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Optimization of Machining Parameters for Al-Li Alloy to Enhance Surface Smoothness Using the Taguchi Method

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Abstract

Al-Li alloys offer a 20% weight reduction compared to conventional high-strength aluminum alloys, while exhibiting superior wear resistance and damage tolerance. Despite their low density, these alloys demonstrate exceptional yield strength and overall mechanical performance. As a result, Al-Li alloys are poised to become the preferred material for aerospace and defense applications, replacing other materials soon. To enhance applications in advanced manufacturing processes, this research tries to predict and optimize surface hardness and roughness based on several machining factors, such as feed rate, depth of cut, and cutting speed. The Al-Li alloy 2099 (94.309% Al and 5.691% Li) was machined using a Hartford CNC machine, the Omnis VMC 1270. A 16 mm Widia ALUFLASH series 3AN9 flat carbide cutting tool was paired with Sol XL coolant in a 1:20 water solution. The machining parameters included spindle speeds of 3000 to 6000 rpm, feed rates of 150 to 450 mm/min, and cutting depths of 0.1 to 0.2 mm. The study identified optimal machining conditions for Al-Li alloy 2099, achieving surface hardness and roughness improvements under 6000 rpm spindle speed, 150 mm/min feed rate, and 0.1 mm cutting depth. These conditions can help reduce costs and experimental time in aerospace applications.

Major Findings: *The feed rate most significantly influences surface roughness, followed by depth of cut and spindle speed. Optimal parameters were identified as a spindle speed of 6000 rpm, a feed rate of 150 mm/min, and a depth of cut of 0.1 mm. Increased feed rates adversely impact surface finish. Both feed rate and depth of cut are essential for improving milling efficiency and surface quality.*

Keywords: *Al-Li Alloys, Machining Parameters, Surface Hardness and Roughness, Taguchi Method*

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1.0 Introduction

Aircraft are built from a range of materials chosen for their mechanical, chemical and physical, properties, including strength, stiffness, fatigue resistance, low density, and corrosion resistance, as well as cost and manufacturability. For instance, wings must withstand bending, torsion, and vibration, necessitating materials with high stiffness and strength. Common materials in commercial aircraft like the Boeing 747 and 787 include composites, aluminum alloys, high-strength steels and titanium alloys, is shown in Figures 1 and 2. Although aluminum once comprised over 70% of aircraft materials, its share has dropped to below 20%, with composites gaining prominence due to their superior performance and cost-effectiveness. However, the environmental impact of extracting the minerals for these materials raises significant concerns, as mining activities can severely affect ecological safety and protection. Analyzing surface collapse in mining areas is essential for ensuring safe excavation and promoting sustainable development. The primary materials used in commercial aircraft, such as the Boeing 747 and 787, include aluminum alloys, composites, titanium alloys, and high-strength steels is shown in Figures 1 and 2. While aluminum once constituted over 70% of aircraft materials, its usage has decreased to below 20%, with composites now favoured for their superior performance and economic benefits[1,2]. However, the extraction of minerals for these materials has significant environmental impacts, as ongoing mining can severely affect ecological safety. Thus, understanding surface collapse characteristics and assessing damage levels in mining areas is critical for guiding safe practices and ensuring sustainable resource development.

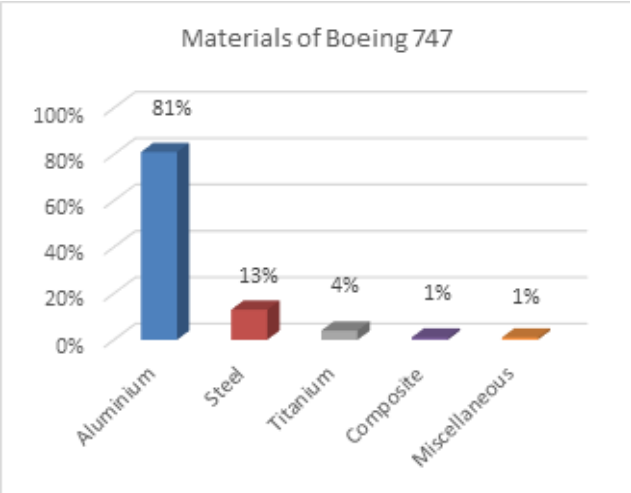


Figure 1. Materials of boeing 747.

