CORRELATION BETWEEN HEAT TREATMENT, MICROSTRUCTURE AND MACHINABILITY FOR TI6AL4V

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Abstract- Titanium alloys are one of the most difficult materials to machine because of their low thermal conductivity and high chemical reactivity which leads to high cutting temperatures and tool wear. This paper focuses on machinability assessment of titanium alloy Ti6Al4V under 3 different heat treatment conditions using turning operation. The experiments were planned using Taguchi design of experiment approach and using L8 orthogonal array, where cutting speed, feed and depth of cut were varied on 2 levels. The machinability was measured in terms of cutting forces and surface finish of the machined workpiece. The chip mechanism and chip microstructural study was carried out to establish a direct relationship between machinability and heat treatment processes.

Index Terms- Chip Mechanism, Chip Microstructure, Heat Treatment, Ti6Al4V

I. INTRODUCTION

Titanium has been an attractive metal for various engineering applications like military, aerospace, automotive, energy and marine constructions because of its higher strength-to-weight ratio, lower density, good corrosion and fatigue resistance, etc. [1-2]. However, most of the engineering applications use titanium components after suitable heat treatment based on the requirement. These heat treatment processes produces different types of microstructures which can be or cannot be favorable to the machining process to be carried out after the subsequent heat treatment. Kosaka et al. [3] analyzed the performance of Ti64 and Ti54M alloys in different heat treatment conditions, and found that their machinability was considerably influenced by the microstructure and concluded that materials with a coarse microstructure were more difficult-to-machine than the ones with a finer microstructure. Navneet Khanna et al. [4] analyzed the effect of heat treatment conditions on the machinability of Ti64 and Ti54M alloys. They further concluded the correlation between heat treatment, microstructure and the chip mechanism after machining. Satyanarayana Kosaraju et.al, [5] worked on Taguchi analysis of cutting forces and temperature in turning titanium Ti-6Al-4V. It has been shown that cutting force and temperature can be reduced significantly for turning operation by conducting experiments at the optimal parameter combination and also by analyzing S/N ratio [5-6]. In this work, machinability of Titanium alloy Ti6Al4V after various heat treatments was analyzed using taguchi analysis and validated using chip mechanism and chip microstructure.

A. Abbreviations

M_s – Martensitic start temperature
V_c – Cutting speed (m/min)
a_p – Depth of cut (mm)
f – feed rate (mm/rev)

II. EXPERIMENTAL DETAILS

A. Heat treatment

Titanium Ti6Al4V raw material with AMS 4928 was procured in the form of round specimen (Ø80 mm) in annealed condition. The beta transition temperature for the material was assumed to be 995^0C. As shown in Fig.1, the as-received micro sample (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 recrystallization and growth [7]. The experimental procedure involves heat treatments, tensile tests, and metallography. Ti-6Al-4V specimens were subjected to 3 different heat treatment processes, viz., mill annealing, solution treatment and beta solution treatment. For heat treatment trials laboratory-scale muffle furnace was used.

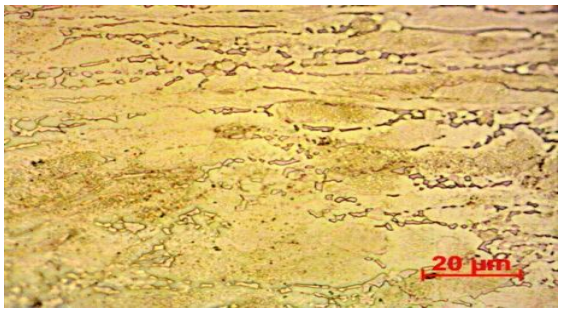


Fig.1 As Received –Microstructure

As shown in Fig. 2 in mill annealing (MA) heat treatment process the specimen was heated to 730 °C for 2 hours followed with air cooling [7]. In solution treatment and annealing (STA), the specimen was

heated to a temperature which was 30 deg less than beta transus temperature to 955 °C followed with water quenching. In next annealing cycle it was further heated to 730 °C for 2 hours followed with air cooling [8], as shown in Fig. 3.

