Paper No: 3307 – 37th MATADOR Conference

Evaluation of Cryogenic CNC Milling of Ti-6Al-4V Titanium Alloy

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Abstract. Machining titanium alloys is always considered difficult due to special material properties of these alloys and the strange behaviour of the materials during machining operations. Cryogenic cooling using liquid gases has attracted considerable research since the early 20th century and is acknowledged as an effective technique for controlling the cutting temperature and improving machinability. Despite announcment of the industrial use of cryogenic milling systems, there are limited scientific studies on the effects of cryogenic cooling in CNC milling of titanium alloys. This paper presents the very first scientific attempt at studying the effects of cryogenic cooling in CNC milling of the Ti-6Al-4V titanium alloy in comparison with dry machining. A series of machining trials have been conducted at the University of Bath and it has been proven that cryogenic machining has the potential to significantly improve the machinability of titanium alloys in CNC milling with considerable reductions in surface roughness and improved tool life. Investigations revealed that the introduction of liquid nitrogen as a coolant resulted in 2.5 times improvement in surface roughness of the machined parts as compared to dry machining while a maximum increase of 1.9% in power consumption was recorded.

Keywords: Cryogenic machining; Titanium; CNC milling; Surface roughness.

1 Introduction

While pure titanium is soft and does not exhibit significant mechanical attributes, titanium alloys show superior mechanical and thermal properties. Good physical, mechanical and thermal properties of titanium alloys such as high strength to weight ratio, high yield stress, very high creep and corrosion resistivity, relatively low density, high toughness, high wear resistance and good biocompatibility have made titanium alloys attractive to many industries such as aerospace, gas turbines, nuclear, biomedical, etc. On the other hand, these properties together with poor thermal conductivity, high specific heat, work hardening tendency and high chemical reactivity with all known cutting tool materials are also responsible for the difficulties of machining titanium alloys, namely short tool life, poor surface quality, low productivity and high machining costs [1-4].

It is known that a big proportion of machining energy is transformed into heat at the cutting zone [5]. In machining titanium, due to the poor thermal conductivity and high thermal capacity of the material, the generated heat cannot be dissipated effectively through the workpiece and chips [2, 6]. Conventional cutting fluids evaporate in contact with hot surfaces and form a hot vapor film over the cutting tool surface [5, 7]. As a result, the generated heat cannot be conducted and accumulates at the cutting zone leading to high localized temperatures, causing excessive tool wear and poor surface quality. Besides these, machining titanium is also characterized by production of serrated chips. This is attributed to high dynamic shear strength and low thermal conductivity of titanium resulting in adiabatic shear banding of the chips as a result of intense shear rates during machining [8-10].

Liquefied gases such as carbon dioxide and nitrogen, also known as cryogens have been researched and identified since 1960s as effective coolants for machining titanium alloys for controlling cutting temperature and improving machinability. In addition, using liquefied gases provides an alternative to conventional oil-based coolants with lower or no environmental and health hazards [11]. While different techniques namely, workpiece cooling, indirect tool cooling and cutting zone cooling could be adopted for cryogenic machining, Hong and Zhao [12] recommended spraying small amounts of a cryogen into the cutting zone. The aim is to reduce the cutting temperature whilst preventing over hardening of the workpiece material as titanium maintains a large portion of its ductility and toughness even at -196°C. Dhananchezian and Kumar [13] reported that spraying liquid nitrogen into the cutting zone in turning Ti-6Al-4V resulted in a 66% and 49% reduction in cutting temperature and cutting force respectively as compared to conventional wet machining. In addition, they found that in cryogenic cooling conditions, cutting tools lasts longer and a 35% reduction in surface roughness could be produced. Hong et al. [11] designed a cryogenic cooling system to spray liquid nitrogen on the flank and rake faces of a carbide cutting tool in turning operations. They declared that their technique yielded more than a fivefold improvement in tool life in comparison with dry machining. Venugopal et al. [14] reported that spraying liquid nitrogen into the cutting zone in turning titanium alloy has remarkably reduced the wear growth rate of a uncoated carbide cutting tool resulting in more than three times longer tool life as compared to dry machining.

Despite the achievements of cryogenic cooling in improving machinability of titanium alloys, the vast majority of studies are focused on turning operations. The aim of this paper is to evaluate the effect of cryogenic cooling on the surface roughness of Ti-6Al-4V alloy using liquid nitrogen in CNC milling, compared with conventional dry machining. In addition, power consumption and tool wear are monitored for each of the machining test scenarios. The collected results are then statistically analysed to evaluate the effect of cryogenic cooling in CNC milling of Ti-6Al-4V alloy.

2 Methods

2.1 Workpiece

It is reported that more than 50% of all titanium alloys in the world are Ti-6Al-4V making this particualr alloy the most used titanium alloy. Almost 80% of this alloy is used in the aerospace industries. Medical prothesis are the second largest application of Ti-6Al-4V, accounting for 3% of the worlds usage [15]. As a result of the wide usage of this type of material in aerospace industries, Ti-6Al-4V is selected as the workpiece material for this research. The aerospace use of this material signifies its importance of machining processes and machining costs as it has high but-to-fly ratio (amount of rough material required to make the final product).

