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Statistical Investigation of Cutting-Parameter Effects on Surface Roughness During Hard Turning of AISI 440C Stainless Steel Using PCBN

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Abstract—This paper presents a statistical investigation of surface roughness in the hard turning of AISI 440C martensitic stainless steel using a PCBN cutting insert. The study focuses on the relative influence of cutting speed, feed rate, and depth of cut and develops a Response Surface Methodology (RSM) framework for prediction and optimization. A Box–Behnken Design was used with three factors at three levels, giving 30 trials in the complete study, divided equally between dry and wet machining. The workpiece hardness was 54–56 HRC and surface roughness was measured using a Mitutoyo SJ-210 tester. The reported dry-turning model achieved $R^2 = 0.9889$, adjusted $R^2 = 0.9689$, and predicted $R^2 = 0.8268$. The ANOVA results identify feed rate as the dominant parameter in the dry-turning model, whereas the complete study reports depth of cut as the dominant factor for the wet-turning model. Analysis of the reported dry experimental table shows that increasing feed rate generally raises surface roughness. The listed prediction errors remain below 2.1%. The results demonstrate that statistical modelling can identify sensitive machining parameters and provide practical guidance for selecting finishing conditions for hardened AISI 440C.

Index Terms—AISI 440C, PCBN, hard turning, surface roughness, RSM, Box–Behnken Design, ANOVA, feed rate, cutting speed, depth of cut.

I. INTRODUCTION

Hard turning is increasingly used as a finishing route for hardened steels because it can combine material removal and finishing in a single process. Compared with conventional grinding, hard turning can reduce process-chain complexity and provide greater flexibility. However, the high hardness and low thermal conductivity of hardened martensitic stainless steels create challenging thermal and tribological conditions.

AISI 440C is a high-carbon, high-chromium martensitic stainless steel used in applications requiring hardness, wear resistance, and corrosion resistance. Surface roughness is an important performance indicator because it affects friction, wear, contact behaviour, sealing, and dimensional quality.

The supplied report combines experimental machining with RSM under dry and wet environments. This paper presents a second, parameter-focused interpretation of the same study, emphasizing the statistical sensitivity of

the machining variables rather than repeating the first paper's overall comparative narrative.

II. RESEARCH GAP

The report notes that previous investigations commonly examine individual machining parameters, while fewer studies provide an integrated model covering cutting speed, feed rate, and depth of cut under multiple machining environments. It also identifies limited use of real-time monitoring and machine-learning approaches for AISI 440C. Therefore, a statistically structured investigation is useful for separating the effects of the principal machining variables.

III. OBJECTIVES

- Quantify the influence of cutting speed, feed rate, and depth of cut on Ra.
- Identify the most sensitive machining parameter under dry turning.
- Evaluate the predictive capability of the RSM model using actual and predicted data.
- Use the findings to establish practical finishing trends for AISI 440C.

IV. MATERIALS AND EXPERIMENTAL PROCEDURE

A. Workpiece and Tool

The workpiece was hardened AISI 440C stainless steel with measured hardness of 54–56 HRC. Machining was performed on an Ace Micromatic Apollo CNC turning machine using a PCBN insert. Both dry and wet turning were included in the overall experimental program.

TABLE I. INVESTIGATED MACHINING PARAMETER LEVELS.

Parameter	Low	Centre	High	Unit
Cutting speed	160	200	240	m/min
Feed rate	0.10	0.15	0.20	mm/rev
Depth of cut	0.05	0.10	0.15	mm

B. Experimental Design

A three-factor Box–Behnken Design was selected within RSM. The report specifies 15 dry and 15 wet trials, for 30 total runs. The experimental conditions were randomized to reduce systematic bias.

$$N = 2k(k - 1) + C_0 \quad (1)$$

where N is the number of runs, k is the number of factors, and C_0 is the number of centre points.

C. Surface Roughness Measurement

After each turning operation, Ra was measured using a Mitutoyo SJ-210 surface roughness tester. A cutoff length of 0.8 mm and evaluation length of 4 mm were used. Three measurements were taken at different locations and averaged for analysis. The resulting data were analysed using a second-order polynomial model and ANOVA. These procedures are explicitly described in the supplied report. □filecite□turn13file3□L173-L181□

V. STATISTICAL MODEL

The general second-order RSM model used in the study is:

$$Ra = \beta_0 + \beta_1 v + \beta_2 f + \beta_3 d + \beta_{12} vf + \beta_{13} vd + \beta_{23} fd + \beta_{11} v^2 + \beta_{22} f^2 + \beta_{33} d^2 \quad (2)$$

The linear coefficients represent individual parameter effects, the interaction coefficients represent combined effects, and the quadratic terms represent curvature in the response surface.

