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An Experimental and Statistical Evaluation of The Cutting Parameters on The Machinability of Hadfield Steel

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ABSTRACT

The effects of cutting tool coatings and cutting parameters (cutting speed, feed rate) on the cutting forces and surface roughness during the turning of Hadfield steel were investigated in this study. Cutting experiments were made on a CNC lathe under dry cutting conditions by employing CVD TiCN/Al_2O_3/TiN-, PVD TiAlN- and PVD TiAlN/AlCrO-coated cementite carbide inserts. Four different cutting speeds (100, 140, 180, 220 m/min), two different feed rates (0.2, 0.3 mm/rev) and a constant cutting depth of 0.8 mm were used as the cutting parameters. At the end of the tests, cutting force and surface roughness results were subjected to variance (ANOVA) and multiple regression analyses. The experimental results showed that the PVD TiAlN coating was superior to the CVD TiCN/Al_2O_3/TiN and PVD TiAlN/AlCrO coatings with respect to cutting force and surface roughness. The correlation coefficients of the statistical model developed at the end of the analysis were R^2= 0.994 and R^2= 0.996 for the cutting forces and surface roughness, respectively. The feed rate was found to be the most effective parameter on the cutting forces and surface roughness, with contribution ratios of 91.31% and 94.79% respectively.

Keywords: *Hadfield steel, Cutting force, Surface roughness, ANOVA, Regression analysis*

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1. INTRODUCTION

Hadfield steels are very tough, non-magnetic alloys having excellent wear resistance as well as maximum strength and ductility [1]. Hadfield steels were first produced by Sir Robert Hadfield at the end of the 19th century. During the last years, due to the excellent wear resistance properties these steels have been widely used in various engineering applications such as excavators, mining, pumping, railway materials, rolling mill components of steel production factories and wear-resistant materials of machine elements [2-4]. Its high hardness, low thermal conductivity and fast deformation hardening make Hadfield steel difficult to machine. Consequently, greater cutting forces, higher cutting temperatures and wearing are present, making control of sizing difficult during machining [5].

Turning processes are commonly used in the engineering industry for the shaping of metals. Surface roughness is one of the most important characteristics determining the quality of the work-piece in the turning process. A good surface roughness provides significant improvements in the tribologic properties, fatigue resistance, corrosion resistance and aesthetic appearance of the finished product [6]. Energy consumption is an important cost factor in production. The power spent during machining determines energy consumption. With the other factors depending on the specific cutting resistance, the main cutting force (F_c) needed during machining is the most significant parameter specifying the power spent and the cost of energy for machining [7]. There are many parameters that affect the cutting forces and surface roughness, such as cutting speed, feed rate, cutting depth, chip angle, nose radius, physical and chemical properties of the machined part and chip breaker geometry. Thus, appropriate machining conditions must be specified in order to obtain high-quality products at lower cost [8-9].

Regression analysis is a widely-used method to investigate the relation between one dependent variable and other independent variables. Many methods have been developed for the modeling and estimation of cutting forces and surface roughness, such as multiple regression, artificial neural networks (ANNs) and mathematical models. Singh and Rao [9] used Response Surface Methodology (RSM) and variance analysis (ANOVA) to investigate the effects of cutting conditions and the tool geometry of AISI 52100 material on surface roughness during hard turning. Lalwani et al. [10] studied the effects of cutting parameters on cutting force and surface roughness during the machining of MDN 250 steel by using RSM. Hao et al. [11] developed an ANN model to estimate the cutting forces for self-propelled rotary tools. In this model, cutting speed, feed rate, cutting depth and tool inclination angle were specified as the input parameters; thrust force, radial force and main cutting force were the output parameters. Kalla et al. [12] utilized mechanistic modeling techniques for the estimation of cutting forces in the milling of carbon fiber-reinforced composites. The model predictions were compared with experimental data and the results showed a significant correlation. Neşeli et al. [13] evaluated the influence of tool geometry on the surface finish in the turning of AISI 1040 steel using response surface methodology (RSM). Their results indicated that the tool nose radius was the dominant factor on the surface roughness. In addition, a significant correlation between the predicted and measured surface roughness was observed. Özel and Karpat [14] applied ANNs for the estimation of tool flank wear and surface roughness in the turning of hardened AISI H13 and AISI 52100 steel under different cutting conditions. They also developed a regression model to obtain special machining parameters by using the experimental data. Nalbant et al. [15] investigated the effects of the coating method, coating material, cutting speed, and feed rate on the surface roughness. The experimental values and ANN predictions were compared by statistical error analysis methods. The surface roughness value was determined by the ANN with an acceptable accuracy.

