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SURFACE ROUGHNESS INVESTIGATION THROUGH INTERPLAY OF CUTTING SPEED AND THERMAL-ASSISTED MACHINING IN HIGH-SPEED MACHINING OF SKD11 STEEL

This study aims to investigate the interplay between cutting speed and Thermal-Assisted Machining (TAM) concerning surface roughness during the high-speed machining of SKD11 steel. The integration of pre-cutting workpiece heating introduces a temperature factor that intricately affects surface roughness. The primary objective is to ascertain optimal speed and temperature ranges that synergistically enhance machining efficiency, curtail costs, and elevate surface quality. The experimental protocol initiates with room temperature milling of SKD11 steel, progressively elevating the temperature gradient to systematically appraise temperature's impact on surface roughness under both conventional and elevated cutting speeds. Subsequent experimentation, conducted within specific temperature thresholds, entails stepwise augmentation of cutting speed to elucidate the influence of high-speed conditions on surface roughness. The ensuing analysis meticulously examines the ramifications of distinct cutting speed intervals on surface roughness. Ultimately, the study furnishes pragmatic recommendations for judiciously selecting cutting speeds and heating temperature parameters across diverse machining scenarios.

1. INTRODUCTION

The primary goal of manufacturing processes is to produce efficiently machined products of high quality. High-speed machining techniques have emerged as a means to fabricate high-precision products while reducing costs associated with fixture assembly and storage [1]. Numerous studies have been conducted to improve machining efficiency and product accuracy through high-speed machining. Compared to traditional machining methods, high-speed machining offers advantages such as rapid metal removal, increased machining productivity, low cutting forces, and improved surface quality [2–5]. In high-speed machining, the chip evacuates the cutting zone at a faster rate, resulting in a significant reduction of cutting heat transferred mainly to the chip [6].

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One essential parameter for evaluating product surface quality is surface roughness, which is influenced by the complex interplay of mechanical and thermal stresses acting on the cutting tool. For instance, Xianhua Tian et al. [7] investigated surface quality in Inconel 718 material using Sialon ceramic cutting tools. The study revealed changes in tool wear mechanisms with varying cutting speeds. In the speed range of 600 to 1400 m/min, wear exhibited a concave pattern, whereas at cutting speeds above 1800 to 3000 m/min, wear was primarily due to adhesion. The authors also observed that Sialon ceramic cutting tools were not suitable for high cutting speeds exceeding 1000 m/min as it exacerbated surface quality deterioration and reduced tool life. Furthermore, the study concluded that dry cutting resulted in significant cutting friction, leading to rapid wear of ceramic cutting tools and increased surface roughness. The machining mechanism was also investigated by Rosemar et al. [8], who concluded that high cooling pressure was more suitable for low cutting speeds but yielded minimal differences in high-speed machining. In another study, SU Honghua et al. [9] examined the machining mechanism of PCD/PCBN tools in the high-speed milling of Titanium TA15. The research demonstrated that increasing abrasiveness correlated with higher surface roughness, with average roughness values of 0.5 μm for PCD tools and 0.7 μm for PCBN tools. The study further suggested that high-speed cutting tool wear was attributed to partial diffusion of the workpiece material onto the tool's front face, with wear oxidation occurring in the contact area between the tool and the workpiece.

Currently, high-speed machining finds extensive application in industries such as mold manufacturing, automotive, aviation, and light industries. However, it also poses certain challenges, including the need for careful selection of cutting parameters, dynamic balancing of cutting tools and machine spindles, high initial equipment costs, significant machine wear and maintenance expenses, regular safety checks, and the requirement for precise machining processes to ensure workpiece accuracy [10]. Additionally, thermal-assisted machining (TAM), also known as machining assisted by heating or hot machining, has gained attention since the early 20th century. Numerous studies on heat-assisted machining have shown promising results compared to conventional machining methods, including increased productivity, improved surface quality, enhanced cutting efficiency, prolonged tool life, reduced cutting vibrations, and decreased cutting forces [11–25]. By employing heat to soften the workpiece material, the advantages of the heating process can overcome certain limitations of high-speed machining.

Each heating method exhibits a distinct set of advantages and limitations, rendering them suitable for specific machining techniques while not universally applicable. The comparative advantages and disadvantages of various heating methods are summarized in Table 1 [6].

