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Chips of Ti-6Al-2Sn-4Zr-6Mo Alloy – A Detailed Geometry Study

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***Abstract*—**Titanium alloys like Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) are widely used in aerospace applications. Component manufacturing, however, is difficult and expensive as their machinability is extremely poor. A thorough understanding of the chip formation process is needed to improve related metal cutting operations.In the current study, orthogonal cutting experiments have been performed and theresulting chips were analyzed by optical microscopy and scanning electron microscopy.Chips from aTi-6246ingot were produced at different cutting speeds and cutting depths. During the experiments, depending of the cutting conditions, continuous or segmented chips were formed. Narrow, highly deformed and grain oriented zones, the so-called shear zone, separated individual segments. Different material properties have been measured in the shear zones and the segments.

***Keywords*—**Titanium alloy,Ti-6246, chip formation, machining, shear zone,microstructure

I. Introduction

TITANIUM alloys are widely used in different brunches of industry. Ti-6Al-2Sn-4Zr-6Mo(Ti-6246) is an(α+β)-alloy showinghigh strength and excellent corrosion resistence. This alloy is primarily used in rotating components of aircraft engines partly replacing Ti-6Al-4V alloy. Machining of Titanium alloys is complicated due to their high strength. Physical properties like a low heat conductivity results in rapid tool wear.[1]

During machining of Ti-6246 long chips are produced so that cutting operations like turning or drilling need to be interrupted to remove the chips from the process zone. Automation of cutting operations is therefore impossible. [2]
The chip formation process needs to be analysed and completely understood to design material and machining conditions and thus improve the machinability.In the present study, orthogonal cutting experiments on a Ti-6246ingot were performed to investigate the chip formationprocess.[3]

II. Material Preparation

Chips were produced by orthogonal cutting (see figure 1, left)of a Ti-6246 ingot (figure 1, right). [3] The tool width was larger than the width of cut so that edge effects were minimized.

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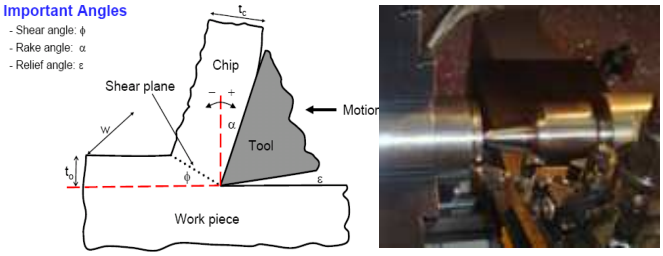


Fig. 1 *Left*: Visualization of the geometry parameters used in the orthogonal experiments, *Right:* Experimental set-up of orthogonal cut

In the experiments,seven different cutting speedsv_c(20, 40, 60, 80, 120, 160, 200, 300 m/min) and fourcutting depths a_p (0.05, 0.1, 0.15, 0.2 mm) have been chosen. A new standard SECO CNMA 120408 (TK 2000) TiN-coated cutting insertwas used for each cut to ensure similar cutting conditions. During the experiments no coolant was used to avoid contaminations.

From the obtained chips a small part (15 to 20 mm)from the beginning of the chip (to minimize tool wear effects)was cut and embedded (polyfast, Isofastat)using180°C at 3 bars (Buehler – SIMPLIMET 1000). All the specimens were groundwith SiC grinding discs (P300, P600, P800, P1200, P2500)and afterwards polished withOPSsuspension (50 ml) having a grain sizeof 0.06 μm mixed with H_2O_2 (10ml) on a Buehler PHOENIX 4000 to remove possible surface layers. The etching process was performed with the Kroll solution composed of HF, HNO_3 and H_2O. Cross sections of the chips were afterwards investigated by optical microscope (Olympus GX 71) and scanning electron microscopy observation (Jeol JSM-7000F) and their geometry was measured.

III. Results and Discussion

The cutting parametersstrongly influencedthe shape of the chips. Figure 2 shows the three types observed during the experiments, namely,continuous chipsshowing a constant chips' thicknesswithhigh density of zones of localized deformation, seefigure 2a, segmented(saw-tooth like) chips in which single segmentswere separated by shear bands,see figure 2c, and a mixed type of continuous and segmented regions which is the typical appearance of chips being machined at the transition speed, see figure 2b. [4]

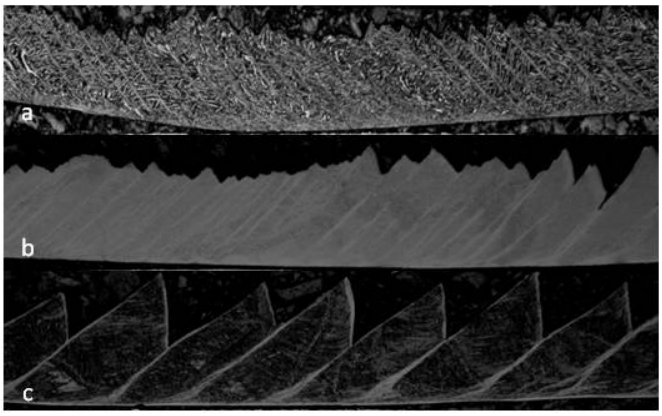


Fig. 2 Optical microscope images of Ti-6246 chips. a: Continuous chips, b:Transition regime, c: Segmented chips

