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Performance of deep cryogenically treated and non-treated PVD inserts in milling

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ABSTRACT

Purpose: The purpose of the research was to analysis the tool performance between cryogenic treated and non-treated PVD inserts by milling process on Inconel 718 material in terms of surface roughness and tool wear.
Design/methodology/approach: The methodology adopted is milling process with various cutting parameters like cutting speed, feed rate and constant depth of cut. Cutting speeds are 20,30,40 m/min with feed rate 0.05, 0.08 & 0.10 mm/ tooth and constant depth of cut is 0.50 mm.
Findings: From the experimental work, the results were encouraging and performance is analysed on surface roughness and tool wear. Cryogenic treated inserts performed better than non treated inserts. Treated PVD inserts produced low surface roughness at high cutting speed with low feed rate. PVD treated inserts formed low flank wear where as untreated inserts formed more flank wear. Chips produced were saw tooth chips.
Research limitations/implications: There are some limitations in carrying out this work due to machine vibration. There was a constraint in measuring the crater wear of the tool.
Originality/value: This experimental work will help other researchers to follow on flank and crater wear using cryogenic treatment. This process can be used for difficult to cut materials like Titanium.
Keywords: Cryogenic treatment; Machining; Flank wear; Surface roughness

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1. Introduction

The technology on cutting tools and cutting inserts are rapidly improving and this development is required to improve the wear behaviour on machining for difficult to cut materials like Inconel 718, Titanium, hard Martensitic stainless steels etc. The improvement in performance can be achieved by increasing the strength of the cutting inserts in terms of wear resistance. One of the processes of increasing the strength of cutting inserts is cryogenic treatment. The cryogenic treatment can be carried on cutting inserts like HSS tools, carbides, ceramics, CBN, PCBN and coated inserts. Unlike coatings that are only superficial surface treatment, cryogenic treatment is applied to the whole volume of material, reaching the core of the tools. This process guarantees maintenance of their properties even after re-grinding or re-sharpening [1]. Several investigators have focussed their attention on studying this process and trying to raise the efficiency of the tool materials [2-3]. Very few investigators have studied on the performance of cryogenic PVD coated inserts on difficult to cut materials like Inconel 718. The important aspect of this process is changes in the mechanical properties and the crystal structure of materials. For the past 30 years, there have been an increasing interest in the effects of cryogenic treatment on the properties of metals. Barron [4] performed abrasive wear tests on a wide variety of steels, and concluded that metals which can exhibit retained austenite at room temperature can have their wear resistance significantly increased by subjecting them to cryogenic treatment. Quek [5-6] concluded that cryogenically treated tool inserts exhibited better wear characteristics than untreated ones at low turning speeds and feed rates. Da silva et al. [1] conducted trials using cryogenic treated HSS tools and found that tool life increased between 82-91% after being treated at -196°C. The hardness and wear resistance of tool steels can be improved simultaneously through cryogenic treatment [7-8]. A hard coating application is another effective way of tool life improvement during machining of stainless steels. Cemented carbide tools are traditionally coated by two methods: chemical vapour deposition (CVD) and physical vapour deposition (PVD) [9]. PVD offers lower deposition temperatures and a sharp cutting edge could be retained easier, which is very important for machining of stainless steels. Cryogenic expresses study and use of materials at very low temperature, below -186°C. Normal boiling point of permanent gases such as helium, hydrogen, neon, nitrogen, oxygen, normal air as cryogens below -180°C. Cryogenic gas have wide variety of applications in industry such as health, electronics, manufacturing, automotive and aerospace industry particularly in cooling purposes. Liquid Nitrogen (LN) is the most commonly used element in cryogenics. Nitrogen melts at -201.01°C and boils at -198.79°C, it is the most abundant gas, composes about four fifths (78.03%) by volume of the atmosphere. It is colourless, odourless, tasteless and non-toxic gas [10]. The research work carried by using operating parameters in milling process are given in the Table 1.

