International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 6 Issue 9 Ver. I ǁ 2018 ǁ PP. 01-08

Investigation of Machinability in Heat Treated SAE 1040 Steel by Experimental Design Method

Ayhan Aytaç*[1], Muhammed Ilivan[2]
[1](*Dr., Turkish Military Academy/ National Defence University, Turkey)*
[2](*Lecturer, Dumlupınar University, Turkey)*
Corresponding Author: Ayhan Aytaç

ABSTRACT: *The purpose of design in engineering experiments is not only to investigate effects of the variables on production, but also to investigate effects of interactions between them. Especially statistical-based experiment design techniques are quite useful for improving the manufacturing process performance in the engineering world. It can be decided to subset of process variables that are the most effective ones by using experimental design. Using experimental design offers advantages such as easier production, better performance, more reliable and shorter design, development and production. In problems that two or more problems are considered, factorial experiment design is a powerful technique. Double-phase steels are widely used in the automotive industry, especially due to their high strength / weight characteristics. These steels provide high strength with the hard martensite phase that is dispersed in the ferrite phase. When the heat treatment parameters are applied correctly between the critical temperatures, a double phase structure is obtained. In this study, the bars prepared from SAE 1040 steel were cooled in water after annealing process between critical temperature, and specimens having double phase microstructures were obtained with two different martensite volume ratios. In the machinability study, the experiments were carried out with full factorial experiment design technique as three factorials (k = 23 and 8 experiments). Type of cutter (CBN and Ceramic cutter), feed rate (0.02 and 0.06 mm / rev) and martensite volume ratio (55% and 78) was used as independent variable (factor) in the experiments, average surface roughness value (Ra) that is dependent variable 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 the surface quality were the cutter tool, the martensite volume ratio, dual interaction of the cutter tool-martensite volume ratio (material hardness), respectively. The results obtained were interpreted together with evaluations that were previously included in the literature.*

KEYWORDS: *Full Factorial Experiment Design, DOE, Dual Phase, Surface Quality, Machinability.*

Date of Submission: 18-12-2018 Date of acceptance: 31-12-2018

I. INTRODUCTION

It has enumerated the heat-treatment practices of the steels of commercial importance like low-carbon lean-alloy steels, medium-carbon high-alloy steels, structural steels, and ultra high-strength maraging steel (1). Heat treatment; It is a term that defines the controlled heating and cooling processes applied to material in solid form and to change mechanical properties of the material (2). The purpose with these processes is to change microstructure and / or mechanical properties of the material. It is generally aimed to achieve better mechanical properties such as better tensile strength, higher impact toughness or high wear resistance by heat treatment in many applications. In practice, however, the heat treatment applied to a material causes the simultaneous change of more than one mechanical property of the material (1-3).

Two-phase ferritic martensite steels are obtained by heat treatment performed in the ferrite austenite phase region to the martensite structure obtained by tempering after austenite conversion. By simply changing the heat treatment temperature in these steels, a wide range of strength and ductility can be provided. Strength enhancing mechanisms can be calculated by the morphology and amount of the second phase (4).

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 (5). 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 (6).

The purpose of design in engineering experiments is not only to investigate effects of the variables on production, but also to investigate effects of interactions between them. Especially statistical-based experiment design techniques are quite useful for improving the manufacturing process performance in the engineering world. It can be decided to subset of process variables that are the most effective ones by using experimental design. Using experimental design offers advantages such as easier production, better performance, more reliable and shorter design, development and production. In problems that two or more problems are considered, factorial experiment design is a powerful technique. When each replay is completed in a factorial experiment, all possible combinations of all levels of all factors are investigated. Effect of a factor is described as the change in factor level generated by the response. This is called main effect. Factorial experiments are the only way to determine interaction between variables (7).

Hossainy et al., (2010) used a factorial experiment design to investigate surface roughness of 195 BHN Cast Iron material by using High Speed Steel (H.S.S.) cutter in their study. Based on the experimental results, the shear rate ranging from 16 to 64 m / min with a 95% confidence interval for surface roughness, estimation models from first order for the cutting depth ranging from 0.15 to 0.3 mm / rev. and in the dry state, tool nose radius from 0.4 to 1.6 mm were developed. The developed models were tested by variance analysis. Based on the developed surface roughness models, contour curves were obtained to correlate surface roughness with material removal rate for different cutting speeds and feeds, which is used to increase efficiency of cutting process (8).