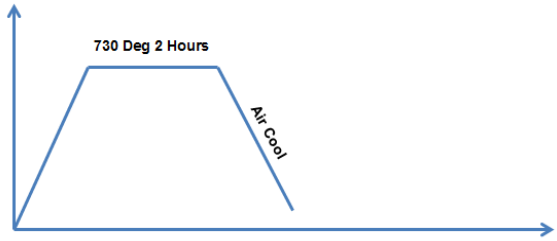


Fig.2 Mill Annealing (MA)

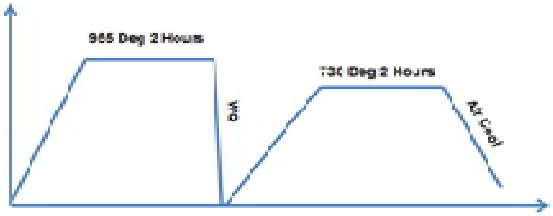


Fig.3 Solution Treatment and Annealing (STA)

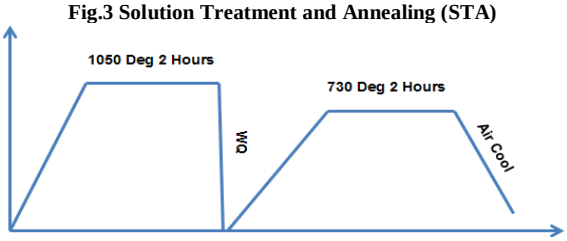


Fig.4 Beta -Solution Treatment and Annealing

As shown in Fig.4 in beta solution heat treatment process (BSTA) the specimen was heated above beta transus temperature to 1050 °C followed with water quenching. In next annealing cycle it was further heated to 730 °C for 2 hours followed with air cooling [8]. Table 1 shows the mechanical properties of the heat treated samples. A small sample was sliced from the heat treated specimen for optical analysis. Fig. 5 shows the optical micrographs of the 3 heat treated samples.

TABLE I – MECHANICAL PROPERTIES

Type of test	Properties	MA	STA	BSTA
Tensile Test	UTS(MPa)	976	997.7	1385
	YS(MPa)	916	937.8	1300
	%E	16.7	14.86	6.2
	%RA	38.2	41.0	10.2
	HARDNESS (HRc)	34.2	36.7	37

In mill annealing heat treatment process, as the heating temperature was well below Ms Temp, the retained beta phase as shown in Fig 5a, helps to maintain the ductility. In Solution treatment and annealing (STA) process, the heating temperature was just below beta transus temperature, followed with water quenching which resulted into formation of transformed beta, as shown in Fig. 5b. The subsequent aging/annealing process forms the precipitation of alpha, leading to higher workpiece hardness and strength [8-9]. In beta solution treatment, the heating temperature was above the beta transus temperature, which produces completely lamellar structure as shown in Fig. 5c. This heat treatment is mainly used for the application where high fracture toughness is desired. [8-9].

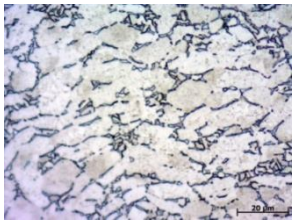


Fig.5a MA

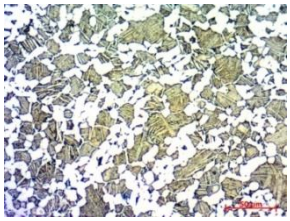


Fig.5b STA

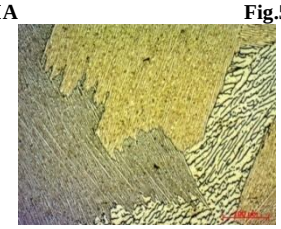


Fig.5c BSTA

Fig.5a-c Microstructures after heat treatment

B. Machining

As shown in Fig.6, the turning experiments were carried out on a precision lathe setup. Dry cutting was performed using coated tungsten carbide cutting tools for heat treated titanium alloy (Ti-6Al-4V) specimen.

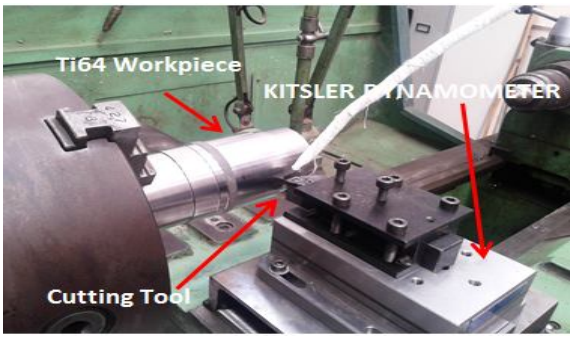


Fig.6 Experimental set up for OD turning

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. Experiments were conducted with the process parameters, given in Table II.

Table II – MACHINING PARAMETERS

Parameters	Level 1	Level 2
Cutting Speed (m/min)	60	80
Feed rate (mm/rev)	0.1	0.2
Depth of cut (mm)	0.5	1.5

Cutting forces were measured by a three component

piezo-electric dynamometer (Kistler Corporation Model 9257A) and the surface finish of the machined workpiece was measured using Mahr Pocket Surf. The chips and inserts were collected for each 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. The experimental values show that the heat treatment condition makes a re-markable effect on the machinability of Ti6Al4V.

