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Investigation of the Milling Methods Effects on Machining Performance of AA 7075-T6 Aluminum Alloy and Process Parameters Optimization

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Abstract

Aluminum alloys are widely used in various industries due to their high mechanical properties and low specific gravity. However, inappropriate cutting parameters can lead to built-up edge (BUE) formation, degrading the workpiece's surface quality and reducing tool life. This study investigates the effects of conventional and trochoidal milling methods on response variables, including surface roughness (Ra), circularity, and cutting forces (Fr), for AA 7075-T6 aluminum alloy. Experimental work was carried out using two cutting methods (trochoidal and conventional), three cutting speeds (175, 225, and 275 m/min), and three feed rates (0.09, 0.12, and 0.15 mm/tooth). The Taguchi method and Grey Relational Analysis (GRA) were used for multi-response optimization, and Analysis of Variance (ANOVA) was used to assess the effect of control factors on machining performance. The results indicate that cutting methods influence the performance of the response variables. Feed rate influenced surface roughness (Ra) by 57.28%, while the milling method influenced circularity and cutting forces by 73.73% and 68.97%, respectively. In addition, the trochoidal milling method exhibited a stable cutting force profile with fewer harmonic components than the conventional method. This stability and the shorter cycle time achieved by trochoidal milling highlight its efficiency advantages. These results suggest that the trochoidal method offers potential applications and efficiency benefits in precision-demanding industries such as automotive and aerospace.

Keywords: AA7075-T6, machining, grey relational analysis, trochoidal milling, optimization.

1. Introduction

Efficiency is a crucial factor for industries in the manufacturing sector, as it has a direct impact on profitability and success. To increase productivity in producing goods and services, businesses continuously seek ways to optimize their processes[1,2]. In CNC machining centers, a critical technology in manufacturing, achieving high machining quality requires optimizing parameters such as cutting methods, machining parameters, and the tools used. Milling operations are widely preferred in the manufacturing sector, and reducing per-part production costs necessitates optimizing surface roughness, precise tolerances, and cutting parameters [3].

In the literature, various studies have been conducted to improve the efficiency of milling processes. These studies focus on optimizing cutting parameters in machine tools, designing tools, developing cutting tool materials, selecting workpiece materials, and planning cutting strategies [4–10].The trochoidal (TR) toolpath strategy enhances tool life and machining efficiency by reducing tool loads and heat generation during machining[11]. Current TR toolpaths are generally created using one of two approaches: the circular and trochoidal models (see Figure 1). The circular model utilizes successive circular pathways with either constant or varying diameters, while the trochoidal model typically follows a continuous, intricate path without straight-line components[12]. In conventional milling, contour-parallel toolpaths are a high-speed milling method for roughing operations, calculated according to contour offset and the cutting operation. However, without pre-treating corners and narrow areas, the contact angle or arc length between the tool and the uncut material can increase significantly. This raises the tool-to-material contact ratio, causing load increases on the tool at varying wavelengths, which can lead to tool fatigue and reduced tool life [13]. An innovative toolpath strategy, the TR cutting method is well-suited for controlling load fluctuations on the tool by keeping the tool contact angle within a stable range [14].

TR milling method guarantees control of the material contact angle, improved tool life, high depths of cut without increasing the risk of tool breakage, and stable machining conditions [15]. The performance of trochoidal milling can be further enhanced by optimizing cutting parameters [16]. Methods like data analytics are commonly used to optimize cutting parameters [17–

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19].Consequently, the TR cutting strategy provides high precision and short cycle times for machining difficult materials, yielding lower force, temperature, and tool wear compared to conventional milling methods [20,21]. Nevertheless, it may be beneficial to conduct additional research in order to gain a more comprehensive understanding of the potential benefits and effectiveness of the trochoidal method [22].

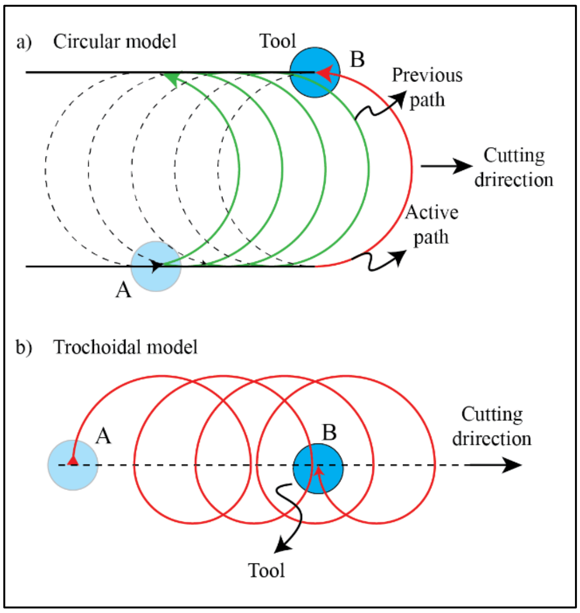

Figure 1. Schematic representation of circular and trochoidal toolpath

Pateloup et al. [23]proposed a new method for toolpath generation, calculating corner radius based on the machine tool's kinematic behavior and radial depth of cut variation. According to experimental results, this method reduced machining time by 15-25% by increasing the feed rate at the corner edges of the machined part. In their study, Wu et al. [24] examined the effects of toolpath strategies on the machinability of nickel-based super alloys. These alloys are commonly used in high-temperature applications, such as aircraft engines, defense, and weapon industries, due to their exceptional strength. The authors conducted a comparative experimental analysis of the wear on tool cutting edges during conventional milling and trochoidal milling. According to experimental findings, it was observed that the wear on the cutting edge during conventional milling operations was four times higher than that of trochoidal milling operations. Rauch et al. [25]also explored cutting parameter selection to facilitate trochoidal milling on CNC machines. They calculated the maximum radial depth based on toolpath parameters and compared it with two interpolation models. Experimental tests with a Ø 32 mm two-flute end-mill on aerospace aluminum alloy (5086) showed increased tool life and reduced machining time. Their findings indicate that trochoidal milling improves tool life and machining efficiency on CNC machines.

