Comparative study of tool life of solid and multi coated ceramic hard alloy tools in turning of high-chromium white cast iron castings

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The tool life of tungsten carbide-cobalt solid and multi-coated (Al_2O_3+Ti(CN)) ceramic hard alloy tools was evaluated by time duration in turning of 28 % high chromium white cast iron castings. Experimental study was performed using the Full Factorial Design of Experiments (FFDoE) method using Minitab statistical software, and a regression model was developed based on process factors: cutting speed V, feed rate f and cutting depth t. The influencing range of the factors was selected at upper and lower two levels. Both of semi-quadratic and linear regression models were developed by using the experimental results. In the first, a semi-quadratic regression equation was generated including each factor and each joint effect. Then, after statistical evaluation re-processing was performed by removing the non significant terms of effects. The experimental results showed that the tool life of multi-ceramic coated hard alloy tool was higher than the solid tungsten carbide by 25 and 16 %n light and heavy turning regime, respectively. The semi-quadratic equation includes eight possible effects of factors, but is only 0.6–0.8 % more accurate than the linear model that includes four effects. Therefore, the linear regression model is sufficient to predict the high-chromium white cast iron machining process with using of carbide-cobalt solid and ceramic coated hard alloy tools. The values expressed by the linear regression model are correlated with the experimental one more than 0.98 %.
Key words: Cutting tools, white cast iron, regression model, turning regime, Minitab statistical software
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Introduction

In the Repair Mechanical Plant of the Erdenet Mining Mongolia, a large number of slurry pumps have been produced to transport of ore slurry in Mineral processing. The impeller, volute case and protective disc, the main working components of this pump, are been cast from high-chromium white cast iron (HCrWCI) containing 28 % chromium and 2 % nickel. After annealing heat treatment, the cast components are machined with tungsten carbide-cobalt (WC+Co) solid alloy tool, to ensure surface dimensional accuracy. The tool material is produced by powder metallurgy using of 94 % tungsten carbide powder and 6 % elemental cobalt, and is intended for machining of cast iron materials. When machining of HCrWCI with the WC+Co solid alloy tool, the efficiency of machining is very low due to impact break and excessive wear of the tool. In the practical conditions, the cutting speed lays just in between 10–20 m/min, and when it exceeds that, it wears out quickly and needed a new one to before replaced. The hardness and surface quality of the casting material significantly affects on the machining speed of the tool. When the hardness of the work piece exceeds 500 HB, the tool life decreases dramatically. Also, foreign non-metallic impurities in the surface of the casting, which enters during the casting process complicate the machining process and cause impact, which is the main cause of tool damage by breaking. This often leads to premature replacement of the tool. For this reason, the machining time of impeller, volute case and protective disc, weighing 260–750 kg each lasts an average of 14–19 hours. From this, it can be seen that the productivity of the HCrWCI with tungsten carbide-cobalt solid tool is very low. This is shown by the following calculations made as a result of preliminary research and observations obtained in the production process (**Table 1**).

From the Table 1, the maximum cutting speed of the protective disk was equal and less than 20 m/min. In case of the impeller and the volute case the cutting speeds are as 3–10 and 8–10 m/min respectively. From this, it can be understood that the cutting speed of HCrWCI with the tungsten carbide-cobalt solid tool alloy does not exceed 20 m/min in production conditions.

Productivity of machining process of HCrWCI depends on tool materials life time and the life time depends on tool materials hardness and structure.

Nexhat Qehaja and Azem Kycyku [1] have constructed tool life model for different hard materials using full factorial design $N=2^k+n_o$ (N – number of experiment, k – number of factors, n_o – number of additional test). Based on the results, they concluded that the tool life decreases with hardness of material, cutting speed, feed rate and depth of cut.

In present days several kinds of hard cutting materials are used in machining process of materials, such as titanium nitrite (TiN), titanium carbon-nitrite (TiCN), titanium-aluminum nitrite (TiAlN or ALTiN), chromium nitrite (CrN) and Diamond [2]. In this work, tool life estimation procedure based on Taylors tool life equation is presented.