III. ANALYSIS

A. 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 [5-6]. 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 forces and surface roughness are desirable for any machining operation. Thus, smaller the better criterion was selected during the present work. Fig. 7a, Fig. 7b and Fig, 7c shows main effect plot for means of cutting forces as a response parameter.

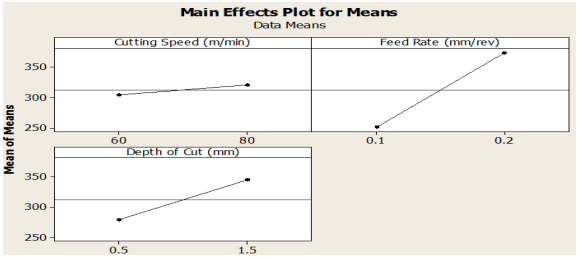


Fig.7a MA

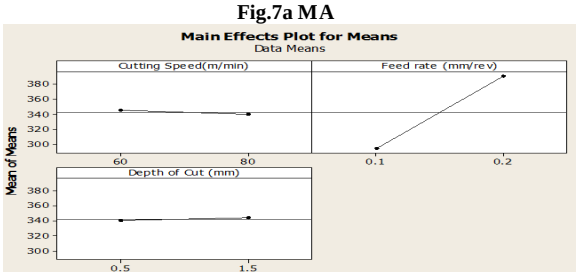


Fig.7b STA

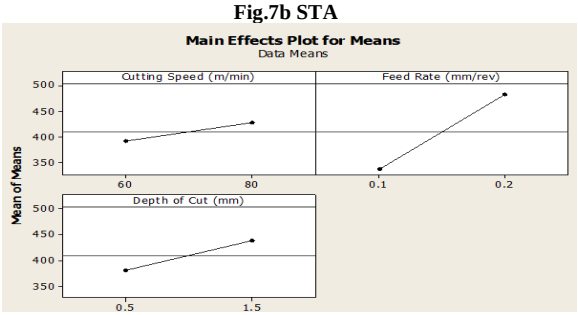


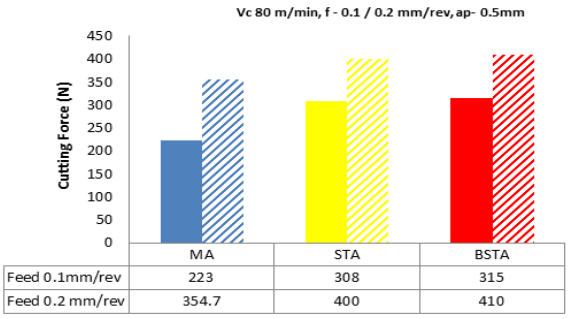
Fig.7c BSTA

Fig.7a-c Main Effect Plots for Means

From the main effect plots for means, it has seen that the feed rate has the greatest influence on cutting forces followed by depth of cut and cutting speed for all 3 heat treated and machined samples. However, the magnitude of mean of means for cutting forces was much higher for beta solution treatment than that of mill annealed and solution treatment. For better machinability, reduction in cutting forces and surface roughness are essential [1]. Hence the factor level that produces the lowest mean needs to be selected during machining of heat treated Ti6Al4V.

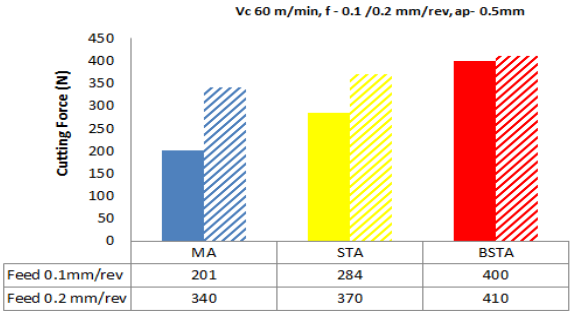
B. Experimental Analysis

Fig. 8 and Fig. 9 shows that, at all the cutting speeds; 60m/min - 80m/min and all the feed rates; 0.1-0.2 mm/rev, with same depth of cut of 0.5 mm, the beta solution treatment produced highest cutting forces when compared to mill annealed and solution treatment. However, effect of increase in feed rate on cutting forces and surface roughness was clearly visible during machining of all the heat treated samples. It indicates that higher feed rate has contributed more in increase in cutting temperature during machining. In mill annealing heat treatment process, the re-tained beta phase helps to maintain the ductility and correspondingly shows better machinability through less cutting forces and surface roughness. In Solution treatment and annealing (STA) process, formation of transformed beta and precipitation of alpha leads to higher workpiece strength. In beta solution treatment, a completely lamellar structure which can produces high shear stress and in consequence higher cutting forces, leading to poor machinability [4].