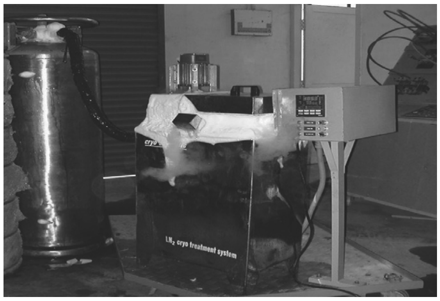
2. Experimental procedures

2.1. Principle of the deep cryogenic treatment

Deep cryogenic treatment comprises of cooling the material over a period for few hours to the sub-zero range, holding at this temperature for a long time and then returning to room temperature. The process is based on the predetermined thermal cycle that involves cooling of the engineering components/materials in a completely controlled cryogenic chamber. The material is slowly cooled to -196°C and soaked at deep cryogenic temperature for 20 hours. The material is then allowed to return slowly to the ambient temperature. The complete cryogenic cycle would take up to 25-30 hours.

Figure 1 (a) shows block diagram for the process, (b) shows the treatment cycle. The materials are treated in the cryogenic chamber. The process involves raising and reducing the temperature. Thermal control is achieved by continuously monitoring inputs and regulating the flow of LN into the chamber and alternating the heat. Precise program control takes the cycle through its three phases of descend, soak and ascend. The entire cycle takes 48 to 72 hours depending on the weight and type of material. It is imperative that a slow descend is followed by soaking period for at least 24 hours at -196 °C and raised to room temperature with a slow ascend. Strict computer control and precise processing profiles assure that optimum results are achieved with no dimensional change or thermal shock. The cooling potential is obtained from a continuous nitrogen gas. It also includes two solenoid valves tied in with a thermocouple and temperature controller allowing easy control of soak temperature. Long stem valves and an appropriate thermometer can be used for manual operation and this save cost very economical. Either way, the system is relatively simple and does not require a large capital outlay to implement. By controlling the flow of liquid nitrogen into the cold box the temperature and cooling rate can be controlled.

b)



b)

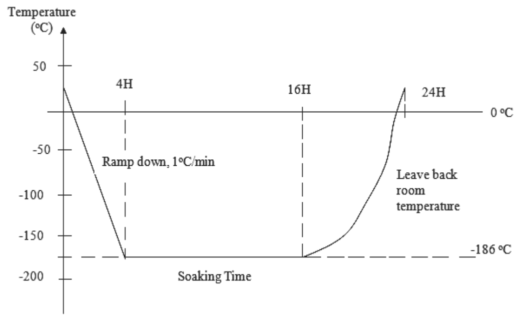


Fig. 1. Line sketch and photo of cryogenic treatment: (a) process diagram, (b) treatment cycle

Table1.
Cutting parameters

Parameters	Range
Cutting speed -m/min	20,30,40 and 50
Feed rate -mm/tooth	0.05, 0.08 & 0.10
Depth of cut -mm	0.50 mm constant

2.2. Equipments for the research

The research work was carried out on a Mazak Nexus 410 A-II C.N.C. vertical milling machine with automatic tool changing systems. The size of the milling cutter was 80 mm diameter and 4 inserts accommodated. The inserts used were PVD inserts treated with cryogenic treatment (referred as CT) and some inserts with out cryogenic treatment referred as (NCT) as per process mentioned section 2.1. The PVD inserts was manufactured by M/s Kennametal as per the specification given in the Table 2. Figure 2 shows specification of the insert. The work material used for this research was Inconel 718 having length of 160 mm, width 50 mm and thick of 46 mm. Tables 3 and 4 gives the chemical composition and mechanical properties. The surface roughness was measured using SJ 400 Mitutoyo make and tool wear measured by Scanning Electron Microscope (SEM). The tool wear was measured as per ISO 3685-1993 standard. It was decided to machine for length of 160 mm. If the uniform tool flank wear occurred and within the level of 0.30 mm as per ISO 3685 of 1993, otherwise it is extended up to 0.6 mm. Figure 3 shows various wear as per ISO 3685 of 1993.