Of notable significance, electromagnetic induction heating machining demonstrates remarkable advantages in terms of heating efficiency during vertical milling, cost-effectiveness in heating, and widespread applicability to hard-to-cut metals and alloys. This research involves the milling of SKD11 steel under both ambient and elevated temperature conditions, aiming to assess cutting performance in both conventional machining and heat-assisted processing. The primary output parameter of interest is surface roughness, serving as a pivotal indicator of product quality across diverse temperature and cutting speed scenarios. Ultimately, recommendations pertaining to cutting strategies and heating temperatures are provided, aiming to achieve objectives such as enhanced tool longevity and improved product surface characteristics.

Table 1. The comparative advantages and disadvantages of various heating methods

Heating Method	Advantages	Limitations
Electric Current Heating (EAM)	- Simple apparatus - Uniform temperature distribution	- Challenges in temperature control and regulation
Laser heating (LAM)	- High precision in heat concentration - Flexibility in laser source adjustment	- Elevated cost - Disparity in heat absorption rates among different materials
Plasma Heating (PEM)	- Intensive heat source concentration	- Complexity in temperature control and regulation
Furnace heating (FAM)	- Simplicity of equipment	- Challenges in temperature control and regulation - Experimental application, not suitable for production
Induction heating (IAM)	- User-friendly - High heating capacity	- Moderate heat source concentration - Restrictions on tool movement

The distinctive contribution of this study is its comprehensive examination of milling procedures applied to SKD11 steel, encompassing a meticulous comparative analysis spanning both standard and heightened temperature contexts. The phenomenon of wear-induced alterations in the dimensional and geometric attributes of the cutting tool is explored, leading to consequential modifications in responses driven by the interplay of deformations, thermal effects, and applied forces. Specifically, this study elucidates the complexities linked with high-speed milling of SKD11 steel, particularly when employing non-carbide-coated hard alloy cutting inserts. The core focus of this scrutiny centres on evaluating cutting performance in both traditional and heat-assisted machining scenarios. Of notable significance, the emergence of surface roughness as a discriminating gauge of product quality adeptly harmonizes with the dynamic interplay of variable temperature and cutting speed conditions. In summary, this inquiry extends strategic directives encompassing cutting methodologies and thermal manipulation, thus facilitating the potential for extended tool lifespan and the attainment of heightened product surface quality

2. METHODOLOGY AND EXPERIMENTATION

The experimentation in this study was conducted on an alloy steel billet, SKD11, adhering to the JIS-G4404 standard from Japan. SKD11 steel is commonly utilized in the production of extrusion molds, plastic injection molds, and pressure-casting molds due to its high hardness, compressive strength, impact toughness, and deformation resistance.

The machining experiment was performed using a Taiwanese high-speed milling machine, MC500 (Fig. 1a). The key parameters of the machine included a spindle rotation speed ranging from 100 to 30,000 rpm, a spindle capacity of 15 kW, a machine table movement speed during processing ranging from 1 to 30,000 m/min, a maximum idle speed of 48,000 mm/min, and a machine plate displacement of X x Y x Z = 500 mm x 400 mm x 300 mm. In this study, an electromagnetic induction heating system was employed to heat the workpiece immediately before machining. The heating system comprised two primary components: the high-frequency heating circuit and the temperature controller.

