Optimization of the High Speed Machining of Hardened AISI 4140 Steel using Vapor Deposited Cutting Tools (Wear and Roughness)

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Abstract: In this study, the main cutting parameters of high speed machining (HSM) including cutting speed, feed rate, depth of cut as well as deposition method were optimized using genetic algorithm considering the average surface roughness (Ra) of work piece and flank wear (V_b) of CVD and PVD coated tool criteria in high speed turning of hardened AISI 4140 Steel. Standard L_{18} orthogonal array has been used for the design of experiment (DOE) applying Taguchi approach. Multiple linear regression model applying Minitab, was used to determine the relationship and interaction between machining parameters and outputs. For genetic algorithm(GA) optimization, the average was applied as a functional output of design of experiments. The results of GA for smaller- the better quality characterization shows the optimum roughness of 1.107 mm and optimum flank wear of 0.461mm. The confirmation tests were carried out in order to validate the response of predicted optimum condition. The results of validation test show a good agreement between obtained optimum condition and the results of genetic algorithm. The analysis of variance was used in order to obtain the contribution of each factor on the output statistically. ANOVA results indicated that the cutting speed and cut depth are the most effective factors on the flank wear by 37.02 and 27.80 percent contribution respectively. The most effective factors on surface roughness were feed rate and cutting speed by 82.49 and 10.50 percent contribution respectively. Stereoscopy and Scanning electron microscopy was used to evaluate the wear mechanism and topography of worn surface.

Keywords: CVD, Flank wear, Genetic algorithm, HSM, PVD, Roughness, Tool wear

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1 INTRODUCTION

In recent years, the trend toward increasing the coating engineering has been increased with the need to apply higher cutting speed and feed rate. As the technology of cutting tools is rapidly improving, such development in coating is necessary to improve the wear resistance and performance of machining on low-machinability materials. Improvement in performance can be achieved by increasing the life of the cutting tools in terms of wear resistance [1] – [3]. In coating processes, the substrate is deposited by a hard, low-friction, chemically inert and thermal barrier layer (thickness of 1-30 μm) [2]. These days the cemented carbides are the most common tool materials available in high production rate [3].

Cemented carbide cutting tools are coated using two different methods: physical vapor deposition (PVD) and chemical vapor deposition (CVD) [1]. Flank wear (Fig.1) is the most common type of wear in cutting tools. The flank wear occurs in any cutting condition but is predominant in low and medium cutting speeds. Flank wear takes place due to abrasion, caused by hard constituents in the work piece and tool (two counter body) or by work hardened debris in tool-chip-work piece interface (three counter body). Crater wear (adhesion wear mode) is localized to the rake side of the insert. Cratering is due to a chemical reaction and temperature in the work piece - tool interface and improves by increasing the cutting speed and temperature. Deeper craters (severe adhesion wear) lead to weakening the cutting edge and may lead to fracture.

In machining the sticky materials, such as low carbon steel, stainless steel and aluminium, adhesive wear is caused by local micro-welding of the chip to the insert. Lower cutting speed increases the formation of built-up edge but there is a stable BUE action mechanism in such conditions. Plastic deformation takes place when the cutting temperature is too high for a certain cutting parameters. In general, harder grades and thicker coatings improve resistance to plastic deformation wear [4]. In addition to wear mechanism, the work piece is the other restrictive criteria. Surface quality, provides considerable improvements in the tribologic characteristics, fatigue strength, corrosion resistance, performance and aesthetic look of the products. The surface roughness of work piece as a limiting factor in choosing the cutting parameters can be affected by tool wear. The parameters which affect the surface roughness and tool wear are mainly cutting tool material, coating material, cutting speed and feed rate.

Obtaining minimum surface roughness and tool wear by the optimization of these parameters is very important from the cost reduction view point. For this reason, in recent years, a number of statistical models have been developed for the analysis and optimization of machining parameters such as response surface methodology (RSM), regression techniques, analysis of variance (ANOVA) and the Taguchi method. The Taguchi-based optimization technique has produced a unique and powerful optimization discipline that differs from traditional practices [5]. Kıvak [1] applied the Taguchi method and regression analysis for optimizing the surface roughness in milling of Hadfield steel with PVD and CVD coated inserts. The CVD TiCN/Al_2O_3-coated carbide inserts showed better performance than PVD TiAlN-coated carbide inserts and could be suggested for milling of Hadfield steel in their study. Günayet al [6] also applied the Taguchi approach to determine the optimal cutting parameters for surface roughness in machining the alloyed white cast iron.

