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Effect of heat treatment conditions on the machinability of Ti64 and Ti54M alloys

Navneet Khanna[a]*, Ainhara Garay[b], Luis M. Iriarte[b], Daniel Soler[b], Kuldip S. Sangwan[a] and Pedro J. Arrazola[b]

[a]*Mechanical Engineering Department, Birla Institute of Technology and Science, Pilani-333031, India*
[b]*Manufacturing Department, Faculty of Engineering, Mondragon University, Mondragon, Spain*
* Corresponding author. Tel.: +91-978-501-1178; E-mail address: khanna@bits-pilani.ac.in

Abstract

Orthogonal tests on cylindrical workpieces were carried out to analyze the effect of heat treatment on the machinability of newly developed Ti54M titanium alloy in comparison with Ti64. This paper focuses on the comparison of forces and temperature of the tool during dry orthogonal cuttings of Ti64 and three different heat treated Ti54M alloys. Forces and temperature are mainly affected by variation in cutting speed and feed, therefore, the depth of cut is maintained constant while cutting speed and feed are varied. Forces and temperature have been measured and chips are analyzed to establish a direct relationship between machinability and the different heat treatment conditions.

Keywords: Titanium alloys; Heat treatment; Microstructure; Cutting forces; Temperature; Chips

1. Introduction

The demand for the titanium alloys has increased because of its large consumption in the aerospace sector as the outstanding strength-to-weight ratio of titanium alloys provides a decrease in weight and, consequently, a reduction in fuel consumption and emissions. The most common titanium alloy Ti64, accounts for more than 50% of the titanium-alloy production [1, 2]. Titanium alloys are one of the most difficult materials to machine because of their low conductivity, which leads to high cutting temperatures and its chemical reactivity with tool materials. The machining of titanium alloys is one of the biggest challenges for their application [3]. However, in order to increase the machinability, new titanium alloys are being developed. One of those new alloys is TIMETAL®54M (Ti54M), developed by TIMET, an alpha-beta alloy with superior machinability and strength comparable to similarly processed Ti64 [1].

Kosaka and Fox [4] and Kosaka et al. [5] 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-cut than the ones with a finer microstructure. They found that the machinability of Ti54M is better than Ti64. Venkatesh et al. [6] found better machinability of Ti54M over Ti64 at high cutting speeds. Armendia et al. [1, 7] concluded that, the difference in microstructure was the reason for the better machinability of the Ti54M alloy. However, Rahim et al. [8] investigated the performance of Ti64 and Ti54M alloys during drilling operation and concluded that Ti64 exhibit superior machinability than Ti54M, considering the better tool life performance. It is noticed that in most of the above research findings; Ti54M always has finer microstructure than Ti64 and microstructure depends on the heat treatment. It suggests that the variation in the machinability must be linked to the difference in microstructure.

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Table 1. Chemical composition and Beta transus of the Titanium alloys

Titanium alloy	Chemical composition (Weight %)					Transus β (ºC)
	Al	Mo	V	Fe	O	
Ti 64	6	-	4	0.15	0.18	995
Ti54M	5	0.8	4	0.5	0.18	966

Table 2. Heat treatment conditions and mechanical properties for the analyzed titanium alloys

Material	Heat treatment	Tensile properties			
		UTS (MPa)	TYS (MPa)	EL (%)	RA (%)
Ti64	Annealed 705°C	990	910	18	39
Ti54M	Annealed 705°C	935	860	23	49
Ti54M	Beta annealed (990°C - 1h water quench + 730°C -2h)	940	840	11	22
Ti54M	STA (920°C - 1h-water quench+ 500°C - 4 h)	1070	960	19	52

In this work, machinability dependence on heat treatment conditions i.e. microstructure has been studied. In order to analyze the effect of microstructure, comparison of the machinability of the newly developed Ti54M alloy in three different heat treated conditions vis-à-vis the extensively used Ti64 alloy is presented. Firstly, the experimental plan and set up including the microstructure of the investigated titanium alloys are presented, then, the results of the experiments are analyzed, and finally, conclusions of the research are highlighted.