In a related study, Luo et al. [26] developed a four-axis trochoidal toolpath to enhance machining performance for complex, difficult-to-machine materials like nickel-based super alloys and titanium alloys used in aircraft engines. Their toolpath design resulted in increased machining efficiency. Orellana and Culqui[27] compared trochoidal and conventional milling strategies in terms of cycle times and tool temperature factors in the machining of AA7075-T6 alloy, which is widely used in manufacturing industries. They conducted experimental designs using the Taguchi L18 orthogonal array design method. The control factors included traditional and trochoidal machining strategies, a two-level cutting methodology, three-level cutting speed Vc (m/min), and three-level feed rate per tooth (mm/tooth). The study measured the machining times (sec) and tool temperature (°C) as response values, with the results indicating that the trochoidal strategy was 93.27% more efficient than conventional milling at certain levels of machining parameters. Additionally, they observed that the minimum temperature for trochoidal milling (25.3 °C) was lower than that of conventional milling (28.9 °C). Based on these results, they suggested the optimal cutting parameters for achieving the best machining time and tool temperature. The loads that act on the cutting tool during machining are a crucial parameter that directly affects machining performance. Jasco et al. [28], an artificial neural network (ANN) was developed to optimize cutting tool loads and machining time. The results of their ANN-based optimization method showed that trochoidal milling yields much better results than conventional methods. In the experimental study, it was found that optimizing the feed rates resulted in a 50% reduction in machining time without any increase in cutting forces.Hayajneh and Abdellahi[29]developed and tested two different gene expression programming models for predicting surface roughness. These models demonstrated the ability to accurately predict surface roughness values based on the cutting parameters used during the milling process.Jatakar et al. [30], examined the effects of damage mechanisms such as Built-Up-Edge (BUE) on spindle vibration signals and showed that meaningful inferences can be made for tool life. BUE occurs when the workpiece material adheres to the cutting edges of the tool due to high temperature, pressure, and chemical bonding. BUE forms periodically and disintegrates, tearing off small pieces from the cutting edge, causing cracks and wear on the side surface of the tool [31].

In this study, a milling operation was performed on AA7075-T6 aluminum alloy using both trochoidal and conventional cutting methods, and the results were comprehensively compared. Although the effects of trochoidal milling on efficiency, tool life, and surface roughness have been investigated in the literature, the detailed analysis of different cutting methods based on multi-dimensional performance criteria such as cutting forces, surface quality, cycle time, and geometric accuracy of the machined part is limited. This study measured cutting forces, the machined geometry's circularity values, surface roughness, and cycle times during milling. These data were analyzed using the Taguchi method's S/N ratios and Grey Relational Analysis to determine the optimal cutting parameters. Additionally, the evaluation of cutting forces in terms of frequency through power spectrum analysis provides a comparative insight into the stability of force distributions generated by both methods at different harmonic frequencies. This study fills a gap in the literature by examining the multi-dimensional performance of trochoidal and conventional milling methods and offers a new perspective by revealing which method exhibits a more stable frequency distribution.

2. MATERIAL and METHOD

Aluminum alloys are widely used in various industries due to their high mechanical properties and low specific gravity[32]. However, it is crucial to correctly determine the cutting parameters to avoid a built-up edge on the cutting tool, which can lead to deterioration of the workpiece surface and reduced tool life when machining ductile aluminum alloys[33]. This study investigated the effects of trochoidal and conventional milling strategies on AA7075-T6 aluminum alloy.

2.1. Experimental Setup

AA7075-T6 aluminum alloy was used as the workpiece material for the milling tests. All surfaces of the workpiece were machined perpendicular to each other and a prismatic test specimen with dimensions of 208x120x60 mm was prepared for the milling tests. The Karcan brand cutting tool, coded 123310073W, made of high-speed steel with three cutting edges (teeth), a cutting edge tip corner radius of 0.2 mm, and a helix angle of 45 degrees, was used in the machining operations. The tool dimensions are provided in Figure 2 and Table 1.

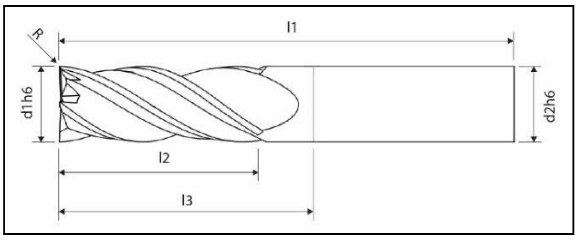

Figure 2. Cutting tool geometry used in the experiments

Table 1. Cutting tool dimensions

d1h6 (mm)	d2h6 (mm)	l1 (mm)	l2 (mm)	l3 (mm)	R (mm)	z (Number of teeth)
10	10	73	25	35	0.2	3

The machining operations were carried out on a HAAS VF-2SS 5-axis machining centre using a Kistler 9123C rotary dynamometer capable of measuring force and torque in three axes. The forces generated during milling create a piezoelectric charge on the dynamometer. The electrical signals generated up to a certain force level are transmitted to an amplifier. The electrical signals arriving at the amplifier are amplified with calibrated coefficients and transferred first to a data acquisition card and then to a computer and digitised using with the Dynoware program. The experimental setup is shown in Figure 3.

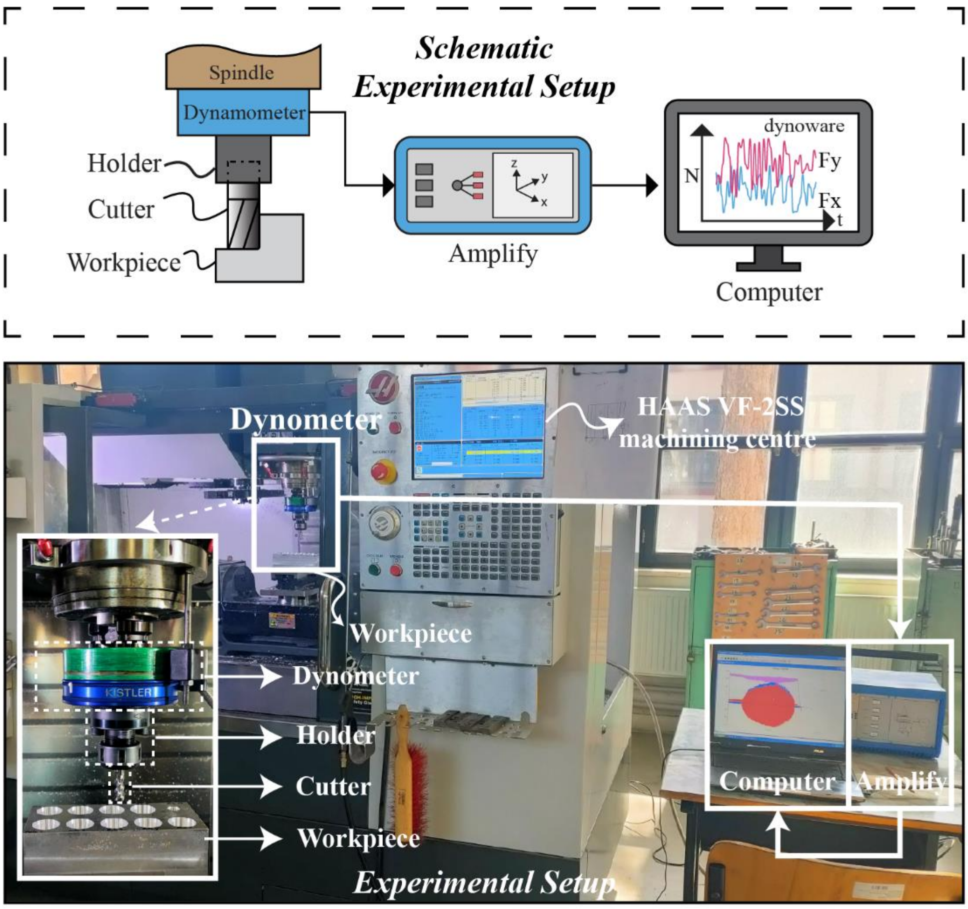

Figure 3. Schematic representation of experimental setup

Circularity refers to how close a given cross-section or surface of a part is to an ideal circle. In other words, circularity indicates whether the edges of an object are equidistant from a center. Ensuring circularity in manufacturing processes increases part compatibility and functionality. Geometric tolerances and dimensional accuracy of the machined part in terms of circularity parameters were measured using a Hexagon Global Performance CMM. Surface roughness values were determined using a Mitutoyo SJ-410 surface roughness tester with three repetitions from different positions for each part.

