

Study on carbide cutting tool life using various cutting speeds for α - β Ti-alloy machining

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Analysis and modelling

ABSTRACT

Current experimental studies have yielded that cutting speed, using carbide cutters, has no significant influence on surface roughness obtained for machining the α - β Titanium alloy Ti-6Al-4V. This paper presents results of experimental investigations carried out on the widely used titanium alloy Ti-6Al-4V using variable cutting speeds as well as different cutting tools at a constant feed rate and depth of cut. The effects of varying cutting speeds on the tool life have been analysed by inspecting the surface roughness of the machined samples and the tool wear observed during machining. As the cutting speed increases, the tool life drops off very rapidly and at higher cutting speed the chips start to ignite because of high heat generation at the cutting zone which is mainly caused by the low thermal conductivity of titanium alloys as postulated. Consequently higher cutting speeds may be used to dramatically reduce the production costs, but the currently available cutting tools will have a very poor tool life. According to this study, it has been identified that the uncoated carbide tool life is comparatively better than that of coated ones at lower cutting speeds whereas the coated ones are preferable at higher cutting speeds. It is expected that the metal manufacturing industries will be highly benefitted by this outcome in selecting the appropriate cutting tool as well as cutting speed according to their desired surface finish and tool life.

Keywords: Titanium alloy machining; Surface roughness; Tool wear; Tool life

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1. Introduction

Machining of Ti-alloys is still troublesome because of several unexpected complexities arise during machining operation. These alloys have some atypical characteristics which have categorised them as difficult-to-machine materials. Ti-alloys can be classified in different ways but according to their metallurgical

characteristics and alloying stabilisers they can be grouped into three main categories:

- 1) α and near α Ti-alloys
- 2) α - β Ti-alloys, and
- 3) β Ti-alloys.

The α - β Ti-alloys represent a mixture of α and β phases and contain additions of both α and β stabilizers. This group of alloys is the largest used in aerospace industries and Ti-6Al-4V is its

most common alloy. The α - β Ti-alloys are chiefly used for strength applications and Ti-6Al-4V accounts for about 45% of the total titanium production [1]. Hence, in this research, the α - β Ti-alloy Ti-6Al-4V has been selected for experiments.

The cutting tool materials influence the machining operations significantly and so it is very important to select the proper tool material for a particular application. To produce a good quality part in an economical way, a cutting tool material should possess some special characteristics. Some of the important characteristics are hardness, specifically hot hardness; toughness; wear resistance; and chemical stability or inertness with respect to the workpiece material [2].

Depending on the material type to be machined, the tool material with essential characteristics is usually chosen for proper machining. Cutting tool materials are generally divided into various categories, such as- Carbon and medium-alloy steels, High-speed steels (HSS), Cast cobalt alloys, Carbides, Coated Tools, Alumina-base ceramics, Cubic boron nitride (CBN), Silicon-nitride-base ceramics, Diamond, and Whisker-reinforced materials.

In order to have higher speeds for higher rates of production, carbides (cemented or sintered carbides) were introduced in the 1930s. Now these are among the most important, versatile and cost effective tool materials for a wide range of applications. To compare the operating characteristics of uncoated and coated carbide tools, it can be noted that the uncoated carbide tools have high hardness over a wide ranges of temperatures, toughness, wear resistance, versatility and wide range of applications whereas the coated carbides have improved wear resistance over uncoated ones, and better frictional and thermal properties. The modes of tool wear and failure are almost similar which are basically flank wear and crater wear. Both of these have the same limitations of not using at low speeds as a consequence of cold welding of chips and micro-chipping [2].

Cutting tools are subjected to high localized stresses, high temperatures, chip sliding along the rake face, and tool flank sliding along the freshly cut surface which directly cause tool wear. Consequently tool life, quality of the machined surface and its dimensional accuracy, and the economics of cutting operations are unfavourably affected. But the rate of tool wear is highly dependent on tool and workpiece materials, tool geometry, cutting fluids, process parameters (such as cutting speed, feed rate, and depth of cut), and machine-tool characteristics [2]. If the tool damage has been increased due to tool wear or any fracture, the resulting machined surface quality and accuracy will be deteriorated and ultimately it will be needed to replace the tool. Hence, it is necessary to develop some criteria by which the time of replacement can be decided.

