

# Optimization of Hard Turning Parameters of AISI 410 Steel Using Taguchi and Regression Analysis

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## Abstract

The appropriate selection of machining parameters is essential for achieving high surface quality during the hard turning of hardened martensitic stainless steel. In this research, effects of the key parameters on the surface roughness during the process of hard turning of hardened AISI 410 stainless steel will be examined. Taguchi L9 orthogonal array has been used to design the experiments and measure surface roughness values after each experiment with the help of Mitutoyo SJ-210 surface tester. Mean response analysis and Analysis of Variance (ANOVA) has been used to analyze the experimental data and determine the significance of machining parameters, and multiple linear regression models have been developed to predict the surface roughness. The Taguchi method has been used to optimize the machining parameters for minimum surface roughness. Feed rate is identified as the most significant machining parameter, while depth of cut and cutting speed are the two important parameters. Surface roughness values in wet turning operation is always smaller than values of dry turning operation, providing an average improvement of 13–25%. The multiple linear regression models have provided the prediction of surface roughness with error less than 9%.

**Keywords:** AISI 410 Stainless Steel, Hard Turning, Taguchi Method, Regression Analysis, Surface Roughness (Ra), ANOVA, Tool Wear.

## 1. Introduction

There are a number of martensitic stainless steels that are extensively used in engineering applications due to their outstanding properties of having high mechanical strength, wear resistance, and corrosion resistance. Among these, AISI 410 stainless steel is commonly used in producing shafts, gears, valves, bearings, pump parts, and surgical equipment, since the mechanical strength and accurate dimensions are crucial requirements. Heat treatment processes are commonly applied in order to improve hardness and increase the life of the components, thus making the machining operation much more difficult due to higher cutting forces and quick tool wear.

Hard turning represents an effective method that can be used as an alternative to conventional grinding in the finishing operation of hardened materials. It provides a variety of benefits such as reduced machining time, reduced production costs, exclusion of the secondary finishing process, and increased accuracy. However, achieving high-quality machined surfaces requires careful selection of machining parameters, particularly cutting speed, feed rate and depth of cut, as these directly influence surface roughness, machining stability and overall process performance.

The surface roughness factor is one of the most critical quality criteria in hard turning due to its direct impact on the functionality of components, wear and fatigue resistance, and assembly efficiency. Hence, establishing the optimal conditions for machining that will reduce the surface roughness while ensuring the efficiency of machining is of great practical interest. The use of statistical optimization techniques helps establish the effect of machining parameters and find their optimal values based on the minimal number of experiments performed. Even though there have been many investigations into the performance of different hardened steels, few attempts have been made to optimize hard turning processes of AISI 410 martensitic stainless steel in both dry and wet machining conditions with the help of coated carbide inserts.

To address these problems, the current research focuses on examining the influence of the cutting speed, feed rate, and depth of cut on the surface finish of AISI 410 stainless steel that is hardened through turning operations carried out under both dry and wet environments. In order to conduct the experiment, the Taguchi L9 orthogonal array approach was applied and ANOVA was utilized in determining the importance of each of the machining factors.

## 2. Literature Review

Hard turning has become an efficient replacement of conventional grinding for processing hardened steels due to its capacity to provide high dimensional accuracy, superior surface finish, and reduced cost of manufacturing. In recent times, research work has been carried out with the aim to study the effects of machining parameters, tool material types, lubricating practices, and optimization methods on machining of martensitic stainless steels and hardened alloys.

Recent research carried out on martensitic stainless steels has shown that machining parameters greatly affect the surface finish of machined surfaces and machining quality, where feed rate is always found to be the most critical parameter for surface finish [1], [2]. Proper selection of cutting parameters has helped to enhance dimensional accuracy by avoiding any machining defects. Studies conducted on coated cutting tools have also indicated improvement in chip formation, machining stability, and residual stress behavior during hard turning process [2].

Studies carried out using coated carbide, coated cermet, ceramic and CBN cutting tools show that the tool material significantly influences in determining tool wear, machining performance, and surface integrity [3]-[5], [9], [10]. The use of coated carbide inserts ensures better wear resistance and performance than conventional tools, but the use of ceramic and CBN tools allows obtaining high-quality surfaces during the hardened machining process. Optimization methodologies are currently used to select the best machining conditions to reduce surface roughness and increase the machining efficiency.