Table 1. Machining characteristics of HCrWCI castings with tungsten carbide-cobalt solid too

Spindle rotation *n*, rpm	radial feed rate *f1*, mm/rev	axial feed rate *f2*, mm/rev	Cutting depth *t*, mm	Initial diameter *d1*, mm	Finish diameter *d2*, mm	Cutting length *L*, mm	Cutting width *h*, mm	Cutting speed *V*, m/min	Cutting time *T*, min	Productivity g/min
Protective disk										
8	0.06	0.08	1.5	840	800	0	4	21.10	166.7	20.00
8	0.06	0.08	1.5	800		51	4	20.10	755.6	19.05
8	0.06	0.08	1.5	390	340		4	9.80	208.3	9.29
8	0.06	0.08	1.5	460		54	4	11.56	800.0	10.95
Total									**1,930.6**	
Impeller										
7	0.2	0.2	1.5	178	145		4	3.91	62.9	9.27
7	0.2	0.2	1.5	145		136	4	3.19	690.8	7.55
7	0.2	0.2	1.5	450	340		4	9.89	209.5	23.44
Total									**963.2**	
Volute case										
4	0.12	0.12	2.5	800		54	4	10.05	288.0	23.81
4	0.12	0.12	2.5	840	800		4	10.55	133.3	25.00
4	0.12	0.12	2.5	215		47	4	2.70	250.7	6.40
4	0.12	0.12	2.5	690		11	4	8.67	58.7	20.54
4	0.12	0.12	2.5	740	690		4	9.29	166.7	22.03
Total									**897.3**	

High chromium white cast iron is a material which is difficult to be machined by using conventional tools, because of large amount of hard chromium carbides. Due to short life time, the turning speed is very low and a frequent tool replacement is occurred often. In order to improve machining ability of HCrWCI, Hongtao Ding and Yung Shim used laser assisted machining method. In this study, a laser beam is used to heat up the work piece simultaneously with machining process. The best results are obtained as 21–30 % decreasing of cutting force at temperature 300 °C – 500 °C on the surface of work piece [3].

Machining ability investigation on HCrWCI was studied by Ravi et al [4] using multi coated hard carbide tool (TiC/TiCN/Al2O3). In this study, the influence of cutting parameters on the cutting forces and metal remove rate (MRR) have been analyzed. Trust force was increased as the depth of cut and feed rate increase, and decrease as the cutting speed increases. The feed force decreases with increase in feed rate/or cutting speed, but increases as depth of cut is increased.

Tool life investigation of carbide cutting tools is conducted by Sobron et al [5]. The research was carried out to obtain an extended value of tool life by the Taylor equation.

Monika and Dheeraj [6] have considered a necessity of effective use of cutting tools to enhance tool life by setting the process parameter optimally. Any kind of machining is aimed to reach maximum amount of work in the potential shortest time and at the lowest possible cost. In order to get maximum output, the cutting parameters must be at their highest values. This causes very short tool life and number of repeated installations for replacing of old tools, therefore, tool costs would become very high. On the other hand, very low machining parameters would lead to very low output or productivity.

The effect of turning parameters on various cutting tool wear is studied in Kannan et al work [7]. Among the cutting tools, the carbide tool showed lowest wear than cermet and high speed steel tools.

Chen et al [8] evaluated the ability of high performance machining of HCrWCI with CBN tools. CBN tools enable to use as higher as 120–140 m/min of cutting speed, which is many times higher than the speed of conventional tools.

To construct experimental model predicting tool wear and tool life for hard machining process of different kind of materials the Taguchi optimization method is used widely [9] Based on Taguchi method, Kir et al [9] obtained optimum cutting entering angle and cutting speed providing lowest tool wear and longest tool life for Ni-Hard 4 cast iron with WC tools. Gunay and Yesel determined that surface roughness of high alloy white cast iron with higher hardness is lower than lower hard one with amount of 0.262 against 0.280 m [10]. Khamel et al [11] analyzed CBN tool wear, surface roughness and cutting force for machining AISI 52100 bearing steel. In their research, they selected flank wear value of the tool as tool life criteria. When value of flank wear reached 0.3 mm, they stopped experiment and measure the surface roughness. Similar study for hardened steel was conducted in Kumar et all work [12].

