EMPIRICAL EVALUATION OF HIGH-SPEED MACHINING AND HEATING SUPPORT ON CUTTING TOOL WEAR AND SURFACE ROUGHNESS DURING PROCESSING OF HEAT-TREATED SKD61 STEEL

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ABSTRACT

This study investigates the optimal ranges of high-speed machining and temperature that achieve a balance between cutting efficiency, cost reduction, improvement in surface quality, and extension of tool life. Milling experiments were conducted on heat-treated SKD61 steel at different temperatures, including room temperature and elevated temperatures, to evaluate the effect of heating on cutting tool wear and surface roughness. After determining the suitable temperature condition, additional experiments were conducted with increased high-speed cutting to examine the influence of cutting speed on tool wear and surface roughness. The results show significant enhancements in wear height (86.45%) and surface roughness (76.55%) when employing high-speed machining parameters such as a speed of 300 m/min, depth of cut of 0.5 mm, feed rate of 0.15 mm/tooth, and heating support at 500°C, compared to machining at room temperature. Furthermore, within the speed range of 300-600 m/min, wear height exhibits minimal increase, while surface roughness is significantly reduced. However, exceeding a speed of 600 m/min leads to notable wear, resulting in detrimental effects on the cutting tool and a sharp increase in roughness. This study provides valuable insights into the reasonable ranges of speed and temperature necessary to achieve specific objectives in terms of quality and productivity.

NGHIÊN CỨU THỰC NGHIỆM ĐỂ ĐÁNH GIÁ GIA CÔNG CAO TỐC CÓ HỖ TRỢ GIA NHIỆT ĐẾN ĐỘ MÒN CỦA DỤNG CỤ CẮT VÀ ĐỘ NHÁM BỀ MẶT TRONG KHI GIA CÔNG THÉP SKD61 SAU NHIỆT LUYỆN

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TỪ KHÓA

Gia công tốc độ cao
Mòn dụng cụ cắt
Nhám bề mặt
Thép SKD61 sau nhiệt luyện
Hỗ trợ gia nhiệt

TÓM TẮT

Nghiên cứu này đề xuất các phạm vi nhiệt độ và gia công tốc độ cao phù hợp nhằm đạt được sự cân bằng giữa hiệu quả cắt, giảm chi phí, cải thiện chất lượng bề mặt và kéo dài tuổi thọ của dụng cụ. Các thí nghiệm phay được tiến hành trên thép SKD61 sau nhiệt luyện ở các nhiệt độ khác nhau, bao gồm nhiệt độ phòng và nhiệt độ cao, để đánh giá ảnh hưởng của quá trình gia nhiệt đối với mài mòn dụng cụ cắt và độ nhám bề mặt. Sau khi xác định điều kiện nhiệt độ thích hợp, các thí nghiệm bổ sung đã được thực hiện với việc tăng tốc độ cắt cao để kiểm tra tác động của tốc độ gia công cao tốc tới mài mòn của dụng cụ và độ nhám bề mặt. Kết quả cho thấy sự cải thiện đáng kể về chiều cao mài mòn (86,45%) và độ nhám bề mặt (76,55%) khi sử dụng các thông số gia công tốc độ cao, bao gồm tốc độ 300 m/phút, độ sâu cắt 0,5 mm, tốc độ nạp 0,15 mm/răng dưới hỗ trợ gia nhiệt ở 500°C, so với gia công cùng chế độ cắt và tại nhiệt độ phòng. Hơn nữa, trong phạm vi tốc độ 300-600 m/phút, chiều cao mòn dụng cụ cắt chỉ ở mức tăng nhỏ, trong khi độ nhám bề mặt giảm đáng kể. Tuy nhiên, vượt quá tốc độ 600 m/phút sẽ dẫn đến mài mòn đáng kể tác động bất lợi lên dụng cụ cắt và độ nhám bề mặt tăng mạnh. Nghiên cứu này cung cấp những hiểu biết có giá trị về phạm vi tốc độ và nhiệt độ hợp lý cần thiết để đạt được các mục tiêu cụ thể về chất lượng và năng suất gia công.

