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Comparative Performance Evaluation of Single and Multilayer Coated Carbide Inserts During Dry Turning of AISI 4340 Steel

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***Abstract*:- Machining cost during machining of heat treated steel involves selection and performance of machining tool. Flank wear and surface roughness are the two main indicators to determine performance and tool life which eventually influences the machining cost. The present work compares flank wear and surface roughness of three single layer coated and one multi-layer coated carbide inserts during dry turning of AISI 4340 steel under constant machining condition with an uncoated carbide insert. Regression models based on experimental data were developed to predict the performance of coated inserts. Single layer and multi-layer coated inserts showed significant reduction in flank wear and surface roughness with minimum chipping compared to the uncoated one. Regression models were with good correlation with the experimental results. The total machining cost per part using multi-layer coated inserts was considerably lower than the single layer and uncoated carbide tools.**

Keywords: Multi-layer coating; Flank wear; Surface roughness

1. INTRODUCTION

Manufacturing of gears, shafts, discs, rotors and bolts for the aircraft, automotive and general engineering industries involves dry machining of heat treated steels. High speed in dry machining cause early tool failure, spalling and rough surface. Davis et al. [1] worked on the dry machining of hardened steel and found cost consideration is a significant factor for the industries to produce a component at its lowest cost without negotiating the quality of machining. Authors also, highlighted that tool life and surface roughness of the workpiece are two major parameters to evaluate the machining performance of a cutting tool. Das et al. [2] applied Taguchi, RSM techniques to model surface roughness and identified cutting speed, feed and depth of cut as influencing parameters in the descending order. Singh et al. [3] developed the mathematical model for predicting the tool life using surface roughness and wear of the tool. Choudhury and El-Baradie [4] predicated the tool-life by using design of experiments in machining high strength steel. Chinchanikar and Chaodhury [5] studied the tool wear and reported that flank wear was the severe form of tool wear along with crater wear, abrasive wear, nose wear, built up edge and chipping off at nose, attributes to the poor surface roughness of the workpiece. Sahoo et al. [6] identified plastic deformation as a cause of rapid tool wear for low hardness tool material. Haron et al. [7] and the tool failed producing high crater due to low abrasion resistance at high temperature. Huang et al. [8] concluded that the wear resistant of tool associated with hardness, residual stress, oxidation resistance, hot hardness and thermal conductivity can be manipulated by coating. Cho and Komvopoulos [9] highlighted that the coated carbide inserts are commonly used cutting tools for improved machining performance due to their ability to maintain hardness at elevated temperature compared to the uncoated tool but attributes to the higher cost. Prasath et al. [10] reported that coating over the insert improves surface roughness and the increase in coating thickness further improves the surface roughness. Widely used coated carbides are in the form of single and multilayer. TiC, Al_2O_3, TiCN are the commonly applicable single coated tools whereas multilayer coating combinations are TiC / Al_2O_3 / TiN, TiC / TiN / TiC etc.

Pal Dey and Deevi [11] concluded that single layer coating as example TiN, AlCrN, TiAlN, Ti(C,N) and AlTiN coated carbide inserts have low coefficient of friction and low wear rates. Joel Rech [12] found that the wear rate and cutting forces for single coating significantly increases after removal of a thin layer of coating. Qingzhong Xu et al. [13] identified the initiation of flank wear and crater wear leads to the catastrophic failure of tool wear for coated inserts. Devia et al. [14] evaluated the HSS cutting tool coated with hafnium and vanadium nitride and found that the tool life increases with the number of coated layers due to the reduction of energy transfer and increase in wear resistance with low coefficient of friction. Cadena et al. [15] investigated the coefficient of friction and wear using PVD AlCrN coated tungsten carbide inserts in turning of titanium alloys. Machining with AlCrN-T coating showed low coefficient of friction and low wear rates. Kumar et al. [16] studied the effects of cutting parameters on the surface roughness of AISI 1045 steel by using TiN coated carbide inserts and reported that feed rate contributes significantly high to the quality of surface roughness compared to other cutting parameters.

Review of literature [1-16] indicated that most of the authors used single coated tools such as TiN and TiCN on tungsten carbide inserts for the machining of ferrous material during dry machining of soft turning. The multilayer coatings were mainly TiC / TiCN / TiN and TiCN / TiC / Al2O3, TiN / TiCN / Al_2O_3 / TiN and TiN / Al_2O_3 / Ti (C, N) for dry machining of hardened steel. Also, Multilayer coated carbide tools pose higher tool life compared to single coated

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carbide tools under lower depth of cut and lower tool life during higher depth of cut. Reports are very scarce on high speed machining of hardened steel alloys with PVD coated single-layer and CVD coated multi-layer carbide. The main concern in machining of hardened steel is the wear on the coated inserts and the surface roughness on machined workpiece. In order to produce better surface finish and longer tool life, appropriate selection of coating material and proper combination of cutting parameters are very important. The main objective of present research was to investigate the performance of uncoated, PVD coated single layer and CVD coated multi-layer tungsten carbide inserts on wear mechanism and surface roughness in machining AISI 4340 (EN24T) steel under dry turning condition.

2. MACHINE SETUP

2.1 Workpiece materials, cutting tool

The workpiece material used in the present work was through hardened EN 24T steel (AISI 4340), generally used for manufacturing gears, nuts, bolts, studs, shafts along with heavy-duty axles, shafts and harsh offshore applications such as hydraulic bolt tensioners and ship borne mechanical handling equipment. The workpiece material was in the form of round bar of diameter 70 mm and length 300 mm and the hardness was 223/227 BHN.

Five inserts, one uncoated, three single coated and one multilayer coated, were selected as cutting tool based on the micro hardness and the hardness of the inserts which are given in Table 1. All the inserts were having 4 microns of coating thickness with identical geometry designated by ISO as CNMG 120408. A left hand style tool holder designated by ISO as PCLNL 2525M12 was used for mounting the inserts.

