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TOOL WEAR ASSESSMENT DURING MACHINING OF INCONEL 718

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Abstract

Machining of superalloy Inconel 718 would have established some issues like, inability of the tool materials to sustain for a longer duration due to the work hardening effect and very high cutting forces causes metallurgical damage on the work pieces. This research paper focuses on the tool life issues of different tool materials associated with the turning of Inconel 718 under different cutting conditions. Further, it is significant to identify the parameters that cause the machining characteristics, in particular the flank wear and to understand the relationship they have with the different controllable parameters. Turning experiments on Inconel – 718 were investigated under different cutting conditions using three controllable parameters namely feed rate, cutting speed and depth of cut. Three different cutting tools such as PVD TiAlN coated carbide inserts, Al_2O_3 – TiC Ceramic and cBN inserts with constant tool geometry were used for all experimental trials. The flank wear occurred on the inserts during every trail are measured and recorded using CARL ZIESS Optical Microscope having 50 X to 1500 X magnification, equipped with Clemex Vision Professional Edition Image Analysis Software. Scanning Electron Microscope (SEM) observations were made to understand the wear pattern encountered by different tool materials. Analysis of Variance (ANOVA) was performed to understand the percentage influence of all the cutting parameters on the flank wear.

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Keywords: Inconel 718; Flank Wear; Cutting inserts, ANOVA

1. Introduction

Inconel 718 (In-718) super alloy has far-reaching utility in various fields of engineering with its special features like corrosion resistance, high temperature resistance, creep resistance, for low temperature

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application the material possess good ductile to brittle transition and high strength to weight ratio etc.In-718 provides good yield strength of 550 MPa at 760°C[1] which is another favorable property for many applications. In aerospace components, 75% by weight and 50 % by weight of modern jet engine were replaced by In-718. Turbine blades of aero engine which operates under elevated temperature and pressure are made of In-718. Machining remains a tough job for this material due to its hot hardness, high temperature strength, chemical wear resistance and work hardening[3]. Work hardening and attrition properties of In-718 cause the tool life deterioration very rapidly resulting in replacement. Tool technological improvement has led to the development of carbide (with or without coating), PCD and cBN/PCBN tools to resist heat and withstand its strength and toughness even at high speed machining. Machining technique like hot machining, high pressure coolant system (HPC), cryogenic machining system, self-propelled rotary tool (SPRT) to some extent has contributed to tool life improvement[4]. Crucial factor for proper machining of material depends on proper selection of tool. Appropriate tool (material and geometry) provides good surface finish on work material[5].

Poor thermal conductivity and work hardening nature increases the temperature at the tool-chip interference which, promotes tool wear. Flank wear and crater were major concern of tool wears. Flank wear contributes a major level in various tool wear test carried out. Abrasion and work material adhesion were predominant factors that cause the flank wear. In c-type inserts at high speed machining, shows severe grooving, BUE, inserts facture, thermal crack and chipping[6]. It has been reported that tool life can be improved by the application of high pressure cooling system at the interface of tool-chip. Along high pressure cooling system, high pressure jet assisted cooling promotes better lubrication over conventional cooling systems[7]. Crater wear promotes at low cutting speed due to cycle of adhesion of work material and its removal[8]. Machining of In-718 (turning), heat generated due to the friction between tool-chip interface remains common and unavoidable problem that affects tool life and surface quality. This process plays quite a negative role in machining hard materials. Lower toughness nature in ceramic tools prevails excessive notching which remain as a factor to reduce the tool life. It has been reported that use of cutting fluid mixed with nano-particles has reduced the friction force and tripled the tool life[9]. Kramer et al. has grouped tool wear into two categories: at low temperature and high temperature region. Abrasion, chipping were under low temperature region where as chemical wear mechanism like thermal cracking, diffusion are classified under high temperature region [4]. Huang et al. reported that several wear mechanisms join hands to form tool failure. These wear mechanisms were categorised as, abrasion, adhesion, diffusion, fatigue, and tribo-chemical wear[10]. Ezugwu et al. studied on machining by using different grades of cBN inserts and K grade of carbide inserts. It was reported that carbide tools performed better than cBN tools. It was also stated that increasing cBN content results in reduction of tool life[3]

According to literature review, the reported works were focused mainly on work hardening effect, surface integrity, tool life and surface quality of In718 machined with any one tool material. Therefore the present study aims at analyzing of tool wear mechanism and tool wear pattern with different cutting conditions such as dry, MQL and flood cooling cutting conditions on three different tool materials such as PVD TiAlN coated carbide, whisker Ceramic and cBN.

