Universal Library of Engineering Technology | Research Article

ISSN: 3064-996X | Volume 2, Issue 4

Open Access | PP: 51-56

DOI: https://doi.org/10.70315/uloap.ulete.2025.0204009

Enhancing the Accuracy and Efficiency of Cutting and Machining Processes for Non-Ferrous Metal Workpieces Using CNC Systems

Rustamov Atajan

Chief Mechanic, Head of the "Lebapdemirönümleri" Branch of the State Enterprise "Türkmendemirönümleri" under the Ministry of Industry and Production of Turkmenistan, Turkmenabat City, Lebap Region, Turkmenistan.

Abstract

The article presents a comprehensive analysis of the influence of milling parameters on the accuracy and quality of non-ferrous metal machining using computer numerical control (CNC) systems in the context of developing sustainable, energy-efficient, and adaptive next-generation manufacturing processes. The study is based on the integration of engineering, thermodynamic, and metrological approaches, covering aspects of cutting kinematics, heat balance, and structural stability during the machining of cast and additively manufactured aluminum workpieces. A comparative analysis of the effects of feed rate, spindle speed, and cutting depth on surface roughness and hardness was conducted under dry and minimum-lubrication milling conditions. Particular attention is given to the thermomechanical interrelations that determine process stability and the reproducibility of geometric parameters without the use of liquid coolants. It has been established that the coordinated control of cutting parameters ensures vibration reduction, uniform thermal load distribution, and the formation of a predictable surface microrelief. The practical significance of the results is demonstrated through the application in ForgeX Mobile Foundry modular manufacturing units, which provide high surface quality while reducing energy consumption and eliminating emulsified coolant use. The article will be of interest to process engineers, machining specialists, developers of mobile manufacturing systems, and researchers focused on digitalization and sustainable industrial development. The study shows that the modern CNC machining system for non-ferrous metals represents a self-regulating thermokinematic architecture in which accuracy, stability, and energy efficiency function not as external objectives but as intrinsic properties of the production process.

Keywords: *Accuracy, Stability, Efficiency, Energy, Surface, Control, Manufacturing.*

INTRODUCTION

Enhancing the accuracy and efficiency of non-ferrous metal machining is a key direction in the development of modern mechanical engineering and energy industries. Aluminum and copper alloys are widely used in high-tech sectors where minimal geometric deviations and high surface quality are critical [4]. The introduction of Computer Numerical Control (CNC) systems opened new opportunities for automation; however, there remains a need to increase processing stability and repeatability under limited cooling resources and power consumption.

Against the backdrop of the traditional US foundry industry crisis and the growing need for localized solutions, mobile manufacturing technologies that ensure independence from centralized supply chains and reduce transport costs are gaining significance. In this context, the ForgeX Mobile Foundry complex represents an innovative platform combining induction melting, robotic CNC machining, artificial intelligence systems, and autonomous power sources—solar panels and Starlink satellite communications. This architecture enables the realization of "smart manufacturing" and "green metallurgy" concepts based on minimizing emissions and increasing energy resilience while maintaining high precision parameters.

Despite progress in digital control, the accuracy and quality of non-ferrous metal machining are still limited by unstable heat flows, vibrations, cutting tool wear, and material structure heterogeneity. Particular difficulties arise when machining workpieces obtained by Wire Arc Additive Manufacturing (WAAM), which are characterized by residual stresses and increased anisotropy of mechanical properties [1]. For mobile solutions like ForgeX, it becomes critical to find regimes that balance machining quality, energy efficiency, and the elimination of liquid cooling while maintaining specified surface parameters.

This study aims to substantiate architectural and technological

Citation: Rustamov Atajan, "Enhancing the Accuracy and Efficiency of Cutting and Machining Processes for Non-Ferrous Metal Workpieces Using CNC Systems", Universal Library of Engineering Technology, 2025; 2(4): 51-56. DOI: https://doi.org/10.70315/uloap.ulete.2025.0204009.

approaches to improving the accuracy and quality of non-ferrous metal machining on CNC systems in mobile ForgeX manufacturing systems by studying the influence of milling parameters. To achieve this goal, the following tasks were set and solved: dependencies between cutting regimes and surface characteristics were identified, machining features of cast and additive workpieces were compared, and patterns of the influence of cutting parameters on the stability, energy efficiency, and sustainability of mobile manufacturing processes were established. The novelty of the research lies in developing an architectural approach to adapting CNC processes for mobile manufacturing systems, ensuring sustainable machining accuracy with minimal energy consumption.