Table 1: Coating of inserts

Sl. No.	Inserts	Hardness (BHN)	Type of coating
1.	WIDIA K313		Uncoated
2.	PN235 (TiN)	2300	Single coated (PVD)
3.	PA11 (TiCN)	3000	
4.	PA310 (TiAlN)	3200	
5.	TN8135 (TiN / Al_2O_3 / TiCN)	3300	Multilayer coated (CVD)

2.2 Experimental set up

Dry turning tests were carried out in a set up shown in Figure 1 by ACE designer, India. The setup has a Jobber XL CNC lathe with PCLNL 2525M12 tool holder attached with Mitutuyo Surface Roughness tester. The CNC lathe has 4000 rpm maximum speed and 5.5 kW continuous spindle motor power with function controller. The cut-off length of the machining was fixed at 0.7 mm.

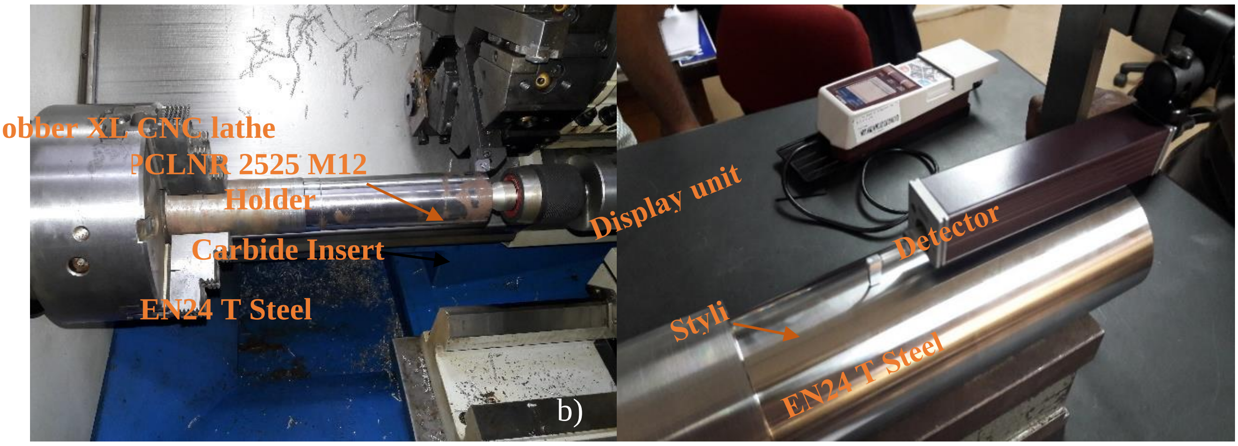

Figure 1 (a) Experimental setup (b) Roughness tester

2.3 Experimental procedure and characterization techniques

Machining parameters for dry turning of EN24T at the set up are provided in Table 2. After each turning operation, roughness of the machined surface was measured using Mitutuyo Surface Roughness tester of Model SJ210 shown in Figure 1 (b). The measurements were repeated three times with 3 mm length interval at three reference lines equally positioned at 120^0 apart on the circumference of the machined bar schematically presented in Figure 2. The surface of the machined workpiece was characterized by average arithmetic surface roughness (R_a), maximum peak to valley height within sampling length (R_z) and maximum peak-to-valley height within assessment length (R_t).

Table 2 Machining parameters for dry turning of EN24T

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Sl. No.	Machining parameters	Descriptions
1.	Machining Time, T_c (min)	2, 4, 6, 8 and 10
2.	Workpiece	EN24 T steel
3.	Cutting speed, *v* (m / min)	150
4.	Feed rate, *f* (mm / rev)	0.2
5.	Depth of Cut, *d* (mm)	0.5
6.	Cutting environment	Dry condition
8.	Tool geometry	CNMG 120408
9.	Tool holder	PCLNR 2525 M12 pin type
10.	Response	Flank wear and Surface roughness

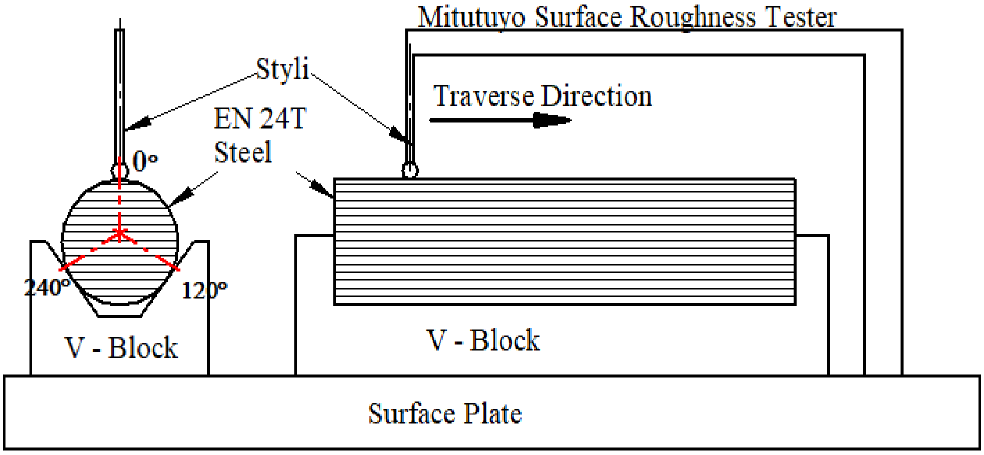

Figure 2. Schematic diagram of measuring surface roughness

Scanning Electron Microscope (SEM) of model Hitachi SU 1500 with a photographic system was employed to characterize the flank wear of inserts after each turning operation. The SEM micrographs were imported to Solidworks software and the average flank wear was estimated considering three replicates along the length. Figure 3 demonstrates flank wear measurement from SEM micrograph using Solidworks software. Tool life criteria based on a maximum flank wear width of h_f = 0.35 mm according to ISO 3685 use to estimate tool life of the inserts.

