QUADRATIC RESPONSE SURFACE MODELING OF SURFACE ROUGHNESS IN CBN GRINDING OF HARDOX 500

VO THANH TUAN[1,a], LE HOANG ANH[2],
HOANG XUAN TU[3], NGUYEN MANH CUONG[3]
[1]*Long An College, Long An Ward, Tay Ninh Province*
[2]*Vinh Long University of Technology Education, Long Chau Ward, Vinh Long Province*
[3]*University of Technology – Thai Nguyen University, Tich Luong Ward, Thai Nguyen*
[a]*Corresponding author: tuan.ckct@gmail.com*

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ABSTRACT

This study investigates the influence of grinding parameters on surface roughness (Ra) in grinding HARDOX 500 steel with a CBN wheel, using a quadratic Response Surface Methodology (RSM). A full quadratic model, including linear, interaction, and squared terms, was initially developed and subsequently simplified through stepwise selection based on the Akaike Information Criterion (AIC). The full model achieved $R^2 = 0.987$ and adjusted $R^2 = 0.964$, while the simplified model achieved $R^2 = 0.985$ and adjusted $R^2 = 0.974$, indicating strong predictive capability with reduced complexity. Analysis of variance (ANOVA) and partial effect size (η^2) revealed that the squared term of depth of cut (t^2) exerted the dominant and statistically significant influence on Ra ($p < 0.001$). In contrast, spindle speed, feed rate, and their higher-order terms played only minor or negligible roles. Diagnostic plots confirmed model adequacy, with residuals evenly distributed and predicted values closely matching experimental data. The findings highlight that precise control of depth of cut is the key factor in achieving the desired surface quality when grinding HARDOX 500 steel, providing practical guidance for optimizing process parameters in industrial applications.

Keywords: *CBN grinding; HARDOX 500 steel; surface roughness (Ra); RSM; depth of cut; stepwise regression; ANOVA*

1. INTRODUCTION

Grinding with cubic boron nitride (CBN) abrasives has become a cornerstone of precision machining for hardened steels and superalloys, largely due to its superior thermal stability, hardness, and wear resistance compared to conventional abrasives. Recent research has focused on both the design of CBN grinding wheels and the mechanics of the grinding process, aiming to improve efficiency, tool life, and surface quality.

For instance, Wang et al. [1] developed structured CBN grinding wheels using laser cladding remelting to enhance wheel trajectory and performance. Meanwhile, Breuer et al. [2] investigated the structural stability of polycrystalline CBN under near-industrial conditions, highlighting its durability in harsh environments. Wear modeling has also attracted considerable attention. Jamshidi et al.

[3] proposed a predictive framework for wear in electroplated CBN wheels, while Bredthauer et al. [5] examined grinding wheel surface morphology and the effects of thermo-mechanical loading. Together, these studies have built a solid foundation for understanding CBN grinding behavior, but they also point to the need for more systematic models to generalize grinding outcomes.

In terms of applications for advanced materials, research has largely focused on turbine disk slot machining and superalloys. Benkai et al. [4] evaluated the grindability of powder metallurgy FGH96 using electroplated CBN wheels, while Deja [6] applied Preston's equation to predict material removal in CBN finishing processes. Similarly, Zhao et al. [7] investigated micro-fracture phenomena in aggregated CBN grains during grinding of Ti–6Al–4V, and Guo et al. [8] used pulsed laser dressing technology to maintain grinding wheel accuracy. These studies demonstrate the versatility of CBN tools in machining aerospace alloys and hardened steels. However, despite the extensive focus on tool design and material removal mechanisms, relatively few studies have systematically modeled surface roughness when grinding ultra-hard steels such as HARDOX 500.

Another line of research has explored bonding methods and grinding wheel structures. Xiao et al. [13] and Ding et al. [14] reported on porous CBN wheels and their performance in grinding Ti–6Al–4V, while Zhang et al. [11] developed ceramic-bonded CBN wheels with improved efficiency. Sato et al. [9] compared the ecological performance of CBN and Al_2O_3 grinding wheels, and Qian et al. [10] investigated grain wear in environmentally friendly superalloy grinding processes. Liu et al. [12] designed composite abrasives for rail grinding, enhancing wheel durability. Overall, these studies highlight continuous innovation in CBN wheel design and performance. Still, most work remains focused on the tool itself, with limited application of statistical models to describe grinding process outputs.