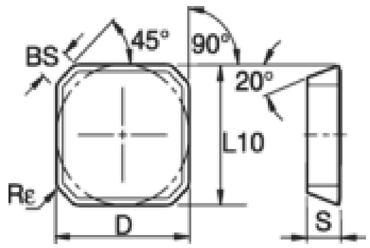


Fig. 2. Specification for PVD inserts

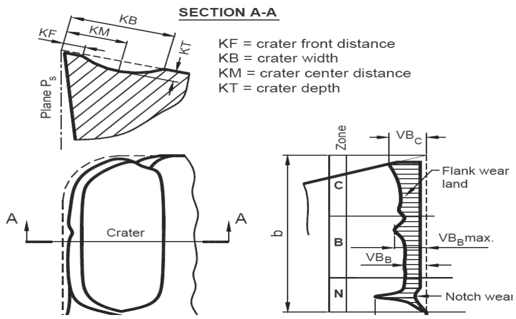


Fig. 3. Various tool wear on a single point tool [10]

Table 2.
PVD insert specification

ISO Cat. No.	D	S	L10	BS	R_E	hm	Hm
SEKN 1203AF SNGN	12.7	3.18	12.7	2.39	1.0	0.20	0.01

Table 3.
Chemical composition

Al	Ti	Cr	Co	Cu	Fe	Mn	Mo
0.2/ 0.80	0.65/ 1.15	17/ 21	1	0.30	17	0.35	2.80/3.3

The chemical properties, other than mentioned in the Table 2, there are traces of Columbium and Niobium of 4.75 to 5.50, Nickel 50 to 55%, phosphorous 0.015%, silicon 0.35%, sulphur 0.015% and carbon 0.085% available in the material.

Table 4.
Mechanical strength [12]

Mechanical properties	Strength
Tensile strength	1375 MPa
Yield strength	1100 MPa
Elongation	18-25%
Density	8.19 gms/cc

2.3. Work material - Inconel 718

Inconel 718 is one of the proven high performance materials which can withstand stringent operating conditions in aerospace, gas turbine and automobile industries. With an increase in their applications, their efficient and rapid fabrication assumes a lot of importance. Shaping super alloys into the desired configuration has always been a challenge. The work material Inconel 718 used, have a length 160 mm, width 50 and thickness of 46 mm.

3. Results and discussion

3.1. Surface roughness

The machined surface characteristics such as surface roughness and surface damage have significant influence on the surface sensitive properties such as fatigue, stress corrosion resistance and creep strength, which in turn affect the service life of components [12].

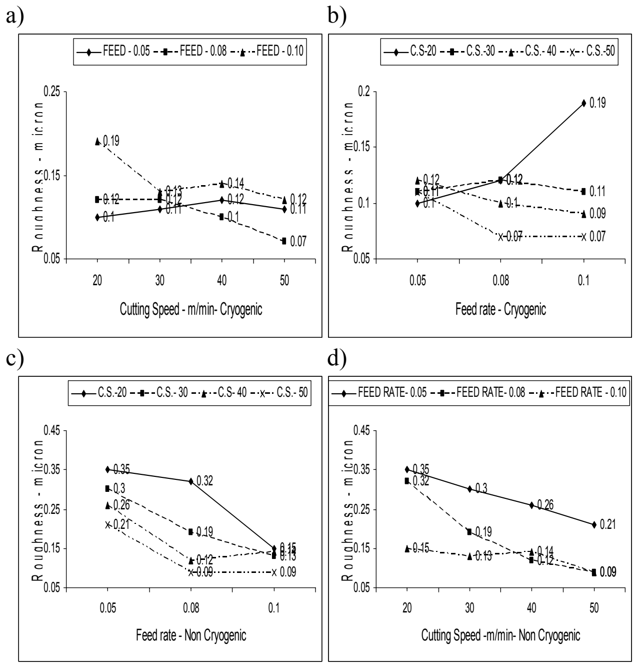


Fig. 4. Graph for roughness by cryogenic tool: a) & b). cutting speed & feed rate respectively, c). & d). non cryogenic & non cryogenic for cutting speed and feed rate respectively

