Chapter 3

Investigation of the Effects of Different Cooling/ Lubrication Conditions and Cutting Parameters on Energy Consumption During Milling of Hybrid Aluminum Composites

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Abstract

In the developing technological world, energy consumption is increasing day by day. Reducing energy consumption on a sectoral basis is very important for sustainable resource use and the improvement of environmental health. The manufacturing sector is one of the sectors where energy consumption is intense. Therefore, even a small improvement in the energy consumption in the machining sector will significantly affect the overall energy consumption, costs, and environmental performance of production systems. Since hybrid aluminum metal matrix composites (AMMC) are difficult to process due to their complex microstructure, energy consumption values during processing are high. For this reason, it is important to determine the most appropriate values by examining the cutting parameters and cooling lubrication conditions during processing to reduce energy consumption. In this article, Al-Gr reinforced hybrid composites containing different proportions of WC and Al_2O_3 reinforcements were produced. The focus is on the energy consumption when milling these composites under different cooling/lubrication conditions and different machinability parameters such as the dry, minimum amount of lubrication (MQL), and cryogenic-LN_2. Taguchi statistical analysis was also used in the experiments. As a result, it was determined that the most effective parameter on the energy consumption values among the control parameters was the feed rate, with a contribution rate of 75.37%. In addition, for minimum energy consumption values, it was observed that the best cutting speed was 150 m/min, the best feed rate was 0.300 mm/rev, and the best cooling/lubrication medium was cryo-LN_2 cooling medium.

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1. Introduction

Aluminum (Al) is widely used in many industrial areas due to its lightness, high corrosion resistance, remarkable mechanical strength, and thermal conductivity, as well as being the most common element in the earth's crust. However, pure Al alone cannot meet the required material properties due to today's challenging living conditions and technological developments [1, 2]. Therefore, studies on materials have shifted from pure Al to single or hybrid-reinforced Al-based composites [3, 4]. Obtaining AMMCs with superior properties on the addition of ceramics such as SiC (silicon carbide), B_4C (Boron carbide), TiC (titanium carbide), Al_2O_3 (aluminum oxide), and carbon base reinforcements such as carbon nanotube, graphene and graphite to the Al matrix possible [5-7]. Recently, studies on composite materials have shifted to hybrid MMCs [8, 9].

Although hybrid AMMCs have attractive and superior thermal, mechanical, electronic, and corrosion resistance properties, soft and hard regions are formed in the material. In addition, their microstructures become complex due to the different reinforcements they contain. Therefore, their machinability becomes more complicated [10-14]. Although hybrid AMMCs have attractive and superior thermal, mechanical, electronic, and corrosion resistance properties, soft and hard regions are formed in the material. In addition, their microstructures become complex due to the different reinforcements they contain. Therefore, their machinability becomes more complicated [15]. The most prominent parameters when examining the machinability of AMMCs are cutting speed, feed rate, depth of cut, and cooling/lubrication conditions. To obtain excellent machined surface quality, it is important to use a suitable cutting fluid and determine the optimum cutting parameters. In addition to being used to cool the tool and workpiece, cutting fluids reduce friction as a lubricant and help improve surface quality, reduce energy consumption, and extend tool life by removing chips from the cutting zone [16]. Conventional dry machining limits its application as high cutting forces and high temperatures occur [17, 18]. Therefore, it is important to use cooling/lubrication and choose the correct cooling/lubrication. On the other hand, using conventional coolant has disadvantages such as adversely affecting the operator's health, high cost, difficult waste liquid treatment, and severe environmental pollution [19]. Research has shifted towards new cooling and lubricating fluids to eliminate both the disadvantages of cutting fluids and the problems in dry machining. In this context, the minimum quantity of lubrication (MQL), pressure-assisted wet cutting, and cryogenic cooling are among the most interesting cooling/lubrication methods [20]. The MQL approach ensures very low consumption of lubricants and effectively reduces cutting temperatures through the advanced nozzle and pressure oils [21]. In addition, it was stated that the tool-chip and tool-workpiece interfaces are better lubricated, and the chip is removed better with the pressure spray approach [22]. Cryogenic fluids such as MQL are also among the important cutting fluids. Liquefied gases such as liquid carbon dioxide (LCO_2) [23], liquid nitrogen (LN_2) [24], helium (He), and hydrogen (H_2) are used as cryogenic cooling mediums. Cryogenic cooling systems effectively reduce cutting temperatures and provide a safe and inexpensive cooling environment [25]. It can also be easily prepared and stored at room temperature [26]. Liquefied gases such as CO_2 (carbon dioxide), N_2 (nitrogen), H_2 (hydrogen), and He (helium) are used as refrigerant gas in cryogenic cooling systems [27]. Among these gases, N_2 is frequently used. This is because nitrogen is abundant in nature and is an environmentally safe and clean gas. Thanks to all the aforementioned unique features, MQL and cryogenic cooling/lubrication systems are sustainable, effective, and environmentally friendly. They tend to reduce energy consumption because they provide green-cutting technology, which is why they are very popular today [27].