There are two different approaches [3] to assess the tool life (T):

- 1) By measuring the size or roughness of machined parts, and
- 2) By measuring the tool wear.

In these approaches, the life is determined when the measured levels of the dimensional accuracy or surface roughness of the machined part or tool wear exceed a threshold limit. Though the first approach is not always easy and cost effective, unfortunately the relationship between tool wear and workpiece surface roughness or accuracy is not always unique. In addition, Ti-alloys have some unusual properties for which it is really difficult to machine these with acceptable surface roughness and dimensional

accuracy. This is why the first approach has been selected in this research to evaluate the tool life.

Cutting speed (V) is considered as one of the most important factors in affecting the tool life. Tool life varies dramatically for varying cutting speeds. Hence, in this research it has been investigated how the cutting speeds influence the life of uncoated and coated carbide cutting tools so that it may help the manufacturers in decision making.

2. Review of the literature

Different studies related to tool life of carbide tools have been conducted by various researchers. Some of the researches have been concerned with the machining of Ti-alloys and some with other difficult-to-machine materials.

Che-Haron investigated the tool life and surface integrity in turning Ti-alloy (Ti-6Al-2Sn-4Zr-6Mo) by using two types of uncoated cemented carbide tools under dry cutting condition. 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:

- Reaching the average flank wear to 0.4 mm or maximum flank wear to 0.7 mm;
- Getting notch at the depth of cut 1.0 mm;
- Reaching crater wear depth to 0.14 mm;
- Exceeding average surface roughness, Ra more than 6 μ m;
- Occurring flaking or fracture.

Considering the above criteria he found that the inserts with finer grain size have a longer tool life [4]. As he used the uncoated carbide tools only, the effect of that machining on tool life of coated one has not been revealed here.

Elmagrabi et al studied the high speed slot milling of Ti-6Al-4V using uncoated and coated carbide cutting tools under dry condition. They considered the tool life and the quality of the surface finish as the factors to define the cutting tool performance. According to their study, PVD coated carbide tool has a life of maximum 11.5 minutes which is comparatively better [5]. Ginta et al established models for tool life prediction in end milling of Ti-6Al-4V using uncoated carbide inserts under dry condition. They employed small central composite design (CCD) to develop the tool life model related to primary cutting parameters. They considered flank wear up to 0.30 mm as the criterion for tool failure. According to their models, cutting speed is the main factor influencing the tool life followed by feed and axial depth of cut [6]. All of these studies have been explored for dry machining, yet wet machining may create better results which are not clear here.

Choudhury & El-Baradie developed first-order and second-order tool life models in terms of cutting speed, feed rate, and depth of cut by using response surface methodology and design of experiment at 95% confidence level for turning high strength steel. They observed the same result obtained by Ginta et al that cutting speed is the key inducing issue on the tool wear, followed by the feed rate and the depth of cut and if any of these three cutting parameters has been increased the resulting tool life will be reduced [7]. Özel & Karpat utilized neural network modelling to predict surface roughness and tool flank wear over the

machining time for variety of cutting conditions in finish hard turning of AISI 52100 and AISI H-13 steel under dry condition. They also compared their neural network models with regression models [8]. But their models were developed for turning steel only and it is almost uncertain to use those models for machining Ti-alloys. Özel et al also developed multiple linear regression models and neural network models for predicting surface roughness and tool flank wear in turning of AISI D2 steel using ceramic wiper inserts. According to their experiment it is indicated that very lower surface roughness R_a values are attainable with wiper tools and they are as low as 0.18-0.20 μm . Following their findings it is shown that neural network models are appropriate for predicting tool wear and surface roughness patterns for a variety of cutting conditions [9]. Feng & Wang developed empirical models for surface roughness prediction in finish turning considering the workpiece hardness, feed, cutting tool point angle, depth of cut, spindle speed, and cutting time. They tried to predict the values of surface roughness by this model and then to verify with extra experiments [10]. However, from these researches it is not properly stated whether it is possible or not to predict the tool life on the basis of surface roughness.