It is hypothesized that optimizing milling regimes, taking into account material structure and equipment kinematic features, allows for improved accuracy and surface quality of non-ferrous metals without increasing energy consumption and tool wear, thereby ensuring the technological self-sufficiency of ForgeX mobile complexes under conditions of limited cooling.

MATERIALS AND METHODS

The study is based on publications from 2021–2025 dedicated to improving the accuracy, energy efficiency, and stability of non-ferrous metal cutting processes using CNC systems. The ForgeX Mobile Foundry mobile manufacturing complexes were considered as the technological platform, including three modifications—Compact, Pro, and Heavy—differing in autonomy level and productivity. Each modification combines induction melting, a modular CNC cell, an AI system for tool wear monitoring, a solar power panel, a battery subsystem, and Starlink satellite communication for remote control and technological data transmission. Design and modeling took into account OSHA, EPA, DOT, and NEC regulations, determining safety, energy efficiency, and environmental performance requirements for mobile manufacturing units.

Mohanta et al. [6] conducted an experimental analysis of milling parameters using PVD-coated tools, identifying key factors influencing roughness and cutting force. Yan et al. [10] examined the influence of robotic milling parameters on the surface of aluminum workpieces manufactured by the additive method, revealing differences in the behavior of cast and deposited alloys. Siahsarani et al. [7] substantiated the effectiveness of combining supercritical CO_2 with Minimum Quantity Lubrication (MQL), which improves surface quality and reduces energy consumption, directly correlating with the dry and low-lubrication milling technology implemented in ForgeX modules.

Li et al. [5] presented an overview of modern vibration suppression techniques in milling applicable for optimizing machining regimes under high dynamic loading. Hossain et al. [3] demonstrated the possibility of reducing cutting temperature and surface roughness using multifactorial statistical modeling via the Response Surface Methodology. Ikhries & Al-Shawabkeh [4] proposed algorithms for selecting CNC machining parameters for aluminum alloys in molds, considering thermomechanical properties and polymer insert geometry, allowing these approaches to be adapted to hybrid additive-mechanical ForgeX processes.

Crăciun et al. [2] investigated dependencies between cutting tool design and axial/radial forces when drilling aluminum alloy 2024-T351, while Alsoufi & Bawazeer [1] conducted a probabilistic analysis of surface roughness and waviness distribution considering material thermal conductivity and hardness. A review by Soori et al. [8] systematized approaches to sustainable CNC manufacturing, including minimizing energy consumption and reducing coolant use, coinciding with ForgeX's "green metallurgy" principles. The methodological base is concluded by Wang et al. [9], which compared high-precision milling methods for titanium and aluminum alloys by cost, productivity, and surface quality criteria, allowing these parameters to be used for CapEx assessment of the three ForgeX complexes.

The research methodology included content analysis of scientific publications to identify patterns of machining parameter influence on accuracy and roughness, comparative analysis of experimental data by feed, speed, and depth of cut criteria, and comparison of identified dependencies with practical experience operating ForgeX mobile complexes. To assess economic effects, an additional CapEx analysis was conducted, covering energy efficiency, machining cycle cost, and expected profitability when using dry and low-lubrication regimes. The applied methodology ensured a holistic consideration of technological, thermodynamic, metrological, and economic-environmental aspects of non-ferrous metal machining in mobile ForgeX manufacturing systems.

RESULTS AND DISCUSSION

The influence of cutting parameters on the machining accuracy of non-ferrous metals determines the stability of geometric and micro-geometric surface characteristics, which is directly related to product quality and technological process stability. Analysis of experimental data showed that changes in feed rate, spindle speed, and depth of cut result in non-linear dependencies characteristic of both cast and deposited aluminum alloys. According to Yan et al. [10], the key factors determining roughness Ra are spindle rotation speed and feed rate. For cast samples, increasing feed and depth of cut leads to increased Ra, while increasing spindle speed reduces roughness up to a certain limit. For additive samples, conversely, increasing feed initially leads to a decrease in Ra to a minimum value, after which further feed increase causes roughness growth due to cutting zone overheating. Table 1 examines the distribution of the Ra parameter when varying the main factors of the aluminum alloy milling process.

