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Experimental investigation and modelling of surface roughness and resultant cutting force in hard turning of AISI H13 Steel

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Abstract. In recent years, turning of hardened steels has replaced grinding for finishing operations. This process is compared to grinding operations; hard turning has higher material removal rates, the possibility of greater process flexibility, lower equipment costs, and shorter setup time. CBN or ceramic cutting tools are widely used hard part machining. For successful application of hard turning, selection of suitable cutting parameters for a given cutting tool is an important step. For this purpose, an experimental investigation was conducted to determine the effects of cutting tool edge geometry, feed rate and cutting speed on surface roughness and resultant cutting force in hard turning of AISI H13 steel with ceramic cutting tools. Machining experiments were conducted in a CNC lathe based on Taguchi experimental design (L_{16}) in different levels of cutting parameters. In the experiments, a Kistler 9257 B, three cutting force components (Fc, Ff and Fr) piezoelectric dynamometer was used to measure cutting forces. Surface roughness measurements were performed by using a Mahrsurf PS1 device. For statistical analysis, analysis of variance has been performed and mathematical model have been developed for surface roughness and resultant cutting forces. The analysis of variance results showed that the cutting edge geometry, cutting speed and feed rate were the most significant factors on resultant cutting force while the cutting edge geometry and feed rate were the most significant factor for the surface roughness. The regression analysis was applied to predict the outcomes of the experiment. The predicted values and measured values were very close to each other. Afterwards a confirmation tests were performed to make a comparison between the predicted results and the measured results. According to the confirmation test results, measured values are within the 95% confidence interval.

1. Introduction

The hard turning process is gradually replacing the traditional grinding in the automotive and tool and die industries. The traditional method of machining hardened materials included heat treatment, rough turning, and then grinding process. As a result of the advances in machine tools and cutting tool technology, hard turning becomes an effective manufacturing process to produce parts with precision and surface quality. Hard turning provides a number of potential benefits to grinding machining like as higher material removal rates, more flexibility, lower energy consumption, elimination coolants, shorter set up time in complex parts process. The hard turning is generally performed without a coolant using ceramics and cubic boron nitride (CBN) cutting tools due to the required tool material hardness.

Especially, advanced alumina-based ceramic cutting tool is widely used as machining of various types of steel, cast iron, non-ferrous metals, and refractory nickel-based alloys [1-5].