Machining performances such as surface roughness, tool wear, chip morphology, and cutting temperature are important when machining composite materials. In addition, reducing the amount of energy consumed during processing is very important [28]. Since electrical energy sources are predominantly produced from fossil fuels, electrical energy consumption in manufacturing increases carbon emissions to the atmosphere, albeit indirectly [29, 30]. When the share of the industrial sector in total energy consumption is examined, it is seen that it has a share of 30-40%. Manufacturing processes, on the other hand, constitute approximately 60% of the energy consumption in the industrial sector [31]. Therefore, the investigation of energy consumption for various manufacturing processes such as additive manufacturing [32, 33], injection molding [34], and metal forming with machining [35, 36] has become an important issue. Mechanical processing constitutes a large part of the manufacturing industry [37]. Energy efficiency in machining is generally very low. Ceramic-reinforced AMMCs are difficult to machine due to their complex microstructure. It, therefore, results in lower material removal rates in turning, milling, and grinding machining processes. This causes longer processing times and, thus, more energy consumption [38]. Reducing energy consumption in enterprises is of great importance to improve its effects on the environment and human health and achieve sustainable production.

The effects of cutting parameters on tool life and energy consumption should be investigated to minimize energy consumption during machinability and maximize cutting tool life [39]. However, although there are many studies on machining, there are not many studies on the environmental effects and energy consumption of machining processes [40]. This study investigated the energy consumption of a new hybrid AMMC reinforced with tungsten carbide (WC) and Aluminum oxide (Al_2O_3) in the machinability processes. Variation of energy consumption values under different cutting conditions such as cutting speed (150-225-300 m/min), feed rate (0.150-0.225-0.300 mm/rev), and different cooling lubricants (Dry, MQL, and cryo-LN_2) analyzed using the statistical method.

2. Material production and Processing parameters

2.1. Composite material production

Machinability tests were carried out on single and hybrid reinforced Al-4Gr composites obtained by adding ceramic reinforcements such as WC and Al_2O_3 in different proportions to the Al-4Gr matrix formed by adding Gr particles at a fixed rate (4%). To produce composite materials, powders with micron dimensions (Al<= 40-70 μm, Gr <=44 μm, WC<=20 μm and Al_2O_3<= 40-70 μm) and high purity (>= 98), It was dried in the oven and weighed in the desired weight ratios (2, 4 and 8%) on a scale with 1/1000 precision. Then it was mixed with the help of a mixer for 120 minutes, poured into molds, and sintered in a vacuum hot press machine (Zhengzhou Golden Highway, SMVB80, China). Finally, the sintering process was carried out in an Argon gas environment at 560 °C and 35 MPa pressure for 10 minutes to prevent oxidation. As a result of the sintering process, experimental samples of 40 mm length, 40 mm width, and 6 mm thickness were produced.

2.2. Machinability process

Machinability tests were carried out on the DAHLIH MCV-860 model CNC milling machine using AlTiN-coated ISO 13399 numbered cutting tools. Three different media, dry, MQL, and cryo-LN_2, were used during machinability. Experiments were carried out by choosing fixed cutting depth (0.5 mm) and three different cutting speeds (150-225-300m/min) and feed rate (0.150-0.225-0.300 mm/rev) as variable parameters cutting parameters. The experiments were carried out using the Zig tool path and down milling.

