating friction reduction through lubrication while effectively clearing chips within the cutting zone. This multifaceted role significantly contributes to elongating tool lifespan and enhancing the overall surface quality of machined components (Yıldırım et al., 2019). Choosing the proper cooling/lubrication is very important when using cutting fluid. In machining with conventional cutting fluids, the cutting tool costs cover 2-4% of the total machining cost, while the total costs of cutting fluids in machinability are considerably higher than the cutting tool

(Amiril et al., 2017; Gajrani et al., 2019). For all these reasons, there is a need for new cooling and lubricating fluids that will overcome the disadvantages of traditional cutting fluids, such as high cost, worker and environmental health problems, and problems in dry machining. This requirement is met by cryogenic cooling, minimum quantity lubrication (MQL), and cryogenic minimum quantity lubrication (CMQL), also known as semi-dry machining recently (Mia et al., 2019; Jawahir et al., 2016; Ahmad-Yazid et al., 2010; Dhar et al., 2007; López de Lacalle et al., 2006). In the MQL method, as the name suggests, the minimum amount of cutting fluid consumed compared to the traditional cooling method ensures that the machining is performed with both more economical and better cutting performance (Kim et al., 2016; Fratila & Caizar, 2011). In addition to the costs, the minimal amount of cutting fluid ensures that environmental and human health damage is prevented or minimized (Thepsonthi et al., 2009). While thermal crack formation in the cutting tool is possible in the traditional cooling method, it is rarely seen in the MQL method. Therefore, the tool life is longer (Liao and Lin, 2007). Another important cutting fluid used in this field is cryogenic fluids. The cryogenic cooling media most commonly used as cutting fluid are liquid nitrogen (LN_2) (S. Şap, 2023b), liquid carbon dioxide (LCO_2) (Shah et al., 2020), cold air, and supercritical carbon dioxide ($scCO_2$). Cryogenic coolants offer a secure, cost-effective, and environmentally conscious cooling solution, presenting ease in preparation and storage at ambient room temperatures. This cooling method ensures safety, affordability, and eco-friendliness while allowing convenient handling and storage without requiring specialized conditions (Yuan et al., 2018). Due to these features, they have been the subject of many studies.

Hence, the primary focus of this study involved an examination of the milling process applied to Al-3Gr-based hybrid reinforced composites, analyzing their response to varied cutting speeds, feed rates, and distinct cooling/lubrication (C/L) conditions. Three different environments were chosen as the cooling/lubricating medium: dry, MQL, and LN_2 cooling techniques. The effects of machinability parameters such as reinforcement ratio, cutting speed, and feed rate on surface roughness, tool wear, and cutting temperature were investigated in detail. In addition, it was aimed to find the optimum machinability parameters (AMMC type, cutting speed, feed rate, and C/L condition) of Al-3Gr-based hybrid reinforced composites. During the process of determining the most effective parameters, machinability assessments were conducted using the Taguchi method. This approach aimed to decrease the number of experiments, eliminate the need for time-consuming trial and error cycles, and lower the expenses associated with conducting experiments. This work aims to find the optimal processing parameters for a novel hybrid AMMC that has not been previously documented in the literature. It will be possible to use it in many industrial areas.

MATERIAL AND METHODS

Test Materials

Metal and ceramic powder particles such as Al, Gr, SiC, and BN required for manufacturing composite materials were obtained from Nanokar (Istanbul, Turkey). The powders supplied are of high purity. Some properties of related powders are given in Table 1.

Table 1. Characteristics of Powders Utilized in Composite Manufacturing (Şap et al., 2023)

Powders	**Density (g/cm^3)**	**Melting temperature (°C)**	**Particle size (µm)**	**Purity (%)**
Al	2.71	660	45-75	≥ 99.90
Gr	2.26	3652	≤ 44	≥ 98.00
SiC	3.21	2830	45-70	≥ 98.00
BN	2.1	2973	≤ 10	≥ 99.00

After the powders were supplied, six different composites based on Al-3Gr by mixing in the desired ratio were produced under the hot press with the powder metallurgy method. These six composites and their contents are given below, respectively.

i. Al-3Gr (97 wt.% Al + 3 wt.% Gr),
ii. Al-3Gr/6SiC (91 wt.% Al + 3 wt.% Gr + 6 wt.% SiC),
iii. Al-3Gr/6BN (91 wt.% Al + 3 wt.% Gr + 6 wt.% BN),
iv. Al-3Gr/1.5SiC-1.5BN (94 wt.% Al + 3 wt.% Gr + 1.5 wt.% SiC + 1.5 wt.% BN),
v. Al-3Gr/3SiC-3BN (91 wt.% Al + 3 wt.% Gr + 3 wt.% SiC + 3 wt.% BN),
vi. Al-3Gr/6SiC-6BN (85 wt.% Al + 3 wt.% Gr + 6 wt.% SiC + 6 wt.% BN)

The vacuum hot press machine, Zhengzhou Golden Highway, used to produce composites after mixing the relevant powders, is an SMVB80 brand and PLC (Programmable Logic Controller) controlled hot press unit. The pressure and temperature values used during production are 35 MPa and 530 °C, respectively. The dimensions of the composite test specimens obtained after production are 40 mm long, 40 mm wide, and 8 mm thick.

Machining parameters

The experiments to analyze the machinability of the produced AMMCs were carried out on a DAHLIH MCV-860 model CNC Milling machine. AlTiN-coated ISO 13399 tool bits were used for cutting.

Table 2. Some Properties of Cutting Tool

Cutting tool geometry	**Cutting tool diameter**	**Tool clamping length**	**Number of insert**	**Insert width**	**Insert length**	**Insert radius**	**Insert materials**	**Milling type**
APKT 1003	12 mm	80 mm	1	6.76 mm	11.45 mm	0.8 mm	Al-Ti-N-W-Co-Cr-Ni	down milling

As cutting parameters, three different cutting speeds and three different feed rates were used as variable parameters, while a fixed value of 0.75 mm was chosen for the cutting depth. Milling was carried out in the experiments by applying a "Zig" toolpath. The cutting parameters were established by taking into account the suggested operating range provided by the manufacturer of the cutting instrument. Details of 6 different composites and three different cooling conditions, cutting speed and feed rate, and test levels used in the experiments are given in Table 3. The experiments were repeated three times to obtain more accurate results.