Traditionally, a wide range of tool steels is used in producing dies and molds. AISI H13 hardened steel exhibits high hardness, toughness, high temperature strength, high resistance to thermal shock, thermal fatigue and thermal softening. Due to its mechanical properties and aggressive cutting conditions, hardened AISI H13 steel is recognized to be a difficult-to-cut material [6]. Many researchers have conducted various studies on cutting edge geometry, cutting force, surface roughness, cutting tool material, tool wear in hard turning of various hardened steels. Özel et al. used Taguchi's L16 orthogonal array to determine the effects of the cutting tool edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and resultant forces in finish hard turning of AISI H13 steel using CBN tools experimental results of their study indicated that the effect of cutting edge geometry on the surface roughness was remarkably significant. The cutting forces were influenced not only by cutting conditions but the cutting edge geometry and workpiece surface hardness also had a significant effect [7]. Yalçın studied the performance of CBN and the mixed ceramic tools in turning soft and hard H13 tool steel with different cutting parameters. The interaction of the cutting parameters on the surface roughness and cutting forces was determined by using ANOVA. The results showed that the surface roughness in hard turning was lower with the CBN than with the ceramic tool [8]. Thiele and Melkote investigated the effects of tool cutting edge geometry and workpiece hardness on the surface roughness and cutting forces in the finish hard turning of AISI 52100 steel. They found that increasing the edge hone radius tends to increase the average surface roughness and the effect of edge hone on the surface roughness decreased with an increase in workpiece hardness. Also, it was revealed that the cutting forces were influenced by the workpiece hardness and the cutting edge geometry. [9]. De Oliveira et al. studied the performance of CBN and whiskers reinforced ceramics in continuous and interrupted hard turning with constant cutting conditions. Their results showed that, in continuous turning, the longest tool life is achieved using PCBN, but similar tool life is attained in interrupted turning using both PCBN and ceramic. In terms of roughness, the PCBN tools showed better results for continuous and interrupted surfaces [10]. Aslan et al. conducted an optimization study by machining a hardened AISI 4140 grade (63 HRC) steel on a lathe by using Al_2O_3 + TiCN coated ceramic inserts. The relationship between the parameters and the responses were determined using multiple linear regression analysis. They found that the VB value decreased as the cutting speed and the depth of cut increased; however, it first decreased and then increased as the feed rate increased. On the other hand, the surface roughness decreased as the cutting speed increased. In contrast surface roughness increased when the feed rate increased [11]. Fnides et al., investigated the effect of three cutting parameters on surface roughness in turning of X38CrMoV5-1 hardened steel treated at 50 HRC using mixed ceramic tool. Their results revealed that the effect of feed rate on surface roughness is more significant than cutting speed, whereas the depth of cut is not significant [12]. Aouici et al. investigated the effects of cutting speed, feed rate, workpiece hardness and depth of cut on surface roughness and cutting force components in hard turning. Mathematical models were developed for surface roughness and cutting force components using the response surface methodology (RSM). Results showed that the cutting force components were influenced principally by depth of cut and workpiece hardness; however, both feed rate and workpiece hardness had statistical significance on surface roughness [13]. Bensouilah et al. adopted ANOVA and RSM to effect of cutting parameters on the surface roughness and cutting force components during hard turning of AISI D3 cold work tool steel with ceramic inserts. The results revealed that the minimum surface roughness obtained with the coated CC6050 ceramic insert. However, the uncoated ceramic insert was useful in reducing the machining force [14]. Günay and Yücel investigated optimizing the cutting conditions for the average surface roughness (Ra) in machining of high-alloy white cast iron (Ni-Hard) at two different hardness levels (50 HRC and 62 HRC). ANNOVA results showed that feed rate is the most significant variable for Ni-Hard with 62 HRC while the cutting speed is the most significant for Ni-Hard with 50 HRC [15]. In a further work, they investigated the effect of cutting conditions for cutting force and surface roughness. They found that depth of cut and feed rate is the most significant factor on surface roughness and cutting force for both the ceramic and CBN cutting tool.

Also they obtained the smallest surface roughness with CBN insert during machining of Ni-Hard with 62 HRC [16]. Xiong et al. investigated the effect of cutting parameters on the tool life and tool wear mechanism of conventional cemented carbide for machining of AISI H13 hardened steel. The results showed that WC–5TiC–10Co ultrafine cemented carbide possessed higher hardness values and transverse rupture strength, and exhibited better cutting performance than conventional inserts under the same cutting conditions [17].

This study aims at investigating the effects of cutting tool edge geometry, feed rate and cutting speed on surface roughness and resultant cutting force in hard turning of AISI H13 steel with ceramic cutting tools of different edge preparations. Taguchi's design and analysis of experiment process has been used to achieve this purpose. L16 orthogonal array was used in the design of experiment. Furthermore, analysis of variance is used to determine the statistical significance of the cutting parameters. Finally, confirmation tests were carried out using the optimal cutting conditions which were determined by Taguchi optimization method. Also, a mathematical model was developed to estimate the resultant cutting force and average surface roughness (Ra) with regression analysis by using experimental results.

2. Experimental

2.1. Experimental Conditions and Equipment's

The hard turning tests were performed on hot work tool steel (AISI H13). The cylindrical AISI H13 specimens utilized in these experiments had a diameter of 45 mm and length of 200 mm. The specimens were through-hardened and tempered to obtain the hardness value of 55 HRC. The chemical composition of AISI H13 steel is given Table 1. Mixed ceramic (Al_2O_3+TiC) inserts with two different types of edge preparations were investigated in this study. The cutting tools used were commercial grade ceramic inserts produced by Kyocera with the geometry of DNGA 150404 S/T02025 PT600M. PT600M is a special coating called "Megacoat". These inserts were clamped mechanically on a rigid tool holder with an ISO designation of DDJNR 2525M-1504. The inserts were positioned into a tool holder characterized by a negative rake angle of $\gamma=-6°$, clearance angle of $\alpha=-6°$, and an approach angle of $\chi=93°$. Cutting forces were measured with a Kistler 9257 B type piezoelectric dynamometer and an associated 5019 B130 charge amplifier connected to PC employing Kistler Dynoware software. During the hard turning tests, the cutting forces known as the primary cutting force Fc, the feed force Ff, and the radial force Fp were recorded. Longitudinal turning was conducted on CNC lathe (Johnford TC35) at a constant depth of cut at 0.1 mm. The length of cut for each test was 20 mm in the axial direction. Average surface roughness (Ra) value which is one of the most important machinability criteria was measured according to ISO 4287 standard. Ra measurements were performed by using a Mahrsurf PS1 surface roughness gauge with a cut-off length of 0.8 mm and sampling length of 5 mm. Ra values were calculated by averaging three roughness values obtained from three different positions of machined surface. The flowchart for modelling of the hard turning parameters is shown in figure 1.