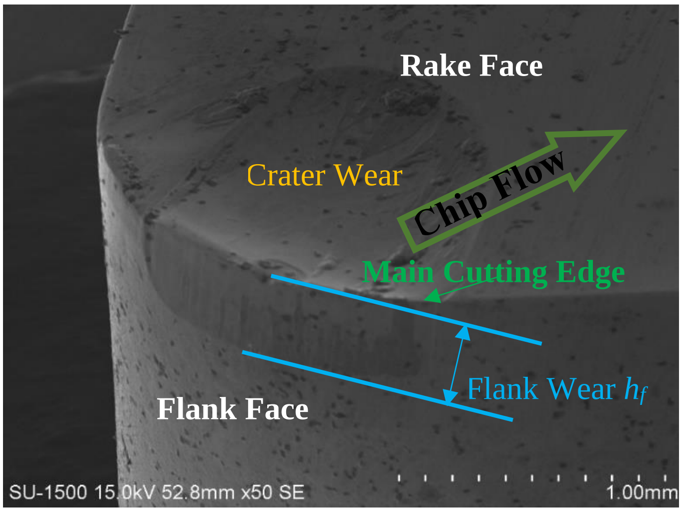

Figure 3. SEM micrograph for measuring flank wear

2.4 Cost analysis

Cost analysis were carried out using Glberts approach. Equation 9 to 12 ware used to calculate tool cost per part using workpiece dimensions, cutting parameters, labor cost, tool life, machining time and time for changing tool and workpiece.

Machining time $T_m = \frac{(\pi * D_f * L_a)}{(1000 * v * f)}$ .... Equation (9)

Machining cost per workpiece = $l * T_m$ .... Equation (10)

Tool changing cost per part = $l * T_d(\frac{T_m}{T})$ .... Equation (11)

Tool cost per part = $S_c(\frac{T_m}{T})$ .... Equation (12)

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Where, D_f – final diameter of workpiece (mm), L_a – axial length of the workpiece (mm), f –feed rate (mm/rev) and v – cutting speed (m/min), l - labour cost, T_d - time taken to change tool and workpiece (5 min), T - tool life for one cutting edge, S_c – Average cost of single cutting edge

The overall machining cost per part (M_c) can be calculated by summing up machining cost per workpiece, the tool changing cost per workpiece and the tool cost per workpiece and is given in Equation 13.

$$M_c = l * T_m + l * T_d \left(\frac{T_m}{T}\right) + S_c\left(\frac{T_m}{T}\right) \quad \text{………………………. Equation (13)}$$

3.0 RESULTS AND DISCUSSION

3.1 Experimental observations

Flank wear (h_f) of cutting tool and three surface roughness parameters (R_a, R_z, R_t) of machined surface of five inserts are shown in Figure 3. The dry turning of EN24T was carried out at constant cutting speed, depth of cut and feed rate.

Table 3 Experimental values of flank wear and surface roughness after successive runs

Carbide Inserts type	Flank wear / Roughness	Run 1 1 Min	Run 2 4 Min	Run 3 8 Min	Run 4 14 Min	Run 5 22 Min	Run 6 30 Min	Run 7 42 Min
Uncoated	h_f (µm)	297.52	452.31	852.33				
	R_a (µm)	2.166	2.628	3.857				
	R_z (µm)	8.666	10.38	14.563				
	R_t (µm)	9.217	11.456	14.256				
TiN	h_f (µm)	139.23	181.32	250.36	372.17	598.43	720.48	928.34
	R_a (µm)	1.413	1.589	1.713	1.834	1.965	2.234	2.521
	R_z (µm)	5.675	5.958	6.934	7.298	7.532	7.856	8.012
	R_t (µm)	6.106	6.498	7.342	7.865	8.865	9.015	9.152
TiCN	h_f (µm)	121.69	154.63	227.13	316.25	475.28	602.58	820.68
	R_a (µm)	1.376	1.512	1.612	1.756	1.854	1.934	2.105
	R_z (µm)	5.421	5.785	6.626	7.15	7.423	7.625	7.894
	R_t (µm)	5.943	6.304	7.19	7.743	8.612	8.823	9.01
TiAlN	h_f (µm)	80.86	132.52	174.83	262.19	371.52	480.56	795.28
	R_a (µm)	1.183	1.3	1.444	1.533	1.698	1.853	1.963
	R_z (µm)	4.632	5.325	5.893	6.418	6.692	6.925	7.325
	R_t (µm)	5.464	5.934	6.765	7.435	8.234	8.536	8.896
TiN / Al_2O_3 / TiCN	h_f (µm)	101.32	145.58	198.54	250.91	325.64	420.45	680.25
	R_a (µm)	1.196	1.32	1.43	1.52	1.598	1.634	1.853
	R_z (µm)	4.532	5.21	5.8	6.125	6.523	6.901	7.125
	R_t (µm)	5.012	5.876	6.249	6.957	7.578	8.487	8.756

3.2 Flank wear with machining time

Flank wear (µm) of coated and uncoated inserts with respect to machining time is displayed in Figure 4. Significantly high wear growth rate was observed for uncoated inserts compared to coated inserts. Maximum machining time was 8 minutes for uncoated inserts however the same was 42 minutes for coated inserts. Minimum wear was obtained for single coated TiAlN inserts. Wear growth rate for multi- layer coated inserts was faster for initial 14 minutes machining and reached to minimum wear for the later period of machining.

