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RESEARCH ARTICLE

OPTIMIZATION OF CUTTING PARAMETERS FOR SURFACE ROUGHNESS AND MICROSCOPY ANALYSIS IN MACHINING HARDENED HIGH THERMAL CONDUCTIVITY 150 (HTCS-150) STEEL

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Abstract. The machining of advanced alloys, such as High Thermal Conductivity Steel 150 (HTCS-150), is essential for manufacturing press hardening dies used in the automotive and metal stamping industries. Achieving the required surface finish on HTCS-150 poses challenges, often leading to surface defects like feed marks, scratches, and micro pits. This study focuses on optimizing machining parameters of HTCS-150 dies, including cutting speed, feed rate, and depth of cut. Controlled milling experiments using a carbide ball-end mill were conducted to optimize surface roughness by developing a Response Surface Methodology (RSM) model with a Box-Behnken design. Microscopy analysis further identified surface defects and provided deeper insights into the effects of machining parameters. The results show that the model developed with quadratic best fit and error percentage less than 10%. Depth of cut had the most significant impact on surface roughness, followed by feed rate and cutting speed. The optimal combinations of 125 m/min cutting speed, 0.30 mm/tooth feed rate, and 0.1 mm axial depth of cut, allow minimum surface roughness up to 0.22 µm. Smaller depths of cut produced finer finishes by minimising peak-valley gaps, while larger depths of cut increased roughness and introduced visible feed marks. Lower feed rates resulted in smoother profiles due to overlapping tool paths, whereas higher feed rates caused surface waviness and higher roughness. Lower cutting speeds created rough surfaces due to weak shearing forces, and higher speeds led to non-uniformity and increased roughness due to material deformation. These results provide a foundation for optimizing machining parameters to enhance surface quality, reduce defects, and improve process efficiency. The developed optimization model offers manufacturers a valuable tool for producing longer-lasting dies and higher-quality products.

Keywords: HTCS-150, optimization, surface integrity, surface roughness

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1. INTRODUCTION

Milling is the operation of removing material with a rotary cutting tool to form the desired shape. During a milling operation, the cutting tool penetrates the workpiece, causing shearing, plastic deformation, chip formation and forming a new machined surface. Milling operations are commonly used in die machining to produce intricately curved components with a fine surface finish with accurate dimensions. A fine surface finish of stamping dies improves accuracy, surface, aesthetics, fatigue strength, and heat-treated ability of stamped component [1-2]. In milling operation, ball-end mills are commonly used in die machining because they can perform flat or free-form sculptured milling. Ball-end milling reacts differently than flat-end milling because the contact condition is constantly changing. The surface could change from shearing to plowing depending on the contact mechanism, resulting in phenomena such as material side flow, ploughing, or thin chips, which impacted the quality, precision, and accuracy of the machined surface [3-4].

Technological advancements have resulted in milling operations making extensive use of the material removal process for stamping dies. For stamping dies, common materials include tool steel up to 62 HRC (AISI D2/SKD 11), cast irons (FC300), tempered steels (AISI D3), and high tempered steels (AISI H13) [5]. Specific dies are typically milled from rough to finish conditions and then manually polished to reduce the effect of feed marks [6]. Given that the die is not in the best possible condition after milling, manual polishing is required and it would take more time, increasing operational costs and causing muscle fatigue in the operators.

As an advancement over the traditional cold die steel, High Thermal Conductivity Steel 150 (HTCS-150) has become a focal point in research on advanced alloys, particularly in the context of the press hardening process. This grade of steel is mainly used for stamping dies to produce high strength steel in the press hardening process. HTCS-150 is normally equipped with an embedded cooling channel to provide quenching when the sheet metal is stamped inside the die enclosure during the hot stamping process. The machining process for HTCS-150 can be very challenging since HTCS-150 is expected to have different surface characteristics than conventional dies as this type of steel has high thermal conductivity of 66 W/m.C. As a result, strategies for machining HTCS-150 with controlled machining parameters are required to assess their impact on surface quality optimization [7-8].

Machining stamping dies with ball-end mills presents challenges due to complex tool-workpiece interactions, resulting in varied and inconsistent reports on surface characteristics. Souza et al. [9] investigated the free-form machining of P20 steel, observing that the central nose of the ball-end mill provided clean cutting, while other regions experienced material plowing, leading to poorer surface roughness. Scandiffio et al. [10] explored tool path direction in free-form milling of 60 HRC AISI D2, highlighting the importance of vibration control for enhancing surface roughness and tool life, and recommending variable lead angles to ensure consistent tool-workpiece contact. In 2017, Scandiffio et al. [11] further examined tool-surface contact during high-speed milling of D6 steel, discovering that effective ploughing with the tool's effective diameter resulted in better surface roughness and tool life. Magalhaes et al. [12] focused on tool path movement in ball-end milling of AISI H13, demonstrating that optimized axial depth of cut and feed rate could improve surface finish by up to 27% and machining time by up to 25%. Mali et al. [13] emphasized that the complexity of the tool path movement with the combination of appropriate cutting parameters are crucial for improving tool life, enhancing surface finish and reducing machining duration in ball-end milling. Recently, Grešová et al. [14] found that 5-axis milling with linear and spiral strategies significantly reduced surface deviations and improved surface quality when machining with ball-end mill. The study also highlighted discrepancies between CAM predictions and actual machined surfaces, offering insights for optimizing milling strategies for both 3-axis and 5-axis machining.

