

Machinability of Rolled Aluminum using Advanced Coated Cutting Tools and Its Characterization



Sachidananda Padhi, Minaketan Behera, Sisira Kanta Pattnaik, Debajyoti Banishree Bej, Saroj Kumar

Abstract: Because of multiple properties like higher values of corrosion resistance, formability, weldability along with greater structural utility aluminum alloys are generally gaining more and more demand in industries and household. With this the requirement for searching of higher quality cutting tool to machine aluminum is also growing. Here different cutting tools like $MTCVD+TiCN+Al_2O_3$, $MTCVD+TiCN+Al_2O_3+TiOCN$, $MTCVD+TiN+TiCN+Al_2O_3+TiN$, PVD AlTiN, cemented carbide (k-10) insert brazed with Polycrystalline Diamond and Polycrystalline Diamond Inserts are being used to machine rolled aluminum in dry condition and then comparative analysis are made. The cutting is of orthogonal type and capstan lathe is used for the same. Under different conditions of cutting the surface roughness along with morphology of chip are analyzed. Under constant depth of cut (doc) along with variable velocities and feed, the turning operation is performed. With SEM and XRD the identification including characterization of cutting tool were also performed. The polycrystalline diamond tool is found to give optimum surface finish, thin type of chip along with mirror like finish during machining operation.

Index Terms: Chip Morphology, Cutting Force, SEM, Surface roughness, XRD.

I. INTRODUCTION

For space technology and vehicle industrial applications aluminum along with its alloys are very favored material [1, 2]. The researchers are still moving on the path of finding the best material as cutting tool to machine aluminum along with its alloy by utilizing variety of coated tools like TiB_2 , TiC, TiN, AlON and Al_2O_3 . [3]. Because of higher quality adhesion property of TiC and TiN (both are CVD coated), these materials are becoming very demanding in the market [4]. In order to machine aluminum the major limitation is the creation of BUE because of the bonding property of material used as cutting tool [5]. The aluminum material is very difficult for machining because of low melting point temperature and higher chemical affinity with coating tool materials. Both tungsten carbide (uncoated) having 6% cobalt content and diamond coated tungsten carbide (lower % of cobalt) are very important to machine aluminum [6]. Because of some special properties like good chemical stability, higher hot hardness and easy to use at higher speed the diamond cutting tools are considered as better choices.

The tribological property is also increased while machining aluminum by advanced CVD and PVD coated cutting tool [7, 8].

The CVD coated polished diamond tool was observed to increase tool life with reduction in cutting force during machining of aluminum-silicon alloy material [9].

It was also observed that without decreasing life of tool machining of many aluminum alloys were possible at greater values of speed [10, 11]. The tool inserts (Polycrystalline Diamond) are having high demand in machining industries. The tool tip is brazed with only a single point which stands as one of the major limitation for PCD (Polycrystalline Diamond) tool. This brazing process takes lots of time. At the time of machining because of wrong handling or incorrect criteria of machining the brazed PCD portion may become loose and then come out. Though PCD tool is having all these limitations, still it is highly preferred at the time of High Speed Machining and hence both production and economy are enhanced [12]. Including high speed, the higher surface finish also plays very vital role as product quality is directly linked with it. Hence it requires very accurate monitoring of surface roughness including tool wear [13]. Chip morphology is also an important aspect in machining. Chip thickness depends upon several parameters such as cutting parameters, the configuration of cutting with work and tool materials. Due to the influence of the above parameters the continuous, discontinuous, serrated chips are produced. Chip morphology and its analysis give the information about the appropriate and stable condition for machining [14].

With the help of coated (TiN) tool along with uncoated carbide tool, the aluminum based Metal Matrix of alumina was machined. The tool wear in coated tool was observed to be less as compared with uncoated tool [15]. In this investigation the surface finish is given much importance and different cutting tool inserts are used to get the required surface finish.

II. EXPERIMENTAL SETUP AND PROCEDURE

In this experiment one rolled aluminum bar of cylindrical shape having 190 mm diameter with length of 460 mm was selected. As per the limitations fixed by tool and workpiece, accordingly the speed values are selected for machining aluminum alloy. The material and types of tool plays more important role in selecting cutting speed while the impact of properties of aluminum alloy are less for this selection. Here in this experimentation two cutting speeds 250, 450 m/min were selected. Due to two numbers of values, sufficient data points are accumulated in order to analyze the change in different machining parameters in connection with cutting speed.

Manuscript published on November 30, 2019.

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In machining operation for selection of proper feed the major factors considered are surface finish requirement for the machined specimen, work material type along with machine rigidity. Two different feeds as 0.125 and 0.18 mm/rev were taken considering low and high feed for analyzing the process variable during machining. It was also detected that doc for machining is having lower effect on the machinability performance. Here constant doc having value as 0.5 mm was selected in metal cutting operation.

