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A review on the effect of milling process parameters on surface roughness and dimensional accuracy of EN31 using Taguchi method

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Abstract: The basic purpose of this review is to check if the quality accepted to the customers lies within the desired tolerance limit or not. Therefore the surface roughness and dimensional accuracy needs to be optimized using a Vertical Milling Centre with the process parameters including spindle speed, feed rate and depth of cut. Utilizing an orthogonal array of L27 (3^3) based on the number of parameters and their levels were investigated. Employing Taguchi's Design of Experiments (DOE) method, experimental data was collected through 27 runs to analyse the impact of these factors. Signal-to-noise ratio (S/N ratio), analysis of variance (ANOVA), and regression analysis were then performed to ascertain optimal levels, response ranges, and the percentage contribution of each parameter. The experimentation took place on a HAAS mini-mill centre, programmed with MasterCam 21 software, while surface roughness was measured using the Mitutoyo SJ-210 instrument, and dimensional measurements were conducted with a digital precision measurement instrument. The comprehensive results of the experiments were compiled and tabulated using Minitab-19.

***Index Terms*:** Taguchi Method, Surface Roughness, Dimensional Accuracy, ANOVA, S/N ratio, Regression analysis, Orthogonal Array

INTRODUCTION

Enhancing the quality of machining processes is a principal objective in modern manufacturing. A CNC vertical milling is broadly employed method in industries. High-quality and fully automated production is in demand everywhere and places a significant emphasis on the surface conditions of the product, with the surface finish of the machined surface being particularly crucial due to its impact on product appearance, and reliability and functions. Consistent dimensional tolerances and surface finish are vital considerations to consider while machining. End milling stands out as the most prevalent metal removal operation, extensively utilized across the globe in various manufacturing industries. The quality of the milled surface holds immense importance, as precise machined surface enhances fatigue strength, corrosion resistance, and creep life. Numerous factors, including vibration, spindle run-out, temperature, tool geometry, feed, cross-feed, tool path, and others, influence the surface generated during milling. To attain the objectives on a VMC milling centre, precise control of machining parameters such as spindle speed, feed rate, and depth of cut is essential. In the pursuit of identifying optimal combinations for three input parameters (spindle speed, feed, and depth of cut) and two responses (surface roughness and dimensional accuracy), a Taguchi design array is employed followed by the regression analysis.

LITERATURE REVIEW

M. Nurhaniza et al. [1] conducted an analysis on the impact of machining parameters on the surface quality of CFRP Aluminium during CNC end milling operations with a PCD tool. The milling parameters under evaluation included spindle speed, feed rate, and depth of cut. To analyze the effects of these cutting parameters, L9 Taguchi orthogonal arrays, signal-to-noise (S/N) ratio, and analysis of variance (ANOVA) were employed. The findings from the analysis suggest that the optimal combination of cutting parameters for achieving a superior surface finish involves *high cutting speed, low feed rate, and low depth of cut*.

João Ribeiro et al. [2] presented a study by applying Taguchi design to optimize surface quality in a CNC for end milling operation. The control factors such as feed per tooth, cutting speed, and radial depth of cut were taken to investigate the contribution for responses. Utilizing an orthogonal array of L9, ANOVA analyses was conducted to identify the significant factors influencing the surface roughness. The optimal cutting combination was determined by optimizing surface roughness as the response by considering the signal-to-noise ratio. The work material involved machining a hardened steel block (steel 1.2738) with tungsten carbide-coated tool. The results revealed a minimum arithmetic mean surface roughness of 1.662 µm, with the radial *depth of cut being the most influential parameter*, contributing 64% to the workpiece surface finishing.

M. Prakash et al. [3] The aim of this study was to apply the Taguchi method to explore the impact of milling parameters like cutting speed, depth of cut, and feed rate. The impact on surface roughness and material removal rate (MRR) was investigated at different levels. The investigation is conducted on a vertical milling machine, and a Tungsten Carbide is chosen as the cutting tool for machining OHNS Steel. The analysis revealed that the most influential controlling factor affecting surface roughness variation was the *feed*, contributing 54.66%, followed by the depth of cut with a contribution of 26.85%. Similarly, for material removal rate (MRR), it was observed that *feed* has the highest influence with a percentage contribution of 54.45%, followed by the depth of cut with a contribution of 34.38%.