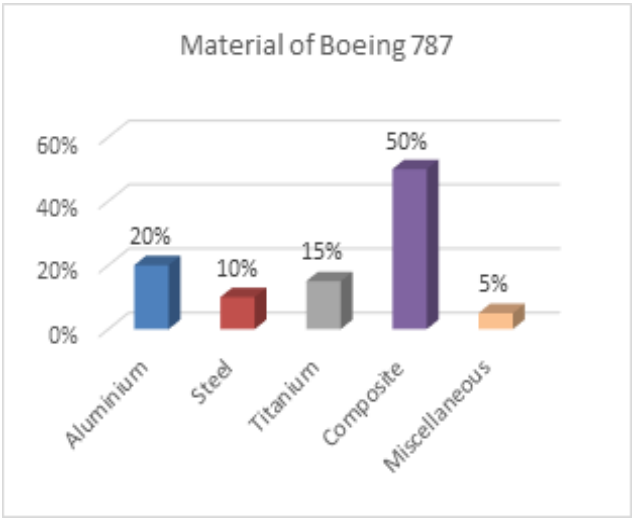


Figure 2. Materials of boeing 787.

Advanced aluminum alloys are a preferred lightweight option in aircraft structures, such as fuselage and wing skins, due to their cost-effectiveness, high ductility, corrosion resistance, and strength. These alloys make up 70-80 % of an aircraft's structural weight and can now rival composites because of advancements in heat treatment. High-strength steels, while economical and offering excellent stability and strength, are primarily used in critical components like gears and undercarriages, accounting for 5-15 % of structural weight. Their use is declining due to high density and corrosion susceptibility[3,4].

Titanium alloys constitute 7% of airframe weight and 36% of engine components, valued for their high specific strength and cryogenic resistance, but they are costly and difficult to manufacture[5].

High-performance composites, including fiber-reinforced materials, are utilized in key structural components like wings and fuselage but face challenges due to their higher costs compared to metals. Research by Alexandre Bois Brochu *et al.*[6] highlighted the anisotropic behavior of Al-Li 2099-T83 extrusions, which affects both tensile and compressive strength.

Yong Xu *et al*[7] identified anisotropic behavior in Al-Li alloys, attributing it to their composition and

processing methods. They recommended approaches to improve both formability and toughness. In separate studies, Nathan Hanapalan, G. Thanigaiyarasu[8] and Arkadeep Bandyopadhyay[9] analyzed the best CNC milling conditions for aluminum 6061, utilizing variable parameters and Mini Tab 18 software for their assessments[10,11].

Haikuo Mou, Xinda Huang *et al.*[12] studied machining aluminum-lithium alloys with liquid nitrogen and air as coolants, finding that surface finish quality is influenced by the feed direction's angle. They also noted that liquid nitrogen improves surface integrity and material removal rates. Mário C. Santos Jr. *et al.*[13] pointed out challenges in machining alloys with hard particles, including high ductility and tool adherence. Selecting the proper cutting tools and factors is crucial for resolving these problems. It is advised to use N-grade cemented carbide, high-speed steel and synthetic diamond (PCD) tools. In their investigation of chip formation in aluminum alloys.

M. Azizur Rahman *et al.*[14] noted that variations in feed rate affect chip shape and can lead to a transition from discontinuous to continuous chip formation. In parallel, Rajesh Kumar Bhushan *et al.*[15] explored the effects of feed rate, depth of cut, and cutting speed on surface roughness while milling 7075 aluminum alloy with SiC composites to identify optimal parameters for enhanced surface quality.

2.0 Materials and Methodology

2.1 Preparation of Al-Li Alloy 2099 Specimen

Alcoa produced Al-Li Alloy 2099 with the purpose of using it in aircraft, emphasizing its good corrosion resistance, low weight, high stiffness, enhanced damage tolerance, and exceptional weldability.