2.2. Taguchi Method

The Design of Experiments (DoE) technique is essential in optimizing any process to identify the factors affecting the process and reduce process variation. The Taguchi method provides a systematic and efficient approach to determining the optimal cutting parameters for milling experiments. This method, which aims to minimize variability in the process, has been shown to improve process performance with minimal experimental analysis using signal-to-noise (S/N) ratios of the desired outputs for the best factor levels[34]. The control factors used in the experimental study were defined as a two-level cutting method (Factor A), a three-level cutting speed m/min (Factor B), and a feed rate mm/tooth (Factor C). Factors B and C were determined according to the cutting tool manufacturer's recommendations and are given in Table 2. Taguchi L18 (2^1x3^2) was selected as the standardized orthogonal array to determine the optimum machining method and cutting parameters for the two- and three-level control factors and to analyze their effects.

Table 2. Test factors and levels

Parameters	Symbol	Level 1	Level 2	Level 3
Cutting Method, CN and TR	A	CN	TR	-
Cutting speed, Vc (m/min)	B	175	225	275
Feed rate, f (mm/tooth)	C	0.09	0.12	0.15

CN: Conventional, TR: Trochoidal

Where noise factors are available, the desired outputs for the best factor levels can be expressed in terms of the (S/N) ratio and calculated using Eq. 1 and Eq. 2. Experimentally measured values such as surface roughness (Ra), circularity (CRY), and average force (Fr) are indicated by y_i, and the number of repetitions is indicated by *n*. In this study, the smaller-is-better performance characteristic given in Eq. 2 is chosen to minimize the outputs.

Larger-is-better

$$\frac{S}{N} = -10log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \quad (1)$$

Smaller-is-better

$$\frac{S}{N} = -10log\frac{1}{n}\sum_{i=1}^{n}y_i^2 \quad (2)$$

In order to investigate the effects of machining methods on geometric tolerance and surface roughness, 28 mm in diameter and 15 mm in depth pocketing operations were applied on the workpiece. In both tool path strategies, the tool clamping length (stroke length) was assumed to be 30 mm. In the CN method, the axial chip depth in each pass was set as 1 mm, and in the TR method, the axial chip depth in each pass was set as 15 mm. Radial chip depth was fixed as 1 mm for both methods. The effects of the machining methods on the workpiece and tool were analyzed with Ra (μm), CRY (mm), and Fr (Newton) measurements. The levels of control factors, process variables, and signal-to-noise (S/N) ratios are given in Table 3.

Table 3. L18 (2^1x3^2) orthogonal array, experimental measurements, and S/N ratios

Runs	A	B	C	Ra	CRY	F_r	S/N Ratios		
							Ra	CRY	F_r
1	1	1	1	0.309	0.010	471.99	10.201	40.000	-53.479
2	1	1	2	0.242	0.016	409.60	12.324	35.918	-52.247
3	1	1	3	0.160	0.018	496.97	15.918	34.895	-53.927
4	1	2	1	0.257	0.016	762.00	11.801	35.918	-57.639
5	1	2	2	0.201	0.015	707.61	13.936	36.478	-56.996
6	1	2	3	0.199	0.019	729.00	14.023	34.425	-57.255
7	1	3	1	0.238	0.019	1232.00	12.468	34.425	-61.812
8	1	3	2	0.177	0.021	1240.91	15.041	33.556	-61.875
9	1	3	3	0.140	0.017	1242.10	17.077	35.391	-61.883
10	2	1	1	0.384	0.047	1401.32	8.313	26.558	-62.931
11	2	1	2	0.232	0.093	2041.99	12.690	20.630	-66.201
12	2	1	3	0.208	0.081	1518.58	13.639	21.830	-63.629
13	2	2	1	0.334	0.039	1608.01	9.525	28.179	-64.126
14	2	2	2	0.277	0.010	1470.18	11.150	26.936	-63.347
15	2	2	3	0.238	0.016	1357.34	12.468	25.680	-62.654
16	2	3	1	0.322	0.018	1682.43	9.843	24.731	-64.519
17	2	3	2	0.244	0.016	1715.02	12.252	20.819	-64.685
18	2	3	3	0.240	0.015	1566.77	12.396	21.310	-63.900

2.3. Gray Relationship Analysis

The analysis of the relationships between control factors and multiple process variables is slightly more complex. Gray relationship analysis (GRA) could effectively used to analyze complex relationships between specific performance characteristics of multiple outputs[35].GRA represents a data set with uncertain points and could be used to provide various solutions to these uncertainties[36]. Data preprocessing is inevitable when evaluating results. Accordingly, the data are normalized to scale them evenly from zero to one. Normalization can be performed using Eq 3 and Eq 4. In this study, the S/N ratios calculated for surface roughness, circularity, and cutting force were normalized. The Gray Relation Coefficient (GRC) was calculated for the experimental results, and the Gray Relational Degree (GRADE) was obtained. The parameter corresponding to the highest GRADE value gives the best levels of control factors for the minimum value of the process variables. In this way, a multi-response problem was transformed into a single-response optimization problem using the GRA technique.

$$x_{ij} = \frac{\max(y_{ij}) - y_{ij}}{\max(y_{ij}) - \min(y_{ij})} \quad (3)$$

Equation 3 can be used for larger-is-better values.

$$x_{ij} = \frac{y_{ij-} \min(y_{ij})}{\max(y_{ij}) - \min(y_{ij})} \quad (4)$$

Equation 4 can be used for smaller-is-better values.

The normalization process was performed using the larger-is-better equation given by Equation 3 for the S/N ratios obtained from experimental measurements. In the next step, the GRC coefficient that gives the relationship between the normalized values and the measurement results can be calculated with Eq. 5:

$$\xi_i(k) = \frac{\Delta min + \zeta \Delta max}{\Delta 0_i(k) + \zeta \Delta max} \quad (5)$$

$$0 < \xi_i(k) \leq 1 \quad (6)$$

$$\Delta 0_i = \|X_0(k) - X_i(k)\| \quad (7)$$

where $\triangle_{0i}(k)$ is the absolute value difference between $X_0(k)$ and $X_i(k)$. $X_0(k)$ is referred to as the reference sequence. $\triangle min$ is defined as the smallest value of $\triangle_{0i}(k)$and $\triangle max$ is defined as the largest value. The value of ζ is the distinguishing or identification coefficient. It is between 0 and 1 and is usually taken as 0.5[37]. Once the GRC is derived, the GRADE value is calculated by Eq. 8 [38,39]:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \quad (8)$$

In this study, 0.5 is defined as the distinguishing coefficient.