2. Experimental Plan and Setup

This section presents the characteristics of the materials for the experiments and the experimental arrangement.

2.1. Workpiece material

Both Ti54M and Ti64 alloys belong to the α + β alloy group. These alloys have very similar chemical composition as shown in Table 1. Due to the presence of higher concentration of β stabilizers (Fe, V and Mo), in Ti54M alloy, the β transus temperature is almost 30^{0}C lower than that of Ti64.

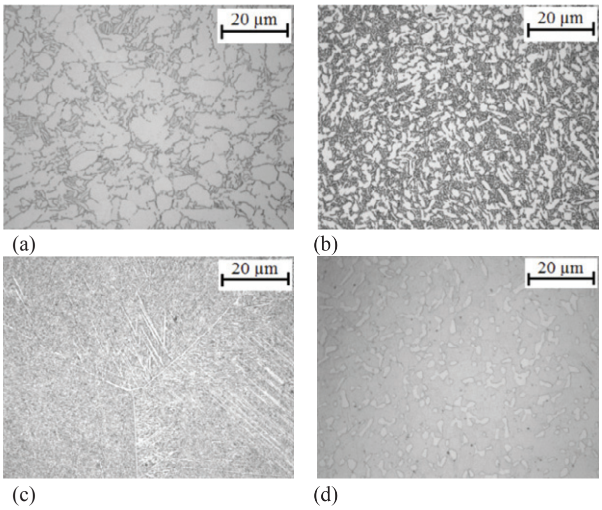


Fig.1. Microstructure of (a) Ti64; (b) Ti54M annealed; (c) Ti54M Beta annealed; (d) Ti54M STA alloys

The workpieces are cylinders with external diameter of 48 mm, and 2 mm of wall thickness, made of heat treated (Table 2) Ti64 annealed, Ti54M annealed, Ti54M Beta (β) annealed and Ti54M solution treated and aged (STA) alloys having Rockwell hardness of 31±3 HRC, 31±3 HRC, 35±3 HRC and 37±3 HRC respectively. It can be seen in Fig.1 that Ti64 and Ti54M alloys in different heat treated conditions show considerable differences with reference to the morphology and volume fraction of the primary α phase.

Thus, Ti64 annealed (Fig.1a) contains coarse α primary grains; Ti54M annealed (Fig.1b) contains much finer primary grains of α; Ti54M beta annealed (Fig.1c) consists of large colonies that contain laths of α and β; and Ti54M STA (Fig.1d) consists of whiter particles of primary α in a transformed β matrix. Aging of this alloy resulted in α precipitation.

2.2. Machining arrangement

Orthogonal dry machining was conducted on a Lagun vertical CNC milling machine. Orthogonal tests of 5 s duration were conducted, and three trials were carried out to determine the results uncertainty. The workpieces were rotated in the spindle of the machining center which was then fed toward the fixed cutting tool to produce an orthogonal cut (Fig.2).

All the alloys were machined at two different cutting speeds (40 and 80 m/min) and three different feed rates (0.1, 0.15 and 0.25 mm/rev), keeping all other parameters constant.

The tungsten carbide cutting tools are extensively used in industrial applications and recognized as the best tool material to machine titanium alloys [3]. Thus, a tool insert from Sandvik, that's CNMG 160408-23 H13A type carbide (K15 grade) was employed.

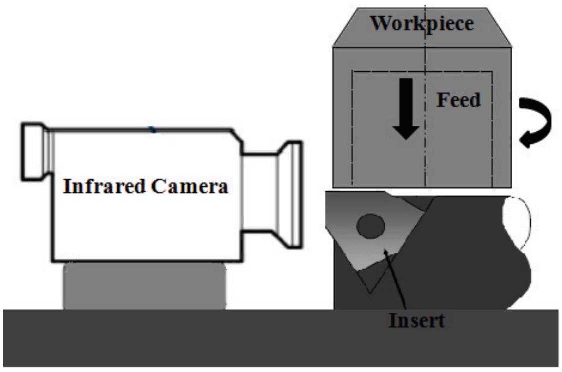


Fig.2. Schematic of experimental set-up

All the applied inserts have been examined by a sensofar PLμ optical profiler in order to control the cutting edge, which was maintained within 34±2 μm.

