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Investigation on the Effects of Machining Performances for Milling Al-30%/SiC-70% Infiltrate Metal Matrix Composites

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ABSTRACT

The unique properties of Al-30%/SiC-70% Metal Matrix Composite (MMC) such as lightweight, high strength, and wear resistance has made it as an alternative material for precision machinery parts. Owing to the presence of hard-abrasive reinforcement particles within the matrix, these materials are known as low machinability rating materials. Furthermore, the absence of a dedicated cutting tool for machining MMC materials is the cause of many intrinsic issues., such as high surface roughness and high cutting temperature. In this work, the application of the Taguchi method to determine the effect of the cutter geometric characteristics and cutting parameters for Al/SiC MMC machining is perform. During the planned experiment, sixes parameters were taking into consideration namely helix angles, rake angles, clearance angles, number of flutes, spindle speed, feed rates and depth of cut. The measured responses are surface roughness and cutting force, which is important for the functionality of the component. ANOVA was used to validate each factor's percentage contribution. The results show that the main factor contributing to fine surface roughness and low cutting force is fewer flutes. Fewer flutes give a smooth chip executable flow, minimizing the friction of the cutting area vital in composites materials such as MMC. Because they provide optimum sheared power, helix angles, spindle speed, and cutting depth also influence the mechanical performance. The clearance angle of both reactions is found to be less important since it only controls the damping process and stability. The main conclusion is that the cutter geometric characteristics and cutting parameters are significantly affected by machining performance and therefore the need for special design cutters is concluded for the efficient production of Al/SiC MMC materials.

Keywords: Metal matrix composite, end mill design, machining performance, Taguchi

1. INTRODUCTION

Metal matrix composites (MMC) or, more specifically, Al/SiC, have been developed as a result of the advancement of such advanced and modern technologies. Its mechanical properties, which include low density, high strength, heat resistance, wear resistance, and lightweight, have made it a popular material in the automotive industry [1-2]. Al/SiC is a composite material made up of an aluminium matrix and SiC particle reinforcement. The composition of the Al/SiC mixture will change the properties of the two materials [3]. MMC is typically made to near net-shape through a casting or infiltration operation. As a result, secondary processes like deburring and machining are essential to obtain the final component dimension.

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When it comes to machining MMC material, however, the manufacturer faces a few challenges. The key issues with this substance stem from the fact that it is non-homogeneous and anisotropic. Consequently, the abrasiveness of the reinforcement combined with the metal matrix has added to the machining process's complexity [4]. Rapid tool wear, rough machined surface, excessive cutting temperature, and high cutting force are some of the issues that have been identified in machining MMC [5-6].

The mechanic of shearing process for the MMC material differs from other homogenous material in which it can deteriorate the material properties particularly in the sub-surface level. The machined surface condition for MMC's can be categorized into three types as depicted in Figure 1. The first category is the uncut particles which due to the failure of the cutter tip to shear and break the hard particle. As a result, could lead to the formation of rough machined surface due to the particle protrude to the outer surface. Second category is the dislocation of particle, as a result of inadequate cutting depth distance between the tool tip and the particle which causing the particle to move downward to the material. Due to this particle dislocation, the workpiece surface hardness can be increase. The last category is the cutting/breaking particle as a result of adequate cutting depth distance between the tool tip and the particle which lead to sufficient shearing action to break the particle. During this stage, the magnitudes of the cutting force known as particle fracture force can increase rapidly which can result in chipping at the tool rake face. In addition, the formation of machined surface is also influence by the ratio between the matrix and the particle

