A Comprehensive Review on Optimization of Process Variables for CNC Milling

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Abstract

Computer numerical control (CNC) milling is a typical manufacturing technique that involves removing material from a work piece using a computer-controlled cutting tool to create a desired shape. The optimization of process variables for CNC milling is important to attaining the necessary quality and efficiency of the operation. This review article aim is to analyze the impact of various process factors on CNC milling performance. The research applies multiple optimization approaches to discover the best process parameters for machining performance. To establish the importance of each process parameter and their interactions, the analysis of variance (ANOVA) approach is applied. It was discovered that optimizing process parameters reduced machining time and tool wear while enhancing surface smoothness and dimensional accuracy. The research gives useful insights into the optimization of process variables for CNC milling, which may benefit manufacturers in improving milling efficiency, quality, and productivity.

Keywords

Analysis of variance, CNC milling, Optimization, Surface quality

Introduction

With the development of manufacturing technologies, many advanced machining operations had been created, and among the major types of machining is CNC milling process that provides more benefits than other conventional methods. Because of enhanced surface quality with good dimensional precision and little tool wear, machining characteristics have changed in response to the work piece and tool materials, tools being used, types of machining processes employed, and so on [1].

In a milling machine where material is removed by spinning a multitoothed cutter that is fed into a movable work piece. Milling creates prismatic components such as square, curved, parallel, flat, and inclined faces, as well as grooves, threads, slots, and tooth systems [2]. Milling machinery are very adaptable. Milling is a machining method used to create work pieces out of free-cutting material.

Today’s customer expects dimensional precision, high surface polish, and precise manufacture, which are hard to provide manually. Even with the most expert operators, the procedure is only possible on a rough scale. It also takes
significantly longer and costs also more. To meet these needs, 
CNC machines were created, and CNC machines were also 
given the ability to automate machining processes while also 
handling batch manufacturing [3].

CNC machining tools have used automated milling oper-
ations. Vertical CNC milling machine technique has enhanced 
considerably to fulfill sophisticated needs in various production 
fields, notably in the highly precise metal cutting manufactur-
ing. It increases productivity, improves machined component 
quality, and reduces production costs [4]. Cutting parameters, 
tool materials, tool geometry, coating technique, lubricants, 
and other factors all have an impact on product quality and 
manufacturing costs. As a result, industries are compelled to 
manage via trial and error. As a result of using the trial and 
error approach, manufacturing costs will be greatly reduced 
while time lost will be minimal [5].

This study provides a review of studies on the optimiza-
tion of different process variables parameters on CNC milling 
performance. The research applies multiple optimization ap-
proaches to find the optimal control parameters for machining 
performance.

**Workpiece Material**

High-strength steel (HSS) alloy EN 24 Steel. It is 
composed of Ni, Cr, and Mo has an excellent tensile strength, 
ductility, and water resistance. EN 24 is also utilized at higher 
temperatures, and it is a useful material to employ since it 
cures quickly and come in premopped. It is usually supplied 
in a heat-treated condition. EN 24 Steel is appropriate for 
commercial shafts, axles, in addition to other robust parts. This 
alloy of steel is often used in offshore applications because 
it possesses effect value even at lower temperatures. EN 24 
Steel is an excellent choice for heavy-duty applications and 
procedures. Figure 1 shows EN 24 Steel workpiece samples 
photograph. Workpiece material dimensions: 100 mm x 45 
mm x 20 mm.

High tensile strength is a property of EN 24 Steel is used 
in a different kind of applications such as aerospace, oil and gas 
sectors, high strength shaft, punches and dies, drill bushings, 
retention rings, gears, locomotives, cranes, rolling mills, and 
coal cutting machines. Table 1 shows the mechanical charac-
teristics of EN 24 Steel.

The chemical composition of the work piece material was 
analyzed using energy dispersive X-ray spectroscopy (EDX). 
Figure 2 shows the spectrum obtained from the EDX for 
EN24 Steel. Table 2 shows the workpiece chemical composi-
tion as determined by EDX.

**Tool Material**

Tungsten carbide (WC) is a suitable material for cutting. 
It offers a wide range of tool grades with varied hardesses. 
Each item is assigned a separate grade. WC-Co is made up 
of tungsten, cobalt (6%), niobium, and titanium. WC-Co is a 
powder metallurgy product that combines WC powder with 
a cobalt binder. This mixture is combined, compacted, and
sintered to produce the final product. WC-Co is a refractory material. It is exceptionally long-lasting and resistant to wear. readily accessible on the market coated WC inserts were employed as cutting tools throughout the experiment. TiC, TiN, TiAlN, Al$_2$O$_3$, and TiCN are common coating materials used to increase the performance of WC implants. These coatings, which typically vary in thickness from 2 to 15 m, are deposited on cutting tools and inserts using a chemical vapor deposition, physical vapor deposition, and various processes. Table 3 shows the specifications for WC inserts.

