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Performance of cryogenically treated CBN inserts on difficult to cut materials during turning

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ABSTRACT

Machining of materials is recognized as removing unwanted materials by using different cutting inserts. In this research, cutting inserts used are CBN inserts and treated cryogenically at -196°C in liquid nitrogen chamber. The inserts are subjected to 30 hours of treatment in controlled atmosphere. The materials used are Titanium and AISI 440 C hard Martensitic Stainless steel. The cutting parameters are cutting velocity 30, 40 and 50 m/min with feed rate of 0.05, 0.10 and 0.15 mm/rev and depth of cut of 0.05, 0.75 and 1.00 mm. The performance evaluated was tool wear, surface roughness. Cryogenically treated CBN inserts produced less tool wear on titanium than AISI 440 C Martensitic stainless steel. The roughness produced was low at high cutting speed with low feed rate. Flank wear was not progressive and varied. In turning AISI 440 C stainless steel, built up edge formed in all cutting speed which is a common phenomena and lead to crater wear formation. The chips produced were saw tooth chips by both materials.
Keywords: Cryogenic treatment; Crater wear; Flank wear; Surface Roughness

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1. Introduction

Machining of materials is recognized as removing unwanted materials by using different inserts with variable cutting parameters. Cryogenic process is treating the work materials and cutting inserts at -196°C. CBN and PCBN cutting tools are used to machine difficult to cut materials like high strength alloy steels, stainless steel, Inconel 718, Titanium etc. Figure 1 shows generally accepted cutting speeds in high speed machining of various materials. High speed turning is recognized as a main manufacturing technology for higher productivity and throughput [1]. Barron [2] 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 increased significantly, by subjecting them to cryogenic treatment. Seah et al. [3] studied and found that cryogenic treated tools improved wear resistance and overall tool lives of tungsten carbide tool inserts. Yong et al. [4] compared the performance of cryogenically treated and untreated tungsten inserts during high speed milling of medium carbon steel. The cryogenically treated inserts exhibit better tool wear resistance than untreated ones.

2. Experimental works and materials

2.1. Principle of deep cryogenic treatment

In this research, CBN inserts were cryogenically treated and the process is explained below. Cryogenic expresses study and use of materials at very low temperature, below -196ºC. Liquid Nitrogen (LN) is the most commonly used element in cryogenics. Nitrogen melts at -201.01ºC and boils at -198.79ºC, it is the most abundant gas, composing about four fifths (78.03%) by volume of the atmosphere. It is colourless, odourless, tasteless and non-toxic gas. 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 ambient temperature. The complete cryogenic cycle would take up to 25-30 hours. 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. 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. In this process, no dimensional change and thermal crack occur. Strict computer control and precise processing profiles assure that optimum results are achieved with no dimensional change or thermal shock. The system is relatively simple and does not require large capital outlay.

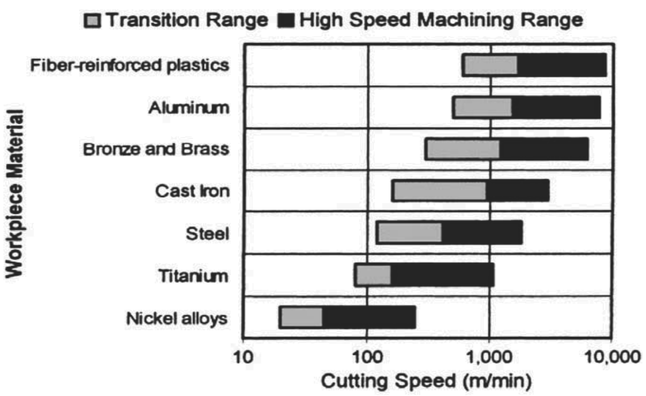

Fig. 1. High-speed cutting ranges in machining of various materials [1]

2.2. Titanium alloy

Titanium (Ti-6Al-4V) alloy is an attractive material in many industries due to its unique and excellent combination of strength to weight ratio and their resistance to corrosion. However, because of its low thermal conductivity and high chemical reactivity, Ti-6Al-4V alloy is generally classified as a difficult to cut material that can be characterized by low productivity and rapid tool wear rate even at conventional cutting speeds. Table 1 shows the chemical properties of Titanium alloy and AISI 440 C Martensitic stainless steel respectively and the chemical and mechanical properties details were given along with test certificates by the supplier.