Response Surface Methodology (RSM) has proved successful in developing mathematical models and optimizing the machining parameters [6], [7]. The multi-objective optimization methodology has contributed to increasing the efficiency of the machining process because it optimizes multiple criteria like minimizing surface roughness, cutting force, and power consumption, and maximizing machining efficiency [8]. More recently, hybrid optimization methodologies based on statistical and artificial intelligence techniques have shown better prediction and optimization capabilities for manufacturing operations [11].

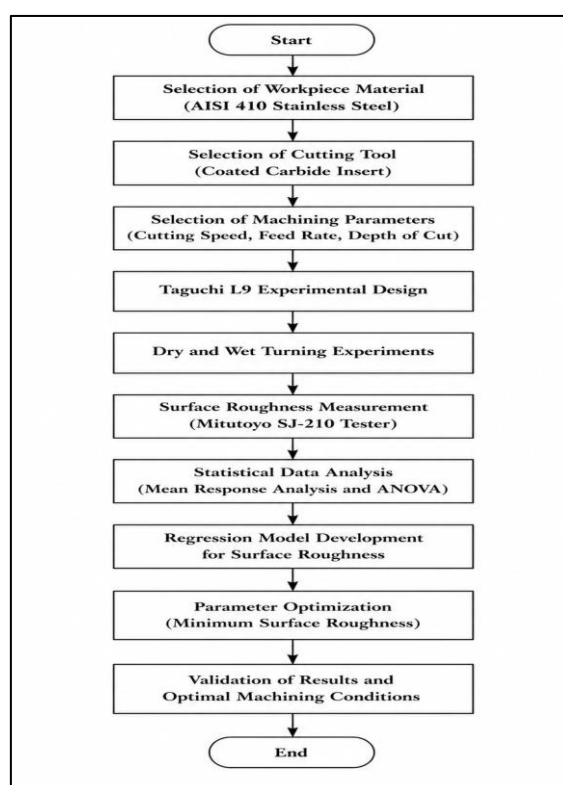
Tool wear is one of the major problems in hard turning processes. According to past literature, abrasion, flank wear, crater wear, diffusion wear, and edge chipping have been recognized as the main wear forms which impact tool life during hardened machining processes

[3], [9], [10]. Besides, the application of advanced lubrication methods and sustainable cutting fluids has been found to minimize friction and cutting temperatures, hence, improve tribology, extend tool life, and surface finish [12].

While considerable research has been done regarding machining optimization and tool performance in hardened steel, relatively few studies have investigated the effect of machining parameters on tool wear in hard turning of AISI 410 martensitic stainless steel in both dry and wet conditions using coated carbide inserts. Additionally, there is scanty literature which applies predictive models with machining parameters optimization in conjunction with tool wear assessment.

### 3. Proposed Methodology

This study seeks to analyze the effects of machining parameters on the surface roughness of hardened AISI 410 martensitic stainless steel during the dry and wet turning processes by determining the optimum machining parameters through the use of Taguchi experimental design, ANOVA and statistical optimization. The entire methodology involved in the study is depicted in Figure 1, and is based on experimentation, machining, statistical analysis, modeling and optimization.



**Figure 1.** Proposed experimental workflow

The entire process of analysis in the study starts with choosing the material for the work piece to be AISI 410 martensitic stainless steel and the cutting tool to be coated carbide inserts. Three machining parameters, namely, cutting speed ( $V$ ), feed rate ( $f$ ), and depth of cut ( $D$ ), are chosen as the input variables. In order to carry out the experiments, an L9 Taguchi orthogonal array was used.

Turning tests were performed in both dry and wet machining conditions.  $Ra$  was measured after each test by means of Mitutoyo SJ-210 surface roughness tester. Data acquired from each test was analyzed by means of mean response analysis and ANOVA. Regression model was then employed for predicting  $Ra$  at various machining conditions. Optimum machining conditions were determined by Taguchi Response Analysis together with ANOVA and optimum values were confirmed by regression model equations.