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1. Introduction

High-speed machining is increasingly utilized in manufacturing high-quality products in both domestic and foreign production and business establishments. The mold industry, automobile industry, aviation industry, and light industry are among the sectors where high-speed machining is primarily applied. Compared to traditional machining, high-speed machining offers the advantage of increased speed, resulting in enhanced machining productivity, reduced cutting force, and better machined surface quality [1]-[5]. During high-speed machining, the chip exits the cutting zone faster, leading to significant reductions in cutting heat as the heat is mainly transferred to the chip [6].

When machining high-hardness materials, the cutting tool geometry and cutting mode parameters (cutting speed, feed amount, depth of cut) are the main factors affecting the machining process and phenomena. Researchers must explore new technological solutions to support the machining process in order to increase machining productivity, improve part surface quality, and reduce product costs. Heat-assisted machining is one such advanced method that is widely applied and delivers remarkable results.

Thermal-assisted machining (TAM) is a machining method performed on conventional machine tools and CNC machines where the workpiece is heated immediately before and during processing [3]. The heating processing method was first studied in 1945 and has been applied in production practice to this day [4], [5]. Compared to conventional machining methods, heat processing offers a range of outstanding effects, including increasing tool life, reducing cutting force, reducing power consumption, reducing tool wear, increasing material separation peeling speed, and improving surface quality [6]-[10]. Heated machining is used for both chip machining (turning, milling, drilling, etc.) and chipless machining (forging, stamping, drawing, etc.). Electromagnetic induction heating is a very efficient, low-cost heating method and a good choice for vertical milling of difficult-to-cut metals and alloys. T.L. Ginta and A.K.M.N. Amin [11] have demonstrated that heating machining with electromagnetic induction can reduce vibrations by 98% and increase tool life many times when machining steel.

SKD61 tool steel is a difficult material to work with, but it is widely used in the mold industry and the automotive industry due to its strength, ductility, and hardness maintained at high working temperatures. Diamond grinding or discharge machining are typically used for machining SKD61, but these methods have limitations due to low material removal rates, expensive tools, and rapid wear. Heat treatment is a technological solution for processing SKD61 steel.

In today's manufacturing industry, the ultimate goal of any machining process is to produce high-quality products with low production costs. To achieve this, researchers have focused on developing high-speed machining techniques that can improve both machining efficiency and product accuracy. One of the critical factors in high-speed machining is tool life, which is heavily influenced by the friction and temperature generated at the contact area between the cutting tool, chip, and workpiece. Recent studies have explored the use of new cutting materials, such as Sialon ceramic, PCD, and PCBN, to enhance tool life and improve product surface quality. For example, Xianhua Tian et al. [7] investigated the machining of Inconel 718 with Sialon ceramic cutting material, demonstrating that cutting force decreases with an increase in initial cutting speed, but then increases when cutting speed continues to increase. Additionally, they found that the wear mechanism of the tool changes with cutting speed, and that high cutting speeds above 1000 m/min are not suitable for Sialon ceramic cutting tools due to worsened surface quality and reduced tool life. R. B. Da Silva et al. [12] also studied the wear mechanism and tool life during high-speed machining of Ti-6Al-4V alloy with PCD tools under pressure, revealing that high cooling pressure is more effective for low cutting speeds. Meanwhile, Su Honghua and colleagues evaluated the tool life of PCD/PCBN materials during high-speed milling of Titanium TA15, demonstrating that PCD tools have a longer life than PCBN tools at the same cutting conditions. In addition to exploring new cutting materials, researchers have also investigated chip formation processes and surface roughness during high-speed machining. Xiaobin Cui et al. [2], for instance, studied the chip formation process and surface roughness when plane milling AISI H13 steel. They found that at cutting speeds exceeding 1400 m/min, the chips formed are short strips, and the color of the chips turns yellow. Meanwhile, L. Ozler et al. [13] studied the tool life when processing austenitic-manganese steel, revealing that the tool life is directly proportional to the workpiece temperature but inversely proportional to the cutting speed. Overall, these studies demonstrate the ongoing efforts to enhance high-speed machining processes, with a focus on developing new cutting materials and understanding the wear mechanisms, chip formation processes, and surface roughness of the machined products.

This study evaluates the impact of high-speed machining and heating support on cutting tool wear and surface roughness when processing heat-treated SKD61 steel. The findings reveal that high-speed machining with appropriate heating support can significantly improve surface quality and increase tool life while reducing costs. The study provides insights into the optimal speed and temperature range to achieve specific quality and productivity objectives. The results of this study are expected to be of great interest and practical significance for researchers, practitioners, and manufacturers in the field of high-speed machining.