Most of the studies referenced have examined machining different die materials using ball-end mills. Given that HTCS-150 is a novel die steel, there is limited information on its surface characteristics post-machining. This study fills this gap by focusing on the surface properties of HTCS-150 during finish milling with ball-end mills. The objectives are to develop a predictive model for optimizing cutting parameters in HTCS-150 machining, to determine the optimal cutting parameters and to investigate the effects of depth of cut, feed rate, and cutting speed on surface roughness, with an emphasis on identifying the most influential parameter. Crucially, microscopy analysis was employed as a major factor to closely examine changes in surface topography and provide in-depth insights into the effects of machining on HTCS-150.

2. MATERIALS AND METHODS

High Thermal Conductivity Steel 150 (HTCS-150) was prepared with sample dimensions that were 50 mm in width, 50 mm in length, and 10 mm in depth. The properties of HTCS-150 are summarized in Table 1, which includes the averages and standard deviations for surface roughness and hardness. Prior to machining, five measurements of surface roughness and hardness were recorded using a Mitutoyo surface roughness tester (Figure 1) and a Rockwell hardness tester. The HTCS-150 surface was then cleaned and smoothed to ensure a flat surface.

Table 1: Properties of HTCS-150 steel and cutting tool used in this study (Data from material supplier, reference [3] and [8])

Properties	Condition
Compositions (EDAX identification at specific location)	16 wt.% Zn, 13 wt.% Cu, 2 wt.% C, 2 wt.% Mo
Average Surface Roughness (measured as received)	0.45 µm (0.11 µm standard deviation)
Hardness (measured as received)	52 HRC (1.14 HRC standard deviation)
Main alloying element (wt.%)	C (0.420), Mo (4.185). Cr (0.064), Cu (0.03), W (3.09)
Thermal Conductivity	Up to 66 W/m.C
TiAlN Coated Ball End Mill, SFRT20	S-shape cutting edge ball end mill
Machining trial parameters	Cutting Speed :120-130 m/min Feed Rate: 0.3-0.5 mm/tooth Axial Depths of Cut: 0.1-0.3 mm

The SFRT20 TiAlN coated carbide ball-end mill shown in Figure 1(a) was used as the cutting tool. The milling process was performed with an SRFH20S02L80 tool holder installed in a DMU 60 CNC machine, as illustrated in Figures 1(c) and (d). Machining operations were executed in a dry environment, covering a total cutting length of 50,000 mm with a consistent radial depth of cut of 0.01 mm.

The optimization of these parameters involved 17 samples using Response Surface Methodology (RSM) and Box-Behnken experimental design, as described in Table 2. Following the machining trials, the evaluation of surface roughness in the machined area was conducted with a surface roughness tester, as represented in Figure 1(b). Measurements were taken at five locations along the feed rate direction. Additionally, a scanning electron microscope (SEM) was used for a comprehensive analysis of the surface microscopy, providing detailed observations of the surface characteristics.

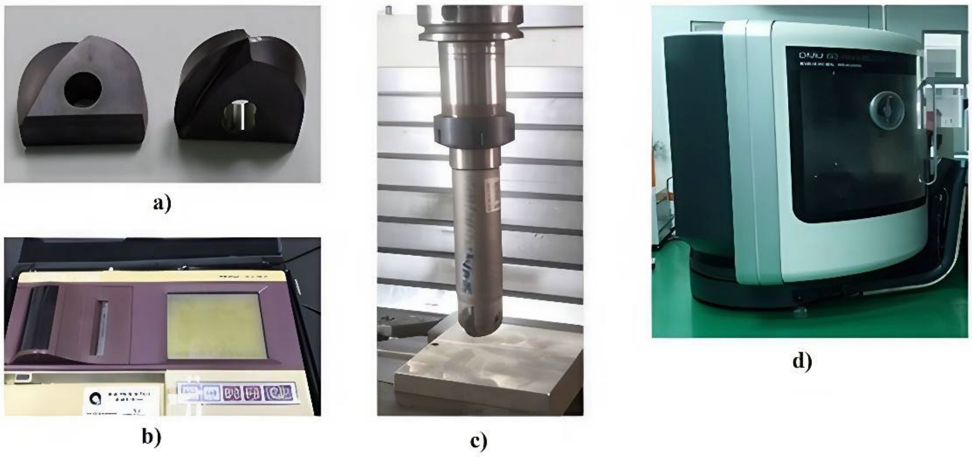


Figure 1: (a) Cutting tool, (b) Mitutoyo surface roughness tester used for measuring surface roughness, (c) Configuration setting prior machining trial and (d) 5-axis CNC machine (DMU 60 Monoblock 5-axis)

Table 2: Experimental layout for the machining trials.