The statistical analysis indicated that the parameters that have the biggest effect on Ra for Ni-Hard materials with 50 HRC and 62 HRC, are the cutting speed and feed rate. Shahrom et al [7] applied the statistical method for studying the effect of lubrication condition on surface roughness in milling. Minimum quantity lubricant (MQL) and wet machining in milling processes of AISI 1060 aluminium was investigated. The result significantly reduced the cost and environmental pollution in case of waste material. Chinchanikaret al [8] Investigated the effect of work piece hardness, cutting parameters and type of coating (coated tool) on the cutting force and chip morphology during turning of hardened AISI 4340 steel at different levels of hardness. The better tool life obtained by CVD coated tool in their study, was attributed to its thick coating and the protective Al_2O_3 oxide layer formed during cutting, which protected the tool against severe abrasion at elevated temperatures.

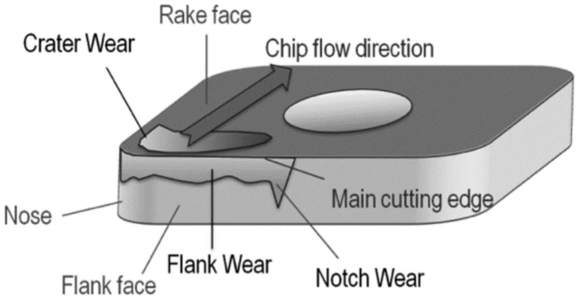

Fig. 1 Modes of wear in cutting tools.

According to literature, it seems important to do a constitutive study on a specific tribo-system (tool-work-machine - coating types) in order to increase the machining performance by means of optimization base on accurate regression. In present research the genetic algorithm has been used to evaluate the optimum tool wear and work piece roughness in high speed machining (HSM). Design of Experiments using standard Taguchi method and considering main parameters - cutting speed, feed rate, depth of cut as well as deposition method - has been done for this purpose. The optimum conditions for HSM was obtained using the capability of MATLAB in genetic algorithms coding. Multiple linear regression model applying Minitab, were used to determine the relationship and interaction between machining parameters and outputs. Scanning electron microscopy was used to evaluate the worn surface and the wear mechanisms.

2 MATERIALS AND METHODS

The AISI 4140 steel was selected for work piece materials. Its chemical composition is given in Table 1. The work piece with dimension of ϕ70 mm × 350 mm were applied to heat treatment at 850ºC (austenite temperature) for 30 minutes and oil quenched followed by tempering at 200ºC for 1 hours and cooling to ambient temperature. The Turning experiments were carried out in dry cutting conditions using CNC lathe machine with Fagor processor model 8055 equipped with a maximum spindle speed of 4500 rpm and a 15 kW drive motor. The applied parameters and relevant levels are tabulated in table 2. The cutting experiments were conducted using two types of cemented carbide tool inserts: PVD-coated and CVD-coated tools, the properties of cutting tools and coating materials are given in Table 3. The orthogonal array L_{18} was selected for designing and conducting the experiments (table 4).

Table 1 Chemical composition of workpiece materials

C	Si	Mn	Cr	Mo	Ni	Cu	Fe
0.37	0.26	0.82	0.94	0.17	0.08	0.20	Balance

The evaluation the worn surface and measurement of flank wear of inserts were done by stereoscope (OPTIKA model) coupled with camera (DINO model) and computer. Scanning electron microscopy was used to evaluate the topography of worn surfaces and wear mechanisms. The average surface roughness (Ra) of the workpiece was measured by a Hand-Held TR200 TIME Ltd. surface roughness tester; the cut-off and evaluation lengths were fixed at 0.8mm and 5mm respectively.