### Process Parameters

**Feed rate (FR)**

It is the rate at which the cutter is moved into contact with the workpiece. The standard unit of measurement is the mm/sec.

**Cutting speed (CS)**

The amount of times a tool’s cutting edge passes over a unit of time.

**Depth of cut (DOC)**

The amount of material removal, or the amount of the work piece’s material removed per unit of time.

**Cutting fluid**

A coolant and lubricant created particularly for metal working procedures such as machining and stamping.

### Response Parameters

**Surface roughness**

This is a main component in identifying the surface quality of an item. Integrating the absolute value of the integrity profile height throughout the assessment length yields the average surface integrity.

**Material removal rate (MRR)**

The required quantity of material removed from the work piece surface per unit time.

**Tool wear**

The regular loss of tool material occurs when the tool’s form changes from its initial shape while cutting.

### Literature Review

[6] examined the milling efficiency of stainless steel (SS) AISI 316 machining utilizing a carbide tool, and a response surface methodology (RSM) technique was used to optimise various output response to identify an optimal configuration for these parameters. The results demonstrate that the DOC had the greatest effect on MRR, whereas FR has a more effect on surface integrity than the other two variables.

[7] analyses the optimization of control variables to decrease the sound that happens in the machining of AISI 2714 steel workpiece material on milling machines without having to compromise surface irregularities. The experiments were conducted based on RSM CCDs. The findings suggest that the FR is the major parameter in lowering surface finish, trailed by the DOC. Although the DOC was the most significant variable in lowering sound intensity, The FR was the second most significant variable.

[8] evaluated CNC milling factors on medical grade PMMA, using single and multi-objective study to determine the best MRR and surface roughness. The results reveal that a combination of 350 mm/min (FR), 1250 rpm (spindle speed), and 1.2 mm (DOC) produced the best MRR and surface roughness (FR). The DOC (54.48%) contributed the most to the GR grade, trailed by FR of 10.36% and, lastly, the spindle speed of 4.28%.

[9] investigate the optimization of milling factors in CNC milling operations using titanium and an uncoated carbide tool. In this experiment, a Taguchi L9 was deployed to provide the best findings for responses variables such as MRR and surface roughness. The optimal results are DOC = 4 mm, speed = 1200 rpm, tool diameter = 10 mm, and FR = 7 mm/min, yielding the best surface roughness = 0.73 m.

[10] using the experimental design established by the Taguchi L9 optimized milling settings for EN 24 Steel workpiece material. According to experimental results, FR was the most influential factor in determining surface roughness, while CS had the greatest impact on MRR.

[11] analyzed process factors for milling of Al-4.5%Cu-TiC metal matrix composite. Machining composite plates with a CNC milling makes use of Taguchi’s L25 design. Grey optimization of CNC milling parameters produces Fe, surface roughness, and Rz as output features. The findings show that the ideal combination of CNC milling variables yields a high grey fuzzy reasoning grade of an 0.8191, which is close to the reference value. This is achieved with a FR of 40 mm/min, a DOC of 0.30 mm and CS of 600 rpm. CS was shown to be the most influential of the three individual process parameters in influencing GFRG by ANOVA.

[12] investigate the best combination of influencing parameters in milling Al 6061 material. Taguchi L16 orthogonal array provides a variety of configurable parameter combinations, including speed, FR, and DOC. An artificial neural network (ANN) model was created and trained using complete factorial design investigational value, and the combination of control constraints for the surface irregularities (surface

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**Table 3: Tool specification.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>WC</td>
</tr>
<tr>
<td>Coating</td>
<td>TiAlN</td>
</tr>
<tr>
<td>Grade</td>
<td>YBG205</td>
</tr>
<tr>
<td>Insert included angle</td>
<td>85 mm</td>
</tr>
<tr>
<td>Cutting edge length</td>
<td>11.25 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>Corner radius</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Clearance angle</td>
<td>11°</td>
</tr>
</tbody>
</table>
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- Roughness) value was discovered using ANN. The confirmation trial confirmed that both had nearly identical surface roughness levels.

- Investigate the Taguchi approach for optimising CNC milling settings for SS grades of AISI-410 and AISI-420. FR of 30 mm/min and spindle speed of 1500 rpm are the best milling variables for surface integrity (surface roughness) of 410 and 420 MSS grades. Surface roughness is found to be most impacted by spindle speed, followed by FR in both grades.

