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Parametric Optimization of End Milling Process for Aluminum Alloys through Taguchi Design of Experiments

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Abstract

End milling is a widely used machining process for producing components with high dimensional accuracy and surface finish. In this study, a numerical investigation of the end milling process was conducted on three aluminum alloys: Al 6061, Al 7039, and Al 2024. A four-flute end mill cutter was modeled in CATIA V5, and machining simulations were performed using ANSYS Explicit Dynamics. The analysis evaluated key machining responses, including equivalent stress, equivalent strain, displacement, and reaction load, to understand the interaction between the cutting tool and workpiece under varying machining conditions. To identify optimal machining parameters, the Taguchi Design of Experiments method with an L9 orthogonal array was employed, considering workpiece material, spindle speed, and depth of cut at three levels each. The simulation results were analyzed using Minitab through Signal-to-Noise ratio analysis and main effects plots. The study revealed that machining performance is significantly influenced by material properties and cutting conditions. The combined use of CAD modeling, finite element analysis, and statistical optimization proved effective for enhancing machining efficiency and evaluating aluminum alloy behavior during end milling operations.

Keywords: **End Milling, Aluminum Alloys, ANSYS Explicit Dynamics, Taguchi Method, Machining Parameter Optimization.**

I. INTRODUCTION

End milling is one of the most important and widely adopted machining operations in modern manufacturing industries due to its capability to produce precise slots, pockets, contours, and complex three-dimensional surfaces. The process utilizes a rotating multi-edge cutting tool that removes material from a workpiece through the combined action of peripheral and end cutting edges. End milling is extensively employed in aerospace, automotive, defense, marine, and precision engineering applications where dimensional accuracy and surface quality are critical requirements. The performance of the milling operation is influenced by several machining parameters, including spindle speed, feed rate, depth of cut, tool geometry, and workpiece material properties. Improper selection of these parameters can result in excessive cutting forces, poor surface finish, increased tool wear, and reduced productivity. Therefore, understanding the relationship between machining parameters and milling performance is essential for improving manufacturing efficiency and product quality.

Aluminum alloys have become indispensable engineering materials because of their low density, high strength-to-weight ratio, corrosion resistance, and excellent machinability. Among the various grades of aluminum alloys, Al 6061, Al 7039, and Al 2024 are widely used in aerospace, transportation, military, and structural applications. Although these alloys belong to the same material family, they possess different mechanical and thermal characteristics that significantly influence their machining behavior. Variations in hardness, strength, ductility, and thermal conductivity affect stress generation, strain development, chip formation, and tool-workpiece interaction during machining operations. Consequently, it is necessary to investigate the machining performance of these alloys under different cutting conditions to identify suitable parameters that can enhance

productivity while maintaining machining quality and minimizing manufacturing costs.

In recent years, numerical simulation techniques have emerged as powerful tools for analyzing machining processes and optimizing cutting parameters without extensive experimental trials. Finite Element Analysis (FEA) enables detailed investigation of stress distribution, deformation, strain generation, and cutting force development during material removal. In the present study, a 20 mm diameter end mill cutter and aluminum alloy workpieces are modeled using CATIA and analyzed through ANSYS Explicit Dynamics. The effects of workpiece material, spindle speed, and depth of cut on machining responses are systematically evaluated. Furthermore, the Taguchi Design of Experiments approach with an L9 orthogonal array is employed to optimize machining conditions and determine the significance of each parameter. The integration of finite element simulation and statistical optimization provides a reliable and cost-effective methodology for improving end milling performance and enhancing the machining efficiency of aluminum alloys.