VI. DRY-TURNING RESULTS

A. Regression Model

The reported dry-turning quadratic model is:

$$Ra = 0.78175 + 0.00049v + 1.05f - 0.043333d + 0.003vf - 0.00125vd + 2.2fd - 4.74\times10^{-6}v^2 + 2.16667f^2 + 3.56667d^2 \quad (3)$$

The model reported $R^2 = 0.9889$, adjusted $R^2 = 0.9689$, predicted $R^2 = 0.8268$, standard deviation = 0.0186 µm, mean Ra = 1.03 µm, and coefficient of variation = 1.81%.

B. Parameter Significance

TABLE II. SELECTED ANOVA RESULTS FOR DRY TURNING.

Factor	F-value	p-value	Statistical finding
Cutting speed	43.17	0.0012	Significant
Feed rate	366.40	<0.0001	Most influential
Depth of cut	32.46	0.0023	Significant
Speed × feed	0.4154	0.5476	Not significant
Speed × depth	0.0721	0.7990	Not significant
Feed × depth	0.3491	0.5803	Not significant

The feed-rate F-value is substantially larger than the F-values for cutting speed and depth of cut. This indicates that, within the studied dry-turning range, feed rate is the most sensitive parameter for surface roughness. The report's complete ANOVA identifies the feed-rate effect as statistically significant at $p < 0.0001$.

C. Effect of Feed Rate

The experimental data show a clear increase in surface roughness at higher feed rates. For the centre-level conditions, Ra increases from approximately 0.94–0.93 µm at 0.10 mm/rev in representative trials to approximately 1.02–1.03 µm at 0.15 mm/rev, while the 0.20 mm/rev trials include values above 1.1 µm. This trend is consistent with the geometric contribution of feed to the theoretical surface profile.

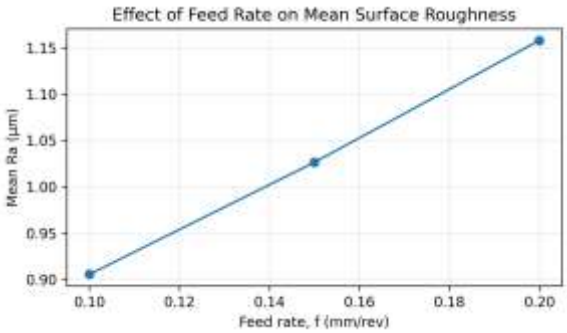

Fig. 1. Mean dry-turning surface roughness as a function of feed rate.

D. Effect of Depth of Cut

Depth of cut also affects the measured Ra, although its statistical contribution in the dry-turning ANOVA is smaller than that of feed rate. The experimental points show that combinations involving the larger depth of cut can produce higher roughness, particularly when accompanied by high feed rate.

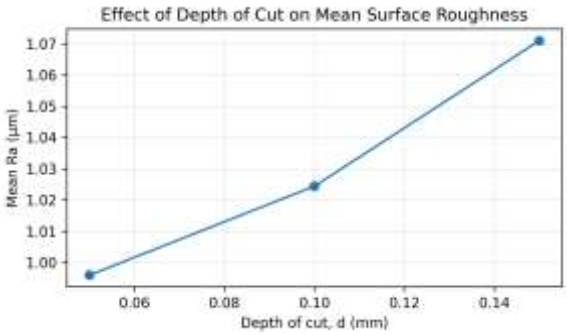

Fig. 2. Mean dry-turning surface roughness as a function of depth of cut.

E. Effect of Cutting Speed

Cutting speed is statistically significant in the dry-turning model. Within the investigated range, higher speed tends to reduce or maintain surface roughness in several combinations. The effect should not be interpreted independently of feed rate and depth of cut

because the response is generated by their combined machining conditions.

