A COMPARATIVE STUDY ON THE EFFECTIVENESS OF COATED AND UNCOATED TUNGSTEN CARBIDE TOOLS FOR DRY MACHINING OF TI-6AL-4V

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Abstract

The dry and near-dry machining processes, commonly known as sustainable machining processes, are currently gaining popularity because of the increasing demand for green and environmentally friendly manufacturing processes. The objective of this study was to investigate the machinability of aerospace material Ti-6Al-4V (grade 5 titanium alloy) under dry machining conditions using both coated and uncoated tungsten carbide tools. An investigation was carried out to reduce tool wear and improve dry machining performance by applying a coating of titanium carbo-nitride (TiCN) and titanium aluminum nitride (TiAlN) on the tungsten carbide tools. Tool wear was found to be a serious issue in the machining of titanium alloys in dry conditions. The major problem of machining Ti-6Al-4V using uncoated carbide tools was alloying of workpiece materials to the tool surface, due to the lack of heat dissipation from the tool-workpiece interface and strong alloying tendency of Ti-6Al-4V. It was found that the adhesion to the cutting tool edges was significantly reduced for tools with TiCN and TiAlN coatings. Due to the minimal adhesion of the chips, tool wear was also reduced. In terms of surface finish, TiAlN-coated tools were found to provide lower average surface roughness compared to TiCN-coated and uncoated carbide tools. There was no significant difference in the machining time between coated and uncoated tools for the same machining conditions. Overall, surface roughness and tool wear were minimized with TiAlN-coated carbide tools during the machining of Ti-6Al-4V. The cutting speed of 50 m/min, feed rate of 0.5 mm/rev, and depth of cut of 0.3 mm with TiAlN-coated tools were found to be the optimum machining conditions for the dry machining of Ti-6Al-4V.

Introduction

Titanium alloys are extensively used in aerospace and automotive industries due to their high specific strength (strength-to-weight ratio), superior mechanical and thermal properties, and excellent corrosion resistance. However, titanium alloys are commonly known as difficult-to-cut materials using conventional machining processes because of their reactivity with tool materials, cutting speed limitation, chipping, and premature failure of the cutting tools [1-3]. The difficulty in the machining of titanium alloys is also associated with low thermal conductivity, high strength, and low young's modules of titanium [4]. Ti-6Al-4V, commonly known as grade 5 titanium alloy, is the most extensively used material among all titanium alloys, and has been found to have important applications in aerospace, automotive, and biomedical industries. Therefore, the machining of Ti-6Al-4V has been of great interest to researchers for many years.

Based on a recent report [5], the amount of used lubricants and coolant fluids was estimated to be around 38 Mt, which is expected to increase by 1.2% over the next few decades. Therefore, many researchers are focusing on the sustainable machining of aerospace materials in order to minimize carbon emissions into the environment and reduce the pollution generated from the machining processes [6]. Among the sustainable machining processes, dry machining, near-dry machining using minimum quantity lubrication (MQL), and cryogenic machining are the reported techniques for machining titanium alloys and other aerospace materials [5]. There have been many studies done on the machining of Ti-6Al-4V using MQL [6-9], high-pressure cooling [10], [11], and cryogenic machining conditions [12-14]. However, in this current study, that literature will not be discussed in detail, as the focus of this paper is on the effectiveness of coatings on the cutting tools, tool wear, and tool life during machining of Ti-6Al-4V.