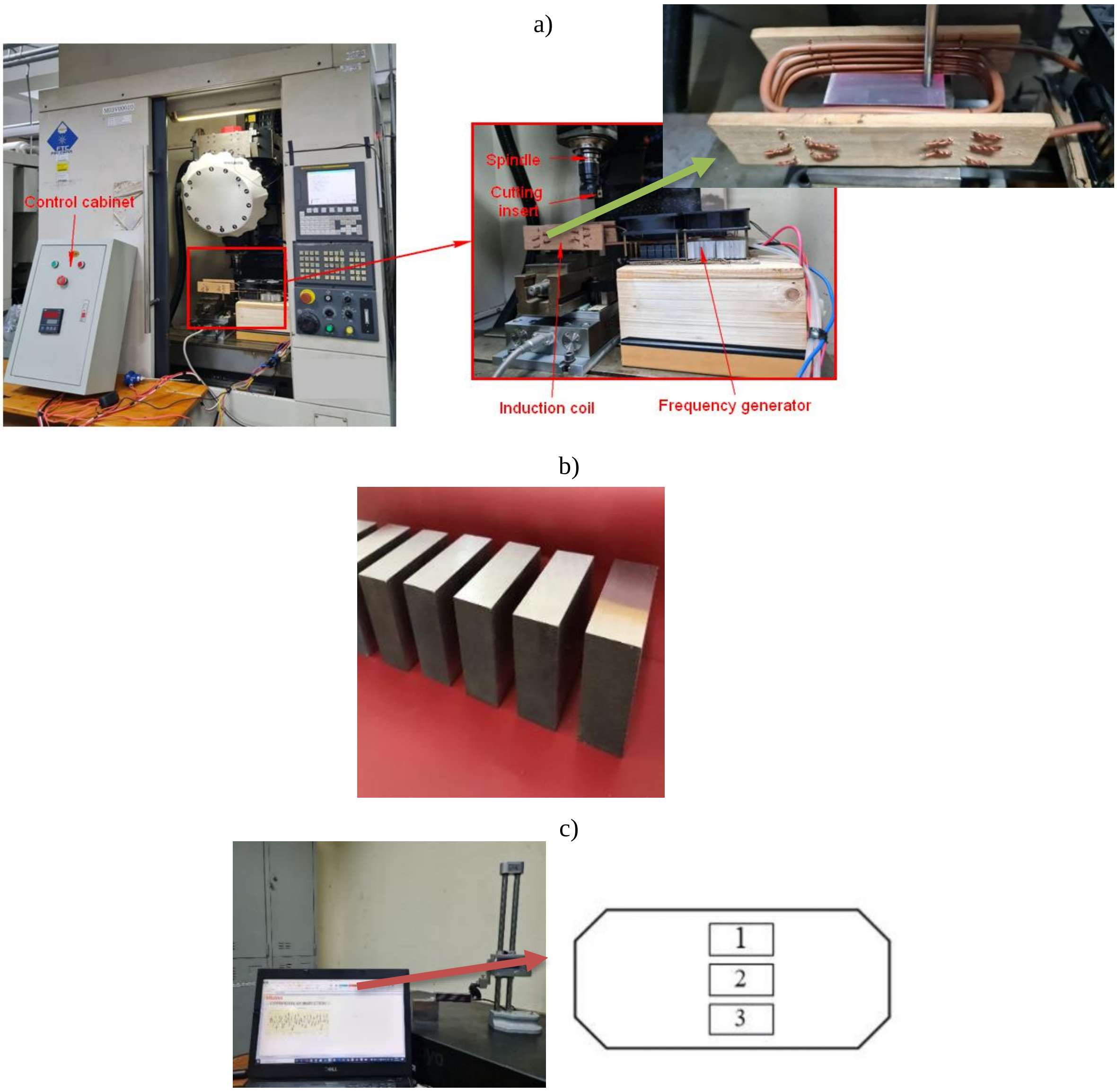


Fig. 1. Machining experiment setup a) CNC machine in TAM, b) workpieces and c) surface roughness and measure method

A temperature sensor was utilized to measure and provide temperature feedback to the controller, ensuring consistent temperature control of the workpiece throughout the machining process. The cutting tools employed consisted of both coated and uncoated hard alloy cutting inserts, manufactured by KORLOY, featuring carbide material. The dimensions of the experimental billet were 70×80×31 mm. Coolant was not used during the machining process (Fig. 1b). The evaluation of workpiece surface roughness subsequent to the machining process was conducted employing the Mitutoyo HD-30AX roughness meter originating from Japan (depicted in Fig. 1c). In this assessment, the measuring head traverses perpendicular to the machining path, and each specimen undergoes measurement at three distinct points, ensuring a robust and dependable analysis within the prescribed reference length domain.

3. RESULTS AND DISCUSSIONS

3.1. MACHINING AT LOW-CUTTING SPEEDS

To investigate the impact of the heating process on surface roughness when heat treating SKD11 steel and compare it with conventional machining methods at low cutting speeds, experiments were conducted at both room temperature and high temperatures using the following parameters:

Experiment 1: $V = 190$ m/min, $f = 230$ mm/min, $t = 0.5$ mm, $T = 25$°C (room temperature).
Experiment 2: $V = 190$ m/min, $f = 230$ mm/min, $t = 0.5$ mm, $T = 200$°C.
Experiment 3: $V = 190$ m/min, $f = 230$ mm/min, $t = 0.5$ mm, $T = 300$°C.
Experiment 4: $V = 190$ m/min, $f = 230$ mm/min, $t = 0.5$ mm, $T = 400$°C.

