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MODELLING OF SURFACE ROUGHNESS WITH VARIANCE ANALYSIS IN TURNING OF AISI 304 AUSTENITIC STAINLESS STEEL

ABSTRACT

In this study, an attempt has been made to optimize and model to surface roughness when turning AISI 304 austenitic stainless steel. The as – received specimens were annealed at 1050˚C for 60 minutes and water quenched. Annealed specimens were then tempered at 700˚C for 30 90 and 240 minutes respectively and followed by room cooling. The experimental studies were conducted under varying cutting speed, feed rate and holding time. A full factorial experimentation, the signal – to – noise (S/N) ratio and the analysis of variance (ANOVA) were employed to the study the surface roughness in turning AISI 304 using CCMT09T308 – 41 insert cutting tools. The conclusions revealed that the feed rate was the most important factor on the surface roughness, whereas holding time was the second ranking factor and cutting speed was the least. A non – linear regression method was also used to model the surface roughness. The high correlation coefficient (0.95) of regression model showed that the model can adequately describe the performance within the limits of factors being studied. The experimental and predicted values were in a good agreement.

Keywords: AISI304, Surface Roughness, ANOVA, Regression Analysis, Austenitic Stainless Steel

AISI 304 ÖSTENİTİK PASLANMAZ ÇELİĞİN TORNALANMASINDA YÜZEY PÜRÜZLÜLÜĞÜNÜN VARYANS ANALİZİ İLE MODELLENMESİ

ÖZET

Bu çalışma, AISI 304 Östenitik paslanmaz çeliğinin tornalanması sırasında yüzey pürüzlülüğünün modellenmesi ve optimizasyonu için yapılmıştır. Deney numuneleri 1050°C'de 60 dakika tavlanmış ve suya çekilmiştir. Daha sonra tavlanmış numuneler 700°C'de sırası ile 30, 90 ve 240 dakika bekletilmiş ve ardından oda sıcaklığında soğutulmuştur. Deneysel çalışmalar farklı kesme hızları, ilerleme miktarı ve bekleme süresi esas alınarak yapılmıştır. Tornalama işleminde CCMT09T308-41 kesme takımı kullanılarak yüzey pürüzlülüğünün ölçümünde tam deneysel çalışma, sinyal gürültü oranı ve varyans analizi yapılmıştır. Yapılan analizler sonucunda, yüzey pürüzlülüğüne etki eden en önemli faktörün ilerleme oranı, bekleme süresinin ikinci ve en az etkili olan parametrenin ise kesme hızı olduğu tespit edilmiştir. Aynı zamanda yüzey pürüzlülüğünü modellemek için doğrusal olmayan regresyon metoduda kullanılmıştır. Regresyon modelinin yüksek korelasyon katsayısının (0.95), gerçekleştirilen modelin yüzey pürüzlülüğünü modellemek için yeterli ve deneysel sonuçlar ile analiz sonuçlarının uyumlu olduğu görülmüştür.

Anahtar Kelimeler: AISI304, Yüzey Pürüzlülüğü, Varyans Analizi, Regressyon Analizi, Östenitik Paslanmaz Çelik

1. INTRODUCTION (GİRİŞ)

Austenitic stainless steels have many applications because of their high corrosion and oxidation resistance properties. However, these materials are considered difficult to machine because of specific properties such as high mechanical and microstructural sensitivity to strain and stress rates. They are prone to work-hardening, which induces mechanical modifications and behavioral heterogeneity on the machined surface, and leads to unstable chip formation and vibrations. Moreover, their low thermal conductivity leads to bad heat conduction at the tool tip and, locally, to very hot points. These thermo-mechanical phenomena affect the surface integrity of the workpiece. Poor tool performance is another problem because of the soft matrix of austenitic stainless steel which dissipates the heat slowly [1]. Austenitic stainless steels are generally regarded as more difficult to machine than carbon and low alloy steels on account of their high strength, high work hardening tendency and poor thermal conductivity [2]. Problems such as poor surface finish and high tool wear are common [3]. Work hardening is recognised to be responsible for the poor machinability of austenitic stainless steels [4].

A little literature survey has been conducted on the machining of AISI 304 austenitic stainless steel. Work to date has shown that little work has been carried on the determination of optimum machining parameters when machining austenitic stainless steels. In this study, turning tests were carried on an AISI 304 austenitic stainless steel to determine the optimum machining parameters.