Besides various cooling techniques, an investigation was carried out to enhance the machinability of titanium alloys by developing new cutting tools and providing various coatings on the existing cutting tool materials. Ezugwu and Wang [15] investigated the problems associated with the machining of titanium alloys and the possible reasons for tool wear and cutting tool failure during machining. They found that the straight tungsten carbide (WC-Co) cutting tools sustained their power in almost all machining conditions during machining of titanium alloys. They suggested that the chemical vapor deposition (CVD) coated carbides and ceramics could not be used, due to their reactivity with titanium and their relatively low fracture toughness and poor thermal conductivity. They also proposed a new machining method of rotary cutting using ledge tools, which could be applied successfully for machining of titanium alloys. An attempt was also made to machine Ti-6Al-4V alloy with wurtzite boron nitride (wBN) cutting tools [16]. No significant difference was found between the wear mechanism of the wBN cutting tools and those of polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) tools. It was reported that the wBN-cBN composite tools could provide more economical machining of titanium alloys. Ezugwu et al. [17] investigated the effectiveness of cubic boron nitride (CBN) tools for machining of Ti-6Al-4V alloy with various coolant supplies. They found that the performance of CBN tools was poorer compared to that of uncoated carbide tools.

Che-Haron [18] investigated tool life and surface integrity during turning of Ti-alloy (Ti-6Al-2Sn-4Zr-6Mo) using two types of uncoated cemented carbide tools under dry cutting conditions. In his experiments, he used four different cutting speeds ranging from 45 m/min to 100 m/min and two different feed rates of 0.35 mm/rev and 0.25 mm/rev. The depth of cut was kept constant at 2.0 mm. The criteria used in his research to reject a tool were: 1) reaching the average flank wear to 0.4 mm or maximum flank wear to 0.7 mm; 2) getting notch at a depth of cut of 1.0 mm; 3) reaching a crater wear depth of 0.14 mm; 4) exceeding an average surface roughness, R_a, of more than 6 µm; and, 5) the occurrence of flaking or fracture. Considering these criteria, it was found that the coated tools provided higher tool life compared to uncoated tools. De Bruyn [19] considered high-speed machining of Ti-6Al-4V utilizing uncoated and PVD-coated carbide tools under dry conditions. They considered the tool life and the nature of the surface finish as the variables when analyzing cutting tool life. As per their study, PVD-coated carbide tools have comparatively higher tool life than uncoated tools.

Tuppen and Voice [20] developed models to predict tool life in the end milling of Ti-6Al-4V utilizing uncoated carbide tools under dry conditions. They utilized a central composite design (CCD) to build up the tool life model identified with essential cutting parameters. As indicated by their models, cutting rate was the principle element affecting tool life, after feed rate and pivotal depth of cut. He et al. [21] analyzed tool wear during the machining of particulate-reinforced titanium matrix composites (PTMCs), and observed that cracking and chipping of cutting tools occurred more often in uncoated tools, though pit wear was more common in coated tools. From the tool life analysis, it was found that the tool life of coated and uncoated carbide tools diminished rapidly at higher cutting velocities. They perceived that wet cutting was superior to dry cutting for coated carbide tools, and the utilization of oil-based coolant could extend the tool life of coated carbide tools.

Fanning [22] investigated the wear of cutting tools for turning Ti-6Al-4V with a specific end goal of creating suitable tool coatings. As per their discoveries, it was found that low thermal conductivity of titanium-based compounds caused a thermal exchange of the tool that prompted quick tool disintegration. They proposed that coating materials with thermal conductivity lower than that of the workpiece material could be utilized to enhance tool life for machining titanium-based alloys. Hosseini and Kishawy [23] presented another strategy for enhancing cutting tool life by utilizing the ideal estimations of speed and feed rate all through the cutting procedure. They also developed a mathematical model from the exploratory information of tool life. Enhancement methods were utilized for improving tool life, while keeping the metal removal rate constant.

Although a number of studies have been conducted on the feasibility of using coatings on the cutting tools for improving tool life and enhancing productivity, very few studies considered investigating the feasibility of titanium carbo nitride (TiCN) and titanium aluminum nitride (TiAlN) coated tools. Therefore, this current study investigated the effectiveness of the TiCN and TiAlN coatings on the carbide tools for dry machining of Ti-6Al-4V. A comparative study on the machinability of titanium alloys (Ti-6Al-4V) for coated (TICN and TiAlN) and uncoated tools in dry machining was conducted. The effect of various operating parameters on machining time, tool wear, and surface roughness for both coated and uncoated tools was analyzed.