ISO standards suggest that surface roughness levels between 5 and 7 indicate semi-finished machining quality, while levels between 8 and 10 correspond to finishing processing. Average roughness (Ra) was used to evaluate surface quality, and measurements were taken at three different locations perpendicular to the machining trace to ensure accuracy. Figure 2 illustrates a comparison of surface roughness between conventional machining and heating at 200°C under a cutting speed of 190 m/min.

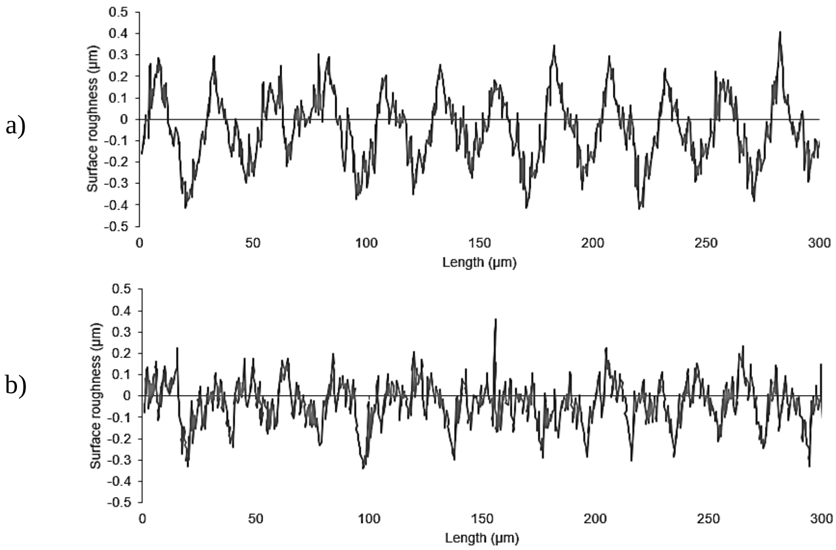


Fig. 2. Comparison of surface roughness between conventional machining (a) and heating at 200°C (b), cutting speed of 190 m/min

The results indicate a significant reduction in roughness when heat was applied, attributed to the thermal softening of the material, which facilitated the cutting process and improved cutting stability.

$$\Delta \mathrm{Ra}(\%) = \frac{\mathrm{Ra}_\mathrm{R}-\mathrm{Ra}_\mathrm{T}}{\mathrm{Ra}_\mathrm{R}} \cdot 100\% \tag{1}$$

where Ra_R and Ra_T represent surface roughness in normal machining and heat processing, respectively.

Figure 3 presents the surface roughness at different temperature conditions corresponding to Experiments 1, 2, 3, and 4, while Table 2 displays the average surface roughness values and the percentage reduction calculated using Eq. (1). It can be observed that as the temperature increases from 200°C to 400°C, the surface roughness decreases. The highest reduction in surface roughness (47.1%) was achieved when heated to 400°C.

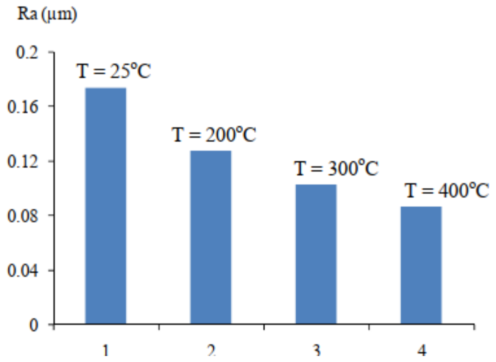


Fig. 3. Surface roughness values and reduction at different temperature conditions

Table 2. Surface roughness values and reduction at different temperature conditions

T (°C)	*T* = 25°C	*T* = 200°C	*T* = 300°C	*T* = 400°C
Ra (μm)	0.174	0.128	0.108	0.092
ΔRa (%)	-	26.4	37.9	47.1