Comparative study to assess of cutting force components for coated and uncoated ceramic tools in hard turning of AISI H11 steel using the Taguchi plan is performed by Aouici *et al.* [13] They developed a mathematical model expressing the effect of cutting parameters on the surface roughness, cutting force and power. Optimization study of machining parameters for surface roughness of AISI 8660 hardened alloy steel was performed by Motorcu [14]. He concluded that feed rate is exerted the greatest effect on surface roughness followed by depth of cut and machining speed.

Rizvi *et al* conducted the experiments to determine the effect of machining parameters on roughness in turning of DIN 17210 steel using Taguchi method. They found that tool life decreases by 59.14 %, 16.02 %, and 2.16 %, respectively, if cutting speed, feed rate and depth of cut increased by 100 % [15].

Based on present situation of machining process of HCrWCI in Erdenet Mine conditions and literature review, the aim of study is defined as to conduct comparative evaluation of life time of solid and multi coated ceramic hard alloys in using Taguchi plan and ANOVA method.

Analitical techniques

Taylor's tool life equation

The most widely used tool-life model is the Taylor tool-life equation (in original form, it uses English units for cutting parameters), which has the following form:

$$vT^n = C_t \quad (1)$$

where T is tool life, C_t is the cutting speed which yields on-minute tool life and n is the exponent depending primarily on the tool material of 0.1–0.17 for HSS tools, 0.2–0.25 for uncoated WC tools, 0.3 for TiC and TiN coated WC tools, 0.4 for Al_2O_3 coated WC tools, 0.4–0.6 for solid ceramic tools.

For a linear T-v_c relationship, Taylor equation is modified as follows

$$T = C_T V^k \quad (2)$$

where C_T is the constant equal to T for V_c=1 m/min and k is the negative slope of the straight line and equal in magnitude to the inverse of the exponent. The slope k can be determined as:

$$\log T = \log C_t + k \log v \quad (3)$$

$$k = tg\alpha \frac{\log T_2 - \log T_1}{\log v_{c2} - \log v_{c1}} \quad (4)$$

Extended Taylor tool-life equation reflecting not only the dominant influence of cutting tool, but also effect of feed rate (f) and depth (t) of cut:

$$T = \frac{C_t}{v^x f^y t^z} \quad (5)$$

can be written as

$$T = C_t v^{-x} f^{-y} t^{-z} \quad (6)$$

After logarithmic transformation it converts into linear mathematical form:

$$\ln T = \ln Ct - x \ln v - y \ln f - z \ln t \quad (7)$$

Taguchi plan

The quality engineering methods of Taguchi is one of the most significant statistical tools for designing high quality systems at reduced cost. The method uses a special design of orthogonal arrays to study the entire process parameter with a small number of experiments only. Taguchi uses signal-to-noise (S/N) ratio. There is several S/N ratios available depending on the type of characteristic; lower is better (LB), higher is better (HB), or nominal is better (NB).Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. A statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant.

$$\frac{S}{N}_{SB} = -10lg\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (8)$$

$$\frac{S}{N}_{LB} = -10lg\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad 9)$$

$$\frac{S}{N}_{NB} = 10lg\left[\sum_{i=1}^{n}\frac{\bar{y}}{s^2 y}\right] \quad (10)$$

Response surface method (RSM)

Quadratic model of tool life can be written as follows:

$$Y = a_0 + \sum_{i=1}^{3} a_i X_i + \sum_{i=1}^{3} a_{ij} X_i X_j + \sum_{i=1}^{3} a_{ijl} X_i X_j X_l \quad (11)$$

Where: a_0 – intercept, a_{ij} – linear coefficients, X_i, X_j X_l – independent variables

Materials and methods

For experimental test 8 cylindrical work-pieces with dimensions 200 mm of diameter and 950 mm of length were prepared by casting in sand molds from HCrWCI alloy melted in electric melting furnace.