2. Experimental Setup and Procedure

The experiments were conducted to investigate the effects of cutting parameters on tool wear during machining of Inconel 718 super alloy with the selected cutting tool and cutting conditions .The experiments were conducted on ACE Micrometric made Simple Turn 5075-SPM CNC lathe machine [fig.

1] that is equipped with variable spindle speed ranging from 50 to 4000 rpm and a 14 KVA motor drive rating. The cutting inserts used were Ceramic, PVD TiAlN coated carbide and cBN and tool holder was PCLNR2525M12 type supplied by Kennametal. The major input parameter on which experiment was carried out were cutting speed, feed rate, depth of cut and cutting conditions. The main aim of the experiment was to analyze the effect of cutting parameters and cutting conditions on the tool wear. The experiments were conducted according to a three level and five parameters L_{27} (3^{13}) Taguchi orthogonal array [11]. Table - 1 shows the properties of work material (Inconel 718) and the tool geometry used in this research work for experimentations. Table - 2 indicates the chemical composition of the work material. Table - 3 present the cutting parameters and their levels/types/conditions considered for experimentations.

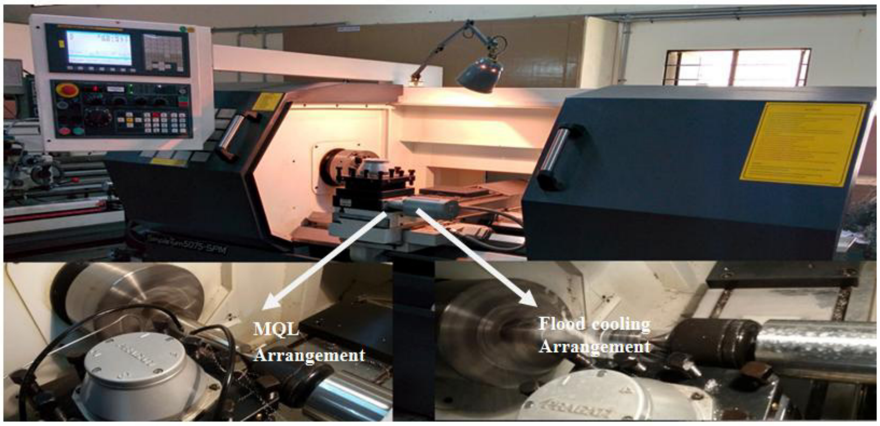

Fig.1. Experimental setup on CNC lathe machine

Table - 1 Work material properties and the tool geometry

Work material		**Tool Geometry**	
Work specimens	Inconel 718	Inclination angle	−6°
Hardness	35 HRC	Orthogonal rake angle	−6°
Size	θ 40 × 60 mm	Orthogonal clearance angle	6°
Density	8.19 g/cm³	Auxiliary cutting edge angle	80°
Young's modulus	206 GPA	Principal cutting edge angle	95°
o holder	PCLNR 2525M12	Nose radius	0.8 mm

Table – 2 Chemical Composition of Inconel 718 (in %)

Ni	Co	Cr	Mo	Fe	Si	Mn	C	Al	Ti	Cu	P	B	S
52.50	1.00	19.00	3.05	17.00	0.35	0.35	0.80	0.60	0.90	0.30	0.015	0.006	0.015

Table - 3 Cutting Parameters and Levels/ Types/Conditions

Parameters	Level1	Level2	Level3
1. Cutting speed (Vc)	60	90	120
2. Depth of cut (d)	0.20	0.4	0.6
3. Feed rate (f)	0.08	0.10	0.12
4. Cutting insert	PVD –TiAlN coated carbide	Ceramic	cBN

5. Cutting condition	Dry cutting	MQL cutting	Flood cooling

3. Results and Discussion

Subsequent to the experimentations, tool wear analysis were carried out with the help of CARL ZIESS Optical Microscope having 50 X to 1500 X magnification, equipped with Clemex Vision Professional Edition Image Analysis Software and Scanning Electron Microscope (SEM) observations were made to understand the wear pattern encountered in different tool materials. Analysis of Variance (ANOVA) was performed to understand the percentage influence of all the cutting parameters on the tool wear.

