International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Impact of Process Parameters on CNC Milling Machine Operation to Optimize the Response Parameter Surface Roughness Using DOE Method

Kulsum Naz [a*], Pinky Mourya [b]

[a,b] *Mechanical Engineering Department, Jaipur Engineering College, Kukas, Jaipur*

A B S T R A C T

CNC machining parameter optimization has traditionally relied on operator skill and expertise, with no material, operation, or situation suggestions. However, the complexity of surface roughness (Ra) has led to scientific methods for selecting cutting settings and equipment to reduce human error and increase productivity. COCOSO MCDM is used to analyze CNC vertical milling parameters on AL6061 alloy. We estimate surface roughness from high-speed milling variables such spindle speed, feed rate, depth of cut, and tool insert type using Taguchi-based DOE. Surface roughness claims surface quality affects machined component appearance and operation, which affects customer satisfaction. Spindle speed, feed rate, cut depth, and tool wear effect Ra. Small and medium-sized firms can cut costs and increase productivity by optimizing high-speed milling variables. The study uses empirical data from 16 experimental runs with spindle speeds from 2000 to 2750 RPM, feed rates from 60 to 90 mm/rev, and cut depths from 0.3 to 0.6 mm. We found a link between these parameters and Ra and material removal. Spindle speeds and feed rates increased material removal but surface roughness, therefore they must be balanced for maximum performance. A spindle speed of 2250 RPM, feed rate of 70 mm/rev, and depth of cut of 0.3 mm yielded a minimum Ra of 2.17 µm and an material removal of 12.992 cm³/min, ideal for smooth surfaces without compromising removal rate.

Keywords: Al 6061, milling operation, Taguchi method, signal to noise ratio, surface roughness

Introduction

In today's competitive industrial climate, CNC machining is essential for producing high-precision components across sectors. Small- and medium-sized companies (SMEs) that make aerospace, automotive, and power generation components need efficient, precise, and flexible production. CNC machining must handle high accuracy, complicated geometries, and thin-walled components in these sectors. SMEs are increasingly using high-speed CNC milling, which is fast and precise but requires careful machining parameter optimization to assure efficiency and product quality. CNC milling requires precise control of spindle speed, feed rate, depth of cut, and cutting insert type. These parameters directly affect machining outputs including MRR, Ra, tool wear, and overcut, making their optimization crucial for economic and quality goals. This parameter selection has traditionally relied on operator expertise, which can be inconsistent and subjective. Tool-maker handbooks are conservative and may not be suitable for current high-speed CNC settings, especially when working with difficult materials or standards.

Manufacturers seeking to cut costs, boost productivity, and maintain quality standards are increasingly using scientific, data-driven parameter optimization methods. High-speed CNC milling, especially with AL6061 alloy, a common aluminum alloy with good machinability, strength, and corrosion resistance, requires balancing several performance parameters. High material removal rate (MRR) is necessary for efficiency, but it can damage surface quality and increase tool wear. Fine surface smoothness is desired but may necessitate slower cutting rates, affecting manufacturing time. Thus, methods to weigh these competing aspects and determine optimal machining settings are needed.

For parameter optimization, multi-criteria decision-making (MCDM) approaches are promising. MCDM methods allow producers to weigh Ra, MRR, and tool wear trade-offs while simultaneously evaluating several, often competing parameters. The Combined Compromise Solution (COCOSO) approach is a successful MCDM strategy since it integrates numerous criteria and provides a balanced solution. COCOSO in CNC milling provides scientifically established, appropriate settings for individual machining circumstances and material properties. This study's use of COCOSO MCDM to optimize CNC vertical milling settings for AL6061 alloy is new. This study balances critical performance measures using a multi-objective approach, unlike standard optimization methods that minimize Ra or maximize MRR. AL6061 alloy is frequently utilized in industries that value low weight, corrosion resistance, and machinability. However, machining AL6061 alloy, especially at high speeds, is difficult because aluminum alloys stick to the cutting tool, causing wear and poor surface quality. In crucial applications, improving AL6061 CNC milling cutting parameters can improve operating efficiency and component quality.

In this work, Taguchi-based Design of Experiments (DOE) and COCOSO MCDM are used to analyze and optimize important machining parameters. Taguchi DOE organizes the experimental procedure to efficiently gather data across spindle speed, feed rate, depth of cut, and insert type combinations. The Taguchi approach simplifies experimental runs and helps determine parameter selection by revealing how each parameter affects performance. After testing, the COCOSO approach evaluates each parameter combination based on Ra, MRR, and overcut to find the ideal values.