(V_c 80m/min, f- 0.1/0.2 mm/min, a_p- 0.5mm)

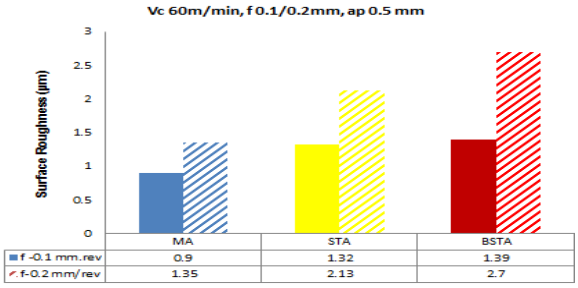
Fig. 8 Effect of MA, STA, BSTA on cutting forces



(V_c 60m/min, f- 0.1/0.2 mm/min, a_p- 0.5mm)

Fig. 9 Effect of MA, STA, BSTA on cutting forces

The surface finish of the machined surface is one of the important response parameter in machinability assessment. This is because any change in machining process such as change in cutting forces, cutting temperature and tool wear will affect the machined surface topography. As shown in Fig.10, at a cutting speed of 60 m/min and feed rates 0.1-0.2 mm/rev, similar trend was observed for beta solution treated workpiece which shows higher surface roughness when compared to mill annealed and solution treated specimen. Increase in feed rate from 0.1mm/rev to 0.2 mm/rev has resulted into increased amount of friction leading to higher cutting temperature which contributed to BUE formation leading to poor surface finish.



(V_c 60m/min, f- 0.1/0.2 mm/min, a_p- 0.5mm)
Fig. 10 Effect of MA, STA, BSTA on cutting forces

C. Chip Mechanism

In this quantitative analysis of chip mechanism, as shown in Fig.11, chip thickness, segment width, chip compression factor were discussed and their significance was correlated with the machinability [1]. The generation of thicker, uneven chips is not favorable for high quality machining as these chips affects the tool cutting area, resulting in non - uniform friction and generating high cutting temperature, high cutting forces and rapid tool wear, etc. Width of segment represents the spacing between shear bands, as the shear bands are formed at the beginning and at the end of each segment [1-2]. Higher the segment width less is the number of shear band formed which is desirable for better machinability.

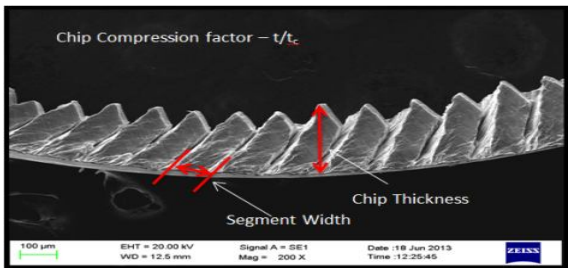


Fig.11 Chip Mechanism

Chip compression factor is the ratio of chip thickness to uncut chip thickness. A minimum chip compression ratio is always desirable to ensure better machinability of titanium alloy [1-2].

As shown in the Table III (a) and Table III (b), mill annealed sample produces less thickened chip, more segment width and less chip compression factor followed by solution treated and beta solution treated specimen. Table III (a) and Table III (b) also showed the effect of feed rate in chip mechanism. With the increase in the feed rate, there was an increase in chip thickness which resulted into higher cutting forces; decrease in segment width which further resulted into more amount of thermal softening and more number of shear band formations leadingto excessive tool wear. Also, higher chip compression factor resulted to higher plastic deformation leading to poor machinability for BSTA specimen [1-2].

Table III:CHIP MECHANISM ANALYSIS

Table III (a) V_c – 60m/min, f – 0.1mm/rev, a_p-0.5mm

Sample	Chip Thickness (µm)	Segment Width (µm)	Chip Compression factor (µm)
MA	504	74.278	1
STA	578	68	1.156
BSTA	678	32	1.358

Table III (b) V_c – 60m/min, f – 0.2 mm/rev, a_p-0.5mm

Sample	Chip Thickness (µm)	Segment Width (µm)	Chip Compression factor (µm)
MA	550	70	1.1
STA	669	47	1.338
BSTA	1310	31	2.62

D. Chip Microstructure

Chip microstructure reveals various important aspects of actual machining conditions [1-2]. Chip microstructure consists of shear bands, crack formation, grain deformation, etc. Shear bands in the chip microstructure represent localized deformation of material in narrow zones. The surrounding area of shear band remains unaffected. This localization of shear band leads to drastic changes in cutting forces which can affect the cutting tool performance [1]. In the MA chips, as shown in Fig. 12, the shear band formation was very less, however as shown in Fig.13, in STA and BSTA, long branching and twin shear band formation was observed. These shear bands leads to increased fluctuations in cutting forces [1].

