American Journal of Engineering Research (AJER)
E-ISSN: 2320-0847 p-ISSN: 2320-0936
Volume-7, Issue-12, pp-43-50
www.ajer.org
Research Paper Open Access

Analysis of Paramaters Affected on Machinability of Dual-Phase SAE 1035 Steel by Full Factorial Experiment Design

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ABSTRACT: *One of the main purposes in machining is to bring surface roughness to the top level. The stage where the most decisive work can be done in improving the product quality is the parameter design phase for both product and process design. In order to determine the most effective parameters and to evaluate the results more efficiently, the full factorial experiment design technique is preferred to realize the experiments in a shorter time. This performed study was done by the aim of investigating the effect of change in terms of hardness, feed rate, and cutting tool of "Dual Phase" steel, which is a class of HSLA (High Strength Low Alloy) steels that increases usage and importance day by day, on surface quality in turning process in the pieces subjected to high forces in machine, device, car manufacturing. Experimental design was carried out in Minitab statistical analysis program with three factorial and two-level $k = 2^3$ 8 experiments with full factorial experiment design technique. Type of cutter (CBN and Carbide cutter), the feed rate (0.02 and 0.06 mm / rev) and martensite volume ratio (44% and 60) were used in the experiments as independent variable (factor), average surface roughness value (Ra) used as dependent value was determined by measurement from 6 different points with three experiments. Experiments were performed in dry cutting conditions in CNC Turning Table that has 1.5 kW power and rotates with maximum 2000 rpm.*
As a result, these three factors are effective in turning these steels on their own. The most effective parameters on surface quality were cutter tool, feed rate, martensite volume ratio (material hardness), respectively. The results obtained were interpreted together with evaluations that were previously included in literature.
KEYWORDS: *Full Factorial Experiment Design, DOE, Dual Phase, Surface Quality, Machinability*.

Date of Submission: 01-12-2018 Date of Acceptance: 18-12-2018

I. INTRODUCTION

One of the main purposes in machining is to bring surface roughness to the top level. Being surface quality of material well has a positive effect on mechanical properties of material. It is required to choose cutting parameters the most suitable to get a good surface quality [1]. Alloy steels are preferred for manufacturing of machine parts owing to their physical and mechanical properties. However, these parts require turning operation to be carried out in order to obtain desired quality product. Components can be machined at minimum lead time, with higher machining parameters such as cutting speed, feed/revolution and depth of cut, which leads to increase in cutting force and surface roughness [2]. Surface roughness places an imperative role in the manufacturing industry. The surface finish affects functional requirements such as load bearing capacity, friction, wear, lubricant characteristics etc. There will be always certain variation between the actual surface roughness value and required surface roughness value [3].

Importance of heat treatment applied in the process of improving mechanical properties has gradually increased with growing technology. Heat treatment is an important mean to obtain excellent properties of all kinds of metal materials. Heat treatment applied to steel plays an important role on defining machinability properties of steel [4-5]. In recent years, increasing material technology and cutting tool technology make the workability of heat treated steels easy and high quality. The physical properties of the coatings were examined by many researchers. The positive contribution of coatings on load capacity increase and friction reduction has been reported [6-8]. After heat treatment applied of steels, internal strains occur in material. This causes problems such as warping in workpiece, burning on surface, and micro crack. Arising these problems can be eliminated with various processes applied after heat treatment [9].

Tulasi et al. (2018) performed experiments on traditional lathe machine by using critical operating speed, feed rate, cutting depth and carbide tipped cutter combination parameters in EN24 steels in their study. These machining parameters are optimized by using Taguchi approach to achieve minimum surface roughness [3].

Qehaja et al. (2015) investigated the study about optimization of a model of surface roughness. They developed based on the response surface method to investigates the machining parameters such as feed rate, tool geometry, nose radius, and machining time, affecting the roughness of surface produced in dry turning process. The experiment has been designed and carried out on the basis of a three level factorial design. Obtained results are in good accordance with the published results in the field, validating the effectiveness of regression analysis in modeling of surface roughness in dry turning process [10].