In study on turning hardened AISI 4140 steel (63 HRC) with Al_2O_3 +TiCN mixed ceramic tools. It was shown that the cutting speed increases, the tool wear decreases. In order to minimize the tool wear, the highest level of the cutting speed, 250 m/min, and the low levels of axial depth of cut, 0.25 or 0.50 mm, should be preferred. Only two interactions, cutting speed-feed rate and feed rate-axial depth of cut, have statistically significant influence on the surface roughness: they explain 28% and 23% of the total variation, respectively [5]. The poor performance of the tool could well be explained by the thermal softening of the tool due to the higher influence of the heat on the cutting tool and less efficient heat dissipation at the lower cutting speeds. It was shown that surface roughness values were found to decrease with the increasing cutting speed. This could be attributed to the presence of built-up-edge at the lower cutting speeds. Inhomogeneous distribution of chip thickness at the lower cutting speeds may also indicate the variation in the cutting forces and this may be another reason for poor surface finish due to the force fluctuations [6]. An experimental study performed on the Inconel 718 workpiece, using SNGN 120712 T01020 ceramic cutting insert (KY 4300 grade) and it was found taht the stresses on the ceramic insert increase with increases in the feed rate and cutting tool stresses were influenced by the feed force and not by the primary cutting force value in the machining of Inconel 718 [7]. Several studies were investigated about the machinability of the various materials. A study was made on the machinability of AISI 304 and AISI 316 austenitic stainless steel using CVD multilayer coated cemented carbide tools under dry turning conditions. The effect of cutting speed, cutting tool coating top layer and workpiece material were investigated on the machined surface roughness and the cutting forces. The results showed that an increase in cutting speed lead to significant reduction in surface roughness [8]. A study presented a finite element model to simulate the effects of cutting – edge radius on residual stress when orthogonal dry cutting austenitic stainless steel AISI 316L with continuous chip formation. Larger edge radius induced higher residual stress in both the tensile and compressive regions, while it had almost no effect on the thickness of tensile layer and pushed the maximum compressive stresses deeper into the workpiece [9]. A study was investigated the performance of PVD TiN/TaN and TiN/NbN superlattice coated cemented carbide tools in AISI 303/304 austenitic stainless steel machining. The results from the machining tests indicate a superior performance of tools coated with the harder lamellae coatings as compared to tools coated with single layer PVD or CVD coatings [10].

From the review of literature, it is observed that AISI 304 austenitic stainless steel machining have attended great importance from different machining perspective. Cutting tool material and machining conditions were changed to explore their effects on machinability. However, optimization of 304 machining parameters and surface roughness model for this steel is rather lacking in the open literature. In this study, we aimed to determine a suitable mathematical equation for predict the surface roughness and optimize the turning parameters to obtain best quality performance.

2. RESEARCH SIGNIFICANCE (ÇALIŞMANIN ÖNEMİ)

In this study, an attempt has been made to optimize and model to surface roughness when turning AISI 304 austenitic stainless steel. A non – linear regression method was also used to model the surface roughness. The high correlation coefficient (0.95) of regression model showed that the model can adequately describe the performance within the limits of factors being studied. The experimental and predicted values were in a good agreement.

3. EXPERIMENTAL METHOD (DENEYSEL METOD)

In this study, AISI 304 austenitic stainless steel was selected for the study. In order to remove the residual stresses induced during the fabrication of specimens, the test-pieces were annealed by keeping them at 1050˚C for 1 hour in an electric resistance furnace with time and temperature controlled automatically and followed by water quenching. The annealed specimens were then tempered at 700˚C for different holding times, namely, 0, 30, 90 and 240 minutes and room cooled. Experiments were carried out in accordance with the ISO 3685-1977 (E) test for single-point turning tools [11] on a DYNA MYTE 3300 CNC lathe (10 kW) using P – 20 grade CCMT09T308 – 41 insert cutting tools. The cutting tool geometry was specified in Table 1.

Table 1. Tool geometry used in the turning tests
(Tablo 1. Deneylerde kullanılan takım geometrisi)

Back rake angle	-6°
Side rake angle	-6°
End clearence angle	6°
Side clearence angle	6°
End cutting edge angle	15°
Side cutting edge angle	15°
Aproach angle	15°
Nose radius	0.8 mm

Experiments were performed under dry machining conditions. Specimens were prepared with 30 mm in diameter and 120 mm length for the experiment with 2.5 mm dept of cut and 90 mm lengths 3 passes chips were removed between chuck and tailstock. A schematic illustration of the test configuration is shown in Fig. 1. The nominal chemical composition—of the AISI 304 is given in Table 2.