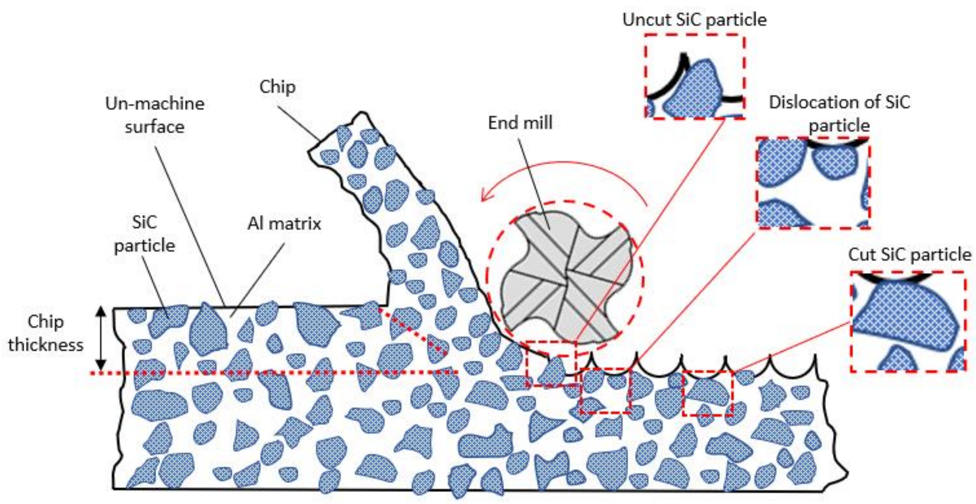

Figure 1. Mechanic of material removal for Al/SiC MMC material.

In general, surface finish plays an important role in most engineering applications such as part lubrication, wear and surface friction. In the context of machining, surface finish value is one of the key performance indicators to evaluate the part accuracy and final dimension. Based on the literature on machining MMC materials, machining parameters such as speed, feed rate, depth of cut and cutting tool geometry have a significant influence on the surface roughness value. Nevertheless, the aforementioned machining parameter will greatly influence the magnitude of cutting force which are important on the tool wear rate. Therefore, the knowledge on the effect of machining parameters towards the machining performances i.e. surface roughness and cutting force is important for the success of machining MMC materials which will be explore in this paper.

2 MATERIALS AND METHODS

2.1 Al-30%/Sic-70% Metal Matrix Composite

A composition of Al-30%/SiC-70% metal matrix composite fabricated through pressure infiltration method was used in the experiment. A key advantage of the pressure infiltration method is that it allows for very high particle volume fractions, producing MMCs with low thermal expansion. Figure 2 and Table 1 show the pressure infiltration process and detail properties of the Al-30%/SiC-70% material respectively.

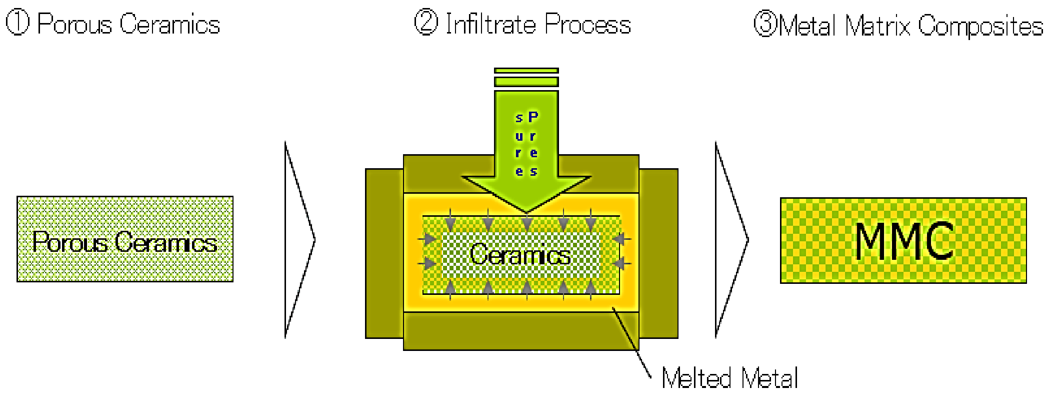

Figure 2. Pressure infiltration process.

Table 1 Workpiece Used in the Experiment

Metal Matrix Composites (MMC)	Al/SiC
Process	Infiltration Method
Composition (vol%)	SiC-70%; Al-30%
Density (g/cm3)	3.0
Flexural strength (MPa)	340
Young's Modulus (GPa)	260
Poisson's Ratio	0.20
Fracture Toughness (MPa*m1/2)	8
Thermal Expansion (×10-6/K)	7
Thermal Conductivity (W/m*K)	160
Specific Heat (J/g*K)	0.6
Volume Resistivity (Ω*cm)	1×10-5
Hardness	HRB-110
	HRC-35
Dimension	10 cm×5 cm×2 cm

