EFFECT OF CRYOGENIC COOLING MEDIA ON MACHINABILITY OF BETA SOLUTION TREATED TITANIUM ALLOY TI6AL4V

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Abstract- Titanium and its alloys are considered difficult-to-machine materials due to several factors such as very high cutting temperature induced at the cutting edge during machining, its high strength at elevated temperature and strong chemical reactivity with many cutting tools. The machinability of titanium alloys was considerably influenced by the heat treatment conditions and its subsequent microstructure produced. A beta solution treatment process (BSTA) produces lamellar microstructure and mainly carried out to improve the fatigue properties of Ti6Al4V. This lamellar microstructure which is coarse produces high shear stress and in consequence produces high cutting forces and cutting temperature which leads to poor machinability. Cryogenic Machining using LN2 was carried out on beta solution treated Ti6Al4V using Taguchi design of experiment approach with L8 orthogonal array, where 3 factors viz. cutting speed, feed rate and depth of cut were varied on 2 levels. During cryogenic machining, LN2 was supplied with high pressure to the cutting zone which receives an effective cooling as well as the chip breaking takes place. The machinability was measured in terms of cutting forces and surface finish of the machined work piece. The chip mechanism study was also carried out to establish a direct relationship between machinability and heat treatment process.

Index Terms- Ti6Al4V, Beta solution treatment, Cryogenic, Taguchi, Chip Microstructure, Chip Mechanism

I. INTRODUCTION

Researchers analyzed the machining of titanium and its alloys more than two decades back. Several methods were tried out since long especially in aerospace industry in order to achieve high productivity with machining titanium. Some of these were using special oil on the cutting tool, modifying titanium properties, and introducing new cutting tool materials [1]. During machining of difficult-to-cut materials, enormous amount of heat is generated by the friction of the tool against the work piece, which is one of the major causes of rapid tool wear. High tool wear also leads to chatter and poor surface finish of the machined part. This higher cutting temperature during machining process adversely affects the machine parts quality, such as dimensional accuracy and surface quality [2]. The conventional coolant fails to penetrate in the chip-tool interface region, results in inefficient removal of heat generated. The use of cryogenic cooling in metal cutting has received renewed recent attention because liquid nitrogen (LN2) is a safe, clean, non-toxic coolant which requires no expensive disposal and can substantially improve tool life [3]. Cryogenic cooling approaches in machining can be classified into several types according to the delivery method; pre-cooling of the workpiece, tool back cooling, tool flank cooling, tool rake cooling and simultaneous rake and flank cooling. The most effective cooling approaches are; only rake cooling or flank and rake cooling. It has been agreed that these cooling techniques reduces the tool temperature and prolong its life, compared to dry cutting. [3]. In titanium alloys, various heat treatment processes produces different types of microstructure which can be or cannot be favorable to the machining process to be carried out after heat treatment. Kosaka et al. [4] analyzed the performance of Ti64 and Ti54M alloys in different heat treatment conditions, and found that their machinability is considerably influenced by the microstructure and concluded that materials with a coarse microstructure are more difficult-to-machine than the ones with a finer microstructure.

In the present work, machinability of beta solution treated Ti6Al4V alloy was analyzed using dry machining and cryogenic machining using LN2. This machinability was compared using Taguchi analysis for cutting forces, surface roughness, chip mechanism and chip microstructure.

A. Abbreviations

BSTA – Beta Solution Treatment and Annealing
Vc – Cutting speed (m/min)
ap – Depth of cut (mm)
f – feed rate (mm/rev)

II. EXPERIMENTAL DETAILS

The experimental process was divided into two steps – one is heat treatment of Ti6Al4V and other is machining trials of heat treated (BSTA) Ti6Al4V.

A. Heat treatment of Ti6Al4V

A commercial available Ti6Al4V alloy material as per standard AMS 4928 was procured in the form of round bar (Ø80 mm) in annealed condition. The beta transition temperature for the material was assumed to be 995°C. As shown in Fig.1, the microstructure of as-received material (transverse direction) shows equiaxed grains of α-phase with β-phase. The β-phase settles along the grain boundaries of equiaxed α-phase. Annealing relieves residual stresses in the material and influence grain recrys-tallization and

growth [5]. Ti6Al4V bars were subjected to beta solution treatment to improve its fatigue properties. Laboratory-scale muffle furnace was used to carry out heat treatment.