The present study was designed to investigate experimentally the effects of coating materials applied to the cutting tools and the cutting parameters (cutting speed, feed rate) on cutting force and surface roughness during the turning of Hadfield steel. Cutting force and surface roughness results were also investigated statistically by making variance and multiple regression analyses.

2. MATERIALS AND METHOD

2.1. Experimental studies

Turning tests were carried out in accordance with the ISO 3685 standard, using a Johnford TC 35 (10 kW) CNC lathe of max 3500 rev/min under dry cutting conditions. Test samples of 60 mm x 150 mm size GX120Mn12 (30 HRC) Hadfield steel (austenitic manganese steels) were used. The chemical composition of the Hadfield steel used in the tests is given in Table 1.

Table 1. Chemical analysis of Hadfield steel

Fe	Mn	C	Si	P	S	Cr	Mo	Ni	Other
84.91	12.4	1.16	0.448	0.028	0.0145	0.959	0.0144	0.0633	0.0028

Cementite carbide cutting tools of three different qualities having SNMG 120408 geometry (Sandvik Coromant) were used in the tests. In order to evaluate the effects of the coating materials on the machinability of Hadfield steel, cementite carbide tools with three different mono- and multi-layered coatings (using PVD and CVD coating methods) were chosen. The cutting tool characteristics used in the turning tests are given in Table 2.

Table 2. Cutting tool properties and cutting parameters

Coated materials	Coated method	Material quality of ISO (Grade)	Coating thickness (μm)	Hardness (Hv)
TiAlN	PVD	S15 (GC1105)	2	1850
$TiCN/Al_2O_3/TiN$	CVD	S05 (S05F)	4	1750
TiAlN/AlCrO	PVD	S20 (GC1115)	2	1750

A Kistler 9275-B type dynamometer which can measure the three force constituents was used in the measurement of the cutting forces. The signals of cutting force from the dynamometer were transmitted to a Kistler 5070-A type multi-channel (8-channel) amplifier, and then recorded on a personal computer. The measurement and evaluation of surface roughness in machinability studies play an important role in the development and specification of the surface qualities of the parts that are produced. Surface roughness measurements were made using the portable surface roughness device Mahr Perthometer M1. The cut-off length and the number of sampling lengths for the surface roughness measurements were selected as 0.8 mm and 5.6 mm, respectively. Three measurements were made on every machined surface and their average was taken. The average surface roughness (Ra) values were considered in the evaluation of the surface roughness,

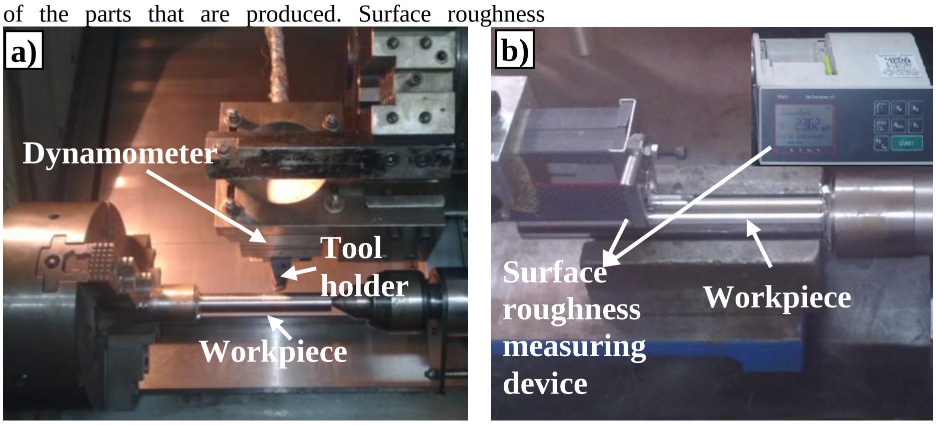

Figure 1. Experimental configuration for measuring of a) cutting force and b) surface roughness