Despite these advances, a clear research gap remains. Most studies emphasize tool design, wear, and performance evaluation, while systematic regression modeling of grinding outputs, particularly surface roughness, is still limited. HARDOX 500, a wear-resistant steel widely used in mining and heavy machinery, presents unique challenges due to its high hardness and impact toughness. For industrial applications, it is essential to develop quantitative predictive models that link grinding parameters to surface roughness, enabling optimization of process conditions.

To address this gap, the present study applies a quadratic Response Surface Methodology (RSM) to model and predict surface roughness (Ra) in CBN grinding of HARDOX 500 steel. Both a full quadratic model and a stepwise-selected model are developed and statistically validated using ANOVA, effect size analysis, and diagnostic plots. By identifying the dominant influence of depth of cut and evaluating the adequacy of reduced predictive models, this work contributes both methodological rigor and practical guidance for achieving optimal surface quality in the grinding of ultra-hard steels.

2. EXPERIMENTAL SETUP

An experimental study was carried out to investigate the effects of key grinding parameters on surface roughness (Ra) during

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the grinding of HARDOX 500 steel using a CBN grinding wheel. The experiments were conducted on a CNC milling machine (Model M-V50C, Mitsubishi, Japan). The workpiece material was HARDOX 500 steel, a wear-resistant alloy known for its high hardness and widely used in mining and heavy-duty equipment applications. After each grinding operation, surface roughness was measured using a Mitutoyo SV-3100 profilometer. The overall experimental setup, including the CNC machine, grinding wheel, and workpiece fixture, is illustrated in Figure 1.

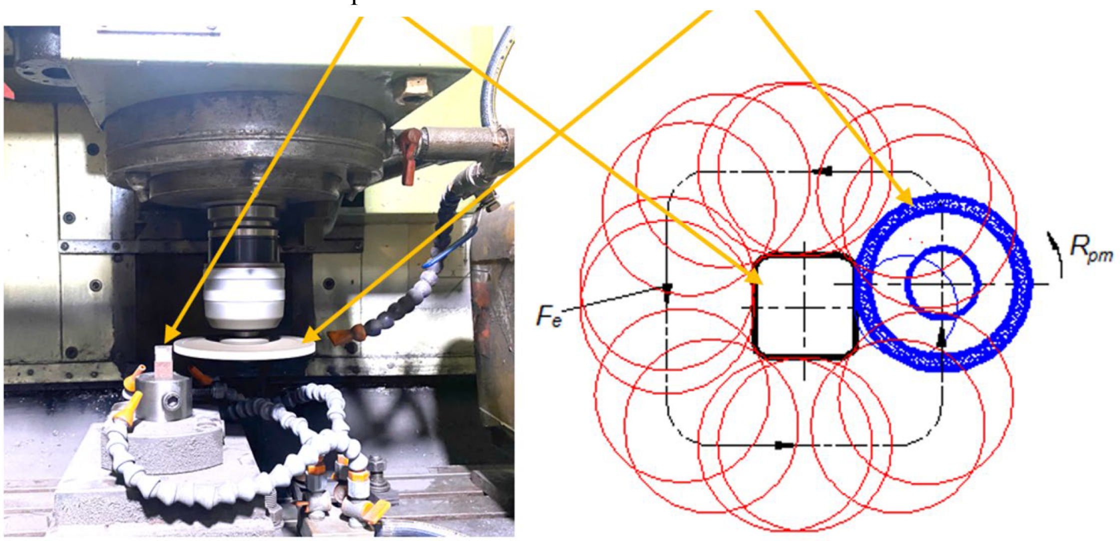

Figure 1. Experimental setup for grinding HARDOX 500 steel using a CBN grinding wheel

Three process parameters were selected as input variables: depth of cut (t, mm), feed rate (S, mm/min), and spindle speed (n, rpm). These parameters were chosen because they play a fundamental role in determining the material removal mechanism and the resulting surface quality in the grinding process. To design the experiments efficiently while minimizing the number of trials, the Box–Behnken design (BBD) was employed. This design consists of 15 experimental runs and allows for the estimation of both main effects and interaction effects without requiring a full factorial design.