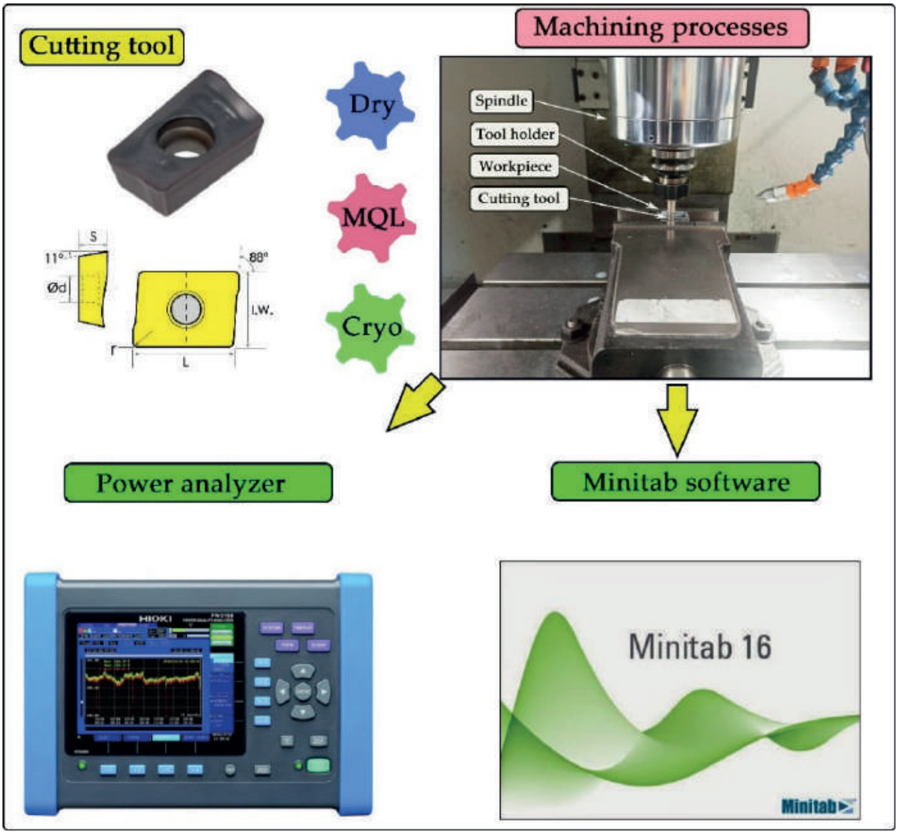

Figure 1. Experimental process diagram.

In the machinability experiments, liquid nitrogen (-196°C) stored in a 35-liter self-pressurized tank (Taylor Wharton LD-35) was used as cryogenic cooling. A two-meter-long steel vacuum hose conveys nitrogen from the tank to the cutting zone and prevents heat losses. A nozzle with a diameter of 5 mm is attached to the end of the hose. The nozzle was fixed at a 40° angle and 40 mm distance from the cutting zone, and cryo-LN_2 was sprayed at 8 bar pressure and 20 L/h flow rate. To make a correct comparison with the cryo-LN_2, the MQL was applied to the cutting zone at a distance of 50 mm from the cutting zone with 8 bar compressor pressure, 50 mL/h liquid flow rate, and 40° spray angle. An example diagram of the experimental process is shown in Figure 1.

It is necessary to use a power analyzer to measure the energy/power consumption values of the input parameters in workability experiments. The HIOKI-PW3198 brand power analyzer is connected to the CNC milling machine as a power analyzer. A special power analyzer software calculates the consumed energy and total cutting power. Power consumption values were obtained by calculating each of the 18 experiments.

2.3. Statistical Taguchi design

To minimize the amount of energy consumed during the processing of hybrid AMMCs, optimum cutting parameters must be determined. Since the number of variables is large, this can be accomplished with many experiments. For this reason, Taguchi L_{18} orthogonal array was used to reduce the number of experiments and to minimize the cost and time. The analysis of the sequence designed using Minitab 19 software was carried out. The milling parameters and levels used are shown in Table 1. The total number of experiments was reduced by statistical analysis. Using the results obtained in the designed experiments, the contribution ratios of the response parameters (shearing speed and feed rate, reinforcement ratio, and cooling/lubrication type) were calculated with the help of analysis of variance (ANOVA).

Table 1. CNC milling parameters and levels [41].

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

The "smaller is better" option, where the smallest value is the best, was used to analyze the consumed energy consumption. The signal/Noise (S/N) value giving the smallest values was calculated with Eq (1).

$$S/N = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} (V^2) \right] \quad (1)$$

Here V; is the response parameter (energy consumption), n; is the repeating number for test conditions, and i; n represents the repetition time. The experimental design showing the experimental numbers and factors according to the Taguchi L_{18} orthogonal array is given in Table 2.