The most important measures of surface quality during the machining process is the average surface roughness (Ra), and it is mostly caused by many machining parameters, such as true rake angle and side cutting edge angle, cutting speed, feed rate, depth of cut, nose radius, machining time etc. [10]. The experimental design methodology plays a key role at early stages of the development cycle, where new products are designed, existing product designs are improved and manufacturing processes optimized, leading to product success. Design of experiments (DOE) is based on the effective use of sound statistical tools that can lead to products that are easy to manufacture and have high reliability, enhanced field performance as well as troubleshooting activities. DOE has been established in many industries like electronics and semiconductors, aerospace, automotive, medical devices, food and pharmaceuticals, manufacturing, chemical, and process industries [11].

The purpose of this study is to make optimization and investigate effect of material and cutting parameters (feed rate and cutting tool type) on workpiece surface roughness that is an important machinability criterion by doing machinability experiments with turning method on steels used in machine production industry. In this study, dual-phased steel specimen obtained in three different hardness after heat treatment was performed to turning process with three different feed rate by using three different cutter type by evaluating factors affecting turning surface quality after literature review. Results obtained from full factorial experiment design were evaluated with regards to adaptation to literature.

II. EXPERIMENTAL STUDY

Used Material and Properties

5035 ERDEMIR quality numbered SAE 1035 Standard Tool produced as hot mill product in Eregli Iron and Steel Factories (ERDEMIR) T.A.S and given chemical composition in Table 1 was used by preparing 12 mm diameter, and hardness measurement was performed by doing heat treatment.

Table 1. Chemical Composition of 1035 quality steel

Quality	Standard	Chemical Composition (% Weight)					
		C	Mn	P	S	Si	Al
5035	SAE 1035	0.36	0.71	0.012	0.006	0.230	0.041

It was utilized from previous studies to define relevant annealing temperatures. Temperatures values in the study performed related to mechanical properties of materials having same chemical composition [12].
It was given water in water to turning specimen annealed 30 minutes in 745 and 760 C° temperatures on the purpose of obtaining three different hardness on same material in total. During preparation of specimen, it was waited to chill oven for two different temperatures to prevent different heat treatment conditions. Specimens were subjected to cooling in water after annealing process. Temperature-time diagram (T-t) belong to aforesaid heat treatment was shown in Figure 1.

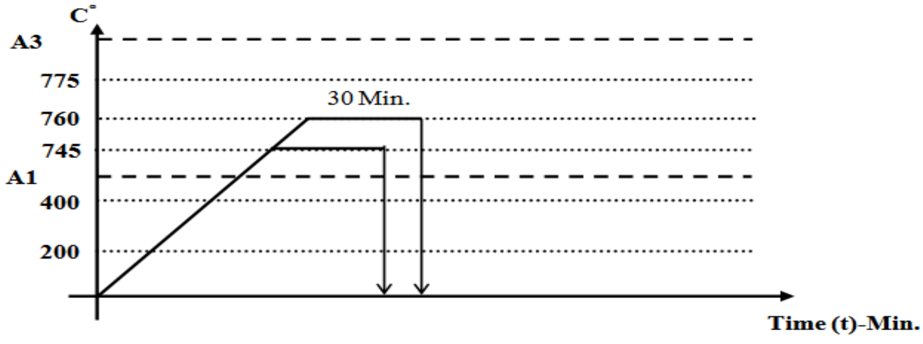


Figure 1. Temperature (T)-Time(t) diagram.

Determination of Martensite Volume Ratio

Martensite amount in microstructure of two-phase steels increases with cooling rate depending on hardening of austenite grains formed in the A1-A3 (Figure 1) temperature range. In addition to this, C level of steel and A1-A3 temperature level directly affect martensite volume ratio, as well. Martensite volume ratios were calculated by point count method from internal structure images obtained after tempering process. Results were given in Table 2.