II. LITERATURE REVIEW

Several researchers have investigated the optimization of machining parameters in end milling of aluminum alloys to improve machining quality and productivity. Jakeer Hussain Shaik and Srinivas J. [1] optimized end milling parameters of Al-6061 using Response Surface Methodology and Genetic Algorithms, concluding that appropriate cutting conditions significantly improve surface finish and reduce tool vibration. M.S. Sukumar et al. [2] applied the Taguchi method and Artificial Neural Networks for face milling of Al-6061 and demonstrated the effectiveness of statistical and predictive techniques in determining optimal machining conditions. Shamsuddin Sulaiman et al. [3] optimized dry milling parameters for Aluminum 6061 using the Taguchi approach and reported improved surface quality under environmentally friendly machining conditions. Tamal Ghosh et al. [4] proposed a surrogate-assisted optimization technique for multi-response end milling of AA3105 alloy and achieved enhanced machining performance. Similarly, Rajesh Kumar et al. [5] utilized a hybrid Grey Relational Analysis and Principal Component Analysis approach for multi-response optimization of Aluminum 6061 milling and successfully identified optimum cutting parameters. S. Prakash et al. [6] employed a GRA-PCA hybrid method for end milling of Al6061-SiCp composites and found that feed rate was the most influential parameter affecting machining force and surface roughness.

Recent studies have focused on advanced optimization and prediction techniques for improving milling performance of aluminum alloys. Muhammad Alif Ihsan et al. [7] integrated Taguchi and PROMETHEE methods for CNC milling optimization of AA6061 and demonstrated improved reliability in machining parameter selection. W. Safiei et al. [8] investigated end milling of AA6061-T6 under Minimum Quantity Lubrication conditions and identified optimal machining parameters that enhanced machining quality while reducing lubricant consumption. Van Que Nguyen et al. [9] developed multi-response prediction models for thin-walled milling of 6061 aluminum alloy and achieved improvements in surface roughness, flatness deviation, and material removal rate. Researchers reported in Measurement Journal [10] that Taguchi-Grey Relational optimization effectively enhanced machining quality and reduced processing time by optimizing spindle speed, feed rate, and tool path strategy. Nashwan Q. Mahmood et al. [11] analyzed surface roughness characteristics of AA6061 using Taguchi and ANOVA techniques and confirmed that spindle speed, feed rate, and depth of cut significantly influence machining performance. The literature indicates that statistical optimization techniques, finite element analysis, and hybrid decision-making methods are effective tools for identifying optimum machining parameters and improving end milling performance of aluminum alloys.

III. MATERIALS AND MACHINING PARAMETERS

This Section presents the materials, tool specifications, machining parameters, and simulation methodology adopted for the end milling analysis of aluminum alloys. End milling is an important machining process used extensively in manufacturing industries to produce components with high dimensional accuracy and superior surface quality. In the present

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investigation, three aluminum alloys, namely Al 6061, Al 7039, and Al 2024, are selected as workpiece materials due to their widespread applications in aerospace, automotive, defense, and structural engineering sectors. These materials possess different mechanical and thermal properties, which significantly influence cutting forces, stress generation, deformation behavior, and machining performance. The primary objective of this study is to evaluate the effect of material selection and cutting conditions on important machining responses such as equivalent stress, total deformation, and equivalent strain generated during the end milling process.

Table 1: End Mill Tool Specifications

Parameter	Value
Tool Type	Flat End Mill
Tool Material	Tungsten Carbide
Tool Diameter	20 mm
Number of Flutes	4
Helix Angle	30°
Rake Angle	10°
Relief Angle	12°
Shank Diameter	20 mm
Tool Length	100 mm
Cutting Direction	Down Milling

A flat end mill cutter with a diameter of 20 mm is employed for all simulation cases to maintain uniformity throughout the analysis. The cutter geometry is developed using CATIA software and consists of four flutes, a 30° helix angle, a 10° rake angle, and a 12° relief angle to ensure efficient chip removal and stable cutting performance. The cutter material is selected as tungsten carbide because of its high hardness, excellent wear resistance, and suitability for high-speed machining applications. The workpiece and cutter models are created in CATIA and imported into ANSYS Explicit Dynamics for simulation. The mechanical properties of the selected aluminum alloys, including density, Young's modulus, yield strength, tensile strength, hardness, and thermal conductivity, are incorporated into the finite element model to accurately represent material behavior during machining.