Table 2. Experimental design of Taguchi L18 orthogonal array [41].

Experiment number	MMC Type (wt.%)	Cooling/ Lubricating	Cutting Speed (m/min)	Feed Rate (mm/rev)
1	1	Dry	150	0.150
2	1	MQL	225	0.225
3	1	Cryo	300	0.300
4	2	MQL	150	0.150
5	2	Cryo	225	0.225
6	2	Dry	300	0.300
7	3	Dry	150	0.225
8	3	MQL	225	0.300
9	3	Cryo	300	0.150
10	4	Cryo	150	0.300
11	4	Dry	225	0.150
12	4	MQL	300	0.225
13	5	Cryo	150	0.225
14	5	Dry	225	0.300
15	5	MQL	300	0.150
16	6	MQL	150	0.300
17	6	Cryo	225	0.150
18	6	Dry	300	0.225

3. Results and discussion

3.1. Examination of energy consumption values

With the increasing population and industrialization, energy needs are increasing daily [42]. Increasing energy consumption significantly reduces the sustainability of natural resources. This situation causes the depletion of fossil fuels such as oil and coal used in energy production. In addition, it accelerates the global warming process due to harmful gases released from these fuels [43]. For this reason, complex energy consumption systems must be used effectively and intelligently, both for the sustainability of natural resources and for the protection of the natural environment. Therefore, using the energy produced more efficiently and reducing the energy consumed is important [44]. For this reason, it is very important to measure energy consumption values and provide energy savings in the machining industry, where energy is used intensively [45]. Machining conditions and cutting parameters used during machining should be investigated to reduce energy consumption values. Therefore, this study investigated the effects of three different cooling/lubrication conditions, such as dry, MQL, cryogenic, and cutting parameters, such as cutting speed and feed rate, on the amount of energy consumed. A three-dimensional surface graph showing the effects of reinforcement ratios and cooling/lubrication techniques on power consumption is shown in Figure 2.

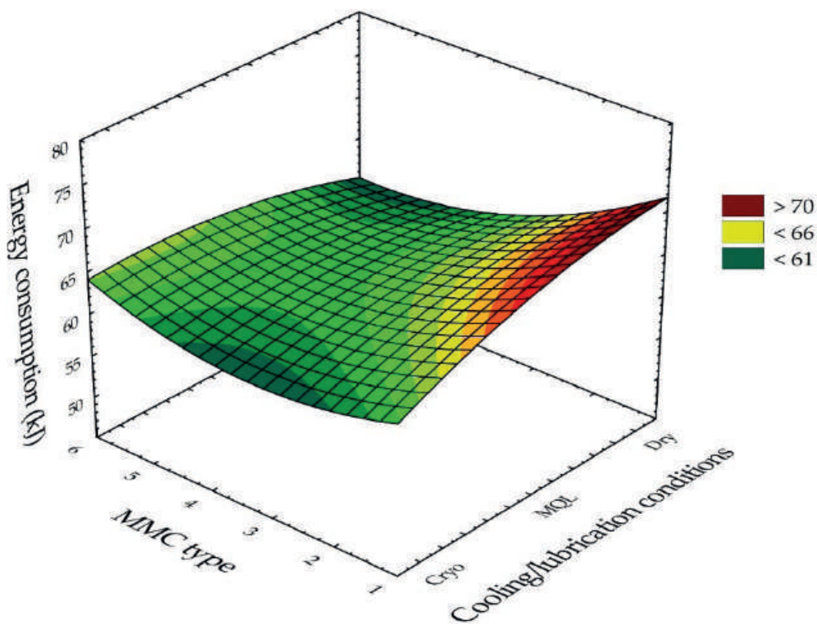

Figure 2. 3D surface drawings showing the effects of different cooling/lubrication conditions and composite types on energy consumption.

