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An Experimental Investigation into the High Speed Turning of Ti-6Al-4V Titanium Alloy

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ABSTRACT

Titanium and its alloys have seen increased utilization in military and aerospace applications due to the combination of high specific strength, toughness, corrosion resistance, elevated-temperature performance and compatibility with polymer composite materials. Titanium alloys are difficult to machine due to their inherent low thermal conductivity and high chemical reactivity with other materials at elevated temperatures. In general, machining difficulties attributed to elevated temperatures are encountered at production speeds in the range of 60 m/min. High-speed machining of these alloys has created considerable interest to researchers, tool manufacturers and end users. This paper provides recent results obtained during turning operations with the aim of improving machinability of titanium alloys. Several tests have been conducted using (i) micro-edge prep geometry of the inserts, (ii) ultra-hard PVD coated, and (iii) nano-layered coated inserts and the effects of speeds and feeds during turning of Ti-6Al-4V titanium alloy are discussed. The initial tests have been conducted under orthogonal (2-D) cutting conditions with no coolant application. Based on these results, several oblique cutting (3-D) tests have been designed and conducted to study the effect of various types of ultra-hard and nano-layered coatings at higher cutting speeds under flooded coolant conditions. The effects of speed and feed on cutting force and tool wear are presented in this paper.

INTRODUCTION

Titanium in Ti-6Al-4V is the most widely used Ti-alloy grade in the aerospace and military industries, and it has been the subject of much experimentation and modeling due to its unique properties. Titanium and its alloys are considered difficult to machine materials. First, titanium is a poor conductor of heat, causing higher temperatures at the chip-tool-work contact area. Secondly, titanium's high chemical affinity with cutting tool materials/coatings accelerates tool wear and tool failure. Finally, titanium alloys are difficult to machine due to low modulus of elasticity, fatigue properties and work hardening characteristics.

A literature search reveals that extensive analytical and experimental studies have been conducted during machining of titanium alloys [1-11]. At present, the cutting speeds used to machine titanium alloys are low due to excessive heat at tool-workpiece-chip contact zone and accelerated tool wear at higher cutting speeds. Temperature-related machining difficulties are encountered at production speeds in the range of 60 m/min, and many wear mechanisms join together to accelerate cutting tool failure. In the past, it has been suggested that the best way to improve machinability is through the application of flooded coolant in copious amounts. However, as cutting speeds increase and maximum temperatures rise, flooded coolant application provides little cooling in the contact region of the cutter [1, 2]. With recent developments in tool-coating technology and application of such tools, cutting speeds ~120 m/min are considered high-speed range for machining titanium alloys.

In this paper, the experimental results conducted at higher cutting speeds (120 and 240 m/min) under orthogonal (2-D) turning conditions will be presented. These tests were conducted under dry cutting conditions with the goal of developing a finite element model (FEM) for machining titanium alloys. The details of FEM analysis have been recently published [17]. Several oblique (3-D) cutting tests have also been conducted at higher cutting speeds to study the performance of various types of ultra-hard and nano-layered coatings of cutting inserts under flooded coolant conditions. The effect of speeds and feeds on cutting force and tool wear are presented. The main objective of this paper is to investigate the upper limits on cutting speeds and feeds that can be used during high speed turning of Ti-6Al-4V titanium alloy with the new trends in ultrahard and nano-coating technologies.

TURNING TESTS

All the orthogonal and oblique turning tests have been conducted using a Hardinge Cobra CNC Turning Center. A 30-

horsepower DC motor drives the turning center spindle, and maximum spindle speed of 4500 rpm can be achieved on this machine. This machine is interfaced with the PC and a three-dimensional (3-D) Kistler Dynamometer for on-line force data acquisition (Figure 1).

FIGURE 1. EXPERIMENTAL SETUP

First, the orthogonal turning tests under dry cutting conditions were conducted using commercially available uncoated and coated carbide inserts with 0° and 5° rake angles. A Ti-6Al-4V titanium alloy tube with a constant thickness of 3.175 mm was used for the tests. The tool was directly fed into the workpiece rotating at the selected cutting speeds. A schematic diagram of orthogonal cutting is shown below in Figure 2.

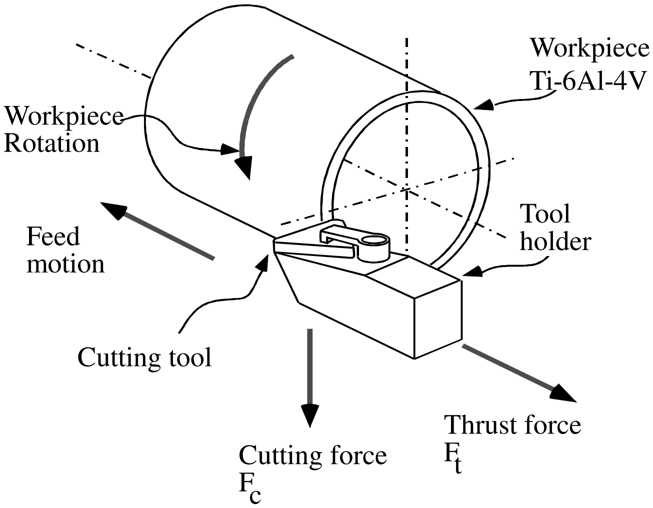


FIGURE 2. SCHEMATIC OF ORTHOGONAL CUTTING

The test conditions used during the orthogonal cutting are given in Table 1.