Table 1. Chemical composition of AISI H13 tool steel (%).

C	Si	Mn	P	S	Cr	Mo	V
0.38	0.97	0.34	0.02	0.002	5	1.34	0.93

2.2. Design of experiment and analysis

A there-factor four-level factorial design was used to determine the effects of the tool edge geometry, feed rate and cutting speed on surface roughness and resultant forces in the hard turning of AISI H13 steel. Four different levels of cutting speed (Vc) and feed rate (f) and two different levels of tool edge geometry (TEG) are chosen as the control factors and their levels were determined as shown in Table 2.

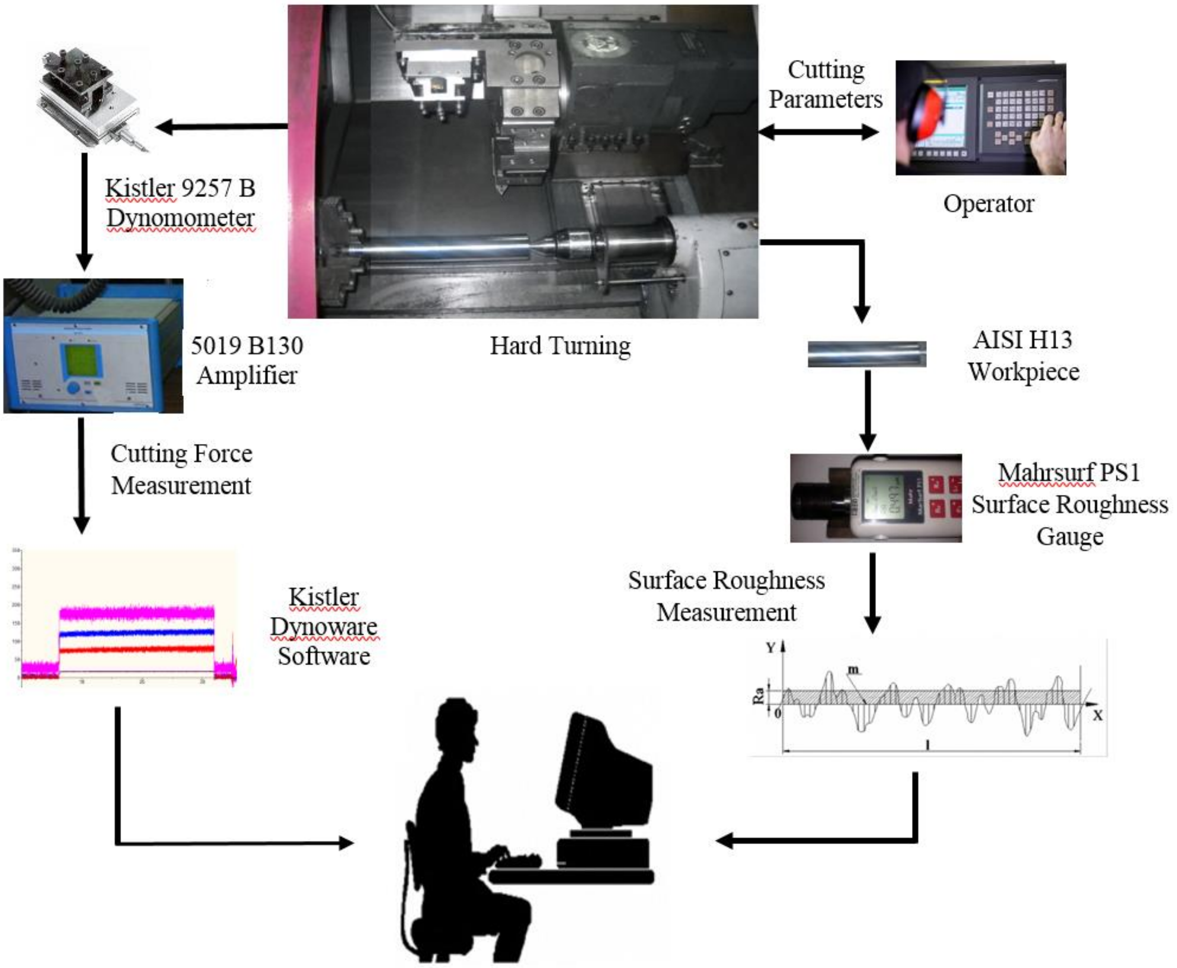

Figure 1. The flowchart for modelling of hard turning parameters.

The parameter levels were chosen within the intervals recommended by the cutting tool manufacturer. The L_{16} mixed orthogonal array of the Taguchi method was used to determine the optimum cutting conditions and analyze the effects of the machining parameters. ANOVA was applied with 95% confidence level to determine the significance level of the variables on average surface roughness (Ra) and resultant cutting force (F). The purpose of ANOVA is to determine which cutting parameters significantly affect the performance characteristics of independents variables. The ANOVA test was performed to evaluate the statistical significances of the fitted regression model and factors involved therein for the response factors namely F and Ra. From the experimental data the effects of three predictor factors (cutting speed, feed rate and cutting tool geometry) upon two response variables were analyzed by using MINITAB statistical software. Cutting conditions have been optimized separately for Fc and Ra. Generally, the smaller-the-better, the higher the- better, and the nominal-the-best quality characteristics use in the analysis of the S/N ratio. The aim of this study was to minimize surface roughness and resultant cutting force. Therefore, the-smaller-the-better performance characteristic for Ra and F were applied in order to obtain the optimal cutting conditions. S/N ratio (η) is defined as follows:

$$\frac{S}{N(\eta)} = -10 \cdot \log\left[\frac{1}{n} \cdot \sum_{i=1}^{o} Y_i^2\right] \quad (2.1)$$

where Y_i is the observed data at the experiment and n is the number of experiments. The S/N ratios of Ra and F were calculated using equation (2.1).

Table 2. Factors and their levels.

Factors	Level 1	Level 2	Level 3	Level 4
A: Cutting speed, Vc (m/min)	60	80	100	120
B: Feed rate, f (mm/rev)	0.04	0.06	0.08	0.10
C: Tool Edge Geometry, (TEG)	1[a]	2[b]		

a: Chamfered tool edge geometry
b: Chamfered + honed tool edge geometry

3. Experimental Results and Discussion

3.1. Analysis of the Signal-to-Noise (S/N) Ratio

Average surface roughness and resultant cutting force occurred during machining of the AISI H13 steel were measured after the experiments performed according to the L_{16} orthogonal array. S/N ratios of the Ra and F data obtained from the experimental results, which will be used to determine the optimal levels of each variable, were calculated according to the equation (2.1). The experimental results and S/N ratios calculated according to Taguchi's "the-smaller-the-better" quality characteristic were given in Table 3.

Analysis of the effect of each control factor on the surface roughness and resultant cutting force was performed with a S/N response table. The response tables of S/N for Ra and F are shown in Table 4. This table, which is made by using the Taguchi method shows the optimum levels of control factors for the optimum surface roughness and resultant cutting force values.

The level values of control factors for Ra and F given in Table 4 are shown in graph forms in figures 2 and 3. Optimum machining parameters of the control factors for minimizing the surface roughness and resultant cutting force can be easily determined from these graphs. The best level for each control factor was found according to the highest S/N ratio in the levels of that control factor. According to this, the levels and S/N ratios for the factors giving the best Ra value were specified as factor A1, B1 and C2.

Table 3. Experimental results and corresponding S/N ratios.