Table 2. Volume of Martensite

Material	745◦	760◦
SAE 1035	% 44	% 60

Average Surface Roughness (Ra) Measurement

Average surface roughness is the arithmetic mean of the height changes measured from the mean line.

$$Ra = \frac{1}{l}\int_0^1 |Z(x)|dx$$

Ra values are calculated automatically by the device to be used in the experiment. Surface roughness was measured with TIME TR200 surface roughness equipment. Three measurement trace to parallel and vertical to cutting direction were measured. The mean of three arithmetical average surface roughness measurement (Ra) in the direction and through cutting were used to show surface roughness of specimen.

Choosing Cutting Parameters and its Levels

Experimental studies within study were performed in CNC Turning Table that has 1.5 kW power and rotates with maximum 2000 rpm. Dual phase steels are a new class of high strenght-low alloy steels (HSLA). A cylindrical workpiece made from 5035 number steel having 0,36 % C ratio that is produced by ERDEMIR as special wheel steel was processed with Al_2O_3 coated Cementite Carbide and CBN cutting tools by applying three different feed rate in dry cutting conditions in the study. Cutting area order is shown in Figure 2. Factors used in machining and its levels were defined with user experience and were specified in Table 3.

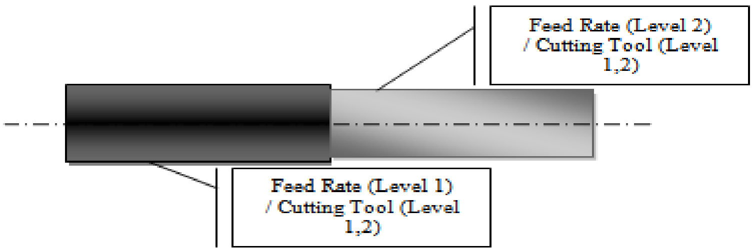


Figure 2. Cutting Area Order

Fishbone diagram is one of output in designing experiments. A fishbone diagram can be created to see relations defined factors to each other's exactly. This diagram specifies all factors representing product or process quality and affecting measured values [13]. It was decided variable and constant factors with the help of fishbone diagram. Factors affecting machinability are collected under four main categories (cutting parameters, rigidity, workpiece, cutting tool) as shown in Figure 3.

Values of variable parameters except factors that has to be constant and that cannot be controlled were taken as compatible with real working environment values as much as possible. Because cooling liquid usage will have positive effect to surface quality, experiments were planned in dry condition to keep experiment numbers in certain amount. Information on the levels of the selected factors is given in Table 3. Before starting the experiment given in Table 4 experimental design matrix is formed by means of coding method using Minitab 18.0 statistic software.

Table 3. The levels of the selected factors

Factors	Information	Low Level	High Level
A	Cutting Tool	Carbide	CBN
B	Feed Rate (mm/Rev)	0,02	0,06
C	Volume of Martensite (%)	44	60

Table 4. Experimental design matrix

Experiments	Levels of Factors		
	A	B	C
1	-1	-1	-1
2	+1	-1	-1
3	-1	+1	-1
4	+1	+1	-1
5	-1	-1	+1
6	+1	-1	+1
7	-1	+1	+1
8	+1	+1	+1