Tungsten carbide-cobalt solid tool with a hardness of 88–90 HRA and multi ceramic coated tools are used in the experimental work. The coated hard alloy consists of three types of ceramic material layers. These are high wear and heat-resistant layers such as aluminum oxide Al_2O_3, titanium nitrite TiN and titanium carbon-nitrite TiCN.

The experimental work was carried out in the Mechanical processing plant using 1M165 type lathe machine. Following turning parameters were selected as factors affecting the tool life of the tools during the experiment process. These include:

1. Cutting speed, V, m/min
2. Feed rate of cut, S, mm
3. Cutting depth, t, mm

Before the beginning of the experiment, the work-pieces were subjected to annealing heat treatment to reduce the surface hardness to 460 HB. Then, in order to ensure surface evenness, the work-pieces surface were machined up to 10 mm of thickness. The plan of the Full Factorial Design of Experiments Method using Minitab software is written in the form of a table called a matrix, in which the factors are indicated not only in their actual, but also coded values. The coded value of the factor is denoted by X_j. The coded and actual values of the factor are interrelated to each other by the following formula.

$$Xj = \frac{A_j - A_{j0}}{\Delta A_j} \quad (12)$$

Here: Xj – coded value of factor, A_{j0} – value of the basic level of factor, ΔA_j - difference between actual and basic level values of factor.

The axial maximum and minimum values of factors are determined at each of upper and lower level of affect and

Table 2. Actual and coded values of factors

Factors	Actual					Coded		
	Symbol A_j	High A_{max}	Low A_{min}	Basic A_{j0}	Interval of changing, ΔA	Symbol X_j	High X^+	Low X^-
Cutting speed, *V*, m/min	*V*	40	20	30	10	X1	+	-
Feed rate, *S*, mm	*S*	0.12	0.08	0.1	0.02	X2	+	-
Depth of cutting, *t*, mm	*t*	2.5	1	1.75	0.75	X3	+	-

are denoted as between – 1 and +1 depending on the level of influence. These are simply written as – and + signs. The actual and encoded values of the variable limits of the influence of factors are shown in **Table 2** below.

Considering that the factors affecting the wear of the cutting tool have not only individual effects but also their joint effects of binary and ternary types, the following non-linear regression model of the incomplete quadratic modeling in three variables type was selected.

$$T=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_{12}X_1X_2+\beta_{13}X_1X_3+\beta_{23}X_2X_3+\beta_{123}X_1X_2X_3 \quad (13)$$

Here: X_i – coded symbols of the factors, β_i – regression coefficients

Since the number of factors affecting the experimental work is 3, and the level of influence of each factor is 2, the full factorial experimental design method was chosen. In this case, the number of experiment run is 8, which is determined by the equation $N=n^k$. Where k is the number of factors, n is the number of influence levels.

The processing method of the experimental data

The results of the experimental work are processed using Minitab statistical software as shown in below.

The effect of each factor is determined by the difference between the effects of each of its upper (+) and lower (–) levels.

$$E_{ij}=\frac{\sum_{i=1}^{n}(X_i-T_i)^+}{n^{k-1}}-\frac{\sum_{i=1}^{n}(X_i-T_i)^-}{n^{k-1}} \quad (14)$$

here: T_i – test results of life time of the tools, min.

Regression model coefficients are determined by next formula

$$\beta_{ij}=\frac{E_{ij}}{n^k} \quad (15)$$

The significance level of the factor is determined by the threshold value expressed by the error level α=0.05, which is shown in the results determined by the Minitab program. The significance level of the equation expressed by the semi-quadratic regression model is re-evaluated by removing the members that do not meet the requirements.

To evaluate the life time limit of the tools exactly, the temperature of the blade tip and the value of the vertical component of the cutting force *Rz* were selected as criteria. When the temperature and the vertical force values reached 425 °C and 170–180 N, the test was stopped and the time was recorded as life time.