Experimental Setup

A Haas Mini Mill machine tool was used to conduct the experiments in this current study. Figure 1 shows a photograph of the machine tool. This is a computer numerically controlled (CNC) machine tool integrated with a computer-integrated manufacturing (CIM) cell along with four other machine tools and assembly system. The machine tool had the option for automatic tool changing, which was used in this study to reduce the experiment time. The workpiece used in this study was Ti-6Al-4V, which is commonly known as Grade 5 titanium alloy or aerospace material. In order to cut the Ti-6Al-4V, four-fluted tungsten carbide tools with 1/8 inch cutter diameter were used. The feed rate and depth of cut were varied for three different settings. The cutting speed was kept at the fixed setting of 50 m/min, which was the highest capacity of the machine tool. The cutting speed was set at the highest available setting in order to maintain high-speed machining of the titanium alloys. For each parameter setting (a combination of cutting speed, feed rate, and depth of cut), three slots of 1-inch length were machined. The machining time was recorded and the surface topography, roughness, and tool wear were analyzed. Table 1 presents the experimental conditions and parameters used in this study. The step-by-step experimental procedure is presented in Figure 2.

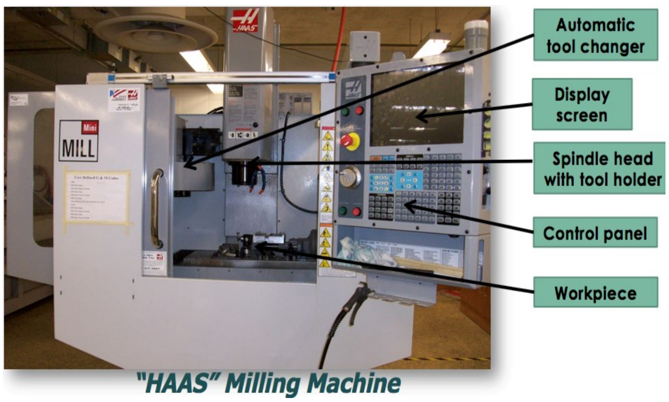


Figure 1. Photograph of the Machine Tool (Hass Mini Mill) Used to Perform the Machining Experiments