After each grinding operation, the surface roughness (Ra) of the workpiece was measured. To ensure accuracy, measurements were taken at three equally spaced positions along the cylindrical surface of each specimen, and the average value was used as the representative Ra for that experiment. This approach helps reduce local variations and improves the reliability of the response data.

The complete experimental plan, including parameter levels and the corresponding measured Ra values, is presented in Table 1. These results provide the experimental basis for subsequent statistical modeling using quadratic Response Surface Methodology (RSM) and analysis of variance (ANOVA), with the aim of identifying the key influencing factors and developing a predictive model for surface roughness in CBN grinding of HARDOX 500 steel.

Table 1. Experimental design matrix (Box–Behnken) and corresponding measured surface roughness (Ra) values

No.	t (mm)	n (v/ph)	S (mm/ph)	Ra (µm)
1	0.01	4000	2500	0.574
2	0.03	4000	2500	3.057
3	0.01	5000	2500	0.402
4	0.03	5000	2500	2.258
5	0.01	4500	2000	0.380
6	0.03	4500	2000	2.524
7	0.01	4500	3000	0.594
8	0.03	4500	3000	3.279
9	0.02	4000	2000	0.588
10	0.02	5000	2000	0.456
11	0.02	4000	3000	0.604
12	0.02	5000	3000	0.414
13	0.02	4500	2500	0.505
14	0.02	4500	2500	0.509
15	0.02	4500	2500	0.506

3. CONCLUSION AND DISCUSSION

3.1. Model Adequacy and Statistical Evaluation

Response Surface Methodology (RSM) was applied to develop predictive models for surface roughness (Ra) in the CBN grinding of HARDOX 500 steel. Both a full quadratic model, incorporating all linear, interaction, and squared terms, and a stepwise-selected quadratic model based on the Akaike Information Criterion (AIC) were evaluated.

The full quadratic model demonstrated an excellent fit, with $R^2 = 0.987$ and adjusted $R^2 = 0.964$, along with a root mean square error (RMSE) of 0.203 µm. The overall F-test confirmed the statistical significance of the model ($F(9,5) = 42.25$, $p < 0.001$). The stepwise model achieved comparable explanatory power, with $R^2 = 0.985$ and a slightly improved adjusted R^2 of 0.974, while using fewer terms ($F(6,8) = 88.21$, $p < 0.0001$). These results indicate that both models provide strong predictive performance; however, the stepwise model offers a more compact structure without compromising accuracy.

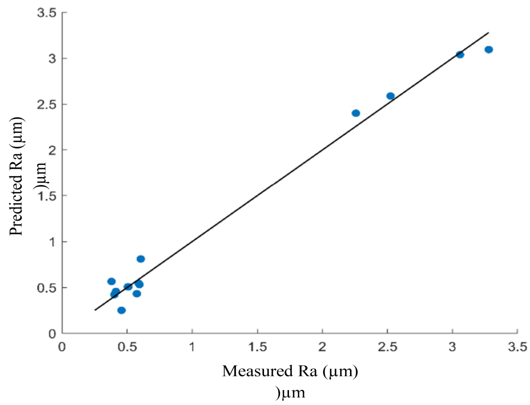

Figure 2. Relationship between experimental and predicted surface roughness (Ra) values (quadratic RSM model)

The comparison plot of predicted and experimental Ra values (Figure 2) shows that most data points lie close to the 45° line, indicating high predictive accuracy. The residual plot against predicted values (Figure 3) reveals that the residuals are randomly distributed around zero, with no evidence of heteroscedasticity. This confirms that the fundamental assumptions of the regression analysis are satisfied.