Fig.1 As Received –Microstructure

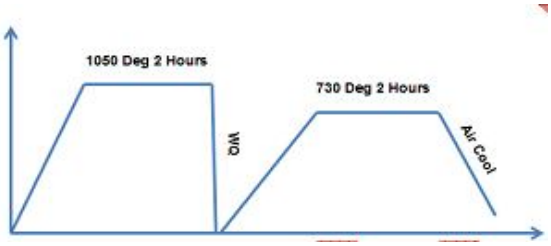


Fig. 2 Beta -Solution Treatment and Annealing

As shown in Fig. 2, in beta solution heat treatment process (BSTA) the specimen is heated above beta transus temperature up to 1050°C followed with water quenching. The water cooled samples were annealed at 730°C for 2 hours and then air cooled [6]. Table I shows the mechanical properties of the heat treated Ti6Al4V. A sample was sliced from the heat treated specimen for optical analysis. Fig. 3 shows the optical micrographs of the BSTA sample. In beta solution treatment, the heating temperature is above the beta transus temperature, which produces completely lamellar structure which is coarse, as shown in Fig. 3. This heat treatment is mainly used for the application where high fracture toughness is desired. [6-7].

TABLE I

Type of test	Properties	BSTA
Tensile Test	UTS(MPa)	1385
	YS(MPa)	1300
	%E	6.2
	%RA	10.2
	HARDNESS (HRc)	37

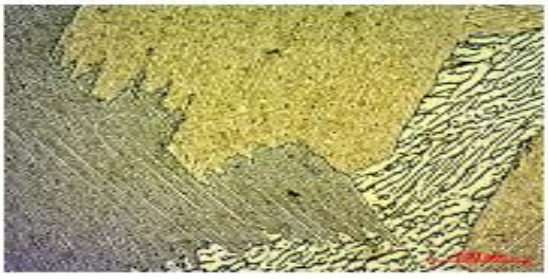


Fig.3 Microstructures of BSTA Ti6Al4V

B. Machining of BSTA Ti6Al4V alloy

As shown in Fig.4, the turning experiments were carried out on a precision lathe setup with dry and cryogenic machining using coated tungsten carbide inserts. The cryogenic system consist of 200L Dura cylinder and a thermally insulated copper tubing with a constant sized nozzle of Ø2 mm at the exit concentrating the flow of liquid nitrogen at the rake face of the cutting tool. The pressure regulator and flow meter were also used for regulating flow of LN2. During machining trials, the copper tube was manually located at closer distance to chip–tool interface and LN2 was supplied directly to the cutting zone with pressure of about 0.75MPa. In order to overcome the drawbacks of full factorial design and to search for the optimal process condition through a limited number of experimental runs, Taguchi's L8 orthogonal array consisting of 8 sets of data was selected. Both dry and cryogenic machining experiments were performed with cutting speed of 40 m/min and 80 m/min; feed rate of 0.1 mm and 0.32 mm and depth of cut of 0.4 mm and 1.0 mm. Experiments were conducted with the process parameters, as given in

Table II.

Exp. No.	Cutting Speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)
1	40	0.1	0.4
2	40	0.1	1
3	40	0.32	0.4
4	40	0.32	1
5	80	0.1	0.4
6	80	0.1	1
7	80	0.32	0.4
8	80	0.32	1



Fig.4 Experimental set up for orthogonal turning

Cutting forces were measured and recorded by using a three component piezo-electric dynamometer (Kistler Corporation Model 9257A) with a computer based data acquisition system (Dynoware). Surface finish of the machined workpiece was measured using Mahr Pocket Surf. The chips were collected after every trial with proper identification for further analysis. Inserts used for the experiment were CNMG 120408MS grade KCU10 Kennametal make with PVD TiAlN coating of deformation resistant unalloyed carbide substrate. Tool holder used was PCLNR2525M12. Chip microstructure and analysis was observed in Karl Zeiss optical microscope.

III. ANALYSIS

A. Cutting Force and Surface Finish The experimental values show that cryogenic cooling using LN2 makes a remarkable effect on the machinability of BSTA Ti6Al4V at all cutting conditions especially at high cutting speeds. During dry machining of BSTA Ti6Al4V having completely lamellar microstructure which is coarse, produces high shear stress and in consequence produces higher cutting forces and surface finish, leading to poor machinability at all cutting conditions as compared to cryogenic machining [8]. Fig. 5 and Fig. 6 shows the effect of dry machining and cryogenic machining using LN2 of BSTA Ti6Al4V on main cutting force and surface finish at all the cutting conditions.

