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PVD-COATED CERMET APPLIED FOR HARD TURNING OFAISI 4340

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ABSTRACT

Study on performance of PVD-coated Ceramic Metal (TiCN-based substrate/TiCN/TiN) cutting tool applied for turning of AISI 4340 steel with hardness of 50 HRC is the objective of the research reported in this paper. The performance was studied through some machinability aspects, i.e. tool wear, cutting time, surface roughness and power. The design of the experiment was done by Taguchi with cutting speed, feed and depth of cut as the independent variables and the machinability aspects as the responses. The results of the study show that flank wear was observed as the tool wear mode and it was attributed to abrasive wear mechanism. Cutting time gained by the cutting tool was reliable, surface roughness was at the quality of smooth turned, and as the surface roughness, power was recorded reasonable for finish turning. As this study recommends the PVD-coated Cermet for finish turning operation and thus, surface roughness becomes the primary response. Optimization was carried out for surface roughness. Since surface roughness was one among 4 responses, the multi-objective genetic algorithm technique was utilized. The result of optimization and the confirmation test showed a good agreement where the optimum surface roughness was about (0.5308-0.5450) microns. It was resulted at cutting speed of 130 m/min, feed of 0.1 mm/rev, and depth of cut of 0.1 mm.

Keywords: tool wear, cutting time, surface roughness, power, optimization, finish turning.

INTRODUCTION

It is well-known that hardmetals are intensively used as the raw materials for cutting tool production. The cutting tool made of hardmetals and dominantly containing WC phase is called Cemented Carbide. Another hardmetal-based cutting tool constitutes of ceramic matrix bonded with metallic binder is called Ceramic Metal (Cermet) [1, 2]. As the advances in coating engineering technology, Cemented Carbide and Cermet are available coated. Coated Cemented Carbide and coated Cermet are widely used for machining processes in metal cutting industry [3]. However, in hard machining application, coated Cemented Carbide is preferred to coated Cermet [4-7].

Literature study showed that there were plenty reports on the application of Coated Cemented Carbide cutting tool [4-7] for hard machining but only a few were on Coated Cermet [refs]. Yang *et al*. [8, 9] reported performance of TiCN-based Cermet coated with TiAlN and TiAlN/CrAlN when used in turning the 9CrSi$_2$Mn steel (ϕ 50 mm) with hardness of (53-55) HRC. Both Coated Cermet were assigned at speed of 280 rpm (44 m/min), feed 0.12 mm/rev, and depth of cut of (0.2, 0.4, and 0.6) mm. The cutting time was constant at 10 minutes. It was reported that the PVD-coated Cermet with TiAlN coating showed a better resistance to adhesive failure and flank wear than the TiAlN/CrAlN coating.

Das *et al.* [10] used PVD-coated Cermet (TiN/TiCN/TiN) for turning of EN24 steel (ϕ 40 mm) with hardness of 48 HRC. Cutting conditions were set at cutting speed of (80, 100, 120) m/min, feed of (0.05, 0.1, 0.15) mm/rev, depth of cut (0.1, 0.2, 0.3) mm, and cutting length of 250 mm. It was reported that flank wear and crater wear were the failure mode of the PVD-coated Cermet. Moreover, surface roughness was reported ranging between (1.20-2.61) microns. In another article of Das *et al*. [11], the activity of turning EN24 steel (ϕ 48 mm) (48 HRC) at cutting speed of (150, 200, 250) m/min, feed of (0.09, 0.17, 0.25) mm/rev, depth of cut (0.4, 0.6, 0.8) mm, and cutting length of 90 mm using PVD-coated Cermet Ti(C, N, O) with thickness of 3 microns was reported. The experimental work showed that flank wear was the dominant tool failure mode and ranging between (0.221-0.77) mm. For surface roughness, Ra was recorded at (1.065-4.011) microns.