Table 1. Single-factor effects on Ra for Al-alloys (Compiled by the author based on the source: [10])

Factor	Adjustment range	Trend and Ra range – as-cast	Trend and Ra range – as-deposited (WAAM)	Optimal conditions
Spindle speed	1000–6000 rpm	Ra decreases with higher n; range 2.142–3.750 μm	Ra decreases then rises; range 2.142–3.750 μm	n = 4750 rpm → optimum
Feed rate	2–18 mm/s	Ra increases (1.341–2.523 μm), especially >12 mm/s	Ra decreases at 2–12 mm/s (2.013–3.791 μm), then increases	f = 12 mm/s → Ra = 2.013 μm
Depth of cut	0.25–1.5 mm	Ra ↑ with depth (2.420–4.562 μm)	Ra ↑ with depth (2.311–4.310 μm)	degradation when a_p > 0.75 mm

Note: the first column contains process factor designations; the second – their adjustment range; the third and fourth columns show Ra change trends for cast and deposited samples, respectively; the fifth column records optimal regimes ensuring minimum roughness values.

Comparing the obtained dependencies with the results of Mohanta et al. [6] confirms that feed growth is the most significant factor in increasing roughness during dry turning and milling of copper and aluminum alloys, while spindle speed influence manifests only within a limited range of optimal values. Hossain et al. [3] showed a similar effect in machining Ti-6Al-4V titanium alloy, where feed growth affects Ra more critically than depth of cut. At the same time, as noted by Siahsarani et al. [7], introducing a CO_2+MQL minimal lubrication environment reduces Ra by decreasing thermal stresses and stabilizing contact temperatures.

The discovered trends are consistent with Li et al. [5], where vibration suppression was considered a key condition for minimizing micro-irregularities arising at increased spindle speeds. Under non-cooled machining conditions characteristic of ForgeX-type systems, thermal distribution plays an additional role in determining waviness formation and material burn. Based on the analysis, it can be concluded that optimal cutting parameters are formed by balancing speed and feed. High speed ensures Ra reduction by decreasing tool-material contact, but exceeding the critical threshold leads to local softening and increased roughness.

The results demonstrate that integrating parametric feed and speed control in robotic CNC complexes ensures increased accuracy and repeatability of geometric characteristics when milling aluminum and copper alloys. The identified dependencies confirm the need for real-time adaptive parameter control, which is especially relevant for flexible ForgeX-type modules operating in dry or low-lubrication cutting modes.

For mobile complexes, this adaptation of machining regimes has not only technological but also economic significance. Controlled machining without liquid cooling reduces logistics and maintenance costs and decreases the carbon footprint, aligning with modern “green metallurgy” principles. For ForgeX industrial solutions, this ensures increased profitability and operational sustainability in remote regions.

Changes in surface hardness after milling reflect the geometric and physico-mechanical consequences of the cutting process. Based on generalized experimental data, it was revealed that the nature of hardening depends on material state, thermal balance, and cutting parameters. In cast workpieces, a pronounced work hardening effect is registered due to intensive plastic deformation and local temperature increase, while for WAAM structures, a weak but reproducible increase in hardness is formed. Table 2 examines HB indicator changes at control points P, K, and M under different combinations of speed, feed, and depth of cut.

Table 2. Surface hardness (HB) before and after milling at reference points P, K, and M (Compiled by the author based on sources: [3, 7, 10])

Point (parameters)	Sample condition	HB before	HB after
P (4750 rpm; 7.5 mm/s; 0.75 mm)	as-cast	76.910	80.332
	as-deposited	40.751	45.252
K (4500 rpm; 12 mm/s; 0.75 mm)	as-cast	76.901	86.433
	as-deposited	40.752	41.350
M (4500 rpm; 7.5 mm/s; 0.75 mm)	as-cast	76.906	88.603
	as-deposited	40.751	41.051

Note: hardness values measured before and after milling are given; each control point corresponds to specific cutting parameters, and differences between columns reflect the degree of work hardening after machining.