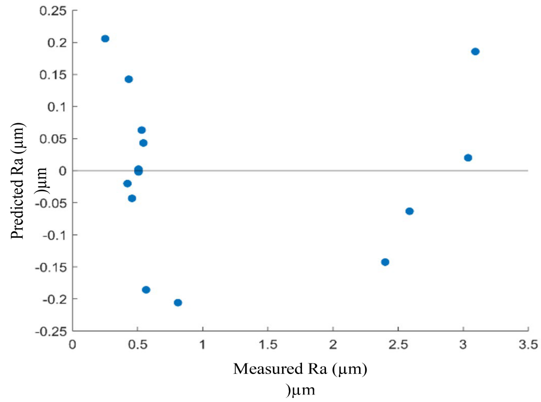

Figure 3. Residuals versus predicted values (quadratic RSM model)

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Table 2. Summary of ANOVA for Ra (full quadratic response surface model)

Term	Degrees of freedom (DF)	F-value	p-value	Effect magnitude
t	1	—	0.069	Moderate (marginal)
n	1	—	0.559	Low
S	1	—	0.656	Low
t·n	1	—	0.184	Low – moderate
t·S	1	—	0.242	Low – moderate
n·S	1	—	0.889	Very low
t^2	1	—	<0.001	Very high (dominant factor)
n^2	1	—	0.618	Low
S^2	1	—	0.565	Low
Error	5			—
Total	14			—

Table 2 confirms that only the squared term of depth of cut (t^2) has a very strong and statistically significant effect on surface roughness ($p < 0.001$). All other variables, including linear, interaction, and other quadratic terms, contribute negligibly to the variation in Ra. This analysis clearly indicates that depth of cut is the most influential factor affecting surface roughness, particularly through its quadratic effect, while the remaining factors play only minor roles.

3.2. Main Effects Analysis

To complement the regression and ANOVA results, main effects plots were constructed to visualize the influence of each input parameter. As shown in Figure 3, surface roughness (Ra) increases sharply with increasing depth of cut (t), particularly when t reaches 0.03 mm. In contrast, spindle speed (n) exhibits a slight decreasing trend, with Ra decreasing marginally at higher speeds. The feed rate (S) shows an approximately linear but weak effect, with Ra increasing slightly as S rises from 2000 to 3000 mm/min. Quantitative analysis from the main effects table supports these observations:

• When t = 0.01–0.02 mm, Ra remains below 0.6 µm; however, at t = 0.03 mm, Ra increases sharply to above 2.5 µm.

• For spindle speed, Ra decreases slightly from approximately 1.2 µm at 4000 rpm to about 0.9 µm at 5000 rpm.

• For feed rate, Ra increases modestly from around 1.0 µm at 2000 mm/min to approximately 1.25 µm at 3000 mm/min.

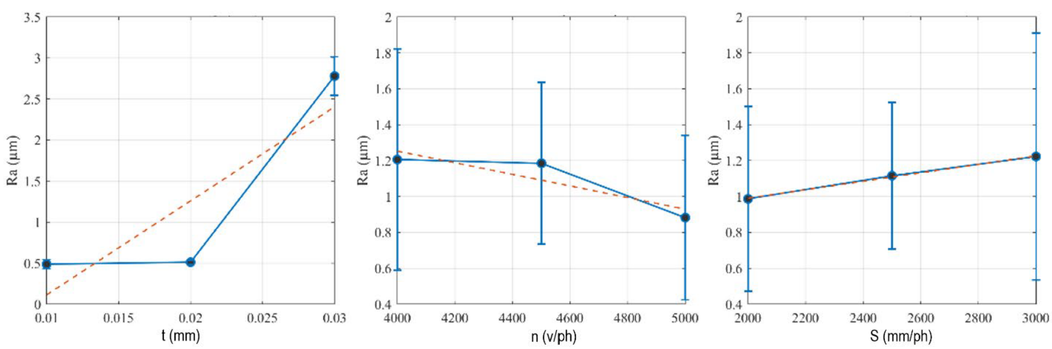

Figure 4. Main effects plot of parameters t, n, and S on surface roughness (Ra) in CBN grinding of HARDOX 500 steel

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3.3. Effect Contribution Analysis

The contribution of each model component was further quantified using a bar chart of effect contributions (Figure 4). The results show that the quadratic term of depth of cut (t^2) accounts for nearly 49% of the explained variance, followed by linear terms (~34%) and other nonlinear contributions (~16%). The residual error is negligible (<2%), confirming the reliability of the RSM model. Including p-values in the contribution table further confirms that only t^2 is statistically significant ($p < 0.001$), while most other terms are not significant. These findings are consistent with the ANOVA results and regression coefficients, reinforcing the conclusion that surface roughness is predominantly governed by the quadratic effect of depth of cut.