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 (9).

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

5040 ERDEMIR quality numbered SAE 1040 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 5040 quality steel

Quality	Standard	Chemical Composition (% Weight)					
		C	Mn	P	S	Si	Al
5040	SAE 1040	0.38	0.75	0.010	0.016	0.210	0.058

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 (4).

It was given water in water to turning specimen annealed 30 minutes in 745 and 775 C$^{\circ}$ 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.

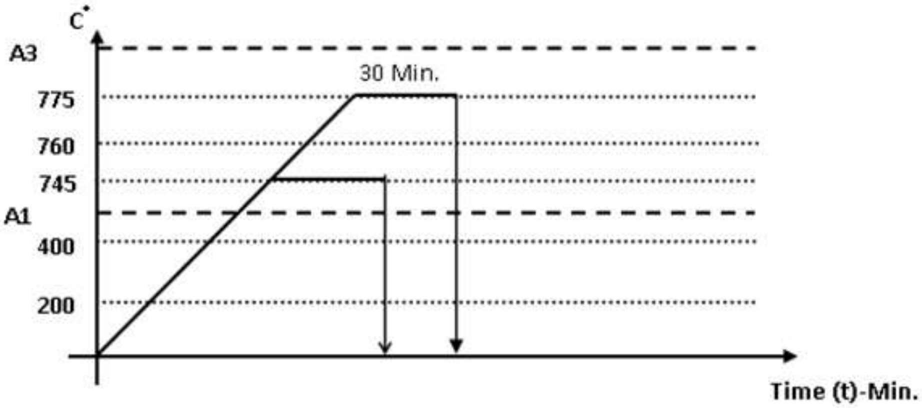


Figure 1. Temperature (T)-Time(t) diagram.

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 (VoM)

Material	745◦	775◦
SAE 1040	% 55	% 78

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 is a new class of high strenght-low alloy steels (HSLA). A cylindrical workpiece made from 1040 number steel having 0,38 % C ratio that is produced by ERDEMIR as special wheel steel was processed with Ceramic 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.

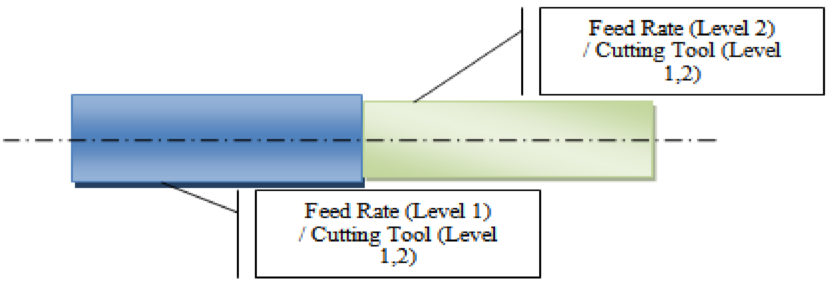


Figure 2: Cutting Area Order

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 (10). 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	Ceramic	CBN
B	Feed Rate (mm/Rev)	0,02	0,06
C	Volume of Martensite (%)	55	78