The numerical simulation is carried out using ANSYS Explicit Dynamics, which is particularly suitable for modeling highly nonlinear contact interactions, large deformations, and transient machining phenomena. The machining parameters considered in the study include workpiece material, spindle speed, and depth of cut, while dry machining conditions are maintained throughout the analysis. To systematically investigate the influence of these parameters and determine the optimum machining conditions, the Taguchi Design of Experiments technique is employed using an L9 orthogonal array. The simulation results obtained from each experimental run are analyzed to evaluate the effect of individual parameters on machining performance. This integrated approach combining CAD modeling, finite element analysis, and statistical optimization provides an effective methodology for improving machining efficiency and understanding the milling behavior of different aluminum alloys.

IV. CAD MODELING

The end mill cutter used in this study is modeled using CATIA V5 to accurately represent the geometry of a practical machining tool. Initially, a circular profile with a diameter of 20 mm is created and extruded to a length of 120 mm to form the cylindrical body of the cutter. This base model represents the shank and core structure of the tool and provides the required rigidity for machining simulation. Subsequently, the flute geometry is generated by creating a helical path with a pitch of 60 mm and a height of 60 mm. A single flute profile is projected along the helix and material is removed to produce the spiral cutting edge. This helical flute design accurately represents the actual end mill geometry and facilitates efficient chip evacuation and cutting action during machining operations.

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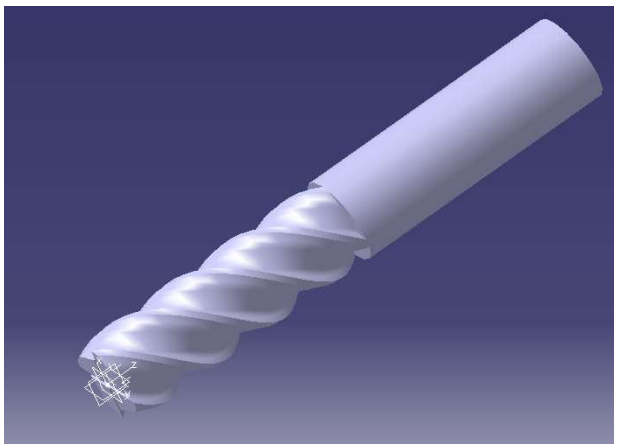


Fig 1: Final end mill bit.

After creating a single flute, a circular pattern operation is applied to generate four equally spaced flutes around the tool axis. Sharp taper faces are also introduced at the tool tip to represent the cutting edges responsible for material removal. The completed four-flute end mill model closely resembles an industrial milling cutter and ensures realistic interaction with the workpiece during simulation. The final CAD model is validated for geometric accuracy and then exported for finite element analysis in ANSYS Explicit Dynamics, where it is used to evaluate machining performance under different cutting conditions.

The workpiece is modeled in CATIA V5 as a solid rectangular block with dimensions of 100 mm × 100 mm × 20 mm. A square sketch is first created and subsequently extruded to obtain the required thickness. These dimensions are selected to provide sufficient machining area while minimizing boundary effects during simulation. The workpiece is defined as a deformable body so that the development of stress, strain, and deformation during the end milling process can be accurately evaluated. Proper geometric dimensions are maintained to ensure realistic representation of the machining environment and accurate numerical results.

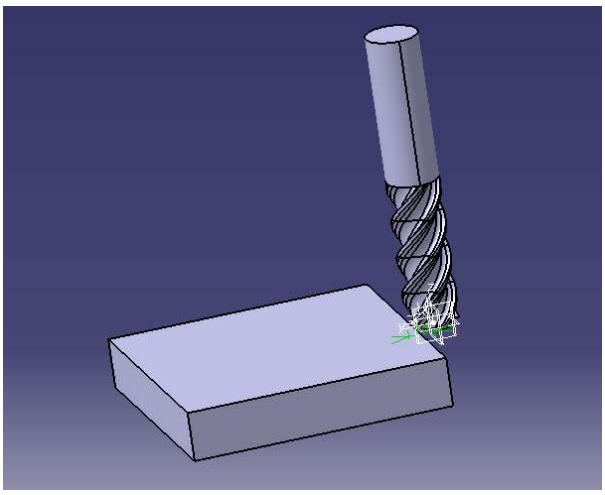


Fig 2:Final model of assembly.