Table 1.
Chemical properties

Alloying elements	Titanium alloy	AISI 440 C
Carbon	0.030-0.031	0.95-1.20
Manganese	< 0.01	1.00
Chromium,	-	16-18
Molybdenum	< 0.01	0.75
Titanium alloy	Balance	-
Aluminum	6.51-6.57	-
Vanadium	4-4.07	-
Fe	0.17-0.21	-
Silicon	< 0.01	-
Copper	0.01	-
Molybdenum	0.01	-

2.3. AISI 440 C martensitic stainless steel

AISI 410, 420 and 440 A, B, C is all considered as Martensitic stainless steel and can be hardened like other alloy steels. In this research, AISI 440 C stainless was used under hard condition. AISI 440 C is widely used in aerospace industries for bearings, steam and water valves, pumps, turbines, compressor components, shafting, cutlery, surgical tools, plastic moulds and nuclear applications which demand high strength and high resistance to wear and corrosion [5]. It has high viscosity, poor thermal conductivity, low corrosion, high work hardening rate and tendency to form built up edge (BUE) at tool edge. AISI 440 C has high chromium and high carbon content and possesses high mechanical strength in this group [6]. Table 2 shows mechanical properties of Titanium and AISI 440 C stainless steel.

Table 2.
Mechanical properties

Grades	Tensile strength	Yield strength	% elongation
AISI 440 C	1965 (MPa)	1900 (MPa)	2
Titanium alloy	147.8 (KSI)	138.5 (KSI)	19.2

2.4. Equipments used

The turning experiments were conducted using NC Harrison 400 Alpha Lathe with 7.5 KW capacity. Three cutting parameters were used as shown in Table 3. The CBN cutting tool is manufactured by Mitsubishi. The tool holder used was by MTJNR 2020 KL16N by Mitsubishi. The rake angle is – 6°, side rake -6° and end clearance angle of 27° with nose radius of 0.80 mm for both tools. AISI 440 C work materials was heat treated by induction hardening process and hardness between 45 to 55 HRC was maintained. The used CBN inserts were treated by cryogenic process as mentioned in section 2.1. All the tests were performed under continuous dry turning.

Table 3.
Operating parameters

Cutting speeds - m min^{-1}	Feed rate-mm rev^{-1}	Depth of cut - mm D.O.C
30	0.05	0.50, 0.75 & 1.00
40	0.10	0.50, 0.75 & 1.00
50	0.15	0.50, 0.75 & 1.00

The experiments were conducted for 100 mm length of turning and each time surface roughness, flank wear and crater wear were measured. The surface roughness was measured by Mitutoyo 410 surface face roughness tester and wear of the tool by Scanning Electron Microscope (SEM). It was decided to turn the work material up to 500 mm length or if the flank wear reached the value of 0.30 mm as per ISO 3685 of 1993 which ever is earlier and the experiment stopped.

3. Results and discussion

3.1. Surface roughness

Dhar et al. [7] reported that the surface roughness was low with cryogenic treated inserts in comparison with non-treated inserts at all cutting speeds. This has been more or less true for all the work - tool combinations undertaken as suggested. Wuyi Chen [8] stated that the surface roughness would be low when the hardness of the material was increased. Lateral plastic flow of the work material in front of the cutting edge increased roughness of the machined surfaces. The harder the material, less plastic flow, the work piece material produced good surface roughness while machining hardened material having hardness 45 to 55 HRC. A better surface roughness can be produced by using the tool with certain degree of tool wear, which has increased the tool nose radius. Two possible reasons are: (i) work material presents less plastic behavior at higher deformation velocity and (ii) the flank wear scar becomes smoother at higher cutting speed. Thakur et al. [9] turned Inconel 718 material by tungsten carbide tool and reported that the roughness value decreased at high cutting speed but increased as the feed rate increased. This was due to increased friction between work material and tool interface which eventually increases the temperature in the cutting zone.