2.4. Analysis of Variance

Analysis of variance (ANOVA) is used to evaluate the effect of one or more independent variables (factors) on a dependent variable. The primary purpose of ANOVA is to determine statistically significant differences between the means between groups. There are two types of variance analysis: one-way and two-way. A two-way ANOVA evaluates the effect of two or more independent variables, while a one-way ANOVA evaluates the effect of only one. The main objective is to determine statistically significant differences between groups in all cases.

3. RESULTS and DISCUSSION

Since the process variables Ra, CRY, and Fr are to be minimized, the S/N response values with the smaller-is-better characteristic given in Eq. 2 are used. Firstly, the effects of the control factors on each response variable were analyzed using the Taguchi method. Then, the multi-response problem was transformed into a single-response system by GRA and analyzed.

Table 4summarises the control factor levels that affect each process variable. These levels were determined based on S/N ratios, which were used to identify the control factors that provide the closest results to the desired target in each process output. As a result of this analysis, the control factor levels with the highest S/N ratio represent the best performance levels for each process variable.

The optimal parameters for minimizing surface roughness (Ra) were found to be the first level of cutting method, the third level of cutting speed, and the third level of feed rate. For the best circularity (CRY), the ideal combination was the first level of the cutting method, the second level of cutting speed, and the first level of feed rate. To minimize cutting force (Fr), the optimal levels were the first for cutting method, first for cutting speed, and third for feed rate.

The choice of these combinations shows that the control factors need to be adjusted at different levels to achieve the desired results at each process output. The use of S/N ratios reveals settings that improve quality by minimizing process variations. Therefore, the best factor levels determined for each process variable represent the optimum operating conditions in terms of the relevant performance criteria. In this way, optimal results in terms of surface quality, geometric accuracy, and cutting force can be achieved in the production process. The S/N ratios provided in Table 6 are visualized in Figure 4 to offer a clearer understanding of the effects of each control factor level on process performance.

Table 4. Effective levels according to S/N ratios

Level	S/N ratios for Ra			S/N ratios for CRY			S/N ratios for F_r		
	A	B	C	A	B	C	A	B	C
1	**13.642**	12.182	10.360	**35.667**	29.972	**31.635**	**-57.46**	**-58.27**	-60.75
2	11.362	12.146	12.892	24.075	**31.269**	29.056	-63.69	-60.34	-60.43
3		**13.178**	**14.255**		28.372	28.922		-63.11	**-60.54**
Delta	2.280	1.032	3.895	11.592	2.897	2.713	6.23	4.84	0.32
Rank	2	3	1	1	2	3	1	2	3

**Bold values indicate maximum values.*

The experimental results show that the forces measured during one pass are lower for the conventional toolpath strategy than for the trochoidal method. The main reason for this difference is that the volume of chips removed in each pass is much smaller in the conventional method compared to the trochoidal method. In the conventional method, the chip with a depth of 15 mm is removed in 15 separate passes in 1 mm axial steps, so that the forces generated in each pass remain at low levels. In the trochoidal method, on the other hand, the 15 mm deep chip is removed in a single pass, so the measured forces appear to be higher in a single pass. However, assuming equal volume removal, it can be concluded that the forces per unit length acting on the tool are lower in the trochoidal method. This is due to the fact that the forces along the 1 mm length of the tool in both methods are considered. This demonstrates that despite the trochoidal method operating at a greater axial depth during the cutting process, it exerts a reduced force on the tool per unit of length. Consequently, it can be concluded that the trochoidal method applies lower forces to the tool in the overall metal removal process, thereby conferring advantages in terms of tool life and process efficiency.

The procedures given in the previous sections were applied to calculate GRADE, and the GRA coefficients according to S/N ratios are given in Table 5.

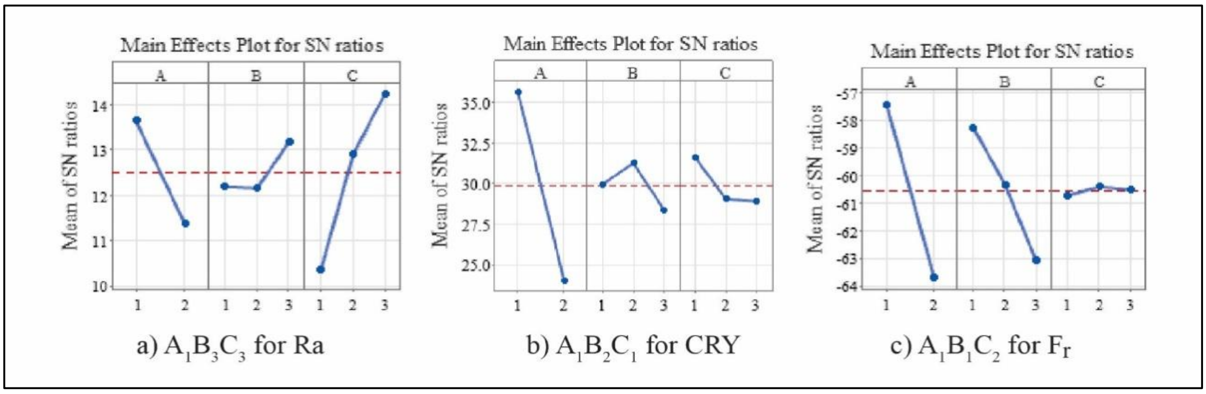

Figure 4. S/N Ratios Representing the optimal control factor levels for surface roughness (Ra), circularity (CRY), and cutting force (F_r)