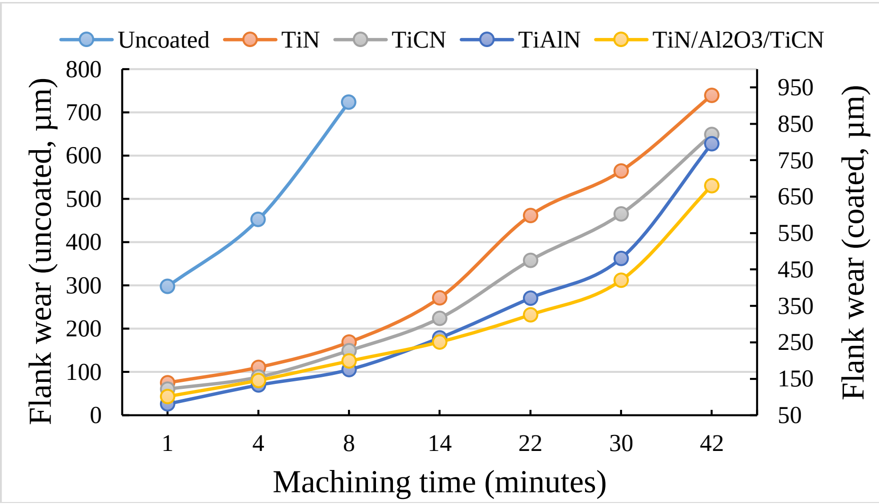

Figure 4 Flank wear (µm) for uncoated and coated inserts

3.3 Surface roughness with machining time

Surface roughness (Ra) of machined surface with respect to machining time is shown in Figure 5. Multilayer coated and TiAlN coated inserts produced lower surface roughness compared to uncoated and coated (TiN and TiCN) tools during the entire machining period.

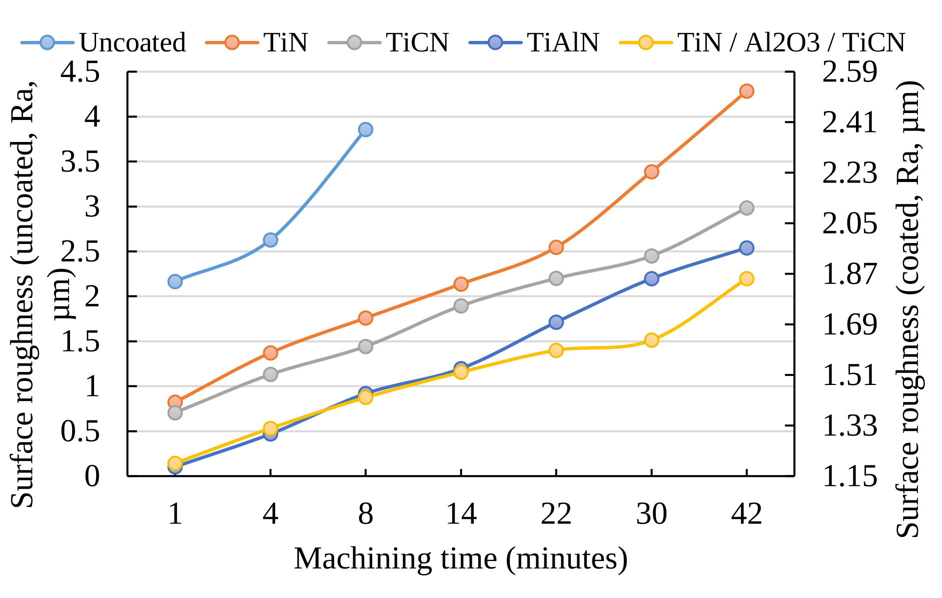

Figure 5 Surface roughness R_a (µm) of machined surface

Further the flank wear of inserts and surface roughness of machined workpiece were analyzed with the help of Scanning Electron microscope (SEM). Figure 6 shows the SEM micrographs of uncoated carbide inserts after one minute and eight minutes of machining.

Severe flank wear, crater wear, notch wear, grooves along with adhered molten chip at the rake face of the insert are visible which can be related to the high wear rate in Figure 4. The excessive wear and formation of grooves can be attributed to the high hardness of the workpiece with low abrasive resistance and low hardness of the tool. High pressure and temperature at tool rake face increased the crater wear with machining time and eventually altered cutting edge geometry of the insert. The presence of adhered chip deformed the rake face. Wear growth rate was accelerated due to the deformed tool. Considerable fragmentation and degradation of the cutting edge is visible at the insert in Figure 6 (b) after 8 minutes of machining lead to the flank wear limit and the turning operation was discontinued.

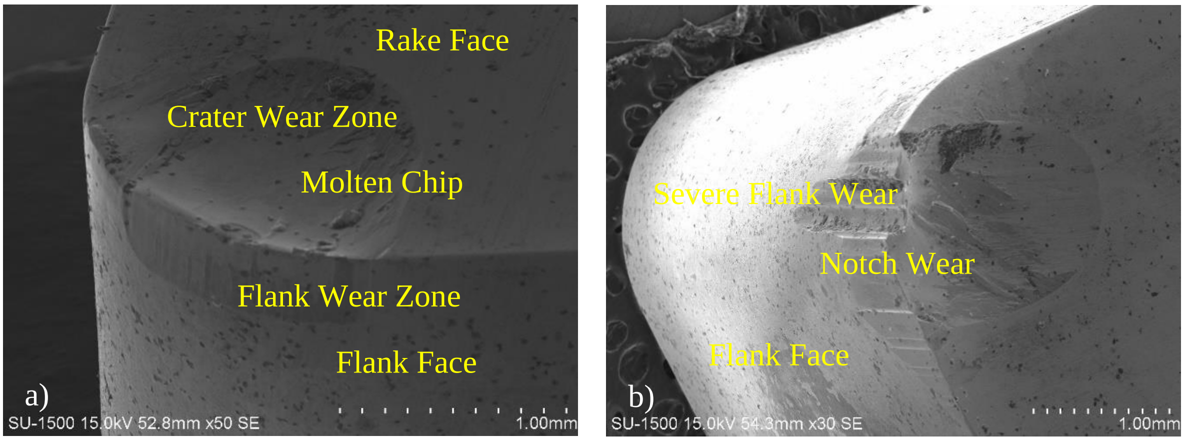

Figure 6 SEM micrographs of uncoated carbide inserts after a) 1 minute and b) 8 minute machining time.

Tool wear rate can be minimized using high hardness tool and high abrasion resistance which could achieve using coated tools. Figure 7 to 9 shows the SEM Micrographs of single coated inserts (TiCN, TiN and TiAlN) after 14 and 42 minutes of machining. Significant flank wear were observed after 42 minutes of machining along with chipping at the rake face. TiN, TICN and TiAlN coated tools are having higher hardness compared to uncoated tools and showed slower tool wear and less wear and crater at the tool surface. TiAlN coated inserts showed slow tool wear rate, minimum flank wear, chipping and surface roughness due to the higher hardness and higher wear resistance at high temperature.