The shear strength of the material reduces and the material behaves like a ductile material and material was sticky in nature which makes the detachment of the chips from the work material difficult, thereby increasing the surface roughness. Manu Dogra et al. [10] found that during the turning of hardened AISI 4340 steel using CBN-TiN coated carbide and PCBN tools, result revealed that tool life of CBN-TiN coated carbide inserts was approximately 18-20 min per cutting edge, whereas PCBN tools produced a tool life of 32 min.

In turning with increased depth of cut the surface roughness was low than 0.50 and 0.75 mm depth of cut on both materials. This is shown in Figure 3 (a) & (d). At cutting speed of 40 m/min with feed rate of 0.10 mm/rev this is the trend. Even though there are variations at different length of turning, titanium produced low surface roughness at 1.00 mm depth of cut at all parameters. This is shown in Figure 3 (b) and (e). At cutting speed of 50 m/min at feed rate of 0.15 mm /rev. the depth of cut 1 mm produced low surface roughness than 0.50 and 0.75 mm depth of cut. Figure 3 (c) and (f) show the variation between the various depth of cut. Titanium seem to have high plastic behavior deformation than stainless steel and always produced low surface roughness for all parameters at higher depth of cut.

3.2. Flank wear

Maximum flank wear values of the inserts were measured at fixed length of turning i.e. 100 mm. Flank wear is primarily attributed to rubbing of the tool along the machined surfaces, causing abrasive diffusive and adhesive wear mechanisms and also high temperature, which affect the tool material properties as well as work piece surface. Figure 2 shows the various tool wear that is likely to occur as per ISO 3685 of 1993.

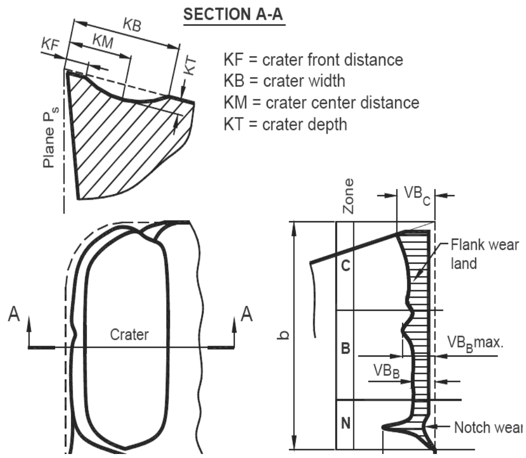

Fig. 2. Various tool wear on a single point tool [4]

Figure 4 (a) to (f) shows the graphical representation of flank wear obtained at various cutting parameters and Figure 5 SEM image of flank wear for the same parameters at final stage. Even though the inserts were strengthened by cryogenic process to resist wear, the temperature at tool tip - work piece interface, the special property induced in the inserts were destroyed by the temperature. Figures 5 and 6 shows the flank wear formed while turning Titanium alloy and AISI 440 C stainless steel respectively. SEM image was taken at the end of 500 length of turning and shown in the Figures 5 and 6 for both materials. Even after turning for 500 mm length, the flank wear formation was minimal and no built up edges (BUE) formed in turning Titanium alloy where as AISI 440 C stainless steel produced high rate of flank wear and formation of built up edges. Built up edges were formed in all parameters. And also in all feed rates. This was due to more rubbing contact between cutting edge and work surface. At high feed rate, more stock of material removed with less time due to high feed rate which causes the material to stick on the tool edge. BUE was also responsible for making the surface rougher at high cutting speed. Notch wear occurred at cutting speed of 50 m/min with feed rate of 0.15 mm/rev and depth of cut 1.00 mm.

