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Experimental Analysis of Machining Parameters In Turning of Aluminum 7075

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Abstract

High-Speed Machining (HSM) of aluminum alloys represents a critical area in manufacturing industries, including automotive, aerospace and consumer electronics. This research presents an in-depth investigation into the effects of key process parameters on the HSM of Aluminum 7075, a high-strength alloy with superior mechanical properties. Utilizing the central composite design of Response Surface Methodology (RSM), the study scrutinizes the impact of process parameters, including cutting speed, feed, depth of cut and tool nose radius on surface roughness. The findings reveal feed and nose radius as primary factors influencing surface roughness while cutting speed and depth of cut play secondary roles. This comprehensive analysis contributes to the knowledge base for efficient machining practices and lays the groundwork for future optimization strategies. It also underscores the necessity for further research into understanding the intricate dynamics of machining parameters to enhance operational efficiency and product quality in the machining of Aluminum 7075 and similar alloys.

Keywords: High-Speed Machining; Aluminum 7075; Process Parameters; Response Surface Methodology; Optimization

1 Introduction

Machining serves as a cornerstone process in the manufacturing industry, enabling the transformation of raw materials into tailored products [1, 2]. Turning, a subset of machining, uses a cutting tool to remove material from a rotating workpiece, creating cylindrical shapes. This process finds application in numerous industries, such as automotive, aerospace, and electronics, due to its versatility and efficiency [3, 4]. Aluminum and its alloys, owing to its lightweight properties, high thermal conductivity, non-toxicity, and recyclability, are indispensable materials across the discussed industries [5]. The high-speed machining (HSM) of aluminum alloys holds immense significance in manufacturing, enhancing productivity and surface finish quality [6–9]. This methodology has displayed notable success in the aeronautics industry, with potential for further optimization [10]. Nevertheless, the HSM of aluminum comes with intrinsic complexities [11, 12]. There is a multitude of process parameters to consider, leading to a lack of consensus regarding the optimal cutting speed for aluminum machining, as initially proposed by Taylor [13]. Critical parameters, such as cutting speed, depth of cut, and feed, have profound implications on surface roughness, which in turn significantly affects the fatigue life of a machined part [14–19]. Other contributing factors include the workpiece material, tooling, and cutting fluid utilization, which markedly influences the cutting forces and chip formation and disposal [20–24]. Within the aluminum family, Aluminum 7075 stands out due to its high strength and superior mechanical properties. Its impressive strength-to-weight ratio, corrosion resistance, and machinability make it the material of choice for high-stress components like aircraft fittings, gears and shafts [25, 26]. However, attaining the desired outcomes, such as optimal surface roughness and material removal rate during the machining of Al 7075, demands rigorous control and optimization of process parameters.

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Thus, even in recent times, researchers have been working on the optimization of machining, particulary the turning of Al 7075. For example, Akhtar et al.[27] tried to optimize the turning operation for Al 7075 while focussing on better quality end product. Veluchamy et al. [28] tried to optimize the turning process to obtain better surface roughness. Lakshmanan et al. [29] tried to optimize the turning process for Al 7075. While previous work on Al7075 turning has primarily focused on optimizing the process of turning Al 7075 at comparatively low speed range, this study seeks to contribute to the existing literature by providing an in-depth exploration into the effects of key process parameters on the HSM of Aluminum 7075 alloy. Utilizing the central composite design method of Response Surface Methodology (RSM), an exhaustive investigation into the effects of cutting parameters, including cutting speed, feed, depth of cut and tool nose radius on surface roughness is conducted. Through this rigorous investigation, the study aims to provide significant insights for efficient machining practices and advance the body of knowledge in the realm of aluminum high-speed machining.

2 Materials and Methods

2.1 Material

The chosen workpiece material for this study is Al 7075 high-strength alloy. This alloy is primarily used in demanding applications, especially in aircraft structures, due to its excellent ductility, strength, fracture toughness, low density, and resistance to corrosion and fatigue [30–32]. Al 7075 is commercially extracted from Bauxite using the Hall (Heroult) process, then further purified to yield 99.9% pure aluminum [33]. The chemical composition and specific material properties of the Al 7075 alloy used in the present study are outlined in Table 1 and Table 2, respectively.

Table 1: Chemical composition of Al 7075 alloy.