Table 2 Variables parameters and their levels

Factors	Symbol	L 1	L2	L3
Deposition method	A (Ct)	PVD	CVD	-
Cutting speed (m/min)	B (V)	180	230	280
Feed rate (mm/rev)	C (f)	0.10	0.15	0.20
depth of cut (mm)	D (d)	0.3	0.6	0.9

Table 3 Specification of coated tools

Grade	Symbol	Coating method		Thickness
GC1125	$HC^{\times}$	PVD	Oxide	4 µm
GC2025	$HC^{\times}$	CVD	Ti(C,N)+ Al_2O_3+TiN	4 µm

$^{\times}$Hardmetal-coated

Table 4 Taguchi's orthogonal array (L_{18})

Experiment no.	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

3 RESULTS AND DISCUSSION

3.1. Design of Experiment (DOE)

Taguchi approach has been used for designing, conducting as well as evaluating the effect of main HSM parameters on the work piece roughness and flank wear of cutting tool. The standard Taguchi array (L_{18}) and mean values of outputs according to Taguchi's ''the-smaller-the-better'' quality characterization is tabulated in table 5. Fig. 2 shows the stereoscopy image of flank wear for tests E10 and E11. In this study. Figure 3 illustrates the average effect of parameters on the flank wear of cutting edge. As shown the PVD coatings are less wear-resistant than tools with CVD coatings. One of the PVD coating features is the reduction of friction coefficient in this process [9]. In PVD coatings, the friction coefficient reduction exists even at high temperatures and leads to abrasion resistance in elevated temperatures [10]. As the cutting speed and depth of the load increase, the flank wear of the tool increases dramatically in higher levels of the cutting speed and cut depth in this study. More relevant details will be discussed in section of wear mechanisms. Nevertheless, In the case of changes in the feed rate, there was no certain increase or decrease trend. After a sharp decrease in flank wear from feed rate in level 2, the wear increases again by increasing the feed rate. Therefore, in order to minimize the flank wear, the feed level should be considered at an optimum level.

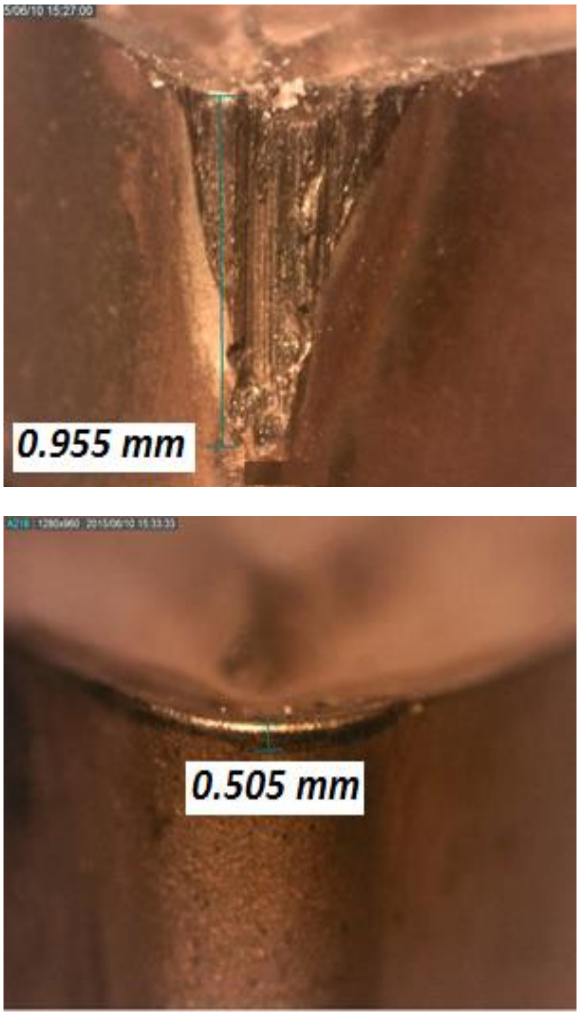

Fig. 2 Flank wear width in E10 and E11.

