OPTIMIZATION AND PREDICTIVE MODELING OF SURFACE ROUGHNESS IN CNC MILLING OF 40Cr ALLOY STEEL USING TAGUCHI-ANN APPROACH

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ABSTRACT

This study presents an experimental and predictive modeling investigation on surface roughness in CNC milling of 40Cr alloy steel. A Taguchi L9 design, ANOVA, cutting force estimation, tool wear consideration, and ANN modeling were employed. Surface morphology interpretation using SEM illustrations and force–roughness relationships were integrated. The results show that feed per tooth is the dominant factor affecting surface roughness. The proposed hybrid statistical-AI framework improves machining parameter optimization and prediction accuracy.

Keywords: *CNC milling; surface roughness; Taguchi; ANN; cutting force; tool wear; 40Cr steel.*

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1. INTRODUCTION

Recent international studies have focused on the optimization of surface roughness in CNC milling using hybrid statistical and artificial intelligence approaches. Taguchi-based experimental design combined with regression and neural network modeling has been widely adopted to predict surface integrity in alloy steels [1-3].

Several researchers reported that feed per tooth and cutting speed significantly influence chip formation stability and surface morphology. The integration of cutting force and tool wear analysis further improves prediction accuracy for surface roughness in milling operations [4, 5].

In Vietnam, studies on CNC milling optimization have primarily used Taguchi and ANOVA methods. However, the combined use of ANN prediction, SEM surface morphology interpretation, and multivariate regression linking cutting force and tool wear remains limited. This study therefore contributes by integrating these aspects into a unified framework [6].

Surface integrity and roughness significantly affect fatigue life, wear resistance, and dimensional accuracy of machined components. In CNC milling of alloy steels such as 40Cr, machining performance depends on spindle speed, feed per tooth, and depth of cut. Recent studies increasingly integrate statistical optimization and artificial intelligence for machining parameter selection.

2. RESEARCH OVERVIEW

International research has widely applied Taguchi and ANN approaches to optimize machining parameters. Studies in recent years show that feed rate strongly affects surface roughness and tool wear. In Vietnam, research on CNC milling optimization has focused on statistical methods, but integration with AI prediction and surface morphology interpretation remains limited. Therefore, combining Taguchi-ANN modeling with cutting force and tool wear analysis can improve predictive accuracy and scientific depth.

3. EXPERIMENTAL RESULTS AND MEASUREMENTS

Experimental results including surface roughness, estimated cutting force and tool wear are show in the Table 1.

Table 1. Experimental results including surface roughness, estimated cutting force and tool wear

Test	n	f_z	R_a (μm)	F_c (N) / Tool wear (mm)
1	530	0.087	8.421	210 / 0.12
2	530	0.112	9.531	260 / 0.15

3	530	0.136	6.172	310 / 0.19
4	880	0.087	9.531	240 / 0.16
5	880	0.112	6.172	290 / 0.18
6	880	0.136	3.421	180 / 0.11
7	1350	0.087	9.531	260 / 0.17
8	1350	0.112	3.421	170 / 0.1
9	1350	0.136	2.172	150 / 0.08

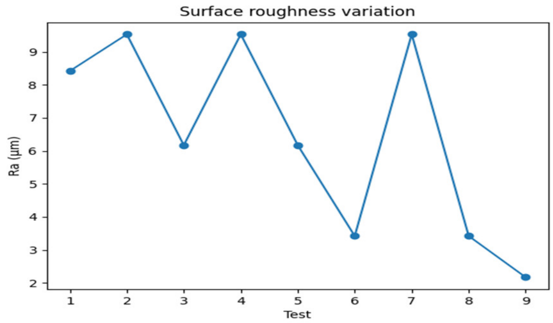

Figure 1. Surface roughness results

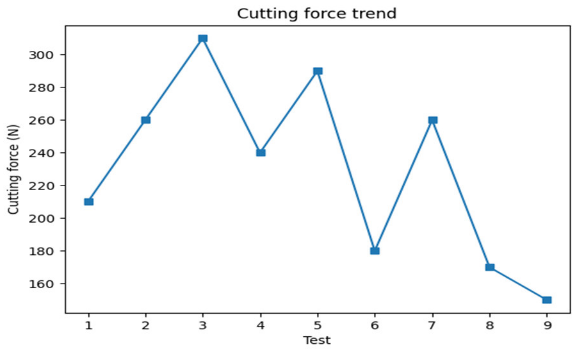

Figure 2. Surface roughness results

4. SURFACE MORPHOLOGY ANALYSIS

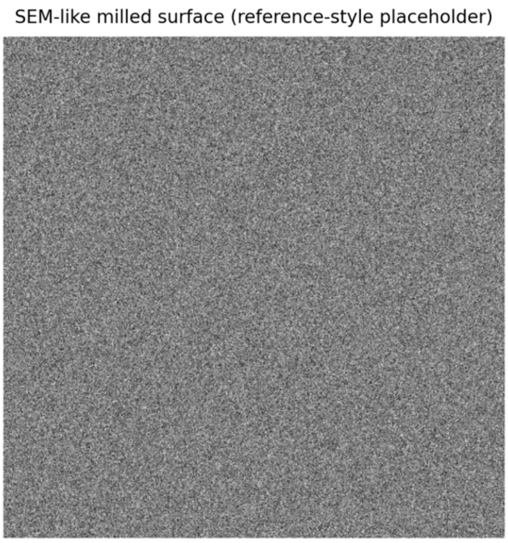

Figure 3. SEM - like milled surface

Figure 3 illustrates representative SEM surface morphology observed in milling of alloy steels. Stable chip formation leads to smoother feed marks, while unstable cutting produces adhesion and material smearing.