Ji *et al*. [12] designed and fabricated a Gradient Cermet Composite in which surface layer had a high hardness, subsurface layer possessed a high bonding strength, and substrate exhibited a high flexural strength. The cutting tool was used in turning of 17-4PH stainless steel with hardness of 43 HRC. It was reported that at cutting speed of 150 m/min, feed 0.1 mm/rev, and depth of cut 0.3 mm; the cutting tool provided tool life up to 89 minutes at flank wear (VB) 0.3 mm while surface roughness was recorded at (1.0-1.5) microns. This achievement was claimed better than the Ti(C, N) Cermet cutting tool with tool life of 49 minutes when assigned at the same cutting condition.

Tiwari *et al.* [13] turned AISI 4340 steel (56 HRC) using multilayer (TiN/TiCN/TiN) Coated Cermet at cutting speed of (70, 140, 210) m/min, feed of (0.05, 0.1, 0.2) mm/rev, depth of cut (0.1, 0.3, 0.5) mm, and cutting length of 175 mm. Surface roughness, material removal rate, and chip reduction coefficient were the response variables. It was reported that surface roughness was ranging between (0.212-1.452) microns. These values were less than finish turning standard criteria (1.6 microns); hence this Coated Cermet could be implemented in hard turning application to get a good quality of finish.

Liu *et al*. [14] prepared CVD-Coated Cermet cutting tool with substrate of Ti(C,N)-12Mo2C-6TaC-6WC-9Ni-9Co (wt%) and coated with four coating layers made of TiN, MT-TiCN, α-Al2O3, TiN (from the interior to the exterior). The cutting tool was used in turning of hardened AISI H13 steel (ϕ 50 mm) with hardness of 50 HRC. Cutting conditions were selected at cutting speed of (300, 500, 700) rpm, feed of (0.2, 0.4, 0.6) mm/rev, and depth of cut of (0.05, 0.07, 0.09) mm. Testing was done until flank wear width of 0.3 mm. It was reported that the CVD-Coated Cermet gave the longest tool life when assigned at cutting speed ⩾ 700 rpm, feed 0.05 mm/rev, and depth of cut 0.2 mm. In the case of tool wear and its mechanism, the excellent diffusion and adhesion wear resistance at elevated temperature were noted and thus, the CVD-Coated Cermet produced a good surface quality of machined surface.

Objective of research reported in this paper is focused on performance study of PVD-Coated Cermet (TiCN/TiN) cutting tool applied for hard turning of AISI 4340 (50 HRC). There were 4 (four) response variables studied to represent the performance, i.e. tool wear, cutting time, surface roughness, and power. Based on the literature study given above and the benefit of coating to surface finish, surface roughness was then decided as the main response variable in this study. Moreover, optimization was carried out by multi objective genetic algorithm (MOGA) and subjected to surface roughness (in Ra parameter). Obtaining the cutting condition with extremum of minimum surface roughness was concerned.

MATERIALS AND METHODS

A commercial PVD-coated Cermet cutting tool with production code SNMG120408 grade 1525 [15] was the cutting tool to be explored in this study. The core substrate of cutting tool was made of titanium carbonitride (TiCN). As for the second hard phase, the core substrate was enriched with (Ti, Nb, W) (C, N) and W-Co binder. The cutting tool was coated with two coating layers, from inner to outer, TiCN and TiN. The total thickness of layers was maximum of 5 microns. The cutting tool was mounted on a tool holder coded MSDNN 2020 K12 to provide tool geometry of major cutting angle +45°, clearance angle +6°, inclination angle -6°, and back rake angle -6°.High strength low alloy AISI 4340 was selected as the workpiece material. The material was hardened through heat treatment process for the purpose increasing its hardness up to 50 HRC. In Table-1, the chemical composition of AISI 4340 is presented, while mechanical property is in Table-2.

As the objective of study, turning experiment was carried out by a CNC lathe machine tool of 5000 rpm and 9.5 kW motor. Dino-lite digital microscope type AM 4515 was installed for tool wear measurement. The method for analysis and measurement of tool wear was associated with ISO Standard 3685 [16]. The measurement of roughness was done by using Surftest SJ-210 unit. The measurement of power during turning was done by using power meter equipment which attached to the power system of lathe machine tool and a portable computer as a real time data logger unit. This equipment was developed in-house by taking the advantage of Arduino board and module.

