Optimisation of Machining Parameters for CNC Milling of Magnesium Alloy AZ91 by Using the Taguchi Technique

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Abstract: The suggested research will focus on finding the best combination of machining settings of Magnesium Alloy (AZ91) using Taguchi's method. Throughout the machining procedure, a multitude of variables impact the quality of the final product. Surface imperfection significantly affects the quality of machined Mg Alloy (AZ91) components. The roughness of the surface (R_a) can be controlled by altering the machining settings, manufacturers have the opportunity to save manufacturing costs without compromising product quality. By minimising waste, enhancing tool life, and lowering the requirement for post-processing activities, optimising dimensions in order to machine the ideal roughness on the surface can help minimise the cost of production. For each such changeable process parameter, the parameters were set at three different levels of research to optimise the process. A carbide end mill was used for machining on a CNC milling machine. Taguchi's approach was used to construct an experiment design (L9 orthogonal array) for the experiments. Using an ANOVA, the significance of each parameter's influence was determined. For optimal AZ91 surface quality, the recommended control factor parameters are 0.22 m, 3000 rpm spindle/speed of cutting, 0.5 mm depth of cut, and 150 mm/min input rate. Surface irregularity was also influenced by the supply rate and the depth of cut, albeit to a smaller amount than by the cutting speed. We used regression analysis and response surface methods to learn more about the relationship between process variables and product characteristics.

Keywords: *Milling, Magnesium, AZ91, Response Surface Methodology, Taguchi, Surface Roughness*

Introduction

When Mg is alloyed with some of the other metals like aluminium, zinc, manganese, silicon, copper, rare earth elements, and zirconium, it transforms into magnesium alloy, which is recognized as the lightest structural metal. "AZ91" is a magnesium alloy with 9% aluminum and 1% zinc, thus the name. It is one of the most used magnesium alloys because of its excellent balance between strength, flexibility, and resistance to corrosion. AZ91 is widely used in several fields, including automobiles, airplanes, and electronics [1]. It is used in the automobile industry for engine blocks, steering wheels, and other components because of its small weight and high strength-to-weight ratio. Landing gear, wing structures, and rotor hubs are just some of the aircraft components that benefit from their utilization in the aerospace industry. It is used for the frames of portable electronic devices like laptops and smartphones because of its reliability and manageable weight. When machining magnesium alloy AZ91, finding the right balance between surface irregularities and metal removing rate is crucial. By adjusting cutting specifications or parameters, using appropriate tooling, employing suitable cutting fluids, and considering the material properties of AZ91, manufacturers can achieve the desired metal removal rate while maintaining an acceptable surface finish. It is extensively used in sectors such as aeronautics, aerospace, automotive, medical, sports, and portable electronics since it is one of the lightest metallic materials and has the density to density-to-resistance ratio must be low [*1-3*]. Because magnesium alloys have a greater melting point than autoignition temperatures (650°C vs. 430°C), mg alloys are also gaining prominence due to their inexpensiveness and high robustness [2],[3] and also, they are frequently employed as lightweight alternatives to aluminium alloys, particularly in sectors where weight reduction is crucial, such as the automotive and aerospace industries. They have a comparable strength-to-weight ratio [4] but a lower density. Material heterogeneity, delamination damage, and surface roughness [5] are two challenges associated with the machining of this material. Because the texture of the surface greatly impacts accurate measurements and high-quality components, Models using experimental design have been developed to make predictions about surface roughness and to quantify machined surfaces [6], requiring a significant investment of both time and effort on the part of the user. In milling operations, surface abrasiveness is determined by the speed of cutting, rate of feed, tool nose radius and cutting depth, lubrication of the cutting tool, The mechanical and physical characteristics of the material being processed, as well as the effects of vibration and wear on the tools. Even slight adjustments to any of the aforementioned factors may have a major effect on the surface that is produced [7]. In manufacturing industry, many machining procedures utilize material removal from mg alloy to produce a They produce a superior item due to their capacity to eliminate waste. while maintaining excellent top texture. One of the most used milling techniques is end milling, a basic or we can say straightforward process of cutting metal into usable shapes for use in manufacturing. During milling processes, manufacturing complex shapes and forms with a high-quality finish is now possible [8],[9],[10]. Modern milling is increasingly automated with machine tools controlled by computers (CNC) because of its ability to increase output with little operator involvement. CNC milling procedures have gotten more challenging as new CNC machines have become more substantial and durable, making it more difficult to establish the correct amounts of cutting parameters [11]. The term “machining” refers to a procedure that includes a few variables. Responses in machining that are either weak (in terms of surface roughness, tool wear, cutting force, temperature, etc.) or strong (in terms of material removal rate [12] may be achieved with the help of the optimization method that provides the best possible range of parameters. Cutting speed, depth of cut, and feed rate were identified as the three most important cutting parameters for end milling machining [13],[14]. Poor parameter choice leads to premature tool wear, which in turn leads to broken workpieces and poor surface quality, both of which result in significant economic losses [15]. Variable cutting parameters and tool shape influence the level of surface roughness achieved during machining (milling) and, therefore, the suitability of the process for a certain application [16]. Machine settings have been optimized with the use of optimization strategies including Taguchi analysis with RSM (response surface analysis) to reduce surface roughness in Mg alloy. To determine the optimal machining parameters, The Taguchi technique employs a statistical trial design based on signal-to-noise ratio. The RSM method employs a statistical model that predicts how changes in the parameters that are used for machining will affect surface irregularity (R_a). To predict surface roughness from known machining parameters, statisticians use a technique called regression analysis [17],[18]. In this study, we account for speed of cutting, rate of feed, and cutting depth, among other important machining characteristics. Different DOE methods (designs of experiments) [19] can be achieved based on the components and levels that were studied. Taguchi’s L_9 orthogonal arrays were employed to construct the DOE in this study [20]. The S/N ratio analysis and preference technique developed by Taguchi are used during the milling stage with the goal of minimizing the amount of polish on the surface and maximizing the effectiveness of the cuts. The roughness of surfaces was assessed with the assumption that lower values are preferable, and the effects of various parameters were calculated by employing a method known as an analysis of variance, or ANOVA for short. The main goals of this research investigation were to determine the most significant aspects of the interactions between the many parameters that influence magnesium milling. and to choose the best production parameters that result in the least degree of surface roughness. In order to accomplish these aims, the average roughness Ra was optimized using the "smaller is better" approach. We conclude by confirming our conclusions via a series of experiments and calculations.