Table 5 Average flank wear and roughness (Ra)

Test no.	Ct	V	F	D	Ra (μm)	Vb(mm)
1	PVD	180	0.10	0.3	1.27	0.545
2	PVD	180	0.15	0.6	1.42	0.550
3	PVD	180	0.20	0.9	1.90	0.630
4	PVD	230	0.10	0.3	1.25	0.655
5	PVD	230	0.15	0.6	1.37	0.685
6	PVD	230	0.20	0.6	1.64	0.760
7	PVD	280	0.10	0.6	1.17	0.805
8	PVD	280	0.15	0.9	1.37	0.865
9	PVD	280	0.20	0.3	1.67	0.690
10	CVD	180	0.10	0.9	1.25	0.955
11	CVD	180	0.15	0.3	1.46	0.505
12	CVD	180	0.20	0.6	1.77	0.570
13	CVD	230	0.10	0.6	1.15	0.759
14	CVD	230	0.15	0.9	1.31	0.850
15	CVD	230	0.20	0.3	1.64	0.845
16	CVD	280	0.10	0.9	1.12	1.102
17	CVD	280	0.15	0.3	1.25	0.755
18	CVD	280	0.20	0.6	1.47	0.930

The surface roughness of work piece for the levels of factors in this study is shown in Fig. 4. Clearly, it can be seen that a tool with CVD coat creates less roughness compared to high speed machining with PVD coatings. As is predictable, the surface roughness decreases by increasing the cutting speed and selecting the lower levels of feed rate. As it was predictable, the surface roughness decreases by increasing the cutting speed and selecting the lower levels of feed rate. In case of cut depth, it seems that this parameter has not much effect on the surface quality. All in all, the machinist should consider the capability and vibration of tool-work piece-machine in selecting the cut depth and feed rate [11].

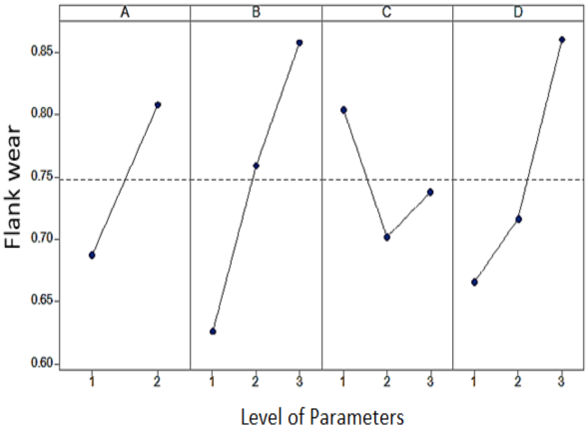

Fig. 3 The average effect of parameters (mentioned in table2) on flank wear.

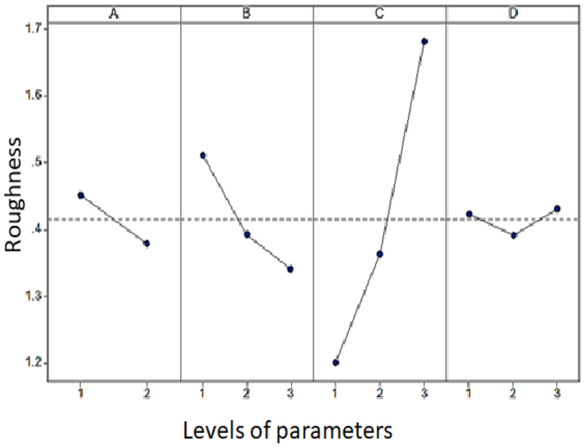

Fig. 4 The average effect of parameters on roughness.

3.2. Mathematical Modeling

The second order linear regression equations were used for the mathematical modeling for more accurate curve fitting of wear and roughness as below Eq. 1:

$$Y = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \sum_{i=1}^{p} \beta_{ii} x_i^2 + \sum_{i} \sum_{j \neq i} \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

The least square method is used, where all β coefficients are regression coefficients. X_i is the independent variable, p is number of variables, and y is the dependent variable. The Pearson correlation coefficient (Eq. 2) was used for further examination of the effect of parameters and their interactions. The closer the correlation coefficient is to values 1 and -1, the more suitable the linear relationship will be between parameters. If the coefficient is equal to zero or very close to zero, it will indicate lack of a linear relationship between two parameters [12].

$$R = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2)}} \qquad (2)$$

Where, (x_i, y_i) is ordered pair of “i” observation. The results of Pearson correlation for wear and roughness (Tables 6) show that the effect of parameter B, C and D are in second order linear relation with wear rate because of larger correlation coefficient. Also in the case of roughness parameters B and C are as second order form. Moreover, interactions B×C, B×D and C×D, indicated in tables 7 and 8, have impressive effect on both of wear and roughness. Parameter D has no significant effect on roughness and so, it is considered as error of regression equation.

