Optimization and analysis of machining performance for the milling process during milling of W-Al-Si-C alloy material

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This study determined the optimum HSS cutting tool technique parameters for milling W-Al-Si-C rods using Taguchi methodology. This paper explains the empirical results of the selection of appropriate cutting settings that assure lower power consumption in high-end Computer Numerical Control (CNC) machines. An experiment employing the Taguchi methodology on an extruded W-Al-Si-C rod was performed on a CNC lathe with cutting speed, feed rate, and depth of cut as the process parameters. The performance characteristics (energy usage) were quantified by a data collection system. Minor energy process parameters were selected after data analysis. Experimental results are presented to demonstrate the worth of the chosen methodology. A total of 350 rpm, 0.37 mm/rev feed rate, and 1 mm of cut depth produced the best MRR result. The maximum material removal rate (MRR) is obtained at lower levels of spindle speed and depth of cut, i.e., 1.452 g/sec.

***Keywords*: Metal Cutting; Cutting Tool; Optimization, Taguchi Analysis; Orthogonal Array; Turning; W-Al-Si-C Alloy.**

INTRODUCTION

The goal of modern industry is to generate low-cost, high-quality goods quickly. The automated and adaptable production methods are combined with Computer Numerical Control (CNC) machines, which can produce parts with high precision relatively quickly[1–4]. The most common method for cutting and then finishing objects is turning and grinding. Selecting cutting settings is crucial to achieving maximum cutting efficiency during a turning operation[5–8]. Typically, manual or empirical values are used to specify the necessary cutting parameters. The cutting settings affect the product's surface roughness, metal removal rate, and dimensional variance. One of the crucial quality parameters of a turned product is surface roughness and metal deposition rate, which are used to assess and analyze the quality of a product. An experimental statistical technique called the Taguchi method has been used to investigate the effects of cutting factors, such as cutting speed, feed, and depth of cut. The Taguchi methodology was used to investigate the impacts of drilling parameters on twist drill temperature for architectural optimization of cutting parameters. Their research demonstrated the Taguchi method as a reliable strategy for experimental design. The Taguchi method and Analysis of Variance (ANOVA) were used to determine a correlation between cutting and line speeds with delamination in a composite laminate, and according to a statistical analysis of hole quality, feed rate, and cutting speed had minimal impact on the measured hole quality properties. When hole position inaccuracy was considered, cutting conditions did not reliably or significantly affect hole quality[9–11]. When drilling composite materials, shear force and surface roughness are examined using Taguchi and the artificial neural network methodology. According to the experimental findings, the drill diameter and feed rate considerably impact the thrust force.

In contrast, the feed rate and spindle speed have the most significant impact on surface roughness. The surface roughness characteristics of CNC milling were improved using the Taguchi design optimization method. When turning W-Al-Si-C coated inserts, Taguchi techniques determine the best surface roughness cutting settings. Three cutting parameters, including insert radius, feed rate, and depth of cut, are tuned for the lowest surface roughness. Taguchi dry drilling method process optimization of cutting parameters for hole diameter precision and surface finish[12–15]. It has been established that the Taguchi technique is effective for process optimization. The Taguchi method converted W-Al-Si-C alloy steel to determine the ideal surface roughness under perfect cutting conditions. The results were then examined using the ANOVA methodology. Surface roughness, tool wear, and MRR are three responses that can be

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optimized using the orthogonal arrangement of the Taguchi technique in combination with Gary's relational scoring[16–18].

Known for its systematic and practical methodology to process optimization, the Taguchi method is a potent tool for building high-quality systems[19–20]. The Taguchi technique for designing experiments has achieved widespread recognition in the technological and scientific world since it is simple to use and put into practice for users with a small statistical background. Through this, engineering produces high-quality goods at cheap development and production costs while minimizing sensitivity to the many sources of deviations in the product and process states.

During the milling of aluminum alloys, the stability increased with the tool having chamfered cutting edges but also generated more heat in the workpiece compared to sharp cutting edges. Higher spindle speeds and lower feeds per tooth resulted in lower temperatures. Proper selection of machining parameters is crucial for thin-walled components[21]. The position of the nozzle significantly affects the surface roughness of the milling process for 7050 aluminum alloy cavities. Optimizing the nozzle position parameters can lead to lower milling force and improved surface roughness. The use of nanofluid minimum quantity lubrication enhances lubrication performance and reduces friction and wear[22]. The machining attempt has been made with abrasive water jet (AWJ) cutting. The process does not cause microstructural changes or hardness reduction, making it an effective method for industrial applications where these factors are important. Other cutting processes, such as heat-based and mechanical, resulted in microstructural changes and reduction of hardness. The feed rate and depth of cut were found to have the most significant impact on surface roughness, while the spindle speed had the most significant impact on MRR[23,24]. All the studies have been conducted the aluminum alloy, but very limited studies have been performed on the W-Al-Si-C material. This research experimentally studied the machining characteristics for MRR.