Table 3. Parameters and Tiers of CNC Milling

Milling parameters		**A-MMC type**	**B-Cooling conditions**	**C-Cutting speed, (V_c)**	**D-Feed rate, (f)**
	Unit	-	-	m/min	mm/rev
Levels	1	(1) Al-3Gr	Dry	150	0.150
	2	(2) Al-3Gr/6SiC	MQL	225	0.225
	3	(3) Al-3Gr/6BN	Cryo	300	0.300
	4	(4) Al-3Gr/1.5SiC-1.5BN	-	-	-
	5	(5) Al-3Gr/3SiC-3BN	-	-	-
	6	(6) Al-3Gr/6SiC-6BN	-	-	-

The study implemented machinability trials under three environmentally-conscious conditions: dry machining, pure Minimum Quantity Lubrication (MQL), and cryogenic liquid nitrogen (cryo-LN_2) application. The objective centered on assessing the influence of different cooling and lubricating mediums on both the cutting tool and the workpiece throughout the machining process. For the cryogenic cooling procedure, liquid nitrogen stored in a Taylor Wharton LD-35 tank of 35-liter capacity was utilized, maintaining a temperature of -196°C. The spray pressure was calibrated to 8 bar, with a flow rate set at 20 L/h. The MQL approach utilized Cuttex Syn 5 as a cutting fluid, administered onto the cutting tool and workpiece via compressed air through a potentiometer-controlled Werte Micro Stn-15 model system. The MQL liquid is administered in comparable circumstances to the cutting zone in order to provide an accurate comparison with the cryogenic liquid. A 5 mm diameter nozzle facilitated the delivery of pressurized oil into the cutting zone, aligning with the prescribed operating ranges advised by the manufacturer. A schematic depiction exemplifying the intricate details of the experimental setups can be observed in Figure 1.

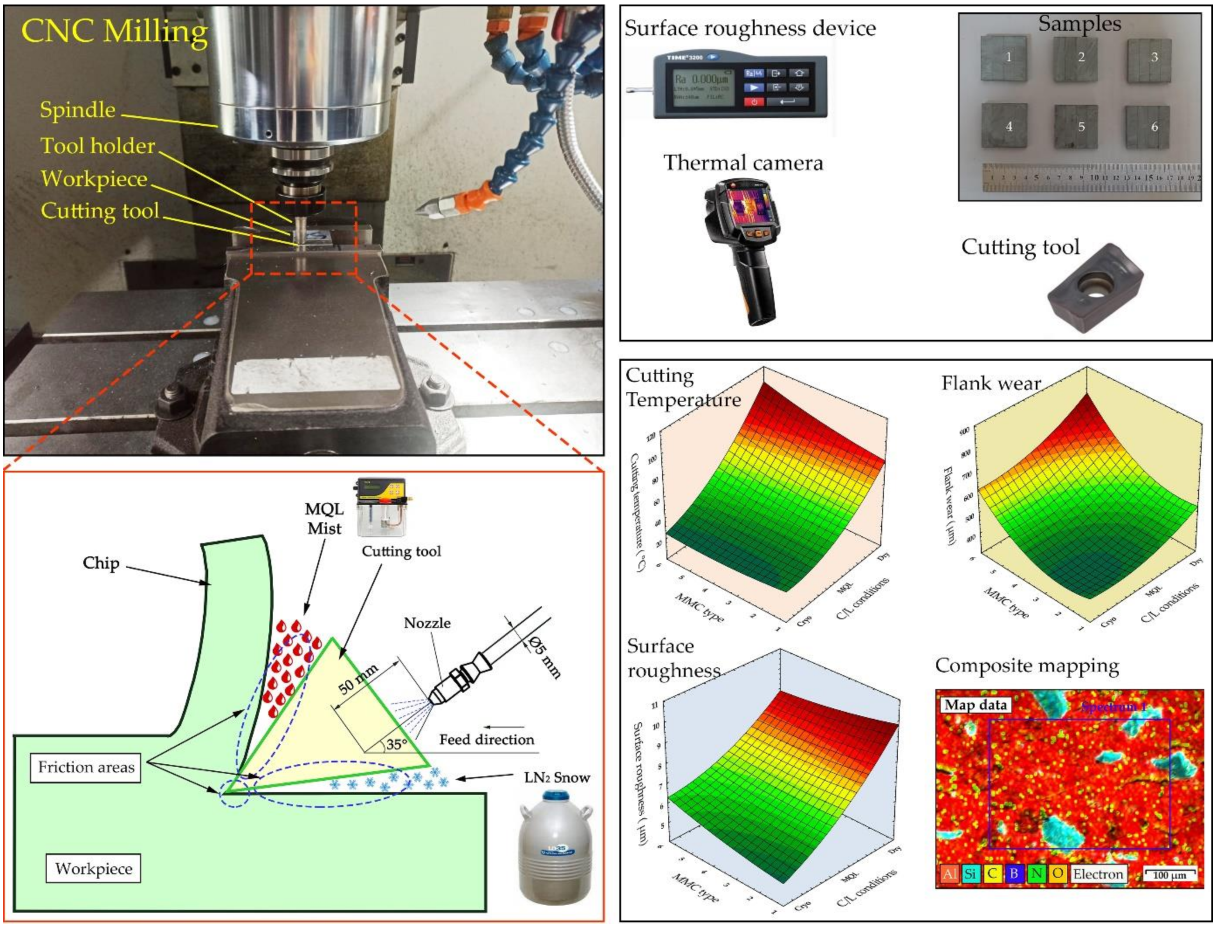


Figure 1. Schematic Representation of The Experimental System

The assessment of cutting temperatures employed the testo-871 model thermal camera, specifically designed to measure temperatures up to 650 °C with a resolution of 240x180 pixels. Measurements were conducted precisely in the final phase before the cutting tool disengaged from the workpiece. Additionally, surface roughness, a pivotal indicator of machined component quality, was gauged using the TIME3200 test device. In the industry, the Ra parameter was generally preferred because it is more preferred in controlling and improving production quality in production processes (Uzun et al., 2022). While performing the measurements, the reference measurement values of the manufacturer were taken into account. Furthermore, the tests were conducted promptly after the machining process, ensuring that the measurement data were not influenced by surface oxidation. Additionally, each sample was subjected to six repeated measurements. Flank wear measurements were conducted using a JEOL JSM 6510 type scanning electron microscope (SEM) instrument. The measurements were conducted according to ISO standards, considering the region of the cutting tool that showed the highest wear.

Taguchi Method

To ascertain the optimal cutting configurations significantly influencing surface roughness, flank wear, and cutting temperature outputs in hybrid AMMC machining, machinability tests were executed utilizing the Taguchi L_{18} orthogonal array. The employment of this array methodology markedly reduces the number of requisite tests, thereby curtailing associated expenses and time commitments. Its prevalent application lies in evaluating outcomes stemming from studies featuring designated variables. Taguchi's framework delineates product and process design quality across three discrete phases: system design, parameter design, and tolerance design. The milling parameters, encompassing composite type, cutting speed, feed rate, and cooling/lubrication medium, were precisely determined and detailed in Table 4. Through the experimental settings and levels adopted in this investigation, the evident suitability and efficiency of the Taguchi L_{18} orthogonal array emerge as the most optimal choice. The Taguchi method opts for a measurable signal-to-noise (S/N) ratio rather than relying on standard deviation as the primary quality characteristic. This ratio signifies the relationship between the mean (signal) and the standard deviation (noise). Typically, S/N ratio attributes fall into three distinct categories: Lowest best, Highest (large) best, and Nominal best. Within this study, the smallest value best option was utilized for all response parameters. The computation of S/N ratios is facilitated through the utilization of Equation (1).