Table 2. Chemical composition of AISI 304 austenitic stainless steel (wt. %)
(Tablo 2. AISI304 paslanmaz çeliğinin kimyasal yapısı)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Nb	V	Fe
0.05	0.28	1.9	0.04	0.01	18.13	8.4	0.44	0.850	0.02	0.05	balance

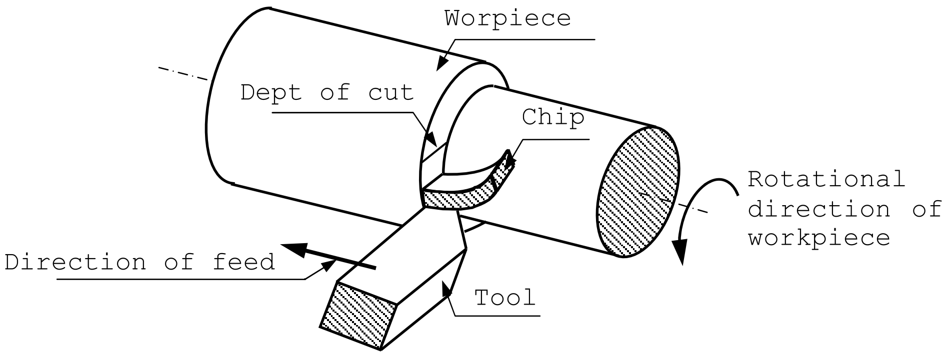

Figure 1. Schematic diagram of the workpiece used in experiments
(Şekil 1. Deneylerde kullanılan deneysel çalışamnın şeması)

Three different cutting speeds, feed rates and dept of cut are chosen as 125, 160 and 195 m/min and 0.2, 0.3, 0.4 mm/rev and 2.5 mm respectively according to ISO 3685 and as recommended by manufacturing companies for cutting tool qualities. Mitutoyo Surftest 211 instrument is used for the measurement of surface roughness. Measurement processes are carried out with three replications. For measuring surface roughness on work-piece during machining, cut-off length and sampling length are considered as 0.8 and 2.5 mm, respectively.

4. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

4.1. Effect of Main Factors on Surface Roughness (Yüzey Pürüzlülüğünü Etkileyen Temel Faktörler)

Table 3 shows the experimental results for surface roughness and corresponding S/N ratios using Equ.3. It is possible to separate out the effect of each cutting parameters at different levels. On the other hand, Figure 2 depicts the plot of main effects for surface roughness. Note that this plot illustrates data means versus factor level. Based on this plot, the effect of each factor can be graphically assessed.

Fig.2a presents that surface roughness is almost constant between 125 and 195 m/min cutting speed interval. It is obvious from this figure that by changing cutting speed during turning operation, surface roughness fluctuates insignificantly between 4.5 and 5 µm. So, it is concluded that the effect of cutting speed on surface roughness is almost negligible. Fig.2b shows that feed rate factor has a significant effect on surface roughness. It can also be seen from this figure that the effect of this factor directly proportional to surface roughness. Any change in feed rate makes a significant increase in surface roughness. Fig.2c. shows that holding time the effect of holding time on surface roughness. The effect of this factor is similar as cutting speed does. The trend is straighter and a slightly decrease of surface roughness was observed with longer heat treatment time. This improvement in surface roughness can be attributed to microstructure of samples. Samples with shorter time hold in furnace probably contained a more carbide preparation structure than longer hold samples. These precipitations probably made the samples hard and difficult to machine requiring more cutting forces which lead vibration during machining. On the other hand, an increase in cutting speed lead to higher temperature occurrence at flow region and decrease the contact area and chip thickness cause lower cutting forces.