2.2 Cryogenic Cooling System

From the literature it has been identified that the best approach for cryogenic cooling is to spray a small amount of cryogen into the cutting zone. This is supported by the fact that titanium maintains a large portion of its toughness even at cryogenic temperatures and does not show ductile to brittle properties by lowering the temperature. In addition, as shown in fig 1.1 and 1.2, the material strength and hardness of titanium alloys such as Ti-6Al-4V increase by lowering temperature which can exacerbate machinability [16].

Unlike single point machining, in milling the cutting tool moves and the cutting zone changes place according to the movement of the cutting tool with respect to the workpiece. As a result the cryogenic cooling should be able to move in accordance to the cutting zone in order to freeze the cutting zone with the minimum amount of cryogen liquid, without over cooling or bathing the workpiece material. By considering this point, a special cryogenic nozzle has been designed by the authors at the University of Bath in order to inject a small amount of liquid nitrogen into the cutting zone along the rake face of a two flute end mill.

2.3 Design of Experiment (DOE)

Single factor full factorial design has been adopted for this research in order to compare the effects of cryogenic cooling with dry machining in a conventional endmilling process. It is clear that the single factor of the experiments is defined as machining environment or cooling system at two levels namely, dry and cryogenic. Other machining parameters including cutting speed, feed rate, immersion rate, depth of cut and machining strategy were kept constant during machining trials. The machining parameters used in this research are provided in table 1.1. The selected monitoring parameters were surface roughness, power consumption and tool wear.

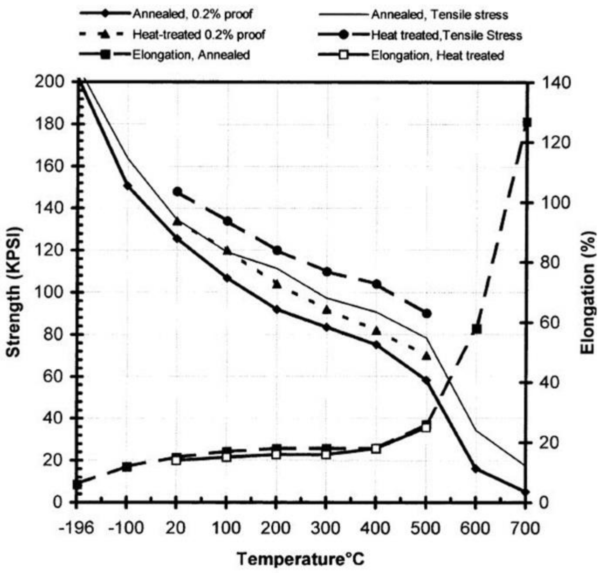

Fig. 1.1. Strength and elongation% of Ti-6Al-4V against temperature [11]

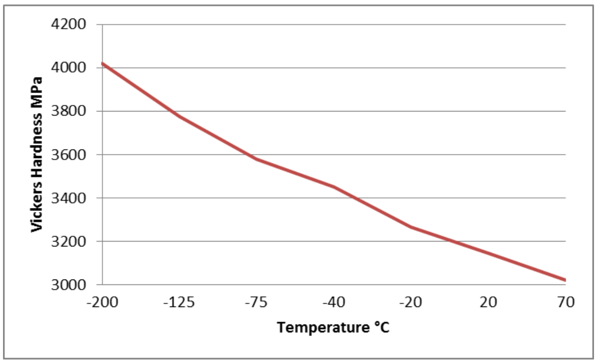

Fig.1.2. Vickers hardness of Ti-6Al-4V against temperature [11]

Table 1.1. Machining parameters used for experiments

Cutting Tool	Solid Carbide Endmill
Tool Diameter	10mm
Cutting Speed	30m/s
Feed	0.15mm/tooth
Immersion Rate	50%
Depth of Cut	1mm

3 Results and Discussion

Two machining trials under cryogenic and dry conditions with similar cutting parameters have been conducted. From these machining trials, the machined surfaces have been evaluated for arithmic surface roughness (Ra). Comparison of surface rougness, illustrated in figure 3, suggests that cryogenic cooling significantly improved the surface finish. In fact, the reduction in surface finish from an average of 2.1µm in dry machining to 0.84, cryogenic cooling resulted in a 2.5 times improvement in surface finish before tool failure. As it is shown in fig. 1.3, the start of the machining path in dry machining has a very high surface roughness which could be explained by instability of the cutting tool at the start of the cutting operation. Another notable peak in both dry and cryogenic surface roughness diagram is at the length of 55mm which is attributed to the chipping of the cutting edge of the cutting tools resulting in higher surface roughness.