- Analyzed the impact of cutting settings on quality of surface and width of burr in micro-milling of Ti-6Al-4V alloy. The input variables include FR, DOC, and speed of spindle. Taguchi-based Grey relational analysis (GRA) was utilized to optimize the input variable for minimum burr width and surface roughness. According to the data, the value of FR for the optimum surface quality was 0.25 m/tooth. The width of burr on the down milling side is greater than the burr width on the up-milling side. Burr width increases as FR and DOC decreases.

- Optimal machining of a hardened steel 1.2738 using WC coated tools. Control parameters include tooth feed, radial cut depth and the CS. To find the important factors impacting surface irregularities, Taguchi L9 was employed, and ANOVA analyses were performed. The findings produced an AM surface irregularity of 1.662 m, with the radial cut depth being the influential variable.

- Studied the influence of control factors such as feed per tooth, speed of the spindle, and DOC on cutting force, the surface irregularities and PC using the metal matrix composites AA6061-4.5%Cu-5%SiC. Milling factors are examined using the CCDs of RSM. The data demonstrate that spindle speed has the greatest influence on all output factors, trailed by FR and DOC.

- Employed RSM in combination with a genetic algorithm (GA) to optimize machining factors for milling AA6082. The purpose of the regression analyses was to provide a mathematical model. Results from regression analysis are found to be 94.4% consistent with the experimental value. With the control variables set to 3000 rpm spindle speed, 1000 mm/min FR, and 0.2 mm DOC, the RSM projected surface roughness values of 1.192 m and 1.195 m, respectively.

- Analyzed the impact of cutting surfaces for CNC milling of aluminum alloy utilizing the Taguchi approach. The Taguchi L9 was employed in the experiments. They used MRR surface roughness as a quality metric in addition to FR, DOC and CS, as milling factors. Constant tests are carried out in dry circumstances with just one tool insert. The relevance of each process parameter determines the MRR and surface integrity. The DOC and FR are shown to be significant elements impacting MRR.

- Examined optimization of milling factors to improve surface quality while reducing energy consumption. Table 4 summarizes various literature survey of process parameter optimization. The investigation was carried-out on SS 304 by a vertical CNC milling machine in a controlled, dry environment. Optimization of machining inputs enhanced energy efficiency, power factor, and surface integrity. Cutting constraints such FR, milling speed, DOC, and radius of tool are selected. The relationship between milling inputs and outputs is described using a neural network termed the radial basic function. Optimal values were obtained using the ASA technique. Milling reactions are observed to be influenced by all input parameters. As compared to the baseline value, improvements in surface integrity (by 39.18%), power factor (by 26.47%), and energy efficiency (by 22.61%) are achieved.

Role of Nanomaterials

In recent times, the utilization of nanotechnology has sparked significant interest due to its promising benefits for improving yields in various processes. Consequently, nanotechnology is being considered in machining operations, involving the use of nanofluids and cutting tools coated with nanoparticles [30].

The use of nanofluids enhances lubrication properties, resulting in improved wettability and better lubrication of the cutting zone, thus minimizing frictional forces. This reduction in frictional force leads to a decrease in cutting forces. Nanofluids also contribute to achieving the lowest surface roughness by incorporating nanoparticles, which enhances the heat transfer rate and improves the properties of the tool’s rake face. Additionally, nanofluids extend tool life by creating an oil mist and forming nanoparticles on the flank face. These oil mist and nanoparticles in the cutting zone create a barrier film, ultimately reducing cutting forces and tool wear. Furthermore, the application of nanofluids reduces tool wear by rapidly removing heat from the primary shearing zone and preventing workpiece hardening [30].

Bai et al. [31] conducted research on nanolubricants, examining their properties at different concentrations during cutting operations. They evaluated various parameters such as surface roughness, specific energy, microstructure, contact angle, and viscosity. Nanofluid was prepared by mixing 0.5% to 2.0% by weight of Al2O3 nanoparticles with cottonseed oil as the base fluid during the milling of Grade 45 Steel.

Conclusions

An optimization of CNC milling control factors is crucial for obtaining the required quality and efficiency of the operation. This study offers an overview of studies that have been carried out to explore the effect of many process factors such as FR, CS, DOC, and coolant, among others, on the response parameters performance of CNC milling. In the view of above review, the following assumptions can be drawn.

- Different process parameters were taken and their impact on response parameters was experimentally studied.
- The study employs various optimization methods to find the optimal input variables that yield the highest machining performance.
Various statistical techniques like Taguchi, RSM, ANN, GRA and GA can be used for optimization.

To determine the significance of individual process parameters and their interactions, an ANOVA approach is used.

The FR, CS, and the tool diameter have an important influence on the milling performance, while the DOC has a lesser impact.

The optimized process parameters were found to reduce machining time and tool wear while improving surface finish and dimensional accuracy.

### Acknowledgements
None.

### Conflict of Interest
None.

### References
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