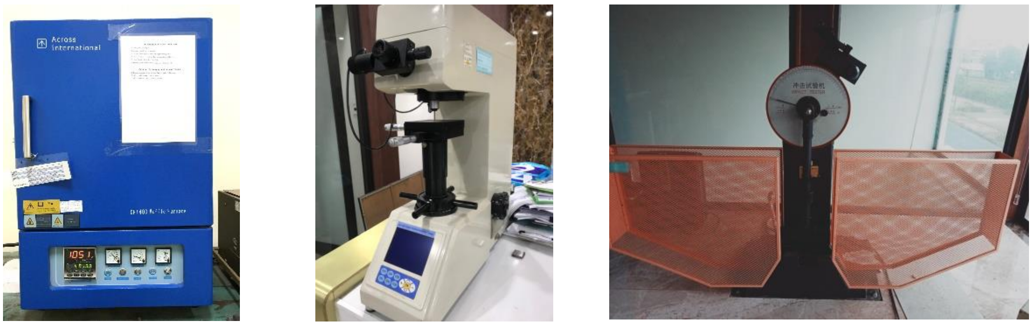
2. Experimental methods

The experimental method involved in the evaluation of the impact of high-speed machining and heating support on cutting tool wear and surface roughness when processing SKD61 steel is presented in this section. The chemical composition of the SKD61 steel is presented in Table 1.

Table 1. *The chemical composition of the SKD61 steel*

Elements	C	Si	Mn	Cr	P	S	Mo	V
%	0.32-0.39	0.8-1.0	<0.4	4.5-5.15	<0.03	<0.03	1.0-1.4	<1.0

Heat treatment furnace and material testing equipment used in the study are shown in Figure 1. The SKD61 steel is heat treated by tempering at 1050°C for 4 hours and then tempered at 580°C for 2 hours, resulting in a hardness of 50 - 52HRC and an impact toughness of 45J. Figure 2 displays the CNC machine, heating system, test specimens, and cutting tool used in the experiment.



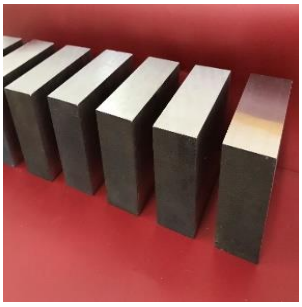
Heat Treatment Furnace *Hardness Tester* *Impact Tester*

Figure 1. *Heat treatment furnace and material testing equipment*

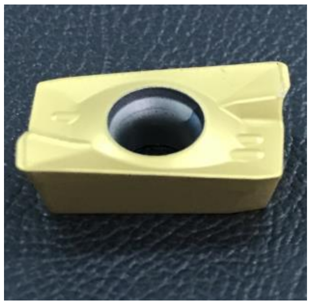
The experiment is conducted on a high-speed milling machine, MC500, from Taiwan, with the following parameters: spindle rotation speed of 100-30000 rpm, spindle power of 15 kW, and table movement speed from 100-30000 mm/min. The maximum idling speed is 48000 mm/min, and the displacement of the machine plate is X × Y × Z = 500 × 400 × 300 (mm × mm × mm). The heat-treated SKD61 billet with dimensions of 70 mm× 80 mm × 30 mm is used, and its surfaces are milled to eliminate defects and ensure smoothness. No lubricants are used during machining, and an electromagnetic induction heating system is used to heat the workpiece just before machining. The heating system consists of two main parts: the high-frequency heating circuit and the temperature controller, which maintains the workpiece under constant temperature control throughout the machining process. A carbide-coated alloy cutting piece with code APMT1604 PDER Grade 8230 from PRAMET is used. Coolant is not used during machining. A device for measuring the wear of the cutting piece and measuring the surface roughness of the workpiece after machining is shown in Figure 3.

CNC machine

Heating system



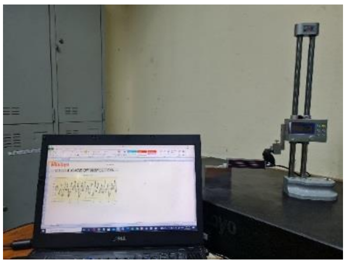
Test specimens



cutting tool

Figure 2. *CNC machine, heater, tested specimens, and cutting tool*

VHX-700



HD-30AX

Figure 3. *The device employed for measuring the wear of the cutting tool and the roughness*

The evaluation of the amount of wear of the cutting piece after each processing uses the method of measuring the wear height of the back of the cutting piece. The wearing height is measured on Keyence's high-precision 4K digital microscope, VHX-700 series. The surface roughness of the workpieces after machining is measured using the Mitutoyo HD-30AX roughness measuring device from Japan.