In addition to surface roughness, power consumption of the CNC milling machine was monitored during the cutting operations using a Hioki 3169-20 power measurement instrument attached to the power line of the machine tool. The instrument has an overall accuracy of 0.5% and was set to measure the power consumption of the machine tool every 1 second. The power consumption of the CNC machine tool for an identical machining path was measured in three different conditions. Initially, in order to give a basis for the power consumption of the machine tool, the power consumption was measured based on the DoE tool path without cutting material. The same process was repeated while cutting Ti-6Al-4V alloy under dry and cryogenic conditions.

Statistical analysis such as t-test and Mann-Whitney revealed that the effect of cryogenic cooling on the power consumption is significant. Introduction of a cryogenic coolant in this research has resulted in up to a 1.3% increase in energy and power consumption of the machine tool. Fig. 1.4 illustrates the power consumption of the machine tool during 20 seconds of machining operation. Interestingly, from figure 4, it can be seen that cutting a titanium workpiece only results in a maximum 1.61% and 2.94% increase in power consumption of the machine tool in dry and cryogenic machining respectively. The difference between the power consumption of the machine tool when it is cutting a material and not cutting a material could be used for further investigations and modelling the heat generated at the cutting zone as a result of plastic deformation.

As shown in fig 1.5, both cutting tools used for the machining trials failed due to chipping of the cutting edges after almost equal machining length. The effect of chipping is also clear in both power consumption and surface roughness diagrams as shown in figures 3 and 4. For instance, chipping of the tool resulted in an average of 4.6% and 5.9% increase in the power consumption of the machine tool in dry and cryogenic machining respectively. This illustrates the potential of the used power measurement system to monitor the tool condition irrespective of machining environment. However while crater and flank wear was significant on the tool used for dry machining, there was no sign of wear on the flank and rake faces of the cutting tool used in the cryogenic machining experiment.

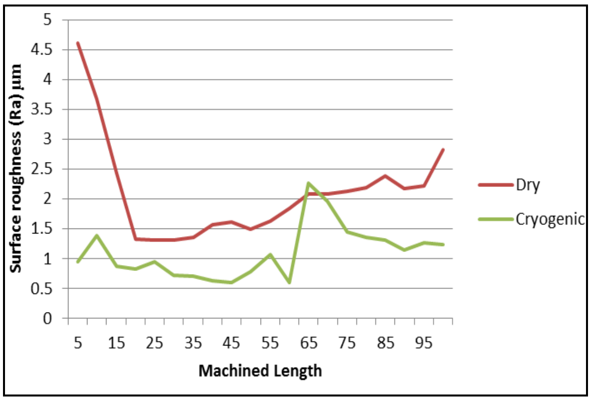

Fig. 1.2. Surface roughness of machined surfaces under cryogenic and dry condition

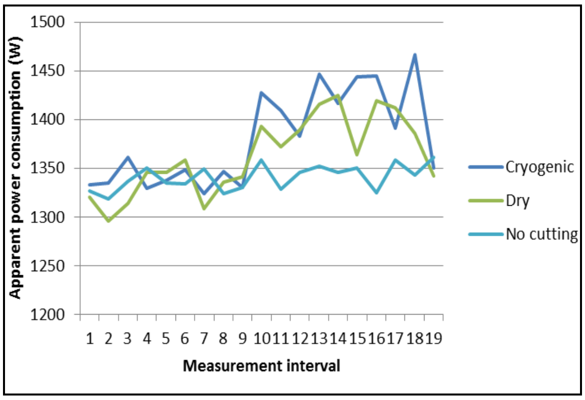

Fig 1.3. Power consumption of CNC milling machine

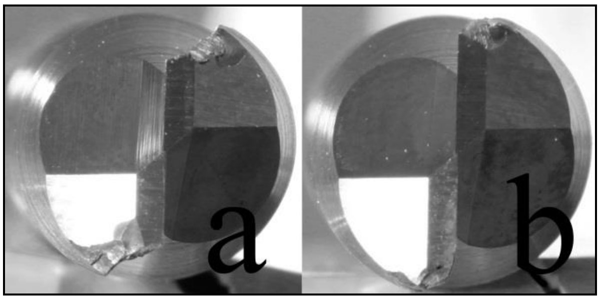

Fig 1.4. Pictorial view of the uncoated solid carbide cutting tools after machining under a) dry and b) cryogenic conditions

4 Conclusion

Study of literature has shown that despite industrial introduction of cryogenic milling systems together with a long history of cryogenic machining, there are limited numbers of scientific studies on cryogenic milling of titanium alloys. In this paper a full factorial design of experiments was used to investigate the effects of cryogenic cooling using liquid nitrogen in CNC milling of aerospace grade titanium alloy namely, Ti-6Al-4V with uncoated solid carbide tools. A series of machining trials were conducted and surface roughness of the machined test pieces and power consumption during machining operations were monitored. Analysis of the experimental results proved that cryogenic cooling is capable of improving surface finish up to 2.5 times as compared to dry machining without a notable increase in energy consumption of the machine tool. Observations of the cutting tools after machining trials shown the capabilitiy of cryogenic cooling in improving tool life by reducing tool wear. However, as sever chipping of the cutting edge was recognised as the main tool failure mechanism, quantitative study of the tool wear was not applicable.

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