This research goes beyond CNC milling parameter optimization to help SMEs enhance their production processes by providing a decision-making tool. This study helps CNC milling firms obtain consistent, high-quality output by using a scientific strategy that reduces subjective judgment and human error. In sectors with tight quality, cost, and time restrictions, the COCOSO method's ability to combine several objectives and produce a balanced solution is very useful. This research also advances automated manufacturing and smart machining. Advanced decision-making tools like COCOSO support Industry 4.0, where data-driven methodologies and intelligent technologies optimise production processes. This work advances autonomous, high-performance production systems by eliminating manual involvement and using mathematical models to anticipate machining outcomes.

This research work tackles the lack of a systematic, optimal approach for finding high-speed CNC vertical milling machining parameters, notably with AL6061 alloy. SMEs in precision manufacturing struggle to balance quality, cost, and productivity. The aerospace, automotive, and power generation industries employ AL6061 alloy for its light weight, high strength-to-weight ratio, and corrosion resistance. Machining efficiency and precision are essential. However, this material's complexity and high-speed CNC milling need careful spindle speed, feed rate, depth of cut, and insert type selection.

CNC machining parameters have traditionally depended on machine operators' intuition or conservative tool-maker handbooks. Traditional methods can produce satisfactory results, but they are subjective and can cause tool wear, poor surface quality, and ineffective material removal. Since AL6061 alloy is prone to tool adhesion and other difficulties, cutting it unsystematically can compromise productivity and quality. Thus, a scientific, methodical approach that reduces human error and boosts efficiency is essential.

CNC milling objectives for MRR, Ra, and overcut may conflict. Higher spindle speeds and feed rates enhance MRR but also tool wear and surface roughness, which quality-conscious organizations may not want. Lower speeds improve surface smoothness but increase machining time and cost. A multi-objective decision-making framework that considers all key factors is needed to balance opposing goals.

Increased global competition requires SMEs to be agile, efficient, and able to change production methods fast, aggravating the challenge. As a repeatable, data-driven strategy, these organizations must optimize machining settings to meet different production needs like small-batch or prototype manufacturing. Unplanned optimization increases costs, lowers productivity, and prevents SMEs from meeting customer quality requirements.

To address these issues, the Combined Compromise Solution (COCOSO) multi-criteria decision-making (MCDM) method will be used to investigate CNC vertical milling machining parameters on AL6061 alloy COCOSO is crucial because it provides a full framework for concurrent factor analysis and reasonable, scientific parameter modification. Taguchi-based DOE with COCOSO is used to discover the optimal parameter configuration for productivity, surface roughness, and tool wear.

Literature Review

With a physical vapour deposition-coated carbide tool and various cutting settings, Kasim et al. (2013) examined tool wear during Inconel 718 ball-nose end-milling. Large radial depth-of-cut wears tools. A mathematical model predicted pitting (notching and flaking) site, determining the maximum cutting load. Predicted pitting model and actual notching/flaking were within 6%.

Kuram and Ozcelik (2013) studied ball-nose end-mill micro-milling aluminum using experiments, modeling, and mono and multi-objective optimization. The Taguchi method examined how spindle speed, feed per tooth, and depth-of-cut effect tool wear, force, and surface roughness. Aluminium's ductility causes plastically deformed workpiece surfaces. First-order models for micro-milling aluminum were created using experimental data with minor errors. Optimization model used Taguchi's signal-to-noise ratio to minimize answers. The responses were optimized simultaneously using gray relational analysis.

CNC machine calibration is time-consuming and expensive, according to Armin Afkhamifar et al. (2016). The designer may investigate error sources to make the CNC machine more reliable and faster to tune. Variational and finite element analysis of geometrical features predict tool tip position error.

Radu Eugen Breaz et al. explored a component class decision-making process for CNC milling, robot milling, and additive manufacturing (DMLS) in 2017. AHP was used to choose between three production processes. Clear, linguistic variable-based AHP criteria. The last ones extracted measurable AHP data using fuzzy inference. An area was addressed with the proposed method.

Tungsten carbide micro milling PCD micro end mill tool wear is tested by Xian Wu et al. (2018). Checking tool wear characteristics and methods. Results show that PCD tool wear is concentrated on the tip and creates a triangular bottom belt. Sticky, micro chipping, and abrasive wear are significant mechanisms. PCD tool wear raises cutting pressures, brittlely fractures tungsten carbide, and causes milled surface defects. A reverse cone is formed by transferring the worn PCD tool tip to the machined groove.