Table 3. Experimental results for surface roughness and corresponding S/N ratios
(Tablo 3. S/N oranına bağlı olarak yüzey pürüzlülüğü için deneysel sonuçlar)

Sample Number	Cutting Parameters Level			Measured Surface Roughness	Calculated S/N Ratio for Surface Roughness
	V	F	T		
	Cutting Speed	Feed Rate	Holding Time		
1	125	0.2	240	2.780	-8.8809
2	160	0.3	90	4.280	-12.6289
3	195	0.3	30	4.300	-12.6694
4	125	0.2	0	3.520	-10.9309
5	195	0.4	0	7.060	-16.9761
6	160	0.4	30	7.106	-17.0325
7	160	0.4	240	6.300	-15.9868
8	125	0.4	90	7.203	-17.1503
9	195	0.2	0	3.380	-10.5783
10	125	0.3	30	4.520	-13.1028
11	160	0.3	0	4.620	-13.2928
12	125	0.4	240	6.690	-16.5085
13	160	0.2	90	3.220	-10.1571
14	195	0.2	0	3.160	-9.9937
15	160	0.2	30	3.220	-10.1571
16	195	0.2	30	2.980	-9.4843
17	160	0.2	240	2.370	-7.4950
18	125	0.3	240	3.880	-11.7766
19	125	0.4	0	7.690	-17.7185
20	195	0.3	240	3.350	-10.5009
21	195	0.2	240	2.040	-6.1926
22	160	0.3	240	3.520	-10.9309
23	195	0.4	240	6.090	-15.6923
24	195	0.3	90	4.176	-12.4152
25	125	0.3	0	4.706	-13.4530
26	195	0.4	30	6.960	-16.8522
27	125	0.2	90	3.160	-9.9937
28	195	0.3	0	4.480	-13.0256
29	195	0.2	90	2.980	-9.4843
30	195	0.4	90	6.503	-16.2623
31	160	0.4	0	7.440	-17.4315
32	160	0.4	90	6.980	-16.8771
33	125	0.2	30	3.380	-10.5783
34	160	0.3	30	4.450	-12.9672
35	125	0.3	90	4.400	-12.8691
36	125	0.4	30	7.480	-17.4780

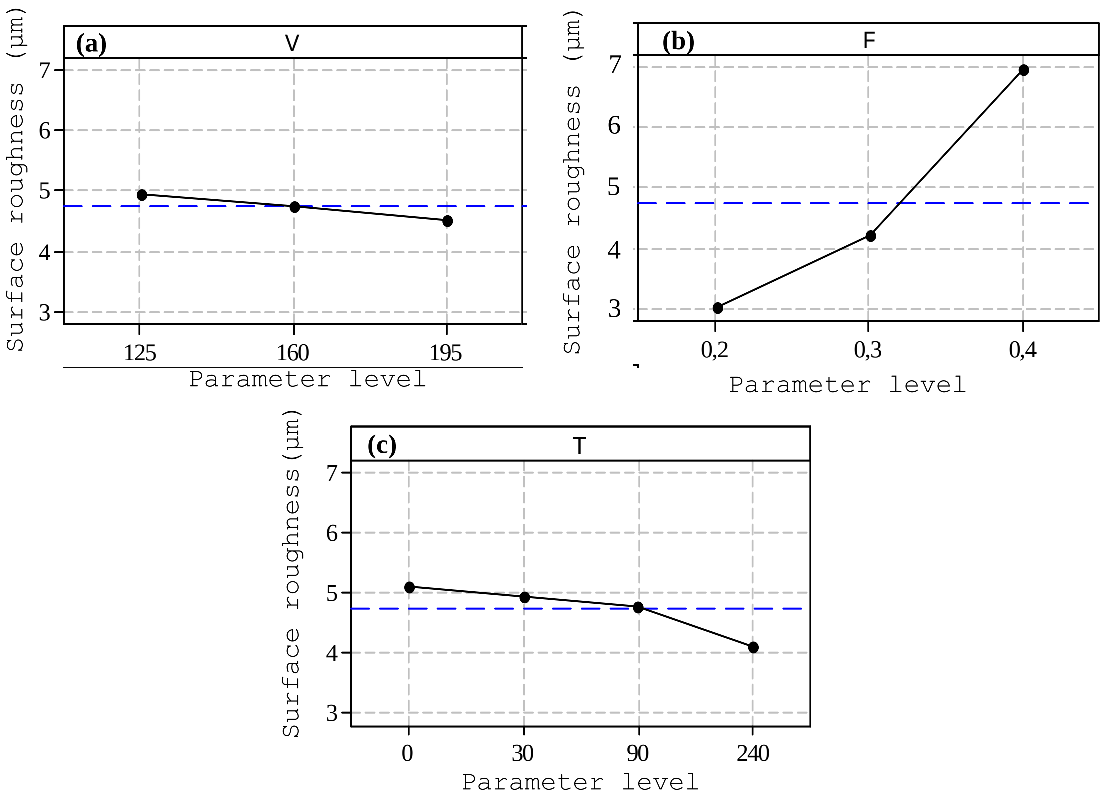

Figure 2. Plot of main effects on surface roughness
(Şekil 2. Yüzey pürüzlülüğünü etkileyen temel faktörler)