1. Experimental Procedure

A. Test Material, its Composition, and Properties

The material AZ91, which was supplied by A.R Casting Engineers Pvt Ltd, was used as test material in this investigation. A square plate with parameters (280X280X10) mm was utilized as the workpiece in the experimental milling experiments. The finish weight is 1.35 kg, and the Gross weight is 2.2 kg. Table 1. lists its parts and Table 2. Shows the Thermal and mechanical characteristics of the material.

Table 1. The material used in the experiment and its chemical makeup (in %)

Al	Zn	Si	Ag	Ni	Fe	Mg	Pb
9.3%	0.95%	0.01%	0%	0.002%	0.005%	89.561%	0%

Table 2. Mechanical and Thermal Properties of AZ91

Thermal Properties		**Mechanical Properties**	
Melting point	585°C (1085°F)	**Ultimate tensile strength**	230MPa (30,000) psi
Thermal conductivity	59.7 W/(m·K) at 25°C	**Yield strength**	140MPa (20,000) psi
Specific heat capacity	1.02 J (g.k) at 25°C	**Elastic Modulus**	45GPa (6500) ksi
		Elongation at break	3-4%
		Poisson's ratio	0.35

It is important to acknowledge that the mechanical characteristics of AZ91 may exhibit variability according to the specific processing technique and heat treatment used. Overall, the alloy demonstrates a favourable strength-to-weight relationship and exceptional ductility, rendering it a widely favoured option for the utilization of lightweight materials in structural applications. However, it also tends to creep under sustained loads at elevated temperatures, which can limit its use in high-temperature applications.

2. Materials & Techniques

The experiment was carried out with the aid of computer numerical control (CNC) equipment., this requires fixing the workpiece to the CNC machine's bed in order to prevent it from moving around and warping as it mills. The Machine numerical control settings (PX-40 Series VMC, PX 40) used in this experiment are listed in Table 3. and shown in Figure 2.

Table 3. Detailed specifications for CNC milling machines.

Category of Machine	**Canter for Vertical Machines**
Machine	PX-40 Series VMC, PX 40

Table Size	915 x 460 mm
Spindle speed(max)	6000 rpm
Spindle motor capacity	8.25 KW
Feed rapid traverse (X, Y & Z Axis)	25 m/min
Feed Cutting	10 m/min
Accuracy (positioning)	0.01 mm

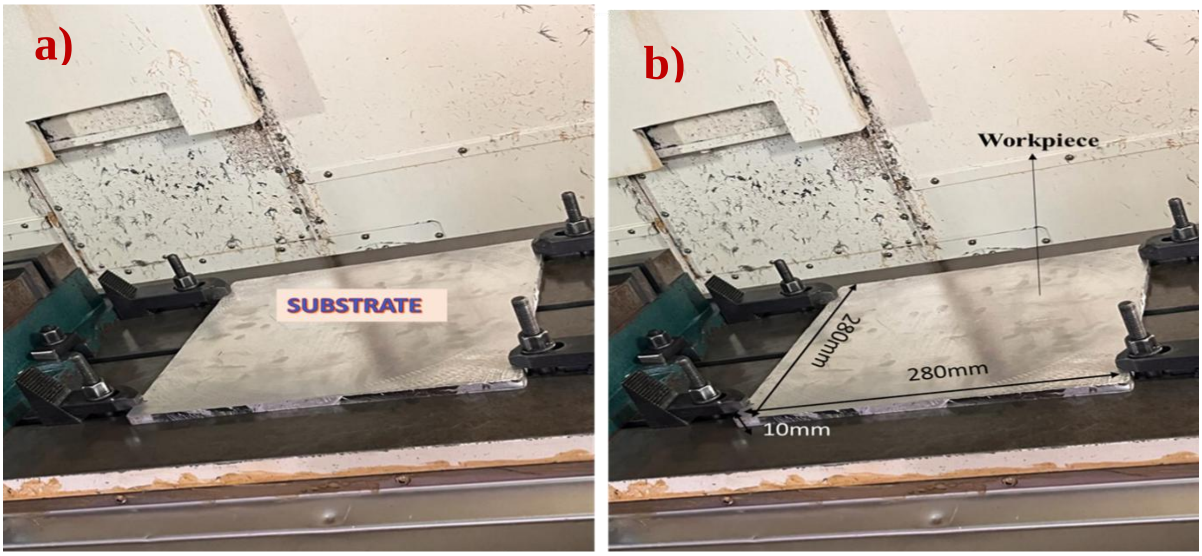

Figure 1. Images a) and b) show the Substrate and Its Dimensions before machining.

3. Workpiece and Tool

A high-hardness tool, such as a solid carbide end mill with a flute length of 40 mm and because of its superior heat conductivity and modulus of elasticity compared to other tool materials, a 6 mm diameter is selected for machining. The selected instrument also contributes to a superior surface quality and excellent dimensional accuracy. Coating solid carbide cutting tools with different materials may increase performance and prolong tool life. Aluminum nitride (AlN) is one such coating often utilized on solid carbide cutting tools. It is a dense ceramic material with excellent thermal consistency and excellent heat conduction.

Aluminum nitride (AlN) is a common coating for solid carbide cutting tools. The high stability at high temperatures and high heat conductivity make this hard ceramic material particularly desirable. The aerospace industry uses it for aircraft components such as landing gear, wing structures, and helicopter rotor hubs. It is used for laptop and smartphone frames in consumer electronics due to its lightweight and durability AZ91 sample used in this study was 280 millimeters in length, 280 millimeters in breadth, and 10 millimeters in thickness. For this experiment, we bought the plate with the specimens on it from a store. The combination of AZ91's low density, high strength, and great corrosion resistance makes it a versatile material with a broad variety of potential uses.