Following the creation of the individual models, the end mill cutter and workpiece are assembled in CATIA V5 to replicate the actual machining setup. Assembly constraints such as coincidence and offset conditions are applied to position the cutter accurately above the workpiece and establish the required depth of cut. The completed assembly is thoroughly verified to ensure correct alignment and contact between the tool and workpiece. Finally, the assembly is exported in STEP (.stp) format and imported into ANSYS Workbench for explicit dynamic simulation. This integrated CAD assembly serves as the foundation for analyzing the influence of workpiece material and machining parameters on end milling performance.

ANSYS Explicit Dynamics is widely used for machining simulations because it can effectively handle highly nonlinear phenomena such as large deformation, high strain rates, severe plastic deformation, and complex contact interactions between the cutting tool and workpiece. During the end milling process, continuous engagement of the rotating cutter with the workpiece generates rapidly changing stresses, strains, and deformation patterns that are difficult to capture using conventional static analysis techniques. The explicit dynamic solver accurately predicts machining responses such as equivalent stress, total deformation, equivalent strain, and cutting forces throughout the cutting cycle. These results provide valuable information regarding the influence of workpiece material and machining parameters on milling performance. The time-dependent nature

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of explicit analysis enables realistic simulation of the material removal process and offers a detailed understanding of machining behavior under different cutting conditions.

The first stages of the analysis involve geometry preparation, geometry cleanup, and meshing. The three-dimensional assembly of the end mill cutter and workpiece developed in CATIA V5 is imported into ANSYS Workbench using STEP format. The imported geometry is verified for dimensional accuracy, proper alignment, and correct positioning of the cutter relative to the workpiece. Geometry cleanup is then performed to remove unnecessary edges, small surfaces, and unwanted features that may increase computational cost without contributing to machining behavior. After simplification, the model is discretized using tetrahedral finite elements. A finer mesh is applied in the contact region between the cutter and workpiece to accurately capture stress concentration and deformation during machining. Proper mesh quality is maintained throughout the model to ensure numerical stability, reliable convergence, and accurate prediction of machining responses.

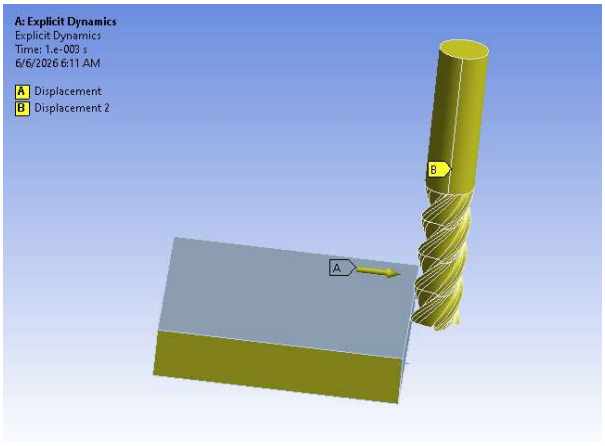


Fig 3: Boundary conditions.

Following meshing, material properties and boundary conditions are assigned to the model. The end mill cutter is defined as a rigid body, while the workpiece is modeled as a deformable body using the material properties of Al 6061, Al 7039, and Al 2024 alloys. Boundary conditions include angular velocity applied to the cutter to represent spindle rotation, fixed support at the base of the workpiece, and feed motion to simulate the actual milling process. Frictional contact is established between the tool and workpiece surfaces to represent realistic cutting interaction. The explicit dynamic solution is then performed using a total simulation time of 1×10^{-3} seconds with very small time increments to capture the transient machining behavior accurately. The solver continuously updates contact forces, stress distribution, strain development, and deformation during the cutting process. The generated results are subsequently used for Taguchi-based optimization to determine the most favorable machining parameters and evaluate the performance of different aluminum alloys during end milling.

The post-processing stage involves analysis and interpretation of simulation results obtained from ANSYS. In this stage, results such as equivalent stress, total deformation, and equivalent strain are evaluated. Contour plots are generated to visualize stress distribution during machining. Deformation patterns of the workpiece are analyzed to understand material removal behavior. High-stress regions are identified to study cutting zone effects. Contact pressure distribution is also examined for tool-workpiece interaction. Graphical results help in understanding machining performance under different conditions.