TABLE 1. MACHINING PARAMETERS FOR ORTHOGONAL TURNING TEST

Work Material	Ti-6Al-4V titanium alloy tube having 50.8 mm dia. and 3.175 mm wall thickness
Tool Holder	Type CTGPL 164
Cutting Tool	• Uncoated Carbide (TPG 432; Grade – K313) • Coated Carbide (TPG 432; Grade – KC5010)
Rake Angles	0° and 5°
Cutting Speeds	120 and 240 m/min
Feed Rates	0.025, 0.050, 0.075, 0.100 and 0.125 mm/rev
Cut Length/Test	5.00 mm
Cutting Fluid	No coolant (Dry)

The average total cutting forces at two selected cutting speeds of 120 and 240 m/min and five selected feed rates using uncoated and coated inserts with 0° rake angle are shown in Figures 3 and 4. The cutting forces increased with increases in feed rate for both uncoated and coated inserts. Also, the forces increased with increases in cutting speed. The coated inserts, in general, seem to generate higher cutting forces. The cutting forces with coated inserts were slightly lower at the feed rate of 0.025 mm/rev at 120 m/min and also at the feed rates of 0.025, 0.050 and 0.075 mm/rev at 240 m/min.

Similar observations can be made with the results at turning with inserts having 5° rake angles (Figures 5 and 6). The cutting forces increased with increases in feed rates as well as the cutting speeds for both uncoated and coated inserts. The coated inserts at the lower speed of 120 m/min, in general, generated higher cutting forces except slightly lower at the feed rate of 0.025 mm/rev. The coatings provided lower cutting forces at higher feed rates at 240 m/min cutting speed.

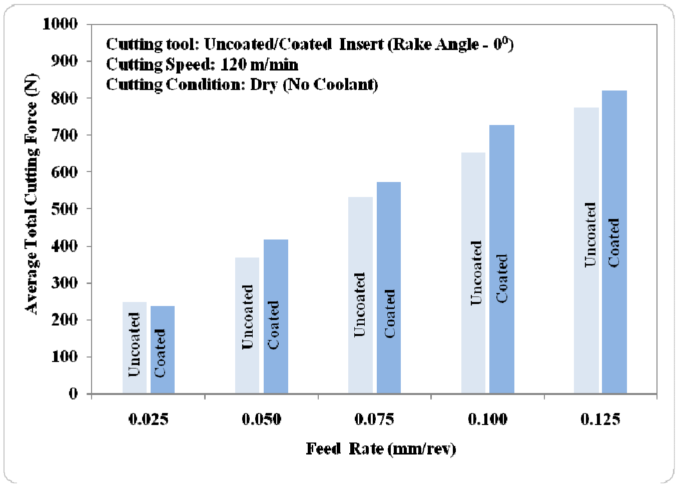


FIGURE 3. FEED RATE V/S AVERAGE TOTAL CUTTING FORCE (CUTTING SPEED - 120 M/MIN)

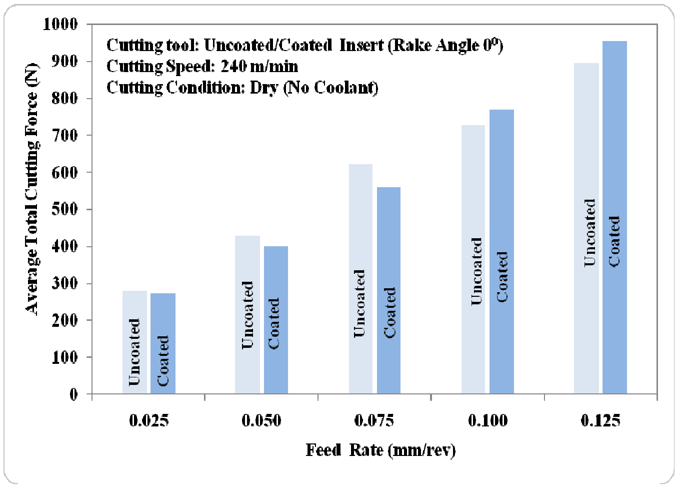


FIGURE 4. FEED RATE V/S AVERAGE TOTAL CUTTING FORCE (CUTTING SPEED - 240 M/MIN)