All the cutting conditions and tooling details are given in Table 3.

A 3-component dynamometer (Kistler 9121) was placed under the tool holder to record the dynamic changes in the cutting forces throughout the testing. To ensure edge sharpness, a new tool insert has been used in each test. A micro thermal imaging system comprising of a FLIR Titanium 550 M infrared camera and a microscopic lens offering a resolution of 10 μm were used to measure temperatures during the orthogonal cutting of all alloys on the cutting edge.

Table 3. Cutting conditions with tooling summary

Cutting conditons	Cutting speed = 40 and 80 m·min^{-1}
	Undeformed chip thickness (t_1) = 0.1 – 0.15 – 0.25 mm
	Depth of cut (p) = 2mm
Cutting tools • Tool holder (DCLNR 2525 M12) • Tool insert CNMG 160408-23 H13a	Rake angle (γ_0) = 7º
	Cutting edge inclination angle (λ_s) = 0º
	Cutting edge angle (κ_r) = 0º
	Corner radius (r_ε) = 0.
	Cutting edge roundness (r_β) = 34±2 μm
	Chip breaker= -15
	Grade = (h13a) k15 micrograin
Coolant	Dry
Workpiece dimensions	Outer diameter = 48mm
	Inner diameter = 44mm
Machine tool	Lagun CNC vertical milling machine

The tool emissivity, as a function of wavelength and temperature was measured with a Fourier transform infrared spectrometer [7], measured filtered radiation had a wavelength range of 3.97-4.01 μm, this allows to obviate the wavelength dependence and only the influence of temperature was taken into account; a different value of emissivity was applied to each pixel depending on its background temperature, the average value of emissivity for the ground carbide was 0.34.

Chips collected in order to study the microstructure and segmentation phenomena.

3. Results and Discussion

3.1. Specific forces

The specific cutting (K_c) and specific feed (K_k) forces for all the analyzed titanium alloys at cutting speeds of 40 and 80 m/min are shown in Fig.3 and Fig.4, respectively. Results plotted for the specific forces represent the average values observed from the experimental tests. The uncertainty (± 10N) is disclosed by the error bars.

It can be seen from Fig.3 and Fig.4 that the specific cutting force decreases with the increase in feed rate. This trend is followed in all heat treatment conditions. However, the difference among the cutting forces is higher at higher feed rates for all alloys. The highest specific cutting forces were noticed for Ti54M Beta annealed at high feed rates. The lower specific cutting forces were observed for Ti54M STA at 80m/min cutting speed.

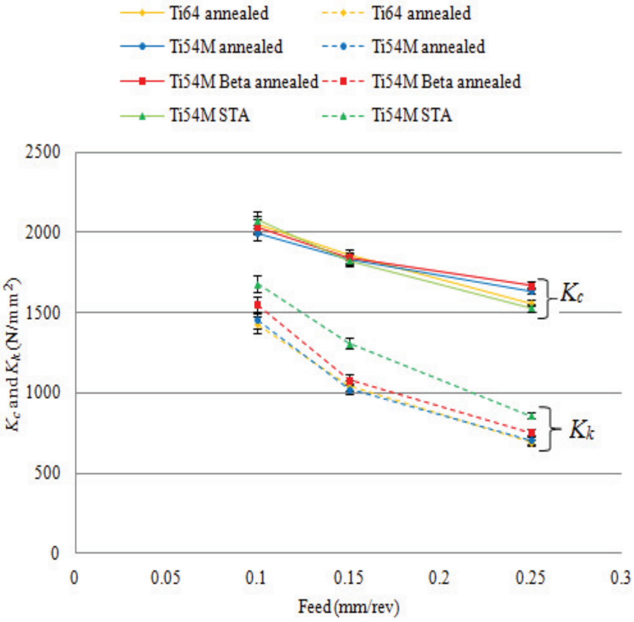


Fig.3. Specific cutting (K_c) and specific feed (K_k) forces for all titanium alloys at cutting speed=40 m/min