Table-1 Workpiece and machining parameters

Material of Workpiece	Rolled Aluminum
Dimension of specimen	Φ 190 X 460 mm
Velocity of cutting	250, 450 m/min
Value of Feed	0.125, 0.18 mm/rev
Value of doc	0.5 mm
Condition of cutting	Dry

Table-2 Specifications of Cutting tools along with tool holders

Sl. no	Material of cutting tools	Specifications	Tool holders
01	Inserts (MTCVD-TiCN-Al ₂ O ₃) coating with superior interlayer adhesion	SNMG120408 MN	MSBNR2525M 12
02	Multilayer(MTCVD-TiCN-Al ₂ O ₃ -TiO ₂ -CN) coating with super interlayer adhesion	SNMG120408 MR	SCLCR2525M 09
03	Inserts (MTCVD-TiN-TiCN-Al ₂ O ₃ -TiN Coated)	SNMG120408 H	SCLCR2525M 09
04	An Advanced PVD AlTiN coating	SNMG120408 MP	SCLCR2525M 09
05	Cemented carbide insert with Polycrystalline Diamond brazing	CCGW09T30 4FST	SCLCR2525M 09
06	Cemented carbide(k-10) insert with Polycrystalline Diamond brazing	SPUN120304 FP CD10	SCLCR2525M 09



Fig-1 Piezoelectric Dynamometer (KISTLER) fitted at bottom of the tool Post

III. RESULT & DISCUSSION

This portion shows the evaluation of machinability study for rolled aluminum which is exposed for symmetrical cutting under different cutting conditions. Here we have considered variation in speed, change in rate of feed, doc. In total 24 sets of experiments are conducted in this work and in total six numbers of cutting tools are utilized. The characterization of tools are made by XRD analysis. Both force analysis and surface roughness analysis are made for different tools to compare between machining conditions. Also tool wear study including chip under-face study are conducted to investigate about tool life and feed marks.

XRD analysis

The XRD graphs of different cutting tools are taken for the conformation of coating. For this conformation, parameter like diffraction angle 2-theta is taken from 20 to 100 degree. Here basically for all tools, WC element peaks are showing due to the mother material.

Characterization of MTCVD-TiCN-Al₂O₃:

The XRD peaks of WC element show variety of peaks under different angles. The planes are (001), (100), (100), (100), (111), (112), (201) with angles of 31.3°, 36.7°, 48.4°, 64.30°, 73.8°, 77.8°, 89.5° respectively.

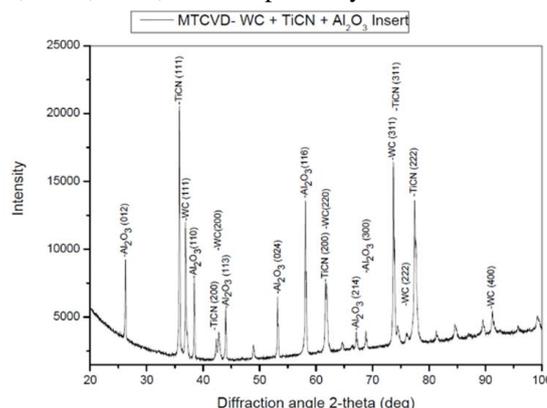


Fig-2 XRD pattern of MTCVD-TiCN-Al₂O₃

In Fig.2, the XRD peaks of TiCN are having high intensity due to good adhesion. Peaks of TiCN element show different peaks at respective diffraction angles. They are (111), (200), (222) planes at angles 35.5°, 43.5°, 77.2° respectively. The peaks of Al₂O₃ element show different peaks are located at corresponding diffraction angles.



They are (012), (110), (113), (024), (116), (214), (300) planes at angles 26.2°, 38.5°, 44°, 54.5°, 58°, 67°, 68.5° respectively.

Characterization of MTCVD-TiCN-Al₂O₃-TiOCN:

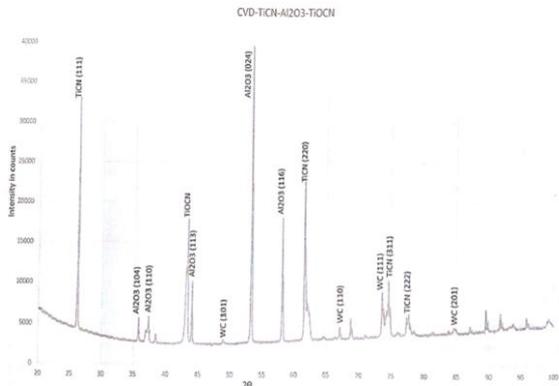


Fig-3 XRD pattern of MTCVD-TiCN-Al₂O₃-TiOCN

XRD peaks of Al₂O₃ are having high intensity due to good adhesion. XRD peaks of WC are showing different peaks at different diffraction angles. They are (101), (110), (111), (201) planes at angles 48.2°, 67.1°, 74°, 85.2° respectively. The XRD peaks of TiCN element shows variable values for different angles. The values are (111), (220), (311), (222) planes at angles of 26.2°, 63.1°, 74.0°, 77.2° respectively. The diffraction values of Al₂O₃ substrate show different values of peaks at different angles respectively. The values of planes are (104) (110) (113) (024) (116) at angles of 36.1°, 37.2°, 44.0°, 53.3°, 58.2° respectively.