Figure 2 and Figure 3, show the images of the workpiece and Tool.

Figure 2. Tool & material of VMC

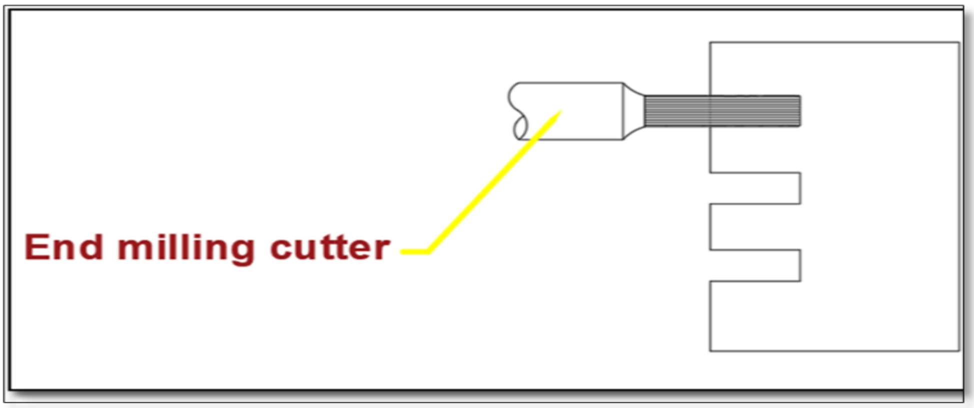

Figure 3. Illustration of end milling cutter and Workpiece

A. Cutting Tool:

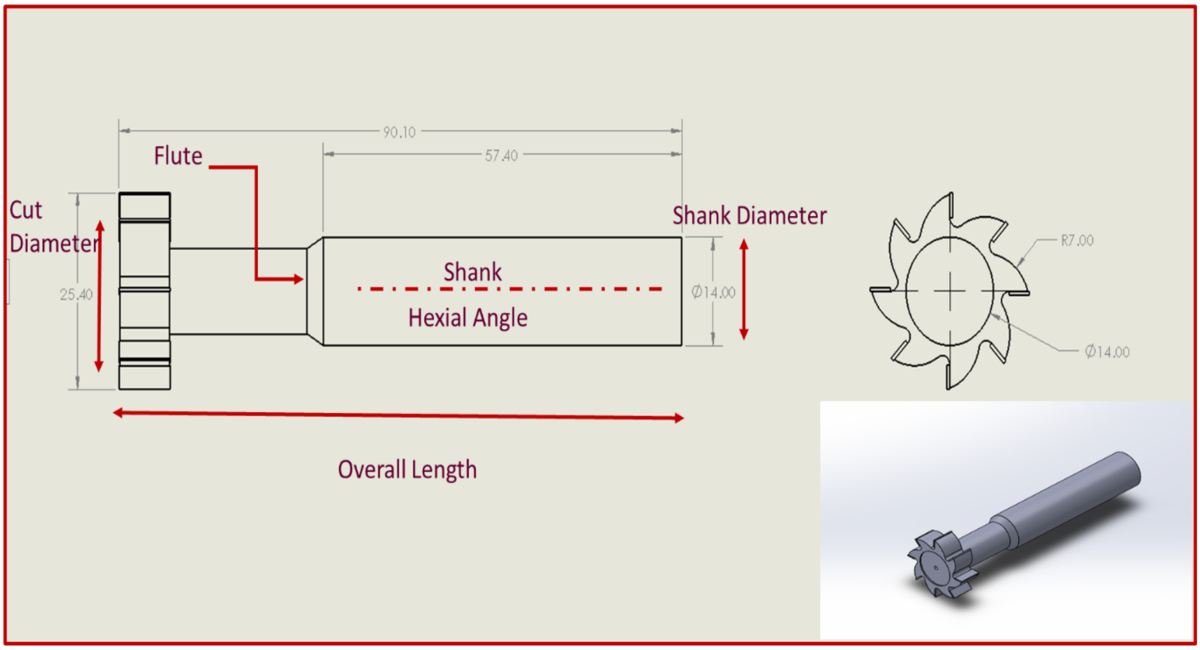

Figure 4. Descriptive view of the End Milling cutting tool in 2-D and 3-D view

B. Substrate after machining:

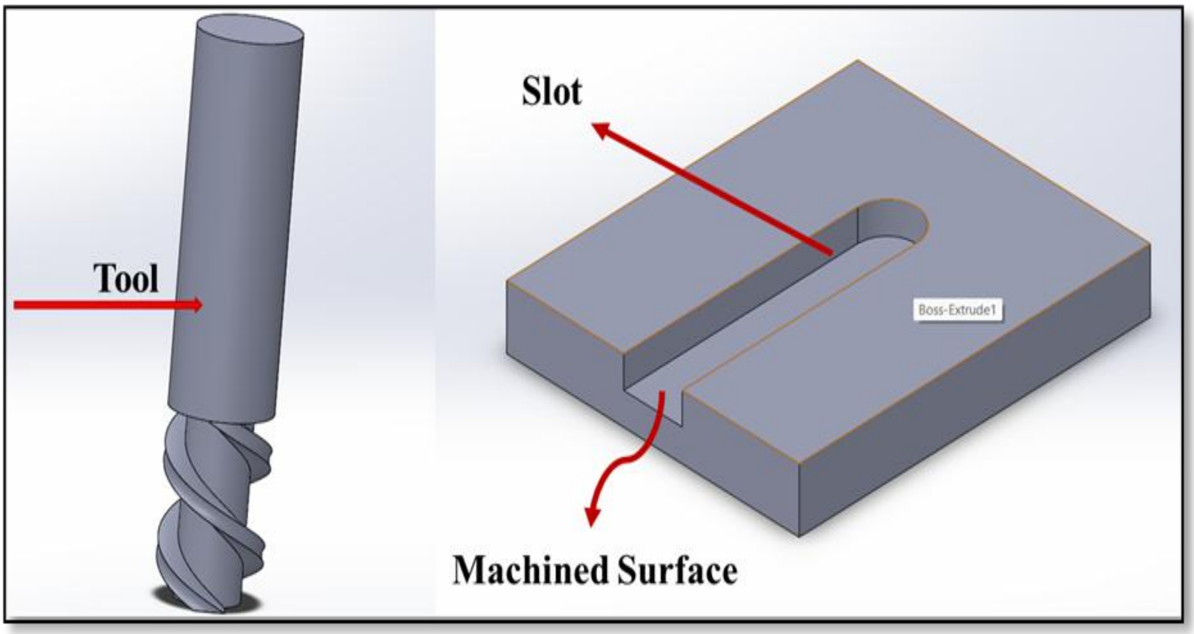

Figure 5. A 3-D view of the Substrate after machining (cutting slot)