Milling cutting temperatures impact tool wear, size and form tolerances, and residual stresses, according to Karaguzel and Budak (2018). Rotary tools create intermittent operations and transient thermal loadings, making milling cutting temperature forecast and monitoring challenging. This study provides novel milling cutting tool temperature modeling and measurement methodologies. The model predicts how milling conditions affect cutting temperatures, particularly tool temperature and radial depth of cut. New measurement method and literature data confirm model predictions.

In 2018, Song Ren et al. studied Kirchhoff plate-multi pocket construction. The authors' subdomain decomposition method gives semi-analytical vibration solutions for this thin-walled design. A dynamic cutting model accounts for cutting position and vibration to represent milling force. Combining the vibration and dynamic cutting models creates the thin wall milling process's governing equation, which fully accounts for dynamic qualities. When cutting discretely, milling thin-walled constructions is stable under the quasi static hypothesis. Semi-discrete analysis analyzes thin wall milling stability. Critical depth of cut is inversely related to mode shape square for each mode. Additionally, multimode and mode coupling effects on milling stability are explored.

A geometrical model for flank-milling surface topography employing circle-segment end mills was developed by G. Urbikain et al. (2018). This time-domain model includes the most important cutting mechanical and kinematical parameters: tool shape, feed rate, radial immersion, and run out. Includes 5-axis tool orientation angles. Experimental data were used to verify the model in a machined aluminum Al7075T wall. This knowledge-based system optimizes and controls production parameters for manufacturers and suppliers.

Machine Overview

On the other hand, machine aspects are also taken into consideration in this research endeavor. This is in addition to the fact that the input parameters for the current study were chosen from previous research work. Choosing a straightforward rectangular bar cut is the first step in the process of cutting the bar with the CNC milling machine. Within the scope of this chapter, each and every one of the machine's technical parameters, in addition to its limitations, are taken into consideration. During the course of this inquiry, the MAXIMIL MATB CNC MILLING machine was employed more than once. In order to accomplish the goals of this research activity, the industrial form of AL-Alloy-6061 has been specifically chosen. The components of the apparatus have been put in place at the JEC in Jaipur.

Figure 1 CNC milling test setup used in present study

For the purpose of this inquiry, the design of experiment (DOE) methodology that is commonly referred to as the "TAGUCHI" method was utilized. When it comes to CNC milling, the metal removal rate (MRR) and the surface roughness quality evaluation are both regarded to be important performance indicators. In CNC MILLING operations, surface roughness is a measurement of the degree of accuracy and geometrical correctness, whereas MRR is used to determine the economics of machining and the speed of production. Surface roughness is a measure of degree of precision.

Factor and Level

Three key process parameters or factors—Spindle Speed, Feed Rate, and Depth of Cut (DOC)—are evaluated to determine their effect on surface roughness in CNC milling. These factors play a crucial role in defining the machining efficiency, surface finish, and quality of the final product. Through the Design of Experiments (DOE) method, specific levels for each factor are established, allowing for a structured approach to test various combinations and analyze their impact on surface roughness.

Factor I: Spindle Speed

Spindle speed is the rotational speed of the CNC milling machine's spindle, measured in revolutions per minute (RPM). In this study, spindle speed is varied across four levels: 2000, 2250, 2500, and 2750 RPM. Spindle speed is an essential factor because it influences the rate of material removal and affects the temperature at the cutting interface. Higher speeds may lead to a smoother surface due to reduced tool vibration, but excessive speeds can cause thermal deformation, impacting surface finish negatively.

Factor II: Feed Rate

Feed rate is the speed at which the cutting tool advances into the material, measured in millimeters per revolution (mm/REV). The levels of feed rate chosen in this study are 60, 70, 80, and 90 mm/REV. The feed rate significantly affects the surface roughness, as higher feed rates may lead to rougher surfaces due to increased cutting force and tool vibrations. On the other hand, lower feed rates can produce finer finishes but may increase machining time.

Factor III: Depth of Cut (DOC)

Depth of Cut (DOC) refers to the thickness of material removed in one pass, measured in millimeters (mm). The levels for DOC in this study are set at 0.3, 0.4, 0.5, and 0.6 mm. DOC influences surface roughness, tool wear, and power consumption. Higher DOC values allow for quicker material removal but can lead to increased tool wear and rougher surfaces, whereas lower DOC values generally yield smoother finishes with longer tool life.