Table 6 Pearson correlation for wear and roughness

Wear (Roughness)	B	C	D
Linear Correlation	0.60(0.316)	-0.17(0.89)	0.53 (0)
Quadratic correlation	0.61 (0.324)	0.27(0.91)	0.55 (0.08)

Table 7 Pearson Correlation Coefficient for wear results

Linear Correlation	C×B	D×B	D×C
wear	0.18	0.72	0.522
roughness	0.55	-0.71	0.50

As mentioned above, Equation 1 is summarized as Eq. 3a and Eq.3b for wear and roughness respectively.

$$Y = \beta_0 + \beta_1 B + \beta_2 C + \beta_3 D + \beta_4 B^2 + \beta_5 C^2 + \beta_6 D^2 + \beta_7 BC + \beta_8 BD + \beta_9 CD \qquad (3a)$$

$$Y = \beta_0 + \beta_1 B + \beta_2 C + \beta_3 B^2 + \beta_4 C^2 + \beta_5 BC + \beta_6 BD + \beta_7 CD \qquad (3b)$$

Regression function is calculated after determining regression coefficients using the least squares error method and Minitab for flank wear and roughness respectively (Eq. 4 and 5). Tables 8 and 9 show the results of regression analysis.

Vb = -0.06 + 0.00887 B - 8.96 C + 0.428 D
- 0.000020 B*B + 31.1 C*C + 0.494 D*D (4)
+ 0.0112 B*C + 0.00089 B*D - 5.74 C*D

Ra = 1.946 - 0.00575 B - 1.46 C
+ 0.000015 B*B + 29.9 C*C – (5)
0.0156 B*C - 0.00096 B*D + 1.34 C*D

Table 8 Regression analysis for average flank wear

Term	Coef	T-Value	P-Value	VIF
Constant	-0.06	-0.06	0.954	
B	0.00887	1.13	0.293	289.25
C	-8.96	-1.46	0.182	175.09
D	0.428	0.53	0.608	98.06
B*B	-0.00002	-1.22	0.257	265.86
C*C	31.1	1.89	0.096	115.09
D*D	0.494	1.09	0.306	45.24
B*C	0.0112	0.9	0.394	55.84
B*D	0.00089	0.43	0.676	42.42
C*D	-5.74	-2.55	0.034	23.23

Table 9 Regression analysis for average

Term	Coef	T-Value	P-Value	VIF
Constant	1.946	2.33	0.042	
B	-0.00575	-0.89	0.392	272.78
C	-1.46	-0.31	0.765	149.04
B*B	0.000015	1.12	0.288	262.35
C*C	29.9	2.2	0.052	110.39
B*C	-0.0156	-1.54	0.154	51.92
B*D	-0.00096	-0.94	0.369	15.85
C*D	1.34	0.87	0.404	19.11

To make comment on the accuracy of a regression equation, its coefficient of determination (R^2 و R_{adj}^2) is usually considered as a criterion. The mentioned values R^2= 94.76% and 88.26% and R_{adj}^2= 91.10% and 75.05% for flank wear and workpiece roughness show that the achieved regression equation is a suitable model for describing changes of outputs.

3.3. Genetic Algorithm

In fact, genetic algorithm is a method for finding an approximate solution of optimization problems using the concepts of biology such as inheritance. In this algorithm, the variables are binary coded. Then using computer simulation of conservation laws, the weaker characters are replaced by more appropriate characters. This process is repeated to gain the best results. The process is iterated as long as the best response is achieved. The fundamental steps for analyzing optimization problems using genetic algorithm code writing are as follows:

1- Defining variables as a chromosome with a constant length, selecting size of a chromosome, determining crossover probability (P_c) and Mutation probability (P_m)
2- Defining a target function for assessing chromosomes
3- Generating population of primary chromosomes randomly
4- Assessing the selected population
5- Copying the best members in a new generation
6- Performing a crossover action for each pair of chromosomes (parents) and generating two new chromosomes (offspring)
7- Performing a mutation action for the selected chromosomes and generating mutated offspring
8- Creating a new generation (merging 5, 6, and 7)
9- Assessing the new generation
10- Returning to Step 5 in case termination condition is not satisfied [13].