Std Run	Machining Parameters			Average Surface Roughness (µm)
	Cutting Speed (m/min)	Feed Rate (mm/ tooth)	Depth of cut (mm)	
1	120	0.3	0.3	0.450
2	130	0.3	0.3	0.344
3	120	0.5	0.3	0.412
4	130	0.5	0.3	0.720
5	120	0.4	0.1	0.300
6	130	0.4	0.1	0.390
7	120	0.4	0.5	0.506
8	130	0.4	0.5	0.630
9	125	0.3	0.1	0.220
10	125	0.5	0.1	0.430
11	125	0.3	0.5	0.470
12	125	0.5	0.5	0.560
13	125	0.4	0.3	0.256
14	125	0.4	0.3	0.360
15	125	0.4	0.3	0.280
16	125	0.4	0.3	0.351
17	125	0.4	0.3	0.276

3. RESULTS AND DISCUSSION

Surface roughness for 17 runs trial was recorded in Table 2. The recorded surface roughness values ranged from 0.2 to 0.7 µm, with Run 9 achieving the lowest roughness of 0.22 µm and Run 4 the highest at 0.72 µm. These results fall within the semi-finishing range, offering a viable alternative to grinding for mold finishing. The ANOVA analysis of surface roughness is detailed in Table 3, revealing a highly significant trend with an F-value of 26.93, a P-value below 0.0001 and an accuracy exceeding 99.99%. The formulation of surface roughness in relation to machining parameters is described by Equation (1), based on the data.

Surface Roughness (µm) =+76.79312 - 1.13940 (Cutting Speed) -30.69350 (Feed rate) -0.161750 (Axial Depth of Cut) + 0.207000 (Cutting Speed. Feed rate) + 0.00426 $(\text{Cutting Speed})^2$ + 7.02000 $(\text{Feed rate})^2$ +1.13000 $(\text{Axial Depth of Cut})^2$ (1)

Table 3: ANOVA analysis table for surface roughness response

Source	Sum of Squares	Df	Mean Square	F-Value	p-Value	
Model	0.2857	7	0.0408	26.93	< 0.0001	Significant
A (cutting speed)	0.0216	1	0.0216	14.27	0.0044	
B (feed rate)	0.0509	1	0.0509	33.57	0.0003	
C (depth of cut)	0.0853	1	0.0853	56.28	< 0.0001	
AB	0.0428	1	0.0428	28.27	0.0005	
A^2	0.0479	1	0.0479	31.63	0.0003	
B^2	0.0207	1	0.0207	13.69	0.0049	
C^2	0.0086	1	0.0086	5.68	0.0411	
Residual	0.0136	9	0.0015			
Lack of Fit	0.0046	5	0.0009	0.4114	0.8218	not significant
Pure Error	0.0090	4	0.0023			
Cor Total	0.2993	16				

Figure 2 compares experimental and predicted values from Equation (1), with an average difference of 5.25%, indicating high model accuracy. This analysis shows that the model reliably predicts surface roughness in machining HTCS-150 steel, with errors under 10%. It is suitable for industry use with similar workpieces and cutting parameters. It should be highlighted that factors such as increased cutting speeds, higher feed rates, or deeper cuts may introduce additional thermal and mechanical effects that influence surface finish in ways not fully captured by the equation. Preliminary tests with extended parameters could provide insight into whether the model's predictions remain within acceptable error margins (under 10%), as shown within the selected range. It should be noted, however, that factors such as increased cutting speeds, higher feed rates, or deeper cuts may introduce additional thermal and mechanical effects that influence surface finish in ways not fully captured by the equation. Preliminary tests with extended parameters could provide insight into whether the model's predictions remain within acceptable error margins (under 10%) beyond the selected range.