3. Results and discussions

3.1. Effect of heating on wearing height of cutting piece during high-speed milling of heat-treated SKD61 steel

The wear rate is a crucial factor that directly affects the productivity and product quality during high-speed machining. Tool wear occurs due to physical and chemical phenomena at the contact surfaces of the chip, workpiece, and tool. The change in the geometrical parameters of the cutting tool affects productivity and the quality of the machined surface. The use of cutting tools with high hardness coatings is necessary to reduce wear and increase tool life, especially for high hardness workpieces. However, carbide coated cutting pieces still experience wear, which increases as the speed increases. To address this issue, the proposed solution in the study is to support heating during the high-speed machining process to increase productivity, reduce the cost of replacing cutting tools, and ensure product quality.

To evaluate the effect of the heating process on cutting piece wear, experiments were conducted with the same cutting mode (V, t, and f) at room temperature, followed by additional experiments with different temperature conditions in ascending order: 200°C, 350°C, and 500°C.

At room temperature, a cutting speed of V = 300 m/min, cutting depth of 0.5 mm, and feed rate of 0.15 mm/tooth resulted in a large and fierce wear phenomenon leading to tool breakage and height. The measured cut-off wear was 1586.41 µm. Figure 4 displays the wearing height of cutting pieces during machining at different temperatures.

The proposed solution of high-speed machining with heating support was then tested to minimize cutting piece wear and reduce the cost of machining work, thereby increasing productivity. To investigate the effect of heating on cutting piece wear specifically, experiments were conducted with the same cutting mode at temperatures of 200°C, 350°C, and 500°C. The study found a significant reduction in cutting piece wear when heating was applied. Specifically, the wearing height decreased by 42.41% at 200°C, 72.75% at 350°C, and 86.45% at 500°C.