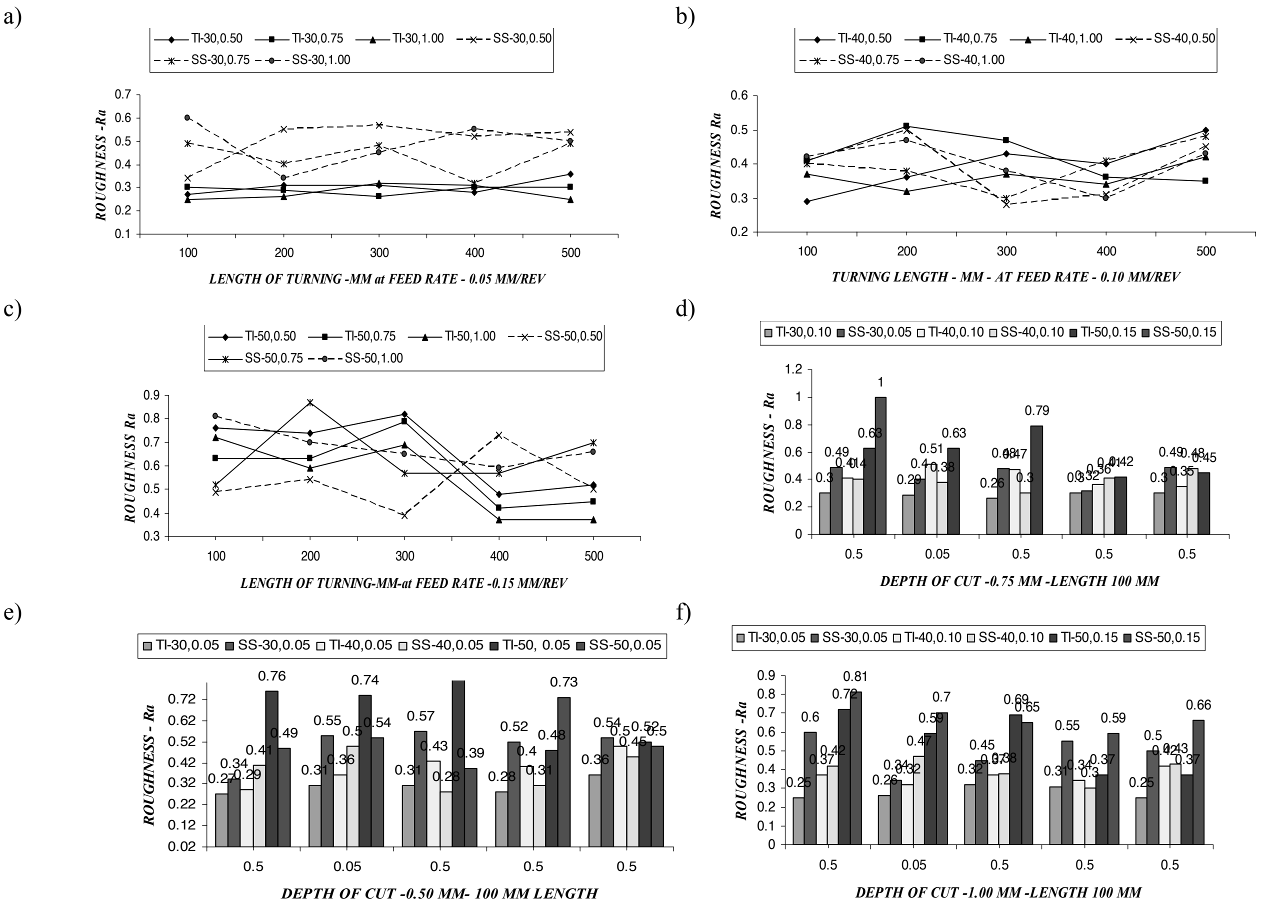

Fig. 3. Graphs showing length of turning Vs surface roughness: a) 30 m/min cutting and feed rate of -0.50, b) 40 m/min cutting speed with 0.10 feed rate, c). 50 m/min cutting speed with 0.15 feed rate, d) DOC of 0.50 mm, e) DOC of 0.75 mm, f) DOC of 1.00