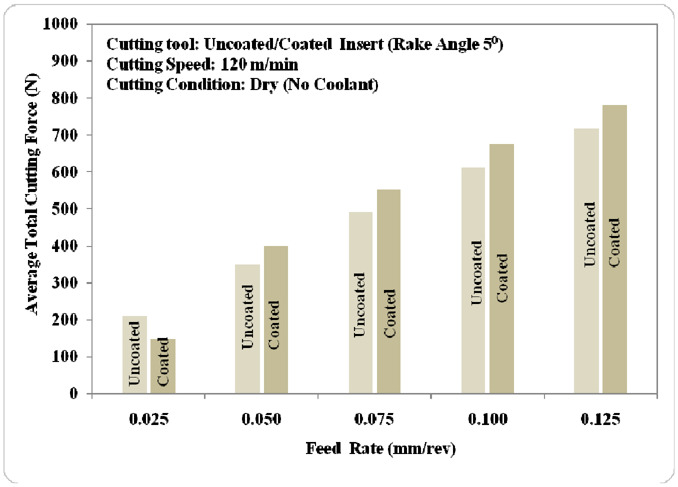


FIGURE 5. FEED RATE V/S AVERAGE TOTAL CUTTING FORCE (CUTTING SPEED - 120 M/MIN)

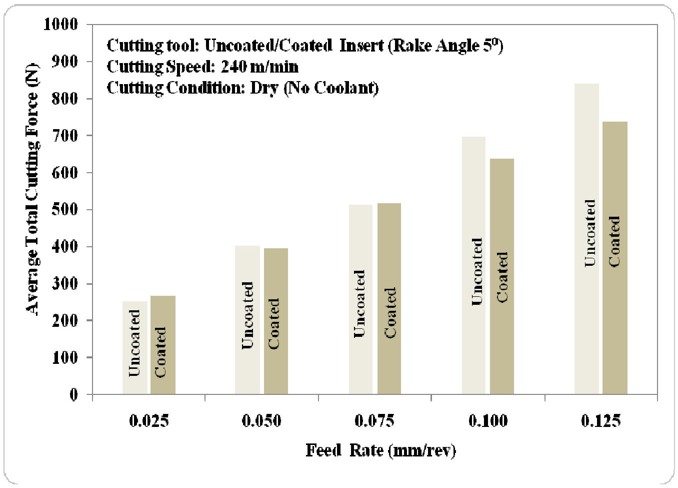


FIGURE 6. FEED RATE V/S AVERAGE TOTAL CUTTING FORCE (CUTTING SPEED - 240 M/MIN)

The test results at 120 m/min and 240 m/min cutting speeds are given in Tables 2 and 3 showing the difference between cutting forces when inserts with 0° and 5° rake angles are used. The cutting forces decreased with increases in rake angle from 0^0 and 5^0.

TABLE 2. AVERAGE CUTTING FORCE AT 120 M/MIN CUTTING SPEED

Feed-Rate (mm/rev)	Average Cutting Force (N)			
	Rake Angle 0°		Rake Angle 5°	
	Uncoated	Coated	Uncoated	Coated
0.025	248.37	236.98	209.37	147.28
0.050	367.76	416.62	348.92	399.33
0.075	532.57	573.09	492.00	552.45
0.100	651.61	726.77	610.18	675.21
0.125	772.76	820.47	717.00	779.48

TABLE 3. AVERAGE CUTTING FORCE AT 240 M/MIN CUTTING SPEED

Feed-Rate (mm/rev)	Average Cutting Force (N)			
	Rake Angle 0°		Rake Angle 5°	
	Uncoated	Coated	Uncoated	Coated
0.025	279.54	271.92	250.73	267.03
0.050	427.73	401.26	401.94	395.15
0.075	621.70	558.87	512.91	517.14
0.100	727.15	768.29	695.29	636.41
0.125	895.00	953.52	839.91	737.4

These orthogonal turning tests have been conducted under dry cutting conditions, thus providing the safe range of high speed turning parameters that could be used in follow-on oblique cutting (outer diameter) with coolant application experimentation. Several newly designed and developed micro-edge prep, ultra-hard and nano-layered coated inserts have been used for these tests. A typical micro-edge preparation is shown in Figure 7.