Lithium contributes to the alloy's strong properties and moderate fracture toughness by reducing density and increasing modulus and strength. At BUREAU VERITAS in Bangalore, spectroscopy was used to determine the chemical composition of a one-inch slab of Alloy 2099. The chemical composition and mechanical properties of the alloy are displayed longitudinally in Tables 1 and 2.

Table 1. Al-Li 2099 alloy composition

Element	Wt %
Manganese	0.33
Silicon	0.053
Zinc	0.62
Lithium	1.62
Titanium	0.018
Zircon	0.074
Iron	0.046
Copper	2.69
Magnesium	0.24

Table 2. Al-Li 2099 alloy mechanical properties

Mechanical Properties	Thickness range (mm) 12.7 to 25.374	Thickness range (mm) 5.4 to 63.5
Tensile strength (MPa)	560	595
Yield Strength (MPa)	525	505
Elongation %	9	9
Toughness (MPa√m)	-	30
E(tension) (GPa)	78	78
Density (g/cm3)	2.63	2.63

Preparation of Al-Li Alloy Specimen: A Hardford Omnis VMC 1270 CNC machine as shown in Figure-3, was utilized to slot mill a 26mm thick 2099 Al-Li slab. The machine was outfitted with a 16mm Widia ALUFLASH 3AN9 solid carbide end mill, which was chosen for its effective high-speed machining. The open-front VMC has a single cast-iron bed that offers strength and precision, as well as four hardened shear box guideways for increased accuracy.

A variety of materials, including as high-speed steel, tool steel, cemented carbide, and diamond, can be used to mill aluminum alloys; however, ceramic tools are

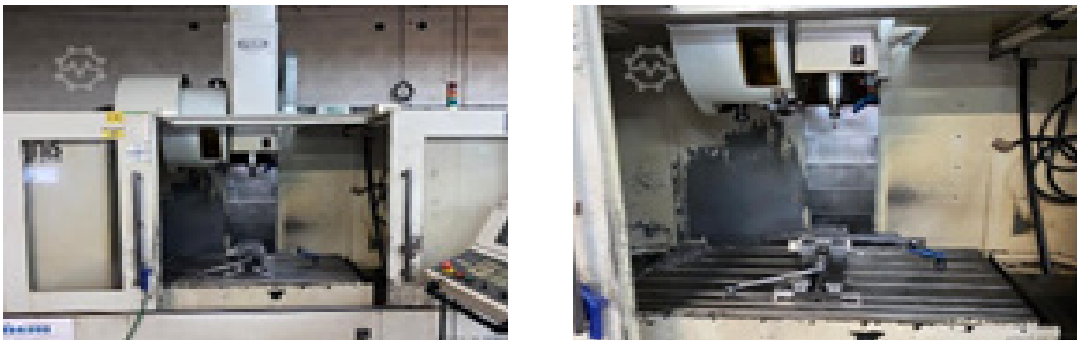


Figure 3. Hardford vmc 1270 machine.