Material for the workpiece selected in this experiment was heat treated AISI 410 martensitic stainless steel with hardness value of about 45 HRC. Cylindrical workpieces with diameter of 75 mm and length of 320 mm were used for this study. The chemical composition of the workpiece material is presented in Table 1.

**Table 1.** Chemical composition of AISI 410 martensitic stainless steel

Cr	Ni	C	Mn	Si	P	S	Fe
13.5	0.75	0.15	1.0	1.0	0.04	0.03	Bal.

Titanium carbide and titanium carbonitride coated carbide inserts (SNMG 120408 MT TT5100, Taegu Tec) with PSBNR 2525M12 tool holder were used for this experiment.

Orthogonal array Taguchi L9 was chosen in order to analyze effect of  $V$ ,  $f$  and  $D$  at three levels each. Machining parameters and its levels are shown in Table 2.

**Table 2.** Machining parameters for the taguchi l9 experimental design

Parameter	Level I	Level II	Level III
$V$ (m/min)	80	100	120
$f$ (mm/rev)	0.04	0.07	0.10
$D$ (mm)	0.4	0.7	1.0

The parameter ranges were selected taking into account tool manufacturer recommendations and pilot studies.

It is noted that  $Ra$  is the chosen performance parameter since it affects the accuracy, hardness, and performance of the machined part. For each machining test, the average  $Ra$  was measured through the use of the Mitutoyo SJ-210 surface roughness tester. Multiple readings were taken at the machined surface and then averaged to obtain more reliable results. It should be stressed that while each experiment was run only once, the  $Ra$  was taken into account three times, after which the average result was considered in the further analysis. In the absence of repeated experiments, the estimation of the error term was carried out by the use of the pooled error method according to the classical Taguchi approach.

The experimental data of the L9 design were analyzed using mean response analysis and ANOVA. The importance of the machining parameters was assessed through percentage contribution analysis. The multiple linear regression equations were used to evaluate the impact of machining parameters on the  $Ra$  for dry and wet turning cases.

The purpose of the optimization is to obtain the machining parameter combination for the minimum  $Ra$  in the hard turning of AISI 410 stainless steel. Based on the experiments, the optimization problem can be formulated as follows:

Minimize:

$$Ra = f(V, f, D)$$

The optimum parameters for the hard turning have been obtained using the Taguchi mean response approach and ANOVA. The use of the regression equations enables one to estimate the  $Ra$  at the specified machining parameters.

Dry Turning

$$Ra_{dry} = \beta_0 + \beta_1 V + \beta_2 f + \beta_3 D$$

Wet Turning

$$Ra_{wet} = \gamma_0 + \gamma_1 V + \gamma_2 f + \gamma_3 D$$

The regression coefficients were determined using least-squares fitting of the experimental data.

#### 4. Results and Discussion

The experimental data generated using the Taguchi L9 orthogonal array for the dry and wet turning processes are summarized in Table 3. The  $Ra$  values obtained ranged between 0.48  $\mu\text{m}$  and 1.05  $\mu\text{m}$  in dry turning, and 0.36  $\mu\text{m}$  and 0.91  $\mu\text{m}$  in wet turning. In other words, wet machining produces lower  $Ra$  compared to dry machining, when the same cutting conditions apply.

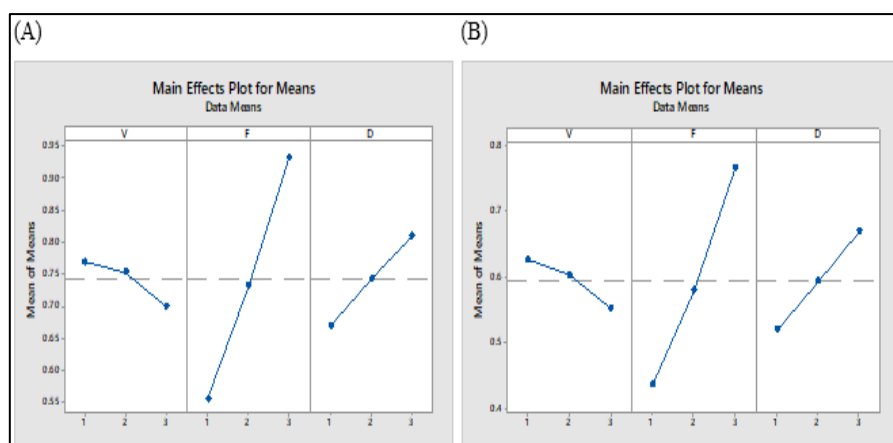
**Table 3.** Experimental results of surface roughness