The surface roughness is relatively fine spaced irregularity on the surface of an object. This irregularity is the results of the machining process, including the choice of the tool, feed rate, cutting speed and environmental conditions [13]. The choice of using cryogenic treated inserts produced lower surface roughness at low feed rate and at high cutting speed (Fig. 4). At low cutting speed of 20 m/min at feed rate of 0.05 mm per tooth, the roughness was 0.19 µm and decreased to 0.12 µm when the cutting speed was increased to 50 m/min. At low cutting speed 20 with feed rate of 0.08 mm per tooth, the low trend like 0.05 mm per tooth feed rate exists, as the cutting speed increased to 50 m/min, the roughness was 0.07 µm. However, very narrow difference was obtained between feed rate of 0.10 and 0.08 mm per tooth. While machining by non treated tool inserts, low surface obtained at high cutting speed with low feed rate. The difference was high at low cutting speed with low feed rate and high cutting with low feed rate. The cryogenic treated inserts performed in maintaining low roughness, which means the cutting edge was not disturbed either by wear or by the heat at cutting zone. The surface roughness was low with cryogenic treated inserts in comparison with non-treated inserts for all cutting speeds. This has been more or less true for all the work - tool combinations undertaken as suggested by Dhar et al. [14].

3.2. Flank wear

Flank wear is the most common tool wear occurring in machining process. Flank wear is primarily attributed to rubbing to rubbing of the tool along the mechanical surfaces, causing abrasive diffusive and adhesive wear mechanisms and also high temperature, which affect the tool material properties as well as work piece surface. The life of the cutting tools plays major role in increasing productivity and consequently is an important economic factor. Abrasion, diffusion and adhesion are the three mechanisms in flank wear of advanced tool materials. Cryogenic treatment on cutting inserts for milling process which can be considered as latest work on Inconel 718 using PVD inserts. Few researchers have studied the work by PVD inserts in milling Inconel 718. Flank wear obtained during milling of the Inconel 718 material is shown in the Figure 5 (a) to (d). Figure 5 (a) and (b) shows the graphical representation of flank wear formed by cutting speed and feed rate respectively. As the cutting speed is low at low feed rate, the contact between the tool edge and work material was more and more flank wear occurred beyond the level of 0.60 mm as ISO 3685 of 1993.

The flank wear was not following uniform wear pattern, so maximum of 0.60 mm was taken for consideration. As the cutting speed was increased with feed rate, duration of contact between the work material and tool was shorter, and faster movement of tool occurred. This causes low rate of flank wear at high feed rate. The cryogenic treated inserts followed trend in flank wear to low value than non cryogenic tool inserts. The flank wear by non treated inserts was irregular in flank wear and it shows the cryogenic treated inserts was strong and tough to resist tool wear than non treated inserts. The cutting edges lost their cutting effect due to presence of heat between tool and work material interface. The performance by cryogenic inserts was good at cutting speed of 50 m/min with high feed rate of 0.10 mm per tooth in terms of tool flank wear and consequently on the tool life. The wear on the flank side by deep cryogenic treated inserts at different cutting speeds are lower than non-treated inserts. As reflected in the Fig. 5 (a) and (b), the cryogenic treated inserts show less flank wear than non-treated inserts and hence better wear resistance during machining. More or less same trend has been observed at all cutting speeds.