2.2 End Mill Design

The geometrical characteristics of the end mill are the core diameter, circle diameter, angle of rake, clearance angle, and helix angle. All geometrical features have their specific role and affect machining performance significantly. The geometric terminology of the end mill and the cutting angles are shown in Figures 3. The rake angle may significantly influence the cutting force, stress distribution, deformation of the chip, steepness of the cutting edge, and rigidity of the tool. An end mill with a positive rake angle will improve the machinability, resulting in a lower cutting force. Further, when using a high rake angle tool, cutting forces and power were minimized and a good surface finished was produced. However, the rim strength of the tool because of friction and stress distribution is decreased by a too big rake angle. A proper selection of the rake-angle value is therefore essential and should be particularly considered for the non-homogeneous Al/SiC material.

Clearance angle can also affect a cutting tool's performance. The splits angle is the angle of the cutting surface to the splits on the cutter. A high-value clearance angle is preferred to achieve a good tool life. However, higher clearance angle values tend to weaken the trimmer that is overheated due to poor heat transfer from the trimmer. For end mills, the space for the chip for the same number of teeth is reduced with smaller clearance angles. Primary and secondary clarifications are provided in such cases. The value of the angles also depends on the end mill diameter. The larger relief angles for smaller end mills. Moderate relief angle values for Al/SiC material must be checked and the tool must not be rubbed with the workpieces. Another way to improve damping and stability can be a high relief corner.

A helix angle is a line angle that tangent to the helix and a plane through the cutter axis or cutting-edge angle, made with a plane that contains the axis of a cylindrical cutter by a helicopter cutting edge. A large angle of the helix can reduce the deflection of the tools by transferring stress to the vertical chip ejection of the end mill. As the helix angle increases, shear stress and friction energy increase. More shearing effects also lead to higher speed and feeds and quicker removal of stocks. The helix angle enables several teeth to be cut at the same time, which makes the cutting effects smoother. Figure 2 shows the information on the cutting angles of the end mill.

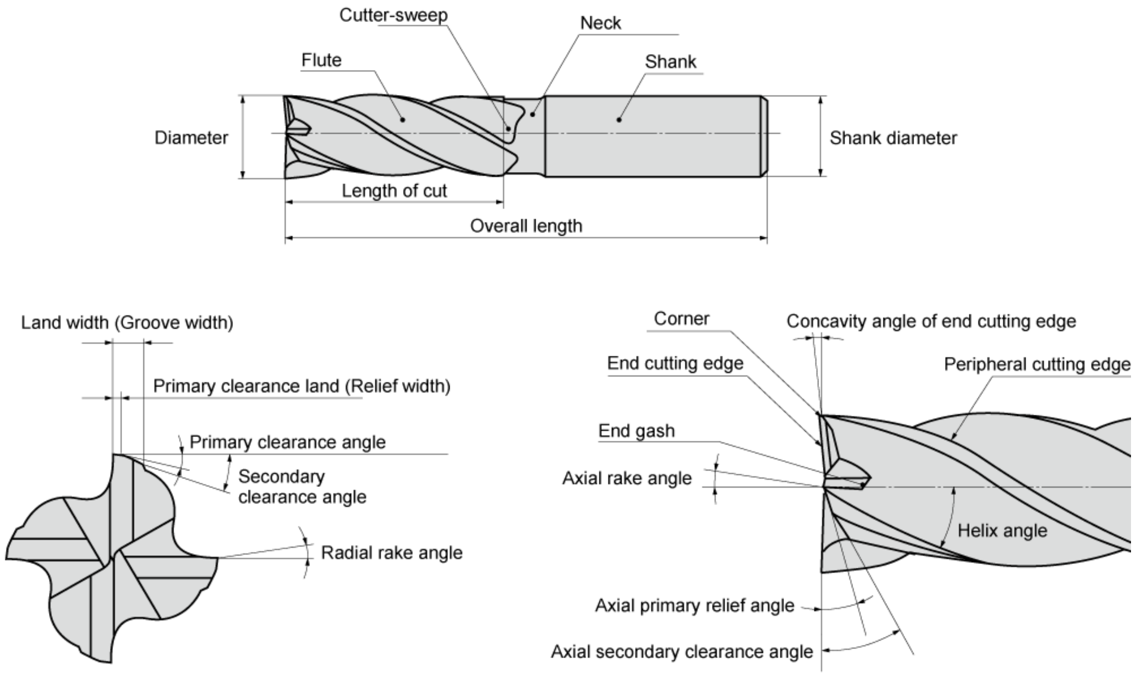

Figure 3. End mill cutting angles.