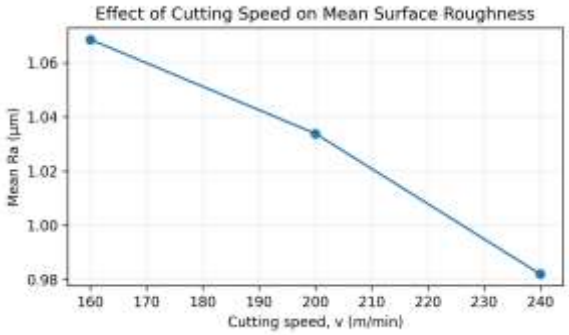

Fig. 3. Mean dry-turning surface roughness as a function of cutting speed.

VII. MODEL VALIDATION

TABLE III. DRY-TURNING MODEL VALIDATION DATA.

Run	Actual Ra	Predicted Ra	Error (%)
1	0.882	0.882	0.01
2	0.931	0.949	1.91
3	1.020	1.026	0.56
4	1.135	1.123	1.05
5	1.013	1.019	0.59
6	0.934	0.946	1.29
7	1.209	1.209	0.01
8	1.030	1.026	0.41
9	0.941	0.947	0.62
10	1.036	1.030	0.55
11	1.027	1.026	0.12
12	0.866	0.848	2.04
13	1.169	1.187	1.52
14	1.118	1.112	0.51
15	1.128	1.110	1.57

The prediction errors in the supplied dry-turning table range from 0.01% to 2.04%. The largest reported error occurs at 240 m/min, 0.10 mm/rev, and 0.10 mm depth of cut. The low error range indicates close agreement between the regression predictions and the listed experimental observations.

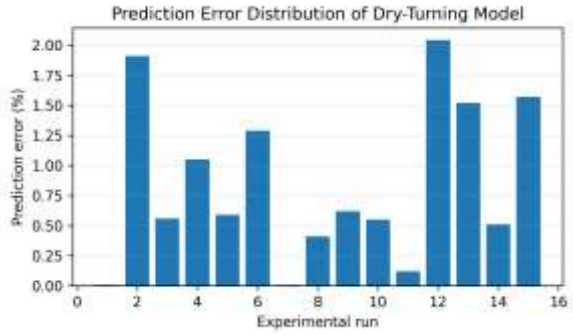

Fig. 4. Prediction error for the dry-turning RSM model.

VIII. DRY–WET INTERPRETATION

The complete study contains 15 wet-turning trials in addition to the 15 dry trials. The reported wet model has $R^2 = 0.9981$, adjusted $R^2 = 0.9947$, and predicted $R^2 = 0.9712$. The wet-turning ANOVA identifies depth of cut as the dominant factor. The reported minimum surface roughness is 0.50 µm for wet machining compared with 0.84 µm for dry machining.

TABLE IV. REPORTED DRY–WET MODEL COMPARISON.

Metric	Dry	Wet
Trials	15	15
Minimum reported Ra	0.84 µm	0.50 µm
R^2	0.9889	0.9981
Adjusted R^2	0.9689	0.9947
Predicted R^2	0.8268	0.9712

The difference suggests that coolant-assisted machining provides a more favourable surface-finish environment within the studied parameter window. The result is consistent with the role of cooling and lubrication in reducing thermal and frictional effects during hard turning. The supplied report explicitly states that the overall study compares dry and wet PCBN turning and uses RSM to identify optimal parameters. □filecite□turn13file0□L21-L38□

IX. DISCUSSION

The strongest statistical finding is the sensitivity of surface roughness to feed rate during dry turning. This is technically reasonable because feed rate directly influences the theoretical scallop height generated by the tool nose and therefore has a strong geometric contribution to Ra. Higher feed also increases chip thickness and can modify cutting forces and vibration.

Cutting speed has a statistically significant but smaller contribution. At suitable speeds, increased thermal softening and improved cutting action may reduce roughness, although excessive speed can increase tool wear and temperature. Therefore, the statistically favourable trend should be interpreted only within the 160–240 m/min range.

Depth of cut is statistically significant in dry turning but less influential than feed rate. In wet turning, however, the reported ANOVA identifies depth of cut as the dominant factor. This difference demonstrates why machining environment should be considered when transferring parameter recommendations from one process condition to another.

The results also show the value of RSM for engineering experimentation. Instead of testing every possible combination, a structured design provides information about main effects, interactions, curvature, and predictive behaviour using a limited number of trials.