2.2. Multiple regression and variance analysis

Regression analysis is the mathematical function of the relation between a variable (dependent variable) and one or more other variables (independent-explanatory variables) [6]. In the multiple regression model, there is more than one estimate variable, as seen in Eq. (1).

$$Y = (b_o + b_1 X_1 + b_2 X_2 + b_3 X_3 + ... + b_n X_n + e_j \quad (1)$$

Y the dependant variable, b_o the intersection point of regression curve with y-axis; b_1, X_1 the coefficient of the first estimate variable; b_2, X_2 the coefficient of the second estimate variable; e_j is the difference between the estimated and experimental values of Y for the i^{th} test. In the study, dependant variables are the cutting force (F_c) and the surface roughness (Ra); independent variables are the cutting speed (V_c), the feed rate (f) and the cutting tool (Ct). The process parameters and their levels are given in Table 3.

Table 3. Process parameters and their levels

Parameters	Symbol	Levels			
Cutting tools	*Ct*	1 (PVD TiAlN)	2 (CVD TiCN/Al_2O_3/TiN)	3 (PVD TiAlN/AlCrO)	
Cutting speed (m/min)	*Vc*	100	140	180	220
Feed rate (mm/rev)	*f*	0.2		0.3	
Depth of cut	*a*	0.8			

Although it is possible to evaluate the effects of cutting parameters and coating characteristics on the cutting forces and surface roughness through graphs, the variance analysis (ANOVA) was applied in order to make a more detailed examination. In the determination of cutting forces and surface roughness, 24 tests were carried out and a full factorial design was implemented. The cutting forces and surface roughness results obtained according to the coating material, cutting speed and feed rate are given in Table 4. ANOVA results clearly put forth the effects of each parameter and the interactions of parameters on the cutting forces and surface roughness. The ANOVA test which was applied to the cutting forces and surface roughness was carried out by using MINITAB R15 software with a confidence level of 95%.

Table 4. Test parameters and results

Experimental run	Coated materials (*Ct*)	Cutting speed *Vc* (m/min)	Feed rate *f* (mm/rev)	Cutting force *Fc* (N)	Surface roughness *Ra* (μm)
1	1	100	0.2	543	1.97
2	1	140	0.2	520	1.53
3	1	180	0.2	500	1.62
4	1	220	0.2	498	1.65
5	2	100	0.2	568	1.99
6	2	140	0.2	561	1.83
7	2	180	0.2	504	1.80
8	2	220	0.2	497	1.99
9	3	100	0.2	581	2.25
10	3	140	0.2	563	1.99
11	3	180	0.2	522	2.12
12	3	220	0.2	514	2.23
13	1	100	0.3	709	3.90
14	1	140	0.3	675	3.64
15	1	180	0.3	675	3.71
16	1	220	0.3	666	3.76
17	2	100	0.3	718	4.18
18	2	140	0.3	701	3.92
19	2	180	0.3	686	4.30
20	2	220	0.3	673	4.26
21	3	100	0.3	732	4.38
22	3	140	0.3	706	4.24
23	3	180	0.3	697	4.32
24	3	220	0.3	680	4.54

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Cutting forces

Fig. 2. shows the variations in the cutting forces depending on the cutting speed, the feed rate and the coating material. For the three different tools, there was a decrease in the cutting forces with the increase of the cutting speed. Depending on the feed rate and the coating material, the cutting speed affected the cutting forces, causing a decrease of 6-13%. This decrease in the cutting forces can be attributed in part to the decrease in the tool-chip interface. The decreased yield strength resulting from the temperature rise due to higher cutting speed also contributed to the decrease in the cutting forces [16]. When examining the force variations depending on the feed rate, it was observed that with a rise in feed rate, the cutting forces increased

markedly. The cutting forces were in the interval of 497-581 N at a feed rate of 0.2 mm/rev. With the increase of the feed rate by 50% at 0.3 mm/rev, they reached the interval of 666-732 N and showed an increase of about 25-34%. Similar studies in the literature state that feed rate increases cutting forces [17]. At this stage, it can be said that feed rate is more effective than cutting speed on the variation of cutting forces. When the effects of different coatings on force variations were evaluated, little variation was observed in any of the cutting parameter combinations; however, the lowest cutting forces were obtained with the PVD TiAlN-coated tools, followed by the CVD TiCN/Al_20_3/TiN- and PVD TiAlN/AlCrO-coated tools. The PVD TiAlN coating were the cause of lower cutting forces; this can be attributed to the low heat-conductivity and friction characteristics of this coating. Under dry cutting conditions especially, it helps to protect the strength of the cutting tool because of its high hardness. The outer layer of the CVD TiCN/Al_20_3/TiN coating is TiN, which has a lower frictional coefficient than the PVD TiAlN/AlCrO coating, and this causes a decrease in the cutting forces.