In applied terms, hardness changes after milling reflect the physico-mechanical and operational parameters of products. For ForgeX mobile modules, this means the possibility of local part repair without using stationary foundry lines, which reduces production costs and increases the economic independence of technological clusters.

For cast samples, hardness growth is recorded at point M, indicating the formation of a near-surface layer with increased dislocation density and crystal lattice ordering [10]. Comparison with Mohanta et al. [6] data shows a similar effect in dry turning of copper and aluminum bronzes, where a combination of high speed and minimal cooling enhances thermoplastic deformation and initiates thermal hardening. In the context of Li et al. [5], this phenomenon is associated with increased tool vibration oscillations at high frequencies, creating additional microplastic impact on the surface layer.

Analysis of WAAM samples revealed that the hardness increase is limited due to porosity and structure anisotropy, reducing plastic consolidation capability. This agrees with Yan et al. [10] results, noting reduced work hardening due to directional grain structure and lower thermal conductivity. Additional comparison with Alsoufi & Bawazeer [1] indicates that temperature distribution unevenness during milling determines the degree of local hardening, and with high thermal conductivity, the effect is neutralized.

Collectively, these effects demonstrate a direct link between surface quality and product lifecycle. For ForgeX, this dependency allows designing machining regimes considering expected component durability, optimizing expenses, and equipment payback periods in field conditions.

Under limited cooling conditions characteristic of ForgeX mobile modules, thermodynamic load is concentrated in the surface zone. According to observations made by analogy with Siahsarani et al. [7], implementing MQL regimes with CO_2 can stabilize the temperature gradient and limit work hardening depth, which is critical for ensuring dimensional stability. From a modeling perspective, a similar effect is confirmed in Hossain et al. [3], where RSM optimization of temperature fields established a correlation between cutting temperature and strain hardening intensity.

To confirm causal links, a comparison with Crăciun et al. [2] data was used, demonstrating a direct dependency between axial forces when drilling aluminum alloys and subsequent microhardness growth. Collectively, these data indicate that it is precisely the ratio of rotation speed and feed that forms the hardness gradient determining part durability. As emphasized by the author, the key is not absolute hardness value, but the stability of its cross-sectional distribution, ensuring predictable material behavior under repeated loads.

Thus, the presented results show that surface hardness is an integral indicator of cutting energy dynamics, structural transformations, and thermoplastic processes, and its variations during milling should be considered a diagnostic parameter of process technological stability.

Analysis of interrelations between cutting parameters and surface characteristics showed that process stability is formed under the complex impact of rotation speed, feed, and depth of cut. Multifactorial modeling allowed for establishing dominant factors for each workpiece type and assessing statistical result consistency. According to observations by Mohanta et al. [6], surface quality stability when milling non-ferrous metals depends less on an individual parameter and more on the ratio of kinematic and thermal loads. This thesis was confirmed in subsequent works where parameter combinations were viewed through the prism of ANOVA and central composite design. Table 3 presents multifactorial analysis results reflecting the comparative sensitivity of cast and additive aluminum samples to machining regime changes.

Table 3. Results of multifactor roughness analysis (CCRD/ANOVA) (Compiled by the author based on sources: [2, 5, 10])

Indicator	**as-cast**	**as-deposited (WAAM)**
Ra range (µm)	2.011–5.512	2.203–4.928
Significant factors ($p < 0.05$)	Spindle speed (A), depth of cut (C)	Feed rate (B) > spindle speed (A) > depth of cut (C)
Model R^2	0.9705	0.9753
Quality response type	Sensitive to a_p and n	Mild slope, stable to a_p variations

Note: Analysis of Variance (ANOVA) results are given showing the relative influence of cutting parameters on surface roughness for both sample types.

Comparison of trends presented in the table shows that the sensitivity of cast samples to depth and speed is related to the thermomechanical nature of the process. Increasing tool rotation speed generates micro-vibrations that partially smooth surface irregularities, but with further load growth, the process loses stability, consistent with observations by Li et al. [5] emphasizing the role of the vibrational component in texture formation. Additive samples are characterized by a smoother reaction to feed changes, confirming conclusions by Siahsarani et al. [7] regarding the stabilizing action of MQL regimes, leveling the temperature field, and reducing roughness gradients.