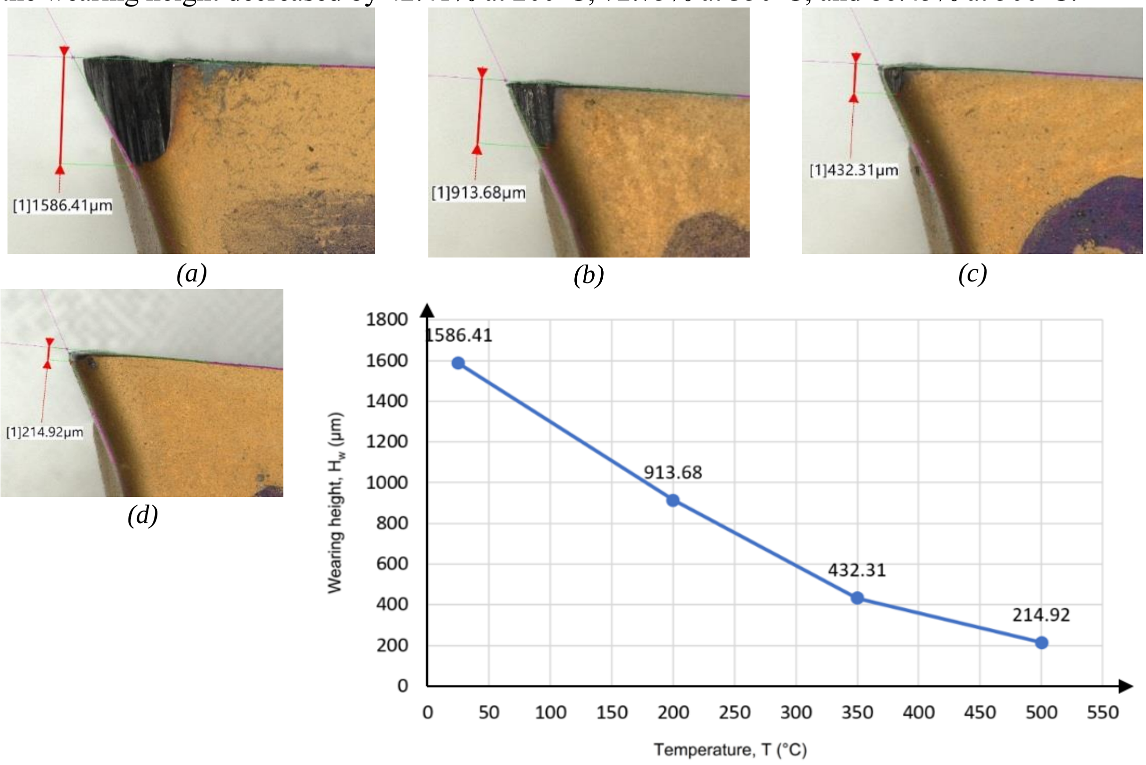


Figure 4. *The wearing height of cutting pieces during machining at different temperatures Room (a); 200°C (b); 350°C (c); 500°C (d) and the relationship (e)*

The study determined that heating has a significant influence on the amount of wearing height of the cutting piece. The heat-assisted milling process of heat-treated SKD61 steel improves the durability and life of the cutting tool. The appropriate temperature for heat treatment of SKD61 steel is 500°C, which improves the durability and life of the cutting tool without affecting the microstructure, mechanical, or chemical properties of the material during machining. Table 2 presents the machining parameters and wearing height results of cutting pieces when milling at different temperatures.

Table 2. *Machining parameters and wear assessment results of cutting pieces when milling at different temperatures*

No.	V (m/min)	f (mm/tooth)	t (mm)	T (°C)	H (µm)	ΔH (%)
1	300	0.15	0.5	25	1586.41	-
2	300	0.15	0.5	200	913.68	42.41
3	300	0.15	0.5	350	432.31	72.75
4	300	0.15	0.5	500	214.92	86.45

$$\Delta H_{W-T}(\%) = \frac{H_{w-R} - H_{w-T}}{H_{w-R}} \times 100 \qquad (1)$$

where: ΔH_{W-T} represent the percentage reduction of wear height. H_{w-R} and H_{w-T} refer to the wearing height (measured in micrometers) when milling at room temperature (R) and high temperature (T), respectively.

The research findings indicate that the introduction of heating support significantly reduces the wear experienced by the cutting piece. Specifically, at a heating temperature of 200°C, the wear decreased by 42.41%. Increasing the heating temperature to 350°C further reduced the wear by 72.75%. Notably, heating to 500°C resulted in the maximum reduction of wear at 86.45%.

The study highlights the substantial impact of heating on the wear of the cutting piece. Increasing the heating temperature during the cutting process effectively decreases the wear of the cut piece. The heat-assisted milling process applied to heat-treated SKD61 steel exhibits remarkable advantages in minimizing piece wear. The study determines that the optimal temperature for heat treatment of SKD61 steel is 500°C. By employing this heating temperature, the study achieves the objective of enhancing the durability and lifespan of the cutting tool while maintaining the material's microstructure, mechanical properties, and chemical characteristics intact during machining.

3.2. Effect of cutting speed on tool wear during heat treatment of SKD61 steel

Table 3. *Machining parameters and assessment results of cutting piece wear at different cutting speeds*

No.	V (m/min)	f (mm/tooth)	t (mm)	T (°C)	H (μm)
1	300	0.15	0.5	500	214.92
2	400	0.15	0.5	500	250.61
3	500	0.15	0.5	500	280.70
4	600	0.15	0.5	500	315.40
5	700	0.15	0.5	500	1023.66
6	800	0.15	0.5	500	1177.15