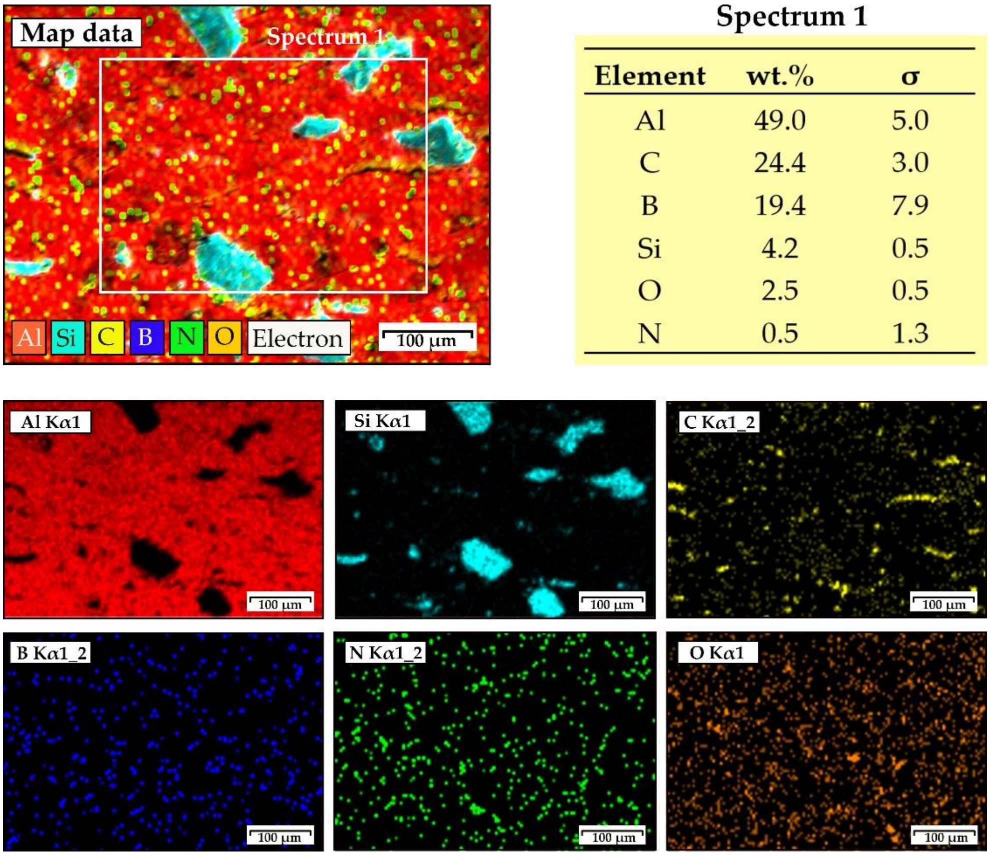
$$\frac{S}{N} = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} (z^2)\right) \tag{1}$$

In this context, “z” denotes the response parameters, specifically flank wear, surface roughness, and cutting temperature. “n” signifies the repetition count for the test conditions, while “i” represents the individual repetition instances within this count.

RESULTS AND DISCUSSION

Assessment of Composite Fabrication

Al-3Gr hybrid composite and its five different versions were milled in macro size. Figure 2 shows an SEM microstructure and mapping analysis for MMC Type 6. These techniques are critical for understanding and evaluating materials' microstructural properties, performance, and manufacturing processes. Upon examination of the scrutinized microstructure, a uniform dispersion of reinforcement particles within the primary matrix was noted. The red color represents the Al main matrix. Another element of the hybrid main matrix, Gr, is shown in yellow as element C. SiC particles with a coarse structure are indicated in light blue. In BN reinforcements, the B element is dark blue, and the N element is green.



Spectrum 1

Element	wt.%	σ
Al	49.0	5.0
C	24.4	3.0
B	19.4	7.9
Si	4.2	0.5
O	2.5	0.5
N	0.5	1.3

Figure 2. SEM Microstructure, EDS, and Mapping Analysis for MMC Type 6

Upon scrutiny of Figure 3, it becomes evident that the reinforcement elements exhibit a homogeneous distribution across the primary matrix. Professional mixing of powder particles before production is very important in this respect. Whether or not the reinforcing elements are distributed homogeneously significantly affects the milling process. It is known that reinforcement elements seriously affect the cutting tool (Şap et al., 2022). Therefore, an inhomogeneous distribution can lead to inaccurate results for the cutting tool and machinability metrics. It can be observed that the amount of porosity in the material is reduced to a minimum with the effect of hot sintering with a vacuum. As a result, the mapping indicates that the material has a uniform distribution and a strong interfacial bond. A study has shown that the homogeneous microstructure of MMC materials contributes to the increase in machinability performance (Değirmenci et al., 2023).

Assessment of Cutting Temperature

Controlling the cutting temperature is very important in the milling process. Providing the correct cutting temperature can offer significant benefits to outputs such as tool life, workpiece quality, process efficiency, and material performance (Şap et al., 2021). Figure 3 presents the graph of the effects of different cutting parameters (V_c, f_n, and C/L conditions, respectively) on the cutting temperature for each MMC type obtained as a result of the experiments. The cutting temperature outcomes exhibit distinct characteristics corresponding to each type of MMC. An observable trend indicates a decrease in cutting temperature with the escalation of reinforcement components and ratios at lower cutting speeds. However, this pattern reverses at higher cutting speeds. Notably, under high cutting and feed rates, there's a likelihood of surface degradation in the composite material, potentially leading to surface defects. In addition, high cutting speeds can increase plastic deformations in the material. Therefore, there may be an increase in cutting temperatures. (Samy et al., 2017). It was observed that the feed rate, which does not affect the cutting temperature as much as the cutting speed, affects the cutting temperature differently for MMC types, similar to the cutting speed.