MATERIALS AND METHODS

W-Al-Si-C materials hold significant importance in modern engineering and industry due to their exceptional combination of properties. These advanced composites are prized for their outstanding high-temperature resistance, making them indispensable in applications where conventional materials would succumb to extreme heat. Their thermal stability ensures structural integrity even under intense thermal stress, a critical factor in aerospace, defense, and high-temperature manufacturing processes. In addition, these materials exhibit wear resistance suitable for cutting tools and protective coatings. Furthermore, their ability to shield against ionizing radiation makes them vital in nuclear and medical applications. The mechanical characteristics and compositions are depicted in Tables 1 and 2, respectively.

Table 1 Mechanical properties of alloy (W-Al-SiC).

Material	Density (kg/m^3)	Tensile Strength (MPa)	Hardness (BHN)	Modulus of Elasticity (GPa)
W-Al-SiC	3255	295	112	95

Table 2 Chemical composition of the alloy (W-Al-SiC).

Elements	Aluminum	Silicon Carbide	Silicon	Titanium	Tungsten	Rest of Elements (Mg, Mn, Fe, etc.)
Percentage (%)	63	15	13	4	4	1

Turning gives metal surfaces, a smooth finish, and reduces the workpiece's diameter, usually to specific gauge. Frequently, the workpiece is turned to change the diameter. In its most basic form, turning can be characterized as machining the rotating workpiece's outer surface using a single-edged cutting tool fed parallel to the workpiece's axis at a distance equal to the outside surface of the workpiece. Taper turning is identical except for the cutter path, which is at an angle to the working axis. Similarly, some unusual cases of the turning process include facing, necking, internal shaping, form turning, external and internal threads, knurling, laborious, etc. Table 2 displays the characteristics of cutting instruments with a tip. Despite the requirement for a single-tipped tool, turning frequently employs multi-tool configurations. Each device functions independently as a single-point cutter in such arrangements. The machining process that produces cylindrical pieces is called turning. The machining of an exterior surface, a single-point cutting tool, and the cutting tool feed parallel to the axis of the workpiece and at a distance that eliminates the outer surface of the workpiece can be characterized as its simplest form.

The Taguchi method is a well-known tool for creating high-quality systems and is a well-known technique that provides a systematic and effective way to optimize processes. The Taguchi technique for designing experiments has gained much recognition in the technological and scientific world since it is simple to use and put into practice for users with little statistical background. This is a specialized technique for obtaining product and process conditions that generate high-quality products with low upfront and manufacturing costs and are minimally susceptible to the many causes of variation. His contributions have also inspired the work of practitioners by promoting the use of less empirical designs and offering a greater understanding of the varied nature and financial ramifications of quality engineering in the industrial sector. Taguchi explains his strategy and employs innovative architecture for:

- Designing and creating products and processes that are resilient to modulus fluctuations.
- Designing products or processes with consideration for environmental circumstances. Reduce variations near a target value.

The teachings of Taguchi apply to all cultures. He suggested using a three-step procedure, including system design, parameter design, and tolerance design, to perform technical optimization of a process or product. The selection of materials, components, initial settings for product parameters, etc. is part of the architectural production process. The process design phase includes the research of processing sequences, the choice of construction tools, estimating the process parameter values, etc. The system architecture is a preliminary functional design. Therefore, its cost and quality may not be ideal.

When the S/N ratio is continuous, the feature can be categorized into three groups: nominal is best, smaller is better, and larger is better. The smaller the solution, the better for the lowest cutting temperature. A common term for quality is specification conformity. Taguchi, however, proposes a definition of quality that considers the demands of the consumer, the producer, and society at large, as opposed to one that relates it to the cost and a lack of resources[25–27]. Losses, per Taguchi, are typically seen as additional manufacturing expenses incurred until the product is distributed. When machining, internal, external, and intermediate noise variables determine how much energy is used to meet the power demand. Some countermeasures can be taken to reduce the impacts caused by these noise factors. The architecture, which encompasses the system design, parameter architecture, and tolerance design, is the most crucial. Equation (1) specifies the formulation of the S/N ratio, which signifies the quality of the response parameter. The formula is applicable for responses "smaller is better."

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

Where y_i mean data for the response parameters, n—number of experiments or readings[28].