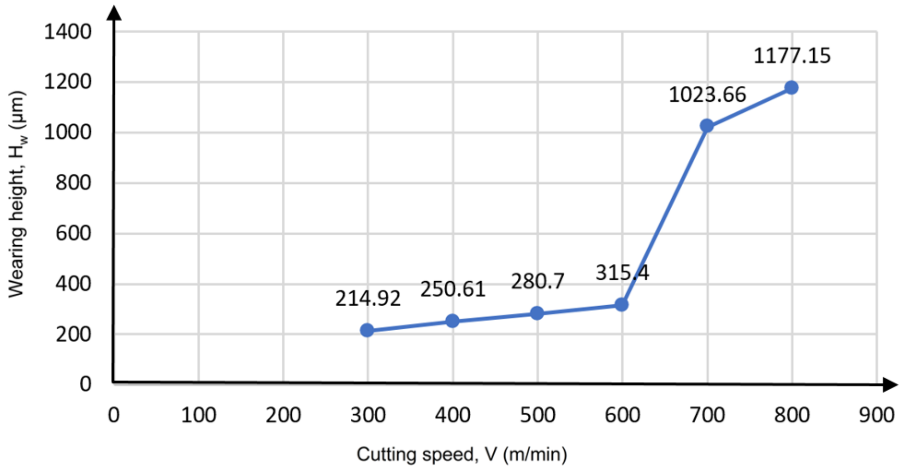
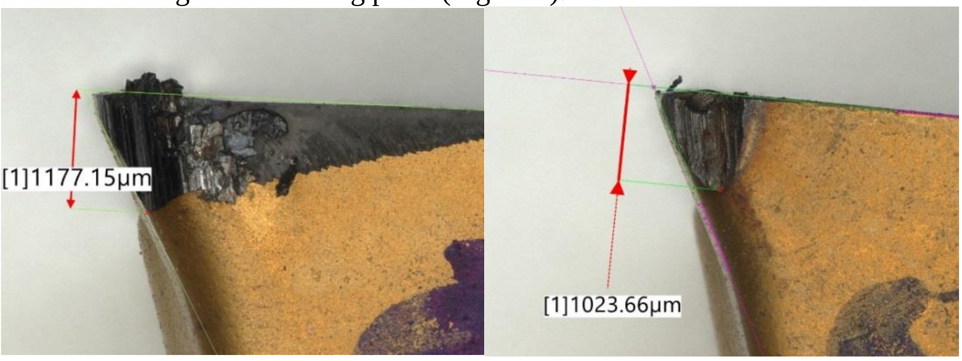


Figure 5. *The variation in piece wear at different cutting speeds*

Based on the aforementioned research findings, it is evident that high temperatures significantly reduce the amount of wear on the cutting tool. Specifically, heating at 500°C greatly improves tool wear while preserving the material's microstructure. The study further explores the impact of higher cutting speeds on wear by analyzing the effect of cutting speed on cutting piece wear during the milling of heat-treated SKD61 steel in a heating environment of 500°C. The results of the investigation are presented in Table 3 and Figure 5.

The experiments were conducted with a constant feed rate, a fixed depth of cut (f = 0.15 mm/tooth, t = 1.5 mm), and the workpiece heated at 500°C. The cutting speed gradually increased from 300 m/min to 800 m/min to assess the effect of high-speed cutting on tool wear. The results indicate that as the cutting speed increased from 300 m/min to 600 m/min, the wear amount exhibited a linear increase. However, at cutting speeds of 700 m/min and 800 m/min, the wear height on the backside dramatically escalated to 1023.66 µm and 1177.15 µm, respectively, leading to severe damage to the cutting piece (Figure 6).



(a) *(b)*

Figure 6. *Wear of cutting pieces in high-speed milling with heating at V = 700 m/min (a) and V = 800 m/min (b)*

Based on these findings, it is recommended to select a cutting speed below or equal to 600 m/min as the upper limit for high-speed milling with heating when working with SKD61 steel after heat treatment.

3.3. Effect of heating process on surface roughness in high-speed milling of heat-treated SKD61 steel

Surface roughness is a crucial parameter for evaluating the quality of machined components. It directly impacts the working quality of the part, including factors such as fatigue strength, lifespan, and noise during operation. The surface roughness of a detail is influenced by various parameters, including cutting technology, cutting geometry parameters, and machining environment. Experimental research was conducted to assess the impact of the heating process on surface roughness.

Table 4. *Machining parameters and the measured roughness results at different temperatures*

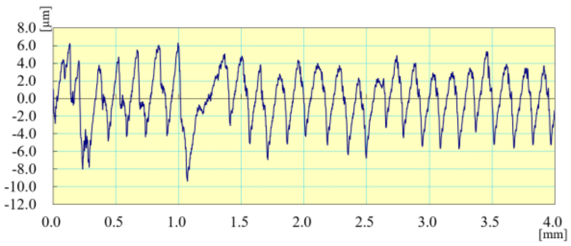
No.	V (m/min)	f mm/tooth)	t (mm)	T (°C)	Ra (µm)	ΔRa (%)
1	300	0.15	0.5	25	2.405	-
2	300	0.15	0.5	200	1.680	30.15
3	300	0.15	0.5	350	0.924	61.58
4	300	0.15	0.5	500	0.564	76.55

The machining process involved using the same cutting parameters: cutting speed of 300 m/min, cutting depth of 0.05 mm, and feed rate of 0.15 mm/tooth at room temperature. Subsequently, the process was adjusted with heating temperatures of 200°C, 350°C, and 500°C, respectively. To ensure accurate roughness measurements, each experiment was tested at three different locations, and the results were averaged. The measured roughness results are presented in Table 4 and Figure 7.