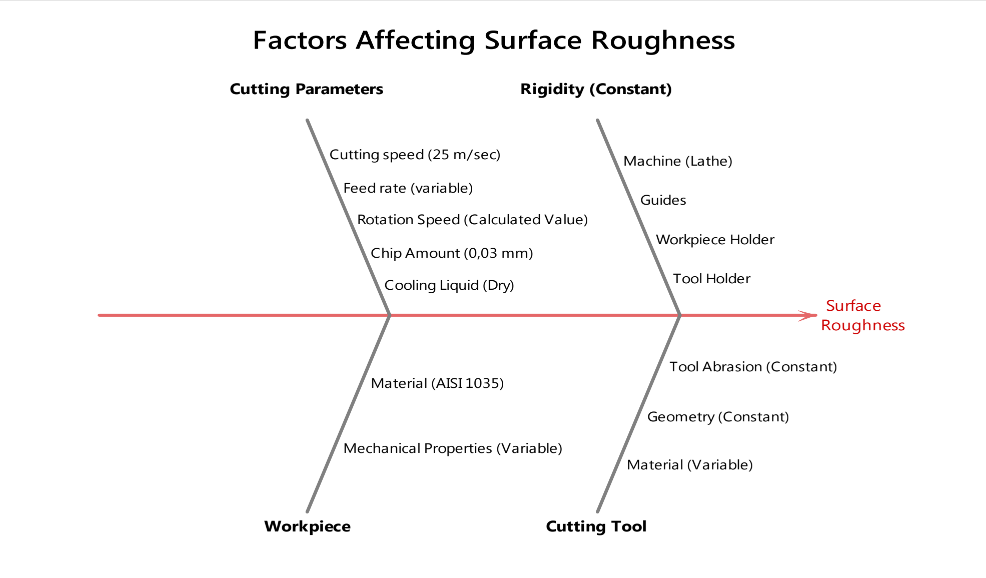


Figure 3. Evaluation of Factors Affecting Surface Roughness with Fishbone Diagram

Results of experimental data and discussion

Average surface roughness values as a result of experiments were shown in a three-dimensional graphic formed as cubes (Fig. 4)

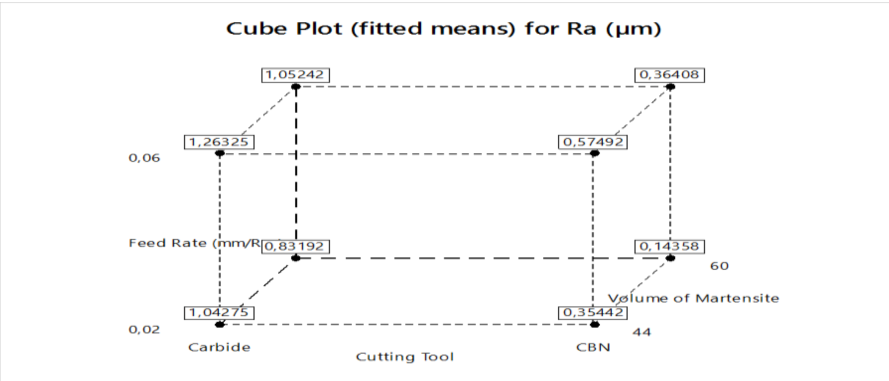
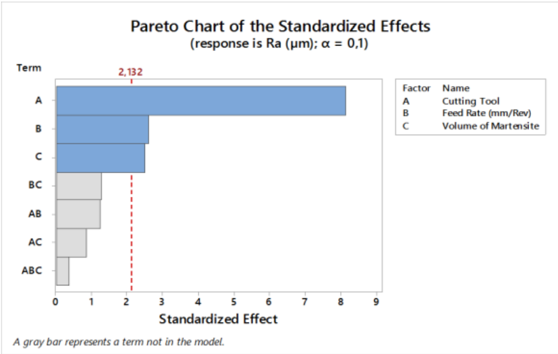
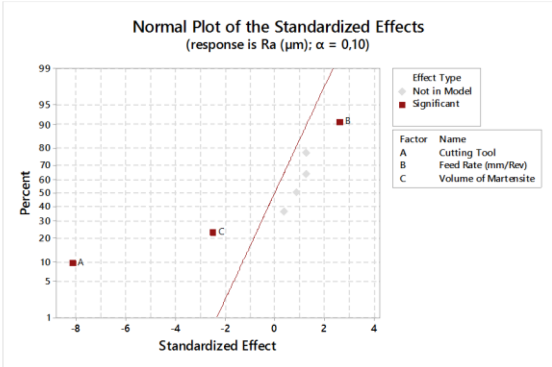


Figure 4. Representation of Experiment Results by Three-Dimensional Graph

As a result of the tests, a pareto graph was created at the α = 0.10 significance level with Minitab-18 program analysis for the roughness (Ra) values determined. In the pareto graph analysis for the main factors and binary / triple interactions given in Figure 5.a, the factors that cross the 2.132 line which is the threshold value of 0.10 are the factors that most affect the surface roughness. As can be seen from the graph, the primary factor is the cutting tool, the second factor is the feed rate, and the third factor is the volume of martensite. The effects of the main factors on the response (surface roughness) are given in Figure 5.b. Normal probability graph (Figure 5.b) clearly shows detection of parameters having significant effect.