4. Experimental design (or DOE)

To achieve optimal results with the parameters, a one-of-a-kind orthogonal array design guided by the Taguchi principle was used, with a small number of tests, overcoming the inherent complexity and difficulty of traditional experimental design methodologies [21]. It's a regulated set of experiments performed to learn more about a process's behavior. Because of its efficiency in locating crucial components, developing a high-quality system, and reducing the amount of time spent on experimentation and cutting., the Taguchi robust design technique is used [22]. Experimental time is cut down by using the orthogonal array's design criterion, which consists of a row of constants and a column of controlled variables. Taguchi proposed the utilization of the signal-to-noise (S/N) proportion as a viable and efficient metric [23]. Figure 4. shows the Taguchi process flow diagram used for optimizing the procedure in this study.

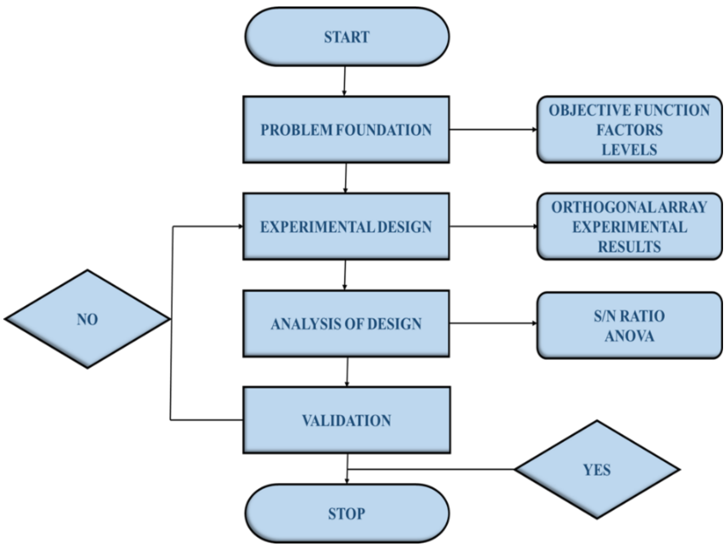

Figure 6. Optimization Method Process Flow Diagram

5. Implementing the Taguchi Method

To better understand the habits of certain processes, this method comprises the creation of an experiment to perform controlled research, followed by testing. The main goal of this investigation was to assess how different variables affect the results of the machining process on milling performance while working with magnesium alloy (AZ91). Statistical studies based on Taguchi methods were used to determine how different machining settings affected the surface roughness. On this subject, there has been a great many research done on milling process parameter optimization, with each study focusing on a unique approach and group of variables. Several outstanding studies using the Taguchi method for optimizing parameters have been published when milling, using a rate of feed of 100–300 mm per minute, a cutting depth of 0.2–1.8 mm, and a speed of cut of 1000–3500 rpm. It is recommended to take your time while adjusting the parameters and levels that are being entered for the machining process. In this particular example, cut depth, feed rate, and speed of cutting were the three most crucial inputs. These values were decided upon after a comprehensive examination and careful analysis of the available CNC machine and tool range (PX-40 Series VMC, PX 40), as well as the decrease in surface irregularities that were sought. Several components and their appropriate amounts are shown in Table 4. for the investigation.

Table 4. Adjustable levels of machining parameters

S. No.	Factors	Levels		
		L1	L2	L3
1.	Speed of cutting (rpm): N	2000	2500	3000
2.	Cutting Depth (mm): D	0.5	0.75	1.00
3.	Rate of feed (mm/min): F	150	200	250

6. Experimental design

As can be seen in Table 5, the nine-experiment L9 orthogonal array (OA) was chosen after careful consideration of three different parameters across three levels [24]. The aforementioned OA successfully finished all nine runs (slots) (L9). There were three variables utilized as inputs or controls in this study: Following a thorough literature study, we settled on the following set of criteria and associated values; the rationale for our choices is provided below.

(a) Speed: The rotations per minute (RPM) of the spindle and the workpiece are tracked in this experiment for fine-tuning reasons.
(b) Feed rate: The rate at which the cutting instrument advances along the path of the incision. The delivery rate is specified in (mm) per rotation.
(c) Depth of cut: The millimeter distance, which is between the untreated and cut surfaces of two workpieces.

Ra was used as a measure of surface roughness as a response variable. The aim was in order to reduce as much as possible the amount of exposed space. The average height deviation of a surface relative to the reference plane is what is meant by its roughness.

Table 5. Selection of L9 orthogonal array

Run	Speed of cutting(rpm)	Cutting depth (mm)	Rate of feed(mm/min)
1	2000	0.5	150
2	2000	0.75	200
3	2000	1	250
4	2500	0.75	150
5	2500	1	200
6	2500	0.5	250
7	3000	1	150
8	3000	0.5	200
9	3000	0.75	250

7 Measuring Device

One of the metrics used to evaluate machinability is surface roughness, which plays a role in deciding whether or not a surface is suitable for a certain purpose (rough surfaces are more susceptible to corrosion and cracking but assist in adhesion [25]. The surface roughness of the machined surfaces was evaluated using a Mitutoyo SJ-201 surface roughness tester with a ranging measurement capability of -200 m to +150 m. (Fig.3). All experiments were performed three times to obtain reliable results. The roughness tester provides both an average roughness value and roughness depths (Rz) in micrometres or microns (R_a).