Characterization of MTCVD-TiN-TiCN-Al₂O₃-TiN:

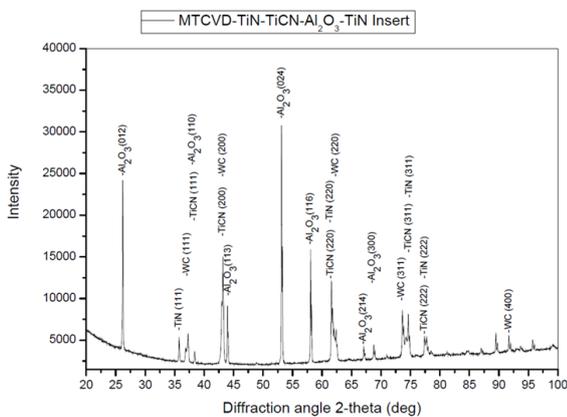


Fig-4 XRD pattern of MTCVD-TiN-TiCN-Al₂O₃-TiN

The XRD form of TiN in fig.4 shows the peaks at 38.03°, 44.18°, 64.46°, 77.67° diffraction angles with (111), (200), (300), (222) planes respectively. XRD peaks of TiCN element show different peaks having planes (111), (200), (220), (311), (222) at diffraction angles of 36.1°, 43.2°, 62.0°, 74.3°, 77.2° respectively. The X-ray diffraction image for Al₂O₃ shows variable peaks with different angles. The values are (012), (110), (113), (024), (116), (214), (300) planes at angles of 26.1°, 37.2°, 46.0°, 56.3°, 57.2°, 68.3°, 69.2° respectively.

Characterization of Advanced PVD AlTiN:

XRD image of PVD AlTiN coating in fig.5 is taken for the conformation of coating. Here single coating layer is located because WC peaks are formed due to the mother material but AlTiN peaks are formed due to the single top layer coating. The peaks for AlTiN are present in (100), (101), (102), (103), (004), (202) & (104) planes at diffraction angles of 32.5°, 36.0°, 48.5°, 64.0°, 74.0°, 78.0° & 85.0°.

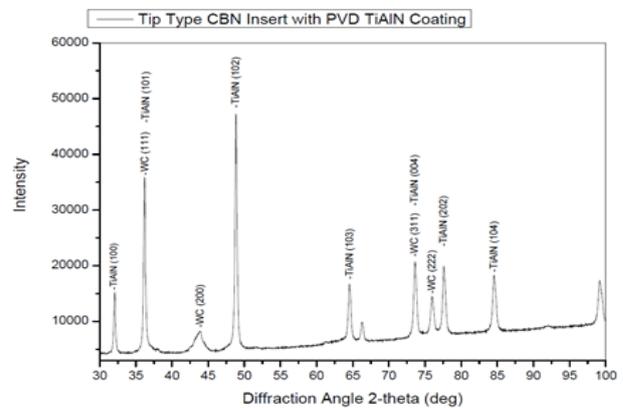


Fig-5 XRD pattern of Advanced PVD AlTiN Characterization of PCD

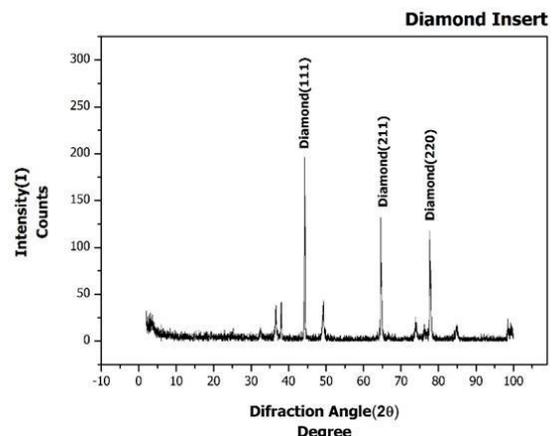


Fig-6 XRD pattern of PCD

The tip of PCD is being brazed with the edge of cutting of tungsten carbide tool. The X-ray diffraction image establishes peak to be at 44.18°, 64.69° and 77.67° respectively. These peaks are available in variable planes like (111), (211), (220) respectively. The diamond slip plane (111) is having very high intensity due to the presence of natural diamond crystal.