L_8 Taguchi's method was used to design all the experimental parameters. It has a total eight number of runs and two-level which are the maximum and minimum values for each factor. To make the tungsten carbide rod cutter according to the design parameters specified, the CNC Tool & Cutter Grinder Michael Deckel S20 Turbo was used. The choice of the cutter type is based on the reliability and cost of the material. Table 4 shows the specification of the end mill used. A total of eight different end mill designs with different helix angles, rake angles, clearance angles, and number of flutes are produced. To study the effects on machining performances as shown in Table 2, machining parameters such as the cutting speed, feed rate, and depth of the cuts are also varied. A three-axis HAAS CNC milling machine was used for the slot milling process to investigate the relationship toward the machining performances namely surface roughness and cutting force.

Table 2 Design Parameter for End Mill

Tool Design	Helix angle (°)	Rake angle (°)	Clearance angle (°)	Number of flutes	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)
1	30	5	6	2	1000	100	0.5
2	30	5	6	4	4000	500	1.5
3	30	15	18	2	1000	500	1.5
4	30	15	18	4	4000	100	0.5
5	60	5	18	2	4000	100	1.5
6	60	5	18	4	1000	500	0.5
7	60	15	6	2	4000	500	0.5
8	60	15	6	4	1000	100	1.5

3. RESULTS AND DISCUSSION

The results of the machining test were presented in Table 3 and Figure 4. The results show the variation on each response value that shows the important effects of both factors, e.g. cutter geometry and cutting parameter. The maximum Ra value with an average of 4.07 µm was obtained by run No. 2 from the observed machining surface conditions, with 30° helix angle, 5° rake angle, 6° clearance angle, 4 flutes, 4000 rpm spindle speed, 500 mm/min feed rate and 1.5 mm depth of cut. The slotted surface for run 2 clearly shows the formation of cutter marks and the black spot that the SiC particles represent. The minimum Ra value with an average of 1.29 µm was obtained by run No. 6 from the observed machining surface conditions, with 60° helix angle, 5° rake angle, 18° clearance angle, 4 flutes, 1000 rpm spindle speed, 500 mm/min feed rate and 0.5 mm depth of cut. The slotted surface for run 6 clearly shows no formation of cutter marks. In addition, the maximum and minimum cutting force were observed from run No. 5 and No. 4 respectively.

Table 3 Experimental Results

	Surface roughness (µm)				**Cutting force (N)**			
	1	**2**	**3**	**Avg.**	**1**	**2**	**3**	**Avg.**
1	1.78	1.82	1.84	1.83	702.45	714.20	709.00	708.55
2	4.11	4.05	3.98	4.07	433.20	425.84	427.25	428.76
3	1.98	2.05	2.11	2.05	1896.72	1942.46	1929.63	1922.94
4	2.82	2.72	2.64	2.70	192.68	166.34	184.18	181.07
5	2.12	2.11	2.08	2.12	1674.86	1448.83	1672.31	1598.67
6	1.21	1.28	1.34	1.29	810.64	890.47	883.65	861.59
7	2.12	1.98	1.85	1.97	872.37	863.28	850.03	861.89
8	1.92	1.89	1.84	1.91	542.96	588.32	562.40	564.56