Some researchers investigated the wear mechanism of coated and uncoated carbide tools while machining steels. Aslantas, Uzun & Çicek and Che-Haron, Ginting & Goh analysed the tool wear mechanism and they observed that fracture and chipping type damages occur more commonly in uncoated tools, whereas crater wear is the more frequent in coated tools. From the tool life curves, it has been observed that the tool life of coated and uncoated carbide tools decreases quickly at higher speeds and the behaviour of tool life against cutting speed for both of these carbide tools was similar in nature. They noticed that wet cutting is better than dry cutting for coated carbide tools and the use of oil-based coolant can increase the tool life of coated carbide tools [11,12]. Though some of the situations will be almost similar to the machining of Ti-alloys, their properties have made the total mechanism more complicated. Jaffery and Mativenga studied the wear mechanisms for turning Ti-6Al-4V in order to develop suitable tool coatings. According to their findings, it has been observed that low thermal conductivity of titanium-based alloys causes heat transfer to the tool that leads to rapid tool deterioration. They suggested that coating materials with thermal conductivity lower than that of the workpiece material can be used to improve tool life for machining titanium-based alloys [13].

Choudhury and Rao presented a new method to improve the cutting tool life by using the optimal values of velocity and feed rate all through the cutting process. They also established a tool life equation from experimental data and the adhesion wear model. Optimization techniques have been used for maximizing the tool life depending on practical constraints while keeping a constant metal removal rate and their investigations have been performed on two different types of steel [14]. Like others, they also considered the tool wear for assessing the tool life but the quality of the machined surface is disregarded here. Seeman et al also studied the tool wear and surface roughness while machining particle reinforced aluminium metal matrix composites (MMC) which is difficult-to-machine material. They further investigated the combined effects of four machining parameters including

cutting speed, feed rate, depth of cut, and machining time on the basis of flank wear (VB_{max}) and surface roughness (R_a). The process parameters have been optimized by means of desirability-based approach response surface methodology [15].

Apart from the machining without coolant, a significant number of researches have been performed on Ti-6Al-4V using cryogenic cooling by liquid nitrogen. In some papers, significant improvement has been noticed in tool life using cryogenic coolant with high feed rate and low depth of cut combinations. Besides, in the cryogenic cooling method, a reduction of the cutting temperature could be achieved by 61-66% and the surface finish could be improved to a maximum of 36% over wet machining. Some researchers suggested cryogenic cooling as a possible solution for high speed eco-friendly machining [16-20]. But in practice, the cryogenic cooling is not that much easier and cheaper as compared to traditional wet machining.

However, from the literatures discussed above it has been detected that investigation of tool life with respect to surface roughness has not properly been explored especially in machining of Ti-6Al-4V with coated and uncoated carbide cutting tools. Hence in this paper it has been tried to create some ideas of measuring tool life using surface roughness and to make a comparison between two different carbide tool lives.

3. Research methodology

This research study is mostly experimental and in this regard a number of machining experiments have been conducted. Initially samples of Ti-alloy (Ti-6Al-4V) of length 340 mm and diameter 65 mm have been prepared for machining.

A conventional lathe machine (Harrison M400) has been used for turning the samples with varying cutting speeds. The feed rate (f) and the depth of cut (d) were kept constant at 0.16 mm/rev and 0.5 mm respectively. To assess the tool life, the average surface roughness (R_a) has been selected as the tool life criterion and if the average surface roughness reaches to 1.5 μm , the cutting tool will be rejected. The steps followed in the research have been illustrated as a flowchart in Figure 1.

The whole process has been executed using both uncoated and coated carbide inserts. During the entire cycle of experimental process, the time is recorded carefully to have the proper tool life. At higher cutting speeds, the temperature generated during machining has been observed.

4. Experiment on tool life

For preparing the samples, the Ti-6Al-4V Ti-alloy bar of diameter 65 mm and length 340 mm has been cut from a long one. The chemical composition (wt.%) of that Ti bar is as follows in Table 1.