S.No.	$V$ (m/min)	$f$ (mm/rev)	$D$ (mm)	$Ra$ Dry ( $\mu\text{m}$ )	$Ra$ Wet ( $\mu\text{m}$ )
1	80	0.04	0.4	0.48	0.36
2	80	0.07	0.7	0.78	0.61
3	80	0.10	1.0	1.05	0.91
4	100	0.04	0.7	0.59	0.48
5	100	0.07	1.0	0.78	0.63
6	100	0.10	0.4	0.89	0.70
7	120	0.04	0.4	0.45	0.34
8	120	0.07	0.4	0.64	0.50
9	120	0.10	0.7	0.86	0.69

The minimum  $Ra$  value was achieved with a  $V$  of 120 m/min,  $f$  of 0.04 mm/rev, and  $D$  of 0.4 mm. On the other hand, the maximum  $Ra$  value was achieved with a  $V$  of 80 m/min,  $f$  of 0.10 mm/rev, and  $D$  of 1.0 mm. From this, one can see that an increase in  $f$  and  $D$  results in deterioration of the surface quality, whereas higher cutting speeds produce better surface finish.

Figure 2 displays mean response curves that describe the effect of  $V$ ,  $f$ , and  $D$  on  $Ra$  in dry and wet turning operations.

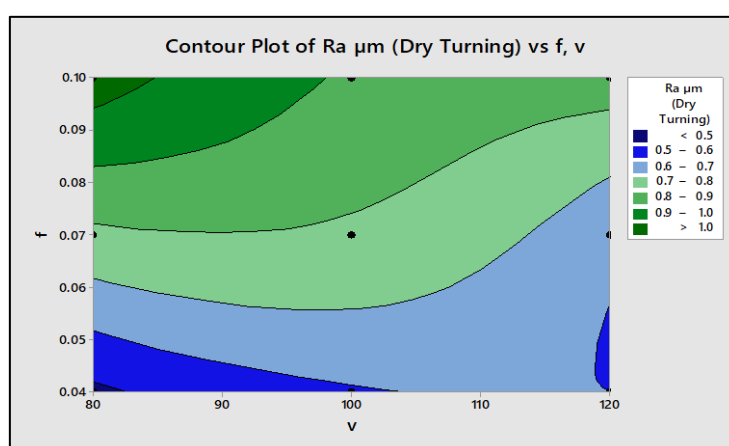
It is possible to observe a visible upward trend in  $Ra$  with the increase in  $f$ . Increased  $f$  increases the feed marks caused by the cutting tool and causes increased uncut chip thickness, thereby causing increased  $Ra$ . On the other hand, increased  $V$  enhances surface finish because of smooth chip flow and decreased built-up edge formation. The effect of  $D$  is less pronounced than that of  $f$  but still contributes to increased cutting forces and vibrations.



**Figure 2.** Mean response graph of surface roughness A) dry turning, B) wet turning

ANOVA analysis shows that the most important variable among all factors is the  $f$ , having the strongest influence on  $Ra$  in both machining environments. When it comes to dry turning operation, the  $f$  affects 83% of the total variability in  $Ra$ , while  $D$  and  $V$  account for 12% and 3% of the total variation, correspondingly. As seen from the regression equations, the increase in  $f$  leads to an increase in  $Ra$ , whereas the increase in  $V$  reduces it.