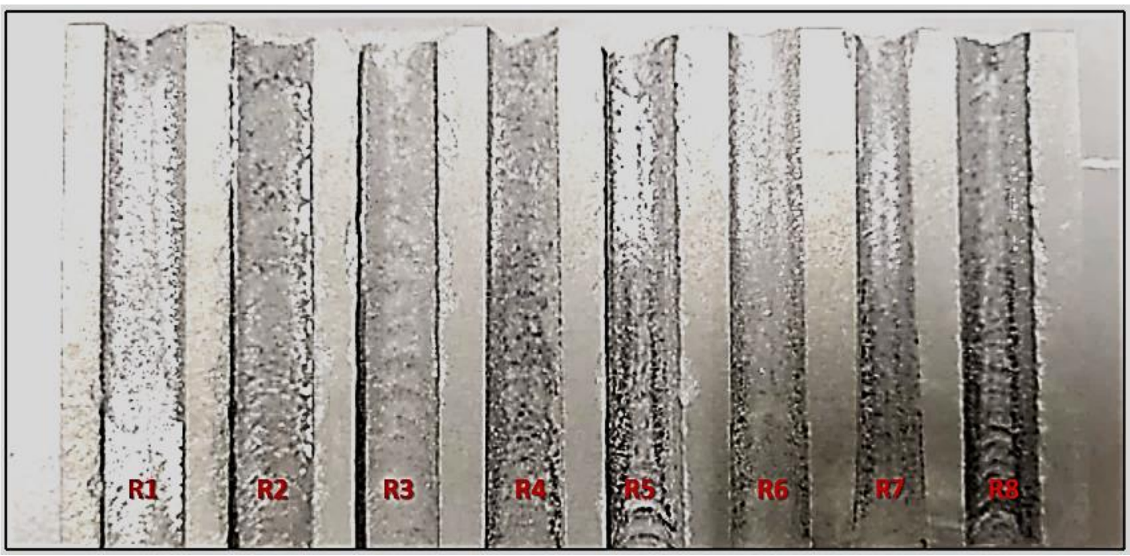

Figure 4. Machining slot.

Further analysis using the Signal to Noise (SN) ratio graph was used to investigate the effects on each factor. Table 4 shows the SN ratios response table for surface roughness. Figure 5 shows the SN ratios graph of surface roughness. The graph shows that the surface roughness produced is significantly influenced by helix angle and spindle speed followed by clearance angle, number of flutes, and depth of cut. A low surface roughness value indicates a better surface profile. Therefore, 'smaller is better' is chosen for the target condition. Based on the result, a lower helix angle value (30°) is required to produce a smooth surface roughness while a higher spindle speed value (4000 rpm) is required to obtain the same surface roughness. This is also accompanied by clearance angle (6°), the number of flutes (4), and depth of cut (1.5 mm) which has the same condition with helix angle and spindle speed. Rake angle (15°) and feed rate (500 mm/min) have the same graph pattern that is to choose a large value.

Table 4 SN Ratios Response Table for Surface Roughness

Level	Helix Angle	Rake Angle	Clearance Angle	Number of Flutes	Spindle Speed	Feed Rate	Depth of Cut
1	-8.076	-6.545	-7.238	-5.975	-4.829	-6.506	-5.494
2	-5.062	-6.593	-5.900	-7.163	-8.309	-6.632	-7.644
Delta	3.014	0.048	1.338	1.188	3.480	0.126	2.149
Rank	2	7	4	5	1	6	3

Figures 6 and 7 show the cutting force response measured using the Dynoware tool on the second experimental run. Based on the figure, it clearly shows why the second run has the lowest cutting force value of 428.76 N on average compared to the other runs. This is because the force in the x-axis and y-axis directions shows a downward trend while machining is in progress. Although the force in the z-axis direction is quite high, it begins to decrease when the machining is almost complete. Slot milling performed on the workpiece focuses on the x and y axes only.