Elements	Zn	Mg	Cu	Cr	Mn	Si	Fe	Ti	Al
Wt. %	5.1-6.1	2.1-2.9	1.2-2.0	0.18-0.28	$<$0.3	$<$0.4	$<$0.5	$<$0.2	87.1-91.4

Table 2: Material properties of Al 7075 alloy

Material properties	**Al 7075**
Physical density	2.8 g/cm^3
Ultimate tensile strength	220 MPa
Yield strength	95 MPa
Brinell hardness number	60
Elongation at break	17%
Modulus of elasticity	70-80 GPa

2.2 Machining setup

The high-speed turning experiments were conducted on a FANUC series Oi-TC model CNC lathe featuring a three-jaw independent chuck, a computer numerically controlled tool slide, and an automatic lubrication motor. The fixture used was a hydraulic-operated, three-jaw self-centering chuck. The lathe was equipped with a PCLNL 2525 M12 tool holder, which housed a CNMG 120408 cutting insert. This insert was characterized by a diamond 80 shape, zero-degree clearance angle, 0.002 mm tolerance, and a clamp-on with a chip breaker. The jigging fixture was designed with specific resting, location and clamping points on the workpiece's diameter, with the resting point at the end face. Figure 1 depicts the discussed setup.

2.3 Experimentation and data analysis

The present subsection outlines the experimental setup and methodology used to gather and analyze data. It's important to note that these are standard practices in conducting an experimental study, with each step in the process having a purpose in ensuring the accuracy and relevancy of the results. A total of 27 experiments were performed based on a face-centered central composite design using response surface methodology, which refers to a specific experimental design model used in optimization processes, often when investigating the response of a system to various parameters. The number of experiments (27 in this case) is determined by the factorial of the levels of the parameters and the total number of parameters. The response surface methodology (RSM) is a collection of mathematical and statistical techniques useful for developing, improving, and optimizing processes, where the main idea is to use a sequence of designed experiments to obtain an optimal response. Four crucial machining parameters - cutting speed, feed, depth of cut, and tool nose radius - were varied at three levels each, with operating levels for these parameters presented in Table 3.

Figure 1: Machining setup used for the HSM of Al 7075 alloy

Table 3: Input machining parameters and their operating levels.

Sl. No.	Cutting parameters	Units	Notation	Levels		
				Low	Medium	High
1	Cutting speed, V	rpm	A	94	188	282
2	Feed rate, f	mm/rev	B	0.2	0.3	0.4
3	Depth of cut, d	mm	C	0.8	1.4	2.0
4	Tool nose radius, r	mm	D	0.4	0.8	1.2

Regression analysis was used for the development of a model for machining quality characteristics. Regression analysis is a statistical process for estimating the relationships among variables. It includes techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. Here, it is used to create a model that can predict machining quality based on the four parameters. The collected data were subjected to Analysis of variance (ANOVA) to statistically estimate the influence of full quadratic factor effects. Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences among group means and their associated procedures. In the present case, it is used to understand how much of the variance in the response, or dependent variable, can be explained by the four machining parameters. Surface roughness is a key measure of the quality of a machined surface and is typically measured using a specific instrument. In this case, a SurfCom Flex 50 surface roughness measuring instrument was used to measure surface roughness at nine different locations on the sample. The average value of these measurements was then used for model development and evaluation. By taking measurements at multiple locations, the model is made more robust and representative of the entire surface, reducing the influence of outlier measurements.

3 Results and Discussion

The experimental design was formulated using the response surface methodology (RSM) in a central composite design (CCD). Table 4 presents the values of each parameter at their respective levels, along with the corresponding surface roughness measurements. An initial inspection of the raw experimental data reveals several noteworthy trends. It is evident that an increase in cutting speed and feed while keeping a low tool nose radius oftenly resulted in a higher surface roughness (Ra), possibly due to increased vibrations and chip load. Conversely, slower cutting speeds and lower feed rates, especially when coupled with larger tool nose radius, seem to improve surface roughness, potentially providing better control over the cutting process. The depth of cut also seem to play a significant role as with a higher depth of cut in combination with a smaller tool nose radius tend to increase surface roughness. This might be probably due to increased interaction of the tool with the workpiece material. It's essential to emphasize that these are preliminary observations. Thus, to obtain a better understanding of these relationships and their statistical significance, rigorous statistical analysis, such as a regression analysis and ANOVA was conducted. The ANOVA was used to test the significance of each of the model terms (factors and interactions) in explaining the variability in surface roughness. The factors included linear, square and 2-way interaction components of each variable.The resulting ANOVA for the investigated factors and the obtained response is reported in Table 5. The Adj SS (Adjusted sum of squares) represents the variability due to each term, while the Adj MS (Adjusted mean square) is the average variability due to each term. The F-value is used to test if the variability contributed by each term is significant. The results show that the feed (f) and nose radius (r) have the highest individual F-values (806.82 and 630.74 respectively), indicating that they have a strong influence on surface roughness. However, cutting speed (V) and depth of cut (d) have low F-values, suggesting that they have a lesser impact on surface roughness. Furthermore, the 2-way interaction between feed rate and nose radius (fr) also has a high F-value (176.71), indicating that the interaction of these two factors significantly influences the surface roughness. This could be due to the fact that the feed rate and tool nose radius are two of the most influential cutting parameters on surface roughness quality.