8 About Measuring Device Roughness Tester

A roughness tester, also known as a surface roughness tester or profilometer, is a tool for determining the surface roughness of a material or component. It operates by sliding a stylus or probe across the surface of the material and measuring the differences in height as the stylus advances.

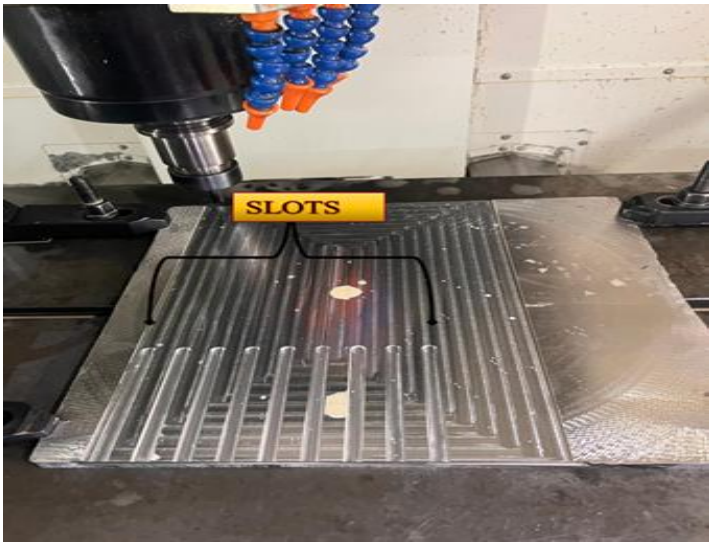

Figure 7. Machined Slots

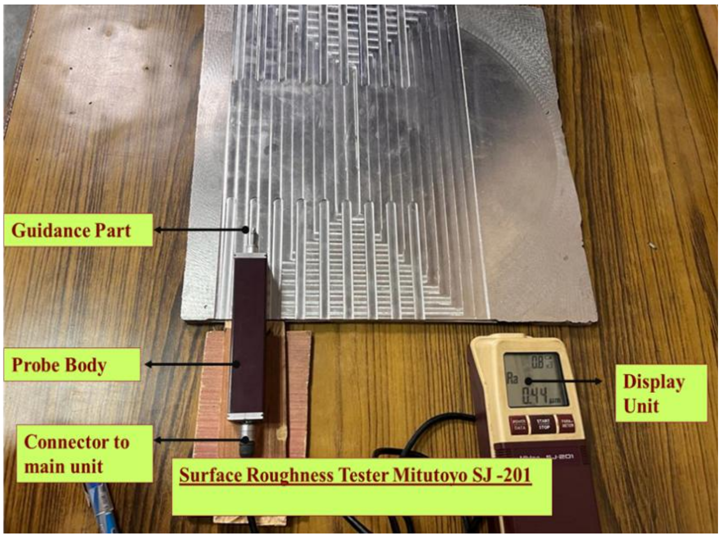

Figure 8. Three samples of machined (slotted) workpiece were prepared for each experimental trial