3.1 Graphical Representation of Flank Wear against Cutting Speed

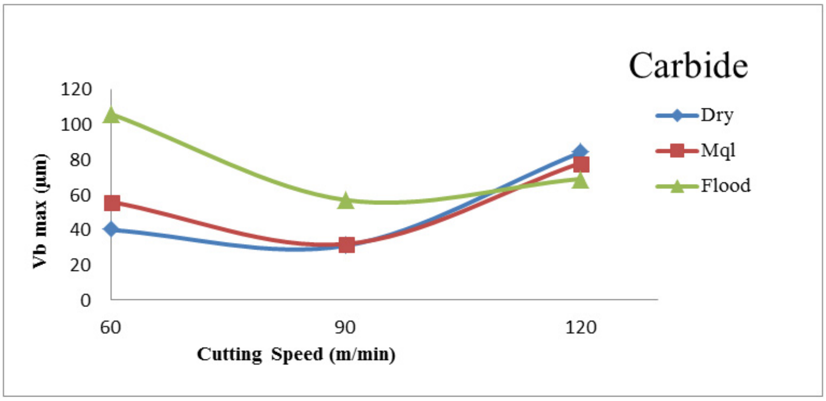

Fig 2a, Max flank wear Vs cutting speed for Carbide tool under different cutting conditions

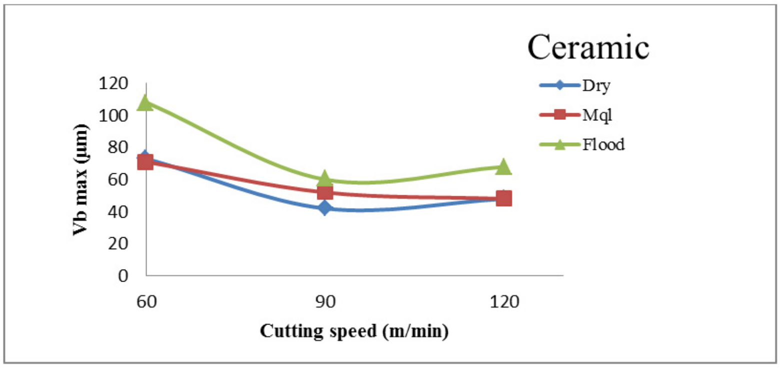

Fig 2.b Max flank wear Vs cutting speed for Ceramic tool under different cutting conditions

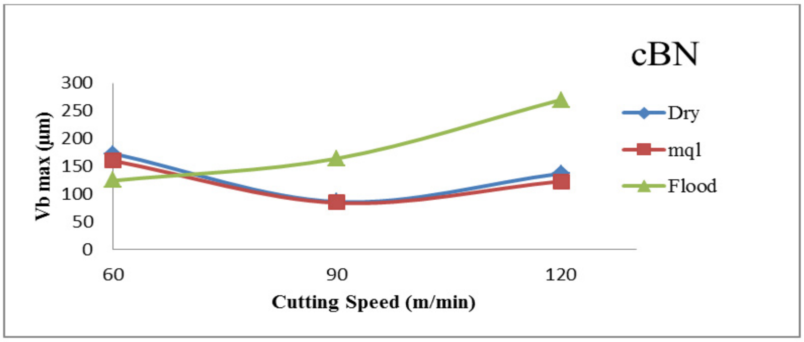

Fig 2.c Max flank wear Vs cutting speed for cBN tool under different cutting conditions

From Fig 2 a., it is being observed that, carbide insert has experienced higher flank wear at high cutting speed of 120m/min. In flood cooling cutting condition higher flank wear was observed at low speed and it gradually decreased with increase in speed. For ceramic tool higher flank wear is observed at low speed (Vc = 60m/min) and as the speed increases from 90 - 120m/min there is a decrease in flank wear as seen in Fig.2b. For cBN tool, at higher speed (Vc = 90 - 120m/min) less flank wear was observed. At flood cooling condition flank wear increases with increase in speed. For dry and MQL cutting conditions there is no considerable changes in flank wear at all the cutting speeds as shown in Fig.2c. Higher flank wear is observed for flood cooled cutting conditions for all tool materials.