Force analysis

Force analysis shows various graphs representing of two cutting velocities having 250 m/min and 450 m/min with feed 0.125mm/rev, 0.18 mm/rev and with constant doc as 5mm. There are four graphs showing the combined cutting velocity, feed rate which indicate the cutting force, feed force values in operation of six cutting tools. Some of the results are as discussed below.

Table-3 Cutting and feed force data of different tool insert at different cutting condition

Tool	Sl. No	Speed(m/min)	Feed(m/rev)	Depth of cut (mm)	Cutting force (Fz)	Feed force (Fx)
1.	01	250	0.12	0.5	87.853	39.948
	02	450	0.12	0.5	86.674	52.015
	03	250	0.18	0.5	113.93	49.056
	04	450	0.18	0.5	95.366	49.624
2.	01	250	0.12	0.5	63.477	7.633
	02	450	0.12	0.5	45.715	13.612
	03	250	0.18	0.5	77.937	63.675
	04	450	0.18	0.5	84.299	34.210
3.	01	250	0.12	0.5	87.432	44.583
	02	450	0.12	0.5	86.281	38.755
	03	250	0.18	0.5	94.912	41.871
	04	450	0.18	0.5	95.752	13.467
4.	01	250	0.12	0.5	36.970	28.263
	02	450	0.12	0.5	72.240	3.375
	03	250	0.18	0.5	95.309	36.533
	04	450	0.18	0.5	89.824	25.279
5.	01	250	0.12	0.5	46.288	33.455
	02	450	0.12	0.5	34.387	25.157
	03	250	0.18	0.5	59.013	2.717
	04	450	0.18	0.5	41.942	12.703
6.	01	250	0.12	0.5	41.233	7.641
	02	450	0.12	0.5	37.488	1.703
	03	250	0.18	0.5	51.336	12.590
	04	450	0.18	0.5	44.485	8.621

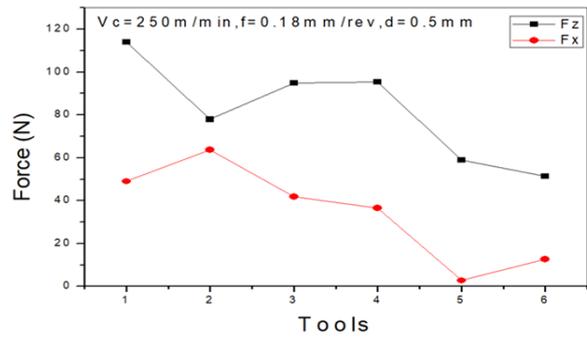


Fig-9 Cutting force vs Tools graphs for Velocity=250m/min, f=0.18 mm/rev, d=0.5mm.

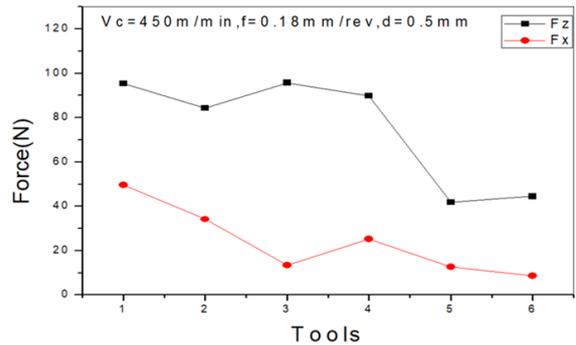


Fig-10 Cutting force vs Tools graphs in velocity=450m/min, f=0.18 mm/rev, d=0.5mm.

In above graphs minimum cutting forces are obtained in PCD tool of C type and S type (tool 5 and tool 6). The highest forces are obtained in coated tool material especially in tool 1 (MTCVD-TiCN-Al₂O₃) and tool 3 (MTCVD-TiN-TiCN-Al₂O₃-TiN). From the above figures (Fig. 7 to Fig.10) it can be concluded that at constant feed rate if we increase the velocity then the cutting force and feed force will decrease. Again with constant velocity if we increase feed rate then the cutting force and feed force values will increase. The S type PCD tool insert is most preferable than C type PCD insert and PVD AlTiN coated tool may be taken as next preference for machining of rolled aluminum under these conditions.

Surface Roughness Analysis

Surface Roughness Analysis shows histogram representing various cutting conditions. Each histogram shows ranges of surface roughness like Ra, Rz and Rmax. The values obtained are in micro meter which are precisely obtained by Taylor Hobson after the experiment. Some of the results are as discussed below.