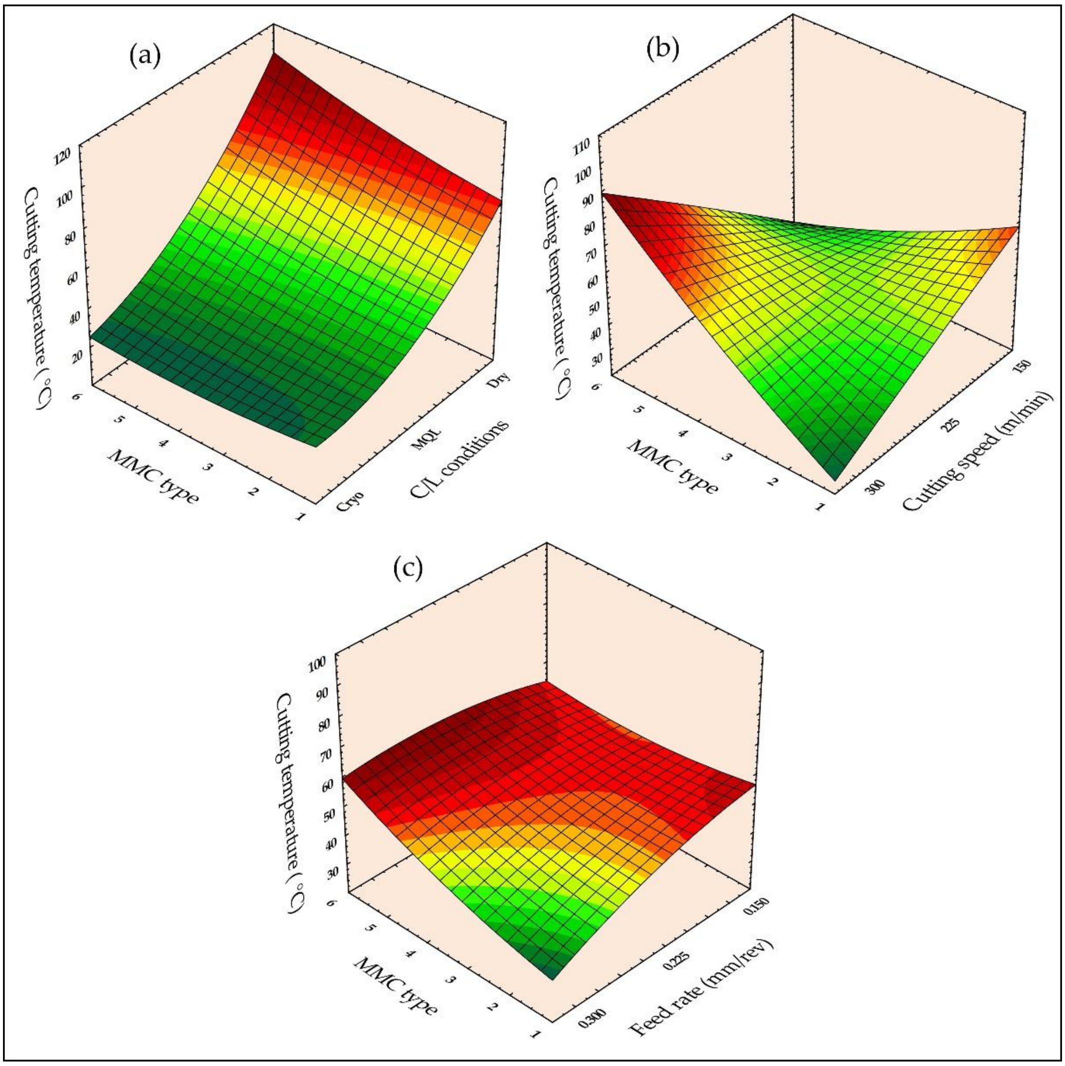


Figure 3. Effect of Different Parameters on Cutting Temperature for MMC Types

Since milling operations in soft materials are performed better at higher cutting speeds, an easier cutting environment is created for MMC types with no reinforcement component and less reinforcement component ratio. This helps to lower the cutting temperature. Furthermore, it is plausible to assert that augmenting the feed rate contributes to a reduction in cutting temperature by diminishing the duration of contact between the material and the cutting tool (Şap et al., 2022). Finally, C/L environments can be seen to have a standard effect. Thanks to its high cooling capability, it has been observed that cryo LN_2 plays an active role in the milling of all MMC types. In addition, the results showed that the MQL medium could be used during the machinability of hybrid composites. A study has shown that cryogenic cooling can reduce high temperatures to more reasonable levels, thanks to a significantly lower freezing point than an MQL environment (Hong et al., 2001). Unlike other conditions, high temperatures were obtained for all MMC types in dry milling operations. The importance of cryo LN_2 and MQL environment in the machinability of hybrid MMCs was revealed as a result of the study. Figure 4 presents thermal images and corresponding temperature distribution graphs illustrating samples processed under various C/L conditions.

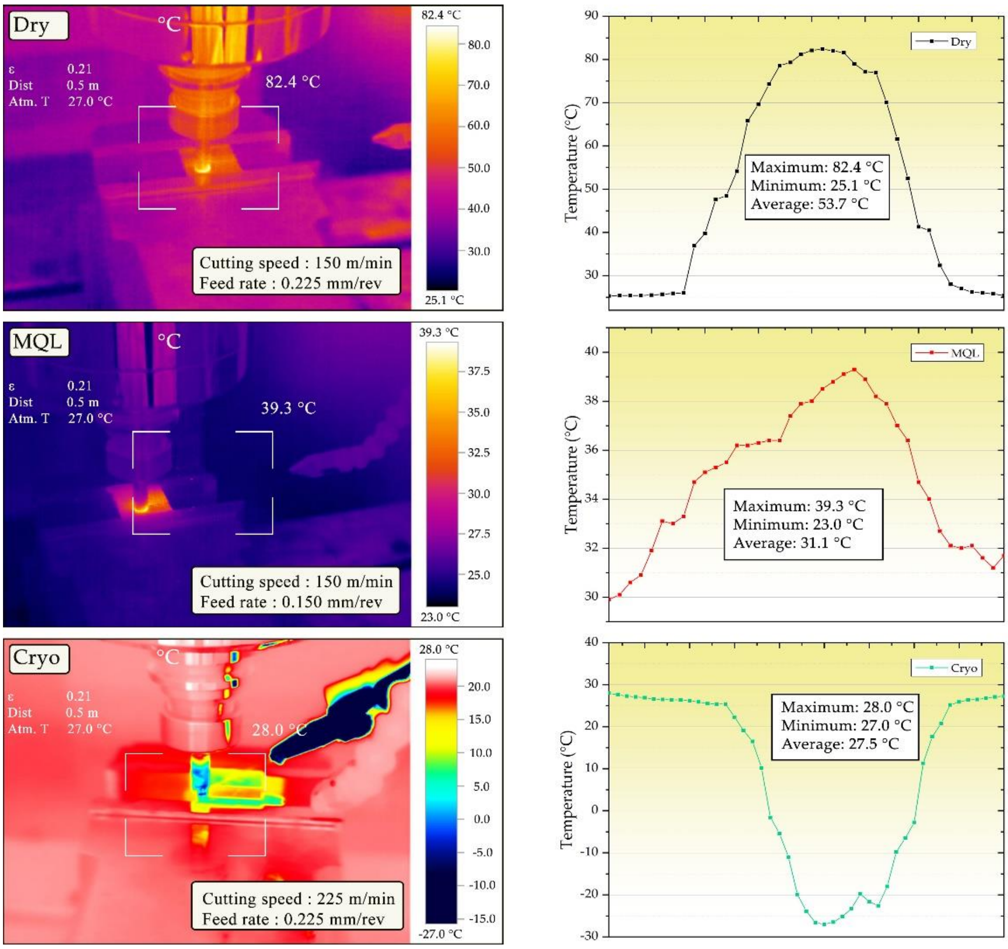


Figure 4. The Thermal Images and Temperature Distribution Graphs Depict The Samples Processed under Distinct C/L) Conditions

Assessment of Cutting Tool Wear

Wear and deformations on the cutting tools during the milling of materials are important factors in workpiece quality and machining performance. This factor is directly related to cutting tool life, machinability metrics, surface quality, and machining cost (Korkmaz & Günay, 2018). Understanding and optimizing wear can increase machining efficiency, improve surface finish, and reduce machining costs (Babu et al., 2022). Figure 5 shows the machinability parameters' effect on the flank wear value according to different composite material types. With an escalation in both reinforcement ratio and type within composite materials, the influence of cutting speed on flank wear becomes more pronounced. Overall, a discernible trend emerged indicating a direct correlation between increased cutting speed and heightened flank wear values. Literature studies have confirmed this phenomenon (Şap et al., 2022). It can be seen in Figure 7 that the highest amount of wear on the cutting tool will occur at high cutting speed and MMC type 6. It was observed that the feed rate change for different MMC types does not significantly affect flank wear. However, although the change in feed rate with increasing type and amount of reinforcement provides a visible change, this is not valid for MMC without supplement and MMC with single reinforcement. In addition, it can be said that there is a slight decrease in V_b with the increase in the feed rate. Dry-cutting conditions offer lower performance compared to cryogenic and MQL (Laghari et al., 2023). In this study, this conclusion was confirmed for all MMC types. Furthermore, an observation surfaced indicating that as the level of MMC type escalated, the efficacy of cryogenic C/L conditions proved more pronounced in regulating V_b (flank wear) to a lower magnitude. The utilization of cryogenic cooling, existing in a liquid state at exceptionally low temperatures, evidently plays a substantial role in mitigating tool wear by minimizing the surface friction coefficient between the cutting tool and the workpiece (Courbon et al., 2013).