After preparing the sample, the Ti-alloy bar was clamped on the lathe machine using 3-jaw chuck and the tail stock centre as shown in Figure 2. During the machining process a cutting fluid of Caltex (Trusol GP) has been applied to keep the cutting zone free from excessive heat and also to reduce friction.

Table 1.
The chemical composition (wt%) of Ti bar

Ti	Al	V	Fe	C	N	H	O
89.661	6.0	4.0	0.18	0.02	0.01	0.009	0.12

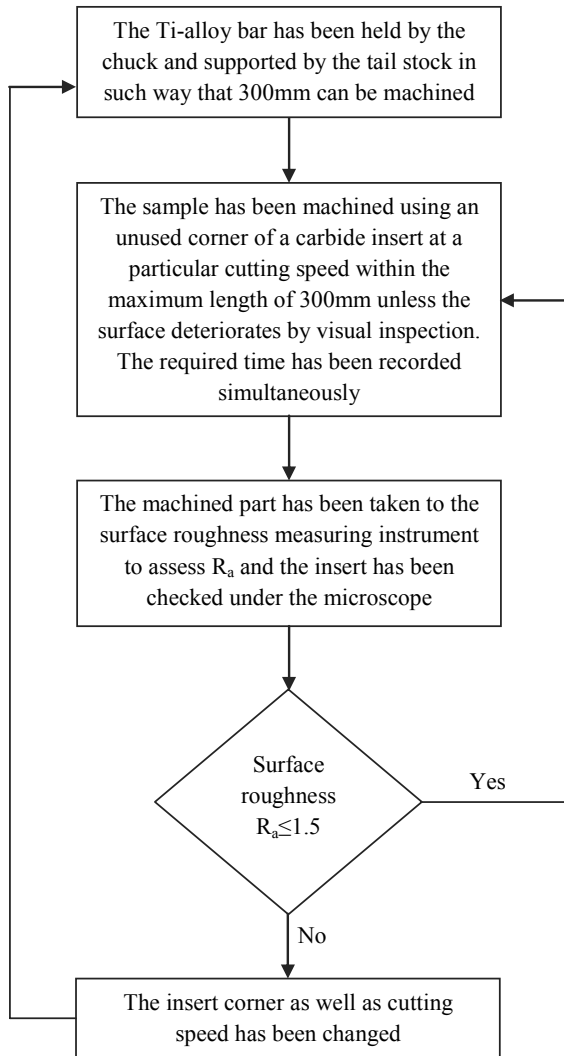


Fig. 1. Flowchart of the research methodology

The resources those have been utilized for the experiments have been listed as follows:

- Carbide inserts (Uncoated CNMG 120404-MF1, 890 and Coated CNMG 120404-MF1, TS2000);
- Tool holder (PCLNR 2525M12 JET);
- Lathe machine (Harrison M400);
- Taylor Hobson Surtronic 3+ surface roughness measuring instrument;
- Compact inverted metallurgical microscope with camera (Olympus CK40M);
- Infrared thermal imaging camera (FLIR SC 620).

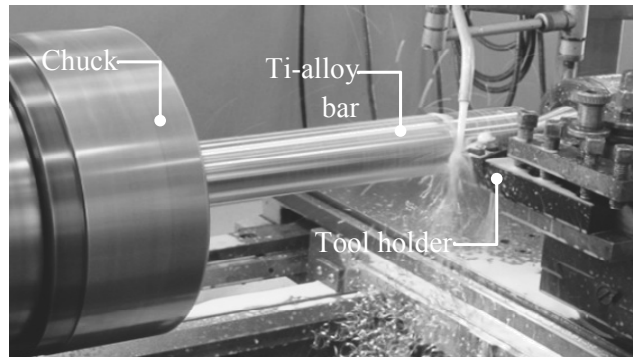


Fig. 2. Machining set up

After every cut, the surface roughness of the machined sample has been assessed by the Surtronic 3+ surface roughness measuring instrument. The measuring process has been depicted in Figure 3. The carbide inserts which have been used in the experiment are suitable for machining this type of super-alloys. The geometry of the both types of inserts is similar and it is listed below:

- Insert shape: 80° diamond;
- Hole shape: Cylindrical;
- Chip breaker: Double-sided;
- Cutting edge length: 12 mm;
- Thickness: 4 mm;
- Nose radius: 0.4 mm.