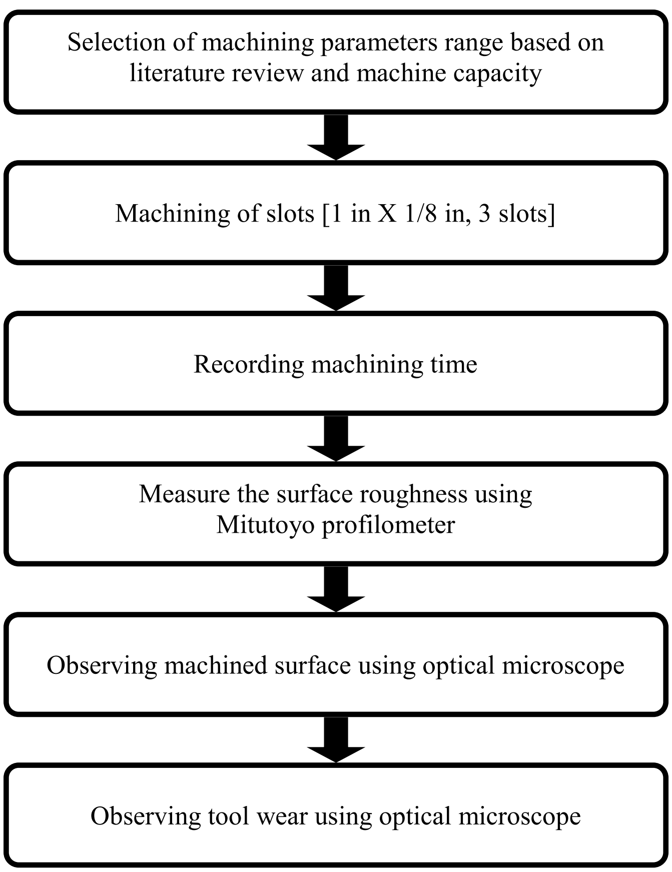


Figure 2. Step-by-step Experimental Procedure Followed in This Study

Table 1. List of Experimental Conditions and Machining Parameters

Experimental Condition	*Machining Parameters*
Workpiece	Ti-6Al-4V (3 in x 3 in x 0.5 in)
Cutting tool	Tungsten carbide (1/8 x 1/8 4F) – Coated and Uncoated
Types of coating	TiCN and TiAlN
Cutting fluid	No Cutting fluid (dry machining)
Cutting speed (m/min)	50 (Maximum limit of the machine tool)
Feed rate (mm/rev)	0.3, 0.5, 0.7
Depth of cut (mm)	0.3, 0.5, 0.7

Results and Discussions

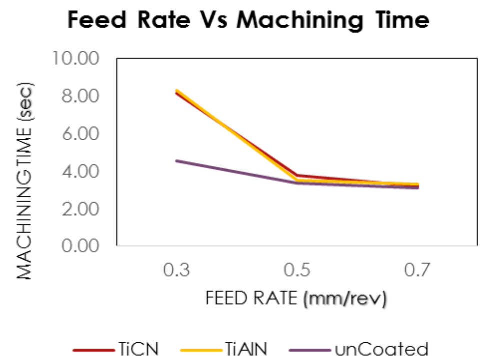
Performance Comparison at Different Feed Rates

In order to compare the machining performance of coated and uncoated carbide tools, the effect of feed rate on the machining time, tool wear, and surface roughness was studied for uncoated, TiCN-coated and TiAlN-coated carbide tools. The feed rate was varied at 0.3, 0.5, and 0.7 mm/rev, while cutting speed and depth of cut remained unchanged at 50 m/min and 0.3 mm, respectively. Figure 3 shows the effect of feed rate on machining time, tool wear, and surface roughness during dry machining of Ti-6Al-4V using uncoated, TiCN-coated and TiAlN-coated carbide tools. It can be seen from Figure 3(a) that for both coated and uncoated carbide tools, the machining time decreased with an increase in feed rate. The machining times at different feed rates for TiCN- and TiAlN-coated carbide tools were found to be very similar. However, the uncoated carbide tools were found to provide slightly lower machining times at lower feed rates, although no significant difference in machining time was observed at higher depths of cut.

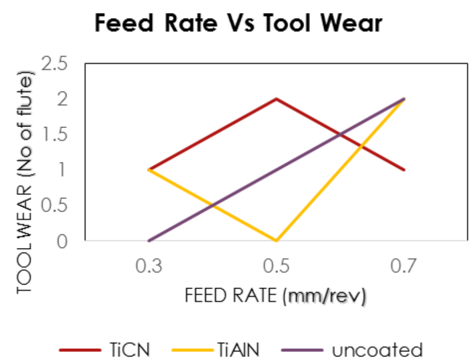
Figure 3(b) shows a comparison of the number of cutting edges/flutes affected at different feed rates for uncoated, TiCN-coated, and TiAlN-coated carbide tools. It can be seen that for uncoated carbide tools, the tool wear/number of worn out edges increased with an increase in feed rate. For the TiCN- and TiAlN-coated tools, the number of worn out edges was lower at higher feed rates compared to those of uncoated tools. Figure 3(c) indicates that the surface roughness obtained at higher feed rates, using TiCN- and TiAlN-coated tools, was significantly lower than that obtained with uncoated carbide tools. Although there was no significant difference in surface roughness at lower feed rates, the difference became significant at higher feed rates. This was due to the fact that the increase in feed rate increased the amount of frictional forces at the tool-workpiece interface. The increased friction caused more heat generation, resulting in more wear in the cutting tool edges. However, the coating of TiCN and TiAlN sustained comparatively higher feed rates, thereby retaining the sharpness of the cutting edges at higher feed rate. The TiAlN was found to provide the smoothest surface finish among the three different types of cutting tools used in this study for dry machining of Ti-6Al-4V.