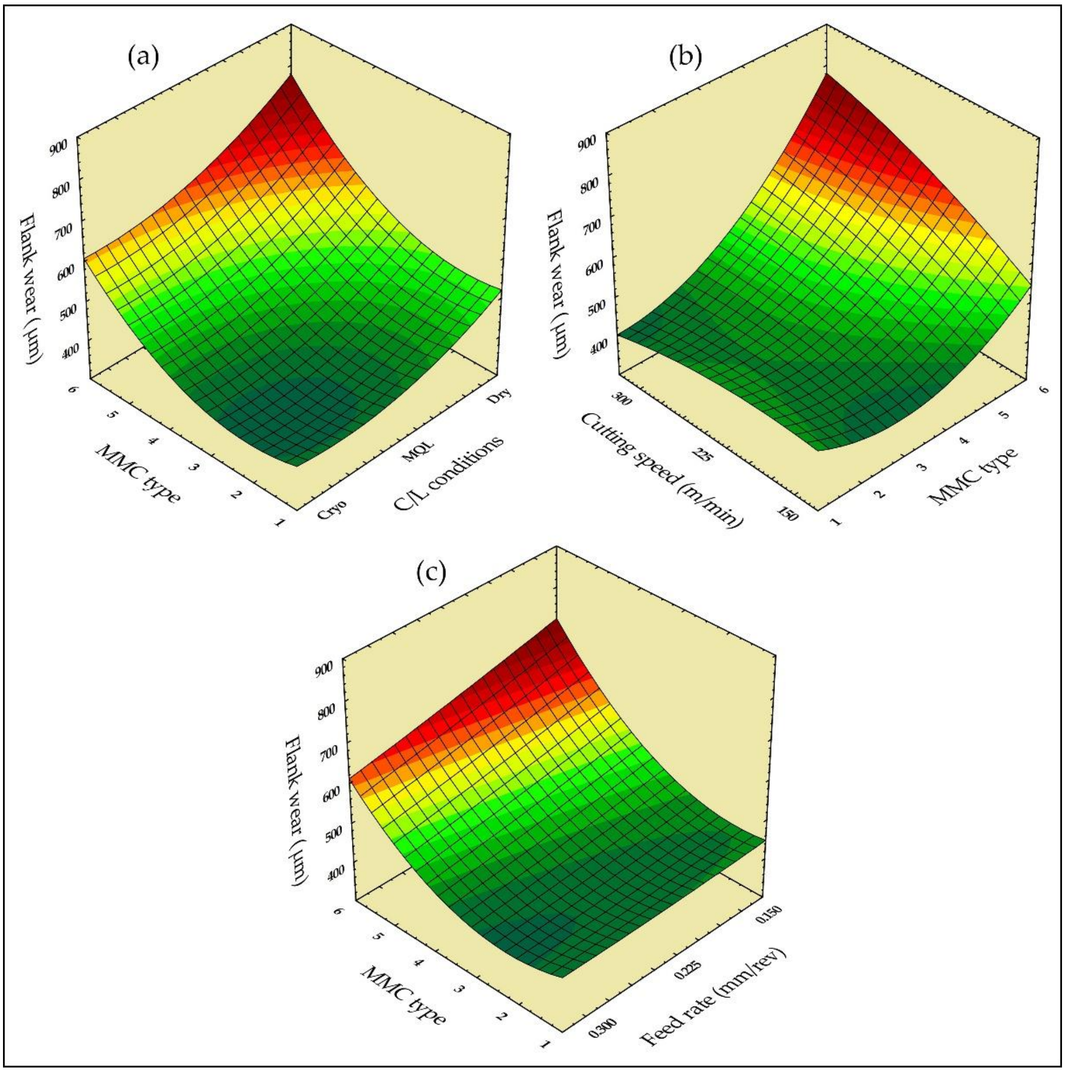
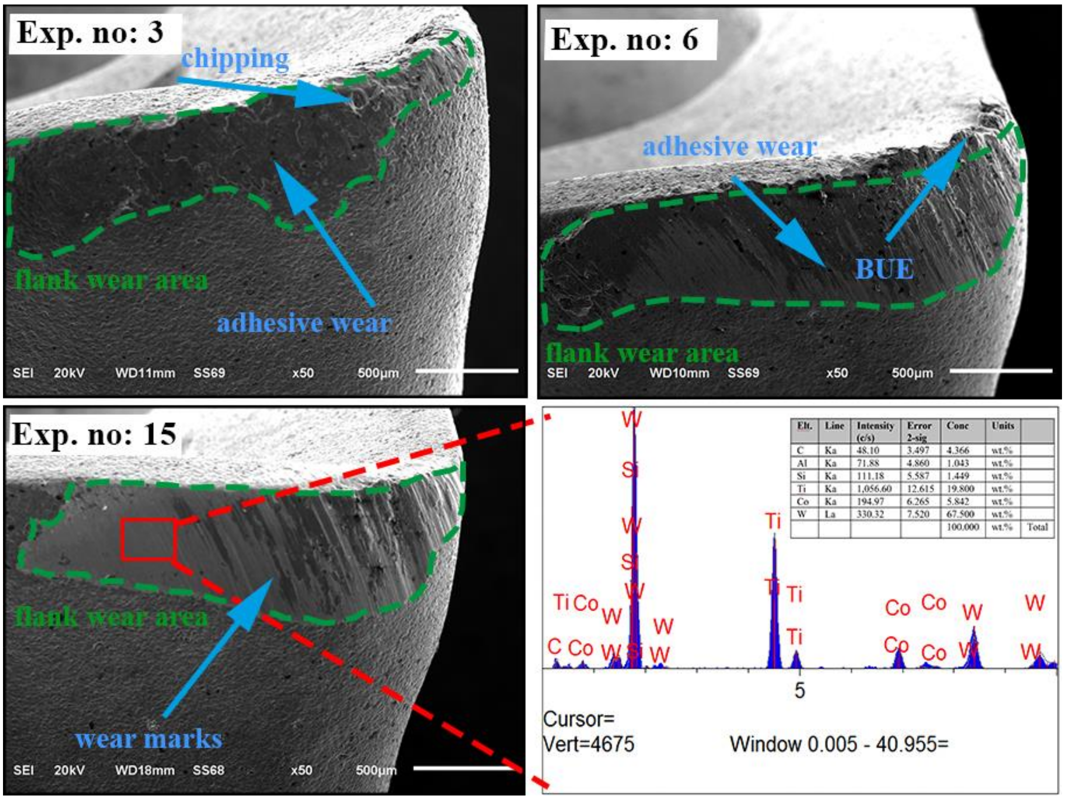