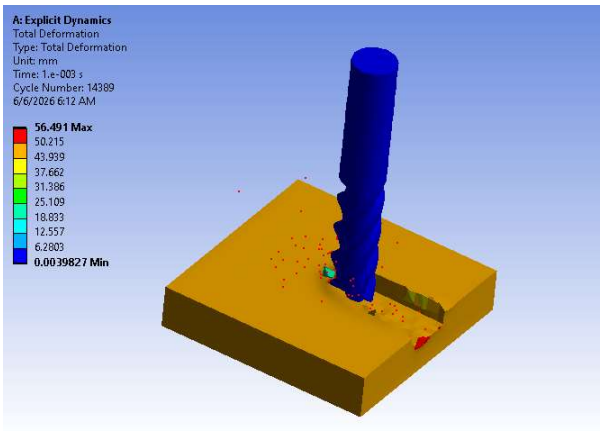


Fig 4: displacement plot for Al 6061 , 3 mm depth of cut and 8000 RPM.

The displacement plot for Al 6061 at a depth of cut of 3 mm and spindle speed of 8000 RPM illustrates the material deformation during the end milling process. A maximum displacement of 56.49 mm is observed near the tool engagement region, indicating effective material removal and chip formation. The higher spindle speed and larger depth of cut increase the cutting

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energy, resulting in greater deformation of the workpiece. The displacement contour highlights the regions of maximum material removal along the tool path and confirms stable machining performance under the selected cutting conditions.

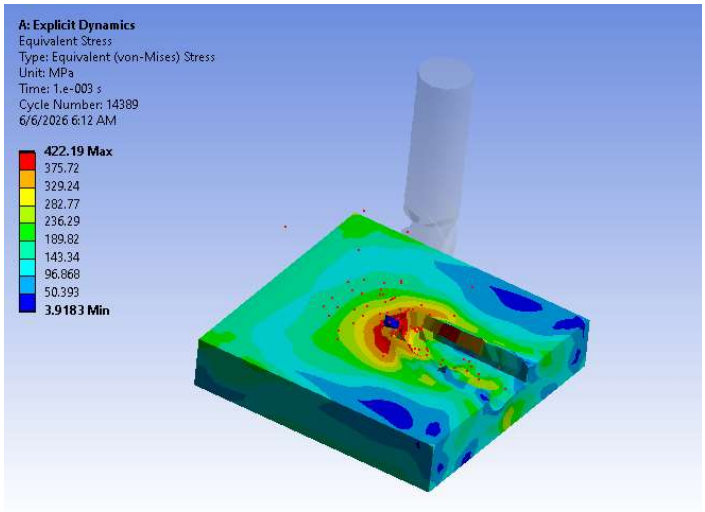


Fig 5: Stress plot for Al 6061 , 3 mm depth of cut and 8000 RPM.

The stress plot for Al 6061 at a depth of cut of 3 mm and spindle speed of 8000 RPM shows the von Mises stress distribution during end milling. A maximum stress of 422.19 MPa is observed at the tool–workpiece interaction zone, where intense plastic deformation and material removal occur. The stress decreases gradually away from the cutting region as the load is distributed through the workpiece. The higher spindle speed and larger depth of cut contribute to increased cutting forces and stress generation. The stress distribution confirms effective material shearing and highlights the significant influence of machining parameters on milling performance.

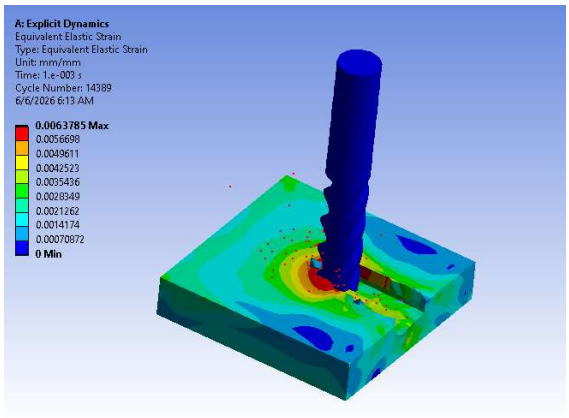


Fig 6: Strain plot for Al 6061 , 3 mm depth of cut and 8000 RPM.