X. PRACTICAL PARAMETER GUIDELINES

- For surface-finish-oriented turning, keep feed rate near the lower end of the investigated range.
- Use cutting speed within the validated 160–240 m/min window rather than extrapolating the model beyond the experimental domain.
- Avoid combining high feed rate and high depth of cut when low Ra is the primary objective.
- Use wet machining when coolant application is acceptable and the priority is minimum surface roughness.
- Revalidate optimized settings whenever insert grade, nose geometry, workpiece hardness, or machine-tool conditions change.

XI. CONCLUSIONS

- AISI 440C hardened to 54–56 HRC was successfully investigated using PCBN hard turning.
- RSM with a Box–Behnken Design provided a structured method for modelling surface roughness.
- Feed rate was the most influential factor in the reported dry-turning ANOVA, with $F = 366.40$ and $p < 0.0001$.
- Cutting speed and depth of cut were also statistically significant in the dry-turning model.
- The dry-turning model achieved $R^2 = 0.9889$ and predicted $R^2 = 0.8268$.
- Prediction errors for the listed dry-turning runs were between 0.01% and 2.04%.
- The complete study reports better surface-finish performance under wet machining, with a minimum Ra of 0.50 µm.
- The findings support using lower feed rates and controlled depth of cut when surface finish is the main objective.

XII. FUTURE WORK

Future research should extend the response set beyond Ra to include tool wear, cutting force, cutting temperature, material removal rate, power consumption, chip morphology, and surface integrity. The report also identifies MQL and cryogenic cooling, machine-learning-based prediction, alternative PCBN grades and geometries, and real-time tool-wear monitoring as promising directions.

REFERENCES

[1] J. Barry and G. Byrne, "Cutting tool wear in the machining of hardened steels: Part I: Alumina/TiC cutting tool wear," Wear, vol. 247, no. 2, pp. 139–151, 2001.

[2] S. Thamizhmanii and S. Hasan, "Measurement of surface roughness and flank wear on hard martensitic stainless steel by CBN and PCBN cutting tools," Journal of Achievements in Materials and Manufacturing Engineering, vol. 31, no. 2, pp. 415–421, 2008.

[3] S. Thamizhmanii and S. Hasan, "Effect of tool wear and forces by turning process on hard AISI 440C and SCM 440 materials," 2009.

[4] S. K. Shihab, Z. A. Khan, A. Mohammad, and A. N. Siddiquee, "A review of turning of hard steels used in bearing and automotive applications," Production & Manufacturing Research, vol. 2, no. 1, pp. 24–49, 2014, doi: 10.1080/21693277.2014.881728.

[5] I. Ozbek, S. Sen, M. Ipek, C. Bindal, S. Zeytin, and A. H. Ucisik, "A mechanical aspect of borides formed on the AISI 440C stainless-steel," Vacuum, vol. 73, no. 3–4, pp. 643–648, 2004, doi: 10.1016/j.vacuum.2003.12.083.

[6] S. S. Gill, H. Singh, R. Singh, and J. Singh, "Cryoprocessing of cutting tool materials—A review," International Journal of Advanced Manufacturing Technology, vol. 48, no. 1–4, pp. 175–192, 2010, doi: 10.1007/s00170-009-2263-9.

[7] Y. Choopani, M. R. Razfar, P. Saraeian, and M. Farahnakian, "Experimental investigation of external surface finishing of AISI 440C stainless steel cylinders using the magnetic abrasive finishing process," International Journal of Advanced Manufacturing Technology, vol. 83, no. 9–12, pp. 1811–1821, 2016, doi: 10.1007/s00170-015-7700-3.

[8] V. Sivaraman and S. Prakash, "Recent developments in turning hardened steels—A review," IOP Conference Series: Materials Science and Engineering, vol. 197, no. 1, 2017, doi: 10.1088/1757-899X/197/1/012009.

[9] A. T. Abbas et al., "Investigation of surface quality and productivity in precision hard turning of AISI 4340 steel using integrated approach of ML-MOORA-PSO," Processes, vol. 13, no. 4, 2025.

[10] N. M. Tuan, T. T. Long, and T. B. Ngoc, "Study of effects of MoS2 nanofluid MQL parameters on cutting forces and surface roughness in hard turning using CBN insert," Fluids, vol. 8, no. 7, 2023, doi: 10.3390/fluids8070188.