When the 3D surface graphics given in Figure 2 are examined in terms of cooling/lubricating fluids, it is seen that the energy consumption values in machining with the MQL system are generally lower compared to dry machining. The lowest energy consumption during processing was realized in the Cryo LN_2 cooling system. The Cryo LN_2 offers the best cooling medium for CNC milling AMMC materials. This is because the cryo LN_2 hardens the tool material with its excellent cooling effect, facilitating the removal of chips from the workpiece. However, very high temperatures are reached during the cutting process due to the friction between the composite material and the cutting tool. These high temperatures are undesirable for both the workpiece and the cutting tool. High temperatures cause thermal stress and cracks in the cutting tool [46]. As this makes the cutting process difficult, it increases both the wear of the tool and the energy consumption. However, it is seen that energy consumption can be reduced by using cryo LN2, by performing better cooling than dry and MQL processing.

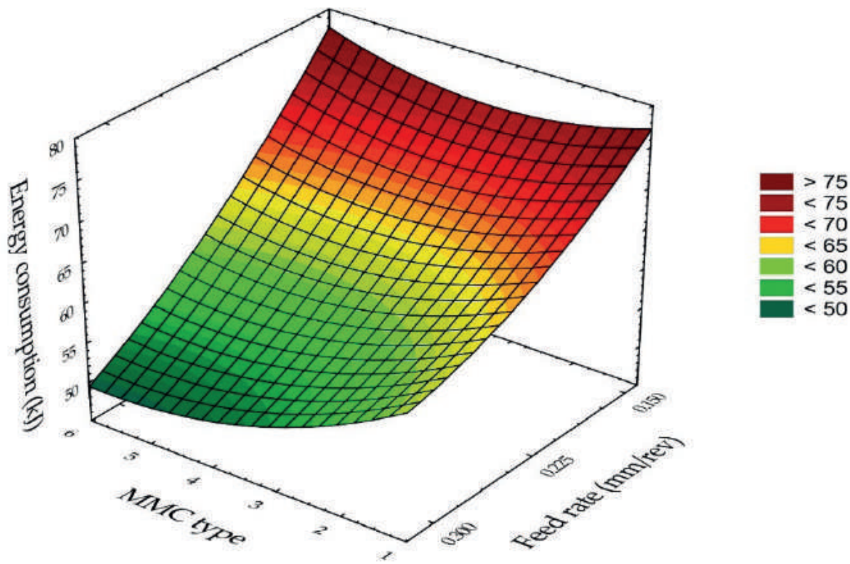

Figure 3. 3D surface drawings showing the effects of feed rate and composite type on energy consumption.

When the feed rate given in Figure 3 and the energy consumption values depending on the composite type are examined, it is seen that the power consumption generally increases with the increase in the reinforcement ratio in the hybrid composite. Although the hardness and strength of the composite increase as the reinforcement ratio and reinforcement number increase, the irregularities in the microstructure due to the increase in the soft and hard structure transition make the machining process difficult [47]. This situation increases the amount of energy consumed during processing. When analyzed in terms of feed rate, energy consumption decreases as the amount of feed during cutting increases, and the lowest consumption was realized at 0.300 mm/revolution feed rate. The same is true for all composite types. At the same time, the increase in feed rate will also reduce the total processing time, thus indirectly reducing energy consumption. However, increasing the feed rate also increases the surface roughness, so it is important to determine the optimum feed rate by considering the surface quality and energy consumption values together.

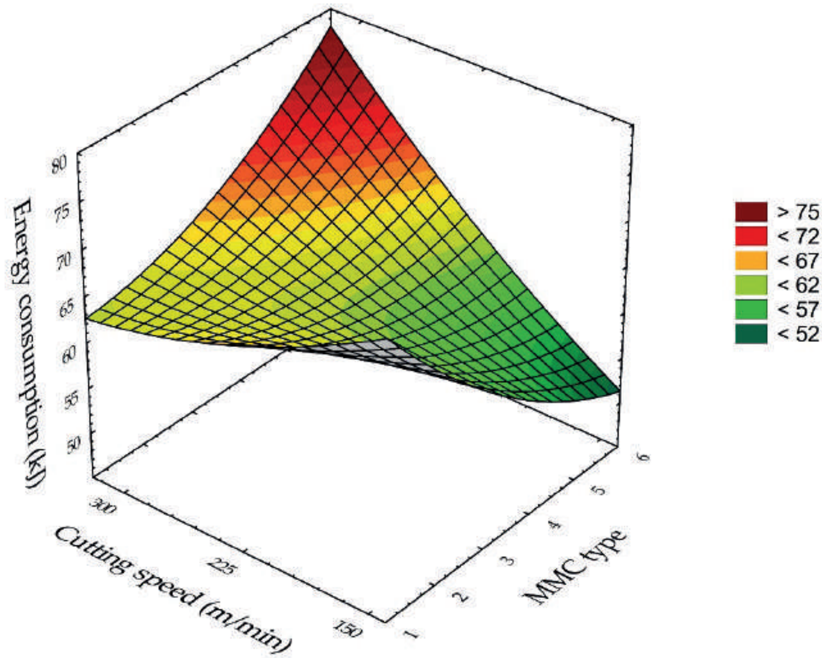

Figure 4. 3D surface drawings showing the effects of cutting speed and composite type on energy consumption.