This is because the increase in temperature and the vertical force directly depends on the wear of the blade. The temperature of the blade tip and the vertical force were continuously monitored during the experiment.

Results and discussion

The results of 2^3 type full-factorial experiments is showing the tool life of the solid (*Ts*) and coated (*Tc*) alloy tools as a function of cutting speed, feed rate and cutting depth, and determined parameters are shown in the **Table 3**. Each experiment was conducted three times and the average value was taken.

For solid hard alloys, the tool life was 152 minutes in the lightest mode of the turning, while it was 64 minutes in the heavy mode of turning. These values were as 197 and 80 minutes for the coated hard alloys, respectively. Here,

Table 3. Experimental results of the tool life of the tools

No.	Factor's designation										Life time of the tools, min	
	Uncoded			Coded							Uncoated	Coated
	V	*S*	*t*	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	*Ts*	*Tc*
1	20	0.08	1	–	–	–	+	+	+	–	152	191
2	40	0.08	1	+	–	–	–	–	+	+	105	130
3	20	0.12	1	–	+	–	–	+	–	+	140	170
4	40	0.12	1	+	+	–	+	–	–	–	90	111
5	20	0.08	2.5	–	–	+	+	–	–	+	125	158
6	40	0.08	2.5	+	–	+	–	+	–	–	76	97
7	20	0.12	2.5	–	+	+	–	–	+	–	114	144
8	40	0.12	2.5	+	+	+	+	+	+	+	64	80

it can be understood that the coated hard alloys are 16–25 % more durable than the solid hard alloys for turning of HCr-WCI samples. Experimental results of life time of the cutting tools are shown in Table 3.

The results of the processing that used the Minitab program are presented in the **Table 4**, expressed for each solid and coated hard alloy tools.

In the results, row 1 shows the nonlinear regression model equation showing each of the single and combined effect of the factors, while the row 2 shows the degree of effect of the factors. Looking at the degree of effect of the factors, it can be said that their single effects are significant, but the combined effect is very small or almost non-significant. The most influential factor is the cutting speed, which is 49 % for solid alloy and 61 % for coated blades. The effect of the cutting depth is 27 % for solid alloy and 31% for coated alloys, while the effect of the feed rates is 12.5 % and 18 %, respectively. From this, it can be seen that the cutting depth of machining is more influential than the feed rate. This is seen from the normal plot of the effect shown in row 3 and the Pareto diagram in row 4. The allowable limit of the effect is indicated by the red line in the Pareto diagram.

Since the combined effects of the factors are not significant from the results in the above table, the results expressed by a pure linear regression model in the form $T = \beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3$ are developed and shown in Table 4.

Row 1 of **Table 5** shows the linear regression model equation for the effects of the three factors, and row 2 shows the statistical indicators such as the effect size, *T-value*, and *P-value*. The *P-values* are all less than 0.05, indicating that their effects are significant. Row 3 shows the analysis results showing the significance level of the regression model. R^2 is 99.92 for the solid alloy and 99.84 for the coated alloy, indicating a very high correlation between the regression model and the experimental results. All statistical figures in row 4–7 of Table 5 shows the satisfaction of the linear regression model to the experimental data.

Conclusion

The cutting life time comparative study of tungsten carbide-cobalt solid and ceramic coated hard alloy tools at machining of High-chromium white cast iron castings containing 28 % chromium and 2 % nickel was evaluated by Full Factorial Design of Experiments method in 8 different combinations of cutting speed, feed rate, and depth of cutting. The results of the experiments and simulations performed using the Minitab program show that the coated hard alloy blade is up to 25 % more resistant than the solid hard alloy tool. This is applicable when the work piece surface has a hardness of no more than 460 HV and is structurally very clean and homogeneous. A linear regression model was developed depending on the parameters such as cutting speed V, feed S, and cutting depth t. The single effect of the above factors on the cutting time is dominant, and the combined effect is insignificant. Due to above factors, we conclude that in turning process of HCrWCI materials, cutting speed has the greatest effect, followed by cutting depth to life time of tools. The effect of feed rate is less than that of cutting depth.