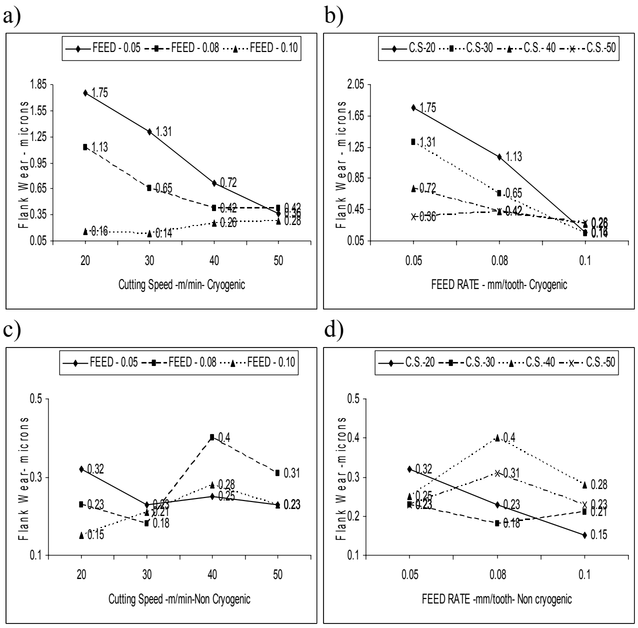
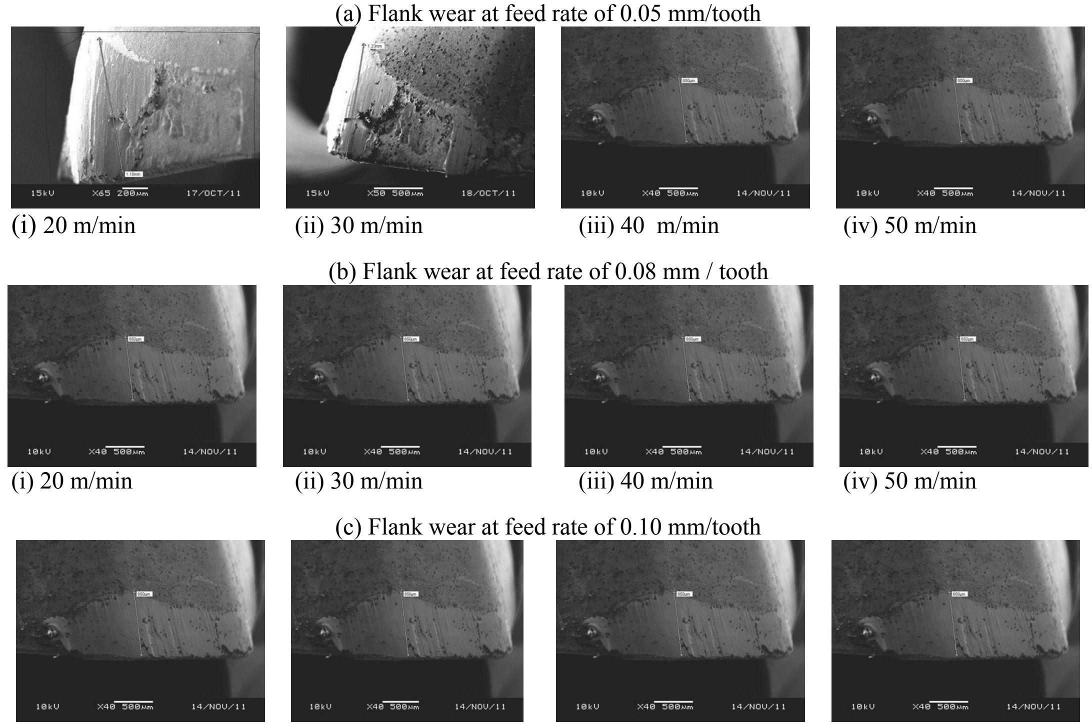


Fig. 5. Graph for flank wear: a) & c) cryogenic, b) & d) non-cryogenic

The inserts used are PVD coated and coatings on tool tip wear out rapidly during milling process in non treated inserts. Finally, a rapid wear rate noticed on the flank side due to fast wear of the coating there by increasing wear. However, as long as the coating exists, tool flank wear was low by cryogenic treated inserts. Figure 6 (a) to (c) shows the various flank wear occurred at various feed rates for cryogenic treated inserts. Figure 7 (a) to (c) shows the SEM view showing flank wear at various cutting speeds and feed rates for non-cryogenic inserts. Some of the edges were chipped off during machining and has not affected the machining performance.

3.3. Crater wear

Crater wear is a dished out section which develops on the rake face of the tool. This is due to high contact stress and high interface temperature. In fact, at low cutting speed, the crater wear is usually insignificant compared with flank wear in normal operations. The crater can be expressed by measuring the depth which is generally maximum at certain distance from the cutting edge.Crater wear is formed by the flow of chips on the rake face of the tool. There is no standard available for maximum size of the crater wear like specification for flank wear. Formation crater wear occur from the cutting edge. The crater wear would lead to fracture of the cutting edges (Fig. 8).