3.2 Microscopic Analysis of Tool Wear

Tool wear is greatly influenced by the three factors namely thermal softening, diffusion and notching at greater depth of cut and at edge. While machining superalloy such as Inconel 718 there are two deformation zones one is primary deformation machining zone and secondary deformation high shear stress zone which produces high temperature and stress. Thermal cracking is observed on rake face of cBN insert at low cutting speed (60m/min) and high feed rate(0.16mm/rev) as shown in Fig 3a. This causes high temperatures at the tool work interface. Notching and thermal cracking on rake face is primary wear pattern in cBN tool at low cutting speed and wet cutting condition. In Fig.3b fracture observed on carbide tool face at 120m/min cutting speed. This wear pattern is the result of severe overload conditions such as very high cutting speed and feed rate. In Fig.3c for ceramic insert at 120m/min cutting speed and 0.16mm/rev feed rate visible flank wear is observed in the form notching. This kind of notching causes poor surface finish on the machined part. This wear pattern appears because of very hard work material to be cut and it generally appears while machining of nickel and cobalt base alloys.

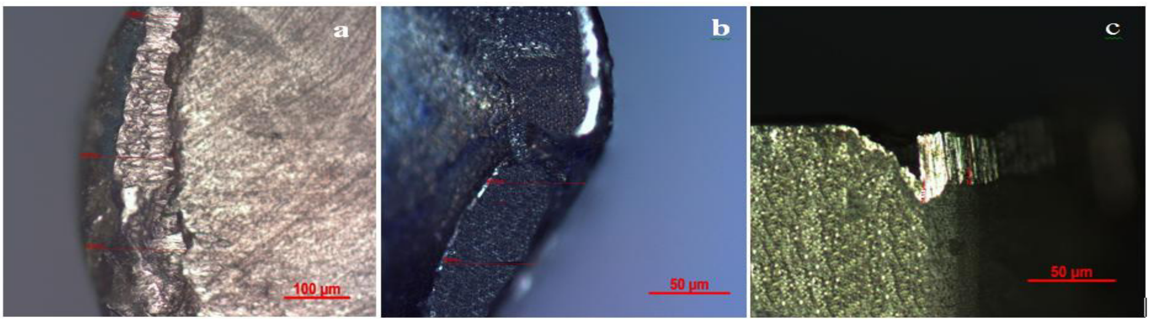

Fig 3. Microscopic Image of cutting tools, **a**. cBN insert with Vc = 60m/min, d =0.2mm f = 0.16mm/rev. **b.** Carbide Insert with Vc = 120m/min, d = 0.2mm, f= 0.12mm/rev. **c.** Ceramic with Vc = 120m/min, d = 0.2mm, f= 0.16mm/rev

3.3 SEM Analysis for Tool Wear

The BUE often leads to chipping of the tool cutting edges as shown in Fig.4a., which s caused due to low speed. The work piece material is adhering to the surface of the tool due possibly to an affinity of the work material to the insert or its coating. BUE is also caused by coolant issues such as improper physical application of the coolant, insufficient anti-weld characteristics. In Fig.4b abrasive wear observed on flank face, deep multiple scratches or scores are observed on the land (flank) of the tool.

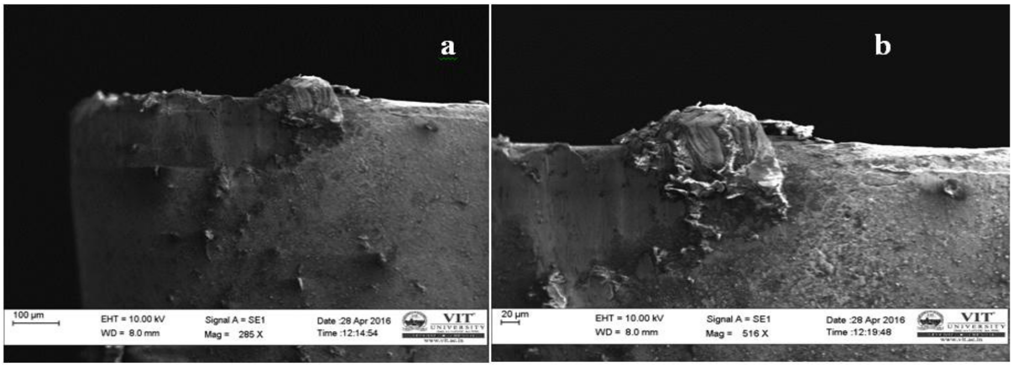

Fig. 4. SEM image for Carbide insert with Vc -60m/min, d = 0.6mm and f = 0 .12mm/rev.

