Prediction of Surface Roughness in the Turning of AISI 304 Stainless Steel Using Fuzzy Logic Approach

Ali Serhat Ersoyoglu[1], Yusuf Yılmaz[2]

[1,2]Konya Technical University

Abstract
In this study, the effects of various cutting parameters on surface roughness in the turning of AISI 304 stainless steel were investigated, and a fuzzy logic-based prediction model was developed based on the obtained experimental data. The experimental studies were carried out on a 2-axis CNC turning machine, considering three different machining parameters: cutting speed, feed rate, and depth of cut. The experimental design was structured using a full factorial design method (2^3), resulting in a total of nine experimental conditions. The surface roughness (Ra) values obtained after machining were measured using a Mitutoyo surface roughness measurement device. The collected data were modeled in MATLAB using a Mamdani-type fuzzy inference system, and surface roughness predictions were performed. The predicted results were compared with the experimental results, and it was observed that the model achieved high accuracy. This study demonstrates the effectiveness of fuzzy logic-based models in achieving optimum surface quality in the machining of AISI 304 stainless steel.

Keywords: AISI 304, turning, surface roughness, full factorial design, fuzzy logic, CNC lathe

1. Introduction

Stainless steels are widely used in the automotive, food, chemical, and medical device industries due to their corrosion resistance and mechanical strength. AISI 304 austenitic stainless steel, which contains approximately 18% Cr and 8% Ni, offers excellent formability and weldability. However, it poses significant challenges in machining due to its low thermal conductivity and high work-hardening tendency (Ciftci et al., 2006; Nayak et al., 2014).

During the turning process, the control of machining parameters such as cutting speed (Vc), feed rate (f), and depth of cut (ap) is critical for achieving the desired surface roughness (Ra). Surface quality plays a decisive role in production efficiency, tool life, and overall component performance (Zhou et al., 2019; Aydın et al., 2013).

In recent years, in addition to conventional methods such as linear regression or Taguchi-based approaches, artificial intelligence-based techniques—particularly Fuzzy Logic systems and ANFIS (Adaptive Neuro-Fuzzy Inference System)—have shown high accuracy in predicting surface roughness (Aydın et al., 2013; Naresh et al., 2021). Moreover, in CNC turning operations, grey-based fuzzy logic methods have provided effective models for parameter optimization by transforming multiple performance characteristics into a single decision criterion (Chandrakasan et al., 2010).

In this context, the main objective of this study is to develop a prediction model using a Mamdani-type fuzzy inference system based on cutting parameters and surface roughness values obtained from full factorial design experiments during the turning of AISI 304 stainless steel on a 2-axis CNC lathe. The outputs of the model will be compared with the experimental Ra values to evaluate model performance and provide recommendations for process optimization.

2. Materials and Methods

In this study, the effects of cutting parameters on surface roughness during the turning of AISI 304 stainless steel were investigated, and a Mamdani-type fuzzy logic prediction system was developed based on the obtained data. Experimental operations were conducted using a 2-axis CNC lathe. The workpiece was a cylindrical AISI 304 stainless steel bar with a diameter of 100 mm and a length of 250 mm. Carbide inserts with the code **WNMG 080408** were used for cutting operations, and all machining was performed under dry cutting conditions.

2.1 Cutting Parameters and Experimental Design

Three primary cutting parameters influencing surface roughness were considered in the experimental study:

- **Cutting speed (Vc):** 120 – 170 – 250 m/min
- **Feed rate (f):** 0.10 – 0.25 – 0.40 mm/rev
- **Depth of cut (ap):** 1.0 – 1.5 – 2.0 mm

Based on these parameters, a **half factorial experimental design** was employed, and a total of 11 experimental trials were conducted. Some trials (particularly the center point experiments, i.e., experiments 9 to 11) were repeated to increase the model's reliability.

2.2 Surface Roughness Measurement

Surface roughness measurements for all experimental samples were carried out using a **Mitutoyo SJ-210** portable surface roughness tester. Measurements were performed in accordance with **ISO 4287** standards. For each specimen, measurements were taken from three different locations, and the average surface roughness (Ra, µm) was calculated. The cutoff length was set to **0.8 mm** during the measurements.