By examining these factors at their respective levels, the DOE method facilitates an understanding of their combined and individual effects on surface roughness. This analysis is essential for optimizing CNC milling operations to achieve the desired surface quality while maintaining efficient machining parameters. The orthogonal array develop for these factors were present in table 1.

Table 1 Orthogonal Array L16 developed in present study

Run	**Spindle Speed**	**Feed Rate**	**DOC**	**Surface Roughness**
1	2000	60	0.3	2.25
2	2000	70	0.4	2.39
3	2000	80	0.5	2.53
4	2000	90	0.6	2.72
5	2250	60	0.4	2.51
6	2250	70	0.3	2.17
7	2250	80	0.6	3.04
8	2250	90	0.5	2.97
9	2500	60	0.5	2.51
10	2500	70	0.6	3.06
11	2500	80	0.3	2.35
12	2500	90	0.4	2.87
13	2750	60	0.6	2.56
14	2750	70	0.5	2.68
15	2750	80	0.4	2.66
16	2750	90	0.3	2.48
Unit	**RPM**	**mm/Rev**	**mm**	**micro m**

In this study, an Orthogonal Array (OA) L16 was employed to analyze the impact of CNC milling process parameters on surface roughness. The L16 OA, part of the Taguchi method in Design of Experiments (DOE), is a powerful tool that allows for the efficient exploration of multiple factors at multiple levels without requiring an exhaustive number of experimental trials. By structuring the experiments in an orthogonal array, interactions between parameters can be investigated systematically and with reduced experimental effort. The L16 OA used here includes 16 experimental runs, each with a unique combination of levels for three key factors: Spindle Speed, Feed Rate, and Depth of Cut (DOC). The parameters and their levels are arranged such that all combinations are adequately represented across the trials, facilitating a balanced assessment of each factor's effect on surface roughness. This structured approach minimizes variation due to uncontrolled factors and enables an accurate analysis of the impact of the controlled parameters on surface quality. In Table 1, each row represents a unique run with specified values for Spindle Speed (in RPM), Feed Rate (in mm/Rev), and DOC (in mm). For each run, the resulting surface roughness (in micrometers) is measured, providing a dataset to assess how changes in process parameters affect surface finish. For example, Run 1 has a Spindle Speed of 2000 RPM, Feed Rate of 60 mm/Rev, and DOC of 0.3 mm, resulting in a surface roughness of 2.25 micrometers. By examining the results across all 16 runs, the study identifies the optimal parameter settings for minimizing surface roughness. Using the L16 OA not only enhances the study's efficiency but also ensures reliable and statistically robust conclusions. This approach allows the identification of parameter combinations that produce the desired surface quality, which is essential for optimizing CNC milling operations.

Result and Discussion

The results of this study focus on the analysis of surface roughness in CNC milling using the Design of Experiments (DOE) approach, specifically employing an L16 orthogonal array. The primary objective is to determine the optimal settings for Spindle Speed, Feed Rate, and Depth of Cut (DOC) that minimize surface roughness. Using the Taguchi method, Signal-to-Noise (S/N) ratios were calculated for each trial under the "smaller is better" criterion, as the goal is to minimize surface roughness. This approach helps in identifying parameter settings that yield the best results with respect to minimizing roughness on the machined surface.

The calculated S/N ratios for each run were used to analyze the impact of each factor (Spindle Speed, Feed Rate, and DOC) on surface roughness. By averaging the S/N ratios across all levels of each factor, we can observe the relative influence of each parameter.

Spindle Speed: The S/N ratios averaged across the levels of Spindle Speed indicate that higher speeds (closer to 2750 RPM) tend to produce slightly lower surface roughness. This is likely due to reduced tool vibration and more consistent cutting action at higher speeds. However, excessively high speeds may generate thermal effects that can adversely affect surface quality, so it's essential to balance speed to avoid excessive wear or thermal distortion.

Feed Rate: Feed Rate also significantly impacts surface roughness, as shown by the variation in S/N ratios across its levels. Lower feed rates (60 and 70 mm/Rev) generally result in smoother surfaces, as slower feed allows for more controlled cutting with less vibration. Higher feed rates (80 and 90 mm/Rev), while quicker for material removal, tend to produce rougher surfaces, as the tool is forced through the material more aggressively, causing increased surface irregularities.