Figure 4 shows the varying power consumption values depending on the cutting speed and the composite type. When the graph is examined in general, in the pure Al-4Gr structure, the increase in the cutting speed does not significantly affect the energy consumption, while the increase in the cutting speed in the processing of hybrid composite materials increases the energy consumption. However, although increasing the cutting speed increases the energy consumption in unit processing, it is possible to balance the total consumption by reducing the total time and improving the surface quality with increasing cutting speed. Therefore, instead of choosing a low or high cutting and feed rate, it is necessary to determine the optimum cutting and feed rate.

3.2. Taguchi analysis

Taguchi statistical analysis method was used to determine the optimum conditions required to minimize energy consumption during processing. The Taguchi method is a powerful tool that can provide simultaneous improvements in quality and cost by determining the most appropriate response parameters. It aims to achieve this by conducting a minimum number of experiments while delivering the most suitable parameter. Therefore this method uses a series of orthogonal series [48]. In this study, the L_{18} orthogonal array of Taguchin was chosen. Signal-to-noise ratios (S/N) and control factors are the basis of the orthogonal array. Table 3 shows the experimental results of the energy consumption values, the predicted values of the statistical analyses, and the S/N ratios.

Table 3. Test results of energy consumption values, estimated values, and S/N ratios

Experiment no	Energy consumption (kJ)	Predict values (kJ)	S/N ratio for Energy consumption (dB)
1	72.27	76.73	-37.1792
2	71.74	67.23	-37.1152
3	61.35	61.41	-35.7563
4	76.01	73.1	-37.6174
5	56.66	61.2	-35.0655
6	61.23	59.6	-35.7393
7	61.6	60.21	-35.7916
8	51.88	54.29	-34.3000
9	76.22	75.2	-37.6414
10	49.68	47.76	-33.9236
11	70.5	70.39	-36.9638
12	61.38	63.4	-35.7605
13	59.12	58.93	-35.4347
14	55.7	54.84	-34.9171
15	77.1	78.15	-37.7411
16	49.72	51.66	-33.9306
17	71.53	70.06	-37.0898
18	65.37	64.9	-36.3076

S/N main effect graphs of input parameters such as composite type, cutting speed, feed rate, and different cooling/lubrication techniques used in the study are given in Figure 5. If the S/N graphs are examined to determine the optimum energy consumption values depending on the input parameters, the best composite according to the reinforcement ratio is the hybrid composite number 4 containing 1% WC and Al_2O_3 reinforcement. In general, it is seen that hybrid reinforced composites are better than single-reinforced composites, and power consumption values increase depending on the increase in reinforcement ratio. When cutting speed was examined, the lowest energy consumption was observed in processing with a cutting speed of 150 m/min. However, as the cutting speed increases, the energy consumption values also increase. On the other hand, the opposite was accurate at the rate of progress. The power consumption values decreased in direct proportion to the increase in the forward speed. It was observed that the ideal value for the feed rate is 0.300 mm/rev. It is seen that the lowest power consumption among the cooling/lubrication options occurs in the cryogenic cooling environment.