On a lathe, turning is the technique used to create cylindrical components. Manual labor or a CNC machine can be used to complete this. When turning, a cylindrical piece of material is spun as a cutting tool and is moved along two axes of motion to produce exact diameters and depths. Turning, also known as boring, can be done inside or outside the cylinder to create tubular modules with various geometries. The turning can be done manually on traditional machines with top lathes that are not computer-controlled. An alternative method of turning is automatic lathes (auto lathes) run by skilled machinists. The role of CNC controllers in contemporary practice is evolving toward that of a CNC machine. Further, Table 3 represents the different input parameters at different levels selected for the experimentations.

A single-point cutting tool removes material from a rotating workpiece during regular turns, resulting in a cylindrical surface. A linear feed is applied to guide the cutting tool in a direction perpendicular to the axis of rotation. Turning is done utilizing a lathe, which can feed the cutting tool with a particular inclination and depth of cut and rotate the workpiece at a certain speed. Therefore, three cutting parameters, cutting speed, feed, and depth of cut, must be specified during a turning operation. Surface roughness is a popular foundation for evaluating machining performance in turning. Theoretically, there is a direct connection between cutting parameters, such as cutting speed, feed, depth of cut, and surface roughness. In instruction to reduce the surface roughness in a tuning process, this work adopts an optimization of the cutting parameters based on the parameter creation of the Taguchi technique. The MRR response can be calculated using Eq. (2)[20].

$$MRR = \frac{(\text{Initial weight–final weight})}{\textit{time taken}} \quad (2)$$

Choosing the cutting settings to ensure excellent cutting performance is crucial in the turning process. Typically, expertise or following instructions is used to identify the desired cut locations. However, this does not guarantee that the chosen cutting parameters will generate an ideal or near-optimal cutting performance for a listed machine and environment. Numerous mathematical models based on statistical regression methods or neural calculation have been evolved to establish the correlation between cutting performance and cutting parameters in mandate to select cutting parameters properly. The cutting parameters' outcomes and their interactions' effects on the surface roughness can also be considered during turning. Three cutting parameters—cutting speed, feed, and cutting depth—were used to develop the procedure for this experiment. According to the machining manual, a cutting speed between 212 and 525 rpm, a feed between 0.35 and 0.42 mm/rev, and a depth of cut between 0.5 and 2 mm is the recommended realizable range of the cutting parameters for the workpiece material used, the tool used, and the machine used. This results in four ranges of cutting parameters.

Table 3 Different input parameters and their levels.

Parameters	Units	Level 1	Level 2	Level 3
Speed	rpm	220	350	530
Feed rate	mm/rev	0.37	0.41	0.44
Depth of cut	mm	0.50	1.00	1.50

RESULTS AND DISCUSSIONS

The current work uses Taguchi techniques to optimize the cutting settings for surface roughness during turning (Table 4). On the four planes, three parameters—cutting speed, feed rate, and depth of cut—are chosen to apply the Taguchi technique. According to the observation of Table 4, the orthogonal L9 configuration was the subject of an initial round of studies. This study investigates the W-Al-Si-C bar's turning performance characteristics using a high-speed steel cutting tool experiment on a lathe, and a Subtonic 10 surface tester is used to measure the surface roughness. Table 5 shows the different input parameters for the Taguchi methodology. The significant process parameter is often the one whose max–min value is more important than 50% of the maximum of the max–min value. According to Table 4, the feed rate and depth of cut are crucial process variables.

The process is barely or barely affected by the cutting speed. An example with the three parameters on three planes was taken from a reference book and compared to the existing methods for maximizing the cutting parameters for surface roughness in turning to evaluate the present work's correctness and performance. Finally, despite several difficulties that may be found in the literature pertinent to the Taguchi method, the benefit is realized in the current study. The following part covers the fundamentals of advantages in the present work. An experiment with three factors and three possible values has nine variables. The results of all experiments then yield 100 precise results. As opposed to the earlier method, the Taguchi orthogonal array generates a list of nine experiments in a particular order, covering every element specified in Table 5. The results of these nine tests are 99.96% accurate. The number of experiments decreased to 27 using this strategy while maintaining the same accuracy. Since finding a random sample of future conditions is impossible, Taguchi suggested that the classic example is insufficient. To better imitate the environment in which the experiment would take place, Taguchi suggested extending each test to include an examination of the theories and perceptions underlying orthogonal configurations. The MRR reduces as the feed rate rises, so the feed rate should be tuned to facilitate machining. For optimum machining of this advanced material/aluminum alloy, the feed rate can be kept between 0.50 and 1.50 mm/rev.

With a standard aluminum alloy, the material elimination rate rises with a depth of cut. Still, with this evolved and optimized stamped material, the MRR first increases with the depth of cut and then falls

Table 4 Taguchi orthogonal array.