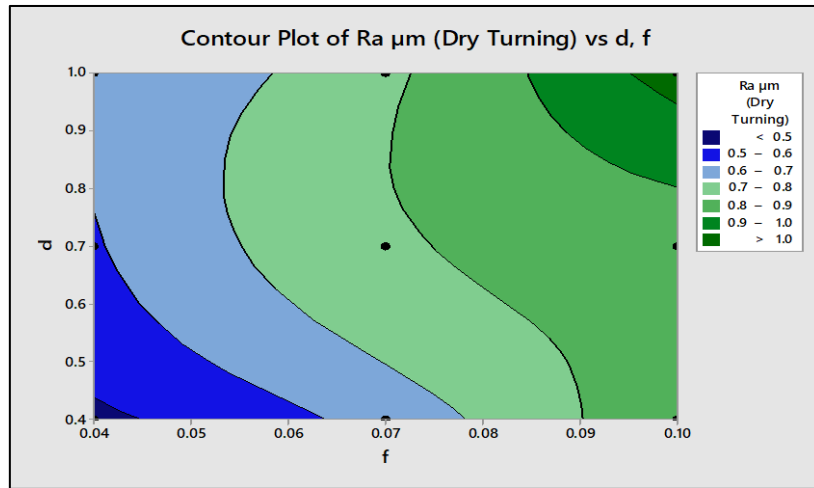
Similarly, for wet turning, the proportion of the variation in terms of  $f$  is 77%, while that of  $D$  is 16%, and that of  $V$  is 4%. The larger percentage of  $f$  indicates that the surface formation in turning process is mainly dependent on  $f$  and not  $V$  or  $D$ . Since in the design of experiment only one observation was obtained per treatment combination, then the residual variance was computed based on pooled error and not through replication of experiments, as it is typical in Taguchi analysis.



**Figure 3.** Contour plot of  $Ra$  vs  $f$ ,  $v$  during dry turning

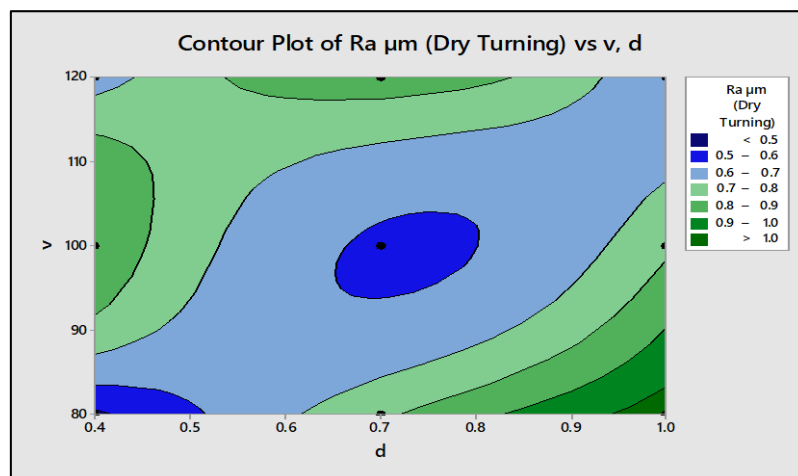
Figure 3 represents the relationship between  $V$  and  $f$  in dry turning. From the contour graph, it can be seen that there is a high correlation between  $f$  and  $Ra$ , where  $Ra$  rises with an

increase in  $f$ . The maximum  $Ra$  area (more than  $1.0 \mu\text{m}$ ) is found at  $f$  around  $0.10 \text{ mm/rev}$  and low  $V$  at  $80 \text{ m/min}$ . The low  $Ra$  area (less than  $0.5 \mu\text{m}$ ) was obtained at  $f$  of about  $0.04 \text{ mm/rev}$  and higher  $V$  of  $120 \text{ m/min}$ .



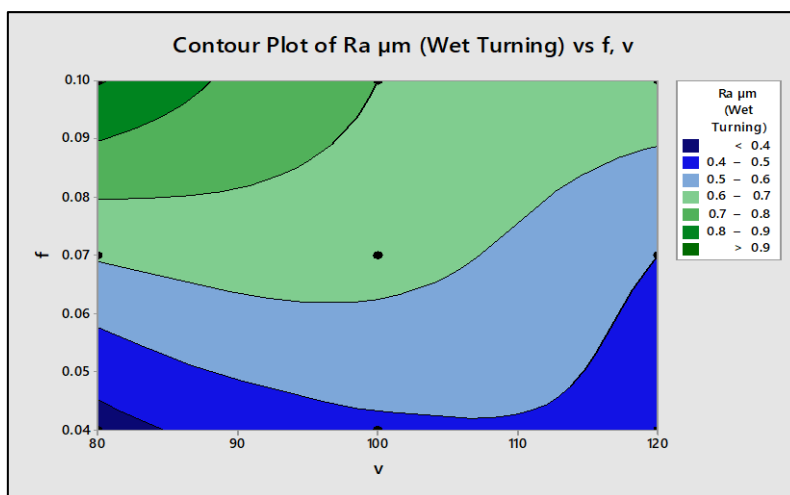
**Figure 4.** Contour plot of  $Ra$  vs  $d$ ,  $f$  during dry turning