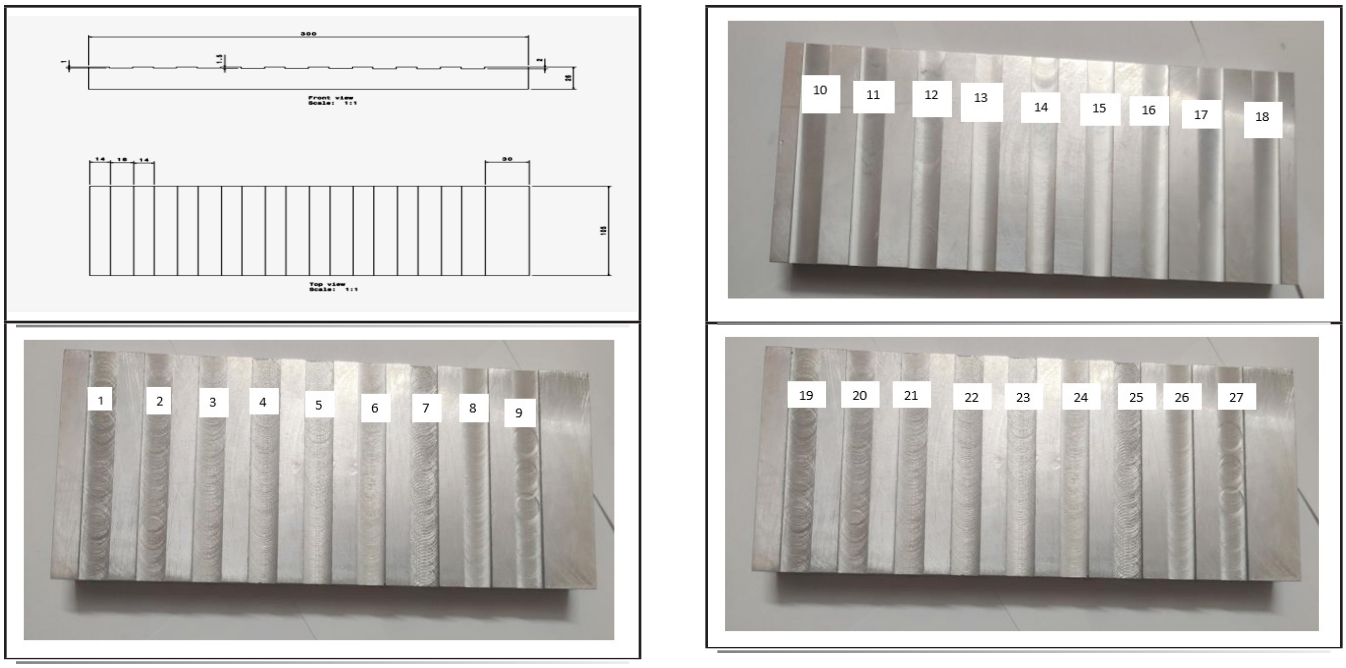


Figure 4. Al-Li work piece with nine slot on the surface.

not appropriate because of their limited lifespan and strong aluminum reactivity. In the same way, aluminum machining presents difficulties for Cubic Boron Nitride (CBN) tools[16]. Titanium-coated inserts may result in quick failure and diffusion problems, however coated inserts can reduce wear.

The machining process employed Sol XL, a high-performance, water-soluble cutting oil known for its emulsifying properties, derived from refined petroleum and specialized emulsifiers. It can be mixed with water up to 600 parts per million to create a stable emulsion and is protected against rust and biodegradation through biocides and inhibitors. While optimal mixing ratios vary by job and water quality, a common ratio for machining Al-Li alloy is 1:20. Nine slots were milled on three slabs, spaced 14mm apart, as shown in Figure 4. High spindle speeds and feed rates were utilized to evaluate the effects of high-speed machining on the alloy, as elevated cutting speeds are crucial for optimal results. The cutting tool specifications (3 teeth, 16mm diameter, solid carbide) and other experimental variables (coolant type) were unchanged through the duration of the experiments[17].

2.2 Surface Roughness Measurement

The surface roughness of the twenty-seven machined

slots on the slab was measured using the accurate and economical TIME 3200 surface roughness tester (TR200), as illustrated in Figure 5. The surface roughness of the twenty-seven machined slots on the slab was measured using the precise and cost-effective TIME 3200 surface roughness tester (TR200), as depicted in Figure 5. The

Table 3. Measured surface roughness of the 27 slots milled at the surface of Al-Li.

Sl No	Cutting Speed (rpm)	Feed Rate (mm/ rev)	Depth of Cut (mm)	Experiment Mean Ra (µm)
1	4000	150	0.1	0.43
2	4000	150	0.15	0.53
3	4000	150	0.2	0.73
4	4000	300	0.1	0.62
5	4000	300	0.15	0.81
6	4000	300	0.2	0.92
7	4000	450	0.1	0.81
8	4000	450	0.15	1.01
9	4000	450	0.2	1.21
10	5000	150	0.1	0.40
11	5000	150	0.15	0.50
12	5000	150	0.2	0.70
13	5000	300	0.1	0.60
14	5000	300	0.15	0.80
15	5000	300	0.2	1.00
16	5000	450	0.1	0.80
17	5000	450	0.15	1.00
18	5000	450	0.2	1.20
19	6000	150	0.1	0.30
20	6000	150	0.15	0.40
21	6000	150	0.2	0.60
22	6000	300	0.1	0.50
23	6000	300	0.15	0.70
24	6000	300	0.2	0.90
25	6000	450	0.1	0.70
26	6000	450	0.15	0.90
27	6000	450	0.2	1.10



Figure 5. Surface roughness tester.