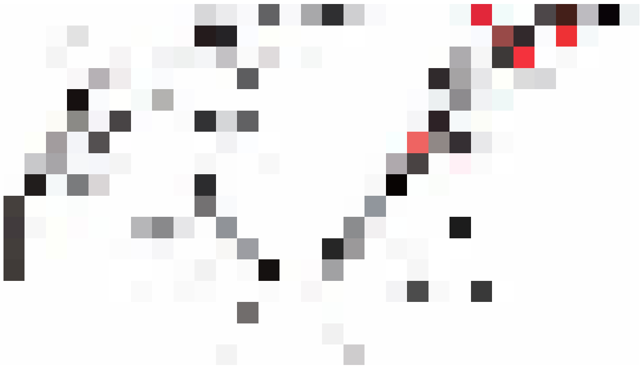


FIGURE 7. MICRO-EDGE-PREP DESIGN

The micro-edge preparation along the corner radius of the insert strengthens tool cutting edge and has shown potential to reduce the heat built up at the cutting edge enabling machining of steel alloys at higher cutting speeds and feeds with less tool wear [18]. The nano-layered and ultra-hard coatings have been specially designed and developed for the study of high-speed turning of titanium (Ti-6Al-4V) alloy. A typical nano-layer coating on an insert is shown in Figure 8. It shows that 10 layers of coatings is 42 nanometer thick, which means each layer is about 4.2 nanometers. The total thickness of the coatings is approximately 3µm.

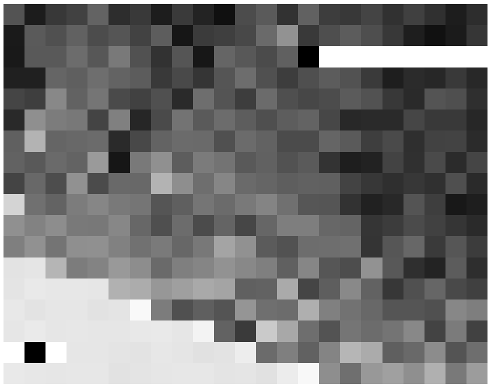


FIGURE 8. HIGH MAGNIFICATION XTEM BRIGHT FIELD IMAGE OF C2-SL SUPER-LATTICE COATING

The following test conditions have been used for oblique cutting tests (Table 4):

TABLE 4. MACHINING PARAMETERS FOR OBLIQUE TURNING TEST

Work Material	Ti-6Al-4V titanium alloy solid bar having 50.8 mm dia.
Tool Holder	Type CTGPL 164
Cutting Tool	• Uncoated (TPG 432; Grade – K313) • Micro-edge Prep. (TPG 432; Grade – K313) - variable hone edge with r_{AA} =0.0375 mm, r_{BC}= 0.0175 mm (Fig. 7)
Coatings	• Coated (TPG 432; Grade – KC5010) • C8: TiAlSiCN nano-layered, • C15: CrAlSiN-CrAlSiYN nano-layered, • C2-SL: TiAlN-CrN nano-layered , • #2390: CrAlN ultrahard coating, • #2391: TiAlN multilayered ultrahard coating • #2393: HfB_2 ultrahard coating
Cutting Speeds	120, 200, 240 m/min
Feed Rates	0.050, 0.075, 0.100, 0.125 mm/rev
Depth of Cut	1.00 mm
Cutting Fluid	Flooded coolant (Trim Sol; 5% vol.)

RESULTS AND DISCUSSION

The first tests were conducted using different cutting speeds and feeds under flooded coolant conditions. The titanium alloy bar was machined for 30 seconds, and forces were measured to capture the effect of a sharp tool. The effect of micro-edge prep and various coatings on the insert at different feeds and speeds are shown in Figures 9 to 15. The effectiveness of different coatings seems to be insignificant at the lower feed-rate of 0.050 mm/rev at all three selected (120, 200, 240 m/min) cutting speeds (Figure 9). Also, at the lower feed of 0.050 mm/rev, the cutting forces do not show significant variation. However, the micro-edge prep insert showed significant increase in the forces (Figures 9 and 10). At the feed rates of 0.075 and 0.100 mm/rev, the cutting forces significantly increase at the speed of 240 m/min (Figures 10 and 11). In fact, work-material adhesion at cutting edge and melting was observed, and none of the coatings could be sustained for the 30 seconds of cutting. The forces seem to increase significantly even at 200 m/min cutting speed when the higher feed rate of 0.125 mm/rev was used (Figure 12). This establishes the maximum cutting speed of 200 m/min in machining titanium alloy for these inserts. In most cases, the uncoated carbide inserts show lower forces even at higher cutting speeds.

Figure 13 shows that the forces increase when increasing the feed rate while turning titanium alloy at 120 m/min. No significant advantage is achieved using ultra-hard or nano-layered coated cutting tools. Micro-edge prep inserts show much higher cutting forces at all selected higher range of cutting speeds. Thus, micro-edge prep tools, which show an advantage in hard turning of steel alloys, do not provide any advantage in machining titanium alloys at high cutting speeds.

At the higher cutting speeds of 200 and 240 m/min, use of higher feed rates rapidly increase the cutting forces (Figures 14 and 15), and the temperature-related machining difficulties become unavoidable as many wear mechanisms join together to accelerate tool wear – and finally tool failure – in a very short period of time.