Table-1. Chemical composition (wt%) of AISI 4340.

P	**V**	**S**	**Al**	**Cr**	**Fe**
0.015	0.020	0.006	0.021	0.790	rest
C	Ni	Mn	Mo	Si	Cu
0.410	1.790	0.650	0.220	0.220	0.050

Table-2. Mechanical properties of AISI 4340.

Density	**kg/m^3**	**7850**
Elasticity	kN/mm^2	205
Expansion	m/m.°C (10^{-6})	0.13
Specific heat	J/kg.°C	475
Conductivity	W/m.°C	44.50
Tensile strength	N/mm^2	1550

Table-3. Design of experiment Taguchi L8 (4x2x2).

Variable	**Unit**	**Code**	**Level**			
			1	**2**	**3**	**4**
Cutting speed	m/min	v	70	90	110	130
Feed	mm/rev	f	0.1	0.2	-	-
Depth of cut	mm	a	0.1	0.2	-	-

Design of Experiment and Optimization Technique

Design Taguchi method was appointed to design of experiment (DOE) [17]. This method is widely used as a DOE in experimental study in machining processes [18, 19, 20]. Taguchi L8 was designed for accommodating 3 (three) independent variables and levels as shown in Table 3. The values of levels were defined based on the recommendation of tool manufacturer [15] and the previous researchers [8-14]. As optimum yield on surface roughness was concerned, the data resulted through the experiment was analyzed statistically. ANOVA and multiple linear regression methods were utilized. The optimization was carried out using multi objective genetic algorithm (MOGA). For the purpose, a brief code had been written by utilizing the available genetic algorithm functions in Matlab®.

RESULTS AND DISCUSSIONS

Tool Wear, Cutting Time, Surface Roughness, and Power

All data shown in Table 4 were recorded from the experimental work. Each cutting condition or run in Table-4 was recorded when the PVD-coated Cermet was assigned to turning AISI 4340 (50 HRC) for cutting length of 200 mm. From Table-4, it can be seen that the longest cutting time recorded was 5.10 minutes (run 1), the highest flank wear width (VB) was 70 microns (run 8), the lowest surface roughness (Ra) was 0.653 microns (run 7), and the lowest power consumption was 311 watt (run 1). Generally, PVD-coated Cermet cutting tool used in this study experienced flank wear as its tool wear mode. The image in Figure-1 is a typical flank wear observed in this study. This wear was attributed to abrasive wear mechanism.

The longest cutting time (5.10 minutes) reached in run 1 was generated when flank wear width of 49 microns (the lowest flank wear). In contrast, the shortest cutting time (1.50 minutes) in run 7 was generated when flank wear of 70 microns. However, the lowest flank wear (49 microns) in run 1 was not necessarily generated the lowest surface roughness. In fact, the lowest surface roughness (0.653 microns) was generated in run 7 in which flank wear was at 67 microns. Moreover, the lowest surface roughness in run 7 was not necessarily indicating low power consumption. In fact, the highest power consumption (410 watt) was recorded at run 7.

The phenomena explained in the latter paragraph were believed due to the nature of wear. Flank wear modified the geometry of the major tool cutting edge unevenly and resulted two possibilities of increasing or decreasing the friction coefficient between the major tool cutting edge and the undeformed chip during chip formation. From Table-4, the value of flank wear width increases with cutting condition and in particular, with cutting speed. Related to the existence of coating layers (TiCN/TiN) applied on the substrate of Cermet cutting tool used in this study; unfortunately, its benefit could not be clearly traced through the trend of data resulted for all response variables.

Table-4. Experimental data.