Factor effects are calculated here to consider effect of factors on surface roughness more accurately than graphical assessment. Table 4 shows the magnitude of factor effects. Using this table, one can sort factors in order of their significance. Also, this table illustrates the proportionality of factor effects to the surface roughness. Positive values of factor effects indicate direct proportionally of the respective factors, while negative values demonstrate that the corresponding factor is reciprocally proportional to the surface roughness. From the examination of Table 4 that the single and squared effect of feed rate is directly proportional to surface roughness and squared effect of feed rate is less important than its pure effect. Cutting speed and holding time have negative effect. However, effect of holding time is higher than cutting speed. Additionally, two - way interaction of factors are also included in Table 4. The interaction of feed rate and holding time has the most significant effect among the two -way parameter interactions.

Table 4. Values of the estimated effects
(Tablo 4. Parametrelerin yaklaşım değerleri)

Term	Effect
V	-0.23709
F	1.96751
T	-0.48757
V^2	-0.01183
F^2	0.76367
T^2	-0.02192
VxF	-0.04812
VxT	-0.06004
Fxt	-0.01530

4.2. Analysis of Variance (ANOVA) (Varyans Analizi)

The purpose of the statistical analysis of variance (ANOVA) is to investigate which design parameter significantly affects the surface roughness. Based on the ANOVA, the relative importance of the machining parameters with respect to surface roughness was investigated to determine more accurately the optimum combination of the machining parameters [12]. The analysis is carried out for level of significance of 1% (the level of confidence is 99%) [13 and 14]. Table 5 shows the results of ANOVA analysis for the surface roughness. The last column of Tables 5 indicates the percentage contribution of each factor on the total variation indicating their degree of influence on the results. The greater the percent contribution, the greater a factor has influence on the performance. According to the Table 5, feed rate was found to be the major factor affecting the surface roughness (93.61%), whereas the holding time was the second ranking factor (4.93%) and cutting speed was the least (0.13%).

Table 5. Results of ANOVA for surface roughness
(Tablo 5. Yüzey pürüzlülüğü için varyans analiz sonuçları)

Source	DF	SS	MS	F	P
V	2	1.18	0.59	0.19	0.13
F	2	97.933	48.967	241.76	93.61
T	3	5.16	1.72	0.55	4.93
Error	33	103.43	3.13	-	1.33
Total	40	207.703	-	-	100
DF-Degree of freedom SS-Sum of square MS-Mean square					

3.3. Non-linear Regression Analysis (Lineer Olmayan Regrasyon Analizi)

For predicting surface roughness by using the cutting parameters affecting on surface roughness must be known mathematical relation between with surface roughness. Usually, regression analysis method is used to obtain this type of equation. In this study, non-linear regression analysis was used to establish a mathematical model between the experimentally obtained the workpiece surface roughness and cutting parameters. The mathematical model relating the workpiece surface roughness (R_a) depending on cutting speed (V), feed rate (f) and annealed time was expressed using power functions in form of;

$$Ra=a_1.V^{a2}.f^{a3}.t^{a4} \quad (1)$$

where a is constants and they were obtained using nonlinear regression analysis method (Gauss-Newton method) by a program written on MATLAB programming language. The calculated coefficients are substituted in Equation 2 and the following relation is obtained as follow:

$$R_a=32.913\ V^{-0.0239}.f^{1.269}.t^{-0.081} \quad (2)$$

and correlation coefficient is obtained as follow:

r= 0.95

The high correlation coefficient (r) obtained for the equation from regression analysis indicate the suitability of the used power function form (model) and the correctness of calculated constants. The predicted surface roughness values given in the above relation (Equation 2) versus the surface roughness values from the experiments is shown in Figure 3. Equation 2 can be used successfully to estimate the surface roughness without experimentation (maximum 5 percent deviation from the experimental results). It is shown in Figure 3 that the regression 95% is confidential.