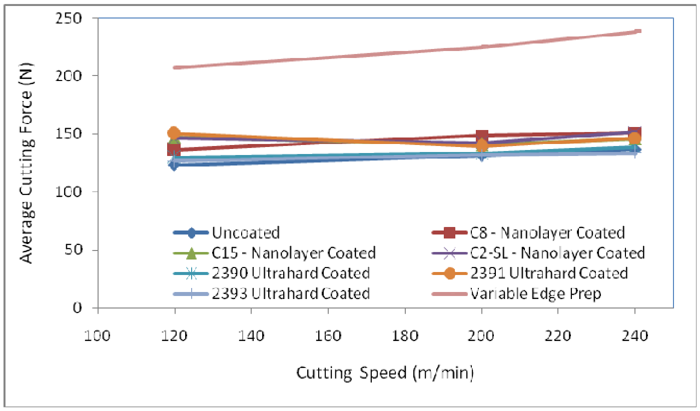


FIGURE 9. CUTTING FORCE V/S CUTTING SPEED AT A FEED RATE OF 0.050 MM/REV (DEPTH OF CUT - 1.00 MM, FLOODED COOLANT)

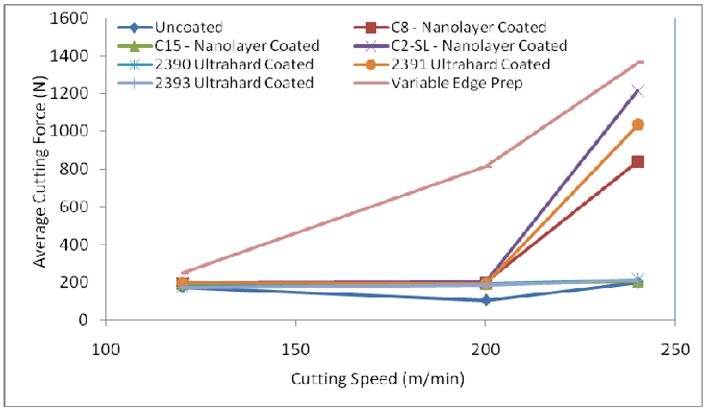


FIGURE 10. CUTTING FORCE V/S CUTTING SPEED AT A FEED RATE OF 0.075 MM/REV (DEPTH OF CUT - 1.00 MM, FLOODED COOLANT)

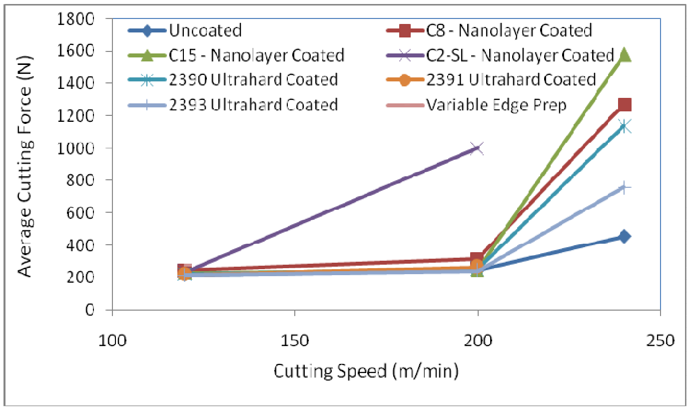


FIGURE 11. CUTTING FORCE V/S CUTTING SPEED AT A FEED RATE OF 0.100 MM/REV (DEPTH OF CUT - 1.00 MM, FLOODED COOLANT)

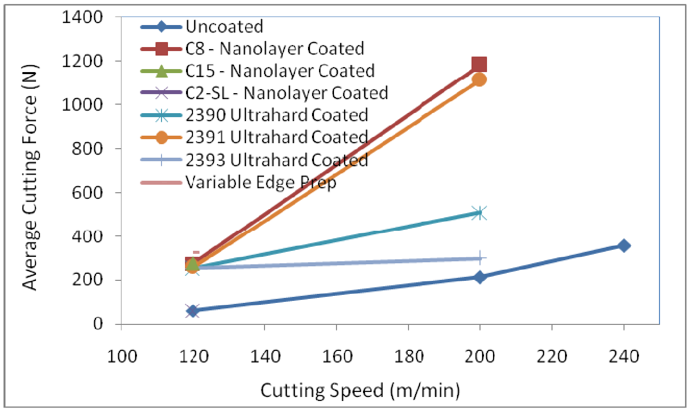


FIGURE12. CUTTING FORCE V/S CUTTING SPEED AT A FEED RATE OF 0.125 MM/REV (DEPTH OF CUT - 1.00 MM, FLOODED COOLANT)