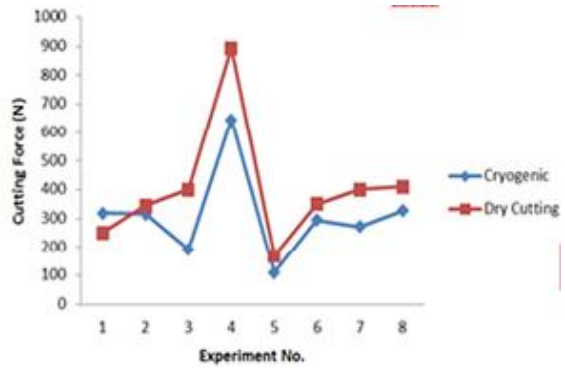


Fig.5 Effect on Cutting Forces

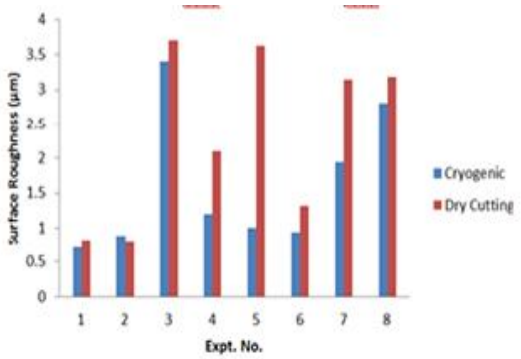


Fig. 6 Effect on Surface Finish

In general, in both machining environments, cutting force decreases as cutting speed increases. This is mainly because increase in the cutting temperature; which results in softening of the work piece material. Therefore requires lesser amount of force to shear work piece material. Also, increase in feed rate increase cutting force due to increased chip load acting on the rake face of the cutting tool [9]. In cryogenic machining using LN2, temperature in the cutting zone reduces significantly because of extreme low temperature of LN2 (-196°C). This will reduce the sticking of work piece material to the cutting tool and thereby improves tool life [9]. Performance of any component is greatly influenced by the surface finish of the any machined components. By changing feed rate from 0.1 mm/ rev to 0.32 mm/rev, in both machining environment, significant rise in the surface roughness value. In cryogenic machining, at higher cutting speeds, surface roughness gets reduced because LN2 forms very thin layer between chip and cutting tool, thereby reducing friction between chip and tool, subsequently reducing cutting force and chip breaks easily, hence produces lower surface roughness. Also due to chip breaking, accumulation of chips at chip-tool interface is less which avoids contact of chips with machined surface, further contributes towards low surface finish. At low cutting speed, this phenomenon is not that much dominant due to formation of thick layer of LN2 between chip and cutting tool. This is mainly due to the accumulation of excess LN2 in the cutting zone.

B. Taguchi Analysis

In Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value for the output characteristic [10-11]. It uses S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available depending on the type of characteristics i.e., higher-the-better, lower-the-better and nominal-the-better. Typically, smaller values of cutting force and surface finish are desirable for any machining operation. Thus, smaller the better criteria for cutting force and surface finish were selected during the present work. The Fig. 7 and Fig. 8 shows main effect plot for means of response parameters for both dry machining and cryogenic machining of BSTA Ti6Al4V.

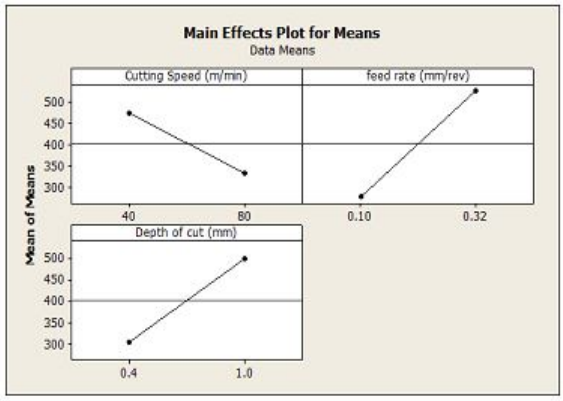


Fig.7 Plot for means for Dry Machining

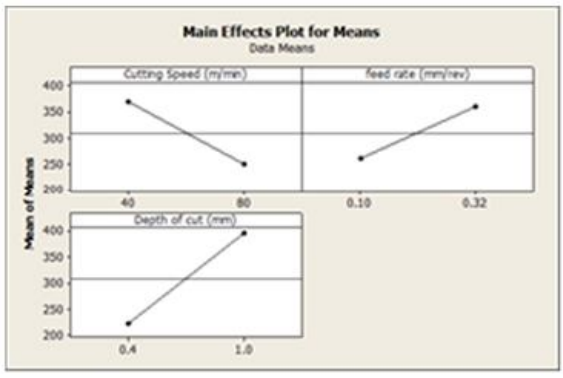


Fig. 8 Plot for means for Cryogenic Machining

From the main effect plots for means shown in Fig. 7 and Fig. 8, it has seen that feed rate has the greatest influence on mean, followed by depth of cut and cutting speed for both dry as well cryogenic machined Ti6Al4V samples. In cryogenic machining of BSTA Ti6Al4V, reduction in the magnitude of cutting forces is observed. Also, the influence of feed rate on the output parameter is greatly reduced. This S/N ratio shows that cryogenic machining of BSTA Ti6Al4V is more efficient at higher cutting speed and feed rate as compared with dry machining of the same.