3.2. MACHINING AT HIGH-CUTTING SPEEDS

The phenomenon of cutting tool wear is a complex and intricate process, characterized by intricate physical and chemical interactions occurring within the contact zone of the tool, chip, and workpiece during high-speed milling operations. This wear-induced process brings about subtle changes in the dimensional and geometric attributes of the cutting tool, leading to consequential alterations in responses triggered by a combination of deformations, thermal effects, and applied forces. The high-speed milling of SKD11 steel presents notable challenges, particularly when employing non-carbide-coated hard alloy cutting inserts. This machining endeavour resulted in notable tool failure, as evidenced by the fracture depicted in Fig. 4a, wherein the fracture height measured 1.301 mm. However, the utilization of cutting inserts with a carbide coating introduced a significant improvement, yielding a seamless machining experience, obviating tool failure, and yielding minimal wear, indicated by a fracture height of 0.191 mm (Fig. 4b). Consequently, the employment of carbide-coated hard alloy cutting inserts emerged as the preferred choice for conducting high-cutting-speed machining experiments. The surface roughness of a machined part significantly affects its workability, durability, hardness, wear resistance, and heat resistance. In this section, machining was performed under the same high-speed cutting conditions (V = 600 m/min, f = 802 mm/min, t = 1.5 mm) while varying the heating levels from room temperature to 500°C to evaluate the impact of heating on surface roughness.

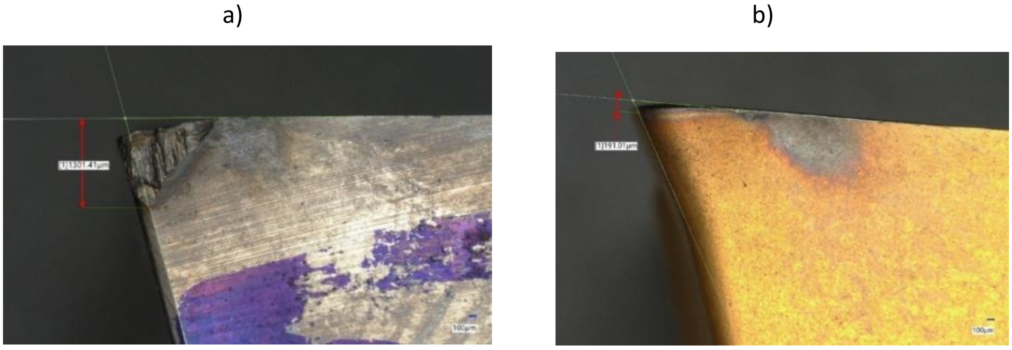


Fig. 4. Visual representations of non-carbide coated hard alloy cutting inserts (a) and carbide coated hard alloy cutting inserts (b) during room temperature milling

Table 3. Surface roughness values and reduction at different cutting parameters, temperature levels

Exp. No.	V (m/min)	f (mm/min)	t (mm)	T (°C)	Ra (µm)	ΔRa (%)
1	600	802	1.5	24	1.256	-
2	600	802	1.5	200	0.354	71.82
3	600	802	1.5	350	0.224	82.17
4	600	802	1.5	500	0.112	91.08

As detailed in Table 3, the cutting parameters, temperature levels, and average surface roughness outcomes are provided. The percentage variation in surface roughness was computed using Eq. (1). To enhance clarity, Fig. 5 illustrates surface roughness images during machining at various temperatures (room temperature, 200°C, 350°C, and 500°C) on the same axes. The correlation between temperature and surface roughness is visually depicted in Fig. 6a, revealing a discernible reduction in surface roughness with escalating temperatures. Specifically, heating to 200°C resulted in a notable reduction in roughness compared to room-temperature machining. Further elevation to 500°C resulted in a significant 91.08% decrease in surface roughness. Additionally, Fig. 6b elucidates the interaction between cutting speed and surface roughness, with other parameters held constant as outlined in Table 4. The findings underscore a substantial increase in surface roughness as the cutting speed is elevated from 600 to 800 m/min. However, upon further increase from 800 to 1000 m/min, the surface roughness exhibits a tendency to decrease. Consequently, the study furnishes valuable recommendations for appropriate temperature and speed combinations based on specific surface quality objectives.

$$\Delta \mathrm{Ra}_{\mathrm{V}}(\%) = \frac{\mathrm{Ra}_{\mathrm{V}} - \mathrm{Ra}_{\mathrm{V'}}}{\mathrm{Ra}_{\mathrm{V}}} \times 100 \tag{2}$$

Where ΔRa_V represents the percentage reduction in surface roughness, and Ra_V and $Ra_{V'}$ denote the surface roughness at different speeds.