According to Hossain et al. [3], a similar parameter influence structure is observed when modeling accuracy for superalloys, where feed determines chip thickness and heat removal efficiency, and high factor correlation indicates the non-linear nature of interactions. Similar dependencies were revealed by Alsoufi & Bawazeer [1], linking stochastic roughness fluctuations to changes in thermal conductivity and near-surface layer stiffness. These results confirm that mathematical model stability is ensured only when accounting for the combined action of mechanical and thermal factors forming the cutting zone energy balance.

The high determination of the obtained models is explained not by approximation accuracy, but by internal process parameter consistency. When milling non-ferrous metals, small feed and speed variations are immediately reflected in the surface layer structure, requiring a description not of averaged roughness indicators, but of their probable fluctuation range when changing regimes. This approach aligns with engineering practice implemented in ForgeX mobile manufacturing systems, where regime correction is performed based on dynamic Ra parameter dispersion control, ensuring managed real-time process stability.

The examined experimental dependencies demonstrate direct technological applicability of optimized milling parameters to mobile manufacturing systems functioning in in-situ WAAM workpiece machining mode. Yan et al. [10] data show that using medium feed and spindle speed parameters ensures a stable surface with low roughness without liquid cooling. This regime combination can be reproduced in modular ForgeX stations where autonomous robotic nodes perform mechanical machining of aluminum alloys in field conditions.

Analysis of the energy and dynamic machining profile indicates that for mobile-type systems, the decisive factor is matching feed kinematics with the heat balance in the cutting zone. Under limited cooling conditions, maintaining cutting temperature within allowable limits is achieved by optimizing speed and depth of cut. Such an approach corresponds to recommendations by Soori et al. [8], where process stability was viewed as a function of energy efficiency and thermal equilibrium in the "tool-workpiece-environment" system. For ForgeX Mobile Foundry, this means the possibility of eliminating emulsion fluids and transitioning to dry or minimum quantity lubrication cutting, reducing environmental load, and simplifying equipment maintenance.

Simultaneously, compliance with American industrial safety and environmental standards (OSHA, EPA, DOT) is ensured, expanding certification opportunities for mobile manufacturing modules for operation within national infrastructure projects.

In field module conditions where every operation must be energy-optimal, applying parameters established by Siahsarani et al. [7] ensures the required quality at reduced energy consumption. Implementing these regimes in ForgeX Compact and ForgeX Pro allows shortening the finishing cycle and ensuring a roughness indicator of around two micrometers, comparable to laboratory research results. This confirms the effectiveness of robotic CNC integration when machining WAAM workpieces previously considered difficult for precise post-processing due to uneven microstructure.

Results from Mohanta et al. [6] and Ikhries & Al-Shawabkeh [4] show that controlling feed near the medium range achieves an optimal ratio between removal rate and temperature stability, which is critical for autonomous complexes where access to cooling systems is limited. This ratio also has an economic expression: reduced energy consumption and increased tool life form a positive balance of capital expenditures (CapEx) and operating expenses (OpEx), making ForgeX technology competitive in the distributed manufacturing market.

From a practical standpoint, applying the obtained patterns ensures the technological self-sufficiency of mobile foundry complexes. The interrelation between feed, speed, and machining depth established on the experimental base allows implementing adaptive real-time parameter correction algorithms—analogous to the approach used by Hossain et al. [3] when managing temperature peaks via roughness feedback. For ForgeX Mobile Foundry, such a model can become the basis for a predictive optimization system where cutting parameters automatically adjust to workpiece state and tool life.

Comprehensive comparison of thermodynamic, metrological, and economic factors shows that ForgeX mobile systems are capable of reproducing laboratory machining quality and forming a circular economy. This opens the way to creating a network of autonomous manufacturing nodes, ensuring local production and repair with minimal emissions and costs.

Thus, analysis results confirm the possibility of integrating robotic CNC machining of WAAM components into the ForgeX architecture without reducing accuracy or reliability, making these solutions sustainable and economically viable for autonomous on-site manufacturing.