C. Chip Mechanism and Microstructure:

Chip mechanism and chip control has greater importance in the metal cutting. One of the important ways to improve the machinability of titanium alloys involves influencing deformation mechanism during machining. Deformation mechanism in machining changes with microstructure, mechanical properties and β phase fraction of the titanium alloys. [12 -13].

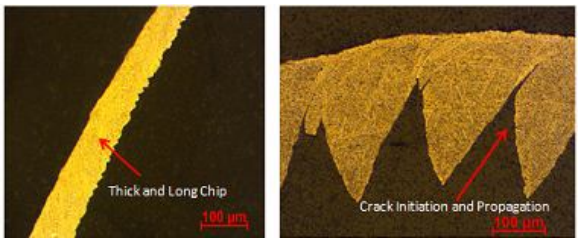


Fig.9 Chip Mechanism in cryogenic machining at Vc = 40 m/min a) f = 0.1 mm/rev b) f = 0.32 mm/rev

Fig. 9 shows the chip microstructure produced during cryogenic machining at lower cutting speed of 40 m/min with different feed rate. It is found that at feed rate of 0.1 mm/ rev, long and thick tabular chips are formed. These chips got accumulated in the chip-tool interface area and cause hindrance to the machining process, resulting in poor tool life and surface finish. Also, small sized cracks are observed at the chip surface which propagates to a smaller depth toward tool end. Thus, it shows that deformation occurs only by thermal softening with no crack formation along the shear plane [14]. When we increase feed rate to 0.32 mm/rev, chip are segmented with crack initiation and propagation at some shear planes. This shows that during cryogenic machining at low cutting speed, deformation mechanism shifted to thermal softening and crack formation from only by thermal softening as we increase the feed rate.

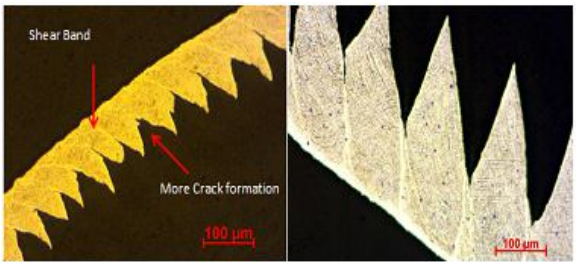


Fig.10 Chip Mechanism at Vc = 80 m/min and f = 0.32 mm/rev a) Cryogenic machining b) Dry machining

At high cutting speed of 80 m/min, in cryogenic machining, large part of deformation is by crack formation at shear plane with small part with thermal softening, as shown in Fig. 10 a. These cracks propagate to a larger depth towards tool end. A large size of crack at the free surface shows increase in the normal stresses on the shear plane. The same is also confirmed by the formation of triangular segments which corresponds to higher intensity of normal stresses acting on the shear plane. During dry machining at higher cutting speed, deformation mechanism occurs by combination of thermal softening and crack formation, shown in Fig 10 b. The chip segment also appears to be trapezoidal in shape which contributes towards more cutting force and more surface finish as compared with cryogenic machining. Thus, at high cutting speed and feed rate cryogenic machining shows better performance than dry machining. In cryogenic machining of BSTA Ti6Al4V, short tabular and curled chips are observed, which contributes towards better machinability. This use of cryogenic coolant also helps in washing out the metal chips from the cutting zone more effectively, which in turns helps to achieve better surface finish.

CONCLUSION

The current study shows that cryogenic machining environment make a remarkable effect on the machinability aspect of BSTA Ti6Al4V. In dry machining of BSTA Ti6Al4V, which has coarse lamellar microstructure shows poor machinability as compared to cryogenic machining because of high shear stress, higher cutting forces, and more thermal softening whereas in cryogenic machining, the nitrogen gas at high pressure helps to cool the cutting zone effectively as well as break the chip away easily. It also provides better lubrication between tool-chip and tool-work piece interfaces due to formation of fluid gas as a result of evaporation of LN2. More ever, cryogenic machining is more beneficial at higher cutting speed and feed rate because it reduces the cutting temperature and resulting less cutting forces and very good surface finish. Also, at these parameters chip Microstructure shows more amount of crack formation. At low cutting parameters cold strengthening of titanium material might increase the cutting force in cryogenic machining. The Taguchi analysis for dry machining concluded that during machining of Ti6Al4V alloy, feed rate is the most influencing factor followed by depth of cut and cutting speed. The effect of most influencing parameter i.e. feed rate in machining of titanium alloy is significantly reduced in cryogenic machining of BSTA Ti6Al4V.

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