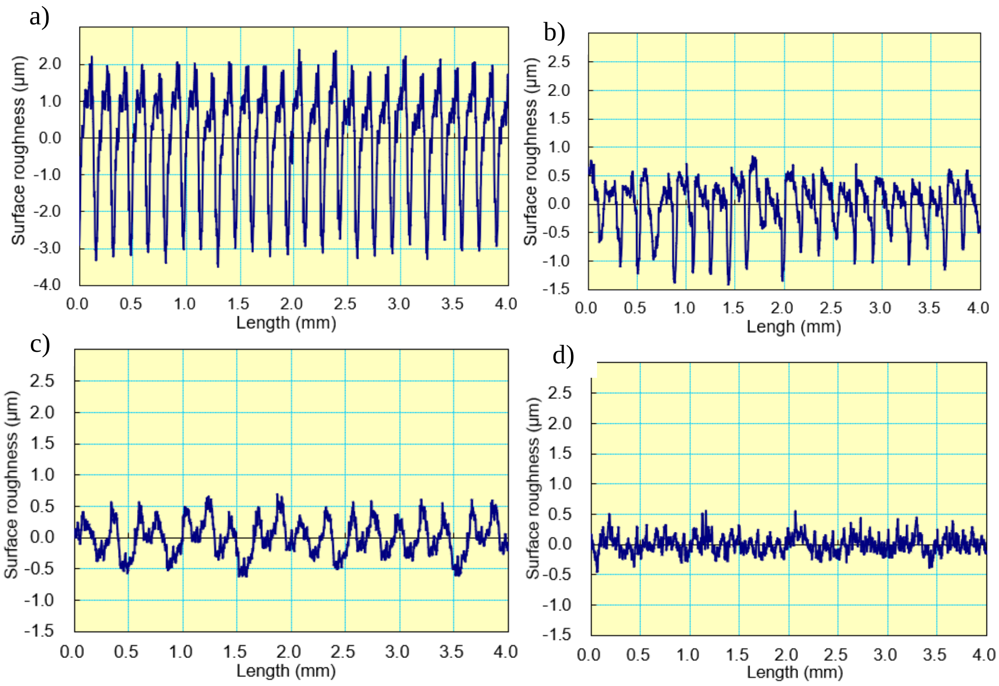
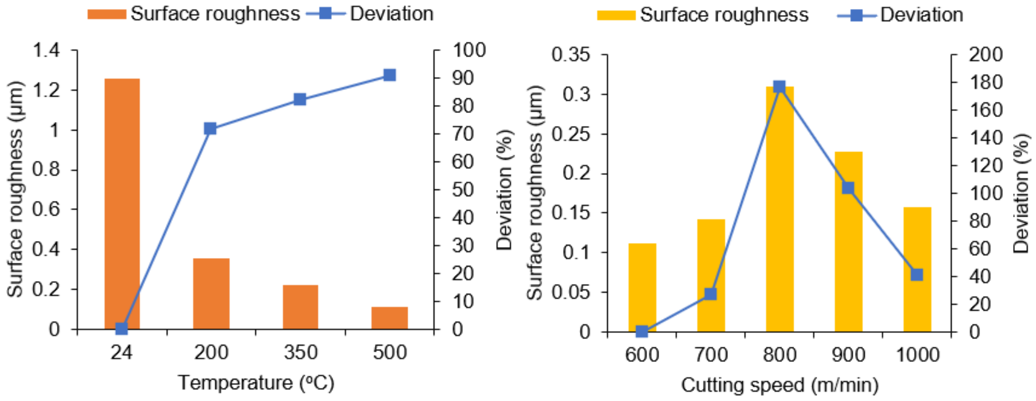


Fig. 5. Surface roughness profile when machining at room temperature (a), 200°C (b), 350°C (c), 500°C (d)



a) b)

Fig. 6. Effect of temperature (a) and cutting speed (b) on surface roughness and deviation (%) when milling SKD11 steel

Table 4. Surface roughness results at different cutting speeds

Exp. No.	*V* (m/min)	*f* (mm/min)	*t* (mm)	*T* (°C)	Ra (µm)	ΔRa (%)
5	600	802	1.5	500	0.112	-
6	700	802	1.5	500	0.142	26.79
7	800	802	1.5	500	0.31	176.79
8	900	802	1.5	500	0.228	103.57
9	1000	802	1.5	500	0.158	41.07

For achieving low surface roughness, it is advisable to employ a heating temperature of 500°C in tandem with a cutting speed of 600 m/min. Conversely, to enhance material removal rates while concurrently maintaining low surface roughness, a cutting speed of 1000 m/min paired with a tempering temperature of 500°C proves optimal for high-temperature machining conditions.