Run	Control factors			Experimental results		Signal-to-noise ratio (S/N)	
	A- (f) (mm/rev)	B-(Vc) (m/min)	C-(TEG)	R_a (μm)	F (N)	R_a	F
1	0.04	60	1	0.523	255.7	5.62997	-46.1967
2	0.04	80	1	0.552	244	5.16122	-45.6350
3	0.04	100	2	0.446	173.1	7.02305	-45.1267
4	0.04	120	2	0.449	167.6	6.95507	-44.7015
5	0.06	60	1	0.509	305.5	5.86564	-48.0791
6	0.06	80	1	0.535	299.6	5.43292	-47.8703
7	0.06	100	2	0.579	227.8	4.74643	-47.1056
8	0.06	120	2	0.480	222.3	6.37518	-47.1045
9	0.08	60	2	0.529	311.4	5.53089	-49.3525
10	0.08	80	2	0.563	284.9	4.98983	-48.4393
11	0.08	100	1	0.736	344.3	2.66244	-48.9713
12	0.08	120	1	0.601	331.4	4.42251	-48.6357
13	0.10	60	2	0.741	344.1	2.60364	-50.2740
14	0.10	80	2	0.775	335.4	2.21397	-49.9645
15	0.10	100	1	0.955	399.5	0.39993	-50.4816
16	0.10	120	1	0.985	385.7	0.13128	-50.0525

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In other words, an optimum Ra value was obtained at a feed rate (A1) 0.04 mm/rev, at cutting speed (B1) 60 m/min and with chamfer plus hone edge (C2) (figure 2). Therefore, by considering the S/N ratios in Table 4, the optimum cutting conditions for the resultant cutting force were A1, B4 and C2. The smallest surface roughness and resultant cutting force and their S/N ratio that can be obtained according to these levels were calculated by using equation (3.1) and (3.2). In these equations, η_G is the S/N ratio calculated at the optimum levels (dB), $\bar{\eta}_G$ is the average S/N ratios of all variables (dB), $\bar{A}o, \bar{B}o, \bar{C}o$ are the mean S/N ratios when the factors A, B and C are at optimum levels (dB), and Ra_{cal} is the calculated surface roughness value. At the end of the machining tests, the average values of the surface roughness and resultant cutting force were calculated to be 0.427 µm and 173.62 N respectively. Similarly, average values of S/N ratio for surface roughness and resultant cutting force were calculated to be 7.387 dB and -44.792 dB respectively.

$$\eta_G = \bar{\eta}_G + (\bar{A}_O - \bar{\eta}_G) + (\bar{B}_O - \bar{\eta}_G) + (\bar{C}_O - \bar{\eta}_G) \quad (3.1)$$

$$Ra_{cal} = 10^{-\eta_G/20} \quad (3.2)$$

Table 4. Response table for S/N ratios of surface roughness and resultant cutting force.

	Surface roughness			Resultant cutting force		
Level	A	B	C	A	B	C
1	6.192	4.908	3.713	-45.41	-48.48	-48.24
2	5.605	4.449	5.055	-47.54	-47.98	-47.76
3	4.401	3.708		-48.85	-47.92	
4	1.337	4.471		-50.19	-47.62	
Δ	4.855	1.200	1.344	4.78	0.85	0.48