Run	Cutting condition			Cutting Time	Flank Wear	Surface Roughness	Power
	v	f	a	(CT) (min)	(VB) (micron)	(Ra) (micron)	(P) (watt)
1	70	0.10	0.10	5.10	49	1.200	311
2	70	0.20	0.20	2.70	51	3.105	350
3	90	0.10	0.10	4.53	57	0.720	335
4	90	0.20	0.20	2.20	53	2.571	370
5	110	0.10	0.20	3.50	62	0.951	385
6	110	0.20	0.10	2.20	59	2.170	376
7	130	0.10	0.20	2.60	67	0.653	410
8	130	0.20	0.10	1.50	70	2.520	386

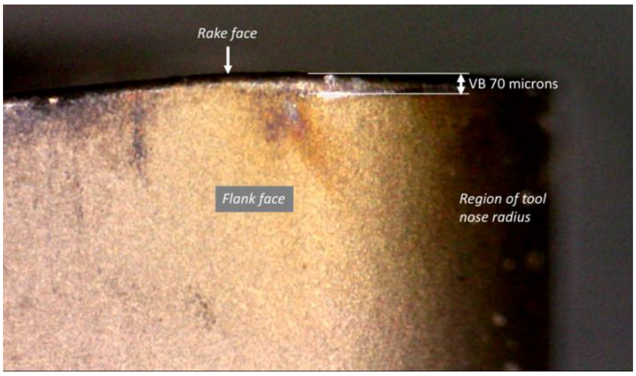

Figure-1. A typical example of flank wear experienced by PVD-coated Cermet cutting tool (run 8 at VB 70 microns) (see Table-4 for cutting condition).

Cutting time was fluctuated within all tested cutting conditions. In general, cutting time decreases as the increasing of cutting speed. When it is related to flank wear width data in Table-4, the flank wear of PVD-coated Cermet was still recorded at its initial wear phase out of the complete course of flank wear evolution as reported in [7]. This fact indicates that the PVD-coated Cermet could provide a reasonable tool life when applied for finish turning of hardened steel alloys.

Surface roughness measured in Ra parameter and recorded for all tested cutting condition can be categorized under smooth turned quality (Ra<3.2 microns). When surface roughness is related to coating layer; however, the benefit of coating layers (TiCN/TiN) could not be traced from the trend of surface roughness data. The values of surface roughness vary for all cutting conditions. The low and high values of surface roughness could be produced at low, middle, and high cutting conditions. As coating is expected for improved surface finish; however, the Ra values were fluctuated within all tested cutting conditions. It seems that the nature of wear is more dominant to role the surface finish rather than the occurrence of coating. In this case, a three-bodies (substrate elements, coating elements, workpiece elements) abrasive wear is believed occurring randomly when generating the roughness machined surface.

The data of power used for turning process as shown in Table-4 tends to increase as the increasing of cutting speed. In contrast, when the values of feed and depth of cut were interchanged for run 5 to run 8, the power tends to decrease. It seems that reducing depth of cut is more significant to decrease power even feed is increased.

Statistical Analysis

Analysis of Variance (ANOVA)

The ANOVA analyses for those response variables (tool wear, cutting time, surface roughness, and power) had been carried out. The results showed that the effect of independent variables (from the highest to the lowest contribution) to response variables were confirmed and could be explained as follows: (1) for tool wear: v, f, and a, (2) for cutting time: f, v, and a, (3) for surface roughness: f, v, and a, and (4) for power: v, a, and f. Cutting speed (v), and feed (f) had considerable influence on the response variables. As surface roughness was the main concern, its ANOVA result is given in Table-5.

Table-5. ANOVA for response variable surface roughness (Ra).

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting speed	3	0.46963	7.24%	0.46963	0.15654	2.96	0.263
Feed	1	5.85162	90.26%	5.85162	5.85162	110.72	0.009
Depth of cut	1	0.05611	0.87%	0.05611	0.05611	1.06	0.411
Error	2	0.1057	1.63%	0.1057	0.05285		
Total	7	6.48306	100.00%				

Multiple Linear Regression

Based on the results of ANOVA analyses, it is reasonable to generate mathematical model for each response surface with v, f, and a as the factors. The models were developed by utilizing multiple linear regression and its mathematical equation is given as follows [21].

$$y= \beta_0+\beta_1 x_1+\beta_2 x_2+\beta_3 x_3+\ldots+\beta_n x_n+\epsilon \quad (1)$$