4. CONCLUSIONS

This study aimed to investigate the influence of high temperature and cutting speed on surface roughness in high-speed milling of SKD11 alloy steel with heating. The experimental findings revealed several key conclusions. Firstly, the application of the heating process during milling at different cutting speeds had a significant impact. It was observed that increasing the temperature for milling support resulted in a decrease in surface roughness. Secondly, as the cutting speed increased from 600 m/min to 800 m/min, the surface roughness exhibited an increasing trend. However, beyond this point, further increases in cutting speed led to a decrease in surface roughness. Thirdly, to achieve a specific surface quality objective, it is recommended to mill at a cutting speed of 600 m/min accompanied by a heating temperature of 500°C. Finally, when the aim is to improve the material removal rate and reduce machining time, the optimal choice is a cutting speed of 1000 m/min along with a workpiece heating temperature of 500°C. This combination enables the attainment of low surface roughness while achieving the desired objectives of increased material removal rate. In summary, this experimental investigation clearly demonstrates the significant influence of temperature and cutting speed on surface roughness in high-speed milling of SKD11 alloy steel with heating, thereby providing valuable insights for optimizing milling parameters and facilitating the achievement of the desired surface quality and enhanced machining efficiency.

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REFERENCES

[1] LIU Z.Q., AI X., ZHANG H., WANG Z.T., WAN Y., *Wear Patterns and Mechanisms of Cutting Tools in High-Speed Face Milling*, 2002, J. Mater. Process. Technol., 129/1–3, 222–226. https//doi.org/10.1016/S0924-0136(02)00605-2.

[2] CUI X., ZHAO J., 2014, *Cutting Performance of Coated Carbide Tools in High-Speed Face Milling of AISI H13 Hardened Steel*, Int. J. Adv. Manuf. Technol., 71/9–12, 1811–1824, https//doi.org/ 10.1007/s00170-014-5611-3.

[3] CALATORU V.D., BALAZINSKI M., MAYER J.R.R., PARIS H., ESPÉRANCE G.L., 2008, *Diffusion Wear Mechanism During High-Speed Machining of 7475-T7351 Aluminum Alloy with Carbide end Mills, Wear*, 265/11–12, 1793–1800, https//doi.org/10.1016/j.wear.2008.04.052.

[4] THI-HOA P., THI-BICH M., VAN-CANH T., TIEN-LONG B., DUC-TOAN N., 2018, *A Study on the Cutting Force and Chip Shrinkage Coefficient in High-Speed Milling of A6061 Aluminum Alloy*, Int. J. Adv. Manuf. Technol., 98/1–4, 177–188, https//doi.org/10.1007/s00170-017-1063-x.

[5] WANG C., XIE Y., ZHENG L., QIN Z., TANG D., SONG Y., 2014, *Research on the Chip Formation Mechanism During the High-Speed Milling of Hardened Steel*, Int. J. Mach. Tools Manuf., 79, 31–48m, https//doi.org/ 10.1016/j.ijmachtools.

[6] LEZANSKI P., SHAW M.C., 1990, *Tool Face Temperatures in High Speed Milling*, J. Manuf. Sci. Eng. Trans. ASME, 112/2, 132–135, https//doi.org/10.1115/1.2899555.

[7] TIAN X., ZHAO J., ZHAO J., GONG Z., DONG Y., 2013, *Effect of Cutting Speed on Cutting Forces and Wear Mechanisms in High-Speed Face Milling of Inconel 718 With Sialon Ceramic Tools*, Int. J. Adv. Manuf. Technol., 69/9–12, 2669–2678, https://doi.org/10.1016/S0924-0136(02)00605-2.

[8] DA SILVA R.B., MACHADO A.R., EZUGWU E.O., BONNEY J., SALES W.F., 2013, *Tool Life and Wear Mechanisms in High Speed Machining of Ti-6Al-4V Alloy with PCD Tools Under Various Coolant Pressures*, J. Mater. Process. Technol., 213/8, 1459–1464, https//doi.org/10.1016/j.jmatprotec.

[9] SU H., LIU P., FU Y., XU J., 2012, *Tool Life and Surface Integrity in High-Speed Milling of Titanium Alloy TA15 with PCD/PCBN Tools*, Chinese J. Aeronaut., 25/5, 784–790, https//doi.org/10.1016/S1000-9361(11)60445-7.