The strain plot for Al 6061 at a depth of cut of 3 mm and spindle speed of 8000 RPM shows the plastic deformation behavior during end milling. A maximum equivalent strain of 0.0063 is observed at the cutting zone where direct tool–workpiece interaction occurs. This high strain concentration indicates significant plastic deformation and effective chip formation caused by the rotating cutter. The strain gradually decreases away from the cutting region due to reduced cutting influence. The higher spindle speed and larger depth of cut contribute to increased strain generation, demonstrating efficient material removal under the selected machining conditions.

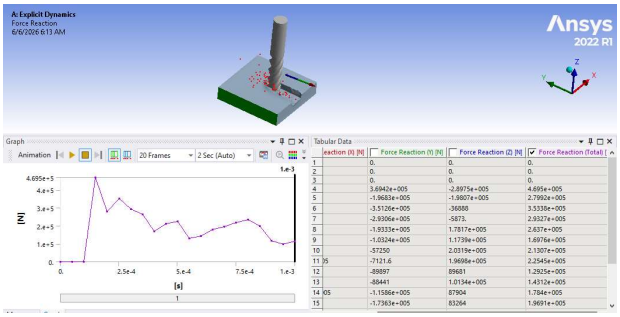


Fig 7: reaction load for Al 6061 , 3 mm depth of cut and 8000 RPM.

The reaction load plot for Al 6061 at a depth of cut of 3 mm and spindle speed of 8000 RPM illustrates the cutting force generated during end milling. A maximum reaction load of 4.65 × 10^5 N is observed at the initial stage due to sudden tool-workpiece engagement and impact loading. As machining progresses, the reaction load gradually decreases and stabilizes because of steady chip formation and uniform material removal. The high spindle speed and larger depth of cut contribute to the increased initial cutting resistance. The plot demonstrates the transition from transient cutting conditions to stable machining behavior.

V. DESIGN OF EXPERIMENTS (DOE) – TAGUCHI TECHNIQUE

Design of Experiments (DOE) is a statistical method used to systematically investigate the influence of multiple input parameters on output responses while minimizing the number of

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experiments required. Among the available DOE techniques, the Taguchi method is widely used because of its simplicity, reliability, and ability to identify optimum process conditions with fewer experimental runs. The method utilizes orthogonal arrays and Signal-to-Noise (S/N) ratios to evaluate the effects of control factors on performance characteristics and determine the best parameter combination. In machining applications, Taguchi analysis helps improve process quality, reduce variability, and enhance productivity while minimizing time and computational effort. In the present study, the Taguchi technique is employed to optimize the end milling performance of aluminum alloys using simulation results obtained from ANSYS Explicit Dynamics.

Table2: Factors and Levels Used in Taguchi Analysis

Factor	Parameter	Level 1	Level 2	Level 3
A	Material	Al 6061	Al 7039	Al 2024
B	Spindle Speed (RPM)	4000	6000	8000
C	Depth of Cut (mm)	1	2	3

Three machining parameters, namely workpiece material, spindle speed, and depth of cut, are selected as control factors, each at three levels. An L9 orthogonal array is adopted to reduce the number of simulation runs from 27 possible combinations to only 9 experiments, thereby saving significant computational resources. The output responses considered are equivalent stress, equivalent strain, total deformation, and reaction load. The simulation results are analyzed using Minitab software, which provides response tables, S/N ratios, and main effects plots for identifying the most influential factors and optimum parameter levels. The selected factors and levels used in the Taguchi analysis are Al 6061, Al 7039, and Al 2024 as workpiece materials, spindle speeds of 4000, 6000, and 8000 RPM, and depths of cut of 1, 2, and 3 mm. This integrated ANSYS–Minitab approach provides an efficient framework for optimizing end milling performance and identifying the most favorable machining conditions.