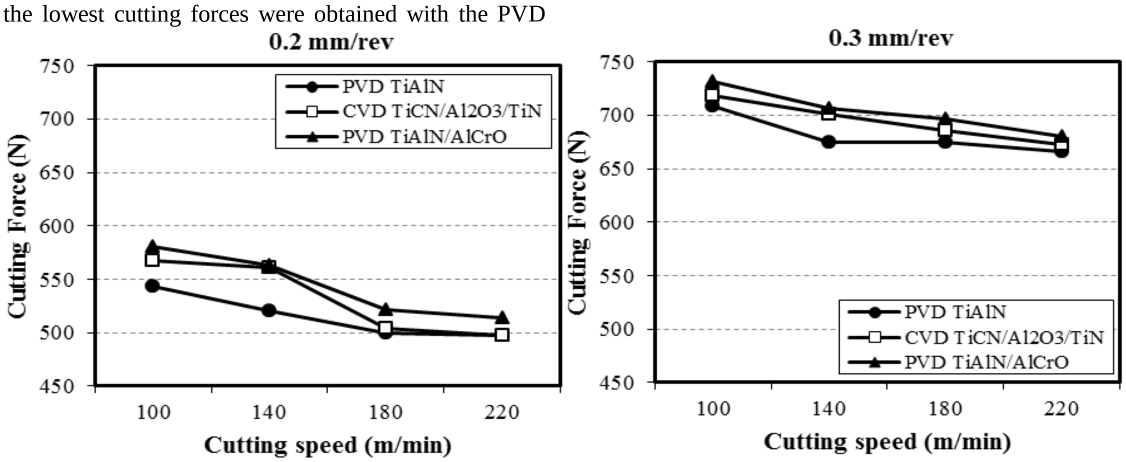

Figure 2. The variation of cutting forces between the three tools depending on the cutting speed and feed rate

3.2. Surface roughness

The graph in Fig. 3. shows the variations occurring at average surface roughness values (*Ra*) depending on the cutting speed, feed rate and coating material. With the three different tools, surface roughness exhibited a decrease in cutting speed of up to 140 m/min, but after this cutting speed an increase was observed as a result of tool wear. At a higher feed rate (0.3 mm/rev), the tendency to increase was higher. As was seen with the cutting forces, the feed rate played an important role in the increase of surface roughness. The surface roughness value was 2 μm at 0.2 mm/rev and it rose to over 4 μm when the feed rate was 0.3 mm/rev. This can be explained by the increasing load on the cutting tool at higher cutting speeds and feed rates, the occurrence of high temperatures at the cutting area and the acceleration of tool wear accordingly [7]. Surface roughness variations at a feed rate of 0.3 mm/rev show a parallelism with the variations in the cutting forces.

When the effects of the different coatings on the surface roughness were examined, the PVD TiAlN-coated tools exhibited the best performance in cutting forces; the lowest surface roughness values were obtained with these tools. The CVD TiCN/Al_20_3/TiN-and PVD TiAlN/AlCrO-coated tools were less effective in performance. One of the most significant characteristics of Hadfield steel is its very fast hardening during deformation [5]. Therefore, tool life is rapidly expended because the cutting tools quickly wear down during machining. It was observed that lower *Ra* values were obtained with the TiN-coated tools. This can be explained by the rapid erosion of the TiN-coating layer during machining due to the above-mentioned characteristics. However, in this study, lower *Ra* values were obtained with the TiAlN-coated tools compared to the CVD TiCN/Al_20_3/TiN-coated tools with the outer layer of TiN.