Table-4 Surface Roughness data of different tool insert at different cutting condition

Tool	Sl. No	Velocity (m/min)	Feed (mm/rev)	doc (mm)	Surface Roughness		
					R _a	R _z	R _{max}
1.	01	250	0.12	0.5	1.08	5.30	7.00
	02	450	0.12	0.5	0.60	3.30	3.90
	03	250	0.18	0.5	1.52	7.00	8.70
	04	450	0.18	0.5	1.54	7.40	8.60
2.	01	250	0.12	0.5	1.40	7.50	9.30

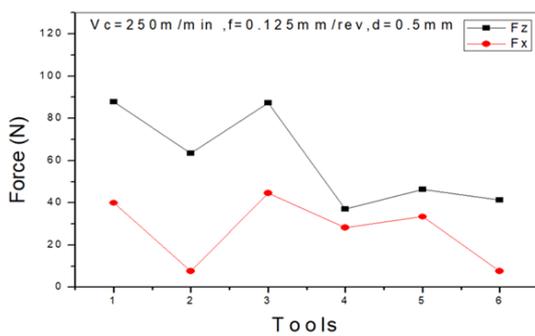


Fig-7 Cutting force vs Tools graphs for Velocity=250m/min, f=0.125 mm/rev, d=0.5mm.

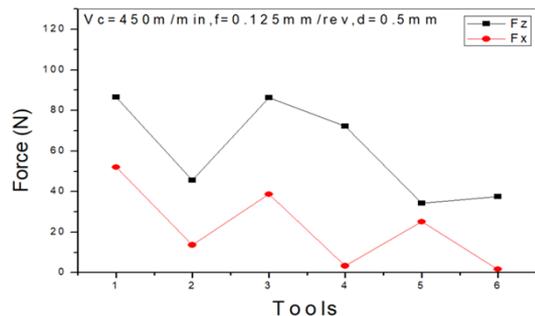


Fig-8 Cutting force vs Tools graphs for velocity=450m/min, f=0.125mm/rev, d=0.5mm.

	02	450	0.12	0.5	1.00	5.20	8.50
	03	250	0.18	0.5	1.26	6.40	8.00
	04	450	0.18	0.5	1.40	7.50	9.00
3.	01	250	0.12	0.5	1.24	5.60	7.10
	02	450	0.12	0.5	0.68	3.80	9.00
	03	250	0.18	0.5	1.50	7.50	9.30
4.	01	250	0.12	0.5	1.42	6.60	8.00
	02	450	0.12	0.5	0.68	3.40	4.20
	03	250	0.18	0.5	1.22	5.70	6.70
5.	01	250	0.12	0.5	1.54	7.40	8.60
	02	450	0.12	0.5	1.20	5.50	6.40
	03	250	0.18	0.5	1.00	5.00	6.50
6.	01	250	0.12	0.5	1.20	6.90	8.80
	02	450	0.12	0.5	1.60	7.60	9.00
	03	250	0.18	0.5	0.78	4.10	8.20
	04	450	0.18	0.5	1.89	8.40	9.60

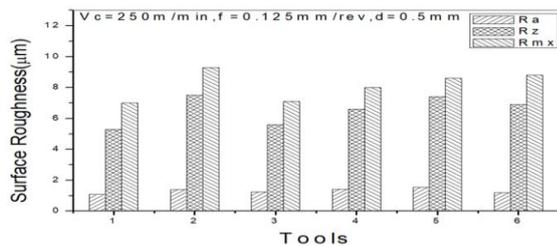


Fig.-11 Surface Roughness vs Tools graphs for velocity=250m/min, f=0.125mm/rev, d=0.5mm.

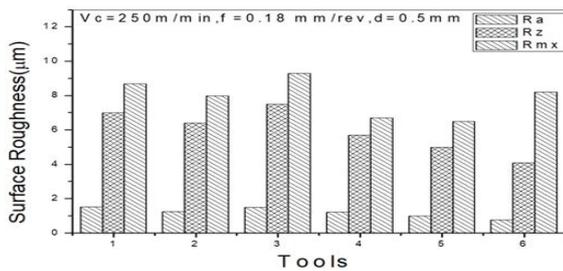


Fig.-12 Surface Roughness vs Tools graphs for velocity=250m/min, f=0.18mm/rev, d=0.5mm.

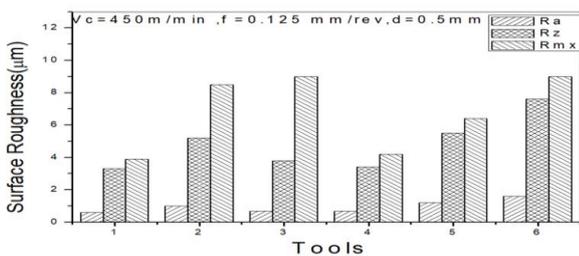


Fig.-13 Surface Roughness vs Tools graphs for Velocity=450m/min, f=0.125mm/rev, d=0.5mm.