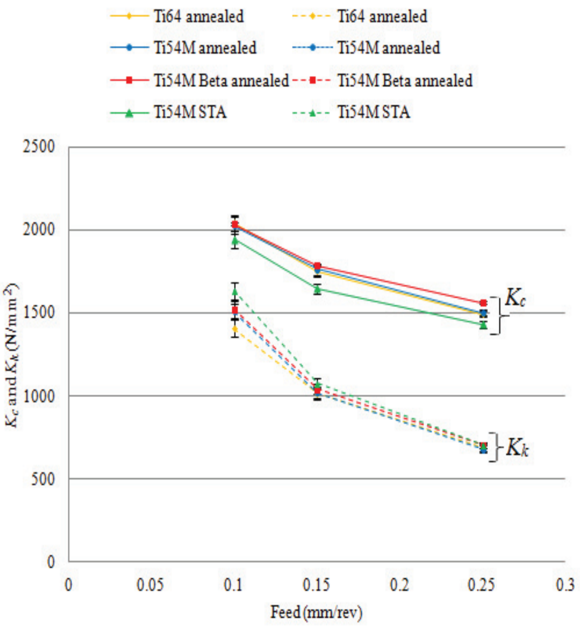
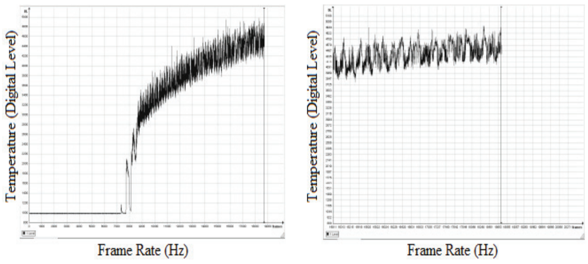


Fig.4. Specific cutting (K_c) and specific feed (K_k) forces for all titanium alloys at cutting speed=80 m/min

Same trend was observed at cutting speed of 40m/min except at lower feed rate, where Ti54M STA showed highest value. In addition, all the titanium alloys show steady decrease in specific cutting force even when hardness and tensile strength differ due to the different heat treatment conditions. The higher specific cutting force achieved in the machining of the Ti54M Beta annealed condition may be due to it's completely laminar microstructure (Fig.1c) with very coarse microstructure. This rough laminar microstructure seems to produce higher shear stress and in consequence higher cutting force [5].

Variation in the specific feed force follows the same trend and decreases rapidly with the increase of feed rate and gets almost halved on increasing the feed value from 0.1 to 0.25 mm/rev. At cutting speed of 40m/min; the highest specific feed forces were observed for Ti54M STA followed by Ti54M Beta annealed alloys. Same trend was observed at cutting speed of 80m/min except at higher feed rate, where both the alloys showed same value of specific feed force. The specific feed force (K_k) values correlated well with the mechanical properties of the alloys, as higher values were obtained for the Ti54M STA alloy. High hardness of Ti54M STA is the reason for it's high specific feed forces and this high hardness is resulting from the precipitation of α during the aging process carried out after solution treatment. The increase in specific forces with decreasing feed rates is due to the size effects of the cutting edge. It is observed that the specific feed forces are more sensitive to change in feed rate than specific cutting forces.



(a) (b)

Fig.5. Temperature timing graph at digital level (a) for 5 sec; (b) for last 1 sec of the cut

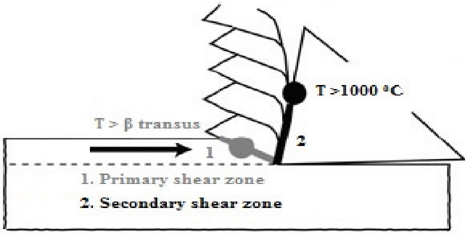


Fig.6. Illustration of cutting zone details

Clear influence on specific feed (K_k) forces has been observed for the Ti54M with STA heat treatment condition. The other heat treatments did not seem to have a clear influence on the forces.

3.2. Temperature

While the temperature has been measured during entire cutting process of 5 sec duration (Fig.5a), the temperature values were extracted for the last 1 sec of cut because, as shown in Fig.5 (b), it is closer to a stationary behavior. Fig.6 shows cutting zone details. The cutting tool temperature for all the analyzed titanium alloys at cutting speeds of 40m/min and 80m/min are shown in Fig.7.