(a) Flank wear at feed rate of 0.05 mm/tooth

(i) 20 m/min (ii) 30 m/min (iii) 40 m/min (iv) 50 m/min

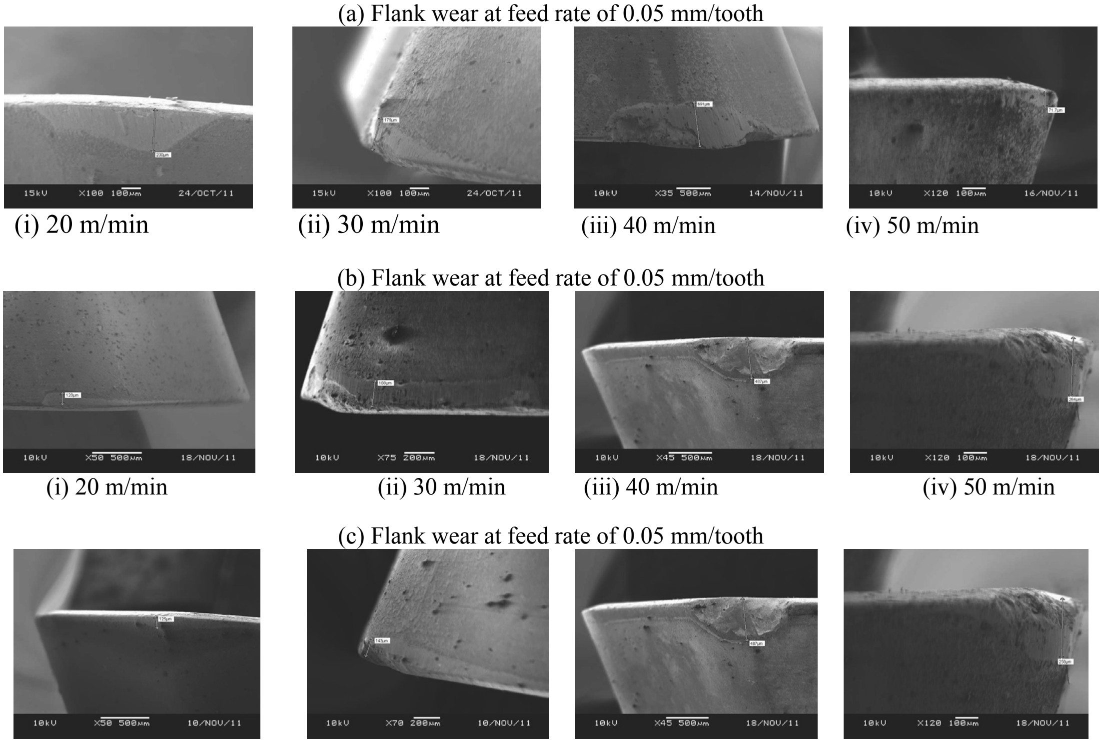
(b) Flank wear at feed rate of 0.08 mm / tooth

(i) 20 m/min (ii) 30 m/min (iii) 40 m/min (iv) 50 m/min

(c) Flank wear at feed rate of 0.10 mm/tooth

(i) 20 m/min (ii) 30 m/min (iii) 40 m/min (iv) 50 m/min

Fig. 6. SEM view flank wear on cryogenic treated inserts at various cutting speeds and feed rates