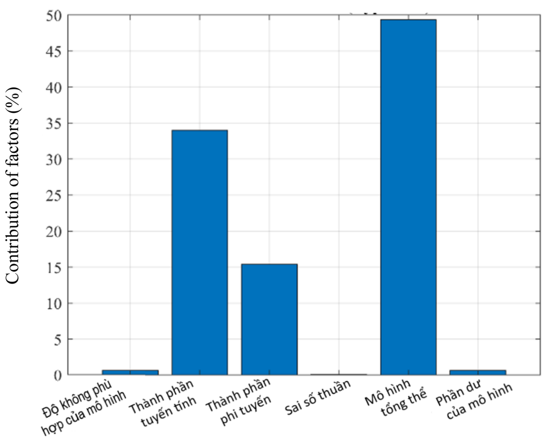

Figure 5. Bar chart showing the contribution of model components to Ra (based on Type I sum of squares)

3.4. Discussion

Kết hợp các kết quả thống kê, đồ thị ảnh hưởng chính và phân tích mức đóng góp cho thấy một kết luận thống nhất:

Chiều sâu cắt (t) là yếu tố quyết định then chốt của Ra, với ảnh hưởng bậc hai đóng vai trò chi phối tuyệt đối.

Tốc độ trục chính (n) có tác động yếu nhưng mang tính tích cực, với tốc độ cao hơn giúp giảm nhẹ Ra.

Lượng chạy dao (S) góp phần nhỏ, gần như tuyến tính, làm Ra tăng khi giá trị tăng lên.

Xét trên phương diện thực tiễn, các kết quả thu được cho thấy rằng trong quá trình mài CBN thép HARDOX 500, chiều sâu cắt là thông số có ảnh hưởng quyết định, cần được kiểm soát chặt chẽ để đảm bảo chất lượng bề mặt cao. Trong khi đó, tốc độ trục chính và lượng chạy dao chủ yếu giữ vai trò điều chỉnh tinh nhằm hoàn thiện quá trình. Kết quả này mang lại định hướng hữu ích cho việc tối ưu hóa các thông số công nghệ trong gia công công nghiệp đối với thép siêu cứng.

Combining the statistical results, main effects plots, and contribution analysis leads to a consistent conclusion:

- Depth of cut (t) is the dominant factor governing surface roughness (Ra), with its quadratic effect playing the primary role.

- Spindle speed (n) has a weak but beneficial influence, with higher speeds slightly reducing Ra.

- Feed rate (S) has a minor, nearly linear effect, causing a slight increase in Ra as its value rises.

From a practical perspective, these findings indicate that in CBN grinding of HARDOX 500 steel, depth of cut is the key parameter and must be carefully controlled to achieve high surface quality. In contrast, spindle speed and feed rate primarily serve as secondary parameters for fine-tuning the process. Overall, the results provide useful guidance for optimizing process parameters in the industrial machining of ultra-hard steels.

4. CONCLUSION

This study applied a quadratic Response Surface Methodology (RSM) to model and analyze the effects of grinding parameters on surface roughness (Ra) in the CBN grinding of HARDOX 500 steel. Based on the experimental data and statistical analyses, the following conclusions can be drawn:

- The full quadratic model demonstrated excellent predictive performance, with R^2 values exceeding 0.98.

- Depth of cut (t) was identified as the most influential parameter controlling surface roughness. Its quadratic effect (t^2) played a dominant role ($p < 0.001$), accounting for nearly half of the explained variance in Ra. This indicates that even a small increase in depth of cut can significantly degrade surface quality.

- Spindle speed (n) showed a weak but beneficial effect, with higher speeds slightly improving surface quality, while feed rate (S) exhibited only a minor linear influence, slightly increasing Ra. Interaction terms were negligible and statistically insignificant.

- Diagnostic plots, ANOVA results, and contribution analysis consistently confirmed the adequacy of the quadratic RSM model, with residual error below 2%, indicating high reliability of the developed predictive equations.

- From a practical standpoint, precise control of depth of cut is the key factor in achieving superior surface quality in CBN grinding of HARDOX 500 steel. Spindle speed and feed rate may be adjusted as secondary parameters for fine-tuning, but their overall influence on Ra is limited.

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