Figure 5. The Effect of Different Parameters on Flank Wear for MMC Types

It is very important to know the type of wear on the cutting tool in terms of tool life and machining efficiency (Babu et al., 2022). Figure 6 presents an SEM-EDS analysis examining the wear mechanism for inserts from different experiments. In addition, flank wear areas occurring in the cutting tool flank area are also shown openly. In general, chipping, BUE (built-up edge), and adhesive wear tool wear mechanisms were found in cutting tools. Nevertheless, it can be asserted that the predominant wear mechanisms observed are adhesion wear and BUE. Figure 7 represents the baseline mapping analysis for experiment 6. Experiment no. 6 was carried out with Al-3Gr/6SiC material in a dry environment at 300 m/min cutting speed and a feed rate of 0.3 mm/rev. When the cutting tool used for the experiment was examined, adhesive wear and BUE formation were observed. The presence of adhesive wear was revealed by SEM-EDS mapping (Figure 7). At higher cutting speeds, friction increases. This causes soft workpiece material to stick to the tool surface, resulting in adhesion wear. In Figure 6 (Exp. no: 6), W-Co-Ni-V represents the tool base material, Al-Ti-N tool coating, and Al-Si-C represents the elements of the MMC type 2 workpiece. Another mechanism seen in Figure 6 is clearly seen as BUE. High cutting speeds (300 m/min) increase friction, increasing the risk of BUE. In addition, excessive friction and a dry machining environment increase the temperature excessively, which can lead to BUE formation. A study supports the current situation. Experiments 3 and 15 in Figure 6 show that BUE formation can be reduced by using appropriate lubrication and cooling methods.



Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units	
C	Ka	48.10	3.497	4.366	wt.%	
Al	Ka	71.88	4.860	1.043	wt.%	
Si	Ka	111.18	5.587	1.449	wt.%	
Ti	Ka	1,056.60	12.615	19.800	wt.%	
Co	Ka	194.97	6.265	5.842	wt.%	
W	La	330.32	7.520	67.500	wt.%	
				100.000	wt.%	Total

Figure 6. The Effect of Different Parameters on Flank Wear for MMC Types

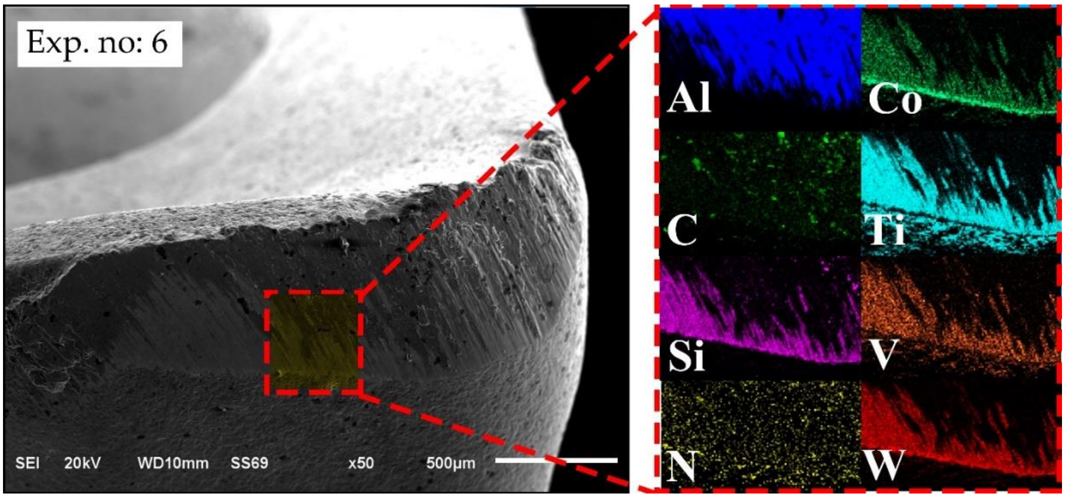


Figure 7. The Effect of Different Parameters on Flank Wear for MMC Types

Surface Roughness of Workpieces

The surface roughness parameter (R_a) stands as a pivotal factor delineating the finished workpiece's surface quality, holding significant importance within the industry, as highlighted in reference (Şap et al., 2021). As depicted in Figure 8, the impact of various machinability parameters on surface roughness concerning MMC types is showcased. Remarkably, the most favorable surface roughness value of 4.835 µm was achieved under specific conditions: high cutting speed (300 m/min), low feed rate (0.15 mm/rev), and machining executed within a cryogenic environment. The escalation in cutting speed notably augmented the temperature within the cutting zone, inducing a softening effect on the composite material. Consequently, the occurrence of BUE on the cutting tool diminished, consequently extending the cutting tool's lifespan, as elucidated in reference (Babu et al., 2022). Consistent with the literature (Binali et al., 2023; Salur, 2022), the progression speed exhibited a corresponding effect on surface roughness, demonstrating a decrease as the feed rate increased. Evidently, the advantage of cryogenic machining in enhancing surface quality across all MMC types was evident. Liquid nitrogen facilitated an endothermic reaction, fostering superior lubrication at the tool-workpiece interface, thereby minimizing friction at adequately lubricated interfaces.

This preventive action against BUE formation further bolstered superior surface quality compared to alternative C/L conditions, aligning with reference (Salvi et al., 2023; Kouam et al., 2015). Moreover, under MQL conditions, milling engenders the formation of a hydrodynamic oil film between the tool and the workpiece, amplifying its active role in milling operations compared to dry machining.