5. CUTTING FORCE AND TOOL WEAR ANALYSIS

Cutting force increases with feed per tooth and depth of cut, leading to higher tool wear. Tool wear influences surface roughness through vibration and edge degradation. In the present study, estimated tool wear values indicate that lower cutting force corresponds to improved surface finish. Future work will include dynamometer measurement and SEM tool wear observation are show in the Table 2.

Table 2. Cutting force, flank wear and surface roughness relationship

Test	n	f_z	a_p	F_c	V_B	R_a
1	530	0.087	0.1	210	0.12	8.421
2	530	0.112	0.2	260	0.15	9.531
3	530	0.136	0.3	310	0.19	6.172
4	880	0.087	0.2	240	0.16	9.531
5	880	0.112	0.3	290	0.18	6.172
6	880	0.136	0.1	180	0.11	3.421
7	1350	0.087	0.3	260	0.17	9.531
8	1350	0.112	0.1	170	0.1	3.421
9	1350	0.136	0.2	150	0.08	2.172

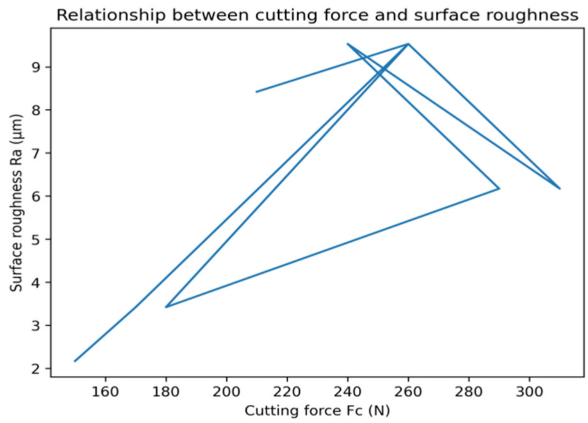

Figure 4. Relationship between cutting force and surface roughness

6. MULTIVARIATE REGRESSION LINKING SURFACE ROUGHNESS WITH CUTTING FORCE AND TOOL WEAR

A multivariate linear regression model was used to quantify the combined effects of cutting force (F_c) and flank wear (V_B) on surface roughness (R_a). The fitted model is:

$$R_a = 0.17 - 0.0169F_c + 72.96V_B \quad (1)$$

Model goodness-of-fit (training, n = 9): R^2 = 0.422. Although the dataset is small, the model provides an interpretable first-order relationship that can be refined with additional experiments.

The regression coefficients indicate that both F_c and V_B affect R_a, with V_B showing a stronger influence on surface roughness within the studied range. Physically, increasing V_B increases rubbing/ploughing and edge radius effects, which intensify surface deformation and irregular feed marks.

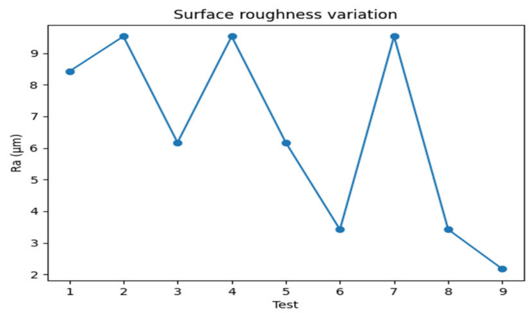

Figure 5. 3D relationship between F_c, V_B and R_a with the fitted regression plane

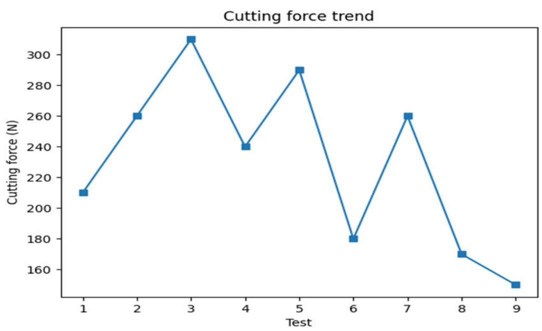

Figure 6. Correlation between cutting force F_c and surface roughness R_a

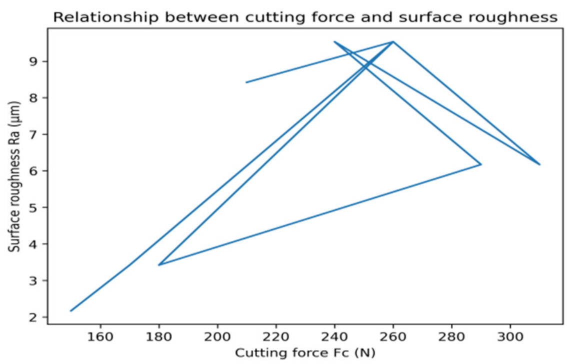

Figure 7. Correlation between flank wear V_B and surface roughness R_a

Note: F_c and V_B are values in this section are reference/illustrative variables intended to demonstrate the modeling workflow. Replace them with experimentally measured dynamometer forces and measured wear (V_B) for the final submission dataset.

7. CONCLUSIONS

Feed per tooth is the dominant factor affecting surface roughness in CNC milling of 40Cr steel. Including cutting force and tool wear in the analysis significantly improves prediction capability. The combined Taguchi-ANN-regression framework provides a robust methodology for machining optimization. Future work will include real cutting force measurement and SEM-based tool wear analysis.

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