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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 operations. Vertical CNC milling machine technique has enhanced considerably to fulfil sophisticated needs in various production fields, notably in the highly precise metal cutting manufacturing. 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 optimization of different process variables parameters on CNC milling performance. The research applies multiple optimization approaches 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 pre tempered. 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 characteristics 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 composition 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 hardnesses. 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

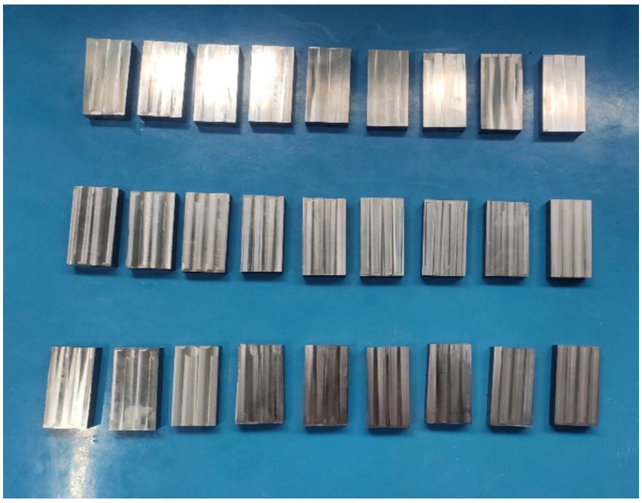

Figure 1: Photograph of the EN 24 Steel workpiece samples after machining.

Table 1: Mechanical properties of EN24 Steel.

Parameter	Value
Tensile strength (MPa)	620
Yield stress (N/mm²)	680 Min
Elongation	13%
Thermal conductivity (W/mK)	40
Hardness (BHN)	201
Density (g/cc)	7.85

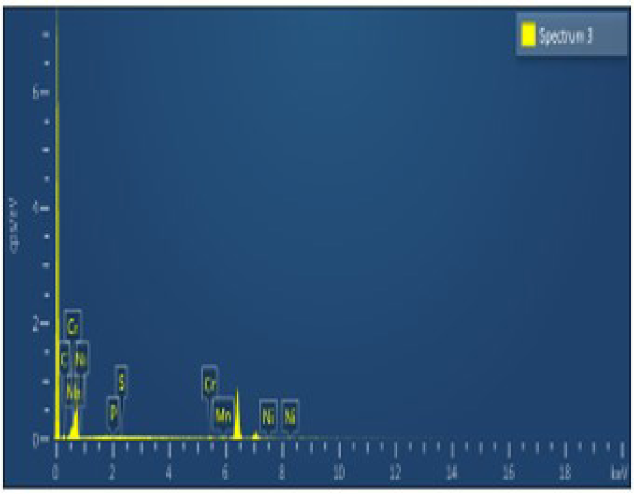

Figure 2: EDX spectrum of EN 24 Steel workpiece.

Table 2: Chemical composition (EDX spectrum) of EN24 Steel.

Element	Line type	Weight %	Weight % Sigma	Atomic %
C	K series	2.66	1.96	11.32
Fe	K series	93.57	2.75	85.60
Si	K series	0.27	0.30	0.49
P	K series	0.00	0.00	0.00
S	K series	0.00	0.00	0.00
Mn	K series	0.00	0.00	0.00
Cr	K series	1.60	0.49	1.57
Mo	L series	1.88	1.69	1.00
Total		100.00		100.00

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_2O_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.

Table 3: Tool specification.

Parameter	Value
Material	WC
Coating	TiAlN
Grade	YBG205
Insert included angle	85 mm
Cutting edge length	11.25 mm
Thickness	3.5 mm
Corner radius	0.8 mm
Clearance angle	11°

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 Fc, 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

roughness) value was discovered using ANN. The confirmation trial confirmed that both had nearly identical surface roughness levels.

[13] 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.

[14] 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.

[15] 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.

[16] 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 matric composites AA6061-4.5%Cu-5%SiC_p. 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.

[17] 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.

[18] 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.

[19] 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 Al_2O_3 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.

Table 4: Summary of various literature survey of process parameter optimization.

Author (Ref.)	Aim of the study	Work piece material	Tool material	Optimization technique	Conclusion
Kaushik et al. [20]	Temperature increase prediction model based on design factors.	Al 7068	HSS end mill cutter	RSM and GA	The helix angle is the most important factor that reduces the peak temperature rise.
Bhirud and Gawande [21]	Work piece temperature increase prediction and measurement analysis.	Al 6063	HSS end mill cutter	Taguchi	DOC was identified to be the essential factor in work piece temperature rises, trailed by spindle speed.
Mahto and Kumar [22]	Minimize the variation level to obtain a better product quality.	hardened steel (DINGX-40CRMOV5-1)	Titanium nitride coated carbide	Taguchi	The optimal combination of FR and DOC for obtaining a low cutting force value was discovered.
Khalid et al. [23]	Examine various machining factors in finding of the ideal combination that would improve surface quality.	Ti-6Al-4V	Carbide insert	RSM	Surface integrity is mainly affected by DOC.
Ravichandra and Hosalli [24]	Impact of control variables on surface integrity and MRR.	20MnCr5 Steel alloy	Carbide end mill	Taguchi	CS was a find out to be effective factor for surface integrity and MRR.
Shi et al. [25]	GRA to determine a best set of control factors with acceptable surface quality.	AZ91D alloy	Uncoated fine-grained carbide grade	Taguchi, GRA	In dry milling, the FR was the essential factor trailed by CS and DOC.
Mukkoti et al. [26]	The effects of deep cryogenic treatment will be studied using experimental and microstructural studies.	P20 mold steel	WC	RSM	Cryogenic-treated tools that have been soaked for 36 h are better for cutting P20 steel than DCT tools that have been soaked for 24 h and tools that have untreated.
Singh et al. [27]	Optimization of CNC end milling using Taguchi-GRA.	AISI H11	Carbide end mill cutter	Taguchi-GRA	FR and CS are essential variables for final machining conditions. DOC is a not important parameter.
Obaeed et al. [28]	Impact of control variables of CNC milling surface integrity.	Al - Alloy 7024	HSS tool	Taguchi	Tool diameter is the most affected variable, trailed by FR, DOC, and lastly spindle speed, with surface roughness being the least affected parameter.
Ahmed and Arora [29]	Optimum sets of control variables are used, with an emphasis on the building of an ANN predictive model to forecast responses.	A36 K02600 Steel	Carbide end mill cutter	Taguchi, ANN, GA	The most important factors for surface quality and energy usage are spindle speed and FR.

- 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.

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Conflict of Interest

None.

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