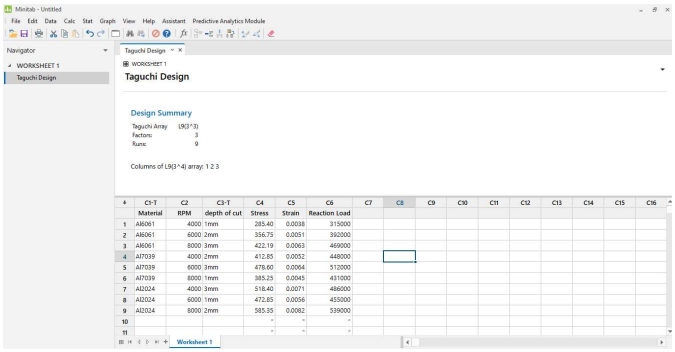


Fig 8: Data given in minitab software.

Taguchi Analysis for Stress

The Taguchi analysis was performed using Minitab software to determine the influence of material type, spindle speed, and depth of cut on the equivalent stress generated during the end milling process. Since lower stress values are preferred for improved machining performance and reduced tool loading, the "Smaller is Better" Signal-to-Noise (S/N) ratio criterion was selected. The response table for S/N ratios indicates that the material factor has the highest Delta value of 3.49, followed by depth of cut with a Delta value of 2.03, while RPM has the lowest Delta value of 1.29. Based on the ranking, the material is identified as the most influential parameter affecting stress generation, followed by depth of cut and spindle speed. The optimum parameter combination obtained from the S/N ratio analysis is Al 6061 (Level 1), 4000 RPM (Level 1), and 1 mm depth of cut (Level 1), as these levels provide the highest S/N ratio and therefore the lowest stress value.

WORKSHEET 1

Taguchi Analysis: Stress mpa versus Material, RPM, depth of cut

Level	Material	RPM	depth of cut
1	-50.89	-51.91	-51.44
2	-52.54	-52.71	-52.90
3	-54.38	-53.19	-53.47
Delta	3.49	1.29	2.03
Rank	1	3	2

Response Table for Means

Level	Material	RPM	depth of cut
1	354.8	405.6	381.2
2	425.6	436.1	451.7
3	525.5	464.3	473.1
Delta	170.8	58.7	91.9
Rank	1	3	2

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Fig 9: Taguchi report.

The response table for means further confirms the influence of the selected machining parameters on stress development. The mean stress values increase significantly from 354.8 MPa for Al 6061 to 525.5 MPa for Al 2024, indicating that stronger materials generate higher cutting stresses during machining. Similarly, the average stress increases from 405.6 MPa at 4000 RPM to 464.3 MPa at 8000 RPM, demonstrating the effect of spindle speed on cutting forces and stress generation. A similar trend is observed for depth of cut, where the mean stress increases from 381.2 MPa at 1 mm depth of cut to 473.1 MPa at 3 mm depth of cut. The Delta values obtained from the means table also rank material as the most dominant factor (170.8), followed by depth of cut (91.9) and RPM (58.7).

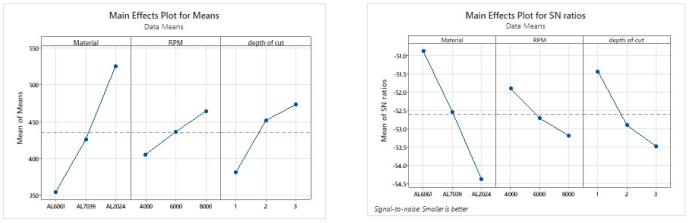


Fig 10: Stress results taguchi results.

The main effects plot for means shows that stress increases with changes in material, spindle speed, and depth of cut. The material factor has the greatest influence, with stress increasing significantly from Al 6061 to Al 2024. Stress also rises as RPM and depth of cut increase, indicating that lower cutting conditions help reduce machining stress.The S/N ratio plot confirms that Al 6061, 4000 RPM, and 1 mm depth of cut provide the highest S/N ratio and the lowest stress values. As factor levels increase, the S/N ratio decreases, indicating higher stress generation. Therefore, the optimum parameter combination for minimizing stress is Al 6061 – 4000 RPM – 1 mm depth of cut.