Figure 4 shows a comparison of the surface topography and roughness obtained by TiCN, TiAlN, and uncoated carbide tools at the different feed rates. It can be seen that for uncoated and TiCN-coated carbide tools, the average surface roughness increased with the increase of feed rate. However, interestingly, for TiAlN-coated tools, the surface roughness was higher at lower feed rates and decreased when higher feed rates were used. This indicated that the TiAlN coating was effective at comparatively higher feed rates. The lowest value of R_a was obtained at the feed rate of 0.5 mm/rev with the TiAlN-coated carbide tools. It was also found that surface roughness was higher when uncoated carbide tools were used at comparatively higher feed rates (0.5 and 0.7 mm/rev). On the other hand, the surface roughness was lower for uncoated carbide tools, when lower (0.3 mm/rev) feed rates were used for machining. The results indicated that the coatings on the tools were more effective when the machining was conducted at higher feed rates or at faster speeds. However, the coatings on the cutting tools were not very effective when the machining was carried out at lower feed rates.

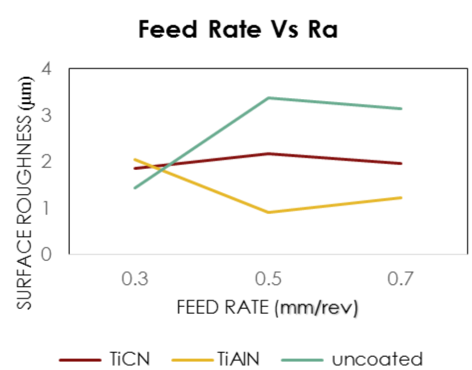
Figure 5 shows a comparison of tool wear for the TiCN, TiAlN, and uncoated carbide tools for dry machining of Ti-6Al-4V at different feed rates. The number for tool wear indicates the number of worn out or affected flute/cutting edges of the tool. It can be seen from Figure 5 that tool wear was the most unpredictable, showing no confirmed trend against different feed rates or coatings. It was found that for machining at lower feed rates, e.g., 0.3 mm/rev, the uncoated carbide tool suffered less tool wear compared to the coated carbide tools. However, at higher feed rates, the coated carbide tools provided lower tool wear than those of uncoated tools. Among all three types of tools, the TiAlN-coated carbide tools suffered the least amount of tool wear in dry machining of Ti-6Al-4V. One important observation was the adhesion of chips on the cutting edge during machining at a feed rate of 0.5 mm/rev using uncoated carbide tools. The adhesion of chips at the cutting edge usually resulted in breakage of the cutting tool at the shank. This was due to improper heat dissipation from the cutting edges at higher feed rates. The coating on the cutting edges could reduce the possibility of adhesion of chips at the cutting edge, as observed from Figure 5. The TiAlN-coated tools at moderately higher feed rates (0.5 mm/rev) provided the best results in terms of tool wear and surface finish.