R Ashok Raj et al. [4] experimentally investigated the machining performance with various cutting speed, feed and depth of cut using side and face milling cutter on EN8 steel. Mainly surface roughness was investigated employing Taguchi design of experiments and analysis of variance (ANOVA). The significant machining parameters were identified by using signal to noise ratio. The result of the experiments indicated *cutting speed played a dominating role* followed by Depth of cut and feed rate respectively, in surface roughness among milling process parameters.
Bala Murgan Gopalsemi et al. [5] utilized the Taguchi method to determine optimal process parameters for end milling during the hard machining of hardened steel. They employed the An L9 orthogonal array, signal-to-noise ratio, and analysis of variance (ANOVA) was employed to examine the performance characteristics of machining parameters (cutting speed, feed, depth of cut, and width of cut), taking into account surface finish and tool life. Wear due to chipping and adhesion was identified as the primary causes. The results obtained through the Taguchi method closely aligned with ANOVA, highlighting *cutting speed* as the most influential parameter. Furthermore, multiple regression equations were developed to estimate predicted values for surface roughness and tool wear.
Lohithaksha M Maiyar et al. [6] explored the parameter optimization of the end milling operation for Inconel 718 super alloy, considering multiple response criteria, using the L9 Taguchi orthogonal array and grey relational analysis. The optimization focused on cutting speed, feed rate, and depth of cut, taking into account surface roughness and material removal rate as multiple performance characteristics. Additionally, analysis of variance (ANOVA) was employed to identify the most significant factors. Confirmation tests were then conducted to compare the experimental results with the developed models, revealing that machining performance in the end milling process can be effectively improved through this approach. *Cutting speed* was found the most significant factor followed by feed rate and depth of cut respectively.
B. Vijaya Krishna Teja et al. [7] conducted experiments to optimize the performance of AISI 304 stainless steel in CNC milling using tungsten carbide tool. Key factors like cutting speed, feed rate, and depth of cut significantly impact surface roughness (SR) and material removal rate (MRR). The study aimed at achieving minimal surface roughness and maximum MRR by strategically selecting optimal levels for these parameters. Utilizing Taguchi's L27 orthogonal array, the experiments explored three levels for cutting speed, feed rate, and depth of cut. Grey relational analysis was employed to establish the relationship between machining parameters and performance characteristics. The analysis reveals that the most influential factor in milling AISI 304 stainless steel is cutting speed (56.90%), followed by depth of cut (22.43%) and feed rate (8.58%).
M. S. Sukumar [8] applied the Taguchi Method to determine the optimal combination of factors in milling Al 6061. The experiment used a Taguchi orthogonal array (L16) for speed, feed, and depth of cut variations. Surface roughness (Ra) was measured, and Taguchi S/N ratios identified optimal parameter combinations. An Artificial Neural Network (ANN) was developed and trained using experimental data, providing a set of control parameters for Ra. While Taguchi and ANN suggested different optimal combinations, confirmation tests showed almost identical Ra values. *Spindle Speed* had the most significant influence followed by depth of cut and feed rate, on the workpiece's surface finish among the considered parameters.
Amit Joshi [9] examined the impacts of CNC end milling process parameters, such as spindle speed, depth of cut, and feed rate, on surface finish using Taguchi Methodology. An experimental plan was executed through a Standard Orthogonal L9 Array. Analysis of variance (ANOVA) results highlighted that the feed rate emerged as the most influential factor in shaping surface finish. The S-N Ratio graph illustrated the optimal configuration of machining parameters, providing the best possible surface finish. Additionally, the optimal set of process parameters was forecasted to maximize the surface finish. It was found that the *feed rate* exhibits the greatest impact on the response, followed by spindle speed, while the depth of cut has the least effect on the response.
Tlhabadira et al [10] conducted an experimental design using Autodesk Fusion and Taguchi's technique, employing an L9 orthogonal array with four factors for each variable. The study aimed to investigate the contribution of factors such as the depth of cut (d), cutting speed (s), and cutting feed (f) to surface roughness. Physical experiments were carried out on M200 TS material, utilizing a DMC 635 CNC vertical milling machine with Siemens 810D, 3-Axis, and carbide inserts. The statistical analysis, combining numerical and physical experiments, resulted in a mathematical model and optimal solutions for evaluating surface roughness in the milling process. The model equations and numerical results were validated against experimental data, demonstrating the successful completion of the study and providing valuable insights for effective milling operations. The obtained results suggest that the mathematical model serves as a reliable decision-making tool for selecting appropriate values of process parameters during milling operations.

TAGUCHI METHOD

This methodology, devised by the Japanese scientist Dr. Genich Taguchi, has made significant contributions to the field of quality engineering. Dr. Taguchi's philosophy emphasizes minimizing deviations from the target value, and he introduced a mathematical model using statistical methods to provide more effective solutions.