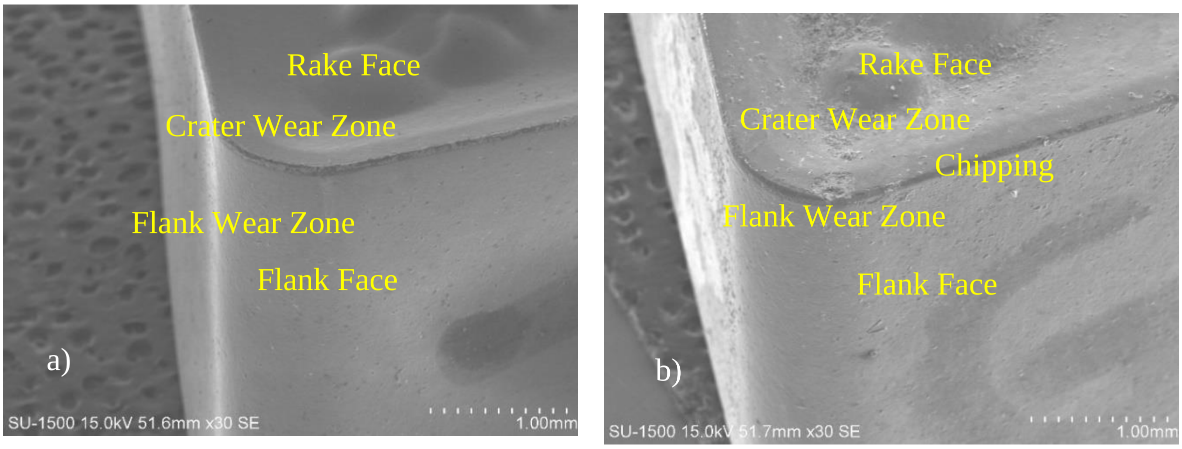

Figure 7 SEM micrographs of TiCN coated carbide inserts after a) 14 min and b) at 42 min of machining

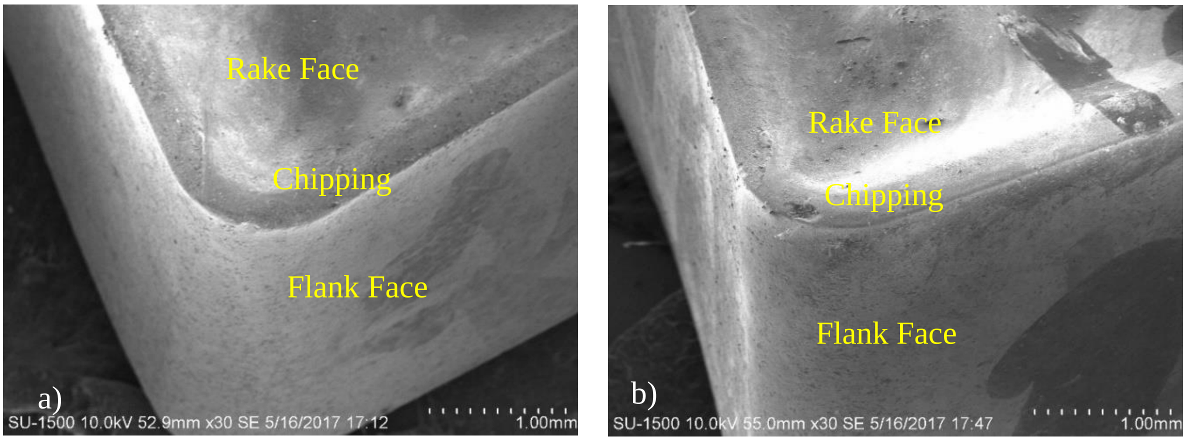

Figure 8 SEM micrographs of TiN coated carbide inserts after a) 14 min and b) at 42 min of machining

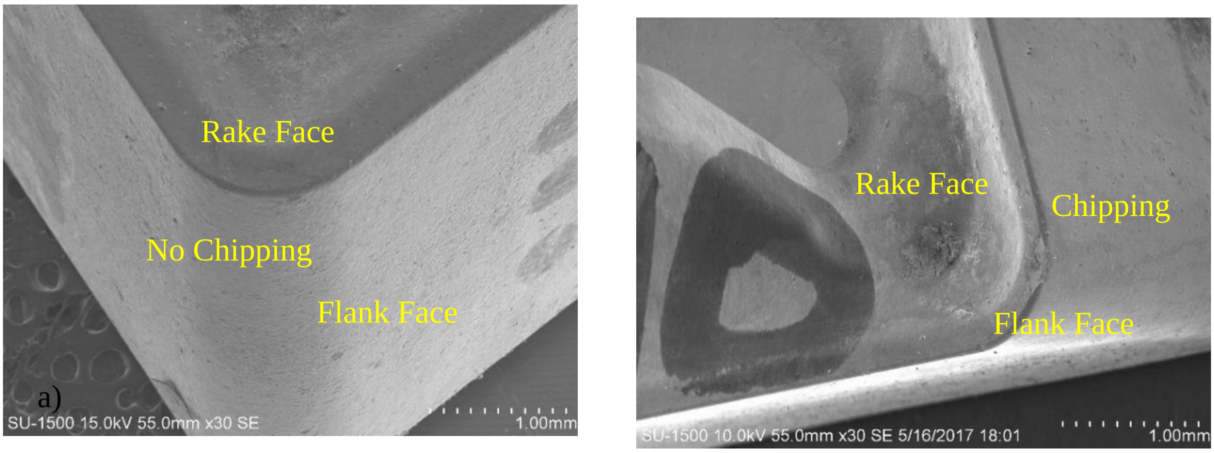

Figure 9 SEM micrographs of TiAlN coated carbide inserts after a) 14 minutes and b) at 42 minutes of machining

TiN/Al_2O_3/TiCN coated inserts produced better surface finish and undergoes slow tool wear rate with minimum flank wear at tool face. SEM micrograph in Figure 10 shows comparative wear of insert after 14 and 42 minutes machining compared to the

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unmachined one. This insert poses higher hardness and wear resistance at high temperature due to multilayer coating. After 42 minutes of machining, peeling off and chipping of the coating layers from tool surfaces at the flank and nose region were observed.