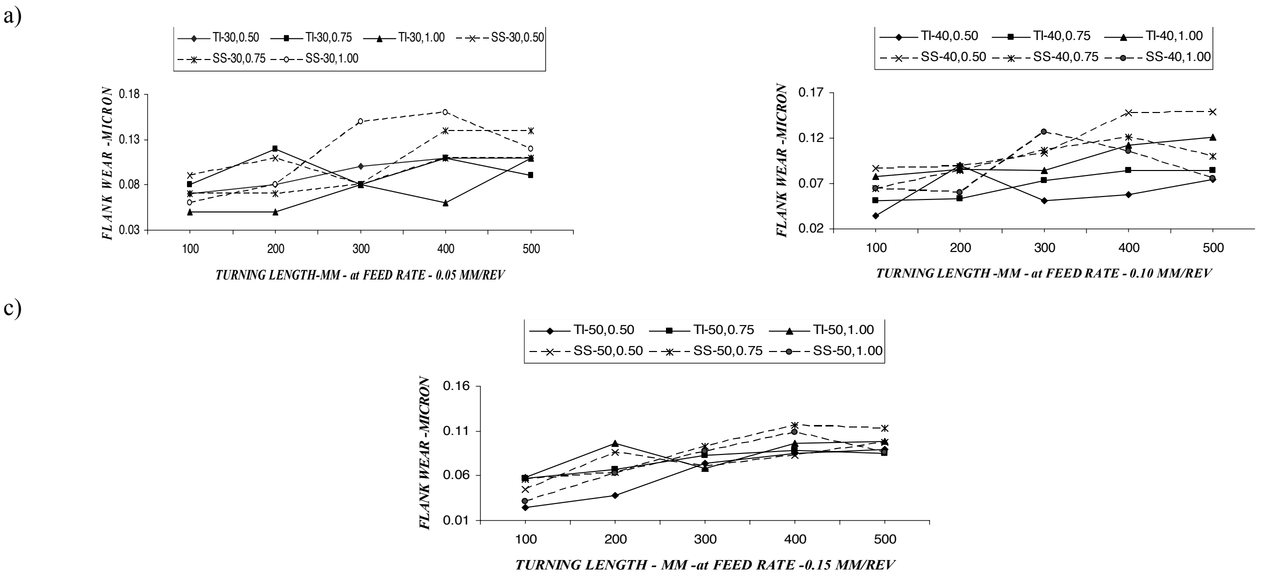

Fig. 4. Graph showing length of turning Vs flank wear: a) 30 m/min cutting and feed rate of -0.50, b) 40 m/min cutting speed with 0.10 feed rate, c) 50 m/min cutting speed with 0.15 feed rate