Table 5. GRA coefficients

Runs	Normalization			DS			GRC			Grade
	Ra	CRY	Fr	Ra	CRY	Fr	Ra	CRY	Fr	
1	0.215	1.000	0.912	0.785	0.000	0.088	0.389	1.000	0.850	0.746
2	0.458	0.789	1.000	0.542	0.211	0.000	0.480	0.703	1.000	0.728
3	0.868	0.736	0.880	0.132	0.264	0.120	0.791	0.655	0.806	0.751
4	0.398	0.789	0.614	0.602	0.211	0.386	0.454	0.703	0.564	0.574
5	0.642	0.818	0.660	0.358	0.182	0.340	0.582	0.733	0.595	0.637
6	0.651	0.712	0.641	0.349	0.288	0.359	0.589	0.635	0.582	0.602
7	0.474	0.712	0.315	0.526	0.288	0.685	0.487	0.635	0.422	0.515
8	0.768	0.667	0.310	0.232	0.333	0.690	0.683	0.600	0.420	0.568
9	1.000	0.762	0.309	0.000	0.238	0.691	1.000	0.678	0.420	0.699
10	0.000	0.306	0.234	1.000	0.694	0.766	0.333	0.419	0.395	0.382
11	0.499	0.000	0.000	0.501	1.000	1.000	0.500	0.333	0.333	0.389
12	0.608	0.062	0.184	0.392	0.938	0.816	0.560	0.348	0.380	0.429
13	0.138	0.390	0.149	0.862	0.610	0.851	0.367	0.450	0.370	0.396
14	0.324	0.326	0.205	0.676	0.674	0.795	0.425	0.426	0.386	0.412
15	0.474	0.261	0.254	0.526	0.739	0.746	0.487	0.403	0.401	0.431
16	0.175	0.212	0.121	0.825	0.788	0.879	0.377	0.388	0.362	0.376
17	0.449	0.010	0.109	0.551	0.990	0.891	0.476	0.336	0.359	0.390
18	0.466	0.035	0.165	0.534	0.965	0.835	0.483	0.341	0.375	0.400

Deviation sequence (DS), Grey relational coefficient (GRC)

The highest value for the calculated GRADE indicates the best factor levels. As a result, the multi-response problem was transformed into a single-response problem with GRA. The Taguchi analysis results according to the GRADE value obtained are given in Table 6. According to Table 6 and Figure 4, the best levels of control factors for process variables are recommended as $A_1B_1C_3$.
The best factor levels according to the average GRADE values given in Table 8 are visualized in Figure 5.

In this study, a multi-way ANOVA was used to examine the interactions of all control factors used in the experimental design. The analysis results at 95% reliability and 5% significance levels for surface roughness, circularity, and cutting forces are given in Table 7. The F value in the tables is a ratio used to compare the effects of the control factors. The factor that affects the result the most is the one with the largest F value. The P value shows the ratio that is how much the variables have significant effects on the results. The sum of squares (SS), mean of squares (MS) values, and contribution of factors to results (CRBT) values are given in the table 7.

It is observed that the feed rate is the most influential parameter on surface roughness because the Pc value is smaller than the other factors when the ANOVA results for surface roughness are analyzed. The P value is a criterion for a significant difference between the mean response values of the control factor levels. When the residual graph of the analysis of variance for surface roughness given in Figure 6 is examined, it is seen that the data are significant.

It is observed that the cutting method is the most influential parameter in the results when the ANOVA results for circularity are analyzed. According to the residual graph given in Figure 7, the data distribution shows that the data is significant.

When the ANOVA for cutting forces is analyzed, the cutting method significantly affects the results, as expected. The high SS value in this analysis can be attributed to the high difference between the average force values measured by the two methods. Indeed, the fact that the trochoidal machining method works at high chip depths causes higher force values to be measured than the conventional method. When the graphs given in Figure 8 are analyzed, it is seen that the analysis for cutting forces is significant.

Table 6. Taguchi analysis according to average GRADE

Factor	Level 1	Level 2	Level 3	Max-Min
A	**0.647**	0.401	-	0.246
B	**0.571**	0.509	0.491	0.080
C	0.498	0.521	**0.552**	0.054
Total mean grey relational grade = 0.524		Recommended Levels: $A_1B_1C_3$		

**Bold values indicate maximum values.*

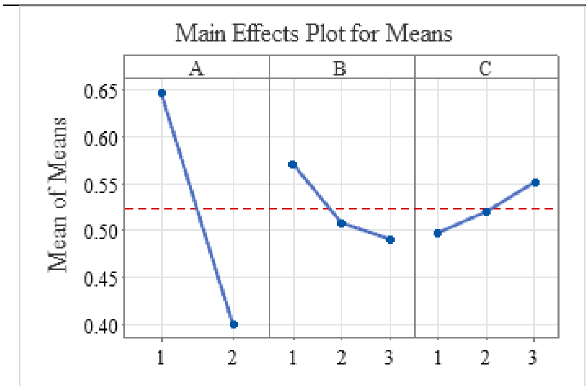

Figure 5. Gray relational degree graph with averages

Table 7. ANOVA results for responses

	Factors	DF	CRBT	SS	MS	F	P
Surface roughness	A	1	25.66%	0.017174	0.017174	24.14	0.00036
	B	2	4.31%	0.002886	0.001443	2.03	0.17420
	C	2	**57.28%**	**0.038342**	**0.019171**	**26.95**	**0.00004**
	Error	12	12.75%	0.008536	0.000711		
	Total	17	100.00%				Model R-sq: 87.25%
Circularity	A	1	**73.73%**	**0.108804**	**0.010804**	**65.75**	**0.000003**
	B	2	6.90%	0.001011	0.000506	3.08	0.083384
	C	2	5.91%	0.000866	0.000433	2.63	0.112597
	Error	12	13.46%	0.001972	0.000164		
	Total	17	100.00%				Model R-sq: 86.54%
Cutting forces	A	1	**68.97%**	**2354781**	**2354781**	**89.67**	**0.00001**
	B	2	21.65%	739255	369628	14.08	0.03229
	C	2	0.15%	5091	2545	0.10	0.7236
	Error	12	9.23%	315116	26260		
	Total	17	100.00%				Model R-sq: 90.77%