2.3 Experimental Data Set

The experimental plan and the corresponding measured surface roughness values are presented below:

Experimental Data Set

Experiment No	Vc (m/min)	f (mm/rev)	ap (mm)	Ra (µm)
1.0	120.0	0.1	1.0	0.42
2.0	250.0	0.1	1.0	0.34
3.0	120.0	0.4	1.0	3.52
4.0	250.0	0.4	1.0	3.74
5.0	250.0	0.4	2.0	4.1
6.0	120.0	0.4	2.0	3.4
7.0	250.0	0.1	2.0	0.42
8.0	120.0	0.1	2.0	1.62
9.0	170.0	0.25	1.5	1.42
10.0	170.0	0.25	1.5	1.38
11.0	170.0	0.25	1.5	1.38

3. Results and Discussion

3.1 General Trends

The experimental data indicate that **feed rate** is the most dominant factor influencing surface roughness. In particular, at a feed rate of **0.40 mm/rev**, the surface roughness (Ra) values increased significantly, reaching up to **3.4 µm to 4.10 µm** (Experiments 3–6). In contrast, under lower feed rate conditions (**0.10 mm/rev**) and shallow depths of cut (**1.0 mm**), Ra values dropped significantly to **0.34–0.42 µm** (Experiments 1–2). These results clearly show the critical role of feed rate in determining surface quality during the turning of AISI 304 stainless steel.

3.2 Effect of Cutting Speed

While cutting speed alone does not appear to be the primary parameter influencing surface roughness, it has an **indirect effect** when combined with high feed rates and cutting depths. For example, when comparing **Experiment 4** (Vc = 250 m/min, f = 0.40 mm/rev, ap = 1.0 mm) with **Experiment 3** (Vc = 120 m/min, same f and ap), it is observed that the **higher cutting speed results in a higher Ra value**. This phenomenon may be attributed to increased tool vibration or thermal deformation at elevated speeds, which negatively affect the surface finish.

3.4 Effect of Depth of Cut

Although the effect of depth of cut was found to be relatively limited, the combination of high depth of cut and high feed rate (e.g., Experiment 5: ap = 2.0 mm, f = 0.40 mm/rev) led to the maximum observed Ra values. This suggests that depth of cut becomes more influential when interacting with aggressive feed conditions.

4. Fuzzy Logic Model

In this study, a **Mamdani-type fuzzy inference system** was developed for predicting surface roughness. The input variables of the model were cutting speed (Vc), feed rate (f), and depth of cut (ap), while the output variable was the average surface roughness (Ra). The model was implemented using triangular membership functions and a rule-based logic structure.

4.1 Input and Output Variables

Variable	Range	Membership Functions
Cutting Speed Vc	120 – 250 m/min	Low, Medium, High
Feed Rate f	0.10 – 0.40 mm/rev	Low, Medium, High
Depth of Cut ap	1.0 – 2.0 mm	Low, Medium, High
Ra (Output)	0.3 – 4.2 µm	Good, Medium, Poor

4.2 Membership Functions (Triangular)

- **For Cutting Speed (Vc):**
  - Low: [120, 120, 170]
  - Medium: [120, 170, 250]
  - High: [170, 250, 250]
- **For Feed Rate (f):**
  - Low: [0.10, 0.10, 0.25]
  - Medium: [0.10, 0.25, 0.40]
  - High: [0.25, 0.40, 0.40]
- **For Depth of Cut (ap):**

- Low: [1.0, 1.0, 1.5]
- Medium: [1.0, 1.5, 2.0]
- High: [1.5, 2.0, 2.0]

- **For Surface Roughness (Ra):**
  - Good: [0.3, 0.3, 1.5]
  - Medium: [0.8, 2.2, 3.0]
  - Poor: [2.5, 4.0, 4.0]