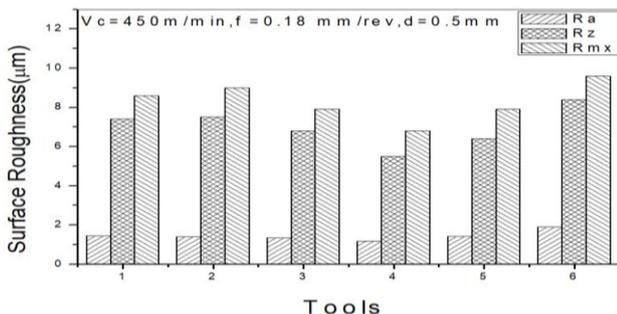


Fig.-14 Surface Roughness vs Tools graphs for Velocity=450m/min, f=0.18mm/rev, d=0.5mm.

From the above figures (Fig. 11 to Fig.14) it shows that there is lesser surface roughness in tool 5 and tool 6. It is due to the presence of natural diamond brazed on the tool tip. The other tool inserts (coated tools) are having higher surface toughness due to the occurrence of chipping and buildup edge formation on the tool tip. So preferably PCD is the best insert for non-ferrous machining. The tool no 4 (AlTiN PVD coated insert) gives very less surface roughness because of hard coating adhesion and single layer coating.

Chip Reduction Coefficient

Chip reduction coefficient is defined as ratio between the chip thickness (S1) with uncut thickness of chip (S2). During calculation of thickness of uncut chip the shear angle is taken as 90° for all the S type tool insert except PCD C-type which is 80° . All the detail values of those six tools are graphically represented by taking constant feed rate and variable cutting velocity.

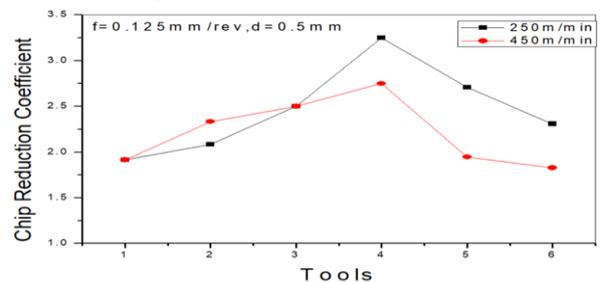


Fig.-15 chip reduction coefficient vs tools graph at constant feed 0.125mm/rev and variable cutting velocity 250,450 m/min

Fig.-15 shows the graphical representation of chip reduction coefficient having constant feed of 0.125 mm/rev, doc as 0.5mm. It shows chip reduction coefficient increases with increase of cutting velocity. It shows chip reduction coefficient is lower in PCD tools especially in tool 6 because of the absence of the tool material defect like chipping and built up edge.

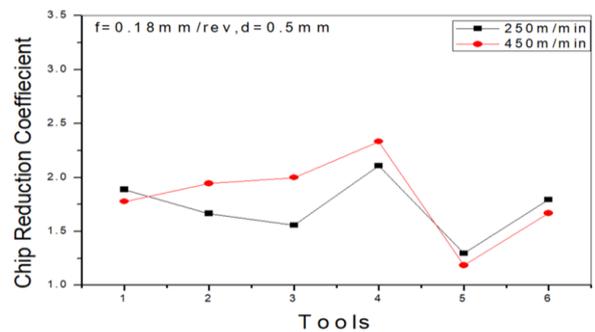


Fig.-16 chip reduction coefficient vs tools graph at constant feed =0.18 mm/rev, variable cutting velocity =250,450 m/min.

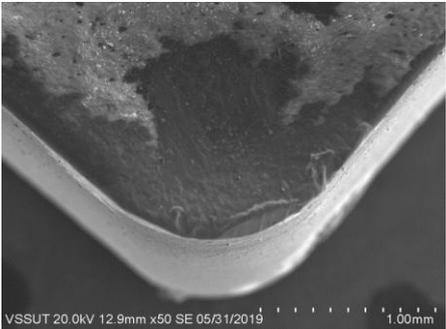
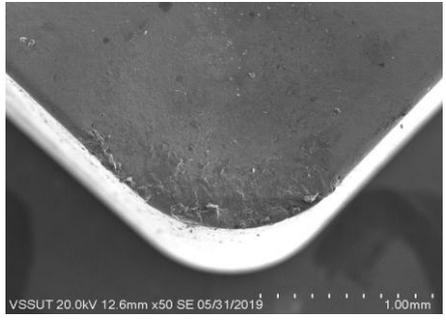
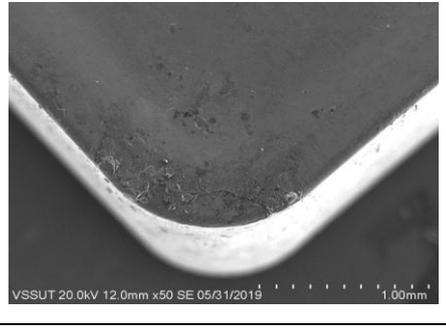
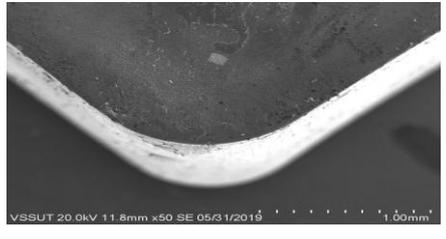
Fig.-16 shows the graphical representation of chip reduction coefficient having constant feed of 0.18 mm/rev, doc as 0.5mm. It shows chip reduction coefficient increase with the decrease of cutting velocity. Here shows the chip reduction coefficient is lower in PCD tools especially in tool 5 because of the absence of the tool material defects and also having good coating adhesion.