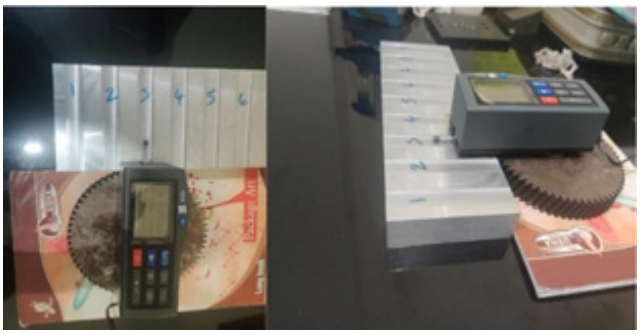


Figure 6. Surface roughness tester (TR200) used for measurement of surface roughness.

usage of this device for measurements is shown in Figure 6. To assure accuracy, three readings were collected at various positions for each slot; the average values are shown in Table 3.

3.0 Result and Discussion

A Hardford Omnis VMC 1270 CNC machine was utilized to slot mill a 26mm thick 2099 Al-Li slab. The machine was outfitted with a 16mm Widia ALUFLASH 3AN9 solid carbide end mill, which was chosen for its effective high-speed machining., with parameters set at 3000-6000 rpm speed, a depth of cut of 0.1 to 0.2 mm and a feed rate of 150-450 mm/min, Sol XL coolant was applied at a 1:20 ratio. The Taguchi method was utilized for data collection, focusing on the Signal-to-Noise (S/N) ratio to optimize the process. Minitab software analyzed key factors affecting surface roughness, identifying significant parameters through Analysis of Variance (ANOVA). The measured surface roughness and S/N ratios from twenty seven slots drilled under these conditions are summarized in Table 4, based on cutting speed, feed rate, and depth of cut. S/N ratios were calculated using the standard formula.

$$\text{S/N ratio} = -10 \log10\left(\frac{1}{n}\sum_{i-1}^{n}(y_i)^2\right)$$

The goal of machining parameters optimization is to achieve the greatest surface smoothness, as shown by the maximum S/N ratio and the lowest mean Ra value. This approach ensures the selected parameters yield a refined surface finish. Table 4 shows that at a spindle speed of

Table 4. The Responsible table for mean Ra & S/N ratio

Sl No	Parameter	Range	Mean Ra	S/N Ratio
1	Cutting speed	4000 rpm	0.867 µm	0.62
2	Cutting speed	5000 rpm	0.778 µm	0.53
3	Cutting speed	6000 rpm	0.678 µm	0.45
4	Feed rate	150 mm/rev	0.600 µm	0.54
5	Feed rate	300 mm/rev	0.767 µm	0.12
6	Feed rate	450 mm/rev	0.956 µm	0.45
7	Depth of cut	0.1 mm	0.600 µm	0.54
8	Depth of cut	0.15 mm	0.767 µm	0.12
9	Depth of cut	0.2 mm	0.956 µm	0.42

Table 5. Parameter ranking based on the value of delta (smaller is better)

Sl No	Parameter	Mean Ra	Delta	Rank
1	Cutting speed	0.867 µm	0.189	2
2	Cutting speed	0.778 µm		
3	Cutting speed	0.678 µm		
4	Feed rate	0.600 µm	0.356	1
5	Feed rate	0.767 µm		
6	Feed rate	0.956 µm		
7	Depth of cut	0.600 µm	0.356	1
8	Depth of cut	0.767 µm		
9	Depth of cut	0.956 µm		