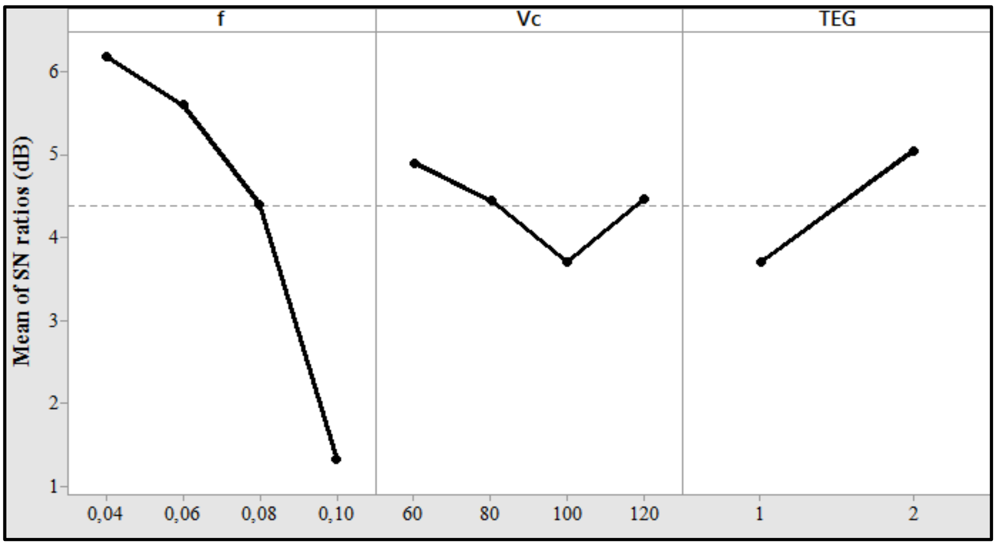

Figure 2. Effect of process parameters on average S/N ratio for Ra

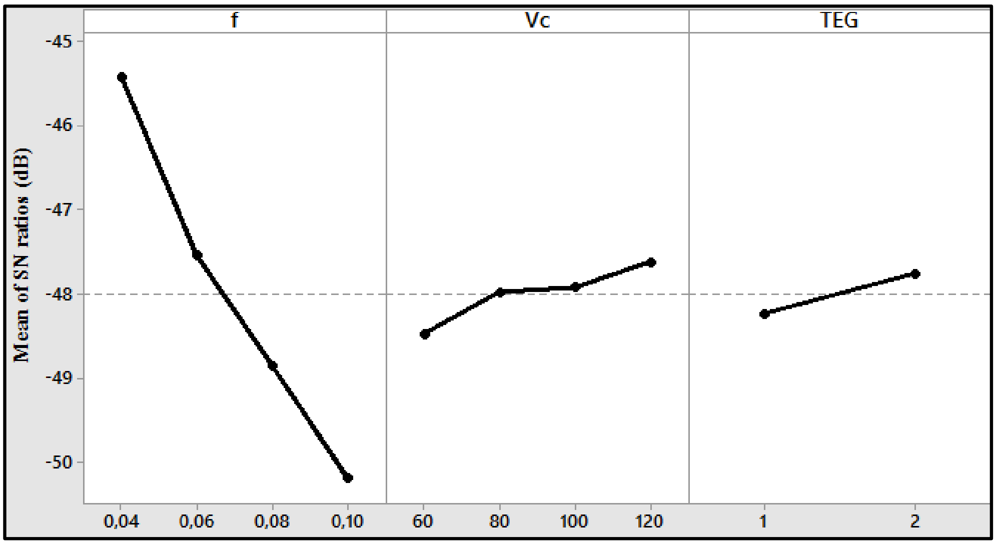

Figure 3. Effect of process parameters on average S/N ratio for F.

3.2. ANOVA method

The analysis of variance (ANOVA) was used to investigate which design parameters significantly affect the surface roughness and resultant cutting force. This analysis was carried out for a significance level of a = 0.05, i.e. for a confidence level of 95%. Table 5 show the P-values, that is, the realized significance levels, associated with the F-tests for each term of variation. The terms with a P-value less than 0.05 are considered to have a statistically significant contribution to the performance measures and the obtained models are considered to be statistically significant. It shows that that the conditions chosen in the model have significant effects on the responses. The ANOVA results for surface roughness are shown in Table 5. This table also shows the degrees of freedom (DF), sum of squares (SS), mean square (MS), F-values (F) and probability (P) in addition to the percentage contribution ratio (PCR) of each factor. F ratios and their PCR were taken into consideration to identify the significance level of the variables. Table 5 indicates that the most effective variable on the Ra value is the feed rate with 80.7% of PCR. It is well known that the theoretical geometrical surface roughness is primarily a function of the feed for a given nose radius and changes with the square of the feed rate value. It is once again shown that feed rate has important effect on surface roughness in hard turning. The other variables having effect on Ra are cutting tool edge geometry with 10.33 %. The cutting speed had a small influence of 4.27%.

Table 5. ANOVA for S/N ratio of surface roughness and resultant cutting force.

Source	DF	SS	MS	F-Ratio	P	PCR (%)
Surface roughness						
A	3	56.177	18.7257	45.95	0.000	80.7
B	3	2.972	0.9906	2.43	0.140	4.27
C	1	7.199	7.1987	17.66	0.003	10.33
Error	8	3.26	0.4075			4.7
Total	15	69.608				100
Resultant cutting force						
A	3	49.7034	16.5678	536.85	0.000	94.9
B	3	1.4984	0.4995	16.18	0.001	2.9
C	1	0.9281	0.9281	30.07	0.001	1.8
Error	8	0.2469	0.0309			0.04
Total	15	52.3768				100

Table 5 showed that the main effects of cutting speed, feed rate and edge geometry are all significant on the resultant cutting force. Table 5 shows that the most effective variable on the resultant cutting force is the feed rate with 94.9% of PCR. The other variables having effect on resultant cutting force are cutting speed with 2.9% and tool edge geometry with 1.8%. The error ratio was calculated as 0.04% and it is the smallest ratio.