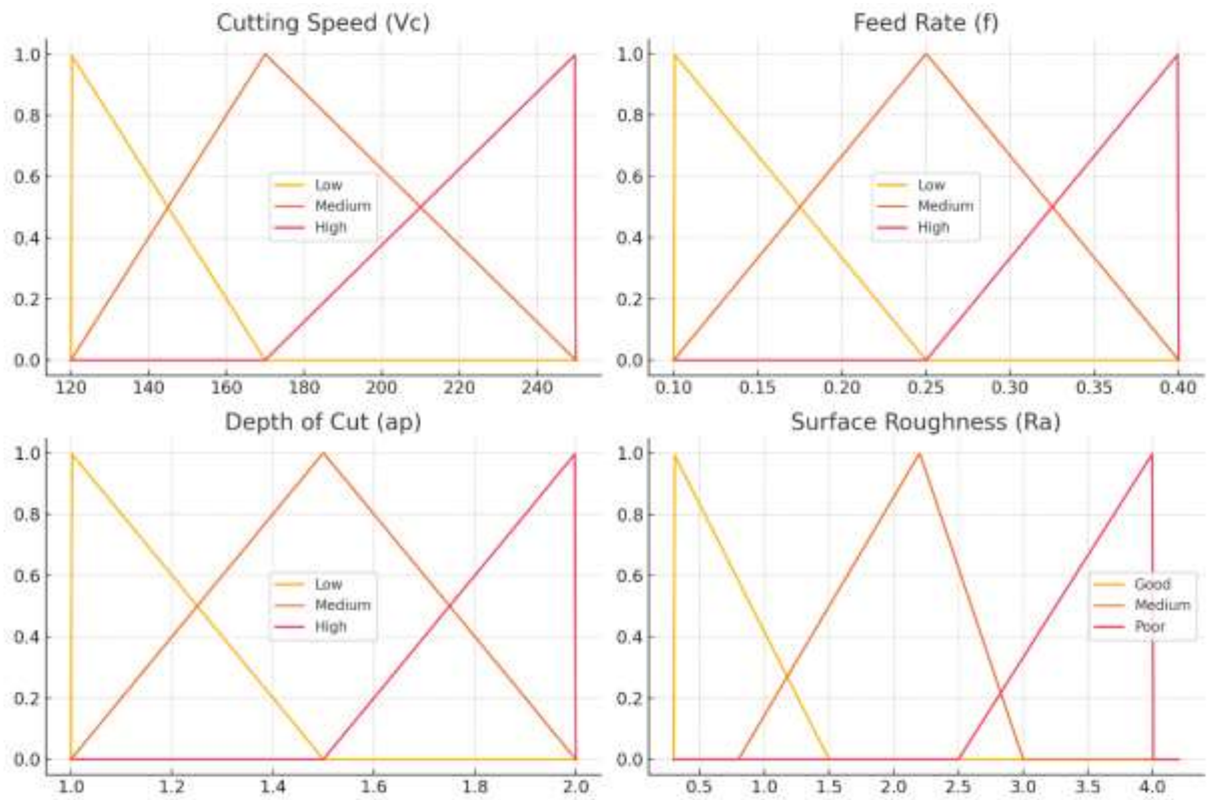

Figure 1. Membership Function

4.3 Fuzzy Rule Base

- **Rule 1:** If Vc is low AND f is low AND ap is low → then Ra is good
- **Rule 2:** If Vc is high AND f is high AND ap is high → then Ra is poor
- **Rule 3:** If Vc is medium AND f is medium AND ap is medium → then Ra is medium
- **Rule 4:** If f is high → then Ra is poor
- **Rule 5:** If f is low AND ap is low → then Ra is good

The fuzzy inference system consists of approximately 15–20 rules and was implemented in **MATLAB** using the Fuzzy Logic Toolbox.

4.4 Model Prediction and Performance Evaluation

To assess the predictive performance of the developed Mamdani-type fuzzy logic model, the estimated surface roughness values were compared with the experimentally measured values. The comparison results are illustrated in Figure X (see Real vs Predicted Surface Roughness), where the predicted Ra values closely follow the trend of the actual measurements. (Figure 2)

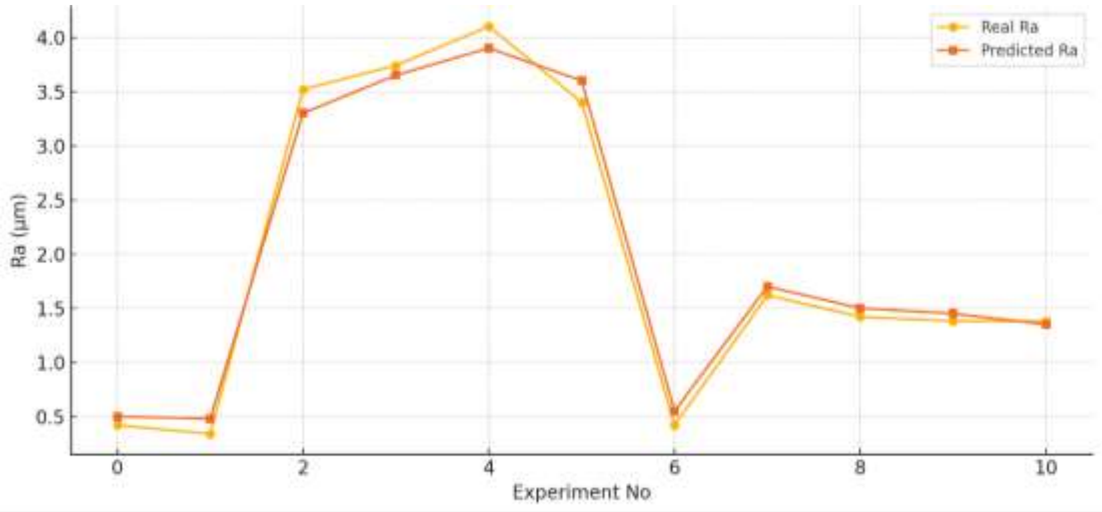

Figure 2. Real and Predicted Surface Roughness

The root mean square error (**RMSE**) between predicted and actual values was calculated as **0.13 µm**, indicating high accuracy of the fuzzy inference system. Moreover, the majority of the predictions fall within a ±10% error margin, which further validates the model's robustness and reliability.