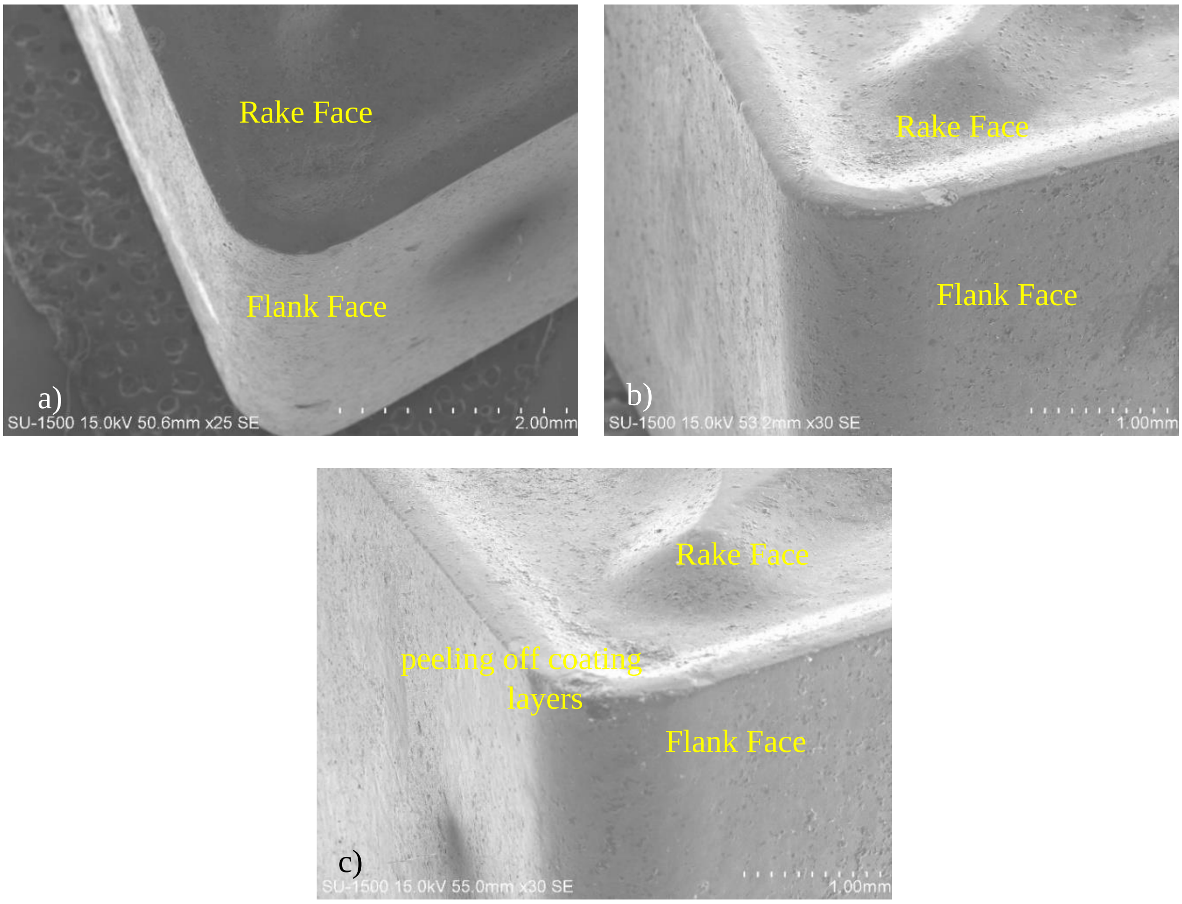

Figure 10 SEM micrographs of $TiN/Al_2O_3/TiCN$ coated carbide inserts a) before machining and after b) 14 min and c) at 42 min machining.

With the progress of machining due to the force and temperature at the work tool interface flank wear initiates at the tool face and the geometry of the tool changes which eventually produces poor surface finish of the workpiece. In case of coated inserts with the progress of machining, peeling off of coating occurs which initiates flank wear and eventually its progress. For the multilayer coatings after peeling off of one layer other protective coatings are available to delay the flank wear initiation. Peeling off coating layers also associated with thermal conductivity of the inserts. Coating materials, sequence of layers, coating method and thickness of each layer plays an important role to determine thermal conductivity of the insert. Effective combination of these determining factors yields satisfactory result. In the present study single coated TiCN, TiN and TiAlN along with multilayer coated insert showed sufficient improvement of surface finish and reduction in tool wear compared to uncoated tool with significant increase in machining time.

4.2 Analysis of Variance and Regression Analysis

Linear regression models for single coated and multilayer coated inserts were developed for flank were and surface roughness. Linear regression model for flank wear (h_f) with machining time (T_m) is given in Equation (1 – 4). Similarly Equation (5 – 8) shows the linear regression model for arithmetic surface roughness average with machining time (T_m).The significance level for the development of the model was considered as $\alpha = 0.05$ with 95 % confidence level. The parameters with the P-value less than 0.05 were considered to have a statistically significant to the performance characteristics.