3.3 Regression equations

The correlation between the cutting conditions and the machining output factors were performed by regression analysis. Regression analysis are used for the modeling and analyzing of several variables where there is relationship between a dependent variable and one or more independent variables. The predictive equations which were obtained by the linear regression model of surface roughness and resultant cutting force are given in equation (3.3) and (3.4). Coefficient of determination (R^2) value for the Ra and F were calculated as 80,34 % and 98.7 %, respectively.

$$R_a = 0.256 + 5.982xf + 0.001162xVc - 0.1043xTEG \quad (3.3)$$

$$F = 147.7 + 2241xf - 0.3346xVc - 11.93xTEG \quad (3.4)$$

The comparison of experimental results and predicted values of machining output factors calculated from equation (3.3) and (3.4) are illustrated in figure 4. Evaluating the figures and R^2 values, the predicted models found for average surface roughness and resultant cutting force are satisfactory. The above mathematical model can be used to predict the values of the surface roughness parameters and resultant cutting force components the limits of the factors studied. The results of comparison were demonstrated to predict the values of surface roughness parameters and resultant cutting force close to those readings recorded experimentally with a 95% confidence interval.

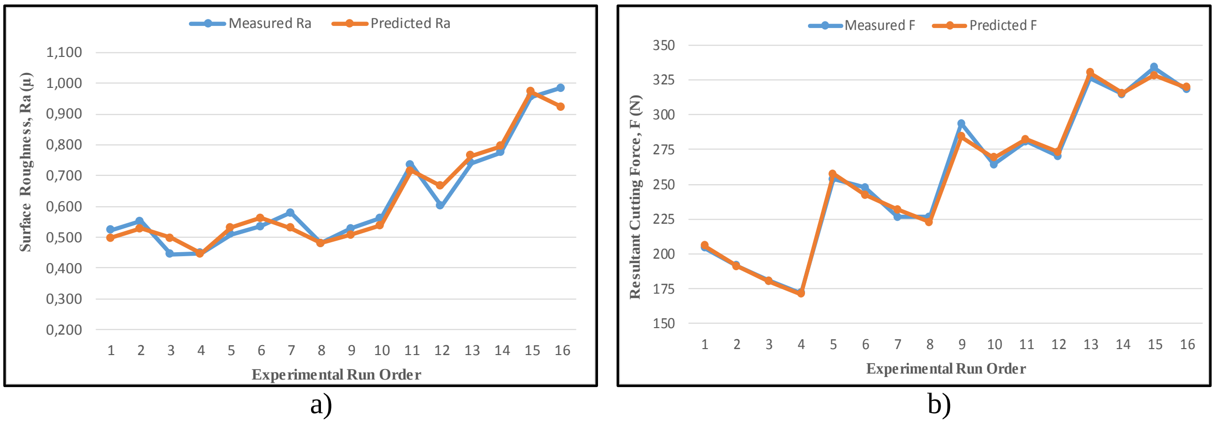

Figure 4. Comparison between measured and predicted values; a) Ra, b) F.

3.4. Confirmation tests

Confirmation tests are a crucial step recommended by Taguchi to verify experimental conclusions. The purpose of the confirmation experiment is to validate the conclusions drawn during the analyzing. For this purpose, the following equations were used in the specification of the confidence interval (Cl) for estimated surface roughness. Confirmation test was required in the present case study because the optimum combination of parameters and their levels i.e. A1B1C2 did not correspond to any experiment of the orthogonal array. Optimum combination of parameters and their levels i.e. A1B4C2 for resultant cutting force corresponded to experiment of the orthogonal array (OA). Therefore, it may be noted that if the optimal combination of parameters and their levels coincidently match with one of the experiments in the OA, then no confirmation test is required.

$$CI = \sqrt{F_{0,05}(1, \upsilon_e) V_e \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)} \tag{3.5}$$

$$n_{eff} = \frac{N}{1+\upsilon_T} \tag{3.6}$$

Table 6. Comparison between confirmatory test results and calculated values

Confirmatory	Experiment results	Calculated values		Differences	
Ra_{mea}(μm)	η_{mea}(dB)	Ra_{cal}(μm)	η_{cal}(dB)	$\lvert Ra_{mea} - Ra_{cal}\rvert$	$\lvert \eta_{mea} - \eta_{cal}\rvert$
0.479	6,393	0.427	7.387	0.052	0.994