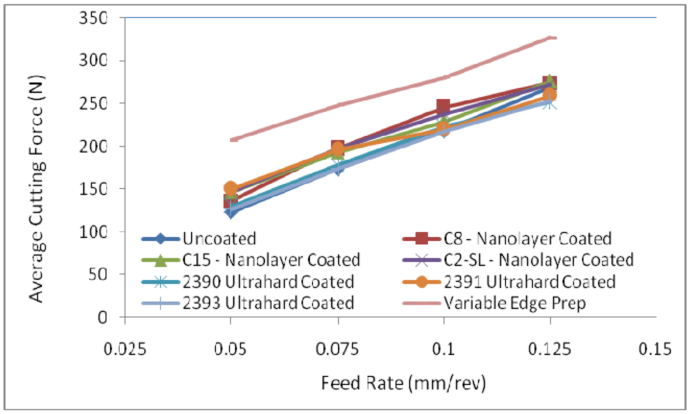


FIGURE 13. CUTTING FORCE V/S FEED RATE AT A CUTTING SPEED OF 120 M/MIN (DEPTH OF CUT - 1.00 MM, FLOODED COOLANT)

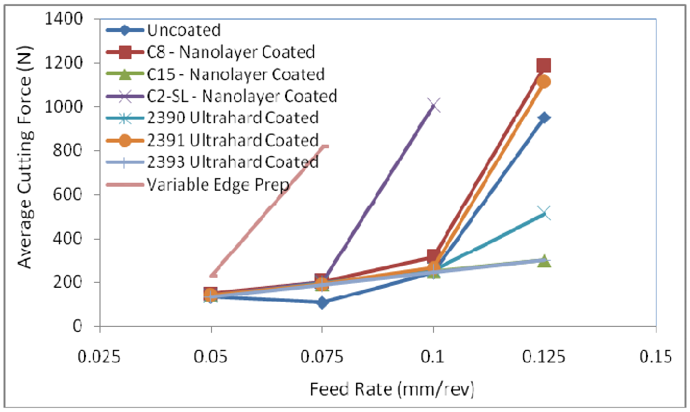


FIGURE 14. CUTTING FORCE V/S FEED RATE AT A CUTTING SPEED OF 200 M/MIN (DEPTH OF CUT - 1.00 MM, FLOODED COOLANT)

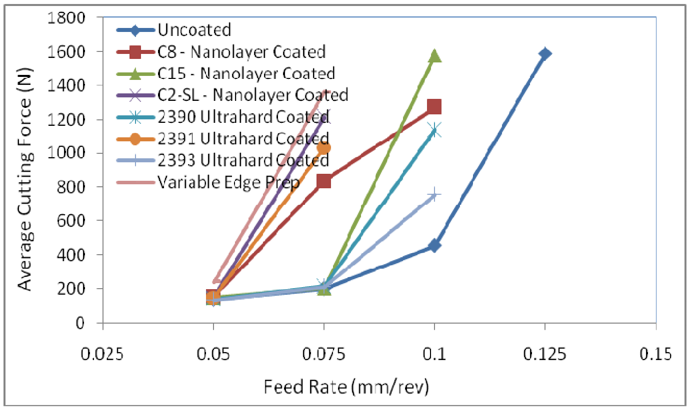
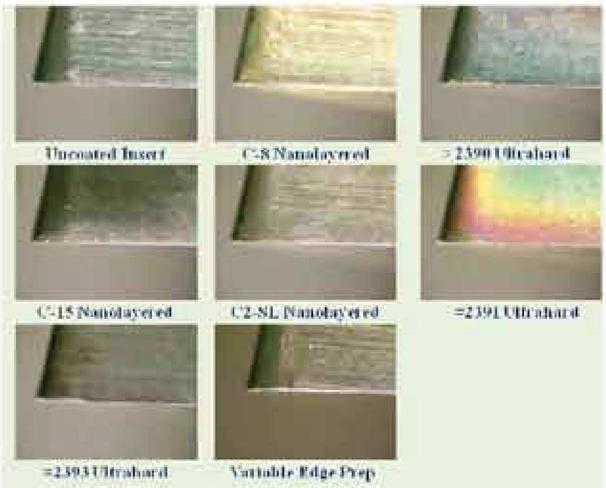
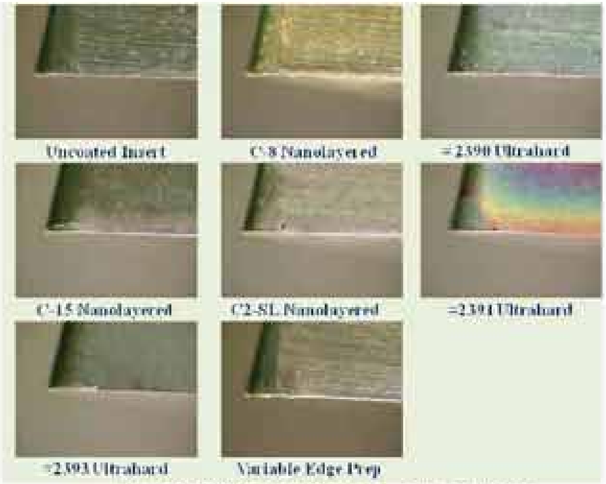


FIGURE 15. CUTTING FORCE V/S FEED RATE AT A CUTTING SPEED OF 240 M/MIN (DEPTH OF CUT - 1.00 MM, FLOODED COOLANT)

Figures 16 (A-C) show tool wear at lower feed rate of 0.050 mm/rev and three selected high cutting speeds of 120, 200, 240 m/min. All the inserts (uncoated, ultrahard and nano-layered coated) show very small amount of tool wear.