In Equation (1), y is the response parameter (tool wear, cutting time, surface roughness and power), β_0 is the intercept, β_{1-3} is the coefficient, x is the independent parameter or in this work is the parameter (v, f, a) of cutting condition, and ε is the error. Those data in Table-4 were analyzed using multiple linear regression method and the following mathematical models were resulted:

$$\text{Cutting Time} = 9.621 - 0.03033v - 17.825f - 5.825a \quad (2)$$

$$\text{Surface Roughness} = -0.189-0.00892v +17.11f +1.68a \quad (3)$$

$$\text{Power} = 194.3 + 1.1555v + 99.5f + 270.8a \quad (4)$$

$$\text{Flank wear} = 29.34 + 0.3058v - 4.8f - 4.8a \quad (5)$$

Multi Objective Genetic Algorithm Optimization

GA can be implemented for single and multi-objective optimization problems. In this study, those mathematical models generated by multiple linear regression given in Equation (2), (3), (4), and (5) are called predictive models and used to formulate the objective functions for multi-objective genetic algorithm (MOGA). All predictive models were assigned as the fitness functions. Although those fitness functions contain the same parameters with conflicting objectives but as the prime solution, surface roughness function plays a major role in the selection process.

The library function *gamultiobj* in Matlab® had been utilized and a simple coding line program was developed for providing the optimization solution. The function file was generated and the boundary values of cutting condition (lower bound at 70 m/min, 0.1 mm/rev, 0.1 mm and upper bound at 130 m/min, 0.2 mm/rev, 0.2 mm) was defined. They were addressed by the line program which developed for MOGA optimization. The program then executed and modified for many times in order to obtain the solution. It has to be noted that there is no universal rule for appropriate choice of GA parameters, such as population size, number of generations to be evaluated, crossover and mutation probabilities, and string length. It was taught by this study that the optimization result was much depending on population size. Indeed, population and generation numbers would prolong time of computation, but calculation would search the best optimum value of minimum surface roughness. In this work, population size of 200 and maximum generation number to evaluate of 1500 (500 times of the number of cutting condition parameters) provided an expected result of optimum surface roughness. The result of MOGA optimization is given in Table-6 and Figure-2. Moreover, the distribution of solution presented in a 3-axes plot (cutting time, power, and surface roughness) is given in Figure-3. The solution of surface roughness is given by the lowest point (dot) within z-axis that yields an extremum of minimum surface roughness.

Table-6. Summary of MOGA optimisation.

Output Item	Output Value
Solution was given by population number	4
The optimum solution of minimum surface roughness (micron)	0.5308
Cutting time at the optimum solution (minute)	3.3124
Power at the optimum solution (Watt)	381.5669
Flank wear at the optimum solution (micron)	68.1336
Cutting condition of optimum solution:	
Cutting speed (m/min)	130
Feed (mm/rev)	0.100002
Depth of cut (mm)	0.100008