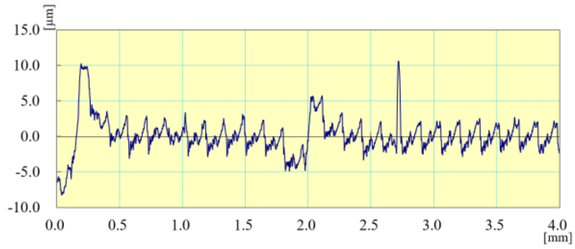
The percentage change in roughness was calculated using the Equation (2):

$$\Delta Ra_T(\%) = \frac{Ra_R - Ra_T}{Ra_R} \times 100 \quad (2)$$

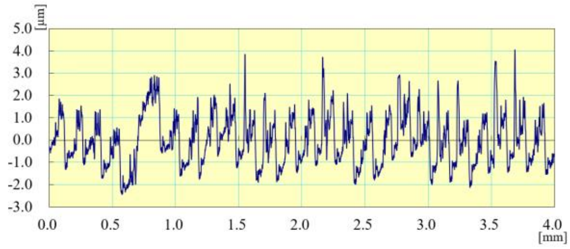
where ΔRa_T represents the percentage decrease in surface roughness, Ra_R denotes the surface roughness when machining at room temperature, and Ra_T represents the surface roughness at high temperature.



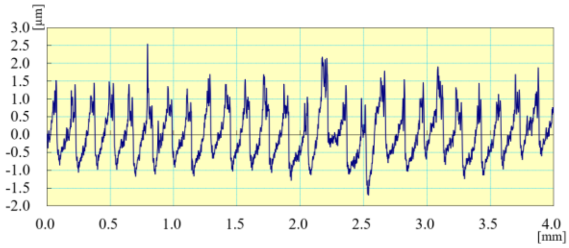
(a) (Ra = 2.405µm)



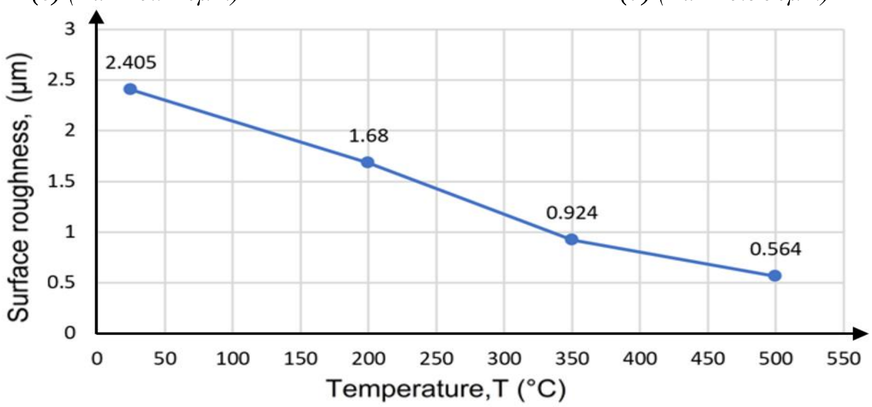
(b) (Ra = 1.680µm)



(c) (Ra = 0.924µm)



(d) (Ra = 0.564µm)



(e)

Figure 7. *The variation in surface roughness at different temperatures: Room (a); 200°C (b); 350°C (c); 500°C (d) and the relationship (e)*

The experimental results indicate that, under the same machining conditions at room temperature, the roughness measured a high value of 2.405 µm. However, when heated to 200°C, the roughness decreased to 1.68 µm, representing a reduction of approximately 30.15%. Furthermore, the roughness decreased significantly when heated to 350°C and 500°C, measuring 0.924 µm and 0.564 µm, respectively, corresponding to reductions of 61.58% and 76.55%.