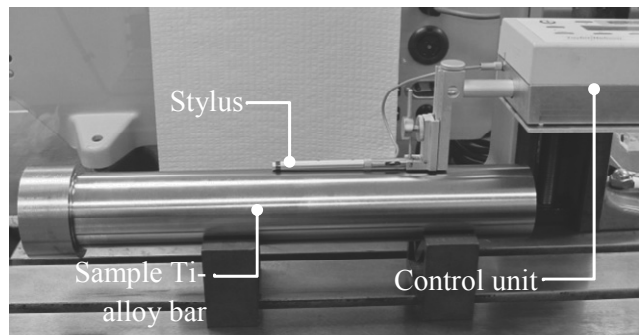


Fig. 3. Surface roughness measurement

After every cycle of machining, the cutting inserts have been examined under the microscope to assess the tool wear. Some images have been also saved by the camera attached with the microscope. During the machining processes, an infrared thermal imaging camera has been attempted to use to monitor the temperature. The aim was to measure the temperature at the tip of the insert, but the problem with the infrared thermal imaging camera is that it can measure the surface temperature only and the tool tip has normally been covered with the cutting fluid. However, it has been recorded a very high temperature on the chip by which a better understanding of cutting zone temperature can be obtained.

5. Results and discussions

The tool life has been assessed by the duration as long as the insert has cut the workpiece maintaining the average surface roughness Ra up to 1.5 μm. It has been considered that this surface roughness value is acceptable by the industries for finishing cut. After getting the tool life for varying cutting speeds, the values are plotted on two different log-log graph papers for two different types of carbide inserts. The graphs have been shown in Figure 4 and Figure 5. It has been observed that the curve is almost linear for both of them which indicate that as the cutting speed increases, the tool life decreases very rapidly.

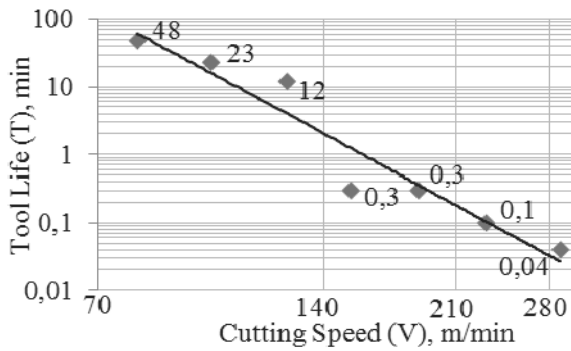


Fig. 4. Tool life curve for uncoated carbide inserts

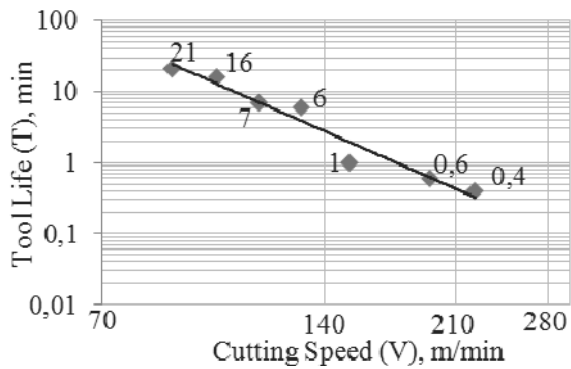


Fig. 5. Tool life curve for coated carbide inserts

To compare the tool life, it has been noticed that at lower cutting speeds the uncoated carbide tool shows longer life though the coated carbide inserts have better structural properties. It has been also detected that the tool wear is lower for coated carbide inserts as compared to uncoated carbide inserts but the resulting surface finish is better by using the uncoated ones. On the contrary, at higher cutting speeds, the tool life is reasonably better for coated carbide inserts though it is very short. But the important thing is that as the cutting speed increases the surface finish improves significantly. However, the carbide inserts are not that much suitable and economical to be used at higher cutting speeds.