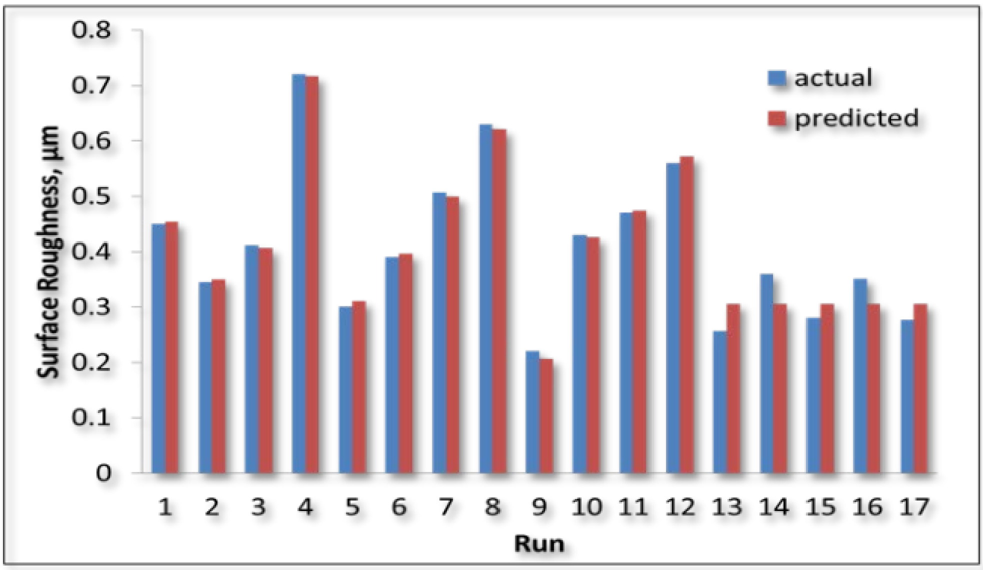


Figure 2: Comparison assessment between experimental and predicted value according to the Equation (1)

Observation of some quality of machined surfaces presented in Figures 3 and 4. Figure 3 shows set of machined surfaces that can be considered in fine surface finish (0.220 µm - 0.450 µm). Figure 3(a) depicts an observation of the surface with surface roughness of 0.220 µm in standard run 9. The surface profiles presented smooth and bright appearances, indicating an effective combination of cutting parameters to provide such a polished surface finish. The appearance of the machined surface for standard run 17 (Figure 3(b)) showed uniform flatness with a regular distribution of scallops throughout the surface. The observation of a surface profile with a higher surface roughness of 0.450 µm (Figure 3(c)) revealed evidence of a surface defects, which was most likely caused by the workpiece's casting process. However, the overall surface remains clean.

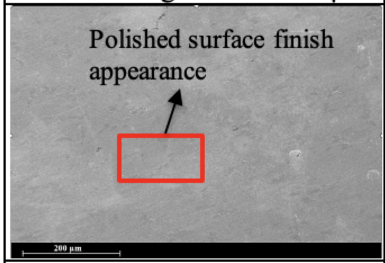
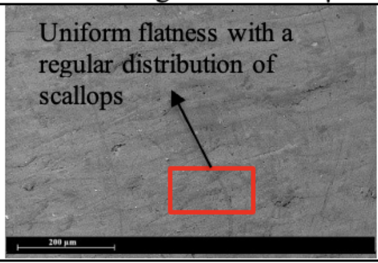
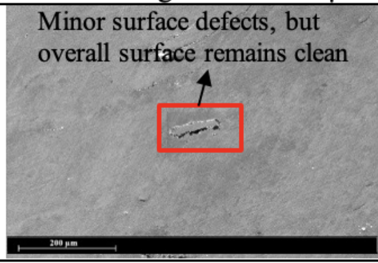
Std run: 9 (125 m/min, 0.3 mm/tooth, 0.1 mm) Surface roughness: 0.220 µm	Std run: 17 (125 m/min, 0.4 mm/tooth, 0.3 mm) Surface roughness: 0.276 µm	Std run: 1 (120 m/min, 0.3 mm/tooth, 0.3 mm) Surface roughness: 0.450 µm
		
(a)	**(b)**	**(c)**

Figure 3: Machined surfaces with fine surface finish (0.220 µm-0.450 µm)

Figure 4 shows set of machined surfaces that can be considered in rough surface finish (0.470 µm-0.720 µm). Figure 4(a) shows an observation of the surface with a higher surface roughness of 0.470 µm in standard run 11. The surface profile shows uneven ploughing from the ball-end mill. The surface profile deteriorates further at standard run 17 (Figure 4(b)), with defects manifested as uneven shearing action and irregularly smeared material side flow throughout the surface. As shown in Figure 4(c), there are many macroscopic cracks and anisotropy of feed marks distributed along the machine surface for standard run 1. This is expected due to the rotational cutting tool's inherent shearing action and an insufficient overlap rate [15-16].