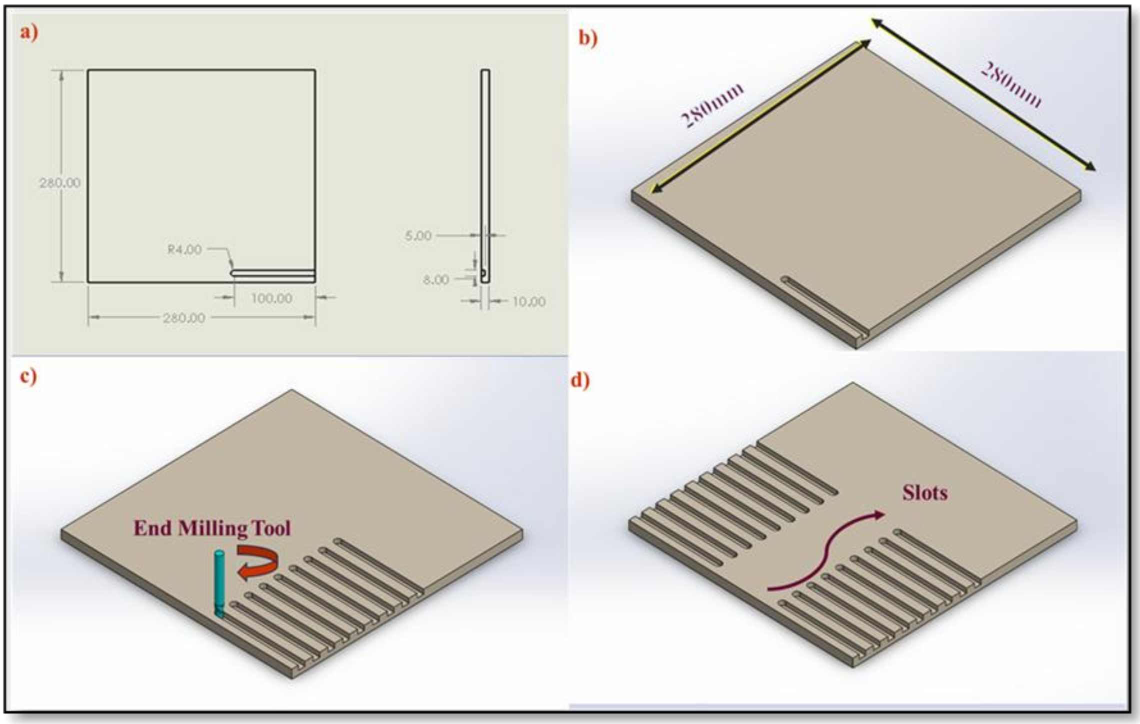

Figure 9. End Milling Process of Slot Cutting

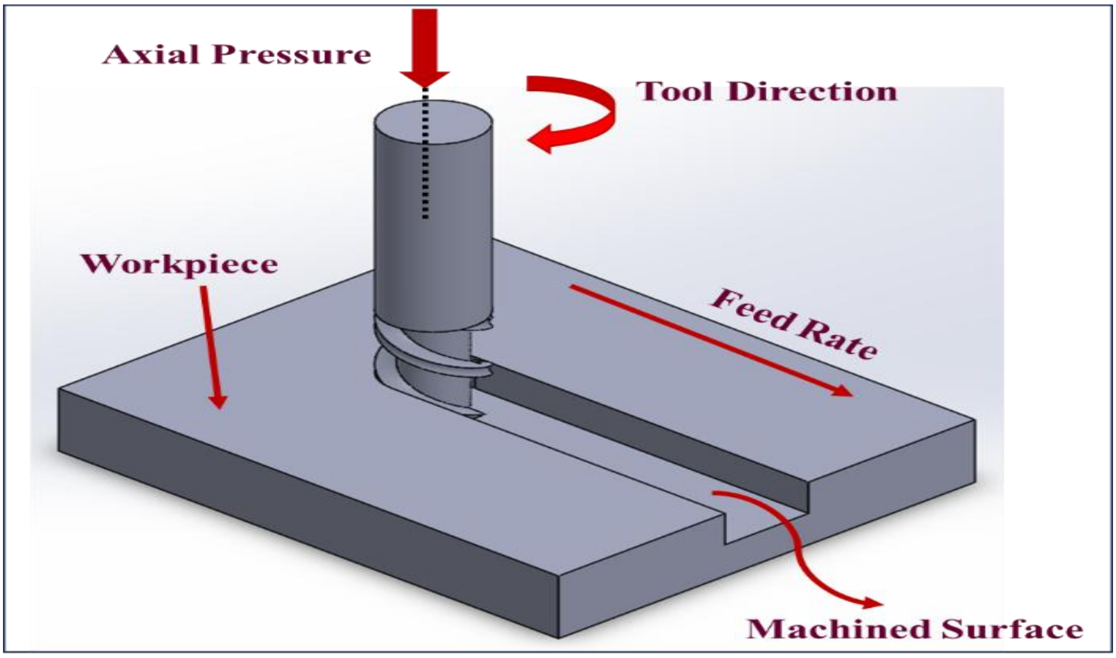

Figure 10. Shows the 2-D and 3-D view of the cutting slots on Mg Alloy (AZ91) with slots Dimensions.

9 Discussions and Results

In **Table 6**, we will find a summary of the findings from the tests that were carried out as part of this research, as well as the data values for the surface roughness and its S/N ratio at each level. The purpose of each experiment was to establish the ideal S/N ratio [26]. As a result, the mean squared deviation ought to be as little as is humanly feasible, which suggests that there ought to be no more than a minimum distance from the threshold of the desired feature. As such, optimizing the signal-to-noise ratio (S/N) of an experiment is of paramount importance [27]. The more desirable the signal is to be heard above any background noise, the greater the signal-to-noise ratio should be. The many permutations of the experimental parameters are shown in Table 5. As can be seen in Figure 6. we ran the experiment three times for each possible combination of input parameters, yielding a total of ten slots. With the right amount of repetition, we can reduce the noise in our measurements of surface roughness (an output parameter).

Table 6. Result of surface roughness (μm)

Experiment	Reading1	Reading2	Average
1	0.25	0.36	0.3
2	0.52	0.55	0.53
3	0.76	0.74	0.75
4	0.37	0.34	0.35
5	0.51	0.51	0.51
6	0.55	0.58	0.56