Table 4: Machining parameters and surface roughness.

Cutting Speed V(rpm)	Feed, f (mm/rev)	Depth of cut, d (mm)	Nose radius, r (mm)	Surface roughness, Ra (microns)
2000	0.3	1.4	0.4	6.86
1000	0.4	2	0.4	11.486
2000	0.2	1.4	0.8	1.166
3000	0.4	2	1.2	4.079
1000	0.2	0.8	1.2	1.085
1000	0.2	2	1.2	0.939
3000	0.4	2	0.4	11.156
3000	0.2	2	1.2	1.084
1000	0.4	0.8	0.4	11.271
1000	0.4	0.8	1.2	4.032
2000	0.3	0.8	0.8	2.851
3000	0.2	2	0.4	3.574
2000	0.4	1.4	0.8	4.848
2000	0.3	1.4	1.2	2.594
1000	0.2	2	0.4	2.698
1000	0.3	1.4	0.8	2.88
2000	0.3	1.4	0.8	2.719
3000	0.4	0.8	1.2	3.788
1000	0.2	0.8	0.4	3.1
2000	0.3	1.4	0.8	2.95
3000	0.2	0.8	1.2	1.098
2000	0.3	2	0.8	2.936
3000	0.3	1.4	0.8	2.742
1000	0.4	2	1.2	3.781
2000	0.3	1.4	0.8	2.889
3000	0.4	0.8	0.4	11.217
3000	0.2	0.8	0.4	3.256

Experimental results have shown that for a fixed high cutting speed, tool nose radius, and a sharp cutting tool, surface roughness increases with increasing feed rate [34]. The interaction between these two factors can affect the contact area between the tool and workpiece material, which in turn can influence the surface quality.

Table 5: ANOVA results for surface roughness

Source	DF	Adj SS	Adj MS	F-Value
Model	14	275.675	19.691	125.91
Linear	4	224.857	56.214	359.44
V	1	0.029	0.029	0.19
f	1	126.182	126.182	806.82
d	1	0.000	0.000	0.00
r	1	98.645	98.645	630.74
Square	4	22.934	5.733	36.66
V^2	1	0.006	0.006	0.04
f^2	1	0.055	0.055	0.35
d^2	1	0.003	0.003	0.02
r^2	1	8.955	8.955	57.26
2-Way Interaction	6	27.885	4.647	29.72
Vf	1	0.144	0.144	0.92
Vd	1	0.078	0.078	0.50
Vr	1	0.012	0.012	0.08
fd	1	0.012	0.012	0.08
fr	1	27.636	27.636	176.71
dr	1	0.002	0.002	0.01
Error	12	1.877	0.156	
Lack-of-Fit	10	1.848	0.185	12.90
Pure Error	2	0.029	0.014	
Total	26	277.55		

The corresponding regression equation in uncoded units was developed and represented by Eq [1]. The equation provided represents a multiple regression model for surface roughness (Ra) as a function of the machining parameters and their interactions. The coefficients in front of the machining parameters (V, f, d, r) and their interaction/square terms represent their effects on surface roughness. The positive coefficients suggest that an increase in the corresponding parameter would increase surface roughness, while the negative coefficients suggest that an increase in the corresponding parameter would decrease surface roughness. For example, the negative coefficient -45.3 in front of the feed rate (f) suggests that an increase in feed rate would significantly decrease surface roughness. However, interpretation of the coefficients should be done with caution, particularly for those parameters involved in the interaction terms. For example, the interaction term between feed rate and nose radius (fr) has a coefficient -32.86, meaning that the combined effect of feed rate and nose radius decreases surface roughness more than what would be predicted by their individual effects.

$$\begin{aligned} Ra =& 0.17 + 0.00042V - 45.3f - 0.58d - 14.45r0.000000V^2 + 14.6f^2 + 0.091d^2 + 11.66r^2 \\ & - 0.000950Vf + 0.000116Vd - 0.000068Vr + 0.46fd - 32.86fr - 0.049dr \end{aligned} \tag{1}$$

The residual, the difference between the experimental and theoretical values, was assessed to gauge the performance of the model. As depicted in Figure 2, the discrepancy between the observed and predicted values did not exceed 0.8, falling within an acceptable margin of error. This suggests that the model is reasonably accurate in forecasting the surface roughness based on the machining parameters and their interactions. This minor discrepancy can be attributed to unavoidable variations in the machining environment, such as fluctuations in machine stability, tool wear, temperature changes, or measurement uncertainties. Despite these inevitable variations, the model's high accuracy underscores its robustness and practical applicability in predicting the surface quality in machining processes. It is crucial to remember that while this model is powerful and has demonstrated accuracy within the scope of this study, every prediction model has its limitations. This model is expected to work best within the range of parameters tested in this study. Using it beyond these parameters may require additional validation to ensure its accuracy.