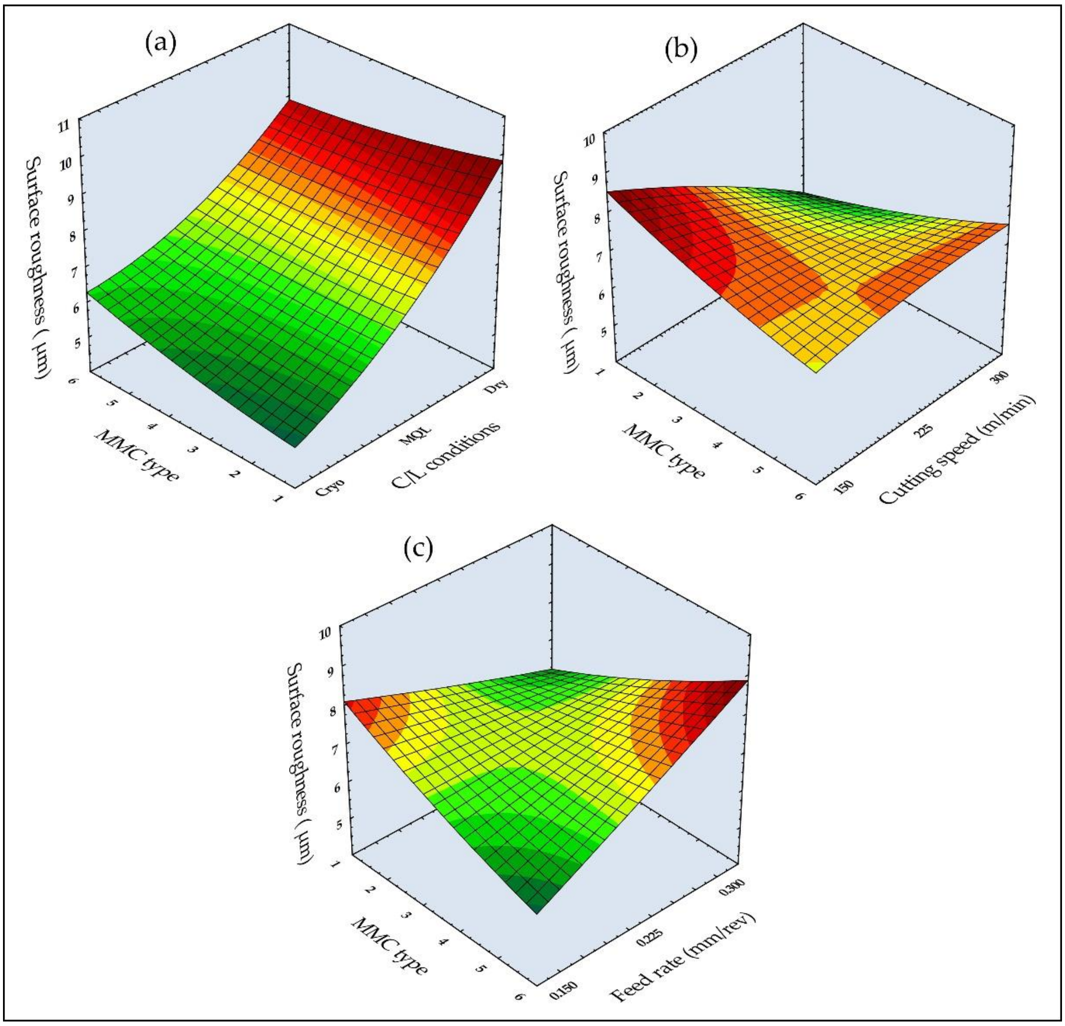


Figure 8. Effect of Different Parameters on Surface Roughness for MMC Types

Statistical Evaluation

The assessment of material machinability metrics was conducted through the application of the Taguchi method, specifically tailored to analyze the experimental materials (Küçük et al., 2017). The preference for the smallest S/N ratio was indicative of superior machinability metrics, hence this criterion was adopted for the examination. To ensure robustness and reproducibility, the experiments were meticulously conducted in triplicate, with subsequent averaging of the attained results. A comprehensive summary of the test outcomes in accordance with the Taguchi L_{18} design is detailed in Table 4. Figure 9 illustrates the primary effect plots, derived through the transformation of response parameters into the S/N ratio. Upon scrutinizing the conditions conducive to achieving optimal cutting temperature, it became evident that a configuration involving low cutting speed, elevated feed rate, and the implementation of a cryogenic cooling environment was notably effective. Notably, high cutting speeds have been established in the literature (Aslan et al., 2022) as a potential cause for increased cutting temperature. Furthermore, it was observed that MMC type 2 exhibited the lowest cutting temperature, while types 5 and 6, characterized by heightened reinforcement type and quantity, manifested the highest cutting temperatures. The formulation denoted as $A_2B_1C_3D_3$ yielded the optimum cutting temperature for the fabricated materials, yet it was discerned from the S/N ratios that the cooling/lubrication (C/L) environment emerged as the most influential parameter. Parallel to the cutting temperature, surface roughness analyses revealed that optimal surface roughness values were achievable through high cutting speed, low feed rate, and the utilization of a cryogenic cooling environment. Specifically, MMC type 3 exhibited the lowest surface roughness values among the diverse MMC types. Similar to cutting temperature, the C/L environment was identified as the parameter exerting the most significant influence on surface roughness values. Consequently, it can be inferred that the most favorable surface roughness formulation corresponds to $A_3B_3C_1D_3$.

Table 4. Experiment Results for Taguchi L_{18} Orthogonal Design

Exp. No	**MMC Type**	**C/L condition**	**Cutting speed, V_c (m/min)**	**Feed rate, f_n (mm/rev)**	**Cutting temperature, T_c (°C)**	**Flank Wear, V_b (mm)**	**Surface roughness, R_a (µm)**
1	1	Dry	150	0.150	74.1	456	9.382
2	1	MQL	225	0.225	44.2	403	6.821
3	1	Cryo	300	0.300	29.2	381	5.215
4	2	MQL	150	0.150	39.3	466	6.768
5	2	Cryo	225	0.225	28.0	431	6.037
6	2	Dry	300	0.300	71.1	572	8.741
7	3	Dry	150	0.225	82.4	442	9.162
8	3	MQL	225	0.300	39.6	384	7.024
9	3	Cryo	300	0.150	25.7	429	4.835
10	4	Cryo	150	0.300	24.6	363	6.417
11	4	Dry	225	0.150	89.3	571	8.496
12	4	MQL	300	0.225	41.2	507	6.654
13	5	Cryo	150	0.225	24.7	460	6.058
14	5	Dry	225	0.300	79.2	624	8.963
15	5	MQL	300	0.150	63.3	581	6.209
16	6	MQL	150	0.300	42.8	565	7.891
17	6	Cryo	225	0.150	29.8	688	5.997
18	6	Dry	300	0.225	98.9	783	8.071