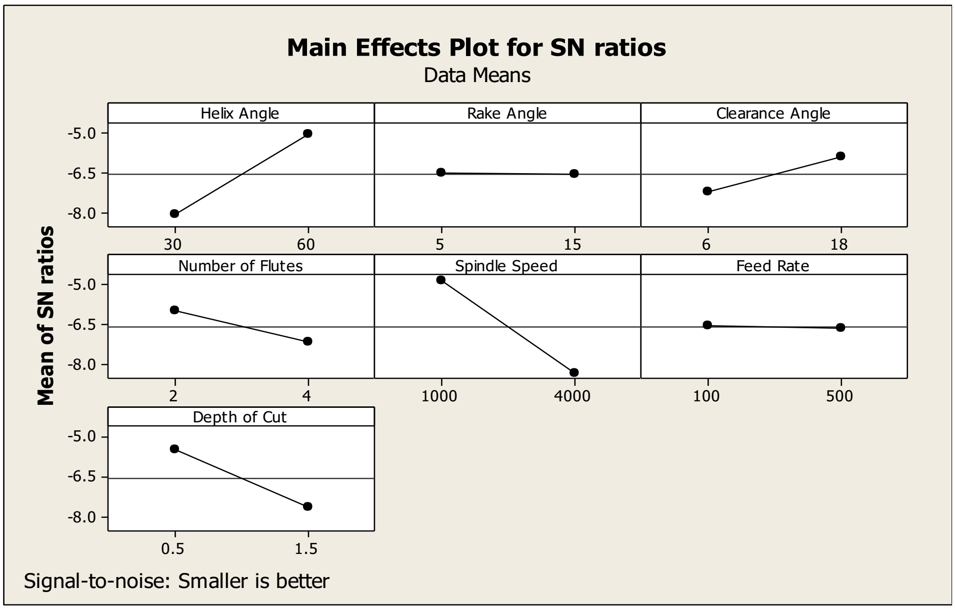

Figure 5. SN ratios graph of surface roughness.

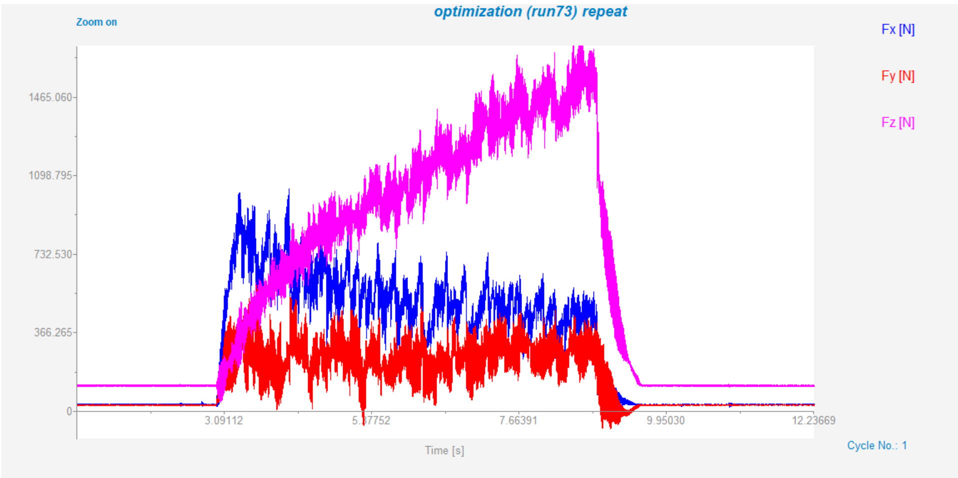

Figure 6 The lowest cutting force graph.

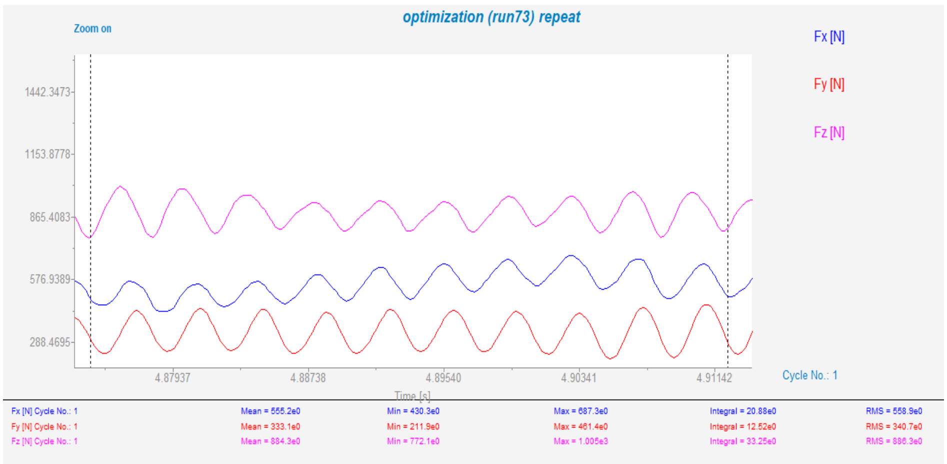

Figure 7. Zoom on the lowest cutting force graph.