This research aims at achieving the minimum flank wear and surface roughness in HSM process. Genetic algorithm code writing in a MATLAB environment was used for this purpose. regression equations were used as a target function for algorithm implementation. The algorithm structure was established by selecting a 20 binary population randomly with the string length of 64 bits (for each 16-bit independent parameter) as the primary population and considering probabilities of crossover and mutation as 80 percent and 10 percent, respectively. A double point crossover method was used for generating two new offspring for each selected pair of chromosomes (parents). Figures 5 and 6 show changes of mean effect, which was calculated by the genetic algorithm. As the diagram shows, mean values of wear and roughness remains constant after about 5 iterations and it converges on 0.461 and 1.107 respectively. The results of optimization of GA is tabulated in table 10.

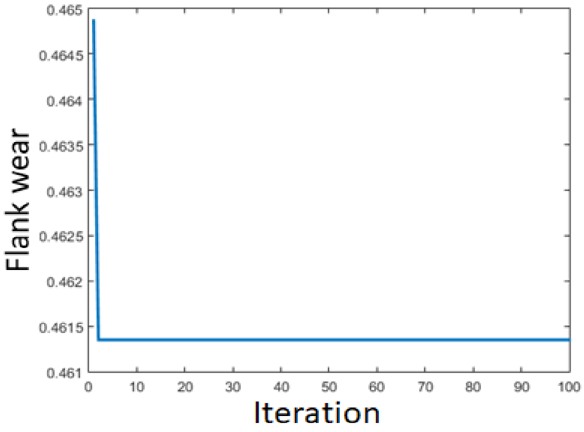

Fig. 5 Plot of Number of Generation Vs S/N Ratio (Velocity).

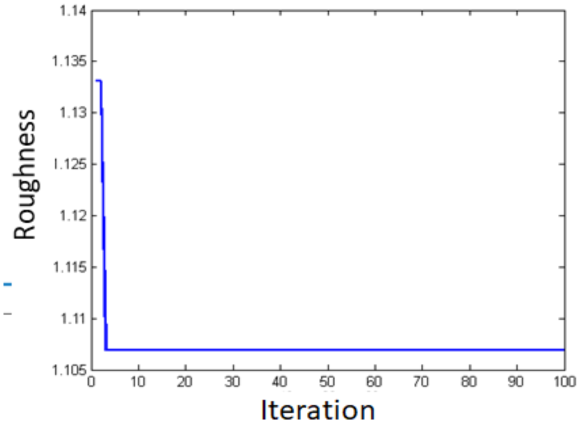

Fig. 6 Plot of Number of Generation Vs S/N Ratio (Velocity).

Table 10 The Optimal condition predicted by GA

	A	B	C	D	Ave.	Test
Roughness	CVD	280	0.1	0.9	1.107	A2B3 C1D3
Flank wear	CVD	180	0.15	0.3	0.461	A2B1 C2D1

3.4. Verification Test

A verification test was used for verifying the optimal results achieved by the genetic algorithm. The mean value of the optimal wear and roughness were 0.505mm and 1.12 μm, respectively. In statistical issues, confidence interval is an approximate range for data, which is used for the reliability of an estimate. Confidence interval is obtained for the mean value of a set of data and observations, C.I.(m), with a certain confidence level using the following equation [14].

$$\mathrm{C.I.}\,(\mathrm{m}) = \mathrm{E}(\mathrm{m}) \pm \sqrt{\frac{\mathrm{F}_{\alpha}(\mathrm{f}_1.\mathrm{f}_2)\times \mathrm{V}_e}{\mathrm{n}_e}} \qquad (6)$$

Where $\mathrm{F}_{\alpha}(\mathrm{f}_1.\mathrm{f}_2)$ is the variance ratio, which is obtained by Table F at the confidence level of 1-α. F_1 is the mean degree of freedom, which is always equal to one, f_2 is the error degree of freedom, v_e is error variance, and n_e is number of equivalent responses. The result of confidence interval calculation for wear and roughness at the predicted levels are tabulated in tables 11 and 12. The results show that the optimal flank wear and roughness obtained from the test has good agreement with those predicted by the genetic algorithm.