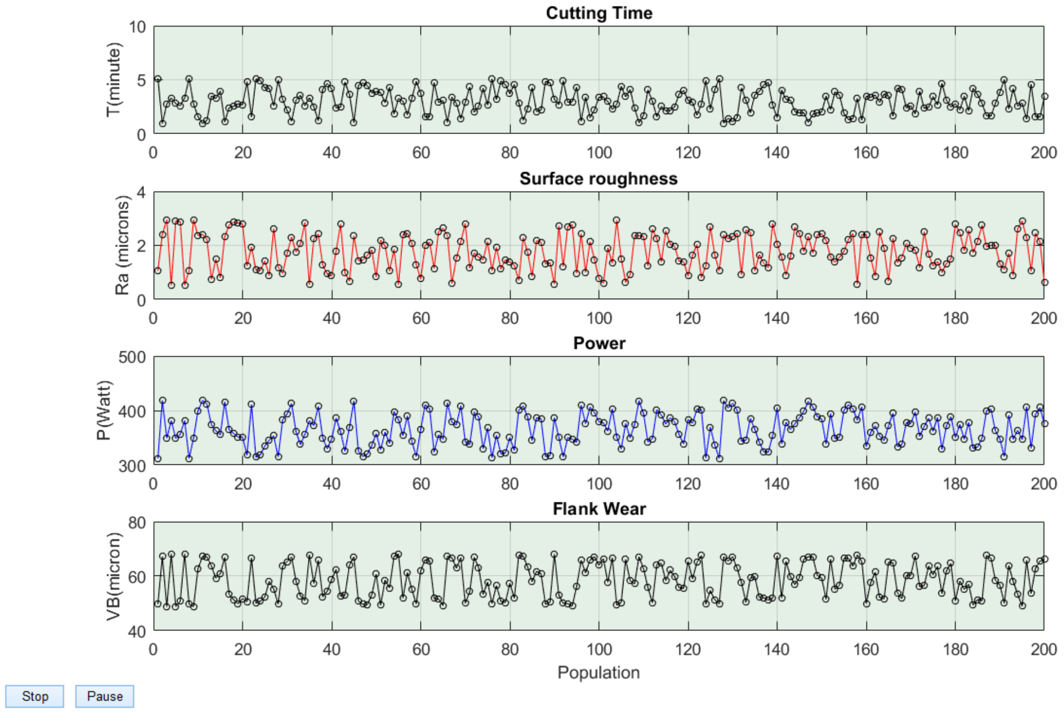

Figure-2. Plot of population vs. value of fitness functions (optimum solution was given by population number 4, see Table-6 for the values) (T: cutting time, Ra: surface roughness, P: power, VB: flank wear)

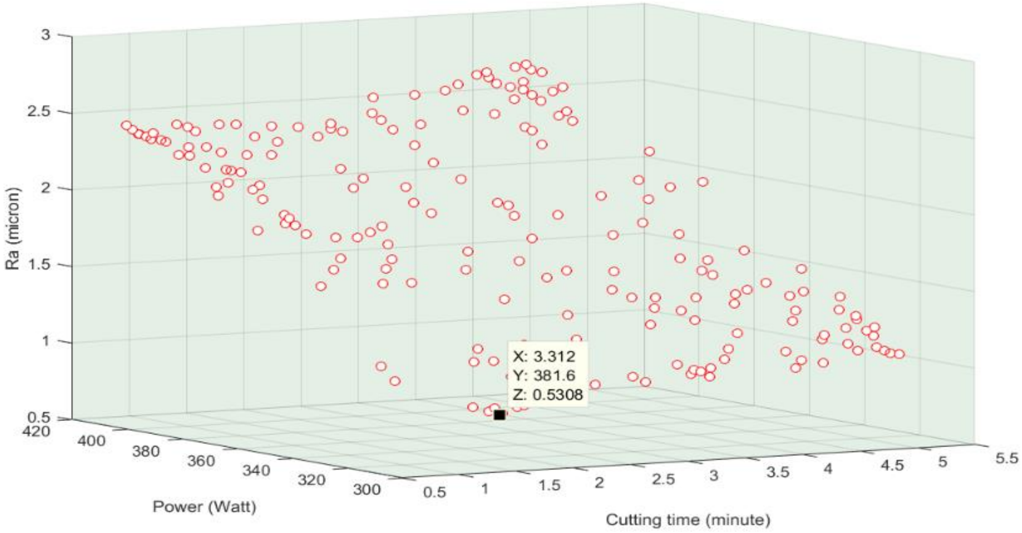

Figure-3. Distribution of solution provided by MOGA optimization for surface roughness (the lowest point yields an extremum of minimum surface roughness).

Table-7. Summary of confirmation test and MOGA optimisation results.

Response variable	**Confirmation test***	**MOGA optimisation***	**|% error|**
Surface roughness (micron)	0.5450	0.5308	2.61%
Cutting time (minute)	3.3130	3.3124	0.02%
Power (Watt)	385.5450	381.5669	1.03%
Flank wear (micron)	70	68.1336	2.67%

*Cutting condition at v 130 m/min, f 0.1 mm/rev, a 0.1 mm and cutting length of 200 mm.