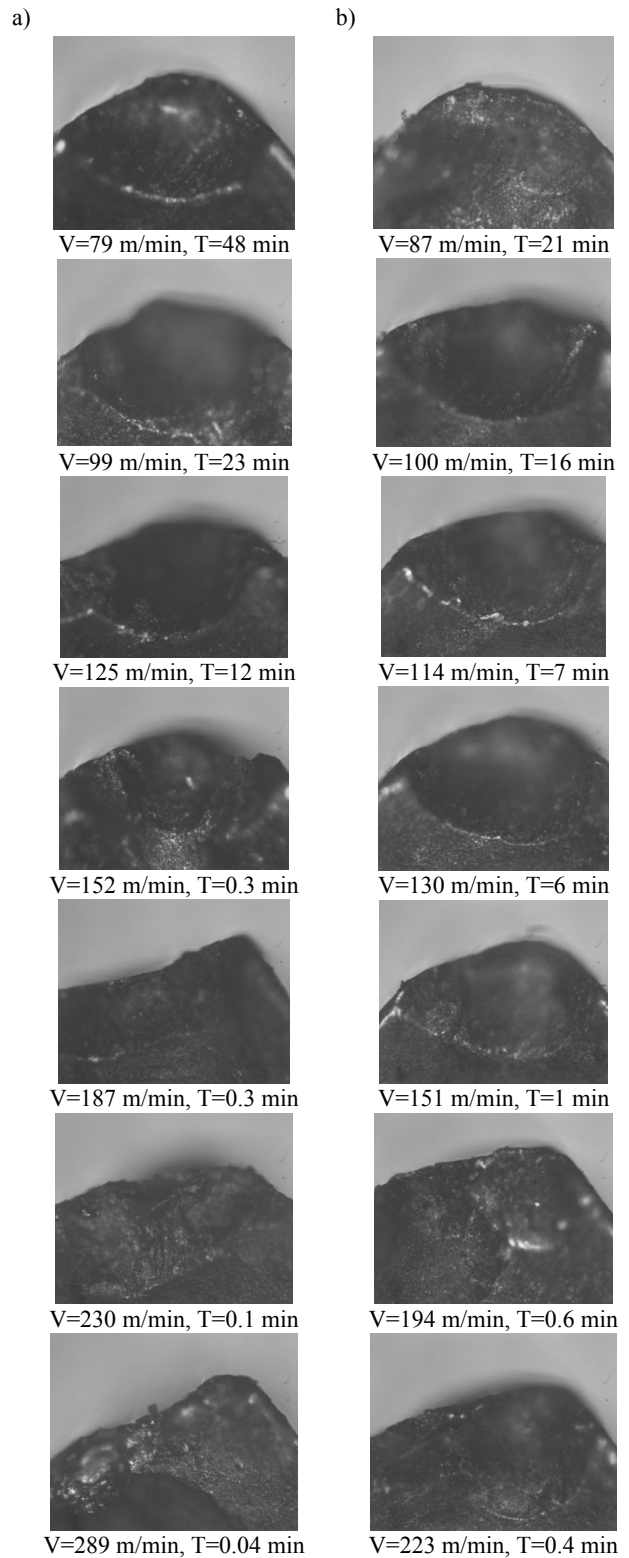


Fig. 6. Microscopic images of worn up uncoated (a) and coated (b) carbide inserts

To understand the tool wear, the microscopic images have been revealed that at lower cutting speeds, the inserts have a self-sharpening tendency which results better surface finish after machining some time. Initially crater wear has been observed on the tool tip and after machining a certain period of time the flank wear has been noticed. Sometimes chipping has been noticed after machining longer period at lower cutting speeds but it is very common at higher cutting speeds. When the tool tip is completely worn up the surface starts to deteriorate rapidly. Deposition of parent material on tool tip and the built-up-edge have been noticed as well. The microscopic images of the worn up inserts for varying cutting speeds have been recorded as in Figure 6.