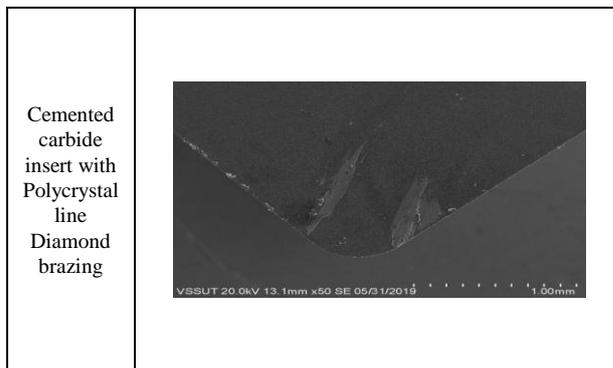
So at high feed rate S type tool is more suitable than C type PCD tool. For all such cutting condition the chip reduction coefficient is greater than 1 in turning operation of rolled aluminum. It indicates that by machining of rolled aluminum the chip expansion happens due to heat absorption of chip and also lubrication properties of aluminum.

Tool Wear analysis

Because of higher temperature generated during the time of machining, materials are eroded along the tool rake face due to lower toughness and lesser wear resistance. The PCD tool showed very less amount of wear on the rake face. This very lower value of deformation on the surface is because of higher wear resistance and higher temperature resistance. There is neither BUE nor BUL on the insert surface. In case of coated tool except PCD, the wear percentage is more due to the formation of BUE, chipping and abrasive wear on tool tip and rake surface of tool inserts.

Table-5 showing tool wear of coated tools

Tool Insert Material	Wear Analysis
Inserts (MTCVD-TiCN-Al ₂ O ₃) coating with superior interlayer adhesion	
Multilayer (MTCVD-TiCN-Al ₂ O ₃ -TiOCN) coating with super interlayer adhesion	
Inserts (MTCVD-TiN-TiCN-Al ₂ O ₃ -TiN Coated)	
An Advanced PVD AlTiN coating	



Chip under-face study

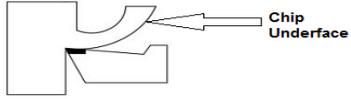
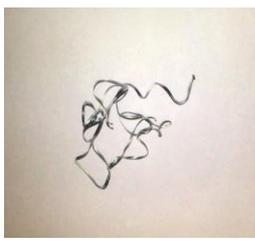
Investigation of chip under face demonstrates the variety of feed marks, breaks created at the time of machining process. During dry turning of rolled aluminum under various cutting condition for PCD and other coated tools, different rough stamps appeared in the chips. Here four combinations (low and high values for speed, feed) were tried to find the condition for the chips for different cutting tool inserts. PCD tool showed better smooth feed marks under greater speed, higher feed conditions.

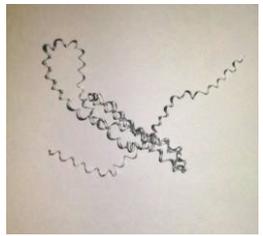
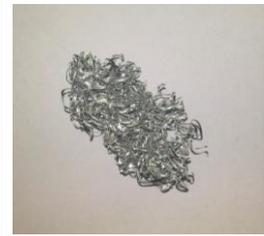
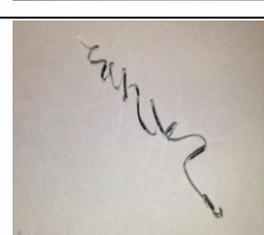
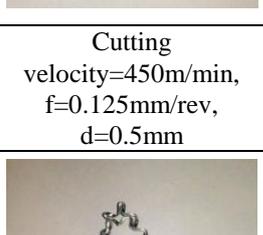
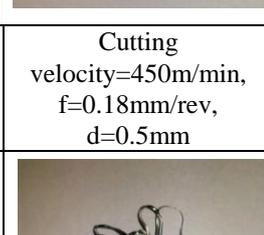
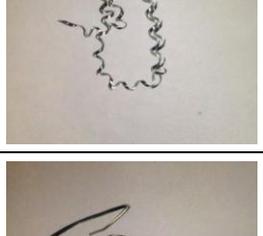
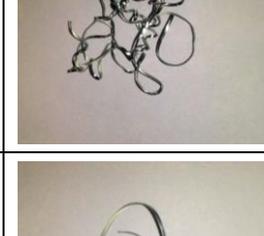
Types of chip formation depends upon the cutting condition, tool material. So basically continuous and discontinuous type of chips are formed.