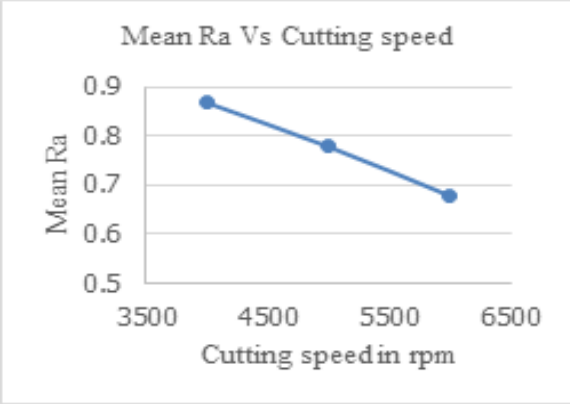


Figure 7(a). Mean Ra vs cutting speed (lower the better).

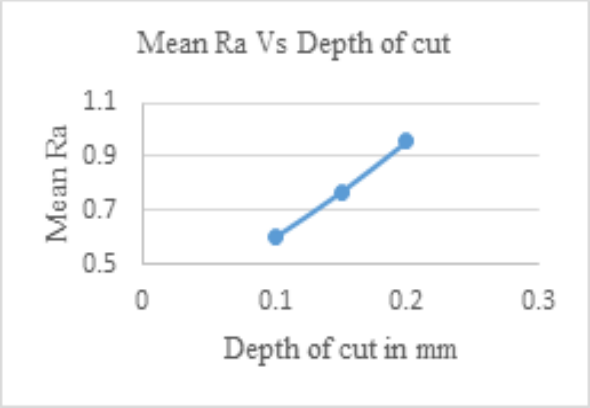


Figure 7(c). Mean Ra vs depth of cut (lower the better).

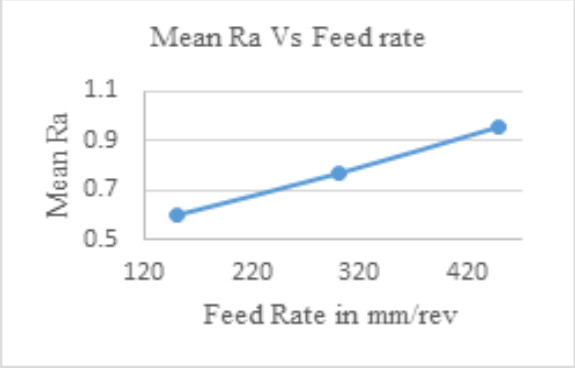


Figure 7(b). Mean Ra vs feed rate (lower the better).

6000 rpm, a feed rate of 150 mm/rev, and a depth of cut of 0.1 mm, the lowest surface roughness found was 0.30 µm. Thus, the optimal parameters for this experiment were identified as 6000 rpm, 150 mm/min, and 0.1 mm depth of cut[14-16].

Tables 4 illustrate the delta tables for means and signal-to-noise ratios. These tables reveal that feed rate and depth of cut have the largest deltas (0.356 and 0.42), indicating they are the most significant factors influencing surface roughness, followed by spindle speed with smaller deltas (0.189 and 0.17). The findings are consistent with those in Tables 4 and 5, showing that feed rate and depth of cut rank highest.

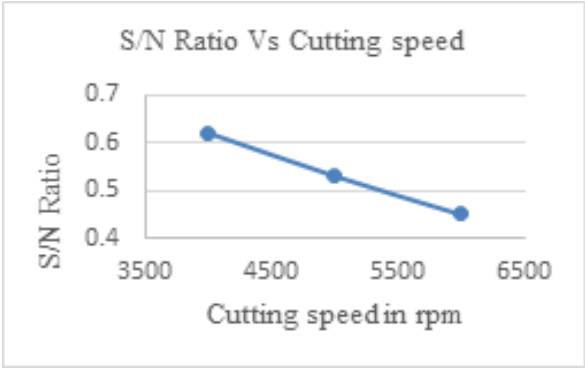


Figure 8(a). S/N Ratio vs cutting speed (Higher the better).