The temperatures raised during the machining process have been also monitored by an infrared thermal imaging camera. But, as mentioned earlier, the problem is that the camera can measure the surface temperature only and as the machining has been performed with a cutting fluid, it cannot measure the exact temperature of the cutting zone under the cutting fluid. The maximum temperature recorded was 212°C during the machining with higher cutting speed, but it is not supposed to be the right temperature of the cutting zone. However, it has been noticed that the chips started to burn at higher cutting speed and so the actual temperature should be much higher than the recorded ones. Besides the camera cannot capture the thermal image instantly and it takes some time to process. Hence it has been difficult to save the required images as the temperature does not stay long at any point. In Figure 7 two sample thermal images have been depicted.

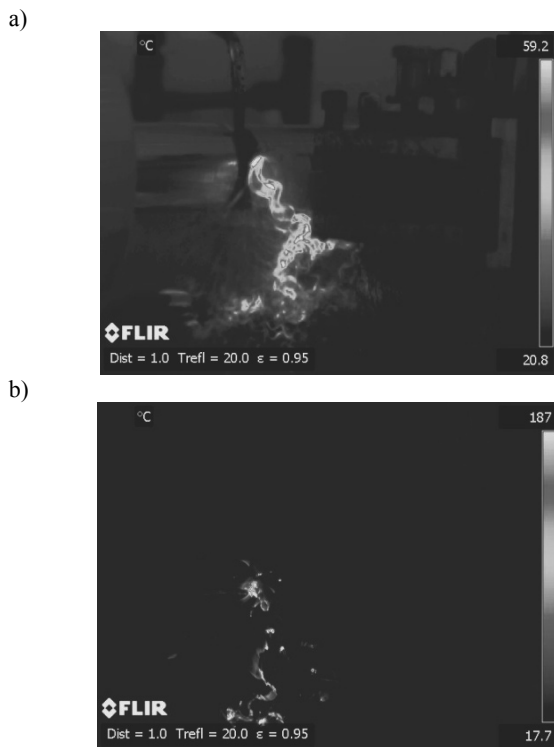


Fig. 7. Sample thermal images at $V=125$ m/min (a) and $V=230$ m/min (b) respectively

At higher cutting speed, due to high friction, high temperature is generated which results to burn the chips produced. In this stage it has been postulated that some chemical reactions have been taken place at the tool tip and the newly formed compounds are adhered with the chips as well as the tool tip. In Figure 8 the burning of the chips are clearly revealed.



Fig. 8. Burning of chips due to high temperature generation

6. Conclusions

Machining of Ti-6Al-4V is still difficult as they have some unusual properties which make the machining process more complicated. Here in this research two different types of carbide inserts have been used with varying cutting speeds to understand the effect of cutting speed on tool life. The findings of the investigation can be concluded as follows:

- 1) Cutting speed is no doubt a significant factor in assessing the tool life and it is true for both of coated and uncoated carbide inserts. As the cutting speed increases, the tool life decreases very sharply.
- 2) At lower cutting speeds, the uncoated carbide tool life is better in comparison with the tool life of coated ones while machining by using cutting fluid. As the uncoated carbide tools are cheaper, it will be more economical to use them at lower speed values.
- 3) The carbide inserts have a self-sharpening tendency at lower speeds which is more significant in uncoated carbide tools. Consequently, the surface finish improves after machining a while.
- 4) As the cutting speed increases, the surface roughness value (R_a) decreases gradually. Hence for better surface finish, higher cutting speeds are recommended but it will shorten the tool life.
- 5) Tool life is highly dependent on the application of proper cutting fluid. If the flow of cutting fluid is stopped, the tool fails very shortly. Hence wet machining is safer as compared with the dry machining and it is more sustainable.
- 6) Though the coated carbide inserts last comparatively longer than the uncoated ones, it is not economical to use any of the carbide inserts at high cutting speed. The tool life may be acceptable up to cutting speed approximately 130 m/min. Hence it is not recommended to use carbide inserts any speed higher than that value.

- 7) At higher cutting speed, the chips start to burn and the breakage of tool tip has been observed.
- 8) From this research it is expected that the effect of cutting speed on carbide tool life will be highly beneficial for machining industries especially who produce parts from Ti-alloy. It will also help them to select the right cutting tool for machining this alloy. Eventually this will help to reduce not only the machining time but also the manufacturing cost which will ensure the sustainability in their business.

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