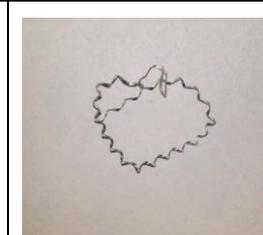
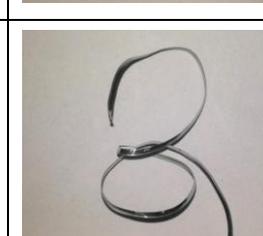
At high feed rate the chip become discontinuous compared to low feed due to more chipping and shear force between tool and workpiece. In case of high speed due to smooth cutting of workpiece the chips are curly and continuous type as compared to low cutting speed.

PCD (S and C type) cutting tool and PVD AlTiN tool produce continuous chips during machining but other tools produce discontinuous and less number of chip circle for machining of aluminum.

Table-6 Photographs shows the chips under-face after machining aluminium with various coated tool and PCD tool.

		
Condition	Cutting velocity=250m/min, f= 0.125mm/rev, d= 0.5mm	
Tool	Cutting velocity=250 m/min, f= 0.18mm/rev, d= 0.5mm	
01.		

02.		
03.		
04.		
05.		
06.		
Tool	Cutting velocity=450m/min, f=0.125mm/rev, d=0.5mm	Cutting velocity=450m/min, f=0.18mm/rev, d=0.5mm
01.		
02.		

03.		
04.		
05.		
06.		

IV. CONCLUSION

In this experiment, a rolled aluminum has been machined using six numbers of various tools having two speeds of 250 and 450m/min with two feeds 0.125 and 0.18mm/rev under constant depth of cut as 0.5mm. The study of chip morphology, surface roughness, tool wear are performed. The SEM images about wear of tool are captured and force analysis is carried out.

- Chips produced by the entire cutting tool are continuous in nature. From the study of chip deformation it was found that in case of PCD smooth feed marks and less amount of micro cracks are found. It is a good indication of good surface texture produced. Chips are continuous in case of PCD (S and C type) and also for PVD AlTiN coated insert. Rather for other coated insert the discontinuous type chips are made.
- At constant feed rate if we increase the velocity then the cutting force and feed force will decrease. Again with constant velocity if we increase feed then force of cutting including feed force value will increase. The S type PCD tool insert is most preferable than C type PCD insert and PVD AlTiN coated tool may be taken as the next preference for machining of rolled aluminum under these conditions.
- The surface integrity obtained using insert (PCD) was observed as superior when compared with other varieties of cutting inserts for high-speed machining. In case of AlTiN coated insert

closer roughness values to PCD was observed.

- The tool wears in case of PCD is very small on the rake face. Tool wear was also found to be less for PVD AlTiN coated insert due to single layer enhanced coating of AlTiN. Very less amount of deformation of surface was observed for PCD due to special wear resistance, high-temperature resistant property. There is neither BUE nor BUL on tool surface. In case of coated tool except PCD the wear percentage is more due to the formation of BUE, chipping and abrasive wear on tool tip and rake surface of tool inserts.
- Chip reduction coefficient enhances with decrease in velocity of cutting. It shows chip reduction coefficient is lesser in PCD tools because of the absence of the tool material defects and also having good coating adhesion. So at high feed rate S type tool is more suitable than C type PCD tool. For all cutting condition chip reduction coefficient is greater than (1) one in turning operation for rolled aluminum. It indicates that by machining of rolled aluminum the chip expansion happens due to heat absorption of chip and also due to lubrication properties of aluminum.

Considering all the above conditions for the machining of rolled aluminum workpiece, for better surface integrity, longer tool life and lesser wear of the tool, the PCD tool was suggested. However for small run and less cost the AlTiN tool will be also preferable as an alternative of PCD. But for smooth and higher productivity PCD tool was found to be best for aluminum.

The knowledge generated in this work should contribute towards improved design, processing of coated cutting tools, PCD during machining for aluminum including its alloy materials.

ACKNOWLEDGEMENT

I would like to acknowledge all the lab staff of VSSUT, Burla for their kind support to carry out this work.

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