Depth of Cut (DOC): DOC shows a clear impact on surface roughness, with lower DOC values (0.3 and 0.4 mm) corresponding to improved surface finish. Lower DOC means less material is removed in each pass, reducing tool pressure and minimizing surface damage. In contrast, higher DOC levels (0.5 and 0.6 mm) increase roughness, as the tool experiences greater resistance and vibration, leading to a less precise cut.

Optimal Parameter Combination

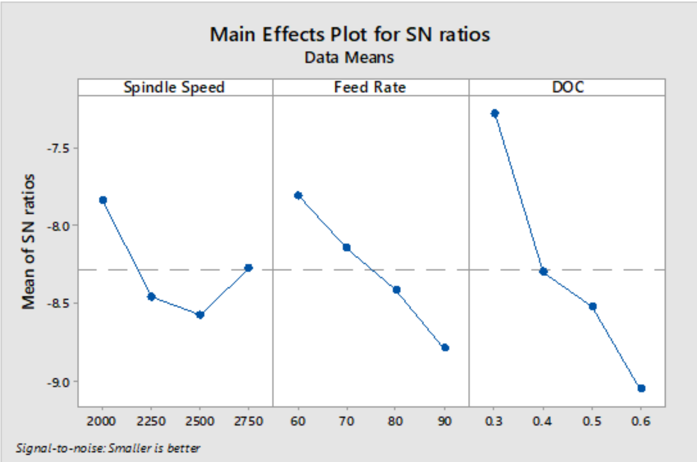

Figure 2 S/N ratio analysis using smaller is better option

From the analysis of S/N ratios, the optimal parameter combination for achieving the lowest surface roughness appears to be a Spindle Speed of 2750 RPM, Feed Rate of 60 mm/Rev, and DOC of 0.3 mm. This combination yields a lower S/N ratio, indicating minimal surface roughness. This result aligns with the theoretical understanding that a higher spindle speed, lower feed rate, and lower depth of cut generally promote a smoother surface finish in milling operations.

Discussion

The findings from this experiment highlight the importance of carefully selecting CNC milling parameters to achieve optimal surface quality. High spindle speeds are beneficial for reducing surface roughness, but only up to a point where thermal and wear effects become a concern. Lower feed rates and shallower depths of cut are both shown to improve surface finish by reducing the forces exerted on the tool and workpiece, which minimizes surface imperfections. The use of the L16 orthogonal array and the Taguchi S/N ratio analysis proved effective for this study, providing a systematic approach to explore the complex interactions between multiple factors. By optimizing the parameters identified through this study, CNC milling operations can achieve smoother finishes, which is critical in applications requiring high precision and aesthetic quality. This approach is also beneficial for reducing production time and costs, as fewer post-machining surface treatments may be needed to achieve the desired surface roughness.

Conclusion

This study aimed to identify the optimal CNC milling parameters for minimizing surface roughness, a key factor in determining the quality of machined parts. Using the Design of Experiments (DOE) approach, an L16 orthogonal array was developed to systematically vary and analyze three process parameters: Spindle Speed, Feed Rate, and Depth of Cut (DOC). By calculating the Signal-to-Noise (S/N) ratio with the "smaller is better" criterion, the study effectively quantified the influence of each factor on surface roughness.

The results indicated that a higher Spindle Speed (2750 RPM), lower Feed Rate (60 mm/Rev), and lower DOC (0.3 mm) yielded the lowest surface roughness. Specifically, high spindle speeds contributed to smoother finishes due to reduced tool vibration, while lower feed rates and DOC minimized cutting force and vibration, enhancing surface quality. This optimal combination offers a practical approach for achieving fine surface finishes in CNC milling, reducing the need for additional surface treatments and improving efficiency.

The use of the Taguchi method and S/N ratio analysis enabled a systematic, efficient exploration of parameter effects, providing valuable insights for manufacturers seeking to optimize machining conditions. This approach not only improves product quality but also lowers production costs by reducing machining time and tool wear. Overall, this study demonstrates the effectiveness of DOE and S/N ratio analysis in optimizing CNC milling parameters, paving the way for further research into the complex interactions of machining factors in various materials and applications.

References

Chang Y-F., Hong R.-C., " A Practical approach to generating accurate iso-cusped tool paths for three-axis CNC milling of sculpture surface parts", Journal of manufacturing processes, Vol.8, No.1, pp. 29-38, 2006.