Here, υ_e is the error degree of freedom, V_e is the error variance, n_{eff} is the repeating number of the experiments (equation 3.5) N is the total number of the experiments, υ_T is the variable's degree of freedom and r is the number of confirmation tests (equation 3.6). Using equations (3.5) and (3.6), confidence value of ±1.472 dB was obtained for surface roughness. Table 6 shows the differences between the values obtained by confirmatory tests and the values calculated by equations (3.5) and (3.6) of the S/N ratios. It is seen that the difference of 0.994 dB is under 5% confidence interval of 1.472 dB for surface roughness. Therefore, the optimal control factor settings for all the cutting conditions were confirmed as confident.

4. Conclusion

In this study, the Taguchi method was used to obtain optimum cutting conditions (feed rate, cutting speed and cutting tool edge geometry) in hard turning of AISI H13 steel. Experimental results were evaluated using ANOVA. The results can be drawn as follows:

- According to the results of statistical analysis, it was found that the feed rate and tool edge geometry was the most significant factor on surface roughness with a PCR of 80.7% and 10.33% respectively. The feed rate was the most significant parameters for the resultant cutting force with a percentage contribution of 94.9%. The other variables having effect on resultant cutting force were cutting speed with a percentage contribution of 2.9% and tool edge geometry with a percentage contribution of 1.8%.
- The optimum levels of the control factors for minimizing the surface roughness and resultant cutting force using S/N ratios were determined. The optimal conditions for surface roughness was observed at A1-B1-C2 (i.e., feed rate = 0.04 mm/rev, cutting speed = 60 m/min and chamfer+honed edges). The optimal conditions for resultant cutting force was observed at the same levels A1-B4-C2 (i.e., feed rate = 0.04 mm/rev, cutting speed = 120 m/min and chamfer+honed edge).
- Cutting edge geometry, feed rate and cutting speed are all found to be effective on resultant cutting force.
- Developed regression models demonstrated a very good relationship with high correlation coefficients (Ra = 0.803 and F = 0.987) between the measured and predicted values for surface roughness and resultant cutting force.
- Confirmation tests at optimal conditions were carried out. According to the confirmation test results, measured values are within the 95% confidence interval.

References

[1] Tönshoff H K, Arendt C and Ben Amor R 2000 CIRP Ann **49** 547-566
[2] Davim J P 2011 *Machining of Hard Materials* (London:Springer) pp 1-31
[3] Grzesik W 2008 A*dvanced Machining Processes of Metallic Materials: Theory, Modelling and*

Application, (Oxfort:Elsevier) pp 245-259
[4] König W, Berktold A and Koch K F 1993 CIRP Ann **42(1)** 39-43
[5] Klocke F, Brinksmeier E and Weinert K 2005 CIRP Ann **54(2)** 22-45
[6] Çiçek A, Kara F, Kıvak T and Ekici E 2013 Int J Refract Met H **41** 461–469
[7] Özel T, Hsu T K and Zeren E 2005 Int J Adv Manuf Technol **25** 262–269
[8] Yalçın B 2015 T Can Soc Mech Eng **39(2)** 323
[9] Thiele J D and Melkote S 1999 J Mater Process Tech **94** 216-226
[10] Oliveira A J, Diniz A E and Ursolino D J 2009 J Mater Process Tech **209(12–13)** 5262-5270.
[11] Aslan E, Camuşcu N and Birgören B 2007 Journal Mater Des **28** 1618–1622
[12] Fnides B, Yallese M A, Mabrouki T and Rigal J F 2009 Mechanika **3(77)** 68-73
[13] Aouici H, Yallese M A, Chaoui K, Mabrouki T and Rigal J F 2012 Measurement **45** 344–353
[14] Bensouilah H, Aouici H, Meddour I, Yallese M A, Mabrouki T and Girardin F 2016 Measurement **82** 1–18
[15] Günay M and Yücel E 2013 Measurement **46** 913–919
[16] Yücel E and Günay M 2013 Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci. **227(10)** 2280-2290
[17] Xiong J, Guo Z, Yang M, Wan W and Dong G et al 2013 Ceram Int **39** 337–346