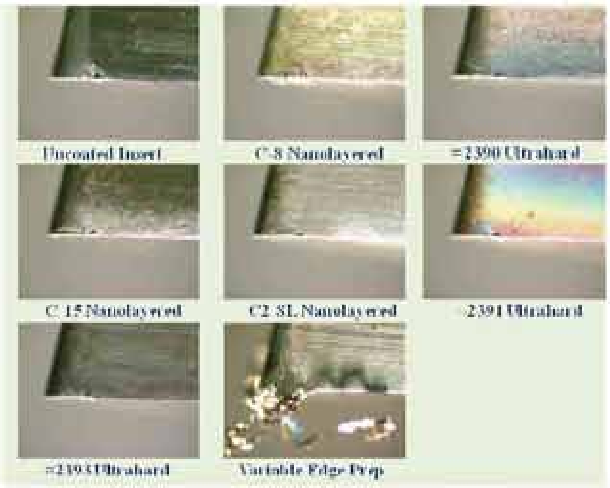
(A) CUTTING SPEED - 120 M/MIN



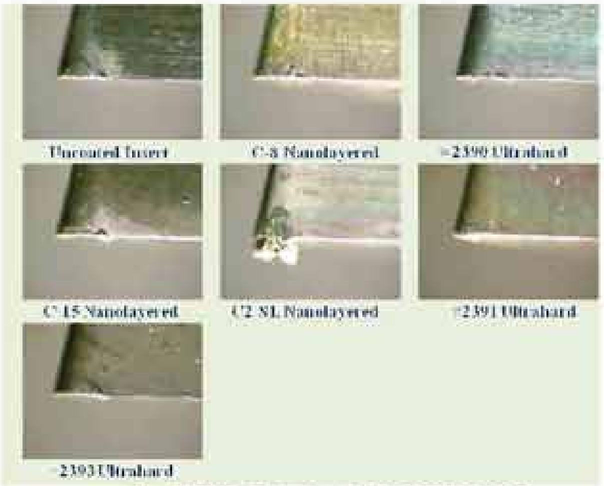
(B) CUTTING SPEED - 200 M/MIN

(C) CUTTING SPEED – 240 M/MIN

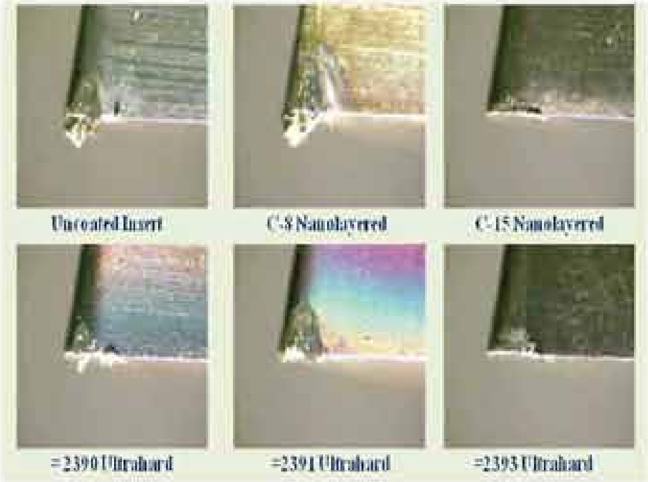
FIGURE 16 (A-C). EFFECT OF CUTTING SPEED ON DIFFERENT COATED INSERT'S FLANK WEAR (FEED RATE - 0.05 MM/REV, FLOODED COOLANT)



(A) FEED RATE - 0.075 MM/REV



(B) FEED RATE - 0.100 MM/REV



(C) FEED RATE - 0.125 MM/REV

FIGURE 17 (A-C). EFFECT OF FEED RATE ON DIFFERENT COATED INSERT'S FLANK WEAR (CUTTING SPEED – 200 M/MIN, FLOODED COOLANT)

(A) FEED RATE - 0.050 MM/REV

(B) FEED RATE - 0.075 MM/REV

(C) FEED RATE - 0.100 MM/REV

FIGURE 18 (A-C). EFFECT OF FEED RATE ON DIFFERENT COATED INSERT'S FLANK WEAR (CUTTING SPEED – 240 M/MIN, FLOODED COOLANT)

However, when the feed rate is increased from 0.050 mm/rev to 0.125 mm/rev at 200 m/min cutting speed, adhesion, melting and chemical reactivity start occurring, and the coatings are unable to sustain themselves. These results are shown in Figures 17 (A-C). When the feed rates are increased at very high speed of 240 m/min, detrimental thermal effects on tool wear can be seen (Figures 18 (A-C)). The tool fails in a very short (few seconds) time as the thermal effects and chemical reactivity become dominant in wear mechanism and tool failure. During these tests, a feed rate of 0.125 mm/rev could not be used. Thus, 0.100 mm/rev feed rate is the upper limit that could be used at 240 m/min cutting speed.