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

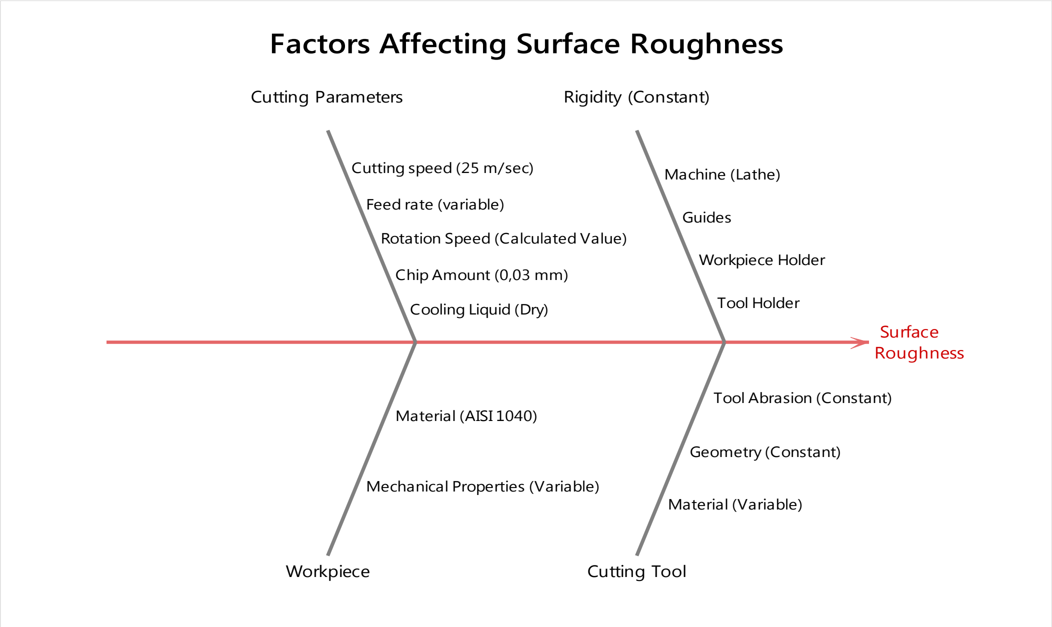


Figure 3. Evaluation of Factors Affecting Surface Roughness with Fishbone Diagram

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)

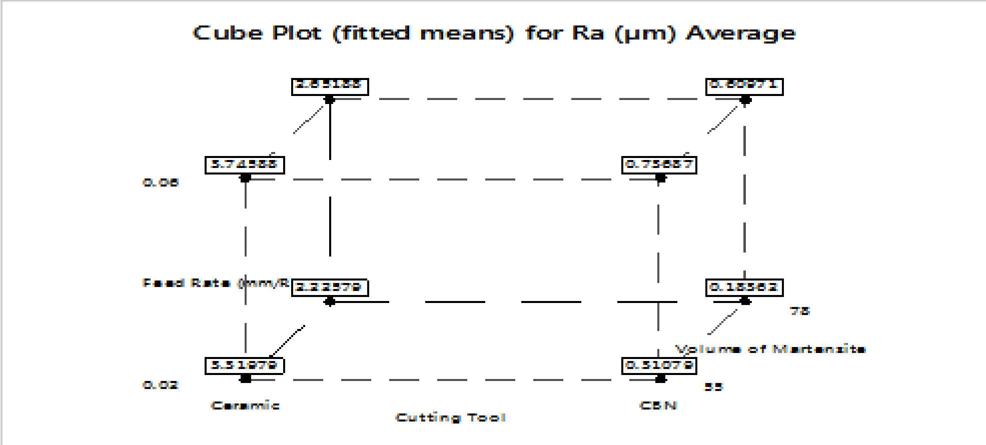
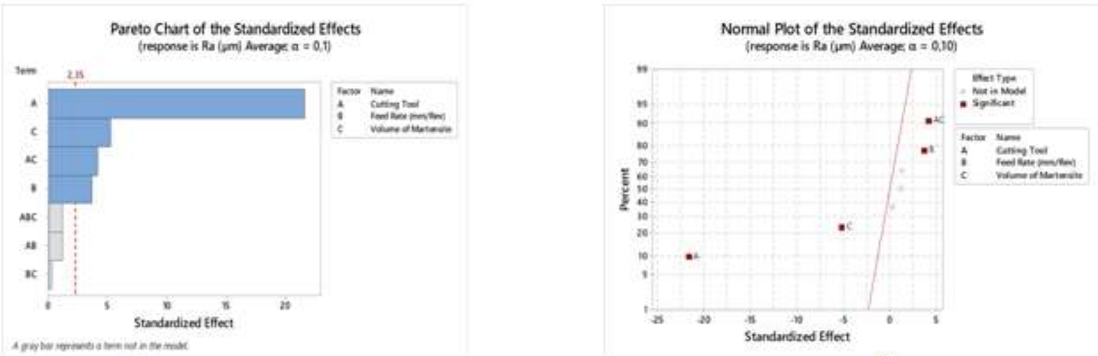