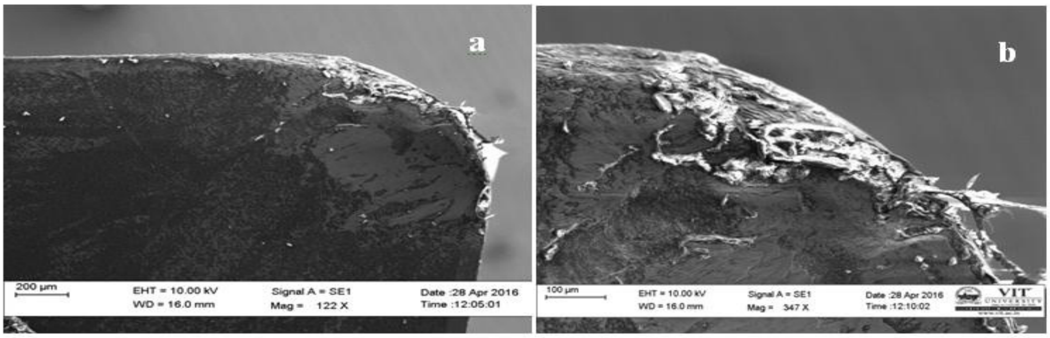

Fig.5. SEM image for Carbide insert with Vc = 90m/min, d = 0.4mm and feed = 0.16mm/rev.

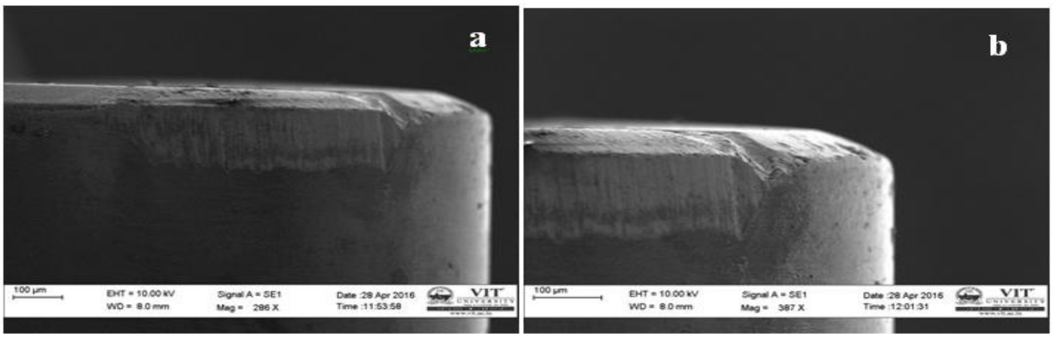

Fig.6. SEM image for CBN insert with Vc =120m/min, d = 0.2mm and f = 0.12mm/rev.

Crater wear is observed in the form of chipping on tool face, the sharp ragged edges appeared on the used insert as shown in Fig.5a. Often, chipping wear leads to a catastrophic failure early in the life of the tool. Crater wear appears as a shallow trough in localized areas as shown in Fig.5b. Crater wear will increase until it reaches the cutting edge causing fracture, surface finish is usually streaked and uneven because of such wear. Normally chipping causes due to mechanical issues such as machine spindle or part fixture vibration will contribute to chipping wear also excessive loads high feed and high cutting velocity on the tool will cause chipping. A metallurgical property of tool and work material such as brittleness leads to chipping wear. Flank wear observed on tool face is the more common wear pattern found during superalloy machining as shown in above Fig. 6a. This wear is uniform over a localized area and accelerates with higher temperatures. It appears as a rough surface on the flank of insert and comparatively less on the face of tool. In Fig. 6b flanking appeared on the face where a large area is missing on the tool face. Flank wear occurs because of high speed and feed conditions. It may accelerate because of cobalt leaching. Cobalt leaching is a chemical reaction between the cobalt binder of the insert and cutting fluid. Flanking occurs because of highly brittle nature of tool with high load conditions and sudden impact when the tool penetrates on the surface of the work piece.