The Taguchi-based experiments involved the following steps:
1. Clearly state the problem and determine the objective.
2. Identifying the factors influencing the performance characteristic.
3. Determine number of levels and their values for all factors.
4. Select the Orthogonal Array.
5. Assign factors and interactions to the columns of the Orthogonal Array.
6. Conduct the experiments and analyze the data using mathematical methods.
7. Interpret the results through graphical representations and tables.
8. Identify the optimal levels of significant factors.
9. Predict the expected results.

Taguchi used S/N ratios as the statistical performance measure to analyze the optimized results. The three of them frequently used are smaller-best, larger-best and nominal-best with their equations as given-

Smaller the better- $\mathbf{S/N = -10*\log [1/n\ \Sigma\ (Y^2)]}$

Nominal the better- $\mathbf{S/N = -10*\log [\Sigma\ (\bar{Y}/s^2)]}$

Larger the better- **$S/N = -10*\log [\Sigma (1/Y^2)/n]$**

METHODOLOGY

I) Workpiece material: The workpiece material selected for the experiments is EN31 Steel. The chemical composition is shown in the table 1.

Table 1 Chemical composition of EN31 steel

C	Cr	Mn	Si	P	S
0.9-1.2	1.3-1.6	0.2-0.4	0.15.0.35	<0.035	<0.040

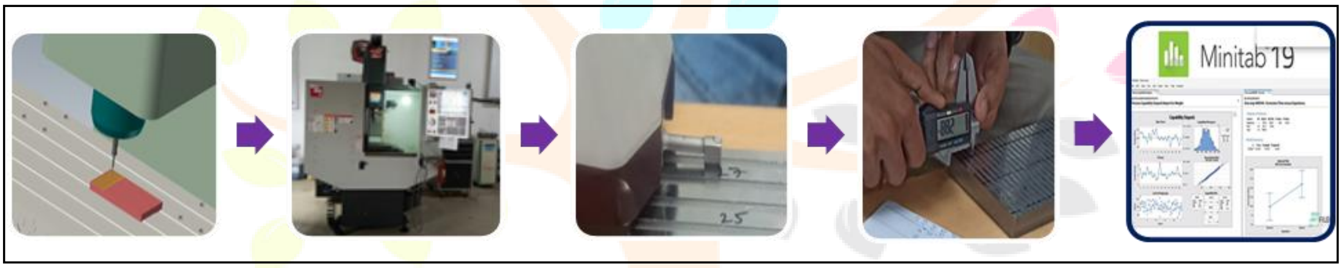
Table 1 Mechanical properties of EN31 steel

Property	Value Range
Hardness (HRC)	60 HRC to 66 HRC
Tensile Strength	700 MPa to 850 MPa
Yield Strength	550 MPa to 650 MPa
Elongation	10% to 15%
Impact Toughness	Good
Fatigue Strength	Good
Density	7.6-7.9 Kg/m^3

II) Cutting tool: A solid carbide end milling cutter if 3mm diameter is used for the machining process.

III) Selected process parameters for experimentations: According to the reviews studied it was found that the Taguchi method is the finest tool for optimization of response variable for input factors. An optimized combination and percentage contribution of all the input factors can be analysed in a systematic manner. Similarly the input parameters taken in this study are spindle speed, feed and depth of cut and the machining was performed in dry condition.

IV) Process setup:



Master Cam Programming | Vertical Milling Centre | Surface Roughness Tester | Digital Vernier Calliper | Minitab 19

DISCUSSION

For CNC milling, the goal was to determine the impact of various parameters, enabling the prediction of surface roughness and other responses. The study aimed to identify the most influential parameter for predicting surface roughness and the methodologies employed. Researchers commonly used Taguchi method comparing them with regression method, fuzzy logic, Gaussian, ANFIS, ANN and perform ANOVA to analyse experimental data involving parameters like spindle speed or cutting speed, feed rate and DOC.

CONCLUSION

The research studies conducted by various authors demonstrate the significance of machining parameters in influencing the surface quality of materials during CNC end milling operations. Utilizing Taguchi methodology and orthogonal arrays, these studies investigated factors such as spindle speed, feed rate, and depth of cut to optimize surface finish and sometimes material removal rate. The analyses employed signal-to-noise ratios, analysis of variance (ANOVA), and grey relational analysis to identify the most influential parameters. These studies contribute valuable insights for achieving optimal machining conditions and improving the performance of CNC milling processes. Here it can be summarized that along with surface roughness output responses like MRR, tool wear etc. were studied except the dimensional accuracy which always play a crucial role in every industry.

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