Figure 4. Representation of Experiment Results by Three-Dimensional Graph

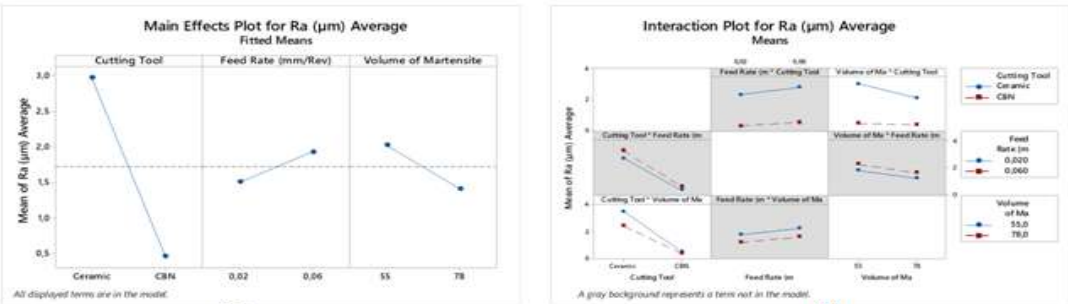
As a result of the tests, a pareto graph was created at the α = 0.10 significance level with Minitab-18 program analysis for the roughness (Ra) values determined. In the pareto graph analysis for the main factors and binary / triple interactions given in Figure 5.a, the factors that cross the 2.35 line 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 VoM, and the third factor is the binary interaction (Cutting tool and VoM). 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

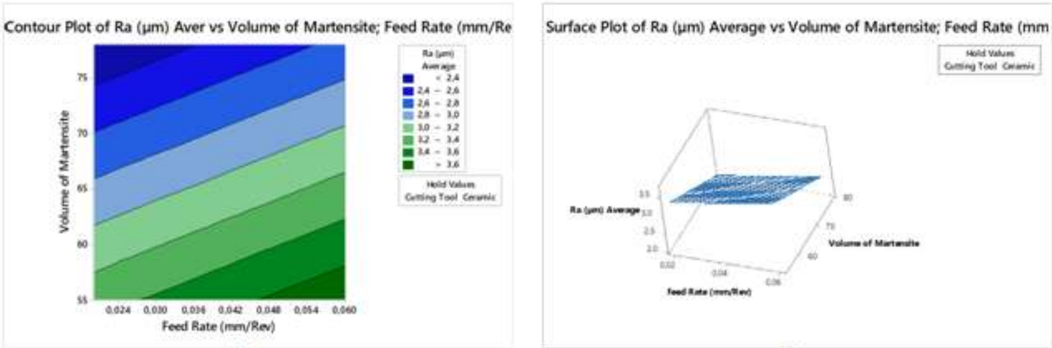
Main factor and binary interaction graphs were shown in Figure 6. As a dual interaction, cutting tool-VoM interaction comes into prominence. In other words, it has an effect on the result, when VoM-Ceramic cutting tool is evaluated together. It does not make any difference when CBN is used. Ceramic cutter tool significantly reduces Ra when VoM increases. This result can be explained by increase in amount of knock on the cutting tool at low martensite ratios. It can be concluded that ceramic cutters are more useful in hard internal structures.



(a) (b)

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

In the case of using Ceramic 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:Ceramic) 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, 78% 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 0,1836 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	78			
Response	Fit	SE Fit	95% CI	95% PI
Ra (µm) Average	0,184	0,130	(-0,231; 0,599)	(-0,485; 0,853)