Based on the above observations, a final set of experiments was conducted at a cutting speed of 120 m/min and feed rate of 0.075 mm/rev. The cutting force and tool wear results are shown in Figures 19 and 20, respectively. It appears that nano-layered coatings (C8 and C2-SL) provide lower cutting forces and longer tool life.

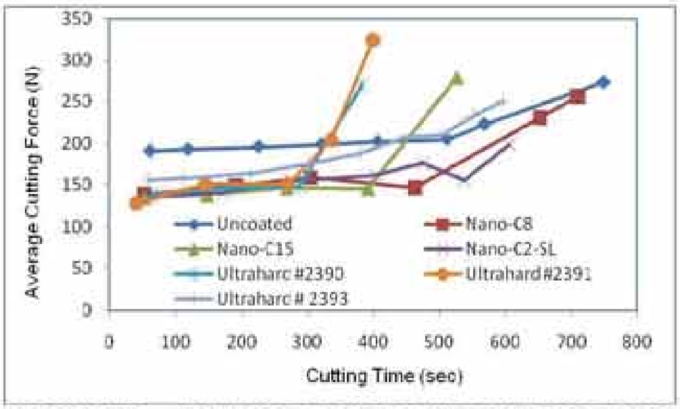


FIGURE 19. CUTTING FORCE V/S CUTTING TIME (CUTTING SPEED - 120 M/MIN, FEED RATE - 0.075 MM/REV, DEPTH OF CUT - 1.00 MM, CUTTING FLUID – TRIM SOL 5% VOL)

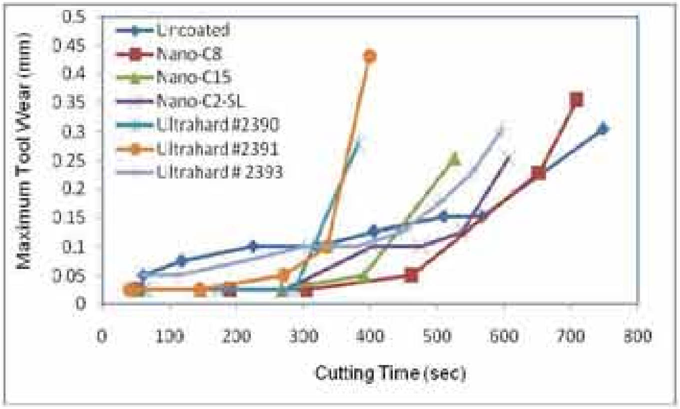


FIGURE 20. TOOL WEAR V/S CUTTING TIME (CUTTING SPEED - 120 M/MIN, FEED RATE - 0.075 MM/REV, DEPTH OF CUT - 1.00 MM, CUTTING FLUID – TRIM SOL 5% VOL)

CONCLUSIONS

This paper presents results of the machining of Ti-6Al-4V titanium alloy with the purpose of improving machinability utilizing micro-edge prep inserts and newly developed ultra-hard and nano-layered coatings on the cutting inserts. The orthogonal (2-D) tests showed that cutting forces increased with increases in cutting speed and feed rate except at the lowest feed arte of 0.025 mm where lower forces were observed with coated inserts. The cutting forces decrease with increases in rake angle from 0° to 5°.

The oblique cutting tests showed that coatings do not show any significant change in cutting forces or tool wear at lower feed rate of 0.050 mm/rev at all three selected cutting speeds of 120, 200, 240 m/min. The micro-edge prep inserts show significant increases in forces and do not seem to provide any added advantage in machining titanium (Ti-6Al-4V) alloy. With coated inserts at higher feed rates of 0.075 and 0.100 mm/rev, the cutting forces increased significantly at the speed of 240 m/min and work-material adhesion and melting due to high temperatures at the insert's cutting edge were observed. None of the selected coatings could be sustained for 30 seconds of cutting at these conditions. The forces seem to increase significantly even at 200 m/min cutting speed when the higher feed rate of 0.125 mm/rev was used. These tests suggest that the upper limit on maximum cutting speed is up to 200 m/min and feed rates within 0.025 to 0.050 mm/rev for high-speed turning of titanium (Ti-6Al-4V) alloy. These results provide good information about the range of process parameters that should be used for machining Ti-6Al-4V.

It seems that C8 and C2-SL nano-layer coatings might prove to be better candidate for high speed machining of Ti-6Al-4V titanium alloy. However, further investigation is required to optimize the process parameters for high-speed turning of titanium (Ti-6Al-4V) alloy.

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