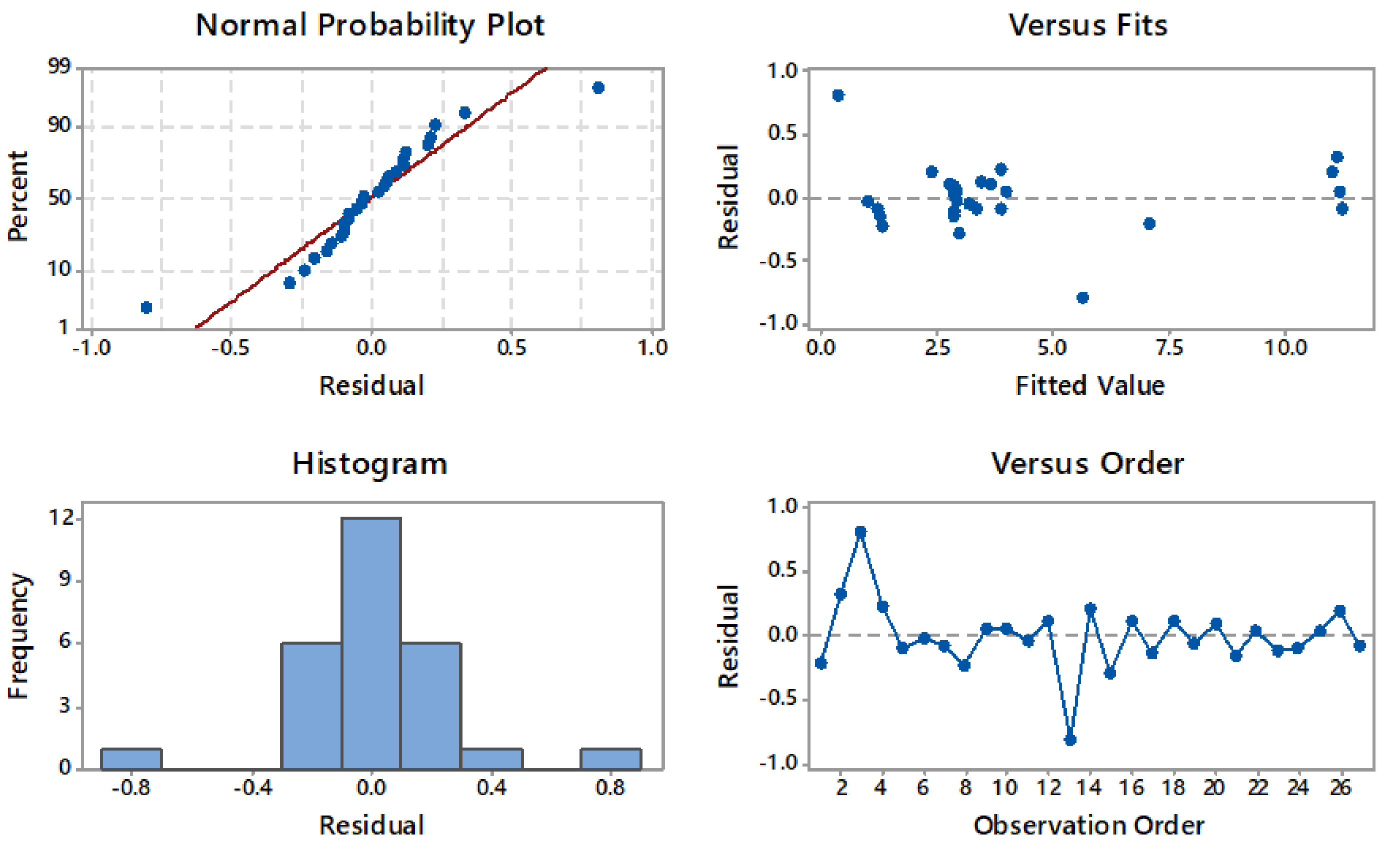

Figure 2: Residual plots for surface roughness

The main effect plots are graphical representations that show the relationship between the dependent variable (in this case, surface roughness) and each of the independent variables (cutting parameters). These plots allow for an intuitive understanding of the impact of each parameter on surface roughness. In Figure 3, the main effects of each factor on surface roughness are displayed. It is seen that feed rate and tool nose radius have a pronounced impact on surface roughness compared to the cutting speed and depth of cut. This reinforces the results from the ANOVA and regression analyses, confirming that these parameters are the primary influencers on surface roughness. While these findings provide valuable insights into the behavior of the system, the study is not without its limitations. Inherent discrepancies between experimental and theoretical values could be attributed to uncontrollable factors, often referred to as "noise," in the machining environment.

Noise can come from a range of sources, such as machine vibration, thermal fluctuations, and even potential human errors in the measurement process. As for future studies, broadening the scope of the analysis to include other potentially influential variables would be beneficial. This might involve looking at different tool materials, workpiece materials, coolant types, or environmental conditions, to name a few. By examining these additional variables, we can gain a more holistic understanding of the machining process, allowing us to better predict and control surface roughness in CNC lathe machining. In essence, understanding how different factors contribute to the final output is key to optimizing the machining process, and further research in this area can lead to significant improvements in surface quality and overall machining efficiency.