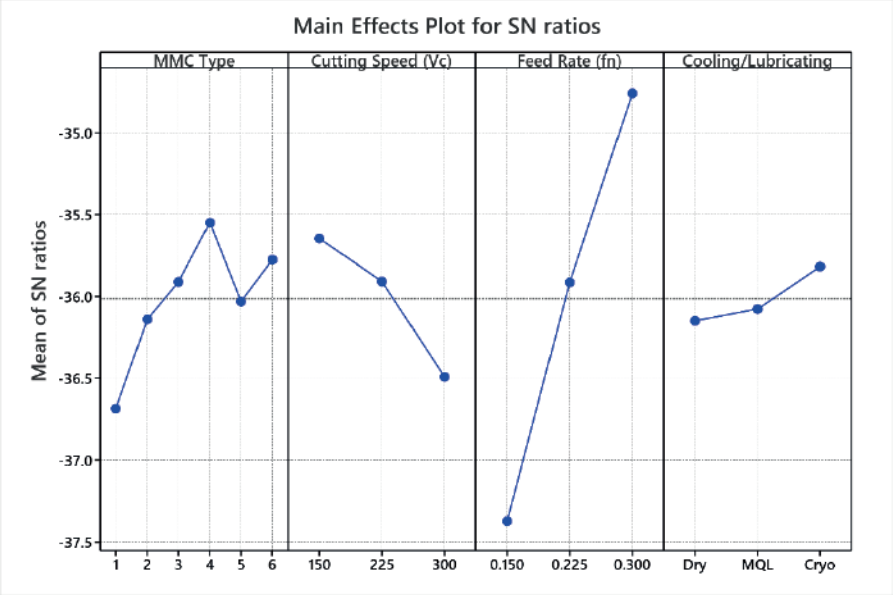

Figure 5. S/N ratios for different cutting environments and different cutting parameters of energy consumption.

3.3. Analysis of variance

The contribution rates of all control factors in energy consumption and the statistically significant "F" and "P" values are given in Table 4. In this study, the ANOVA method, which provides linear modeling for evaluating the relationship between domains, was used to determine statistical significance and the contribution rates of control factors on the response parameter. For the analyses to be statistically significant, the "P" value of each factor must be less than 0.05, and the confidence level must be 95% or higher for the statistical estimates to be accurate [49]. When the results obtained in this study are examined, it is seen that the "P" values are less than 0.05, as they should be. The fact that "P" values are less than 0.05 shows that the analysis is statistically significant. "F" values are used to calculate control factors' contribution to energy consumption. According to the analysis results, the most effective factor in energy consumption is the rate of progression, with 75.37%. The next most effective control factor was MMC type and cutting speed, with 8.23%. Cooling/lubricating fluids have less effect.

Table 4. ANOVA results of energy consumption values.

Energy consumption	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**Contribution rate (%)**
MMC Type	5	2.2435	2.2435	0.4487	1.45	0.33	8.23
Cutting Speed (Vc)	2	2.2437	2.2437	1.1218	3.61	0.093	8.23
Feed Rate (fn)	2	20.546	20.546	10.273	33.09	0.001	**75.37**
Cooling/Lubricating	2	0.3639	0.3639	0.182	0.59	0.585	1.33
Residual Error	6	1.8626	1.8626	0.3104			6.83
Total	17	27.2598					100.00

The Taguchi method is an analysis method that changes a selected factor at different levels to determine the relationship between the response parameters of the control factors, keeps other factors constant, and estimates by repeating this process for each parameter. It is widely used in the manufacturing sector. It provides convenience in measuring the effect of input parameters and finding optimum values by reducing the number of experiments in cases where the experiments are difficult and expensive. Figure 6 shows the quadratic regression model graph with the experimental results for energy consumption to identify the relationships between the variables and to test whether there is a linear relationship between them.