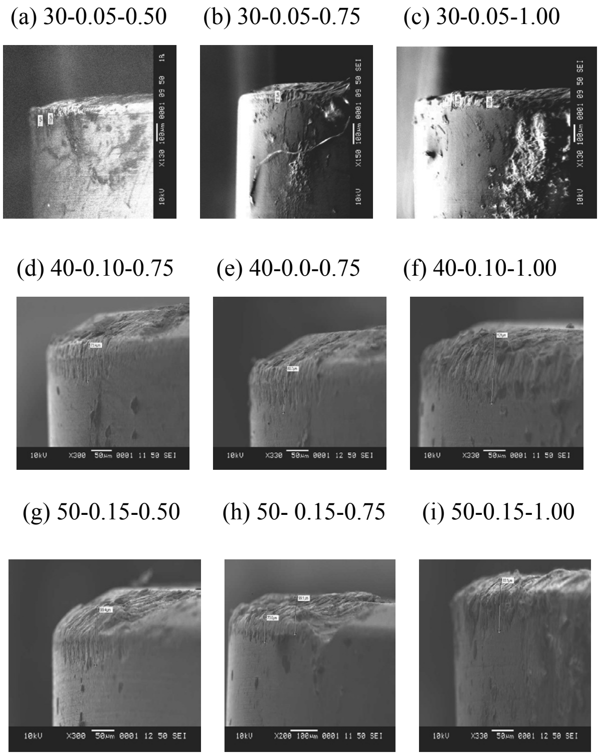

Fig. 5. SEM view on flank wear on Titanium alloy

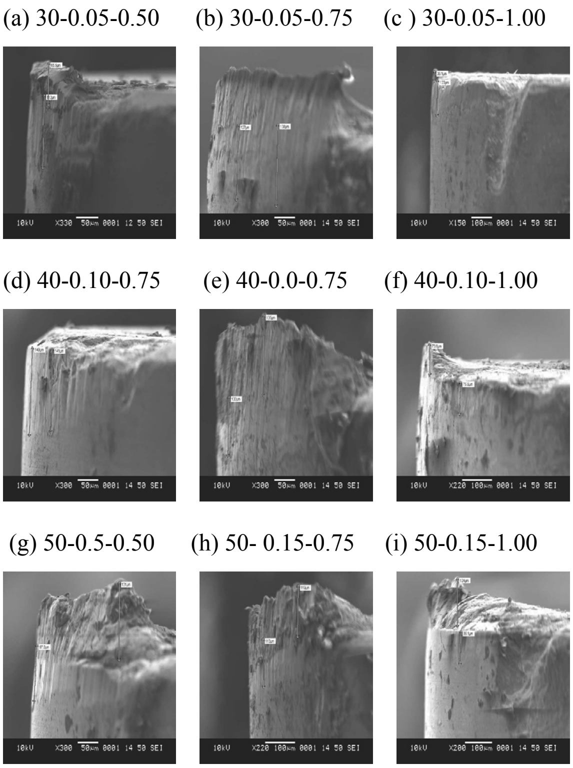

Fig. 6. SEM view on flank wear on AISI 440 C alloy steel

3.3. Crater wear

Crater wear is formed at rake face of the tool. Figure 2 shows the various crater wear formation which is represented by K_T. The ISO 3685 of 1993 recommends the criterion of tool life due to crater wear and can be calculated by using the formula as given below.

$$K_T = (0.06) + 0.3f \quad (1)$$

where f is the feed rate and K_T is the depth of crater.

Crater wear is dished out section which develops on the rake face of the tool. The formation of crater wear occur little away from the cutting edges. This was due to high contact stress and high interface temperature. In fact at low cutting speed, crater wear is usually insignificant compared with flank wear in normal operations. There is no standard available for maximum depth of the crater specification like flank wear. Deeper crater will lead to failure of the cutting edge. Crater wear formation was more in using HSS, carbide inserts and other low strength cutting inserts.

When machining using CBN, PCBN and other high strength inserts the formation of wear take longer time. At high cutting speeds crater wear formation would be more severe and depth of crater will be deeper. While turning difficult to cut materials the formation of crater wear was more due to saw tooth chips. In turning Titanium alloy the formation of crater wear was low than stainless steel. The stainless steel contains hard carbides which was responsible for deep crater wear. Figure 7 shows SEM view on crater wear while turning Titanium and AISI 440 C stainless steel.