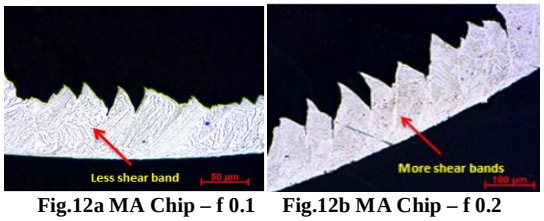


Fig.12a MA Chip – f 0.1 Fig.12b MA Chip – f 0.2
Fig. 12 MA Chip Microstructure
(V_c – 60m/min, f – 0.1/0.2 mm/rev, a_p-0.5mm)

However, with an increase in the feed rate from 0.1mm/rev to 0.2 mm/rev, as shown in Fig. 12b, and Fig. 13b, the shear band formation was increased with more deformed grains, which increases the abrading forces on the cutting tool.

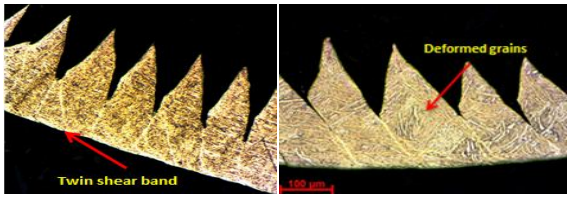


Fig.13a STA Chip – f 0.1 Fig.13b STA Chip – f 0.2
Fig. 13 STA Chip Microstructure
(V_c – 60m/min, f – 0.1/0.2 mm/rev, a_p-0.5mm)

For MA and STA chips more triangular segment formation was observed which shows that the deformation mechanism was carried out less by thermal softenting and more by crack formation. This crack formation was mainly because of higher normal stresses acting at the shear plane. For BSTA chips as shown in Fig.14a and Fig.14b, more trapezoidal segment formation was observed which showing that the deformation mechanism was dominated less by crack formation and more by thermal softening. This thermal softening was mainly because of the branched shear bands formed at the segment base which further resulted into delayed fracture of the segments, as shown in Fig.15a and Fig.15b.

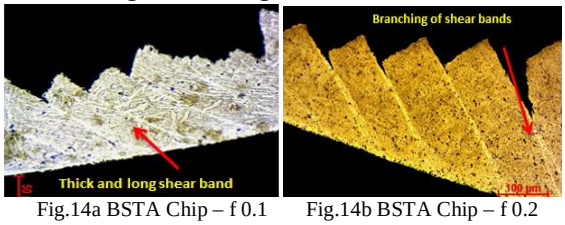


Fig.14a BSTA Chip – f 0.1 Fig.14b BSTA Chip – f 0.2
Fig. 14 BSTA Chip Microstructure
(V_c – 60m/min, f – 0.1/0.2 mm/rev, a_p-0.5mm)

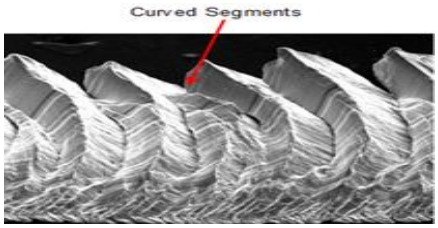


Fig.15a SEM image for curved BSTA chip

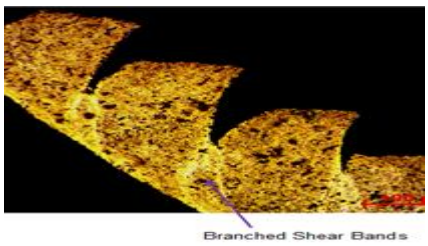


Fig.15b Optical image for curved BSTA chip

CONCLUSION

The current study shows that the heat treatment processes and the corresponding microstructure produced make a remarkable effect on the machinability aspect of Ti6Al4V. It has seen that the lamellar microstructure in beta mill annealed input condition leads to high shear stresses and correspondingly higher cutting forces. Deformation mechanism in BSTA input condition was mainly carried out by excessive thermal softening which has resulted into poor surface finish. Thus beta solution treatment produces poor machinability than that of mill annealed and solution treated input condition. The Taguchi analysis concluded that during machining of Ti6Al4V alloy, feed rate was the most influencing factor followed by depth of cut and cutting speed

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