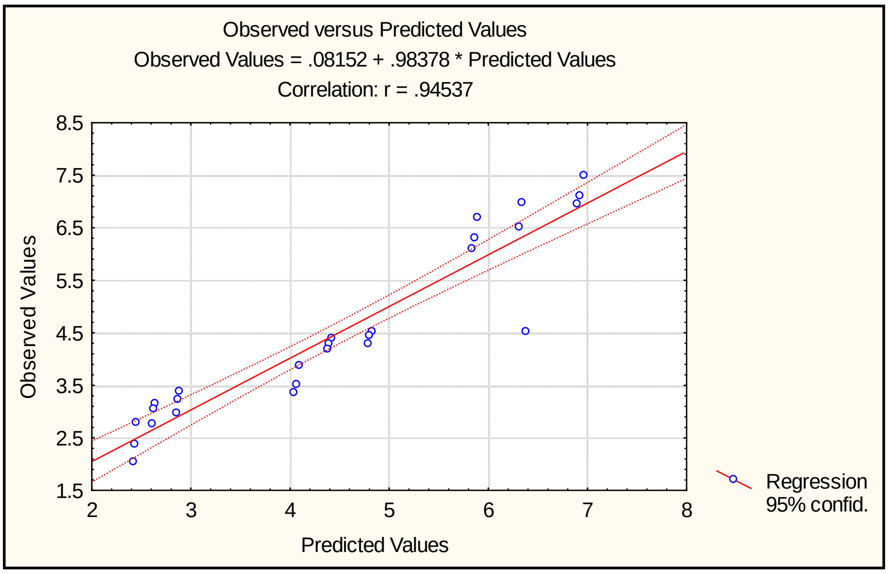

Figure 3. Comparison of actual and measured surface roughness
(Şekil 3. Yüzey pürüzlülüğünün deney sonuçları ile analiz sonuçlarının karşılaştırılması)

3.4. Determination of the Optimum Condition (Uygunluk Şartının Belirlenmesi)

Optimal condition is detected by means of signal to noise (S/N) ratio method. The rationale behind this method is to find a condition under which the effect of signals (controllable factors) is the greatest of all compared with effects of noises (uncontrollable factors). S/N ratio statistics (η) can be obtained as follows [15]:

$$\eta = -10 \cdot \log_{10} \cdot \left(\frac{1}{n} \cdot \sum_{i=1}^{n} y_i^{\,2} \right) \qquad (3)$$

where y_i is the *i*th observation of a treatment combination and n is the number of replications. Here, the lower surface roughness is indication of better performance. Therefore, the smaller is the better was selected for determination of S/N ratio. The factor level which produces the largest η is detected as the factor level which pertains to the optimal condition. The S/N ratio results are given in Table 6. Accordingly, the optimal turning performance for surface roughness was obtained at 195 m/min cutting speed, 0.2 mm/rev feed rate and 240 minute holding time conditions. Thus, V3F1T4 (level 3 for V, level 1 for F and level 4 for T) was found the optimal turning performance for surface roughness.

Table 6. S/N ratio for surface roughness
(Tablo 6. Yüzey pürüzlülüğü için S/N oranları)

Symbol	Turning parameters	Mean S/N ratio (dB)			
		Level 1	Level 2	Level 3	Level 4
V	(Cutting speed)	-13.370	-12.961	-12.462*	-
F	(Feed rate)	-9.494*	-12.469	-16.831	-
T	(Holding time)	-13.711	-13.369	-13.093	-11.552*
*Optimum level					

4. CONCLUSIONS (SONUÇLAR)

In this research, an experimental investigation was performed to consider surface roughness in turning of AISI 304 austenitic stainless steel. Mathematical model for surface roughness has been developed to correlate the important turning parameters. The experimental plan was full factorial design method. Two important turning parameters such as cutting speed and feed rate were considered as machining conditions. Pre – machining, the specimens were heat treated for different holding times. Thus, holding time was chosen as a factor that effecting machined parts' surface roughness and it was considered as model variables. The relative effect of each factor and combination of factors on surface roughness was obtained by analysis of variance (ANOVA). The turning parameters were optimized by using S/N ratio approach. Summarizing the mean features of the results, the following conclusions may be drawn:

- The surface roughness increase with feed rate significantly.
- The surface roughness decrease with cutting speed and holding time straightly.
- According to the ANOVA results, the most important factor on surface roughness was found as feed rate (93.61%), while the holding time was second ranking factor (4.93%) and stirrer geometry was the least (0.13%).
- According to S/N ratio results, the combinations of V3F1T4 were the optimal turning conditions for surface roughness.
- The predicted values by regression equation match the experimental values reasonably well, with R^2 of 95%. The model is suitable for predicting surface roughness when machining AISI 304 austenitic stainless steel without making experiments.

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