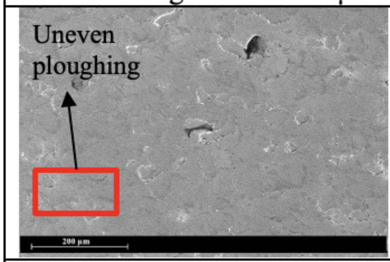
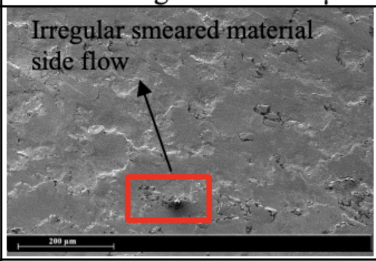
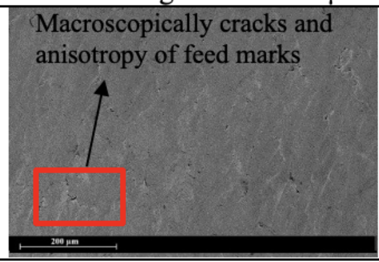
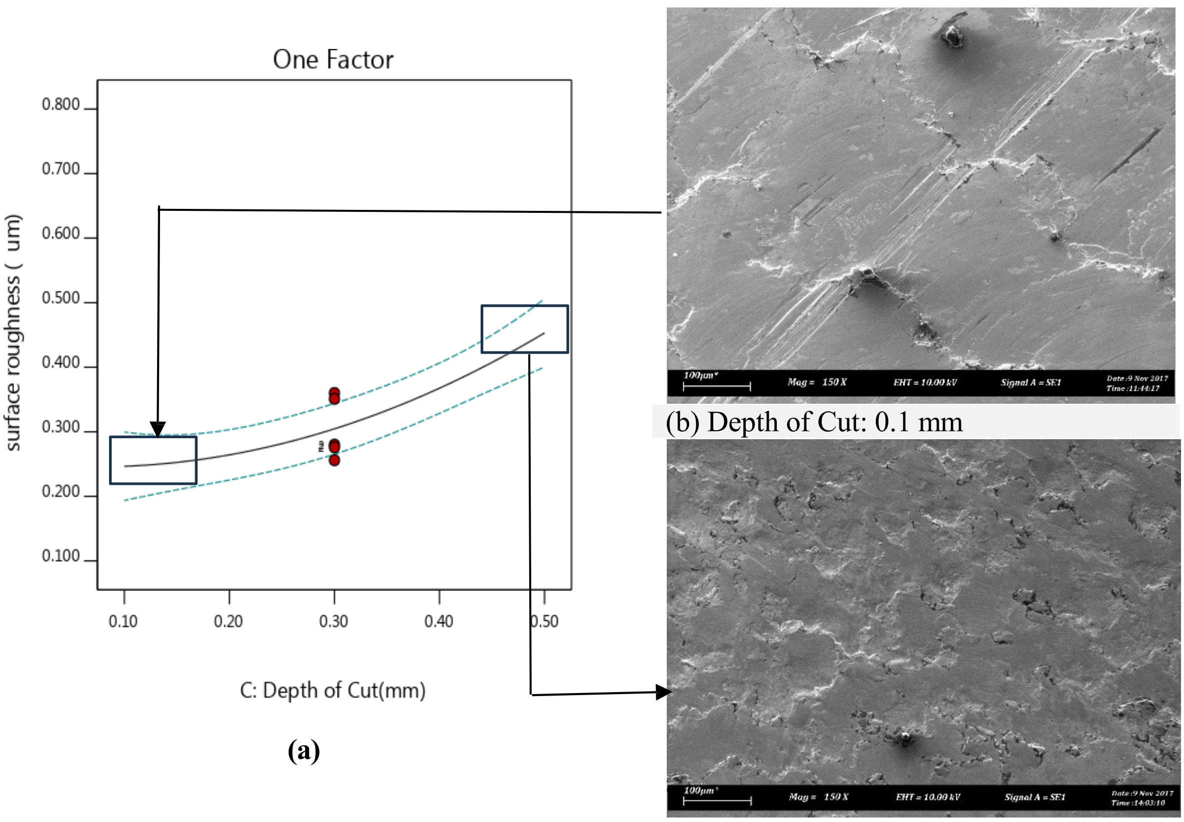
Std run: 11 (125 m/min, 0.3 mm/tooth, 0.5 mm) Surface roughness: 0.470 µm	Std run: 8 (130 m/min, 0.4 mm/tooth, 0.5 mm) Surface roughness: 0.630 µm	Std run: 4 (130 m/min, 0.5 mm/tooth, 0.3 mm) Surface roughness: 0.720 µm
		
(a)	**(b)**	**(c)**

Figure 4: Machined surfaces with rough surface finish (0.470 µm-0.720 µm)

According to Hadzley et al. [3], the high thermal conductivity of HTCS-150, one of the contributing factors being the presence of copper elements, significantly enhances heat dissipation in the cutting zone. This high thermal conductivity allows heat to be absorbed within HTCS-150, potentially reducing wear. Consequently, this enhances cutting tool performance, allowing the tool to last longer and maintain its nose radius shape. When machining is performed with incorrect parameter combinations, the inherent slicing may compromise the surface, causing increased deformed layer overlap. This can result in an uneven workpiece with a less desirable surface finish. Additionally, improper machining can cause the workpiece material to overheat and melt, leading to various issues as outlined above. Under certain parameter combinations, the surface finish can improve further [7,16].