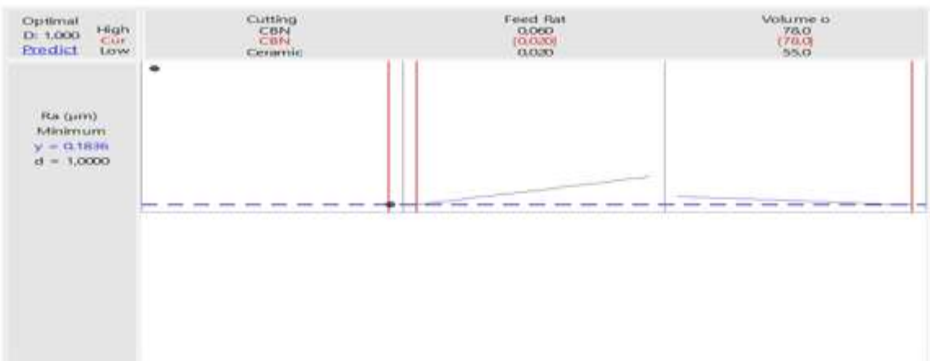


Figure 8. Optimization Results

Regression and Analysis of Variance Results

In multiple regression analysis; backward extraction method was used by using 8 values (23 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 ($p = 0.014 < 0.1$). 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 = 99.43% (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).

Term	Effect	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant		1,7230	0,0583	(1,5375; 1,9086)	29,55	0,000	
Cutting Tool	-2,5256	-1,2628	0,0583	(-1,4483; -1,0772)	-21,66	0,000	1,00
Feed Rate (mm/Rev)	0,4261	0,2130	0,0583	(0,0275; 0,3986)	3,65	0,035	1,00
Volume of Martensite	-0,6106	-0,3053	0,0583	(-0,4908; -0,1197)	-5,24	0,014	1,00
Cutting Tool*Volume of Martensite	0,4834	0,2417	0,0583	(0,0562; 0,4273)	4,15	0,025	1,00

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,164905	99,43%	98,68%	0,580130	95,98%

Regression Equation in Uncoded Units

Ra (µm) Average = 3,062 - 2,660 Cutting Tool + 10,65 Feed Rate (mm/Rev) - 0,02655 Volume of Martensite + 0,02102 Cutting Tool*Volume of Martensite

In variance analysis, significance of model contribution of factors investigated their effects on result variable at the $\alpha = 0.10$ 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 88,50%. 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	4	14,3332	99,43%	14,3332	3,5833	131,77	0,001
Linear	3	13,8659	96,19%	13,8659	4,6220	169,96	0,001
Cutting Tool	1	12,7571	88,50%	12,7571	12,7571	469,12	0,000
Feed Rate (mm/Rev)	1	0,3631	2,52%	0,3631	0,3631	13,35	0,035
Volume of Martensite	1	0,7456	5,17%	0,7456	0,7456	27,42	0,014
2-Way Interactions	1	0,4674	3,24%	0,4674	0,4674	17,19	0,025
Cutting Tool*Volume of Martensite	1	0,4674	3,24%	0,4674	0,4674	17,19	0,025
Error	3	0,0816	0,57%	0,0816	0,0272		
Total	7	14,4148	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 0,321 µm stayed within estimation limit of surface roughness value in performed verification test.

Regression Equation in Uncoded Units

Ra (µm) Average = 3,062 - 2,660 Cutting Tool + 10,65 Feed Rate (mm/Rev) - 0,02655 Volume of Martensite + 0,02102 Cutting Tool*Volume of Martensite

Table 8: Estimation Values of Verification Test

Variable	Setting
Cutting Tool	CBN
Feed Rate (mm/Rev)	0,04
Volume of Martensite	78

Prediction

Fit	SE Fit	95% CI	95% PI
0,396667	0,116605	(0,0255765; 0,767757)	(-0,246080; 1,03941)

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 1040 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 98.68%.
2. The most effective parameter on Ra is the main factor of the cutting tool. VoM factor is the second important factor on Ra.
3. The third important factor on Ra is Cutter tool-VoM binary interaction.
4. VoM-Ceramic cutting tool is effective on the result when evaluated together. It does not make any difference when CBN is used.
5. Bilateral factor interactions have a significant effect on the result.
6. Optimization has been performed to determine conditions for obtaining the best value for Ra value. Determined factor levels (CBN, 0,02 mm / rev, 78% VoM) Ra value was determined as 0,1836 µm

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Ayhan Aytaç" Investigation of Machinability in Heat Treated SAE 1040 Steel by Experimental Design Method" International Journal of Research in Engineering and Science (IJRES), vol. 06, no. 09, 2018, pp. 01-08