**Bold values indicate maximum values.*

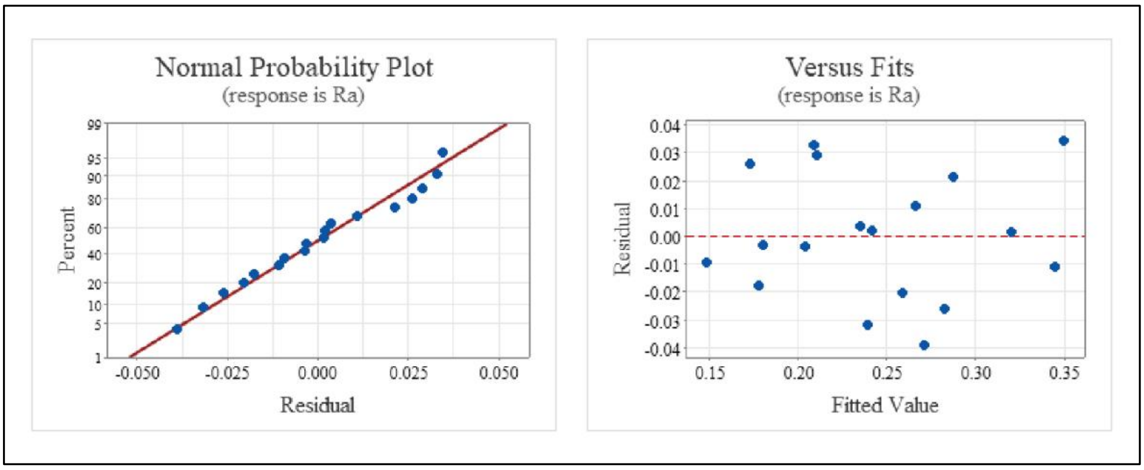

Figure 6. Residual graphs for surface roughness

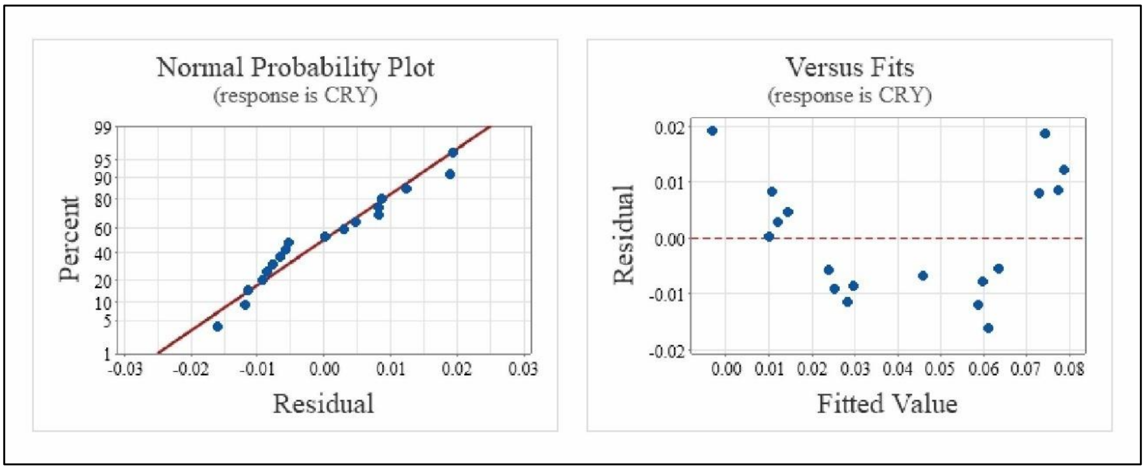

Figure 7. Residual plots for circularity

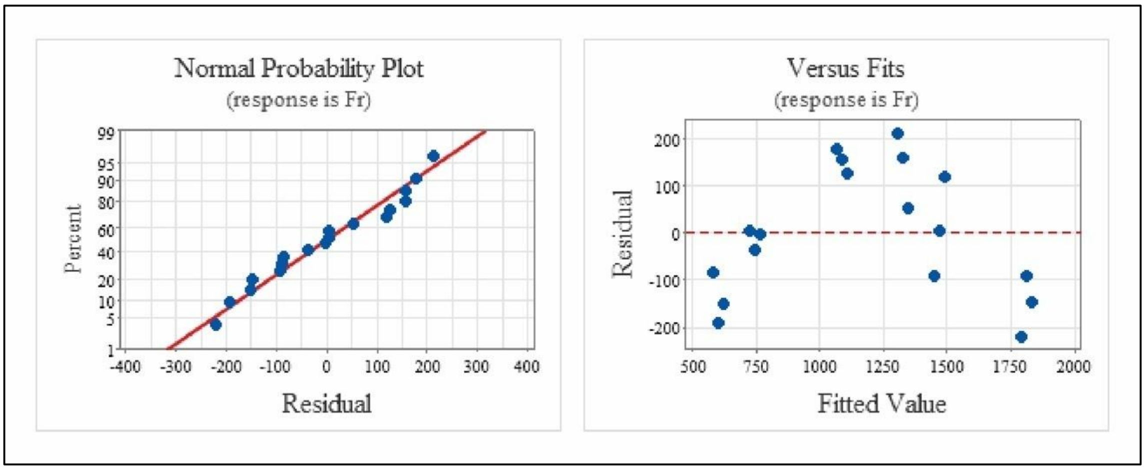

Figure 8. Residual plots for average cutting force

3.1. Relationships and analysis of control factors on multiple responses

GRA simplifies the multi-response problem to the single-response GRADE given in Table 5 to examine the relationships of control factors on multiple responses. The sum of the squares of the SS_T deviations from the total mean of the calculated GRADE values (γ_t) can be calculated as follows;

$$SS_T = \sum_{j=1}^{p} (\gamma_j - \gamma_t)^2 \quad (9)$$

Where γ_j is the mean of the GRADE at the optimal level and p is the number of control factors affecting multiple response variables. The SS_T calculated by equation 9 can be used to evaluate the effects of control factors on GRADE performance. ANOVA was performed to analyze the effects of control factors on multi-response variables, and the results are presented in Table 8:

Table 8. Analysis of variance according to GRADE structures of controls

Factor	DF	SS	MS	MS	F	P
A	1	0.272	0.272	94.9	89.67	0.0000005
B	2	0.021	0.011	3.67	14.08	0.0572164
C	2	0.009	0.004	1.53	0.10	0.2568249
Error	12	0.034	0.003			
Total	17	0.336			Model R-sq: 89.77%	

When the analysis of variance results are analyzed in Table 8, the F value is a ratio that shows which parameters have a high effect on performance according to Fisher's test. Here, factor A is the most influential parameter on the GRADE value of multiple response performances reduced to a single response. The residual plot given in Figure 8 shows that the experimental measurements are significant for the analysis results.

3.2. Experimental Findings

After conventional machining, BUE formation was observed on the cutting edges, rake face, and primary and secondary relief surfaces of the tool. The primary cause of BUE formation can be attributed to the cutting forces and high heat input acting exclusively on the tooltip and the prolonged total machining time.

During the machining process, BUE continuously forms and disappears; however, over a certain period, these formations start to accumulate on the cutting surface, layering up and altering the tool geometry. When detached, these accumulated structures on the cutting edge may lead to cracks and fractures on the tool surface.

This study examined the tools used during milling under a microscope, and BUE formations were observed on tools operating under various parameters, as shown in Figure 10. This finding does not provide conclusive information on whether the BUE is temporary or permanent; however, it offers insight into the parameters under which tool wear mechanisms related to BUE formation become active.

It was observed that BUE formation was not detected at many essential levels of the cutting parameters or very little for some levels when the cutting tools used on the trochoidal (Level, A_2) machining method were examined.

In the trochoidal method, a high axial cutting dimension of the tool increases the chip size removed in one pass. The oversized chip is effectively removed from the cutting zone, and the likelihood of returning it to the chip zone is reduced. The conventional method operates at a much smaller depth of cut than trochoidal cutting. The chips produced at small depths of cut are easier to break. Removing a small chip shape from the cutting zone can be more difficult. Therefore, the chip is more likely to re-enter the cutting zone after cutting. The return of the chip to the cutting zone causes an increase in force and temperature. Accordingly, the heat and force generation during cutting is more stable in the trochoidal method than in the conventional method. In addition, the cutting pressure on the unit cutting edge is lower when the total cutting forces are proportional to the high edge. Heat and cutting pressure are the main factors in BUE formation. Therefore, the lower occurrence of BUE in the trochoidal method can be attributed to the higher depth of cut and chip size.