(a) Machining Time



(b) Tool Wear



(c) Surface Roughness

Figure 3. Effect of Feed Rate on Machining Time, Tool Wear, and Average Surface Roughness (R_a) for Uncoated, TiCN-coated, and TiAlN-coated Carbide Tools [d.o.c. = 0.3 mm, cutting speed = 50 m/min]

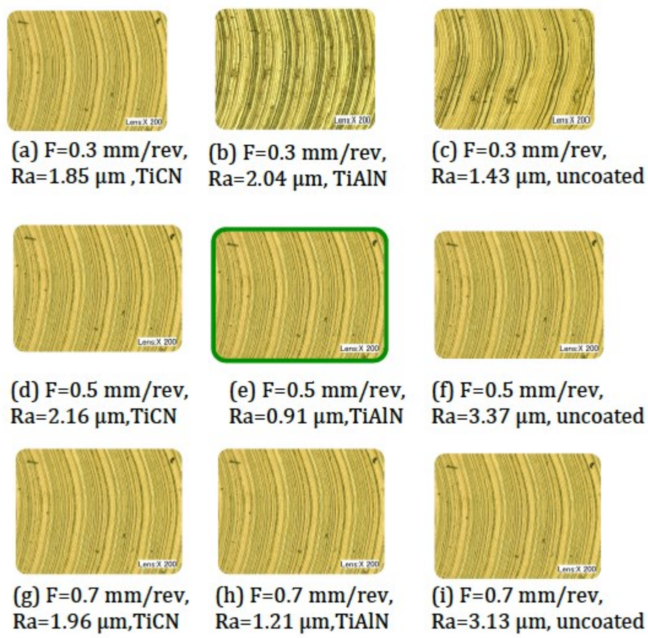


Figure 4. Comparison of Surface Topography and Roughness of Ti-6Al-4V at Different Feed Rates for TiCN, TiAlN, and Uncoated Carbide Tools [d.o.c. = 0.3 mm, cutting speed = 50 m/min]

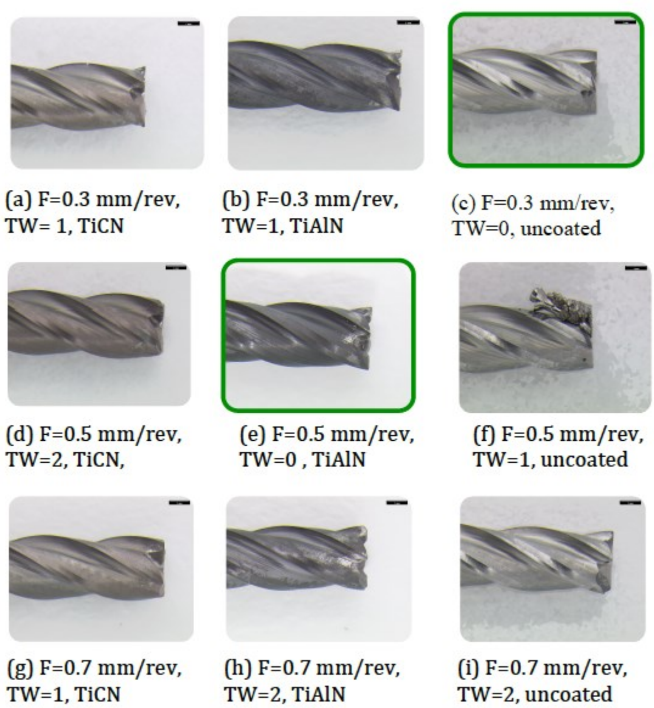


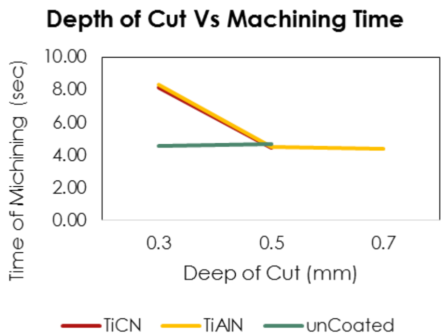
Figure 5. Comparison of Tool Wear during Dry Machining of Ti-6Al-4V at Different Feed Rates for TiCN, TiAlN, and Uncoated Carbide Tools [d.o.c. = 0.3 mm, cutting speed = 50 m/min]