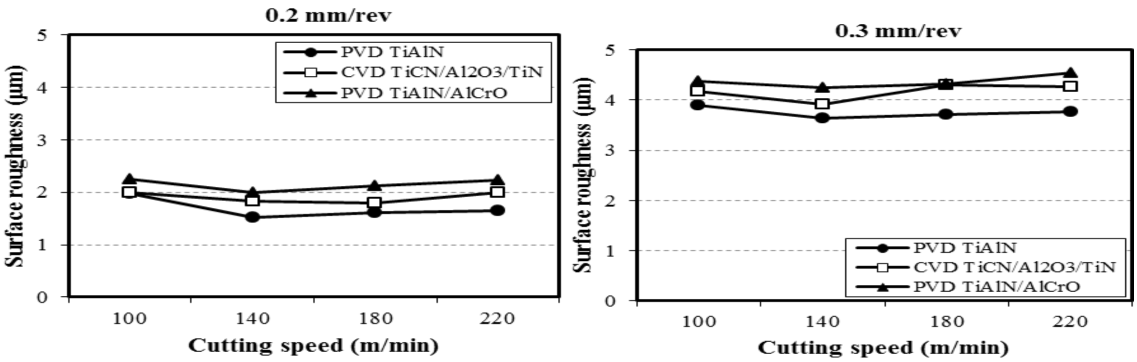

Figure 3. The variation of surface roughness between the three tools depending on the cutting speed and feed rate

3.3. Statistical analysis of cutting forces and surface roughness

The present study used, ANOVA to analyze the effects of cutting tools, the cutting speed and the feed rate on surface roughness and cutting forces. In addition, multiple regression analysis was used to derive the mathematical models of the control factors and their interactions. The experimental plan undertaken was evaluated at a confidence level of 95%. The ANOVA results for cutting forces are given in Table 5. The ANOVA results for the cutting forces showed that coating materials (*Ct*), cutting speed (*Vc*), feed rate (*f*) independent variables and (Ct^*Vc) and (Vc^*f) interactions with respect to *P* values were effective on the cutting forces (P<0.05). However, (Ct^*f) interaction was ineffective on the cutting forces (statistically at confidence level of 95%, P>0.05).

When the contribution ratios of independent variables were examined, the feed rate was observed to be the most effective parameter on the cutting forces, with a contribution ratio 91.31% (Table 5). From the graphs in Fig. 4, it can also be seen that the feed rate is the most effective parameter. Since the theoretical surface roughness is a function of the feed rate, the most effective parameter on the surface roughness is feed rate [18]. From the aspect of effect ratios, feed rate is followed by cutting speed, coating material independent variables and cutting speed-feed rate, coating material-cutting speed and coating material-feed rate interactions, respectively.

Correlation coefficient R^2 is accepted as a measure of the success of the regression equation for the explanation of variability in data. The coefficient of certainty of the statistical model developed as a result of the analysis for cutting forces was R^2=0.994. This demonstrates that the measured data at the end of the tests and the estimated data as a result of the multiple regressions are very close to each other, indicating that the developed model was appropriate. In other words, the effect of feed rate, cutting speed and coating on the cutting forces was determined to be 99.4%. The obtained model is given in Eq. (2).

$$Fc = 321 + 43.2Ct - 1.35Vc + 1398f - 2.19Ct^2 + 0.00180Vc^2 - 0.0769CtVc - 36.2Ctf + 1.86Vcf \quad (2)$$

R-Sq = 99.4% R-Sq(adj) = 99.0%

Tablo 5. ANOVA results for the cutting forces

Source of variance	Degree of freedom, *DF*	Sum of squares, *SS*	F Ratio □ = 5%	P-Value	Contribution rate (%)
Ct	2	2756	61.27	0.000	1.57
Vc	3	10573	156.73	0.000	6.07
f	1	157950	7024.35	0.000	91.31
*Ct*Vc*	6	600	4.45	0.046	0.27
Ct f*	2	53	1.17	0.372	0.01
*Vc*f*	3	892	13.23	0.005	0.48
Error	6	135	-	-	0.29
Total	23	172959	-	-	100