The reason for these observations is that machining at room temperature leads to higher cutting forces and increased tool temperature compared to hot machining. Consequently, this results in higher surface roughness. However, when machining in a heated environment, the cutting forces are significantly reduced due to the softening of the workpiece caused by heat. This leads to a more stable and easier cutting process, resulting in improved surface quality.

3.4. Effect of cutting speed on surface roughness in high-speed milling of SKD61 steel after heat treatment

Table 5. *Machining parameters and surface roughness results at different cutting speeds*

No.	V (m/min)	f (mm/tooth)	t (mm)	T (°C)	Ra (µm)
1	300	0.15	0.5	500	0.564
2	400	0.15	0.5	500	0.41
3	500	0.15	0.5	500	0.31
4	600	0.15	0.5	500	0.205
5	700	0.15	0.5	500	0.387
6	800	0.15	0.5	500	0.442

To assess the impact of cutting speed on surface roughness during high-speed milling in a heated environment, experiments were conducted with a fixed cutting depth of 0.5 mm, a feed rate of 0.15 mm/tooth, and a constant heating temperature of 500°C. The cutting speed was incrementally increased from 300 m/min to 800 m/min. The surface roughness results obtained from the different experiments are presented in Table 5 and depicted in Figure 8.

The study reveals that as the cutting speed increases from 300 m/min to 600 m/min, the surface roughness exhibits a notable fluctuation, characterized by both increases and decreases. However, when the cutting speed further increases from 600 m/min to 800 m/min, the surface roughness tends to consistently increase. This trend can be attributed to a significant increase in cutting wear as the cutting speed reaches higher levels.

The results of the investigation provide insights into the relationship between cutting speed and surface roughness, highlighting the importance of optimizing the cutting parameters to achieve desired surface quality during high-speed milling of heat-treated SKD61 steel.

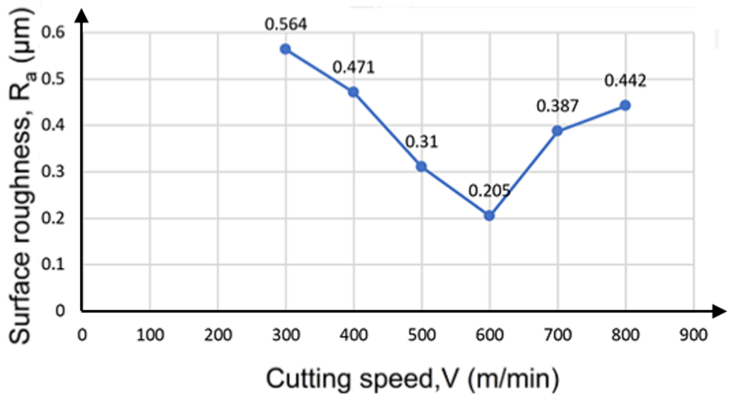


Figure 8. *The variation in surface roughness at different cutting speeds*

4. Conclusion

The experimental investigations on the effects of high temperature and cutting speed during high-speed milling with heated SKD61 alloy steel have yielded several significant conclusions. Firstly, the wear rate shows relatively uniform behavior within the cutting speed range of 300 m/min to 600 m/min but experiences a dramatic increase beyond 600 m/min. Secondly, increasing the milling temperature leads to a reduction in surface roughness. Moreover, the amount of wear exhibits a direct proportionality to surface roughness during high-speed machining with heated SKD61 steel, although the influence of cutting speed on surface roughness surpasses the effect of wear when the cutting speed exceeds 800 m/min. The milling mode with a cutting speed of 300 m/min at a temperature of 500°C demonstrates optimal wear performance. However, considering the objective of increasing material removal rate and reducing machining time, a cutting speed of 600 m/min and a tempering temperature of 500°C are recommended as ideal choices since they still enable achieving low surface roughness under these conditions. Lastly, the heating process proves to have a significant effect, particularly when employing low-cost carbide-coated cutting tools, as it can be easily implemented. These findings contribute to the understanding of temperature and cutting speed effects on tool wear and surface roughness in high-speed milling processes, offering valuable insights for optimizing machining parameters and enhancing the efficiency and quality of milling operations involving heat-treated SKD61 steel. Further research can explore additional factors and variables to gain a more comprehensive understanding of high-speed milling with heating support.

Acknowledgments

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