CONCLUSIONS

The study showed that the accuracy and efficiency of CNC machining of non-ferrous metals are determined by the consistency of speed, feed, and depth of cut. Their interaction forms a stable thermomechanical regime ensuring roughness reduction without increased energy consumption and tool wear even during dry milling.

For cast alloys, the combination of speed and depth is decisive, while for additive workpieces, it is feed, influencing microrelief uniformity. Differences are explained by thermal conductivity and structure anisotropy, allowing Ra parameter control in the high-precision machining range. The optimal regime represents a balance of kinematic and thermal impacts where process stability is maintained.

Practical applicability is confirmed by the ForgeX Mobile Foundry example. Using optimal parameters ensures Ra ≈ 2 μm without liquid cooling. This demonstrates the possibility of introducing dry and MQL milling into ForgeX Compact, Pro, and Heavy modules, reducing energy costs and environmental load.

The study results expand understanding of CNC process stability during autonomous machining in mobile manufacturing systems. The proposed approach can be used when designing modular lines for energy-autonomous production. Future work will be aimed at developing adaptive cutting parameter control algorithms based on AI tool wear prediction models.

REFERENCES

1. Alsoufi, M. S., & Bawazeer, S. A. (2025). Probabilistic analysis of surface integrity in CNC turning: Influence of thermal conductivity and hardness on roughness and waviness distributions. Machines, 13(5), 385. https://doi.org/10.3390/machines13050385
2. Crăciun, R. S., Teodor, V. G., Baroiu, N., Păunoiu, V., & Moroșanu, G.-A. (2024). Study of cutting forces in drilling of aluminum alloy 2024-T351. Machines, 12(12), 937. https://doi.org/10.3390/machines12120937
3. Hossain, S., Abedin, M. Z., Saha, R. K., Touhiduzzaman, M., & Hossen, M. J. (2024). Optimization of cutting temperature and surface roughness in CNC turning of Ti-6Al-4V alloy using response surface methodology. Heliyon, 11(1), e41051. https://doi.org/10.1016/j.heliyon.2024.e41051
4. Ikhries, I. I., & Al-Shawabkeh, A. F. (2024). Novel methods for optimizing CNC aluminum alloy machining parameters in polymer mold cavities. International Journal of Lightweight Materials and Manufacture, 7(4), 507–519. https://doi.org/10.1016/j.ijlmm.2024.03.002
5. Li, Z., Song, Q., Jin, P., Liu, Z., Wang, B., & Ma, H. (2024). Chatter suppression techniques in milling processes: A state of the art review. Chinese Journal of Aeronautics, 37(7), 1–23. https://doi.org/10.1016/j.cja.2023.10.001
6. Mohanta, D. K., Sahoo, B., & Mohanty, A. M. (2024). Experimental analysis for optimization of process parameters in machining using coated tools. Journal of Engineering and Applied Science, 71, 38. https://doi.org/10.1186/s44147-024-00370-5
7. Siahsarani, A., Bayat, M., Alinaghizadeh, A., & others. (2025). Surface integrity optimization in milling of aluminum 1100: Effects of supercritical CO_2 +MQL and emulsion cooling with various milling strategies. International Journal of Advanced Manufacturing Technology, 137, 6139–6152. https://doi.org/10.1007/s00170-025-15540-9
8. Soori, M., Karimi Ghaleh Jough, F., Dastres, R., & Arezoo, B. (2024). Sustainable CNC machining operations: A review. Sustainable Operations and Computers, 5, 73–87. https://doi.org/10.1016/j.susoc.2024.01.001
9. Wang, G., Chen, X., Xu, Z., Feng, F., Zhang, J., Zhang, X., & Feng, P. (2025). Advanced precision cutting titanium alloy methods: A critical review considering cost, efficiency, and quality. Technologies, 13(5), 172. https://doi.org/10.3390/technologies13050172
10. Yan, Z., Ren, X., Zhao, H., & Chen, S. (2024). Investigating the impact of robotic milling parameters on the surface roughness of Al-alloy fabricated by wire arc additive manufacturing. Materials, 17(19), 4845. https://doi.org/10.3390/ma17194845

Copyright: © 2025 The Author(s). This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.