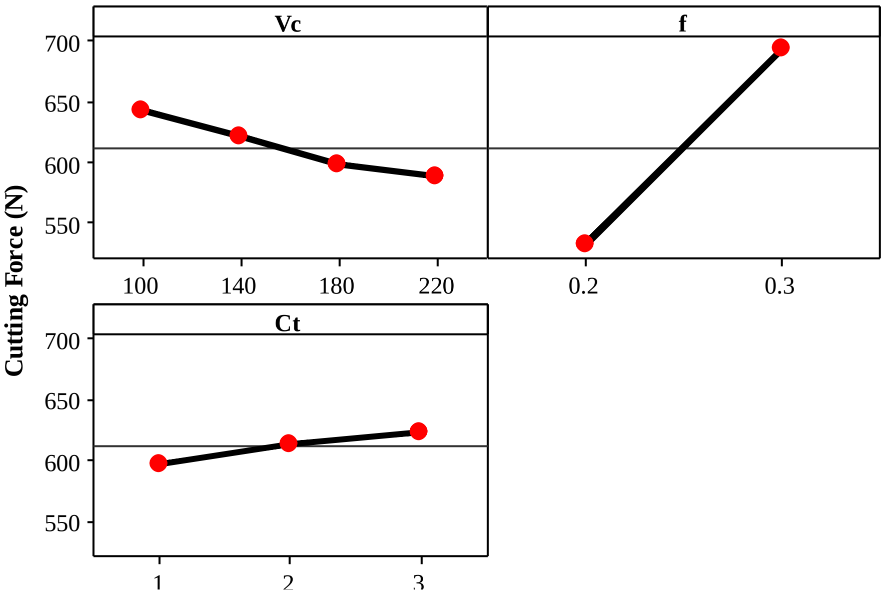

Figure 4. The effect of cutting parameters and coating materials on the cutting forces

When the ANOVA results were examined for the surface roughness (Table 6) it was seen that coating material (*Ct*), cutting speed (*Vc*), feed rate (*f*), independent variables with respect to P values were effective on the cutting forces (P<0.05), whereas (*Ct***Vc*), (*Ct***f*) and (*Vc***f*) interactions (statistically at confidence level of 95%) had no effect on the surface roughness (P<0.05).

When the contribution ratios of the parameters on the surface roughness were examined (Table 6) it was again seen that the most effective parameter was feed rate, with a contribution ratio of 94.79%, followed by coating material, cutting speed, coating material-feed rate interaction, cutting speed-feed rate and coating material-cutting speed interaction, respectively. This is also clearly verified by the angle of gradients in the graphs (Fig. 5).

The coefficient of certainty (R^2=0.996) of the statistical model found as a result of the analysis shows that the conformity of the model was high; the effect of feed rate, cutting speed and coating material on *Ra* was 99.6%. The obtained model is given in Eq. (3).

$$\begin{aligned} Ra = &-0.521 + 0.053Ct - 0.0231Vc + 18f - 0.0431Ct^2 + 0.000054Vc^2 \\ &+ 0.00116\,CtVc + 0.813Ctf + 0.0138Vcf \end{aligned} \tag{3}$$

R-Sq = 99.6%   R-Sq(adj) = 99.3%

Tablo 6. ANOVA results for the surface roughness

Source of variance	Degree of freedom, *DF*	Sum of squares, *SS*	F Ratio □ = 5%	P-Value	Contribution rate (%)
Ct	2	1.1602	95.73	0.000	3.81
Vc	3	0.2283	12.56	0.005	0.70
f	1	28.5580	4712.76	0.000	94.79
*Ct*Vc*	6	0.0625	1.72	0.264	0.09
Ct f*	2	0.0460	3.80	0.086	0.11
*Vc*f*	3	0.0295	1.62	0.280	0.04
Error	6	0.0364	-	-	0.46
Total	23	30.1208	-	-	100