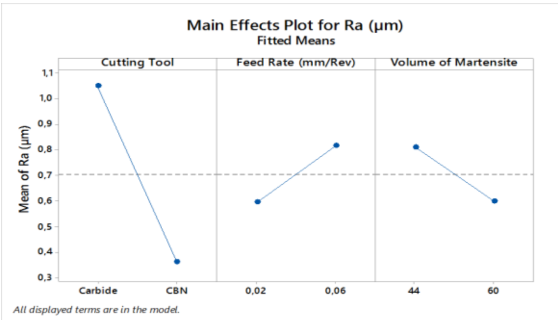


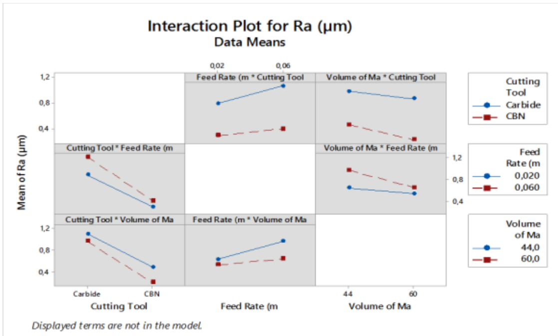


(a) (b)

Figure 5. a) Pareto graph showing factor effects b) Main factors- normal effect graphs

The main effects (the second and third effect factors (feed rate and volume of martensite) are the dual interaction graphs shown in Figure 6. Feed rate and VoM in dual interactions are effective on the result. In other words, while the martensite volume ratio is low, the increase in the feed rate increases the surface roughness and feed rate lose its importance in the hardness of material increase. This result can be explained by the increase in the amount of knock on the cutting tool at low martensite ratios.

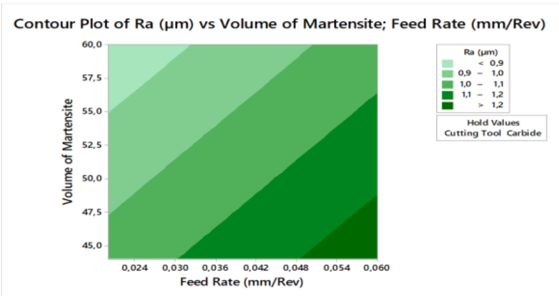


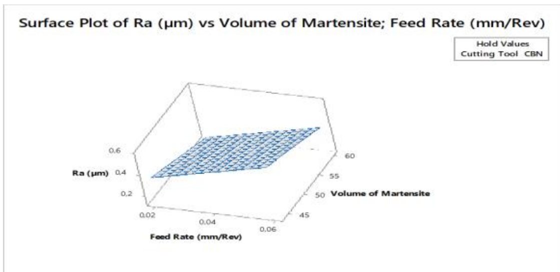


(a) (b)

Figure 6. a) Main factor effects graph b) Binary factor effects graph

In the case of using Carbide cutter, contour curves of effect of interaction between feed rate-martensite volume ratio on surface roughness is given below. Surface roughness reaches the lowest value by keeping feed rate at lowest level in high martensite volume ratio. Result obtained from the contour graphics will be crosschecked by investigating the best factor values with the optimization to be performed (Figure 6-7).





(a) (b)

Figure 7. (a) Contour Curves of Feed Rate-Martensite Volume Ratio Dual Interaction (VoM) (Cutting tool:Carbide) b) 3D Surface Graph

Optimization

Movements between upper and lower levels of factors may produce different results on the response. Within the scope of the study, optimization (optimization) was performed for the purpose of determining factor values that will optimize desired value from response (surface roughness). The response optimizer tool satisfaction function approach was used in the Minitab program.