Table 4. Results expressed by the nonlinear regression model

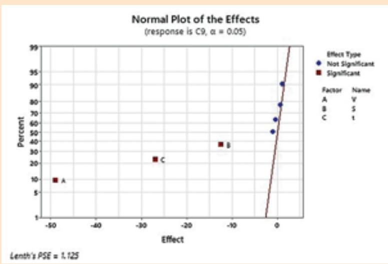
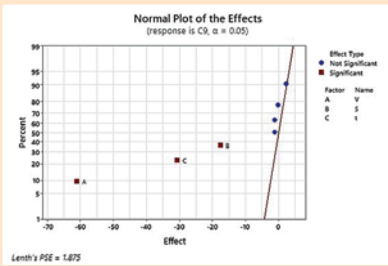
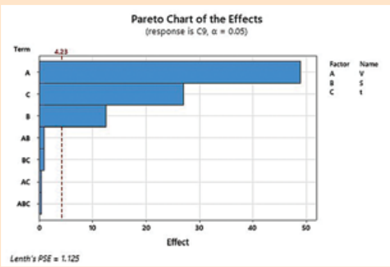
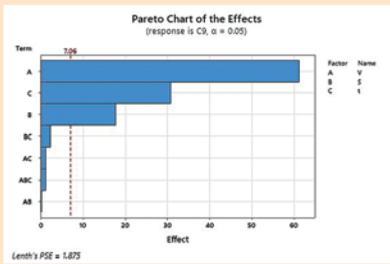
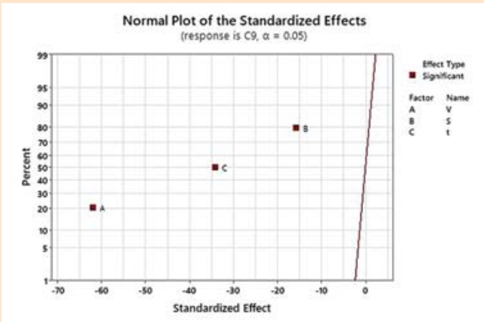
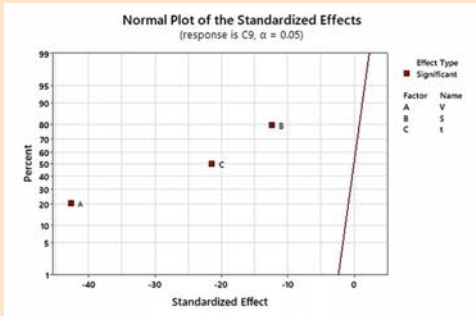
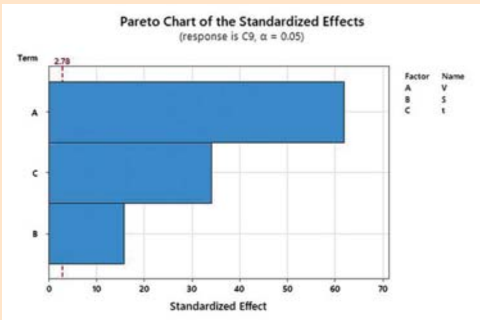
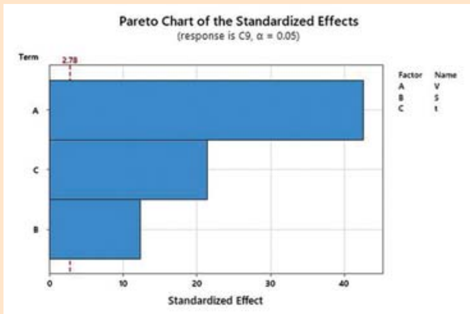
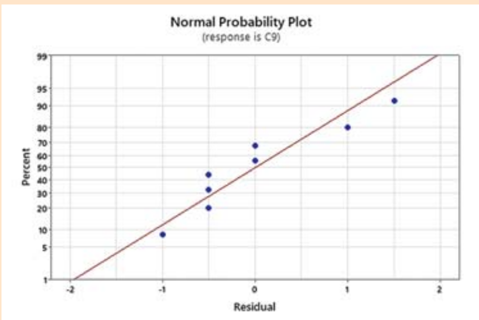
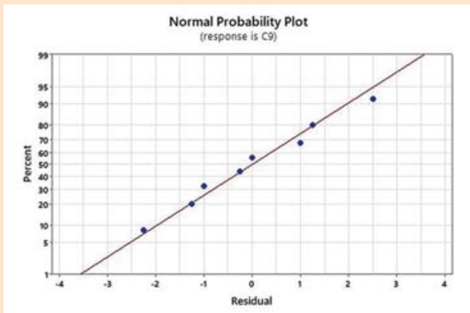
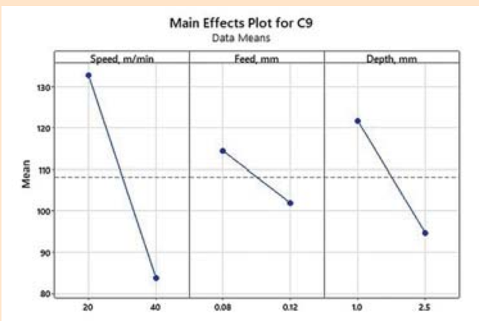
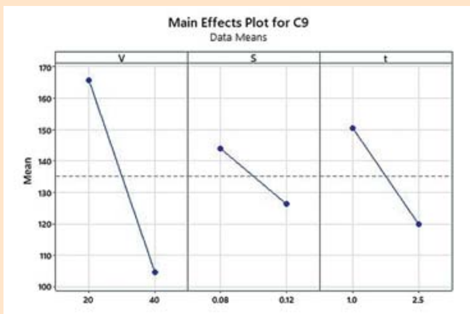
№	Solid tool							Coated tool						
1	$Ts = 232.3 - 1.85 \cdot V - 208.3 \cdot S - 15.3 \cdot t - 5.4 \cdot V \cdot S - 0.2 \cdot V \cdot t - 16.7 \cdot S \cdot t + 1.7 \cdot V \cdot S \cdot t$							$Tc = 336.0 - 3.6 \cdot V - 775.0 \cdot S - 38.0 \cdot t + 6.7 \cdot V \cdot S + 0.3 \cdot V \cdot t + 200.0 \cdot S \cdot t - 4.2 \cdot V \cdot S \cdot t$						