S. No.	Job No.	Spindle Speed (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)
a)	1	1	1	3
b)	2	1	2	2
c)	3	1	3	1
d)	4	2	1	2
e)	5	2	2	1
f)	6	2	3	3
g)	7	3	1	1
h)	8	3	2	3
i)	9	3	3	2

Table 5 Observation table.

Speed (N, rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)	Time (s)	Initial Weight (g)	Final Weight (g)	Diff. of Weight (g)	MRR (g/s)
220	0.37	1.50	11.7	209	192	17	1.452
220	0.41	1.00	11.1	202	184	18	0.818
220	0.44	0.50	9.6	187	176	11	0.543
350	0.37	1.00	8.7	180	170	10	1.294
350	0.41	0.50	8.1	172	165	7	0.641
350	0.44	1.50	7.5	166	161	5	0.563
530	0.37	0.50	6.9	163	159	4	0.588
530	0.41	1.50	6.2	162	153	9	1.132
530	0.44	1.00	5.6	156	149	7	0.961

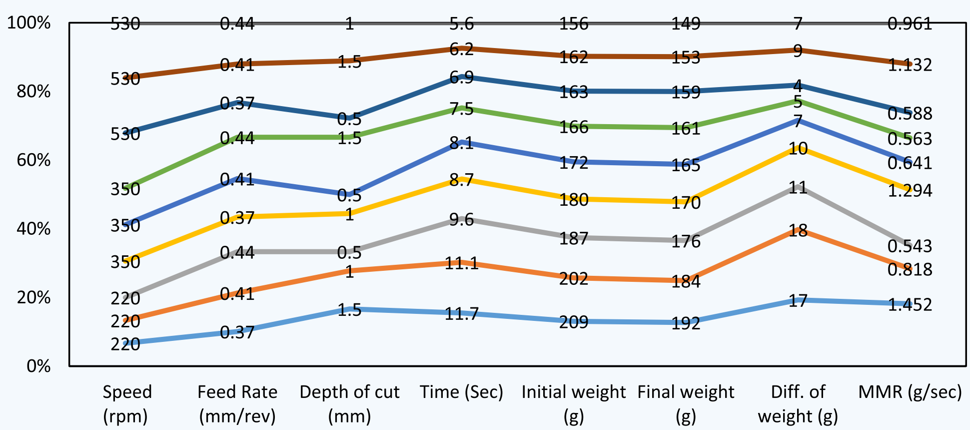

Figure 1 Variation of all experimentally determined parameters.

dramatically with the depth of cut. For this reason, machining at higher depths becomes difficult, necessitating further optimization of the depth of cut. The research led us to conclude that at the indicated speed, the depth of cut is more significant than 0.50 mm and less than 1 mm. The Taguchi optimization methodology determines how various parameters change as spindle speed increases. The results are displayed in Table 5. Further, **Fig. 1** shows the variations of all experimentally determined parameters.

CONCLUSIONS

This study examines the use of an orthogonal array with desirability function evaluation for optimizing the multipower W-Al-SiC machining process. The method simplifies the optimization of multiple complex characteristics, such as surface roughness and power consumption. The study also emphasizes the importance of considering factors like ease of use, power consumption, and tool and work pressures for improved surface finish.

- ❖ Effective experimental design aids in process optimization and identifies variables that affect variability.
- ❖ Factorial designs are simple to create but can grow too large to be helpful.
- ❖ The study found that the feed rate and depth of cut were the most significant process parameters affecting the machining of W-Al-Si-C material, while the cutting speed had a relatively lower impact.
- ❖ Through the Taguchi methodology, the research determined that a cutting speed of 350 rpm, a feed rate of 0.37 mm/rev, and a depth of cut of 1 mm produced the best MRR. This combination resulted in an MRR of 1.452 g/sec, which signifies efficient material removal.
- ❖ Unlike standard aluminum alloys, the MRR for W-Al-Si-C material exhibited a unique behavior concerning the depth of cut. It increased up to a certain depth of cut and then decreased significantly, suggesting that machining at higher depths requires further optimization.

Further work can be extended for different materials. The additional working parameters like voltage, current, depth of cut, and lubricant can be measured to evaluate the process performance. Various other metal matrix composites available in the market could be used for further study. Micro-surface finishes are also a promising research area. Different Taguchi models and ANN can be applied to measure the process performance. The optimized cutting parameters identified in this study can be applied in industrial settings to improve the efficiency of CNC machining processes, reduce power consumption, and enhance product quality when working with W-Al-Si-C material.

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CONFLICT OF INTEREST

No potential conflict of interest was reported by the author(s).

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