In multi-purpose optimization method; level of individual satisfaction function (d) for each response to be optimized and combined satisfaction function (D) to cover all responses are investigated in which combination of factors can achieve the best values. While singular satisfaction function (d) evaluates optimum point that factors can reach individually, satisfaction function of whole system (D) shows approximation to result with obtained factor values. Satisfaction level takes value between 0 and 1. A value of 1 indicates ideal state, while a value of 0 indicates that one or more values are out of acceptable limits. Because combined satisfaction function was obtained as D = 1 in the study conducted, it was determined that the best factor values (CBN, 0.02 mm / rev, 60% VoM) were achieved without a deviation from the ideal situation. Combined satisfaction function (D) of system and single satisfaction function (d) of response seem to have same value since there is only one response. Response (y) value (Ra), which can be reached by applying the best factor values, was found as 0,1436 µm. Optimization results showing factor levels were given below (Table 5 and Figure 8).

Table 5. Factor Levels Obtained as a Result of Optimization

Variable	Setting			
Cutting Tool	CBN			
İlerleme Hızı	0,02			
Volume of Martensite	60			
Response	Fit	SE Fit	95% CI	95% PI
Ra (µm)	0,1436	0,0845	(-0,0911; 0,3783)	(-0,2630; 0,5501)

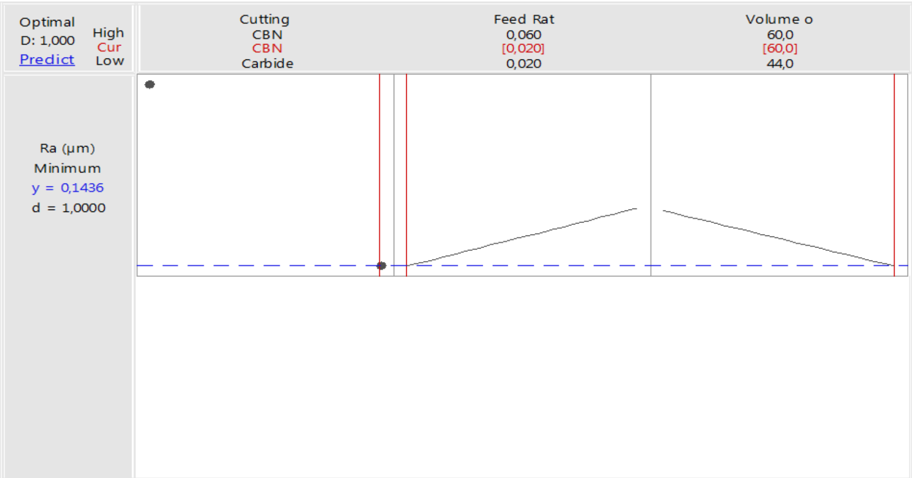


Figure 8. Optimization Results

Regression and Analysis of Variance Results

In multiple regression analysis; backward extraction method was used by using 8 values (2^3 full factorial) obtained for two levels of each parameter as a result of the experiments. In the regression analysis, it is aimed to explain the relationship between variables functionally and to define this relationship with a model.

All the main parameters in first stage, binary interactions of the parameters were modeled, according to p possibility value specified for each factor in analysis performed step by step in the level of $\alpha = 0.10$ significance (confidence): The most effective parameter ($p = 0.000 < 0.1$) was found to be cutting tool on Ra. After these factors, it was seen that the most important factor was VoM ($p = 0.060 < 0.1$). The stepwise procedure removed the following terms in order to obtain sufficient degrees of freedom to begin: Cutting Tool*Feed Rate (mm/Rev); Feed Rate (mm/Rev)*Volume of Martensite. The rate of explanation of the change on Ra (coefficient of regression determination) was R^2 = 95.20% (R^2 (corrected) = 98.68%). The results of the regression analysis were presented in Table 6.