$TiN = 20.024\, T_m + 109.62$ $R^2 = 0.992$ ……………………… Equation (1)
$TiCN = 17.249\, T_m + 90.161$ $R^2 = 0.998$ ……………………… Equation (2)
$TiAlN = 16.464\, T_m + 43.65$ $R^2 = 0.975$ ……………………… Equation (3)
$Multi\ Layer = 13.079\, T_m + 77.153$ $R^2 = 0.968$ ……………… Equation (4)

$TiN = 0.025\, T_m + 1.456$ $R^2 = 0.986$ ……………………… Equation (5)
$TiCN = 0.017\, T_m + 1.449$ $R^2 = 0.953$ ……………………… Equation (6)
$TiAlN = 0.019\, T_m + 1.247$ $R^2 = 0.958$ ……………………… Equation (7)
$Multi\ Layer = 0.014\, T_m + 1.263$ $R^2 = 0.911$ ……………………… Equation (8)

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Analysis of variance (ANOVA) table was built to check the adequacy of the linear regression models. Table 4 and 5 shows ANOVA table for flank wear and arithmetic surface roughness average (R_a), respectively for single and multilayer coated inserts. The model showed determination coefficient for flank wear, maximum and minimum R^2 values are 0.972 and 0.902 respectively. Similarly, determination coefficient for surface roughness, maximum and minimum R^2 values are 0.998 and 0.972 respectively. These values of determination coefficient are close to unity which implies good agreement with experimental results and signifies model validity.

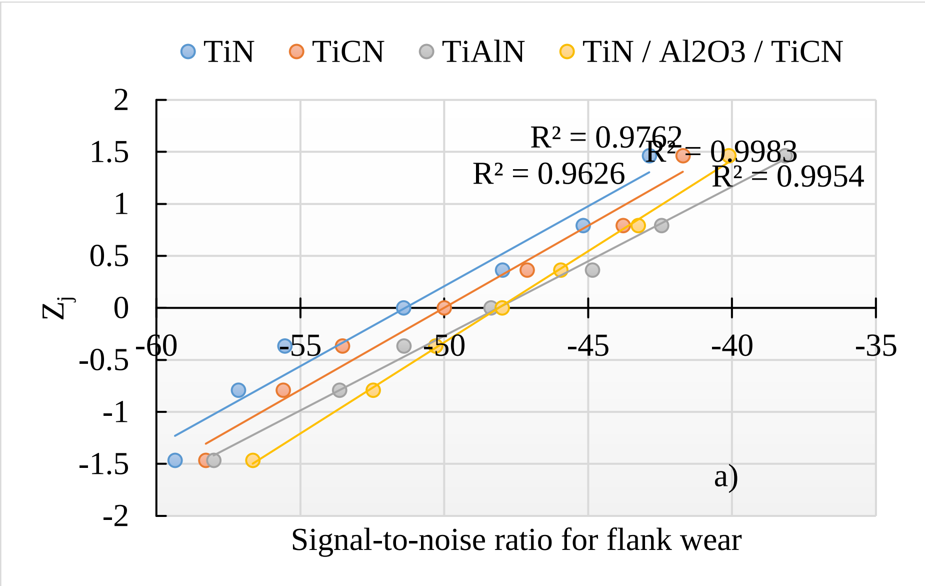
Table 4 Analysis of Variance for flank wear (h_f)

		d_f	SS	MS	F	p	Remark
TiN	Regression	1	534660.435	534660.43	705.76	0.00	Significant
	Residual	3	3787.83	757.56			
	Total	4	538448.26				
TiCN	Regression	1	396726.8	396726.8	3563.871	0.00	Significant
	Residual	3	556.5954	111.3191			
	Total	4	397283.4				
TiAlN	Regression	1	361451.7	361451.7	197.524	0.00	Significant
	Residual	3	9149.568	1829.914			
	Total	4	370601.3				
TiN / Al_2O_3 / TiCN	Regression	1	228113.7	228113.7	150.2404	0.000	Significant
	Residual	3	7591.622	1518.324			
	Total	4	235705.4				

Table 5 Analysis of variance for arithmetic surface roughness average (R_a)

		d_f	SS	MS	F	p	Remark
TiN	Regression	1	0.863	0.863	365.663	0.00	Significant
	Residual	3	0.012	0.002			
	Total	4	0.874				
TiCN	Regression	1	0.367	0.367	102.101	0.00	Significant
	Residual	3	0.018	0.004			
	Total	4	0.385				
TiAlN	Regression	1	0.469	0.469	115.697	0.00	Significant
	Residual	3	0.020	0.004			
	Total	4	0.490				
TiN / Al_2O_3 / TiCN	Regression	1	0.272	0.272	51.453	0.00	Significant
	Residual	3	0.026	0.005			
	Total	4	0.298				

Normal probability plots using experimental values of residuals for flank wear and arithmetic surface roughness average in Figure 11 were generated to verify the normality assumptions. The signal to noise ratio for experimental values lies close to predicted values form model which can be seen from the R^2 values and it validates the models.



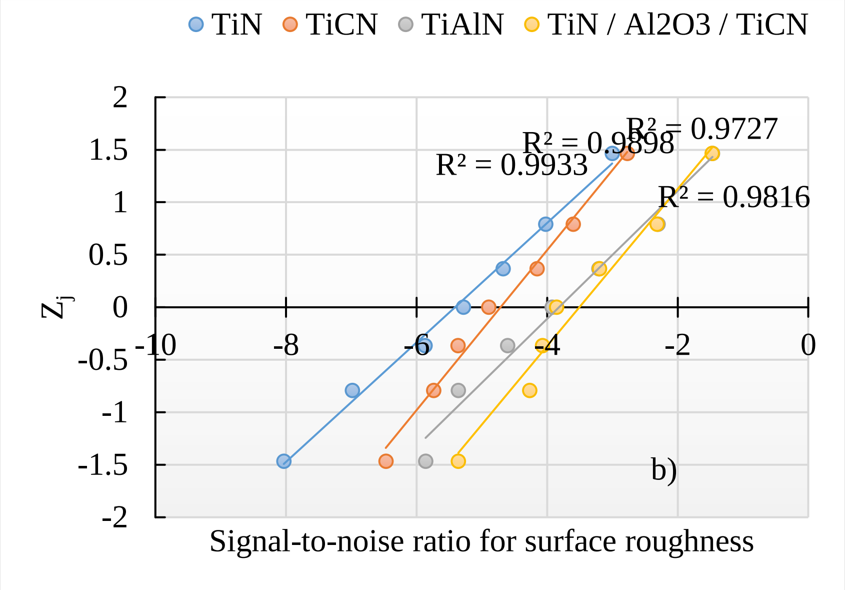


Figure 11 Normal probability plots of S / N ratio for a) flank wear and b) surface roughness

The predicted values from Equation 1 to 8 and experimental values for flank wear and surface roughness are plotted in Figure 12 which shows good agreement and it can be concluded that the linear regression models are valid to predict the flank wear and surface roughness with machining time at the given cutting conditions.