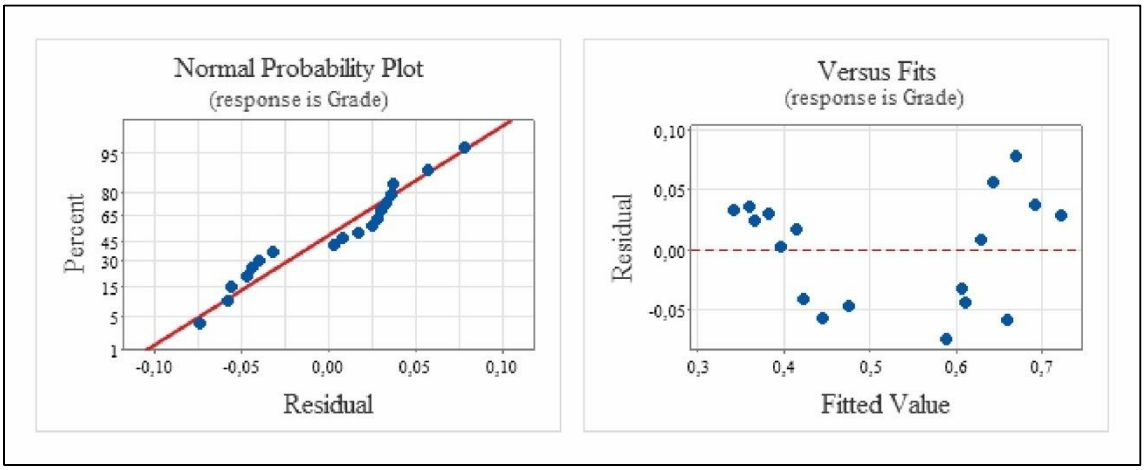

Figure 9. Variance analysis waste graphs according to GRADE values

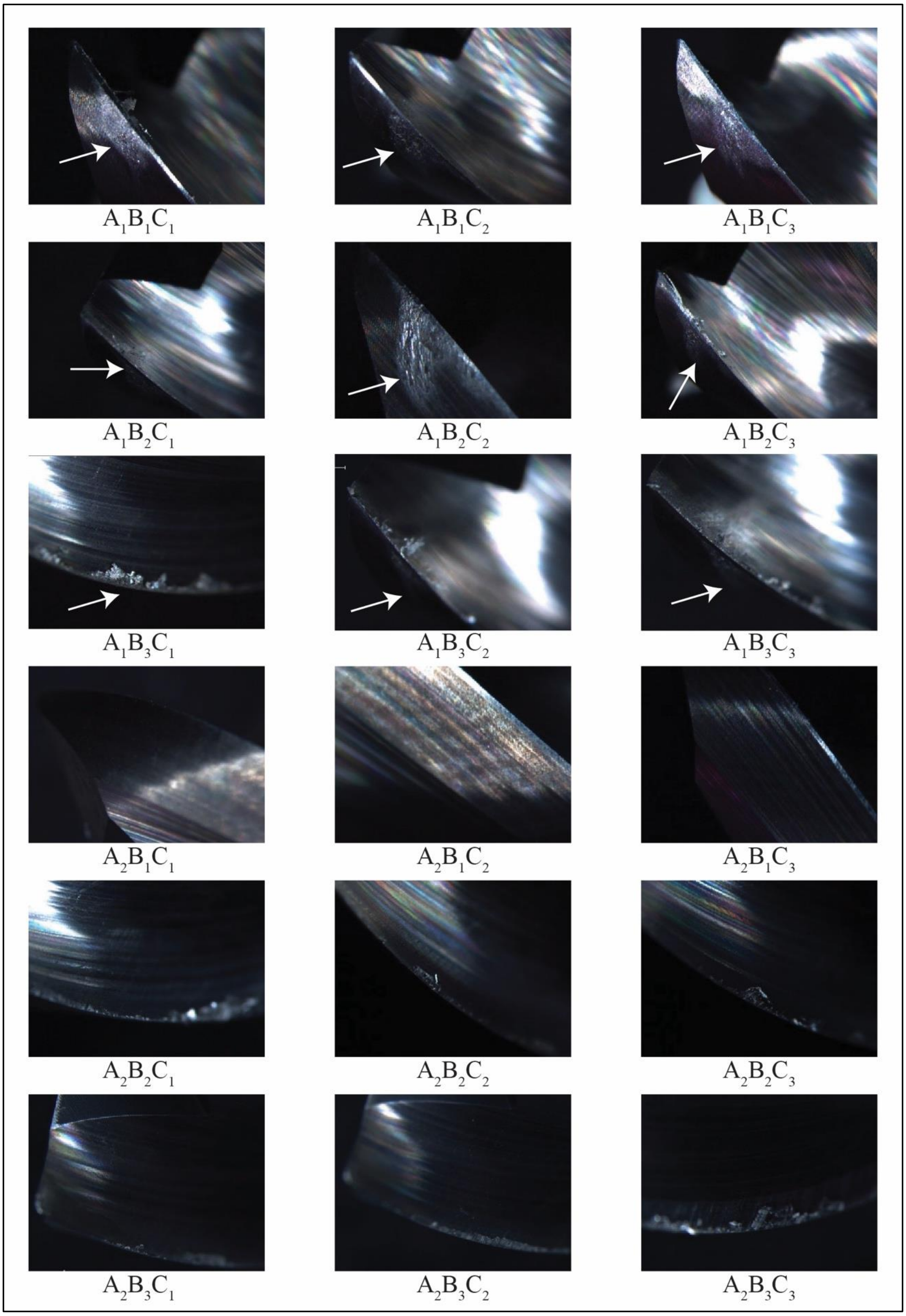

Figure 10. Cutting edges after milling process

The milling experiments using Trochoidal and Conventional methods revealed significant differences in cutting forces concerning machining time and frequency components. In the Trochoidal method, the 15 mm depth of cut was removed in a single pass, resulting in a shorter machining time than in the Conventional method. In the Conventional method, however, the 15 mm depth of cut was removed in 15 separate passes of 1 mm each, leading to a noticeably longer machining time. This difference was observed when overlaying the cutting force measurement graphs (Figure 11, a).

Additionally, the analysis of power spectral density (PSD) for cutting forces revealed that the Trochoidal method exhibited a single dominant frequency component (Figure 11, b and c), whereas the Conventional method showed multiple frequency components (Figure 11, d and e). This indicates that trochoidal cutting generates a more stable and uniform cutting force, while the conventional method results in a complex, multi-component force structure. Unstable cutting forces, as seen with the Conventional method, have the potential to induce forced vibrations, which increase the likelihood of chatter due to the system's resonance and regenerative mechanisms under improper cutting conditions[40]. This phenomenon negatively impacts tool life and surface quality, as high force fluctuations lead to accelerated wear on the cutting edge and a degraded surface finish on the machined part. In contrast, the stability and uniformity of cutting forces achieved with the Trochoidal method help to minimize these adverse effects, enhancing surface quality and tool life by reducing the incidence of chatter and associated wear mechanisms. These findings suggest that the Trochoidal method provides more efficient and stable performance in both machining time and force spectrum.