Colak O., Kurbanoglu C., Kayacan M.C., " Milling surface roughness prediction using evolutionary programming methods", Materials & Design, Vol.28,No.2 pp. 6570666, 2007

Salami R., Sadeghi M.H., Motaket B., "Feed rate optimization for 3- axis ball-end milling of sculptured surfaces", International Journal of Machine tools and Manufacture, Vol. 47, No. 5, pp. 760-767, 2007

Osornio-Rios R.A., de Jesus Romero-Troncoso R., Heirera-Ruiz G., Castaneda-Miranda R., "The application of reconfigurable logic to high speed CNC milling machines controllers", Control Engineering Practice, Vol.16, No. 6, pp. 674-684, 2008

Zaghbani I., Songmene V., "A force-temperature model including a constitutive law for dry high speed milling of aluminium alloys", Journal of Materials Processing Technology, Vol. 209, No. 5, pp. 2532-2544, 2009.

Tang W.X., Song Q.H, Yu S.Q., Sun S.S., Li B.B., Du B., Ai X., "Prediction of chatter stability in high-speed finishing and milling considering multi-mode dynamics", Journal of Materials Processing Technology, Vol. 209, No. 5, pp. 2585-2591, 2009.

David Edwards, J. and Robert Mee, W. Thesis report on Fractional Box-Behnken Designs, Germany, 2000

Topal E.S. "The role of step-over ratio in prediction of surface roughness in flat-end milling", International Journal of Mechanical Sciences, Vol.51, No. 11-12, pp. 782-789, 2009

Arif, Mustafizur Rahman, and Wong Yoke San, "Analytical modeling of ductile-regime machining of tungsten carbide by end milling Muhammad", International Journal of Advanced Manufacturing Technology, 2010.

Kious M., Ouahabi A., Boundraa M., Serra R.., Chekname A., "Detection process approach of tool wear in high-speed milling". Measurement, Vol. 43, No.10, pp.1439-1446, 2010

Alao, A.R. and Konneh, M. "Application of Taguchi and Box-Behnken designs for surface roughness in precision grinding of silicon", International Journal of Precision T echnology, Vol. 2, No. 1, pp. 21-38, 2011

Mahdavinejad, R.A. and Saeedy, S "Investigation of the influential parameters of machining of AISI 304 stainless steel", Sadhana Vol. 36, Part 6, pp. 963-970, 2011

Kaya B., Oysu C.Ertunc H.M., "Forced-torque based on-line wear estimation system for CNC milling of Inconel 718 using neural networks", Advances in Engineering Software, Vol. 42, No.3, pp.76- 84, 2011.

Farouki R.T., Li S., "Optimal Tool orientation control for 5 Axis CNC milling with ball-end cutters", Computer Aided Geometric Design, Vol. 30, No.2, pp. 226-239, 2013

Zuperl V., Cus F., Reibenschuh M., "Neural control strategy of constant cutting force system in end-milling", Robotics and Computer- Integrated Manufacturing, Vol. 27, No. 3, pp. 485-493, 2011.

Heo E.Y. Kim .D.W., Lee J.Y., Lee C.S., Chen F.F., High-speed pocket milling planning by feature based machining area portioning", Robotics and Computer-Integrated Manufacturing, Vol.27, No.4, pp. 706-713, 2011

Shokrani, Dhokia V., Newman S.T., Imani-Asrai R." An initial study of the effect of using liquid nitrogen coolant on the surface roughness of Inconel 718 nicked-based alloy in CNC milling, Procedia CIRP, Vol.3, pp.121-125, 2012

Wojciechowski S., Twardowski P., " Tool life and process dynamics in high-speed ball-end milling of hardened steel", Procedia CIRP, Vol. 1, pp. 289-294, 2012

Dumitrache A., Borangiu T., "IMSIO- image-based milling tool paths with tool engagement control for complex geometry", Engineering Applications of Artificial Intelligence, Vol.25, No.6, pp. 1161-1172, 2012

Imani B.M., Pour M., Ghoddosian A., Fallah M., “Improved dynamic simulation of end-milling process using time series analysis”, Scientia Iranica, Vol. 19, No.2, pp.294-302, 2012

Kasim M.S., Che-Haron C.H., Ghani J.A., Sulaimon M.A., Yazid M.Z.A., “Wear mechanism and notch wear location prediction model in ball nose and milling of Inconel 718,” Wear, in press, 2013

Kuram E., Ozcelik B., “Multi-objective optimization using Taguchibased grey relational analysis for micro-milling of AI 7075 material with ball-nose end-mi;”, Measurement, Vol.46, No.6, pp.1849-1864, 2013