7	0.28	0.3	0.29
8	0.42	0.4	0.41
9	0.55	0.55	0.55

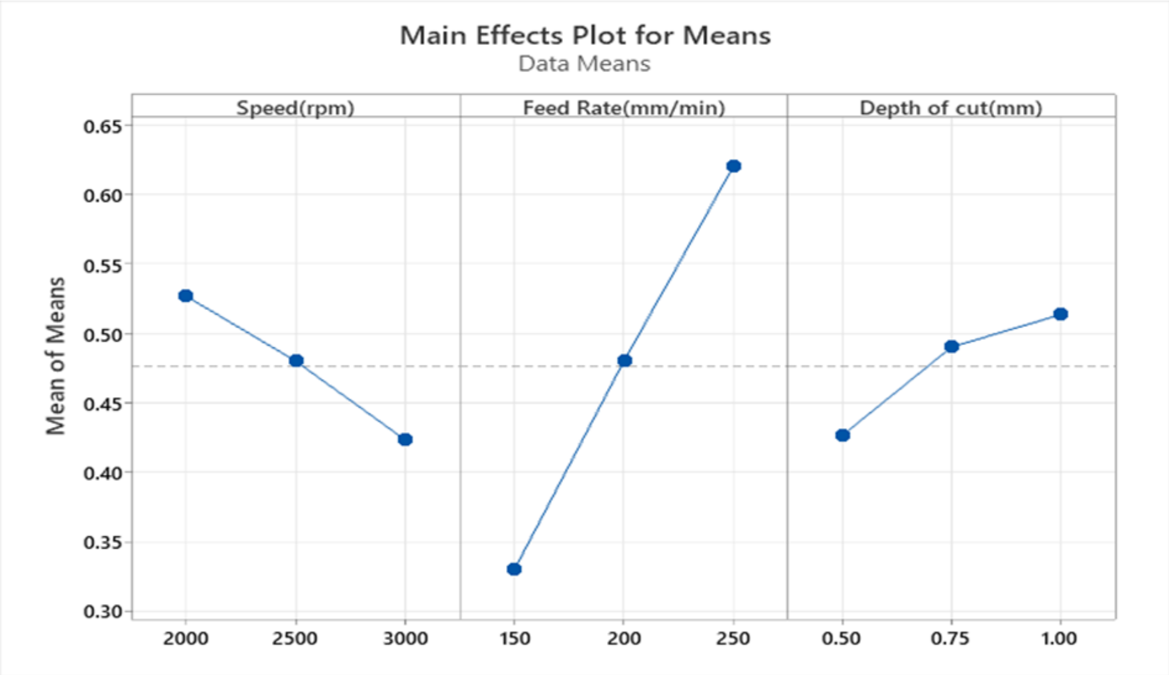

Figure 11. Plot graph for means

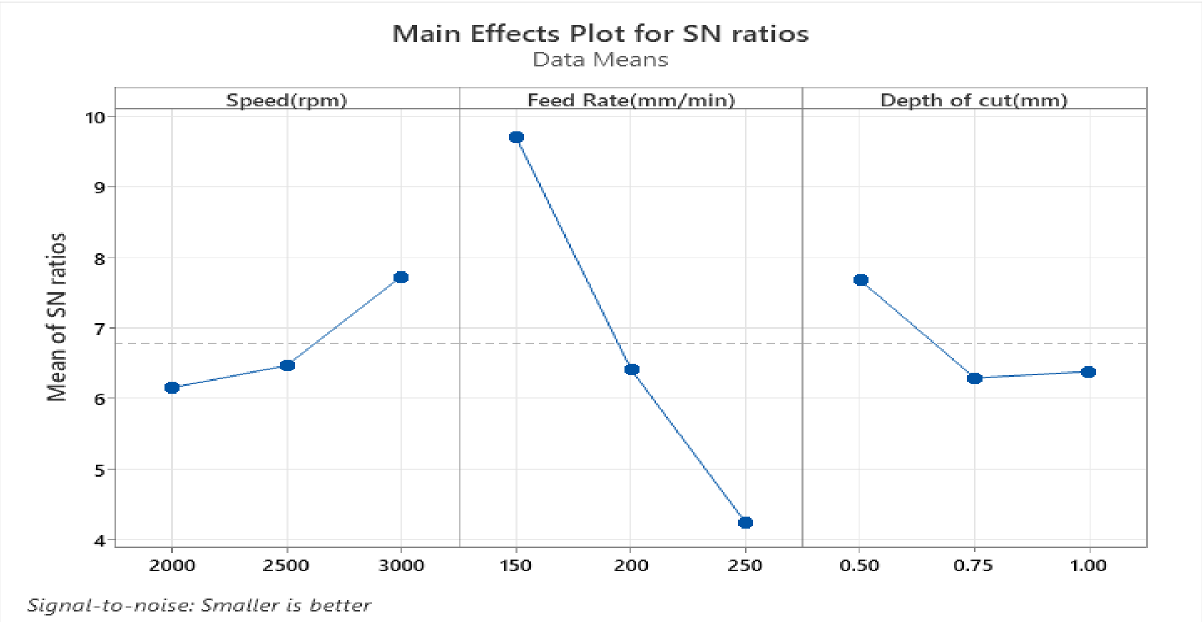

Figure 12. Plot graph for SN Ratios

10 Anova

Analysis of variance, known as ANOVA, is a method used in statistics. for comparing the degree of change across many categories or influences. It helps determine whether the means of different groups are significantly different from each other. In the context of parameter optimization, ANOVA can be used to identify which parameters or factors have a significant impact on the performance of a system or process. By using this technique, you can gain insights into which parameters are crucial for optimizing a system or process, allowing you to focus your efforts on the most influential factors. This helps in efficiently allocating resources and achieving better performance.

It is used to examine the relationship between input variables and outcome measures [28]. Table 7. also includes the analysis of variance (ANOVA) results for the evaluated output components. In this investigation, we calculate sums of squares and variances and apply an F-test to choose crucial ingredients with 95% confidence. When thinking about surface roughness, feed rate (77.30%) was the most important metric, followed by cutting speed (9.81%) and depth of cut (6.90%).

Contribution Percentage = Square Root of the Number of Factors Divided by the Total Square Roots

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.153433	94.02%	0.153433	0.051144	26.18	0.002
Speed(rpm)	1	0.016017	9.81%	0.016017	0.016017	8.20	0.035
Feed(mm/min)	1	0.126150	77.30%	0.126150	0.126150	64.58	0.000
Depth of cut(mm)	1	0.011267	6.90%	0.011267	0.011267	5.77	0.061
Error	5	0.009767	5.98%	0.009767	0.001953		
Total	8	0.163200	100.00%				

Table 7. **ANOVA** for surface roughness

11 Experiment for Verification

For the machined surfaces, the primary objective of the validation stage of the objective of this study is to determine the most optimal values for the process parameters. A, B, and C. The expected mean () is the average value predicted by the data from the experiment. Both the confidence interval around the mean value and the confidence interval around the range of the parameters must be supplied [29],[30]. The results of three tests using the optimal machining settings combination are shown in Table 8.

Table 8. Confirmation Experiment Outcomes

Machining parameter	Level	Surface Roughness, R_a(μm)		
		Experiment 1	Experiment 2	Average
Speed of cutting (rpm)	3000	0.23	0.25	0.22

Cutting Depth (mm)	0.50
Rate of Feed (mm/min)	150

The projected 94% confidence interval was determined. The best-expected value is 0.23µm while the actual (average) number is 0.22µm. Experimental result validity was established by determining that the results of the confirmatory experiment were within the confidence range.

a. **Verification of the model using experiments**

The impact of machining settings on surface irregularities (Ra) was investigated using a first-order regression model. was analyzed [31],[32],[33]. The MINITAB - 20 program and experimental data calculated the regression coefficient.

The use of multiple linear regression, in real factor form, the equation for surface roughness (Ra) looks like this:

$$\mathbf{R_a = 0.025 - 0.000103*cutting\ speed + 0.002900*feed + 0.1733*depth\ of\ cut}$$

Experiment	Measured values Ra (µm)	Estimated values Ra (µm)	% Error
1	0.25	0.36	13.33
2	0.52	0.55	-1.88
3	0.76	0.74	-24
4	0.37	0.34	-5.71
5	0.51	0.51	1.96
6	0.55	0.58	1.78
7	0.28	0.3	10.3
8	0.42	0.4	-7.31
9	0.55	0.55	3.63
		Average Error	-0.87

Table 9. Measured and anticipated Ra values is compared.