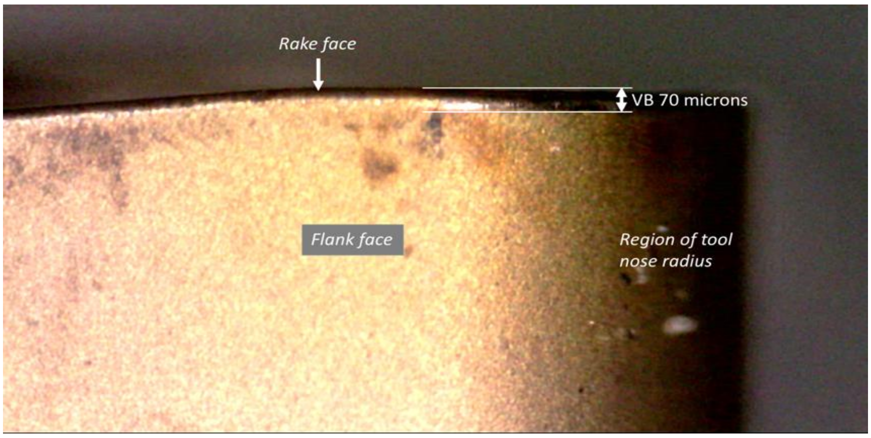

Figure-4. Flank wear at VB 70 microns of PVD-coated Cermet cutting tool resulted from confirmation test (see Table 7 for cutting condition).

Confirmation Test

The result of MOGA optimization had been verified through turning test at cutting speed (v) of 130 m/min, feed (f) of 0.1 mm/rev, and depth of cut (a) of 0.1 mm. The result of confirmation test and its comparison to the optimization result is as shown in Table 7. The result of confirmation test shows a good agreement with the result of MOGA optimization.

The evidence of worn tool used for confirmation test is given in Figure-4. The worn area of cutting edge was similar to testing under run 8 (Figure-1). The similarity was due to fact given by ANOVA in which among cutting parameters, cutting speed (v) had considerable influence on flank wear (VB). Run 8 and conformation test were carried out at the same cutting speed of 130 m/min.

CONCLUSIONS

The study on performance of PVD-coated Ceramic Metal (Cermet) cutting tool applied for turning of hardened AISI 4340 steel (50 HRC) had been carried out successfully. Concerning with tool wear, cutting time, surface roughness, and power as the response variables used to represent the tool performance, the following conclusions could be drawn from the results of experiment.

Flank wear was observed as the wear mode of PVD-coated Cermet and it was attributed to abrasive wear mechanism. Related to the existence of coating layers (TiCN/TiN) applied on the substrate of Cermet cutting tool, the benefit of coating layer to reduce the flank wear rate could not be observed in this study. Moreover, the fluctuation values of all response variables in this study (tool wear, cutting time, surface roughness, and power) could not describe the benefit of coating layers.

Cutting time was recorded longer at low cutting condition but still good enough at high cutting condition. In this study, cutting time was recorded at the phase of initial flank wear. As the complete course of flank wear evolution is initial, gradual, and abrupt wear phases; the cutting time has possibility to be prolonged.

Surface roughness measured in Ra parameter and recorded for all tested cutting condition can be categorized under smooth turned quality. Power for all tested cutting condition also recorded at reasonable values for finish turning.

The results of surface roughness, flank wear data, and cutting power lead to conclude that the PVD-coated Cermet cutting tool is suitable for finish turning of hardened steel with light cutting load which is characterized by relatively high cutting speed but low feed and depth of cut.

The optimization using multiple objective genetic algorithm (MOGA) shows that the optimum yield of surface roughness (as the primary objective besides flank wear, cutting time, and power) could be obtained at cutting speed of 130 m/min, feed of 0.1 mm/rev, and depth of cut of 0.1 mm. At the cutting condition, the extremum minimum of surface roughness was predicted at 0.5308 microns. The conformation test showed that the surface roughness was at 0.5450 microns or 2.61% error to the MOGA result. This result indicates that the MOGA method and the confirmation test show a good agreement and provide a reliable result of optimization.

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