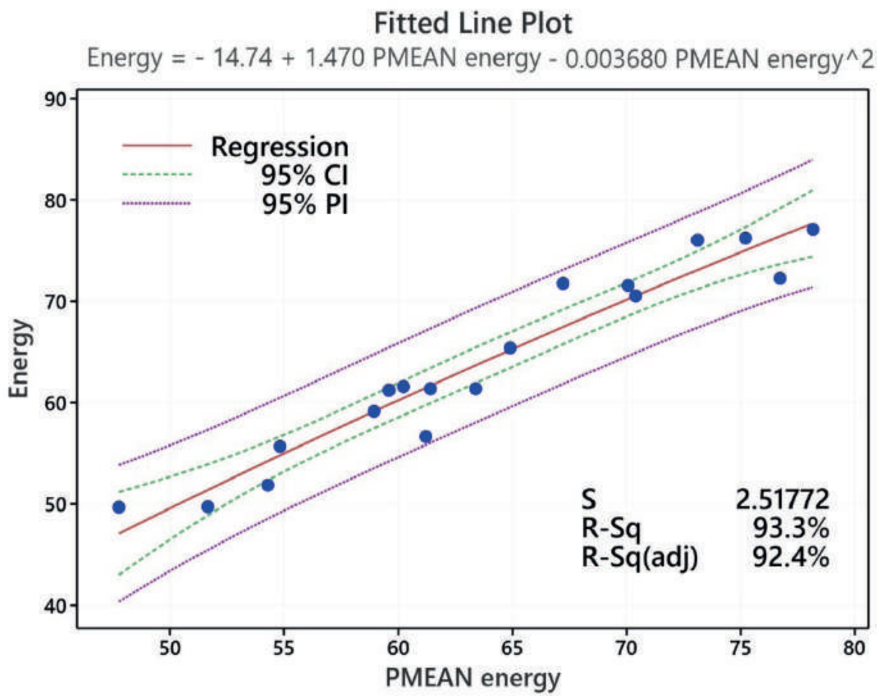

Figure 6. Quadratic regression model graph with experimental results for energy consumption

In the regression analysis, four independent variables were used, namely, the number of reinforcements and reinforcement ratio, cutting speed, feed rate, cooling/lubrication environment, and energy consumption was chosen as the dependent variable. The energy consumption values required for milling hybrid aluminum composites were obtained with the analysis of variance and the regression equation (Eq 2) performed at a 95% confidence level. The comparison of the results estimated by ANOVA with the experimental energy consumption results for all samples is given in Figure 7. It was observed that the predicted values were realized with a high accuracy rate of 93.3%.

$$\text{Energy consumption} = -14{,}74 - 1{,}470 \times (\text{predict}) - 0.003680 \times (\text{predict})^2 \quad (2)$$

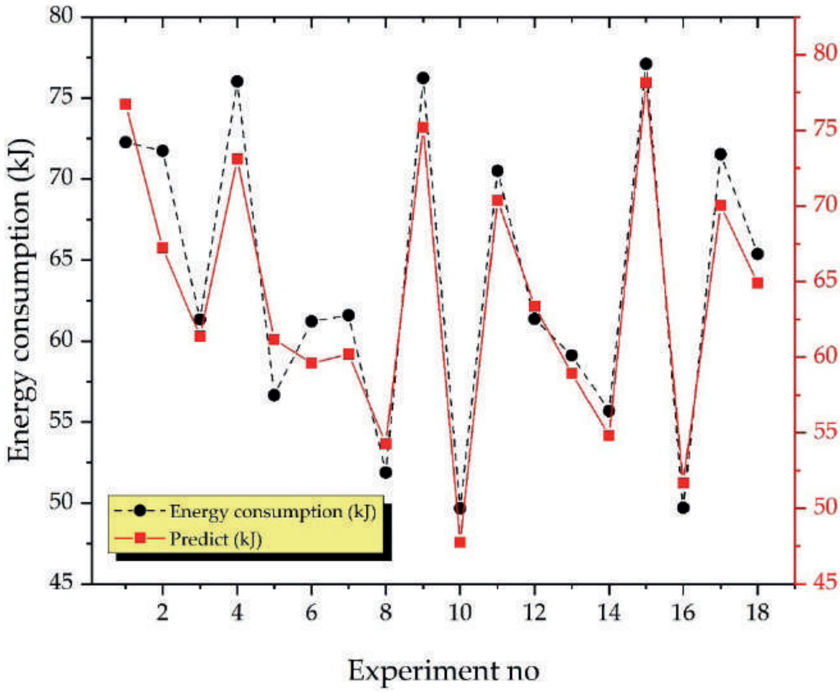

Figure 7. Comparison of experimental energy consumption results with predicted results

4. Conclusions

This study investigated the energy consumed in milling hybrid Al composites reinforced with ceramic reinforcements such as WC and Al_2O_3 in different ratios under different cutting speeds, feed rates, and cooling/lubrication conditions. In addition, the required energy consumption values during milling were evaluated using Taguchi and ANOVA statistical methods. As a result of the study, it was determined that the most effective parameter among the control factors on energy consumption values was the speed of progress, with 75.37%. In addition, the optimum values at which minimum energy consumption values are obtained are 1% WC and 1% Al_2O_3 reinforced composite, 150 m/min cutting speed, 0.300 mm/rev feed rate, and cryo-LN_2 cooling medium. Finally, it was seen that determining the ideal cutting parameters and cooling/lubrication conditions in the processing of composite materials is of great importance in minimizing environmental damage and energy consumption values.

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