3.4 Analysis of Variance (ANOVA) for Tool Wear

Taguchi L27 experiments were carried out and observed data were analyzed using minitab17 software to plot the response graph for signal to noise ratio for maximum flank wear. The S/N ratio for flank wear was defined with smaller the better outcome. The rank for the parameters is distributed based on the response of signal to noise ratio. The most influencing parameter for flank wear is tool (Insert material) and cutting speed as shown in Table 4. ANOVA was carried out from the experimental observations on flank wear (Table 5) and the percentage contribution is calculated for a confidence level of 95% by following backward elimination $\alpha = 0.05$. From the *p* value can be estimated the significant and insignificant values which do not influence the flank wear. The most significant parameter is tool material with 57.2% contribution for flank wear. The R-square (R-sq) value is above 90% which mean 90% correct value for any variability and the regression equation for flank wear achieved. Optimized cutting parameters and conditions for better flank wear are calculated from means of SN ratio value graph (smaller is better) as shown in Fig. 7. The optimized parameters and conditions are found to be 90m/min cutting speed, 0.4mm depth of cut, 0.16mm/rev feed rate with carbide tool under dry cutting conditions.

Table - 4 Taguchi Analysis of Wear against Vc, d, f, Tool material and Cutting Condition

Level	Vc	d	f	Tool material	Cutting condition
1	-37.74	-39.16	-38.73	-35.23	-36.59
2	-37.99	-34.66	-37.87	-42.92	-39.34
3	-38.07	-39.97	-37.12	-35.64	-37.87
Delta	0.33	5.31	1.61	7.69	2.75
Rank	5	2	4	1	3

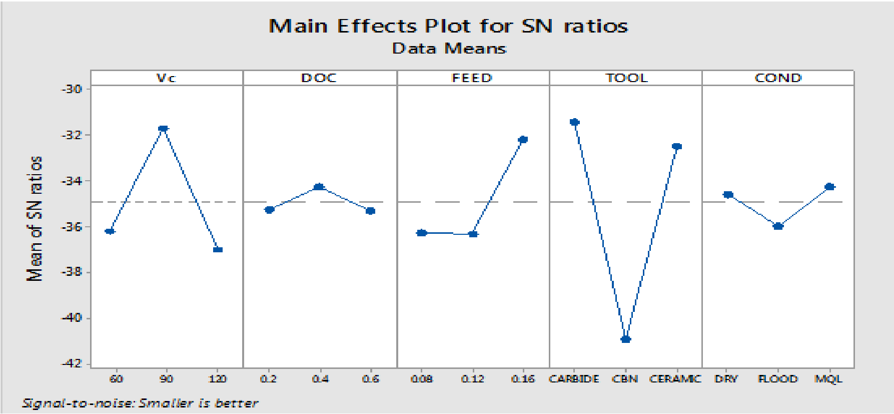

Fig.7. Signal to noise ratio for flank wear

Table - 5 ANOVA for Flank Wear

SOURCE	Dof	Adj ss	Adj ms	F-value	P-value	P %
Vc	1	2398.5	2398.5	3.62	0.076*	3.55
D	1	599.8	599.8	1.55	0.232*	0.88
F	1	924.5	924.5	2.34	0.110	1.36
Tool material	2	38613.5	19806.7	51.34	0.0003	57.2
Cutting Condition	2	469.1	234.5	0.61	0.557*	0.69
Vc * f	1	7157.5	7157.5	18.55	0.001	10.60
Vc * Tool material	2	3093.5	1546.8	4.01	0.040	4.58
Vc * Cutting condition	2	9372.9	4686.5	12.15	0.001	13.88
ERROR	14	4862.4	385.8			7.20
TOTAL	26	67491.7				
S = 19.6417 R-sq = 92.79% R-sq(adj) = 86.54%						

4. Conclusions

In machining of Inconel-718 Ni-base supper alloy the tool wear is greatly influenced by factors such as thermal softening, adhesion, diffusion, notching and thermal cracking. cBN tool has shown severe wear pattern and higher wear values when compared to ceramic and carbide tools. For flood cooled cutting condition higher flank wear values are observed for all type of tool materials. From ANOVA the main influencing parameter for tool wear are types of tool (insert) material followed by cutting speed.

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