Figure 5 illustrates the variation in surface roughness with increasing depth of cut. The graph shows that increasing the depth of cut results in linear increase of surface roughness (Figure 5(a)). At a depth of 0.1 mm, the surface roughness is approximately 0.25 µm. As the depth is increased to 0.5 mm, the surface roughness increases to nearly 0.4 µm. Observations of the surface profile indicate that maintaining a lower depth of cut results in a smoother surface, as shown in Figure 5(b). The study by Xu et al. [17] highlights the critical role of depth of cut in determining surface roughness during automatic machining. This increase in surface roughness with greater depths of cut can be attributed to several factors. Firstly, smaller depths of cut result in a finer surface finish due to the reduced cross-sectional area being machined. This minimizes the peak and valley gaps at the scallop formations, leading to a smoother surface profile. Conversely, larger depths of cut introduce more significant irregularities and waviness, as depicted in Figure 5(c). The larger cross-sectional area sectionized by the tool nose radius creates more pronounced peaks and valleys, resulting in visible feed marks along the cutting path and increased surface roughness. Additionally, the study suggests that maintaining a lower depth of cut not only improves surface finish but also reduces the thermal load on the cutting tool. At higher depths of cut, the increased material removal rate generates more heat, which can accelerate tool wear and affect the stability of the machining process. This is particularly relevant for materials like HTCS-150, where efficient heat dissipation is crucial to maintaining tool performance and workpiece integrity.



(a)

(b) Depth of Cut: 0.1 mm

(c) Depth of Cut: 0.5 mm

Figure 5: (a) The impact of cutting depth on surface roughness in HTCS-150 machining, (b) Surface profile at the 0.1 mm depth of cut, and (c) Surface profile at the 0.5 mm depth of cut

Additionally, enhanced surface finish can be realized by operating at the minimum feed rate during machining. As presented in Figure 6(a), up to a 50% reduction (from 0.45 µm to 0.3 µm surface roughness) can be achieved when the feed rate is reduced from 0.5 mm/tooth to a minimum of 0.3 mm/tooth. Minimum surface roughness is achieved at lower feed rates because less material is removed by the cutting tool, resulting in overlapping tool-paths. This minimizes the peak and valley gaps between scallops, flattening the surface texture. This is demonstrated in Figure 6(b), where a smooth surface profile is presented by machining at a lower feed rate of 0.3 mm/tooth. In contrast, machining at a feed rate of 0.5 mm/tooth exhibits considerable tool path overlap and surface waviness, as shown in Figure 6(c). At elevated feed rates, excessive tool path overlap imposes friction and severe material deformation, accelerating the cutting heat. Accumulation of heat may aid in tool wear and reduce the flow stress of HTCS-150. Due to the material of the workpiece being softened, the shearing action from the round edge of the cutting tool can cause instability in the workpiece deformation. Further machining will promote edge rounding of the cutting tool, facilitating waviness of the machined component.

Sharma et al. [18] also emphasizes the significance of optimizing machining parameters to achieve the desired surface roughness. Their study on the end milling of hybrid composites using response surface methodology (RSM) found that feed rate is a critical parameter influencing surface roughness. By optimizing the feed rate, they were able to achieve a significant reduction in surface roughness, similar to the findings presented here. This reinforces the importance of carefully selecting and controlling feed rates to enhance surface finish and overall machining quality.