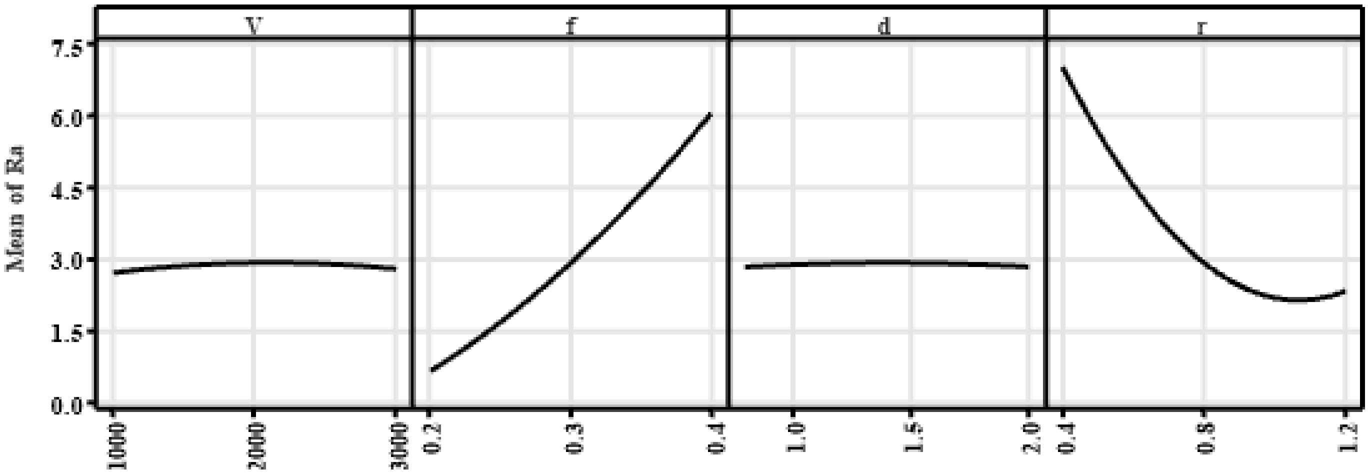

Figure 3: Main effect plot for surface roughness

4 Conclusion

The present study delves into the intricate dynamics of High-Speed Machining (HSM) of Aluminum 7075, offering valuable insights into the relationships between various process parameters and their effects on surface roughness. A key revelation of this research is the significant impact of the feed and nose radius on surface roughness, while cutting speed and depth of cut played secondary roles. These findings illuminate the complex interplay between process parameters in HSM of Aluminum 7075 alloy, forming a foundation for enhanced machining optimization strategies. This understanding is particularly valuable for industries reliant on aluminum components such as automotive, aerospace and electronics, as it offers avenues for improved manufacturing efficiency. Gaining precise control and optimization of machining processes through an understanding of parameter interactions leads to high-quality products, increased productivity and reduced operational costs. This research not only enriches the knowledge base on HSM of Aluminum 7075 but also opens avenues for future exploration. Uncharted areas for future research include the impacts of variables such as machine tool quality and type, vibrations, auxiliary tooling, and lubricants. Investigations into different aluminum alloys in comparison with Aluminum 7075 would also be an interesting extension of this work.

Declaration of Competing Interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

Deepak V Lokare: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Software, Writing - original draft, Writing - review and editing

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