In order to determine coefficients of regression equation, t-test was applied. Effects belong to factors in the model are seen here. Since coding method was not used in the experimental design matrix, regression equation coefficients were obtained as noncoded (Table 6).

Table 6. Regression Analysis Results

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		0,7034	0,0423	(0,5861; 0,8208)	16,64	0,000	
Cutting Tool	-0,6883	-0,3442	0,0423	(-0,4615; -0,2268)	-8,14	0,001	1,00
Feed Rate (mm/Rev)	0,2205	0,1103	0,0423	(-0,0071; 0,2276)	2,61	0,060	1,00
Volume of Martensite	-0,2108	-0,1054	0,0423	(-0,2228; 0,0119)	-2,49	0,067	1,00

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,119553	95,20%	91,60%	0,228688	80,80%

Regression Equation in Uncoded Units

Ra (µm) = **1,168 - 0,3442 Cutting Tool + 5,51 Feed Rate (mm/Rev) - 0,01318 Volume of Martensite**

In variance analysis, significance of model contribution of factors investigated their effects on result variable at the α = 0.10 significance level is investigated. When the contribution ratios of the factors determined that they are in model by regression analysis are examined, it is seen that the highest contribution value belongs to Cutting Tool factor with 79,57%. It is also possible to conclude that the most effective factor on Ra is the cutting tool factor, which supports other analysis results. VoM factor is seen as the second most important factor. The results of variance analysis were presented in Table 7.

Table 7. Variance Analysis Result

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	3	1,13375	95,20%	1,13375	0,37792	26,44	0,004
Linear	3	1,13375	95,20%	1,13375	0,37792	26,44	0,004
Cutting Tool	1	0,94761	79,57%	0,94761	0,94761	66,30	0,001
Feed Rate (mm/Rev)	1	0,09724	8,17%	0,09724	0,09724	6,80	0,060
Volume of Martensite	1	0,08890	7,46%	0,08890	0,08890	6,22	0,067
Error	4	0,05717	4,80%	0,05717	0,01429		
Total	7	1,19092	100,00%				

Verification Test

In order to check accuracy of regression equation obtained according to optimization results given in Table 8, a verification test was performed. The value of the surface roughness value of 0,241 µm stayed within estimation limit of surface roughness value in performed verification test.

Regression Equation in Uncoded Units

Ra (µm) = 1,168 - 0,3442 Cutting Tool + 5,51 Feed Rate (mm/Rev) - 0,01318 Volume of Martensite

Table 8. Estimation Values of Verification Test

Variable	Setting
Cutting Tool	CBN
Feed Rate (mm/Rev)	0,04
Volume of Martensite	60

Prediction

Fit	SE Fit	95% CI	95% PI
0,253833	0,0732112	(0,0505664; 0,457100)	(-0,135393; 0,643060)

III. RESULTS

In this study, the variables which may be effective in minimizing the surface quality value were determined, and then experiments were performed in the way of 8*3 experiments as three replicates by using two factors and two levels in accordance with the full factorial experimental design plan. The results were analyzed in Minitab 18.0 program and the results were compared with the literature. SAE 1035 steel with dual phase used widely used in industry was used as workpiece.

1. Ra change explanation rate of the regression model which was formed at the α = 0.10 confidence level was found to be 91.60%.
2. The most effective parameter on Ra is the main factor of the cutting tool. Feed rate is the second important factor on Ra.
3. The third important factor on Ra is VoM factor.
4. The surface roughness reaches the lowest value by keeping the feed rate at the lowest level in the high martensite volume ratio.
5. Binary factor interactions have no significant effect on result variable
6. Optimization was performed to determine the best value for Ra value. With the determined factor levels (CBN, 0,02 mm / rev, 60% VoM) Ra value was determined as 0,1436 µm.

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Ayhan Aytaç"Analysis of Paramaters Affected on Machinability of Dual-Phase SAE 1035 Steel by Full Factorial Experiment Design"American Journal of Engineering Research (AJER),vol.7,no.12,2018,pp.43-50