Table 11 Result of C.I for flank wear

	GA	Experimental
Flank wear	0.461	0.505
C.I.(95%)	0.461±0.112	
	f_1=1, f_2=10, n_e=2.25, MS_e=0.005704, α =0.05	

Table 12 Result of C.I for flank wear

	GA	Experimental
Roughness	1.107	1.12
C.I.(95%)	1.107±0.085	
	f_1=1, f_2=10, n_e=2.25, MS_e=0.003266, α =0.05	

3.5. ANOVA

ANOVA is one of the statistical applications, which examines the effect of variables on a response individually. In other words, ANOVA specifies contribution of the effect of each factor on output. Contribution percentage (P) for a specific factor is obtained from dividing total Net Square by sum of total squares. Tables 13 and 14 shows the ANOVA results based mean value of test output for "the smaller, the better" QC. With approximately 37.02 percent of contribution, cutting speed has the maximum effect on the flank wear. Cut depth and deposition method has 27.8 and 14.91 percent respectively. Although the feed rate parameter has slight effect on flank wear, it has considerable effect on surface roughness of work piece with 82.49% contribution. the surface roughness is less affected by cutting speed, cut depth and even deposition method in selected levels. By pooling the share of deposition method and cut depth into the contribution of error, the total error hardly reaches 7 percent.

Table 13 Result of ANOVA for flank wear

	DF	Contribution	Adj MS	F-Value	P-Value
A	1	14.91%	0.065522	11.49	0.007
B	2	37.02%	0.081325	14.26	0.001
C	2	7.29%	0.01601	2.81	0.108
D	2	27.80%	0.061085	10.71	0.003
Error	10	12.98%	0.005704		
Total	17	100.00%			

Table 14 Result of ANOVA for flank wear

	DF	Contribution	Adj MS	F-Value	P-Value
A	1	2.62%	0.022756	6.97	0.025
B	2	10.50%	0.045572	13.96	0.001
C	2	82.49%	0.357872	109.59	0
D	2	0.62%	0.002672	0.82	0.469
Error	10	3.76%	0.003266		
Total	17	100.00%			

3.6. Wear Mechanisms

The wear behavior and wear mode strongly depends on tribo-system of tool-chip-work piece interface. The abrasive wear is determined by hardness of tool, carbide distribution in tool and work piece material, built up edge, cutting parameter as well as production method of cutting tools [4], [15].

At lower cutting speed where the temperature is not high enough, a stable built-up edge (BUE) protects the cutting edge against the abrasive and adhesive wear. However, the formation and rebound mechanism of BUE causes a sudden failure in cutting edges in chipping form at low cutting speed. The relative motion between tool and blank at such condition is stick–slip. At higher cutting speeds, this relative motion changes to slip so that the BUE will be unstable to play a wear particle (debris) role, causes three body abrasion wear. Fig. 7 shows the SEM topography of BUE in the cutting edge. The segregated carbides and hard partied from tool and blank have the same effects. As can be seen in V=180 m/min the abrasive wear is predominant wear mechanism. In elevated cutting speed (280 m/min) with relatively higher tool-work interface temperature, the softened BUE and carbide do not have enough hardness or cold work ability to scratch the surface severely.