2	Effect level of Factors							Effect level of Factors						
	V	*S*	*t*	*VS*	*Vt*	*St*	*VSt*	*V*	*S*	*t*	*VS*	*Vt*	*St*	*VSt*
	–49	–12.5	–27	–1	–0.5	1	0.5	–61	–18	–31	–0.2	–1.2	2.2	–1.2
3														
4														

Table 5. Results expressed by linear regression model

№	Solid Carbide Tool				Ceramic Coated Tool			
1	$Tsc = 244.5 - 2.45 \cdot V - 312.5 \cdot S - 18.0 \cdot t$				$Tmc = 307.25 - 3.1 \cdot V - 443.8 \cdot S - 20.5 \cdot t$			
2	Values	*V*	*S*	*t*	Values	*V*	*S*	*t*
	Effect	–49	–12.5	–27	Effect	–61.25	–17.75	–30.75
	T-Value	–61.98	–15.81	–34.15	*T*-Value	–42.6	–12.4	–21.4
	P-Value	0.00	0.00	0.00	*P*-Value	0.00	0.00	0.00
3	*S*	*R*-sq	*R*-sq(adj)	*R*-sq (pred)	*S*	*R*-sq	*R*-sq(adj)	*R*-sq (pred)
	1.12	99.92%	99.87%	99.70%	2.03	99.84%	99.71%	99.34%

№	Solid Carbide Tool	Ceramic Coated Tool
4		
5		
6		
7		

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