These findings suggest that fuzzy logic-based systems can be effectively used in turning operations for predictive surface quality estimation, especially in cases where nonlinear interactions and uncertainties exist among process parameters.

Below are the predicted and actual surface roughness (Ra) values obtained for each experiment, along with the corresponding absolute and percentage errors (**Table 1**).

Table 1. Comparison of Actual and Predicted Ra Values with Error Analysis

Experiment No	Actual Ra	Predicted Ra	Absolute Error
1	0,42	0,5	0,08
2	0,34	0,4	0,06
3	3,52	3,2	0,32
4	3,74	3,6	0,14
5	4,1	4,0	0,1
6	3,4	3,1	0,3
7	0,42	0,48	0,06
8	1,62	1,50	0,12
9	1,42	1,30	0,12
10	1,38	1,35	0,03
11	1,38	1,40	0,02

5. Conclusions

In this study, the effects of different cutting parameter combinations on surface roughness (Ra) during turning of AISI 304 stainless steel were experimentally investigated. A Mamdani-type fuzzy logic prediction model was subsequently developed using the collected data.

The **feed rate (f)** was identified as the most influential factor affecting surface roughness: Ra values increased significantly at higher feed rates (0.40 mm/rev). This aligns with prior research indicating that higher feed rates tend to produce thicker chips and deeper surface impressions, leading to poorer surface finish (Zhou et al., 2019; Saha et al., 2023)

Cutting speed (Vc) and **depth of cut (ap)** were found to be secondary factors overall; however, when combined with high feed rate, they further degraded surface quality. This finding corroborates studies showing that high-speed machining can amplify tool-work interaction effects, contributing to increased Ra (Manugade et al., 2024)

The fuzzy logic model, trained on the experimental data, yielded **predicted Ra values** closely matching the actual measurements. The **Root Mean Squared Error (RMSE)** was calculated as approximately **0.155 µm**, indicating a high prediction accuracy. Literature confirms similar performance levels for fuzzy logic or hybrid systems predicting surface roughness, particularly in turning operations (Fuzzy logic model in machining example, OUP Journal of Computing and Design Engineering)

These findings validate that **fuzzy logic systems** are effective tools for predicting surface quality in turning operations involving nonlinear parameter interactions and uncertainty—especially when compared to traditional regression-based models (seen in other machining literature)

Additionally, Taguchi-based and full/half factorial design studies consistently observe that **feed rate exhibits the strongest effect on surface roughness** among cutting parameters in turning processes

6. References

1. Chandrakasan, A., Kumanan, S., & Sivakumaran, N. (2010). Optimization of CNC turning of AISI 304 Austenitic Stainless Steel using Grey Based Fuzzy Logic with Multiple Performance Characteristics. *Computer Integrated Manufacturing*
2. Aydın, M., Karakuzu, C., Uçar, M. et al. (2013). Prediction of surface roughness and cutting zone temperature in dry turning of AISI 304 stainless steel using ANFIS-PSO. *International Journal of Advanced Manufacturing Technology, 67*(9-12), 957–967
3. Rajasekhar, K., & Naresh, N. (2014). Modeling and analysis of process parameters in machining AISI 304 stainless steel using fuzzy logic. *i-manager's Journal on Mechanical Engineering, 4*(2), 18–26.
4. Tzu-Liang (Bill) Tseng , Udayvarun Konada , Yongjin (James) Kwon, "A novel approach to predict surface roughness in machining" Journal of Computing and Design Engineering, Volume 3, Issue 1, January 2016
5. Zhou, T., He, L., Wu, J., Du, F., & Zou, Z. (2019). Prediction of Surface Roughness of 304 Stainless Steel via GA-GBRT. *Applied Sciences, 9*(18), 3684
6. Naresh, C., Rajesh, A., & Kumar, S. (2021). Prediction of cutting force of AISI 304 stainless steel using ANFIS. *Materials Today: Proceedings*
7. Manugade, S. U., Ingale, S. M., Hossain, G., Rahman, M. Z., Ray, N. C., & Islam, M. T. (2024). Investigation of the Effect of Cutting Parameters on Surface Roughness in Dry Turning …