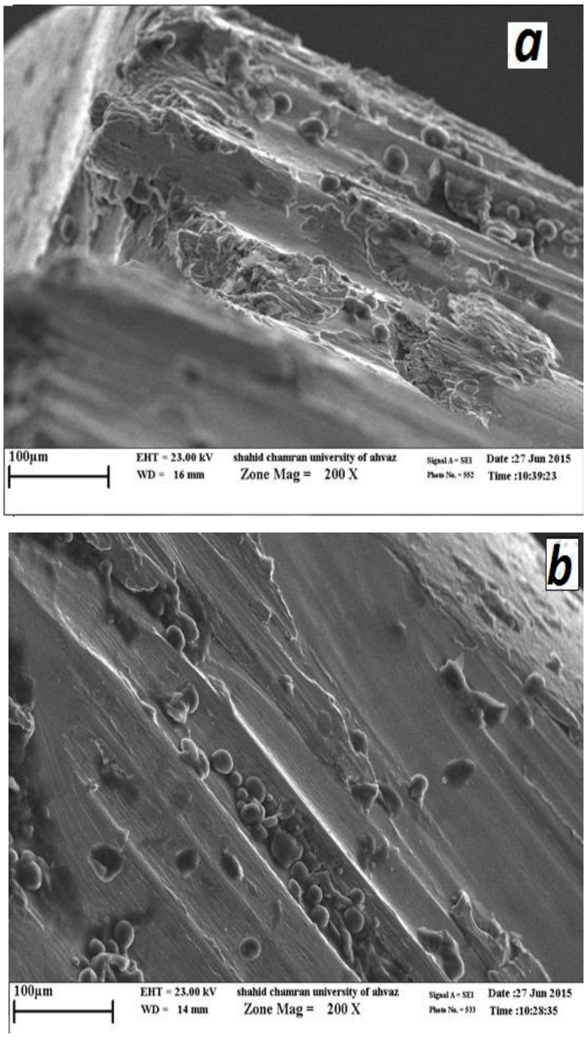

Fig. 7 SEM topography of rake face: (a): V=180m/min and (b): V=280 m/min SEM topography of flank surface.

Fig. 8 illustrates the rake face wear in tool-chip interface using SEM topography for cutting speeds of 180 and 280 m/min. In the rake face, the presence of BUE as a thermal barrier layer protects the rake face against the tool-chip interface temperature. The wear mode in rake face in such condition is moderate adhesive (Fig. 8a). At a certain cutting speeds, the wear particles (debris) begin to soften, and therefore lose their abrasive role at flank wear. Softening and rebounding of the thermal barrier layer leads to heat transfer from cutting zoon to rake face that softens the rake face and forms a crater in rake face. Adhesion wear mechanism is identified by deep craters. The depth of crater always increases proportionally with cutting speed (Fig. 8b).

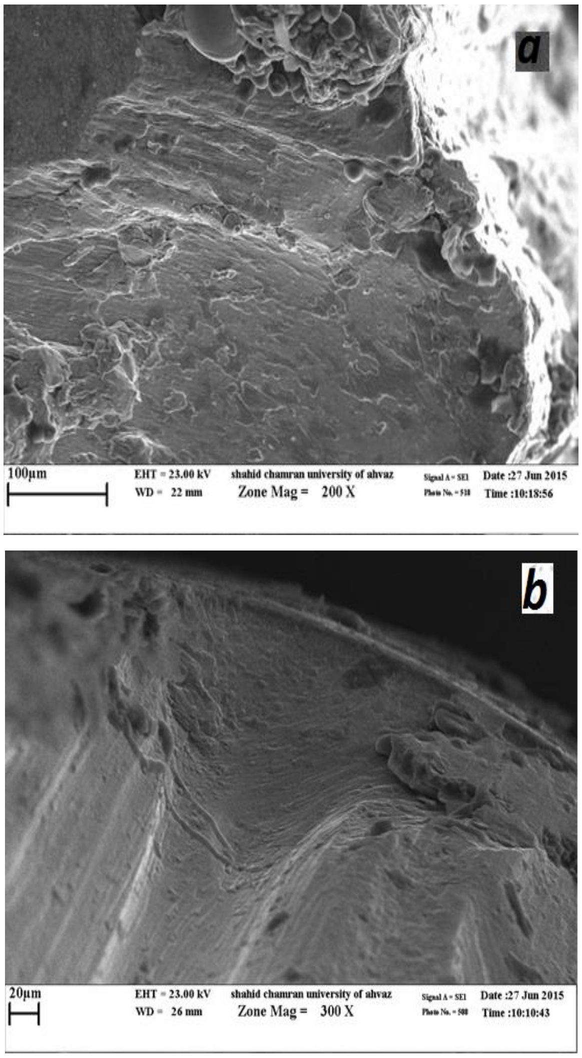

Fig. 8 SEM topography of rake face: (a): V=180m/min and (b): V=280 m/min.

4 CONCLUSIONS

The wear behavior of tool and surface roughness of work piece in high speed machining of AISI4140 by CVD and PVD tools have been studied. A brief conclusion of findings is as below:

1- The minimum amount of flank wear and surface roughness using the genetic algorithm is 0.461mm and 1.107 μm respectively. Therefore, the optimal amount of wear and roughness were obtained in (CVD/180/0.15/0.3) and (CVD/280/0.1/0.9) respectively.

2- The validation test shows a good agreement with genetic algorithm optimization results.

3- The evaluation of wear surfaces shows that the predominant wear mechanism is abrasion wear by presences of mild adhesive wear.

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