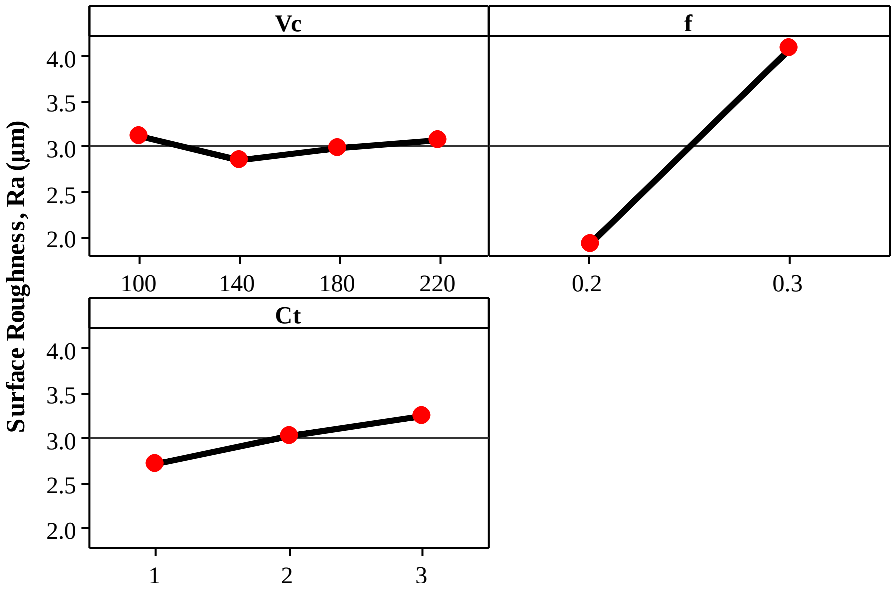

Figure 5. The effect cutting parameters and coating materials on the surface roughness

The comparison of measurements of the cutting forces and surface roughness obtained at the end of the tests and the estimated values obtained as a result of the multiple regressions is given in Fig. 6. It can be observed that there is a strong relation between the estimated values for both of the cutting forces and the surface roughness and response variable. The absolute errors for cutting forces and surface roughness were found to be 0.87% and 2.06%, respectively. Results from the mathematical models indicate that they can be successfully applicable for the prediction of the cutting forces and surface roughness.

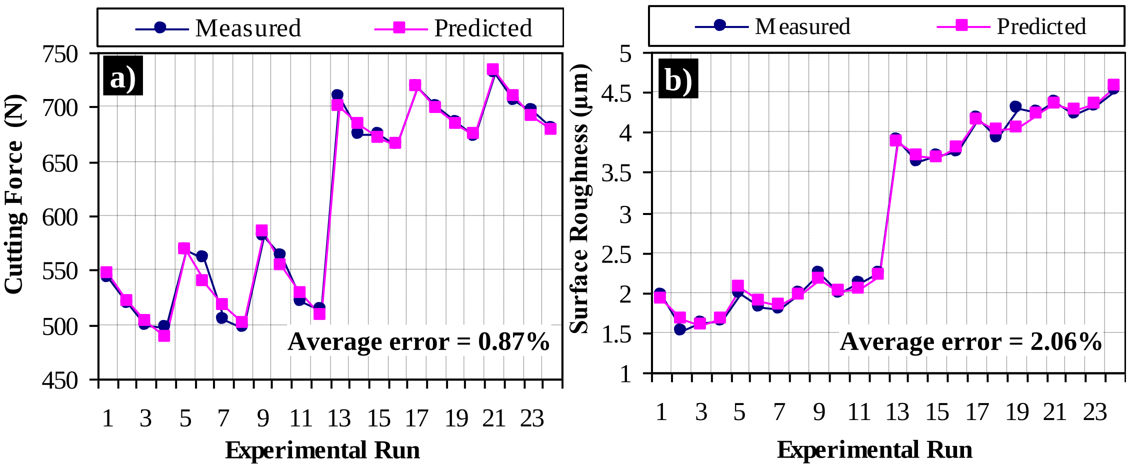

Figure 6. The relation between the values measured during the test and the estimated values a) cutting force, b) surface roughness

4. CONCLUSIONS

The effects of coating materials and cutting parameters on the machinability of Hadfield steel was experimentally and statistically investigated in this study, and the following conclusions were obtained:

i. The cutting speed caused decreases of 6-13% on the cutting forces, depending on the feed rate and coating material. The feed rate was observed to have a greater effect than the cutting speed on the variation of the cutting forces.

ii. Different cutting parameter combinations did not vary significantly with different coatings. The lowest cutting forces were obtained with the PVD TiAlN-coated tools.

iii. Again, as with the cutting forces, the feed rate played an important role in the increase of surface roughness. TiAlN-coated tools exhibited the best performance on surface roughness and the lowest surface roughness values were obtained with these tools.

iv. The correlation coefficients of the statistical model that was developed at the end of the analysis came out to be R^2= 0.994 and R^2= 0.996 for the cutting forces and surface roughness, respectively.

v. The feed rate was found to be the most effective parameter on the cutting forces and surface roughness, with contribution ratios of 91.31% and 94.79%, respectively.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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