Results plotted for temperature represent the average values observed from the experimental tests. The uncertainty in thermal measurements is revealed by the error bars.

Titanium alloys have low thermal conductivity and therefore, heat generated during chip formation cannot be effectively dissipated into the material surrounding the primary shear zone and it leads to high temperature values in the primary shear zone [9]. This high temperature can reach above β transus temperature (Fig.6) and may result in microstructural changes [10]. The chip then guided along the rake face of the cutting tool (secondary shear zone), leading to an increase in local tool temperature due to friction between tool and chip (Fig.6). As it can be depicted from Fig. 7, a tendency for a higher heat generation rate as the feed rate and cutting speed are increased.

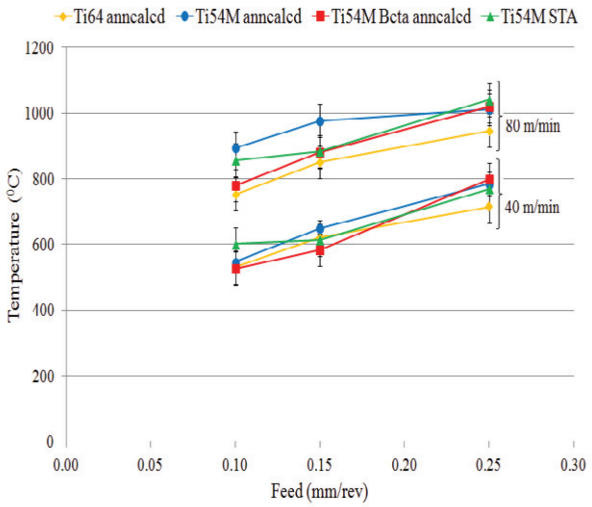
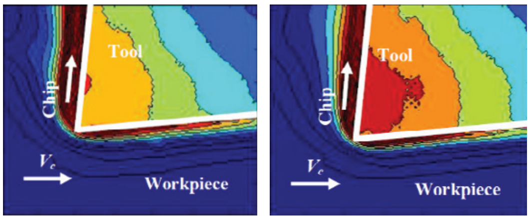
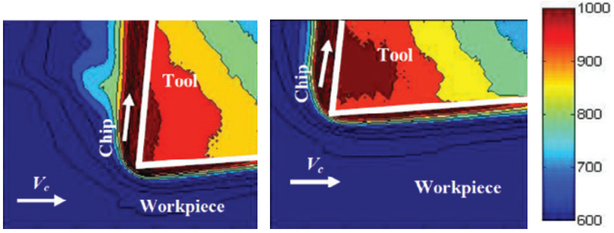


Fig.7. Temperature graph for all titanium alloys at cutting speed = 40 m/min and 80 m/min



(a) Ti64 annealed (b) Ti54M annealed



(c) Ti54M Beta annealed (d) Ti54M STA

Fig.8. Thermal maps for all titanium alloys at cutting speed= 80 m/min and feed= 0.25mm/rev

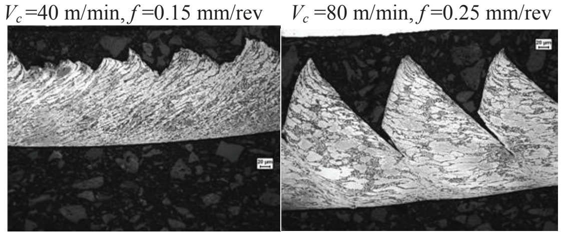
At high cutting conditions; the local tool temperature reached above 1000 ^{0}C for all the three different heat treated Ti54M alloys (Fig.8).