[10] KAUPPINEN V., 2004, *High-Speed Milling - a New Manufacturing Technology*, 4th Int. DAAAM Conf. Ind. Eng. – Innov. as Compet. Edge SME, 131–134.

[11] LONIKAR K.V., 2015, *Laser Assisted Machining (LAM) of Inconel 718 with Thermal Modeling and Analysis of Process Parameters*, 4/07, 308–312.

[12] HARPREET SINGH E.M.G., Er.Sandeep Sharma., 2015, *Analysis of Surface Roughness and Material Removal Rate In Dry And Thermal Assisted Machining oF EN8 STEEL*, Int. J. Eng. Sci. Res. Technol., 4/11, 577–583.

[13] XAVIERAROCKIARAJ S., KUPPAN P., 2014, *Investigation of Cutting Forces, Surface Roughness and Tool Wear During Laser Assisted Machining of SKD11Tool Steel*, Procedia Eng., 97, 1657–1666, https//doi.org/10.1016/j.proeng

[14] MAKWANA R., PRAJAPATI H., 2014, *Experimental Investigation on Effect of Machining Parameters on Surface Roughness in Thermally Assisted Turning of Mild Steel*, Int. Conf. Multidiscip. Res. Pract., I, VIII, 488–489.

[15] YANG J., SUN S., BRANDT M., YAN W., 2010, *Experimental Investigation and 3D Finite Element Prediction of the Heat Affected Zone During Laser Assisted Machining of Ti6Al4V Alloy*, J. Mater. Process. Technol., 210/15, 215–2222, https//doi.org/10.1016/j.jmatprotec.2010.08.007.

[16] KONIG A.K.Z.W., 1993. *Laser-Assisted Hot Machining of Ceramics and Composite Materials*, Int. Conf. Mach. Adv. Mater., 847, 455–463.

[17] LUYEN T.T., NGUYEN D.T. 2023, *Improved Uniformity in Cylindrical Cup Wall Thickness at Elevated Temperatures Using Deep Drawing Process for SPCC Sheet Steel*, J. Braz. Soc. Mech. Sci. Eng., 45/348, https://doi.org/10.1007/s40430-023-04270-2.

[18] MAC T.-B., LUYEN T.-T., NGUYEN D.-T., 2023, *Assessment of the Effect of Thermal-Assisted Machining on the Machinability of SKD11*, Alloy Steel. Metals, 13/699.

[19] LUYEN T.T., MAC T.B., NGUYEN D.T., 2023, *Simulation and Experimental Comparison Study Based on Predicting Forming Limit Curve of SUS304 Sheet Material*, Mods. Physics. Lett. B, 2340001.

[20] MAC T.-B., LUYEN T.-T., NGUYEN D.-T., 2023, *The Impact of High-Speed and Thermal-Assisted Machining on Tool Wear and Surface Roughness during Milling of SKD11 Steel*, Metals, 13/971.

[21] DONG T., TOAN N., DUNG N., 2023, *Influence of Heat Treatment Process on the Hardness and Material Structure of SKD61 Tool Steel*, Mods. Physics. Lett. B, 37/2340014.

[22] LUYEN T.T., NGUYEN D.T. 2023, *Improved Uniformity in Cylindrical Cup Wall Thickness at Elevated Temperatures Using Deep Drawing Process for SPCC Sheet Steel*, J. Braz. Soc. Mech. Sci. Eng., 45/348.

[23] LUYEN T.T., MAC T.B., BANH T.L., NGUYEN D.T., 2023, *Investigating the Impact of Yield Criteria and Process Parameters on Fracture Height of Cylindrical Cups in the Deep Drawing Process of SPCC Sheet Steel*, Int. J. Adv. Manuf. Technol.

[24] PHAN N.H., TOAN N.D., SHAILESH S., 2023, *Simultaneous improvement of Z-Coordinate and Overcut in EDM of Titanium Grade 5 Alloy Using a Carbon-Coated Micro-Tool Electrode*, Mods. Physics. Lett. B, 2340004.

[25] DONG T.P., TOAN N.D. 2023, *A study on the Investigation of the Microstructure of SKD61 Steel After Selected Quenching and Tempering Processes*, Mods. Physics. Lett. B, 2340022.