Figure 4 represents the interaction of  $f$  and  $D$ . From the contour distribution, it is clear that both  $f$  and  $D$  play a role in increasing surface roughness. The minimum  $Ra$  area is located at low  $f$  ( $0.04 \text{ mm/rev}$ ) and low  $D$  ( $0.4 \text{ mm}$ ).



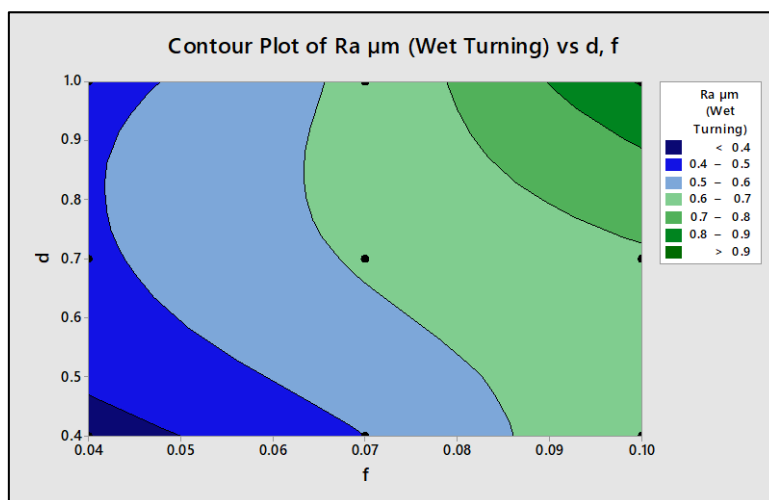
**Figure 5.** Contour plot of  $Ra$  vs  $v$ ,  $d$  during dry turning

The interaction between the  $V$  and  $D$  is depicted in Figure 5. A clear low-roughness zone can be seen at a  $V$  of  $100\text{-}120 \text{ m/min}$  and  $D$  of  $0.6\text{-}0.8 \text{ mm}$ . Increase in the  $D$  above these values causes an increase in cutting forces and vibrations that results in an increase in  $Ra$ . Lower  $V$  also lead to higher  $Ra$  due to chip formation instability.



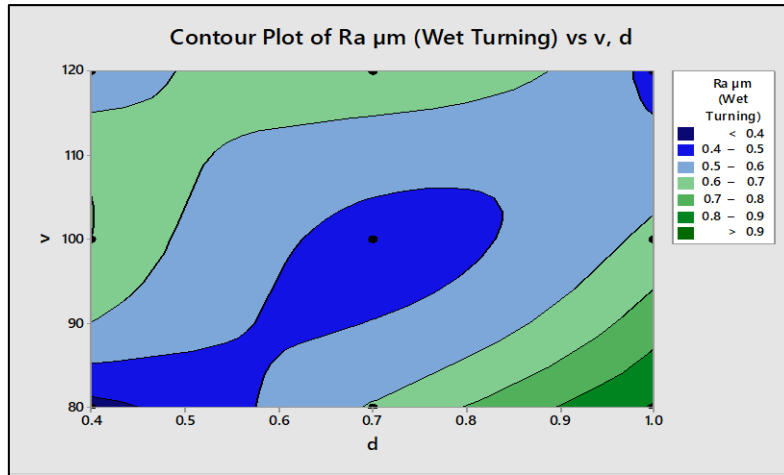
**Figure 6.** Contour plot of Ra vs f, v during wet turning

In Figure 6, the contour plot indicates that the low-roughness zone is much wider than the one for dry turning. *Ra* with values below 0.4 μm can be obtained when using low *f* and high *V* levels. Using the cutting fluid will lower friction and the temperature effect, leading to smooth chips and improved surface quality.