At lower cutting values, very similar temperature values were observed for the analyzed alloys, but temperature difference of 100 ^{0}C was observed between Ti54M and Ti64 alloys at higher cutting parameters. Arrazola et al. [11] observed that the specific feed force (K_k) indicates the friction and rubbing effects over the rake surface and hence explains the amount of heat generated at the tool–chip contact zone. Therefore, higher temperatures were expected in the machining of Ti54M STA and Ti54M beta annealed alloys compared with other analyzed alloys, but machining of the both alloys along with Ti54M annealed produced higher temperature than the Ti64 alloy at the high cutting speeds (Fig.7). However, due to the uncertainty (±50ºC [7]) in thermal measurement system, it cannot be stated effectively that the temperatures generated in the machining of the Ti54M alloys are higher than Ti64 at high cutting speeds. Fluctuation in the tool–chip interface during titanium machining could be a probable cause of this uncertainty in the thermal measurement process.

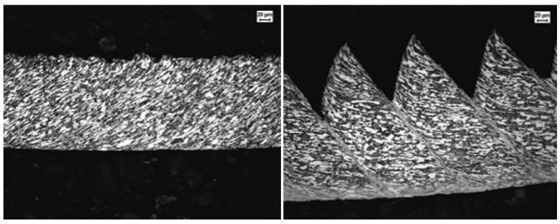
It is observed that the local tool temperature is more sensitive to change in cutting speed than feed rate. The aforementioned discussion does not show an apparent relation between the microstructure of the analyzed titanium alloys and the local tool temperature.

3.3. Chip analysis

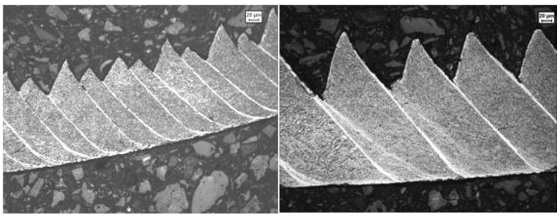
Optical microscopy of chip section obtained for different alloys are shown in Fig. 9.



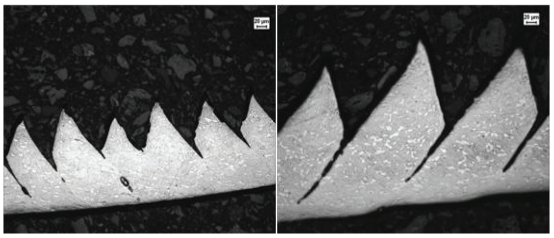
(a) Ti64 annealed



(b) Ti54M annealed



(c) Ti54M Beta annealed



(d) Ti54M STA

Fig.9. Chip morphology as a function of feed and cutting speed in the orthogonal cutting of titanium alloys

It may be observed for Ti64 alloy that with low values of cutting speed and feed, aperiodic segmented chips were produced. A transition from aperiodic to periodic occurred with the increase of both cutting parameters. Chips produced from Ti54M annealed alloy at low values of varied cutting parameters were fairly of uniform thickness (continuous) along their length but at higher cutting conditions segmented chips were produced. Segmented chips were obtained in the machining of Ti54M Beta annealed alloy at all cutting conditions. Chips produced for Ti54M STA at higher cutting speed and feed exhibit a much larger deformed volume at primary shear zone compared to the lower cutting parameters, indicating a greater amount of microstructural deformation and subsequently, overheating has been observed. This result matches with recent study held by M. J. Bermingham et al. [12] on the Beta annealed Ti64 alloy. It is found that segmented chips are not always periodic for all the alloys at same cutting conditions.

The above mentioned discussion shows a direct relationship between the different heat treatment conditions of the analyzed alloys and chip morphology.

4. Conclusion

The major conclusions of the machinability studies of Ti64 and Ti54M alloys carried out in this work at different cutting parameters are:

- It is found that the specific feed forces are more sensitive to variation in feed rates than the specific cutting forces. The high specific feed forces were observed for Ti54M STA due to it’s high hardness achieved during aging process. No clear differences have been found between other analyzed alloys regarding the measured forces.
- Measurement of local tool temperature in the rake face has revealed that the temperature generated for Ti64 alloy and different heat treated Ti54M alloys is very similar.
- The chip morphology differs significantly with the different heat treatment conditions of the analyzed titanium alloys.

The results supplement and synergize the existing knowledge available regarding the titanium alloys machinability dependence on the different heat treatment conditions i.e. microstructure.

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