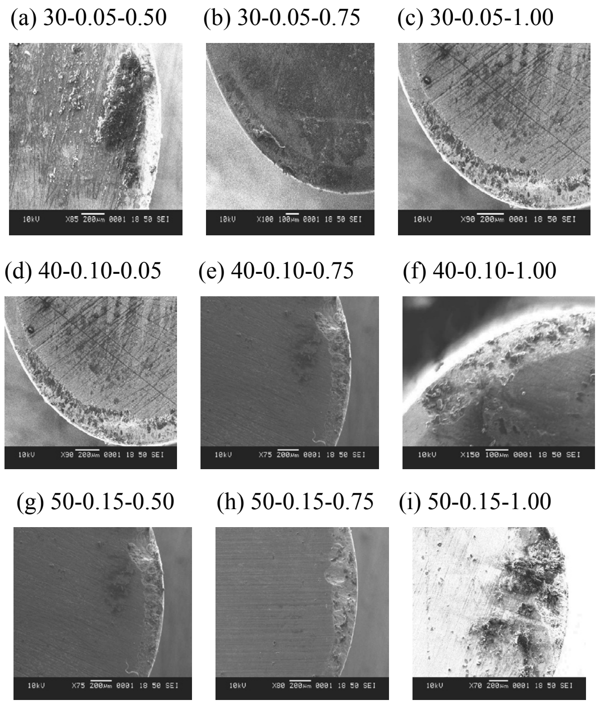

Fig. 7. SEM view on crater wear on Titanium alloy

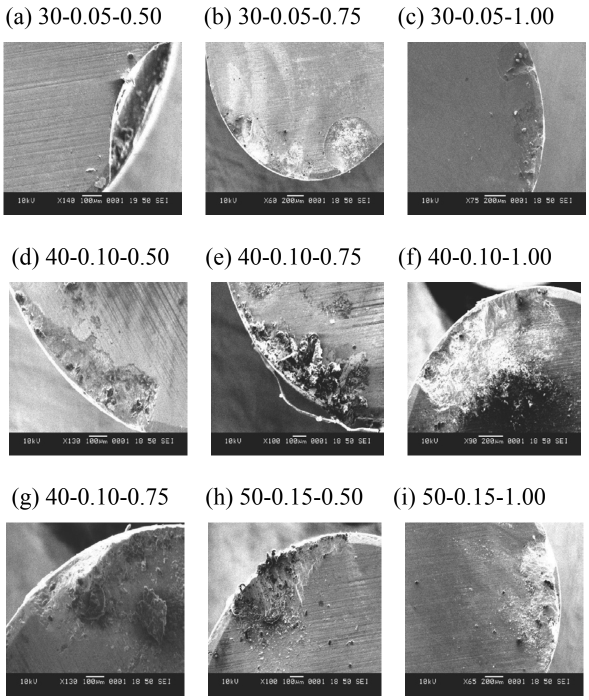

Fig. 8. SEM view on crater wear on AISI 440 C Martensitic stainless steel

Figures 7 and 8 show the crater wear observed in SEM image by Titanium and AISI 440 C stainless steel respectively. At low cutting speed with low depth of cut, the crater wear was low by Titanium alloy than stainless steel. At low D.O.C of 1 mm, crater wear was more. In turning, AISI 440 C crater wear was low at low D.O.C and increased at 1mm depth of cut. Comparing both materials the crater wear created by Titanium alloy was less than AISI 440 C stainless steel corresponding to same parameters.

4. Conclusions

The following conclusions were arrived in this research:

1. The surface roughness produced at high cutting speed was low with low feed rate. At high cutting speed with low feed rate and depth of cut 1 mm both Titanium and AISI 440 C stainless steel produced low surface roughness.
2. Formation of flank wear in turning Titanium alloy was low than AISI 440 C stainless steel. As the length of turning was increased, naturally there were more rubbing between insert and surface and thus more wear occurred. More ridges formed due to abrasion.
3. High flank wear formation was due to hard carbide present in the material.
4. More crater wear formation found during turning of AISI 440 C stainless steel than Titanium turning. One important reason was the chips produced were saw tooth shape in turning stainless steel than Titanium alloy and more abrasion occurred on the rake side of the tool.

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