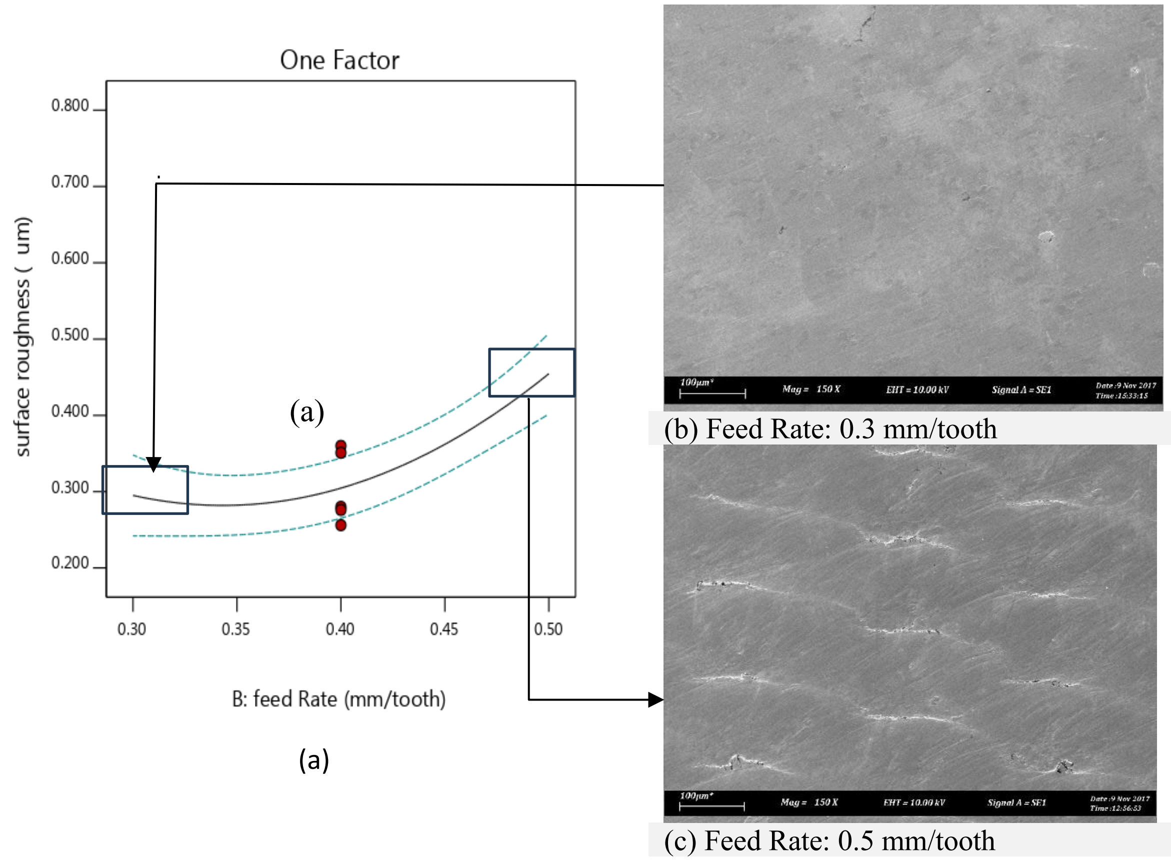
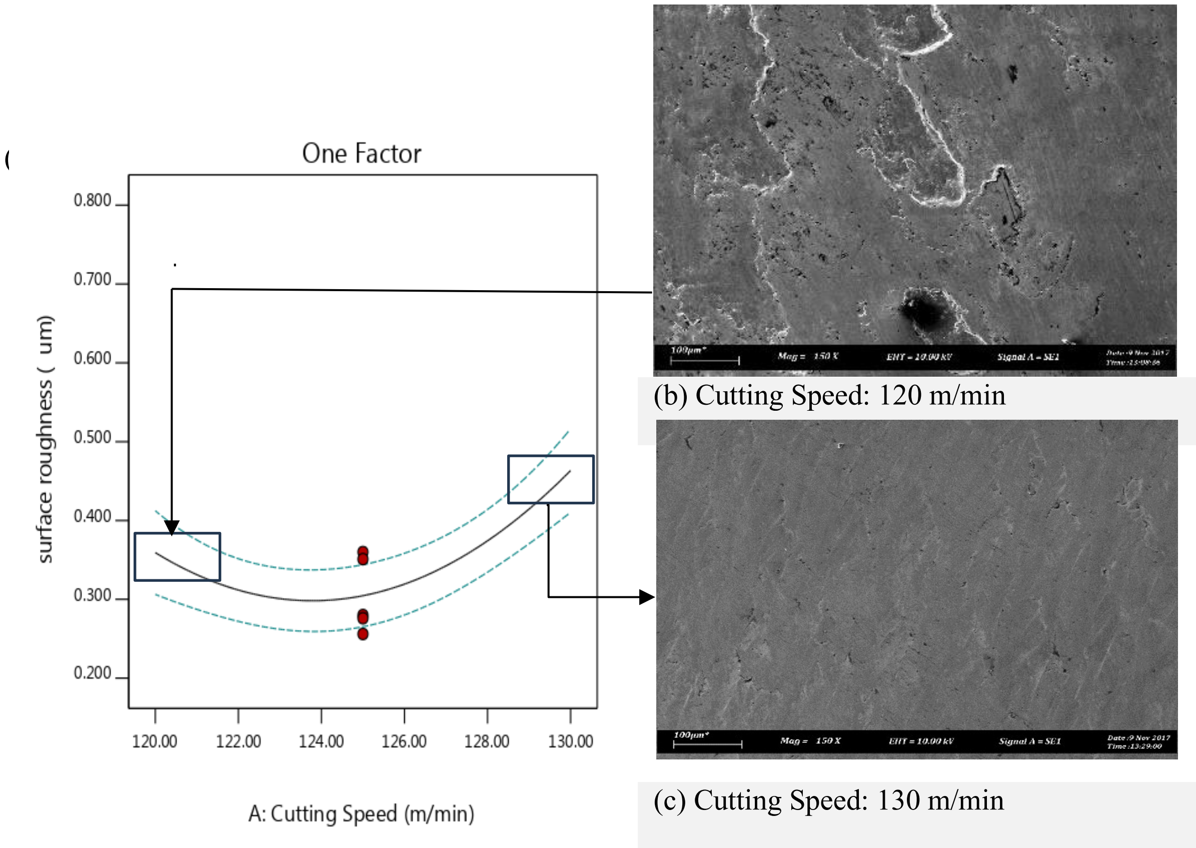