Figures 8 and 9 show the cutting force response measured using the Dynoware tool on the third experimental run. Based on the figures mentioned, it shows on the third experimental run, the cutting force on all three axes. x, y, and z. It does not show a downward trend, but they increase when slotting is done on the workpiece. This has caused the value of the cutting force on the third run is the highest value which is 1922.94 N on average.

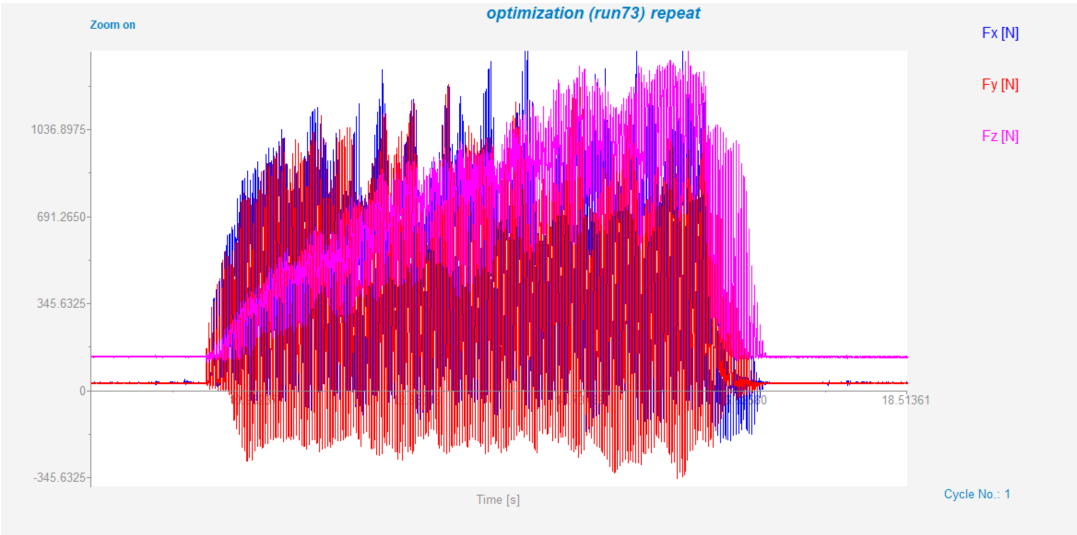

Figure 8. The highest cutting force graph.

Figure 9. Zoom on the highest cutting force graph.

Table 5 shows the SN ratios response table for cutting force. Figure 10 shows the SN ratios graph for cutting force. Lower cutting force values are required to produce good machining quality. This is because the cutting force is often closely related to the friction that leads to the cutting temperature. Therefore, 'smaller is better' is chosen to obtain good machining quality. This graph shows that the cutting force is influenced by helix angle and spindle speed followed by rake angle and number of flutes. Based on this graph, the low cutting force value can be obtained if the helix angle value (60°) clearance angle value (18°), feed rate value (500 mm/min), and depth of cut value (1.5 mm) are high and the spindle speed value (1000 rpm), rake angle value (5°) and the number of flutes value (2) is low.

Table 5 SN Ratios Response Table for Cutting Force

Level	Helix Angle	Rake Angle	Clearance Angle	Number of Flutes	Spindle Speed	Feed Rate	Depth of Cut
1	-55.16	-58.25	-55.80	-61.44	-59.16	-55.45	-54.96
2	-59.25	-56.15	-58.60	-52.96	-55.24	-58.96	-59.45
Delta	4.09	2.10	2.80	8.48	3.92	3.51	4.49
Rank	3	7	6	1	4	5	2