Comparison of Performance at Different Depth of Cuts

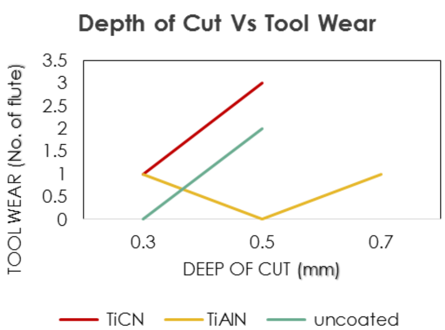
Figure 6 shows the comparison of machining time, surface roughness, and tool wear during dry machining of Ti-6Al-4V using TiCN, TiAlN, and uncoated carbide tools at various depth of cuts. The depth of cut was varied at 0.3 mm, 0.5 mm, and 0.7 mm, while keeping the cutting speed at 50 m/min and feed rate at 0.3 mm/rev. It can be seen from Figure 6 that no data were available for machining at 0.7 mm depth of cut for uncoated and TiCN-coated carbide tools. This was because of tool breakage at 0.7 mm depth of cut. At least two attempts were made using each of the TiCN-coated and uncoated carbide tools for machining at 0.7 mm depth of cut, and the tools broke for both attempts. Only TiAlN-coated carbide tools could successfully machine the Ti-6Al-4V at 0.7 mm depth of cut, 50 m/min cutting speed, and 0.3 mm/rev feed rate.

It can be seen from Figure 6(a) that for TiCN- and TiAlN-coated tools, the machining time slightly decreased with depth of cut, whereas for uncoated carbide tools, the machining time remained unchanged with the increase of depth of cut. The tool wear (number of affected cutting edges) was found to increase with the increase of depth of cut, as can be seen from Figure 6(b). This was due to the fact that an increase in the depth of cut causes the cutting tool to dig at higher depths and removes more material from the workpiece. The increased depth of cut also increased the frictional forces between the tool and the workpiece, causing the possible breakage of the tool. In case of TiAlN-coated carbide tool, there was no significant tool wear when machining was conducted at 0.5 mm depth of cut. For all three depths of cut, the TiAlN-coated tool was found to provide lower tool wear among the three types of cutting tools. Figure 6(c) shows a comparison of the surface roughness parameter, R_a, for machining of Ti-6Al-4V using TiCN-coated, TiAlN-coated, and uncoated carbide tools. The surface roughness was found to slightly decrease with the depth of cut for TiAlN- and TiCN-coated tools. However, no significant difference in surface roughness was observed with respect to the depth of cut for machining with uncoated carbide tools.

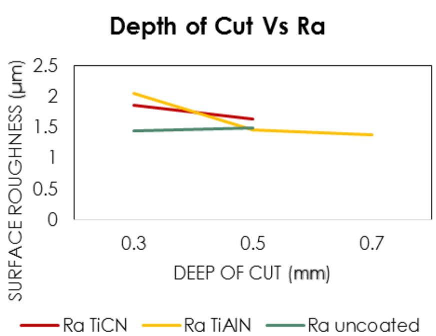
Figure 7 shows a comparison of surface topography and roughness obtained using TiCN, TiAlN, and uncoated carbide tools at different depths of cut. It can be seen that no data were available for machining at a 0.7 mm depth of cut for TiCN-coated and uncoated carbide tools because of the tool breakage. No significant trend in surface roughness was obtained against the depth of cut. The TiCN-coated tools were found to generate a rougher surface compared to TiAlN-and uncoated carbide tools. The TiAlN-coated carbide tool exhibited interesting results by providing the highest surface roughness at lower depths of cut and the lowest surface roughness at higher depths of cut. In the case of tool wear, the TiAlN-coated carbide tool exhibited the best performance among the three different types of tools, as can be seen from Figure 8.