Figure 6: (a) Relation between feed rate and surface roughness in machining HTCS-150 steel, (b) Surface profile at the 0.3 mm/tooth feed rate and (c) Surface profile at the 0.5 mm/tooth feed rate

Figure 7(a) illustrates the variation in surface roughness due to changes in cutting speed when machining HTCS-150 steel. The graph demonstrates that initially, at a cutting speed slightly higher than 120 m/min, the surface roughness measures approximately 0.4 µm. As the cutting speed increases to 125 m/min, the roughness improves slightly, reducing to around 0.3 µm. However, when the cutting speed is further raised to 130 m/min, the surface roughness increases again, reaching about 0.5 µm. Figure 7(b) illustrates the surface profiles achieved at a cutting speed of 120 m/min. When the workpiece is being machined at a low cutting speed, the rotary cutting tool's weak shearing force is unable to cleanly slice the object, leading to chip ploughing and the possibility of a rough surface finish. Increasing the cutting speed to 125 m/min demonstrates a stabilized surface finish where the surface profile appears fine and smooth. This suggests that a medium cutting speed is optimal for machining HTCS-150 to achieve fine surface quality. Implementing a higher cutting speed of 130 m/min affects the intensity of temperature generation, facilitating the material to soften and allowing the feed marks to yield to the side of the feed marks. A small piece of softened workpiece could easily attach to the tool's flute vicinity, resulting in a built-up edge [19]. When tool-workpiece engagement occurs, the built-up edge causes changes in tool nose radius and disrupts the contact condition. This is demonstrated in Figure 7(c), where the surface finish shows signs of non-uniformity due to increasing material deformation and friction, which causes the surface finish to deteriorate.

According to Abellán-Nebot et al. [20], factors such as cutting speed, feed rate, and tool geometry significantly influence surface roughness in machining processes. The study emphasizes that optimizing these parameters not only improves surface quality but also enhances machining sustainability by reducing energy consumption and material waste. In the context of HTCS-150 machining, maintaining an optimal cutting speed around 125 m/min aligns with these findings, as it minimizes surface roughness and promotes sustainable machining practices.



(b) Cutting Speed: 120 m/min

(c) Cutting Speed: 130 m/min

(a)

Figure 7: (a) Relation between cutting speed and surface roughness in machining HTCS-150 steel, (b) Surface profile at the 120 m/min cutting speed, and (c) Surface profile at the 130 m/min cutting speed

4. CONCLUSIONS

This study explores into optimizing cutting parameters and assessing microscopy of machined surface quality of High Thermal Conductivity Steel 150 (HTCS-150). The significant outcomes are:

- The developed model successfully guides the optimization process and surface control in HTCS-150 machining. It predicts surface roughness with an impressive average error of less than 10%.
- The minimum surface roughness of 0.22 µm were achieved using a cutting speed of 125.0 m/min, a feed rate of 0.3 mm/tooth, and an axial depth of cut of 0.1 mm.
- The depth of cut has the biggest impact on surface roughness, following with the feed rate and subsequently cutting speed.
- Smaller depths of cut produce finer surface finishes due to reduced peak-valley gaps. Larger depths of cut increase surface roughness, resulting in visible feed marks and surface irregularities.
- Lower feed rates lead to a significant polished surface finish, creating smoother surface profiles due to overlapping tool paths. Higher feed rates cause tool path overlap and surface waviness, leading to higher surface roughness.
- Lower cutting speeds lead to rough surfaces due to weak shearing forces, while higher speeds result in non-uniformity and increased surface roughness due to material deformation and friction.

The insights gained from this study could be applied to develop specialized machining guidelines for HTCS-150, potentially leading to the commercialization of optimized tools and machining strategies. Collaboration with tool manufacturers and industries using HTCS-150 in press hardening could accelerate the adoption of these findings in industrial applications, offering a competitive edge in manufacturing high-quality dies with minimal post-processing.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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