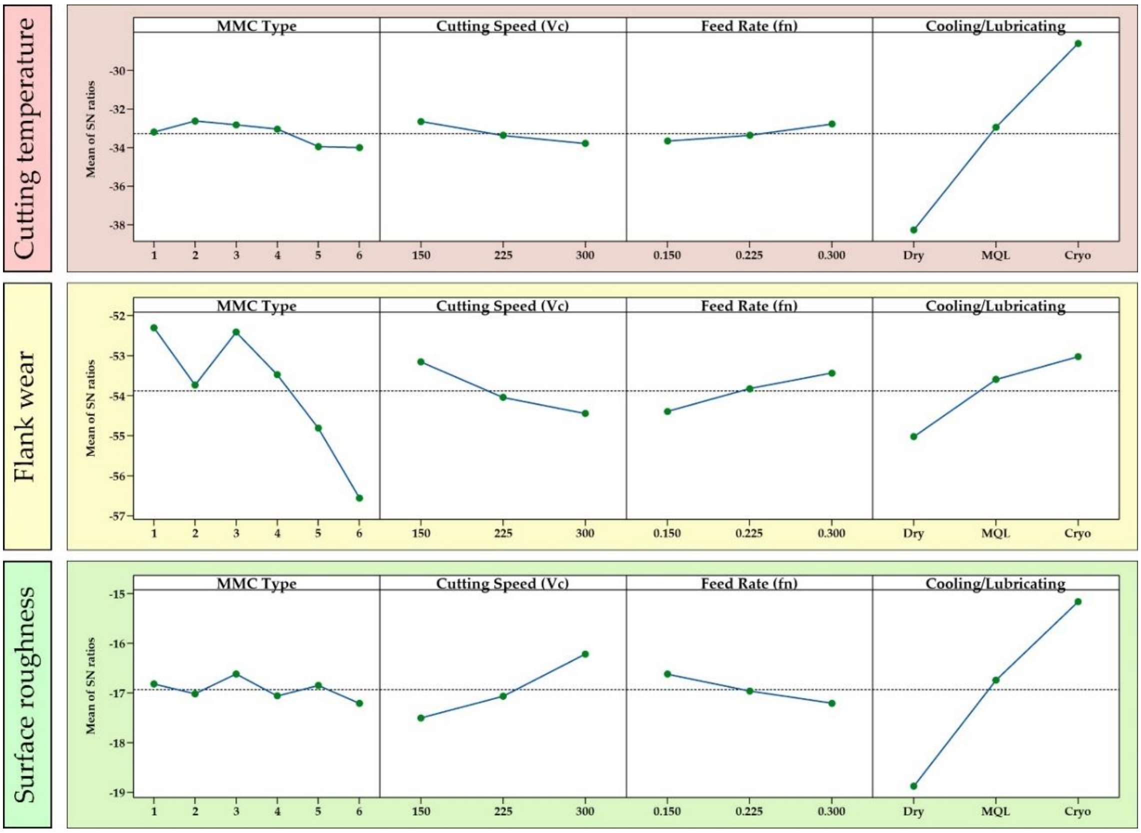


Figure 9. S/N Ratios of Different Parameters of Taguchi Analysis

Upon analyzing the flank wear observed in the cutting tool, a distinct trend emerged indicating an escalation in V_b values under conditions of high cutting speed coupled with low feed rate. The augmentation in cutting speed was noted to contribute to heightened plastic deformation, while the reduced feed rate extended the duration of tool-material interaction. Therefore, an increase in V_b values can be observed. Optimum wear values were determined in MMC type 1, low cutting speed, high feed rate, and cryogenic C/L environment. Due to the fact that MMC type 1 material does not contain reinforcement particles, it can be said that the amount of wear after milling is lower than other materials. $A_1B_1C_3D_3$ formulation can be determined as the optimum wear value formulation.

The study scrutinized the influence of machinability parameters on the outcomes through an Analysis of Variance (ANOVA) performed at a 95% confidence level. The P value helps to determine the significance of the data among the factors examined. For a factor to be significant, its P value must be <0.05. ANOVA analysis and Taguchi analysis help to statistically evaluate the effect of factors affecting the machinability of these materials. From this point of view, when Table 5 is examined, it can be said that the most important factor for cutting temperature is C/L conditions (90.84%). When the wear on the cutting tool is examined, it is seen that all machinability parameters are significant for this metric. It can be said that the most significant factors for this metric are MMC type (65.91%), C/L condition (19.81%), cutting speed (9.78%), and feed rate (3.39%). It was observed that there were two significant factors (C/L condition 86.34% and cutting speed 9.12%) in surface roughness, another machinability metric. In general, the most important factor for the surface roughness is expected to be the feed rate, while the C/L condition for these milled composite materials has been.

Table 5. Experiment Results for Taguchi L_{18} Orthogonal Design

ANOVA for Cutting Temperature

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
MMC Type	5	268.4	2.54%	268.4	53.67	0.75	0.61468
Cutting Speed (V_c)	2	143.8	1.36%	143.8	71.88	1.01	0.42016
Feed Rate (f_n)	2	128.4	1.21%	128.4	64.22	0.9	0.45576
Cooling/Lubricating	2	9615.8	90.84%	9615.8	4807.9	67.25	0.00007
Error	6	428.9	4.05%	428.9	71.49		
Total	17	10585	100.00%				

ANOVA for Flank Wear

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
MMC Type	5	148238	65.91%	148238	29648	71.36	0.00002
Cutting Speed (V_c)	2	21995	9.78%	21995	10997	26.47	0.00106
Feed Rate (f_n)	2	7622	3.39%	7622	3811.1	9.17	0.01497
Cooling/Lubricating	2	44550	19.81%	44550	22275	53.62	0.00015
Error	6	2493	1.11%	2493	415.4		
Total	17	224898	100.00%				

ANOVA for Surface Roughness

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
MMC Type	5	0.1717	0.52%	0.1717	0.0343	0.27	0.91480
Cutting Speed (V_c)	2	2.9982	9.12%	2.9982	1.4991	11.72	0.00847
Feed Rate (f_n)	2	0.5509	1.68%	0.5509	0.2755	2.15	0.19736
Cooling/Lubricating	2	28.372	86.34%	28.372	14.186	110.86	0.00002
Error	6	0.7678	2.34%	0.7678	0.128		
Total	17	32.86	100.00%				

CONCLUSION

In this study, a new AMMC that can be used in the automotive industry, which is not included in the literature, has been produced. Six different ratios of composite materials were successfully produced for these materials to examine the machinability properties. Variable parameters including different cutting speeds (150-225-300 m/min), diverse feed rates (0.15-0.225-0.3 mm/rev), and varied cooling/lubrication (C/L) conditions (dry-MQL-cryo) were considered pivotal in assessing the machinability properties of the materials. To mitigate experimental costs, the Taguchi method was strategically employed, conducting experiments structured within the L_{18} orthogonal array. Crucial machinability metrics encompassing cutting temperature, flank wear on the cutting tool, and surface roughness were meticulously scrutinized. Consequently, the deductions drawn from the conducted experiments and subsequent analyses are as follows:

The vacuum sintering used during the production of the Al matrix composite materials prevented the formation of slag and provided an excellent macro structure for machinability tests. Thanks to the homogeneous and long-term mixing, it has been determined that there is no serious internal structure defect in the materials, and it has been observed that the gaps and cracks that affect the machinability are at a minimum level.

With the Taguchi experimental design method, machinability tests of composite materials were performed with high accuracy (average 97% for different machinability metrics). It has been proven that the Taguchi method can be used safely in the machinability of AMMCs.

It has been determined that the factor affecting the cutting temperature the most is C/L conditions. C/L conditions are of great importance for cutting temperature control during the milling of AMMCs. In particular, it has been determined that cryogenic cooling has a very important effect on the milling of AMMCs.

The observed impact of composite materials on cutting tool flank wear predominantly hinges upon the specific reinforcement type and its corresponding quantity within the composite. This effect stands out as the most influential factor contributing to flank wear in the machining process. It has been observed that C/L conditions are the most effective parameter affecting flank wear after materials. It was predicted that the lowest wear amount obtained in the experiments was 0.36 mm, which would decrease by 16% with the fulfillment of the optimum conditions.

It has been determined that the most important factor affecting surface quality is C/L conditions. The experiments achieved the best surface quality with 4.835 µm for Al-3Gr/6BN material with high cutting speed, low feed, and cryogenic C/L conditions.

Surface roughness values for the produced composite materials were high due to the different matrix and reinforcement particles they contain. These main features distinguish these composite materials from traditional alloy, metal, and polymer materials.

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