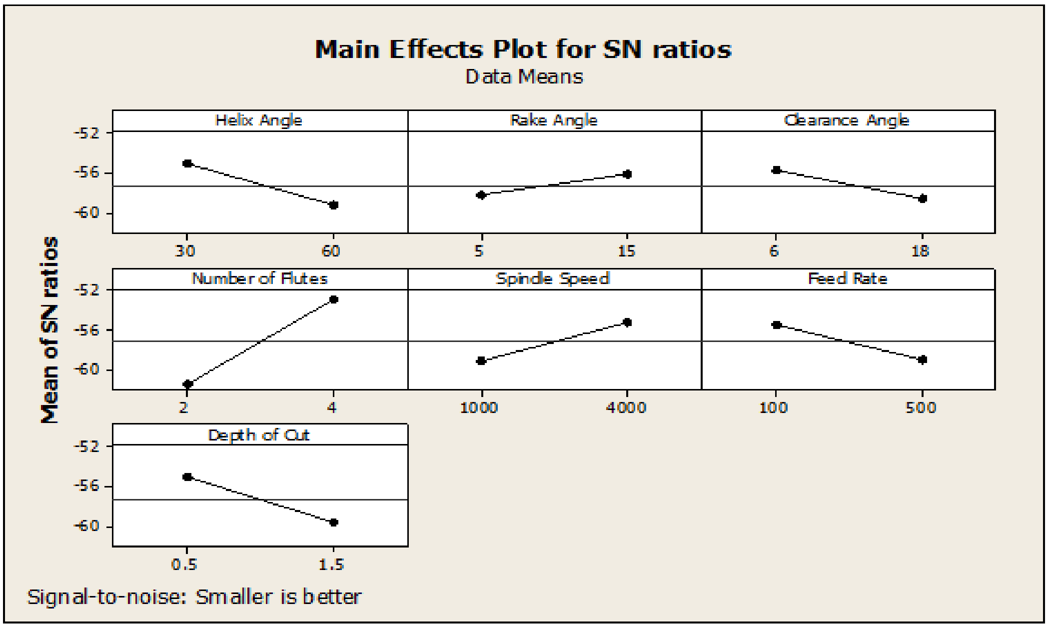

Figure 10. SN ratios graph of cutting force.

Based on Tables 6, ranking differences can be seen for each input parameter influencing the respective response output. Surface roughness is greatly influenced by spindle speed while for cutting force, a large value of flutes affects it. Both factors are less influenced by the rake angle. Therefore, rake angle will be discarded for the ANOVA input.

Table 6 Summarizes Ranking

Input parameters	Surface Roughness Ranking	Cutting Force Ranking
Helix Angle	2	3
Rake Angle	7	7
Clearance Angle	4	6
Number of Flutes	5	1
Spindle Speed	1	4
Feed Rate	6	5
Depth of Cut	3	2

Table 8 Analysis of Variance (ANOVA) for Surface Roughness and Cutting Force

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Helix Angle	1	33.372	33.372	33.372	3.77	0.303
Clearance Angle	1	15.654	15.654	15.654	1.77	0.410
Number of Flutes	1	143.913	143.913	143.913	16.26	0.155
Spindle Speed	1	30.710	30.710	30.710	3.47	0.314
Feed Rate	1	24.681	24.681	24.681	2.79	0.343
Depth of Cut	1	40.310	40.310	40.310	4.56	0.279
Residual Error	1	8.849	8.849	8.849		
Total	7	297.489				

According to ANOVA analysis, as shown in Table 7, the number of flutes is the most significant input parameter for obtain better surface roughness and cutting force of Al/SiC MMC as the lowest p-value which is 0.155. For the clearance angles, the p-value is 0.410 which larger than the p-value of the others input parameters. Thus, it is showing the clearance angles contribute to a less significant effect on surface roughness and cutting force of Al/SiC MMC compared to others.

4. CONCLUSION

With their tailored enhanced properties, the usage of metal matrix composite (MMC) continues to growth while, at the same time, posture significant challenges in terms of poor machinability. It is evident that cutter geometrical features namely helix angles, rake angles, clearance angles, and the number of flutes as well as cutting parameters which are spindle speed, feed rate, and depth of cut have a significant impact on surface roughness and cutting force. The most important factor affecting surface roughness and cutting force value is the number of flutes followed by the depth of cut, helix angle, spindle speed, and feed rate. Lastly, clearance angle gives less significant effects on machine surface roughness and cutting force. The findings from the deliberately conducted experiments proved that careful selection of the machining parameters and cutter geometry is the key to achieving an economical and accurate cutting process for MMC.

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