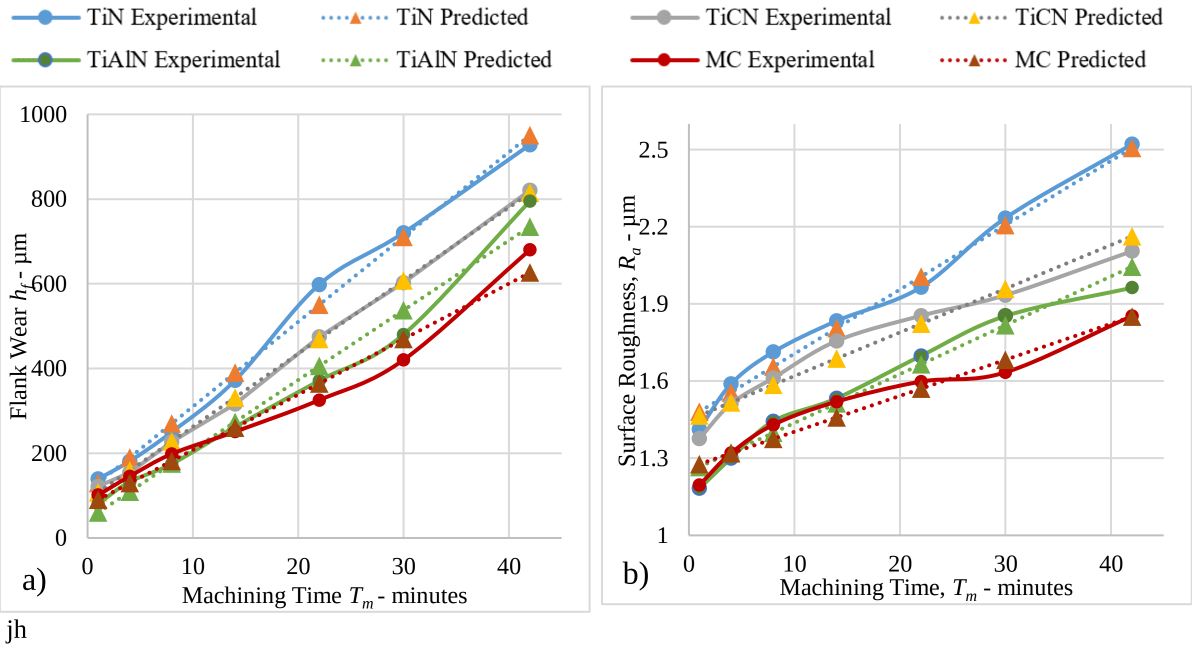


Figure 12: Experimental and predicted values for (a) flank wear and (b) surface roughness with machining time

4.3 Cost analysis

Total machining cost per part in INR is calculated according to Equation. A cylindrical workpiece with a finished diameter of 40 mm, 180 mm cutting length, 22 ± 1 R_C hardness were used considering cutting parameters as 150 m/min cutting speed, 0.2 mm / rev feed, and 0.5 mm depth of cut for 0.35 mm flank wear. Workpiece and tool change time was considered as 5 minutes. Tool life of inserts and machining cost per parts are given in Table 6 along with the market price of each inserts.

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Table 6 Cost analysis of inserts

Sl. No	Cost Analysis	Tungsten carbide inserts				
		Uncoated	Single-layer coated			Multi-layer coated
1.	Cutting tool		TiN	TiCN	TiAlN	$TiN / Al_2O_3 / TiCN$
2.	Operations cost, *l* in min^{-1}	05	05	05	05	05
3.	Machining cost per part (INR)	3.77	3.77	3.77	3.77	3.77
4.	Tool life for single edge *(min)*	4	14	22	22	32
5.	Tool changing cost per part (INR)	4.71	1.35	0.86	0.86	0.59
6.	Mean value of single cutting edge (INR)	41.25	50	50	50	60
7.	Tool cost per part (INR)	7.78	2.70	1.71	1.71	1.18
8.	Total machining cost per part (INR)	16.26	7.82	6.34	6.34	5.54
9.	Market price of each inserts (INR)	165	200	200	200	240

From the cost analysis it was observed that total machining cost per part for uncoated inserts are costliest and multilayer coated inserts are most economical though the market price of uncoated inserts is minimum and multilayer coated are maximum.

5. CONCLUSION

A comparative study of coated and uncoated carbide inserts was carried out using an uncoated, three single coated and one multilayer coated tool on the flank wear of tool and surface roughness of EN24T steel under dry machining conditions experimentally and analytically. Single coating materials were TiN, TiCN and TiALN and multilayer coating was $TiN/Al_2O_3/TiCN$. The following conclusion can be drawn from the present study.

- Single layer and multilayer coated inserts improved surface roughness and reduced flank wear of tool significantly compared to uncoated insert.
- Machining time improved from 8 minutes to 42 minutes for single layer and multilayer coated inserts compared to uncoated insert.
- Flank wear, nose wear, grooves, crater wear and molten metal adhering at the tool face was observed at the SEM micrographs of uncoated inserts after 8 minutes of machining while Peeling off and chipping of coating was observed for single layer and multilayer coated inserts. Peeling off and chipping of coating initiates flank wear at tool face and its progression with machining time. Coating material, sequence of layers, layer thickness and coating method contributes to the mechanical and thermal properties of inserts. For multilayer coating after depletion of one layer subsequent layers are available to delay the initiation of flank wear.
- Linear regression model for predicting flank wear and surface roughness with machining time were developed for coated inserts and validated with ANOVA. Regression models were with good correlation with the experimental results.
- The total machining cost per part using multi-layer coated inserts was considerably lower than that of single layer and uncoated carbide tools although the market price of each multilayer coated inserts were higher than the other inserts.

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