The findings demonstrate the potential advantages of trochoidal milling in industrial applications. Specifically, the trochoidal milling method reduces tool loads and heat buildup, extending tool life and enhancing machining efficiency. Our study shows that the trochoidal method can manage cutting forces with a more stable frequency distribution when machining difficult materials, and it outperforms the conventional method in terms of performance criteria such as surface quality and cycle time. When applied with optimal cutting parameters, these results indicate that trochoidal milling offers significant advantages in reducing per-part costs and increasing production speed. These benefits contribute to sectors requiring precision machining and high production rates, such as the automotive, aerospace, and defense industries.

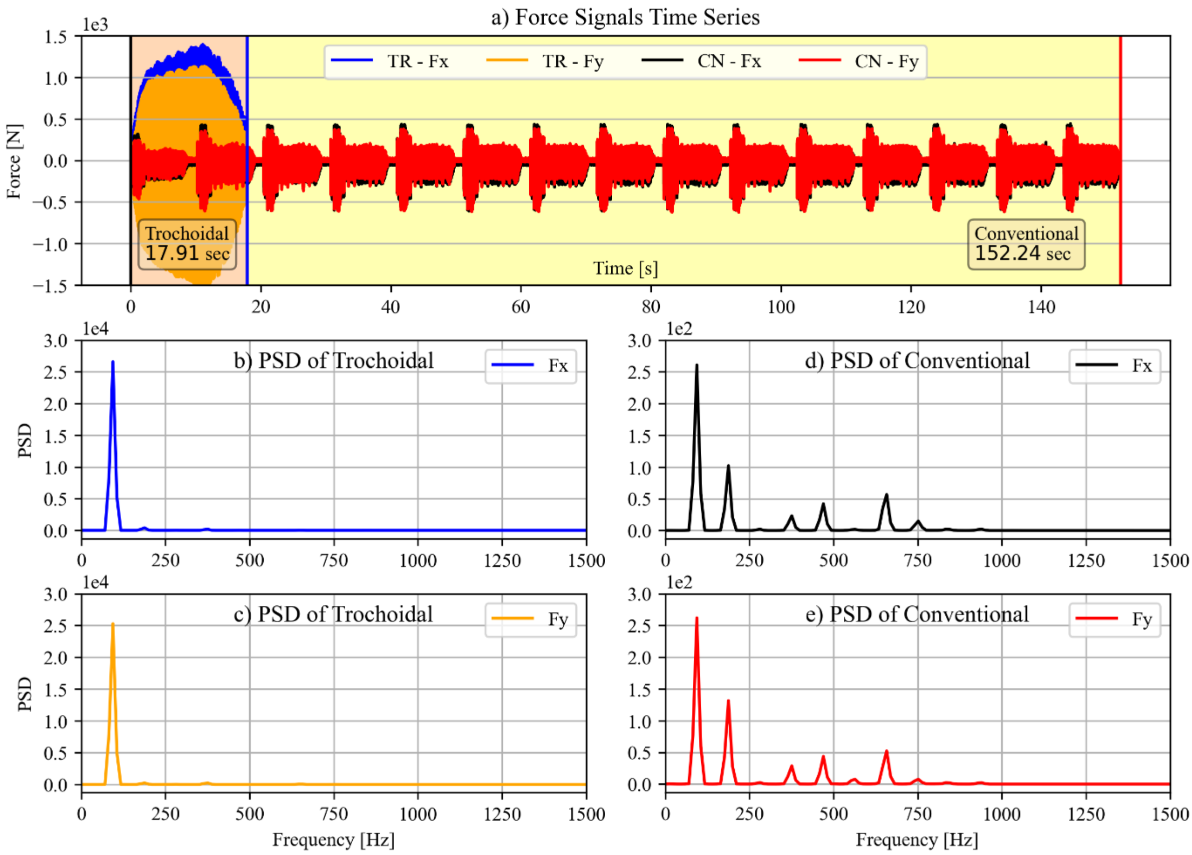

Figure 11. Force measurements for Trochoidal and Conventional milling experiments number three (According to GRD)

4. CONCLUSIONS

In this study, the performances of conventional and trochoidal milling methods were investigated depending on the cutting conditions, and the optimum cutting parameters were determined. The experimental design was based on the Taguchi L18 orthogonal array with two levels for the cutting method (Factor A), three levels for cutting speed (Factor B), and three levels for feed rate (Factor C) as control factors. The results were evaluated according to the S/N ratios of surface roughness (Ra), circularity (CRY), and cutting forces (Fr) response values. The optimum cutting parameters for each response value were determined by Taguchi analysis. In addition, the multiple response problem was reduced to a single response problem by GRA, and the cutting parameters were optimized. Finally, the effects of the control factors on the response variables and GRADE were analyzed separately by ANOVA. The results are summarized below:

- The best average surface roughness value was obtained at $A_1B_3C_3$ levels of control factors.
- The best value for circularity was obtained at the $A_1B_2C_1$ levels of the control factors.
- The best value for the average cutting forces was obtained at the $A_1B_1C_3$ levels of the control factors.
- The optimum levels of cutting parameters for GRADE were obtained as $A_1B_1C_3$.
- The most effective parameter on the average surface roughness was found to be the C factor with a rate of 57.28%.
- The most influential parameter on the average circularity values was the cutting method, with an influence rate of 73.73%.
- The most influential parameter on the average cutting force values was the cutting method, with an influence rate of 68.97%.
- The cutting method was the most influential parameter on GRADE values.
- Examining the time series provided in Figure 10 reveals that the total machining time for material removal in the trochoidal cutting method is significantly shorter than in the conventional cutting method. This demonstrates the efficiency advantage of the trochoidal method compared to the conventional approach.
- The results indicate that the trochoidal milling method provides a more stable cutting force profile with a single dominant frequency component, whereas the conventional method exhibits a more complex and fluctuating force structure due to the presence of multiple frequency components. It has been evaluated that the unstable force components observed in the conventional method may negatively impact quality parameters such as surface roughness, while the stable force components in trochoidal milling could have a positive effect on these parameters.

The present study offers valuable insights into the comparative performance of trochoidal and conventional milling methods. It is important to acknowledge certain limitations of this study. It should be noted that the experiments were conducted under specific cutting parameters and material types, which may influence the generalisability of the results. It would be beneficial for future studies to explore a broader range of materials, cutting parameters, and machine configurations to validate and extend these findings. Additionally, investigating the effects of different tool geometries and cooling methods could enhance milling performance. Further research in these areas would contribute to a more comprehensive understanding of the optimal conditions for trochoidal milling in various industrial applications.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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