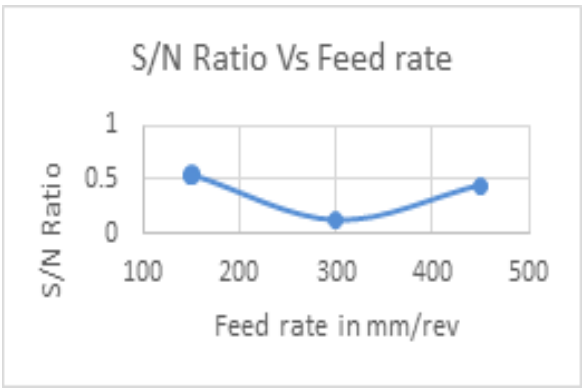


Figure 8(b). S/N Ratio vs feed rate (Higher the better)

In milling, the relationship between feed rate and spindle speed is directly related to surface roughness[18]. Thermal softening of the material can occur when the spindle rotates quickly, raising the temperature at the tool-workpiece interface. Easy tool feeding is made possible by this decrease in thrust forces, which can also improve surface smoothness[19,20]. On the other hand, high feed rates could distort the workpiece and lower its surface quality.

Analysis in Figure 8(a) indicates that increasing spindle speed from 4000 to 5000 rpm results in higher surface roughness, while a further increase to 6000 rpm leads to a slight decrease in roughness[21,22].

This reduction in thrust forces allows the machine to operate more efficiently, potentially improving surface finish. However, if the feed rate is excessively high, the thrust force exerted by the tool can deform the work piece, negatively impacting surface quality[23,24].

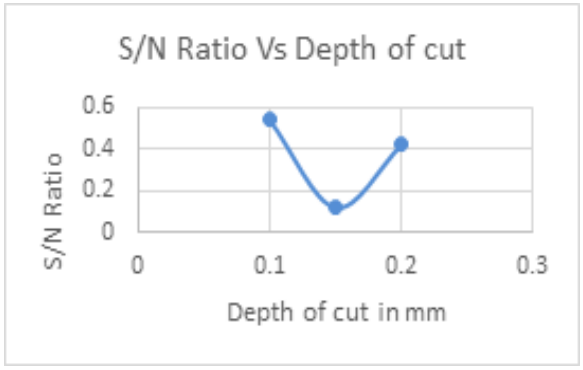


Figure 8(c). S/N Ratio vs depth of cut (Higher the better).

The data shown in Table 5 indicates that the parameters that are most important are the depth of cut and feed rate. Figure 7(a) shows the consequences of changing spindle speed. It can be seen that surface roughness increases when cutting speed is increased from 4000 rpm to 6000 rpm. Figures 7(b) and 7(c) show the impacts of changing the depth of cut and feed rate. They show that decreasing the surface smoothness is the result of increasing the depth of cut and feed rate, respectively.

Similarly Figure 8(a), (b) and (c) illustrate the variation of S/N ratio for different cutting speed, Feed arte and depth cut, observed that the trend of S/N ratio is opposite to the trend of Mean Ra.

3.0 Conclusion

This study examines the effects of slot milling on Al-Li 2099 alloy, detailing the machining parameters for wet milling. Surface roughness was assessed using the Taguchi method, which identified key variables and optimal settings.

Al Al-Li alloys, widely used in military and aerospace applications, offer substantial weight savings and performance improvements. For example, switching to Al-Li in NASA's Space Shuttle enhanced payload capacity for transporting components to the International Space Station. Recent advancements in these alloys, like the 2099 and 2050 grades, have improved formability and reduced production issues.

With superior corrosion resistance compared to conventional aluminum alloys, Al-Li alloys are particularly beneficial in marine environments. Third-

generation Al-Li alloys exhibit reduced crack initiation and propagation, enhancing their suitability for naval applications. By replacing traditional aluminum alloys, especially in aircraft structures, Al-Li can significantly lower weight and fuel consumption.

For optimal surface finish, it is advisable to maintain a low feed rate, use higher spindle speeds, and employ a low depth of cut. Additionally, using Sol XL coolant is crucial for achieving a smooth surface without imperfections.

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