**Figure 7.** Contour plot of Ra vs d, f during wet turning

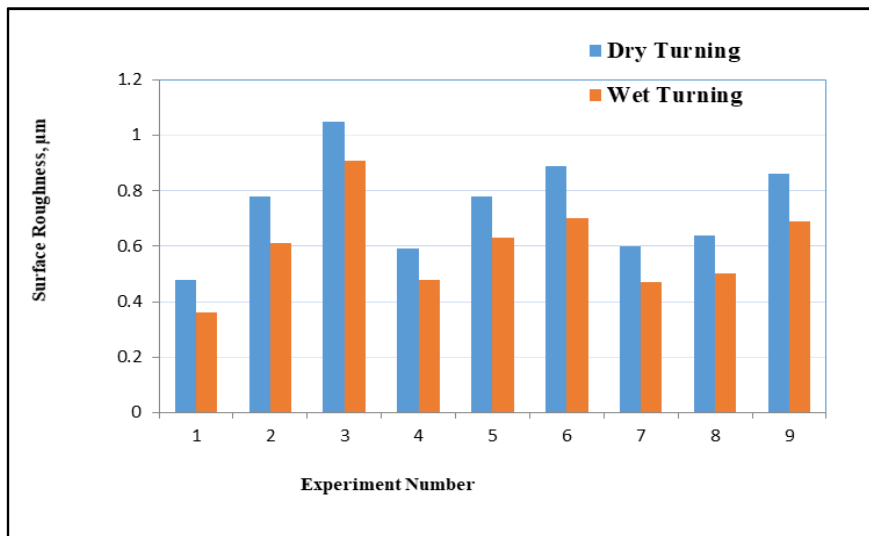
Figure 7 depicts the fact that an increase in *f* is still the major reason for roughness increment in wet turning process. Nevertheless, the contour gradients are shallower compared to the gradients obtained in dry turning process. Thus, the adverse effect of increased machining parameters is partially reduced by the cutting fluid.



**Figure 8.** Contour plot of Ra vs v, d during wet turning

Figure 8 indicates that the optimal surface quality can be obtained in the medium-to-high  $V$  and moderate  $D$  ranges. The cooling effect prevents tool wear.

The proposed models showed prediction errors of 1-7% for dry turning and 1-9% for wet turning. The low prediction errors suggest close proximity of experimental data and predicted data, thereby confirming the efficacy of the proposed models for optimizing machining parameters.



**Figure 9.** Comparison of surface roughness under dry and wet turning conditions

Surface roughness in dry and wet turning is compared in Figure 9. In all experiments conducted, wet turning showed lesser values of  $Ra$  than dry turning. The percentage improvement varied between 13% and 25% based on the machining process. The reason for

the improvement in  $Ra$  was due to the lubricating effect of the cutting fluid which reduced friction and cutting temperatures, thus reducing the build-up of edges.

Experimental findings verify the fact that  $f$  plays a dominant role as a machining factor affecting  $Ra$  in the hard turning process of AISI 410 martensitic stainless steel material. Wet machining offers better surface quality owing to improved lubrication and cooling. It is evident from the contour diagrams, ANOVA analysis, and the regression equations that optimal machining performance could be attained under high  $V$ , low  $f$ , and low-to-medium  $D$ . In addition, the regression equations and the statistical optimization technique offer a good approach in choosing machining factors to reduce surface roughness.

## 5. Conclusion

The current research has been conducted to assess the effect of machining parameters on the surface roughness of hardened AISI 410 martensitic stainless steel during dry and wet turning. For the assessment of the machining process and selection of the optimal cutting parameters, an experimental plan based on Taguchi's L9 method, ANOVA, and regression modeling has been used. It has been found that the  $f$  is the most significant factor determining the value of  $Ra$ , while  $D$  and  $V$  have less effect on it. The optimal combination of cutting parameters included a  $V$  of 120  $m/min$ ,  $f$  of 0.04  $mm/rev$ , and  $D$  of 0.4  $mm$ , providing the lowest  $Ra$  value during both wet and dry turning. During wet turning, the  $Ra$  value was 13–25% lower than during dry turning due to better lubrication and cooling. The developed regression models predicted  $Ra$  with errors below 9%. Overall, the proposed statistical approach provides a reliable guideline for optimizing hard-turning performance and improving machining quality in industrial applications.

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