(a) Flank wear at feed rate of 0.05 mm/tooth

(i) 20 m/min (ii) 30 m/min (iii) 40 m/min (iv) 50 m/min

(b) Flank wear at feed rate of 0.05 mm/tooth

(i) 20 m/min (ii) 30 m/min (iii) 40 m/min (iv) 50 m/min

(c) Flank wear at feed rate of 0.05 mm/tooth

(i) 20 m/min (ii) 30 m/min (iii) 40 m/min (iv) 50 m/min

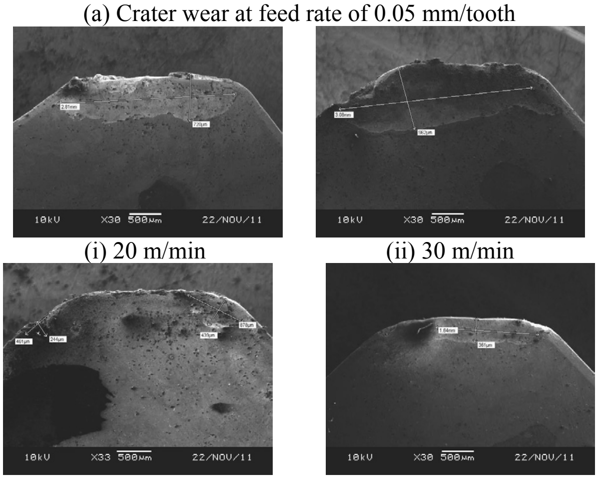
Fig. 7. SEM view flank wear on non-cryogenic treated inserts at various cutting speed and feed rates

The ISO 3685 recommends the criterion of tool life due to crater wear as given by the Equation 1 [9]:

$$K_T = 0.06 + 0.3\ f, \qquad (1)$$

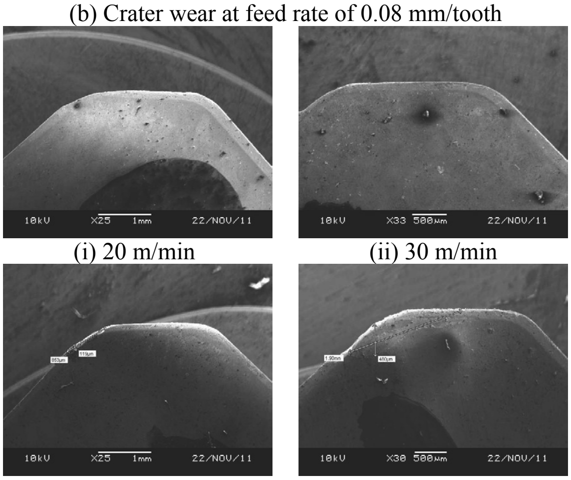
where f is the feed rate and K_T is the depth of crater wear. The threotical value obatined on feed rate is for reference and it may be difficult to follow in practical situation.

(a) Crater wear at feed rate of 0.05 mm/tooth



(i) 20 m/min (ii) 30 m/min (iii) 40 m/min (iv) 50 m/min

(b) Crater wear at feed rate of 0.08 mm/tooth



(i) 20 m/min (ii) 30 m/min (iii) 40 m/min (iv) 50 m/min

Fig. 8. SEM view on crater wear at various cutting speeds

Table 5.
Theoretical crater wear

Feed rate - mm/tooth	$K_T = 0.06 + 0.3\ f$
0.05	0.075 mm
0.08	0.084 mm
0.10	0.09 mm

Table 5 shows the theoretical value of crater wear; however, actual wear could not be measured due to certain constraints. The depth of crater is minimal which cannot be measured. It is more likely that it will be more or less than the theoretical value. The pattern of crater wear by cryogenic and non cryogenic inserts was same. The chips produced by machining Inconel 718 were saw tooth chips. Due to own weight of the chips, the chips fell down more quickly without wearing the rake face of the tool. Flank wear formation were less in cryogenic treated inserts and correspondingly the crater wear also were less than cryogenic treated inserts.

4. Conclusions

The results obtained by the research using cryogenic and non-cryogenic PVD tool inserts are drawn as below:

1. The cryogenic treated PVD inserts produced low surface roughness at high cutting speed at low feed rate. This is the results for all the cutting speeds with low feed rates which produced low surface roughness. The optimum cutting speed for PVD coated insert were between 40 to 50 m/min with low feed rate of 0.05 mm per tooth. The non treated PVD inserts performed in terms of surface roughness was little more than the treated inserts.
2. The cryogenic tool inserts formed low flank wear at high cutting speed with high feed rate than non treated inserts. Long tool life is possible with cryogenic treated PVD inserts in machining Inconel 718.
3. The crater wear formation begins from the cutting edge. The flank wear on cryogenic treated inserts was low and the crater wear is also low. The chips fell down by its own weight and crater at the rake face was also low. In practical applications, crater wear was low than theoretical values.
4. The chips produced were saw tooth and did not affect the crater.

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