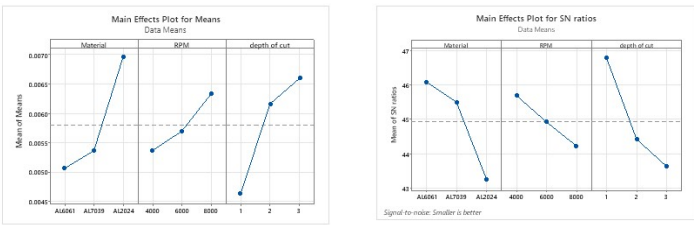


Fig 11: Strain results taguchi results.

The Taguchi analysis for strain was conducted using the "Smaller is Better" criterion to minimize material deformation during end milling. The main effects plot shows that strain increases from Al 6061 to Al 2024 and rises with increasing spindle speed and depth of cut. Among the factors, depth of cut has the strongest influence on strain generation, followed by material and spindle speed.The S/N ratio plot indicates that the highest S/N ratio occurs at Level 1 of all factors, corresponding to Al 6061, 4000 RPM, and 1 mm depth of cut. Hence, this parameter combination is identified as the optimum condition for minimizing strain and reducing material deformation during machining.

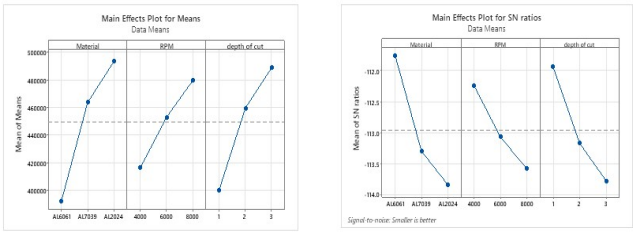


Fig 12: Reaction load results taguchi results.

The Taguchi analysis of reaction load was performed to evaluate the influence of machining parameters on cutting force during end milling. The main effects plot indicates that reaction load increases from Al 6061 to Al 2024 and rises with increasing spindle speed and depth of cut. This behavior shows that stronger materials and more aggressive cutting conditions generate higher cutting forces.The S/N ratio plot shows that the highest S/N ratio occurs at Al 6061, 4000 RPM, and 1 mm depth of cut, indicating the lowest reaction load. As the factor levels increase, the S/N ratio decreases, reflecting higher cutting forces. Therefore, the optimum parameter combination for minimizing reaction load is Al 6061 – 4000 RPM – 1 mm depth of cut.

CONCLUSION

The present study investigated the end milling performance of Al 6061, Al 7039, and Al 2024 aluminum alloys using ANSYS Explicit Dynamics and Taguchi optimization. A 20 mm diameter four-flute carbide end mill was modeled in CATIA and analyzed under different combinations of material, spindle speed, and

depth of cut using an L9 orthogonal array. The simulation results showed that Al 6061 exhibited the lowest stress, strain, and reaction load values, indicating superior machinability, while Al 2024 produced the highest stress and strain levels under identical machining conditions. Taguchi analysis revealed that workpiece material was the most influential factor affecting machining performance, followed by depth of cut and spindle speed. The optimum parameter combination for minimizing stress, strain, and reaction load was identified as Al 6061, 4000 RPM spindle speed, and 1 mm depth of cut. The study concludes that lower spindle speeds and smaller depths of cut significantly reduce cutting forces and material deformation, thereby improving machining efficiency and overall milling performance.

FUTURE SCOPE

Future research can expand this study by considering additional machining parameters such as feed rate, tool inclination angle, helix angle, and tool diameter to achieve a more detailed understanding of end milling performance. The effectiveness of different cutting tool materials, including coated carbide, HSS, ceramic, and PCD tools, can also be investigated to improve tool life and machining efficiency. Furthermore, the numerical results obtained from ANSYS Explicit Dynamics may be validated through CNC milling experiments to enhance model accuracy and reliability. Advanced optimization techniques such as Grey Relational Analysis (GRA), Response Surface Methodology (RSM), Genetic Algorithms (GA), and Artificial Neural Networks (ANN) can be employed for multi-objective optimization. In addition, future studies can be extended to advanced materials such as titanium alloys, magnesium alloys, and composite materials to evaluate their machining characteristics and optimize cutting parameters for industrial applications.

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