The expected and observed values of Ra are compared in Table 9. The deviation sequence is a depiction of the actual deviation and expected value. The first-order regressive model predicts Ra values that are generally near to the experimental values, with an average error of -0.87, The model's performance is similar to the reported values found in published studies, suggesting its potential usefulness in future investigations.

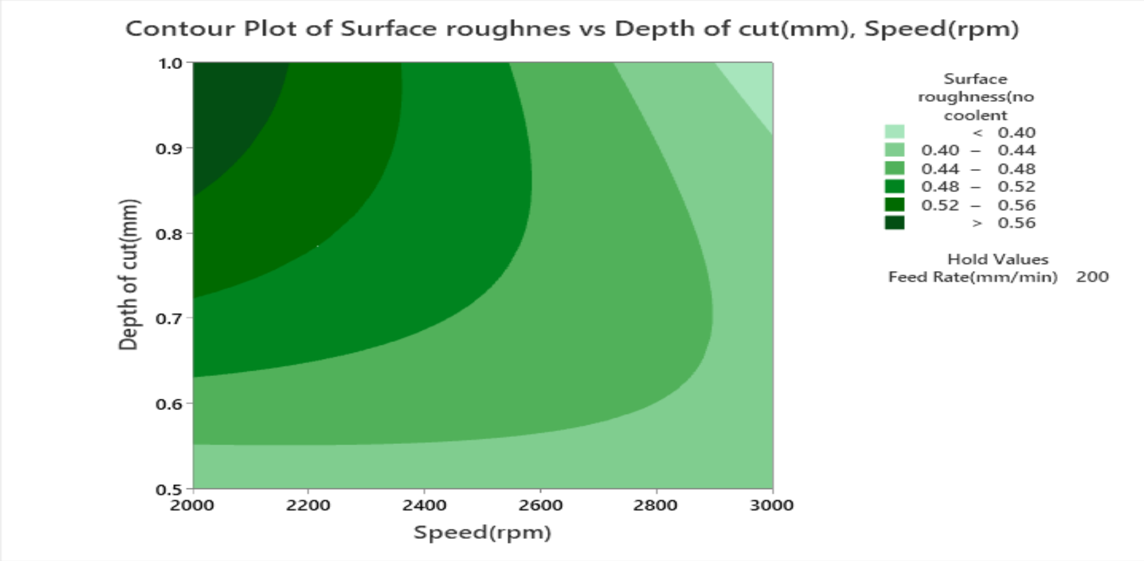

Figure 13. The roughness of the surface as a function of the cutting speed (in revolutions per minute)., cutting depth (mm), and Rate of feed (200 mm/min) is shown graphically in this contour plot.

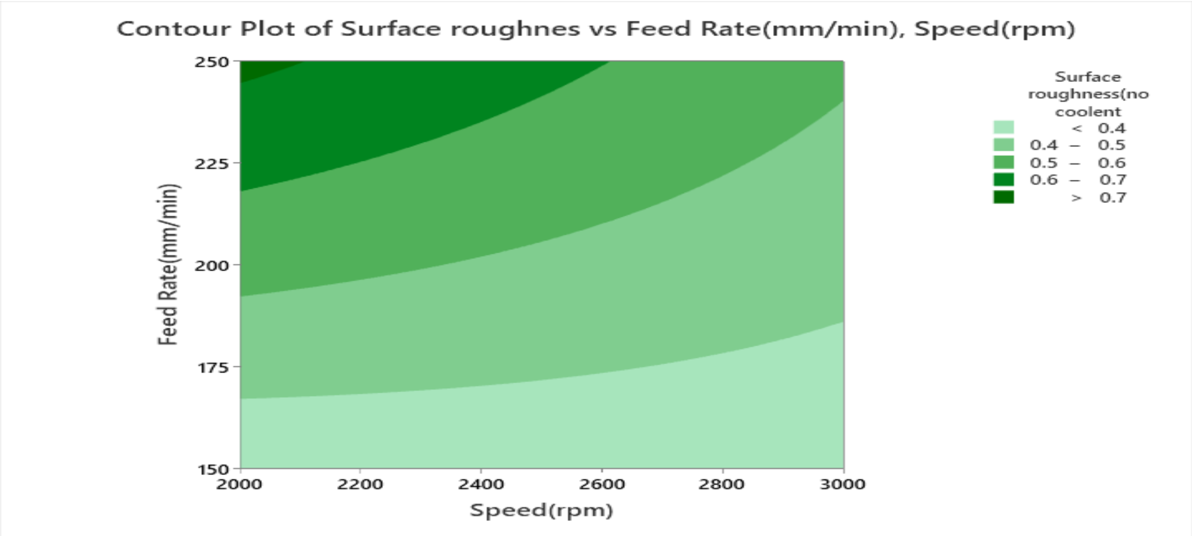

Figure 14. The Roughness of the surface as a function of the cutting speed (in revolutions per minute) and feed rate (mm/min) are shown graphically in this contour map.

12 Conclusions

a) The Taguchi strategy is a popular and effective method for analyzing experimental data. This method may be used for any operation that needs enhancement. In this research, The DOE-Taguchi technique determines the optimal machining settings for achieving a smoother surface.

b) The experiment shows the optimal value of machining parameters and their respective ranks: feed rate 150 mm/min (rank 1), speed of cutting 3000 rpm (rank 2), and cutting depth 0.5 mm (rank 3). A surface roughness of 0.22 m may be attributed to these characteristics.

c) Cutting speed (9.81%) and cutting depth (6.70%) are the next two most influential factors in the roughness of the surface after feed rate (77.3%), according to the analysis of the variance data.

d) The surface roughness of Magnesium Alloy initially rises when the spindle speed is decreased. As the cutting depth is raised, the surface irregularities also increase; however, as the rate of feed is decreased, the Mg-Alloy surface roughness is reduced and experimental results gathered in this inquiry are connected to the information gathered in the last investigation.

e) The RSM approach to optimizing milling parameters for reduced surface roughness is, thus, an efficient and effective strategy.

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