(a) Machining Time



(b) Tool Wear



(c) Surface Roughness

Figure 6. Effect of Depth of Cut on Machining Time, Tool Wear, and Average Surface Roughness (R_a) for Uncoated, TiCN-coated, and TiAlN-coated Carbide Tools [cutting speed = 50 m/min, feed rate = 0.3 mm/rev]

(a) DoC=0.3 mm, Ra=1.85 µm, TiCN
(b) DoC=0.3 mm, Ra=2.04 µm, TiAlN
(c) DoC=0.3 mm, Ra=1.43 µm, uncoated

(d) DoC=0.5 mm, Ra=1.63 µm, TiCN
(e) DoC=0.5 mm, Ra=1.45 µm, TiAlN
(f) DoC=0.5 mm, Ra=1.48 µm, uncoated

(g) DoC=0.7 mm/min, TiCN
(h) DoC=0.7 mm, Ra=1.37 µm, TiAlN
(i) DoC=0.7 mm, uncoated

Figure 7. Comparison of Surface Topography and Roughness of Ti-6Al-4V at Different Depths of Cut for TiCN, TiAlN, and Uncoated Carbide Tools [cutting speed = 50 m/min, feed rate = 0.3 mm/rev]

(a) DoC=0.3 mm, TW= 1 , TiCN
(b) DoC=0.3 mm, TW=1 , TiAlN
(c) DoC=0.3 mm, TW=0, uncoated

(d) DoC=0.5 mm, TW=3, TiCN,
(e) DoC=0.5 mm, TW=0 , TiAlN
(f) DoC=0.5 mm, TW=2, uncoated

(g) DoC=0.7 mm,TiCN
(h) DoC=0.7 mm, TW=1,TiAlN
(i) DoC=0.7 mm, uncoated

Figure 8. Comparison of Tool Wear during Dry Machining of Ti-6Al-4V at Different Depths of Cut for TiCN, TiAlN, and Uncoated Carbide Tools [cutting speed = 50 m/min, feed rate = 0.3 mm/rev]

Conclusions

In this study, a comparative experimental investigation was carried out on the performance of uncoated and coated carbide tools for dry machining of Ti-6Al-4V. The effectiveness of TiCN- and TiAlN-coated carbide tools was evaluated in terms of machining time, surface roughness, and tool wear. The following conclusions were drawn from this study:

- The TiAlN-coated carbide tools provided improved machining performance compared to uncoated and TiCN-coated carbide tools. A cutting speed of 50 m/min, feed rate of 0.5 mm/rev, and depth of cut of 0.3 mm, while machining with TiAlN-coated tools, were found to be the optimum conditions for dry machining of Ti-6Al-4V.
- Dry machining using the TiAlN-coated carbide tools provided comparatively smoother surface finishes with lower average surface roughness. The surface roughness and the tool wear were comparatively higher for machining with uncoated tools.
- Tool wear was found to be unpredictable and the number of affected flutes increased with an increase in depth of cut and feed rate. The coating of TiAlN was found to be effective in reducing tool wear at higher feed rates and depths of cut.
- The machining of similar lengths of slots was found to be slightly faster with uncoated tools compared with the coated tools at lower feed rates and depths of cut. However, at higher settings, there was no significant difference in the machining time for coated and uncoated carbide tools.

Ongoing and Future Research

In this paper, the authors present the partial results of the on-going funded research project on sustainable machining of aerospace materials. There is on-going research on the analysis of chip morphology for different machining conditions. Chips were collected during the machining at different cutting parameters with coated and uncoated carbide tools, and are currently under investigation. In addition, future research will focus on the cutting force analysis during the dry machining of Ti-6Al-4V using coated and uncoated carbide tools. It can be hypothesized from the results of this current study that there may be a reduction of cutting forces during the machining of Ti-6Al-4V with TiAlN-coated tools that resulted in the reduced tool wear and improved surface finish at higher cutting speeds, feed rates, and depths of cut. The application of green/environmentally friendly cutting fluids and minimum quantity lubrication (MQL) will be considered in the future research.

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Biographies

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