Table I summarizes the optical observationsof the chip shapesin dependence of the machining conditions. Continuous chips were only observed at the lowest depth of cuts (0.05 mm and 0.1 mm) and low cutting speeds between 20 m/min and 40 m/min. Transition between continuous and segmented is seen either at the smallest depth of cut (0.05 mm) and medium cutting speeds (80 m/min and 120 m/min) or at the smallest cutting speed (20 m/min) and large depths of cut 0.15 mm and 0.2 mm. Chips made at other conditions were fully segmented.[5]

TABLE I
DEPENDENCE OF MACHINING CONDITIONS ON SHAPES OF CHIPS, CONTINUOUS (C), TRANSITION (T) AND SEGMENTED (S)

Cutting speed v_c [m/min]	Depth of cut a_p [mm]			
	0.05	0.1	0.15	0.2
20	C	C	T	T
40	C	C	S	S
80	T	S	S	S
120	T	S	S	S
160	S	S	S	S
200	S	S	S	S
300	S	S	S	

Figure 3 shows five main geometrical parameters which were measured from individual chips, namely themaximal and minimal segments' height(h_{max}, h_{min}[mm]), the segments' shear angle (Φ [°]), the segments' width (W [mm])and the sheared distance (d[mm]).[6]

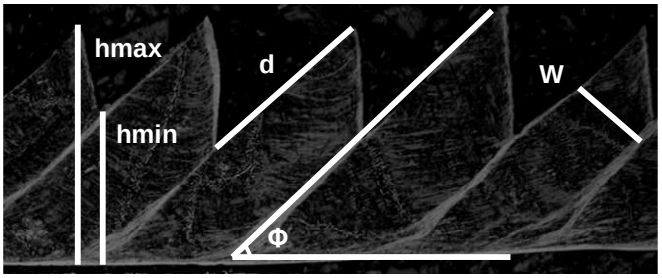


Fig. 3Geometrical parameters obtained from the chips: Minimum and maximum heighth_{max}, h_{min}, shear angle Φ, sheared distance d and segment width W

Figure 4 shows the heights of chipsas a function of cutting speed. The black lines represent the maximum height and the red lines indicate the minimum height, respectively. For the depth of cut of 0.05 mm the average maximum height of the chip is larger than 0.05 mm. Assuming volume constancy of the chip its compression ratio is about 140%. Similar results were obtained for a cutting depth of 0.1 mm. In chips with a depth of cut of 0.15 mm, a compression ratio about 140% was observed only for speeds between 40 m/min and 160 m/min. At speeds of 20 m/min and 200 m/min, the average maximum height was similar to the cutting depth. At the maximum cutting speed of 300 m/min the average heights were smaller than the depth of cut by more that 300%. This can be explained by ignition of the chips during the experiments at these extreme cutting conditions. Consequently, at the highest cutting depth(0.2mm) we finished the experiments ata cutting speed of 200 m/min to avoid machine problems and tool failure.

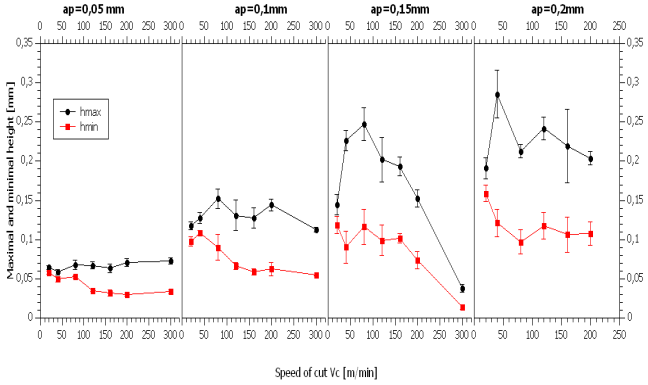


Fig. 4 Chip heights as a function of cutting speed,maximum height (black), minimum height (red)

Figure 5 shows the correlation between the segments' shear angleΦ and the cutting speed for each depth of cut.The red curve represents the measurements performed at the beginning of the chip. The angles indicated by the black curve were measured from the middle of the long chip to study possible influences of tool wear. For the smallest depth of cut we see that the shear angle decreases with cutting speed from approx. 55° to 45°. Shear angles of samples cut at higher cutting depths are around 50° independent of the cutting speed.

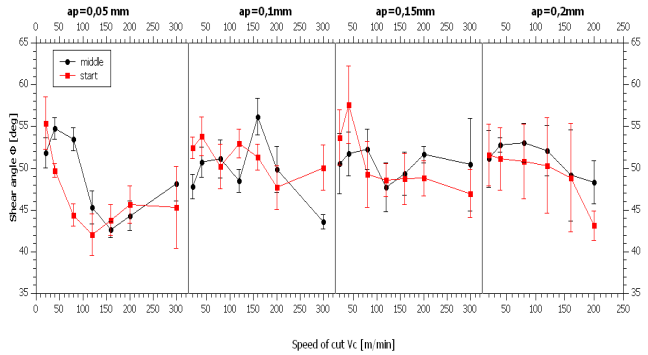


Fig. 5 Correlation between the segments' shear angleΦand the machining conditions. The red curve represents the begin of cut, the black curve is taken from the middle of the long chips

Figure 6 shows the correlation between the sheared distance d and the cutting speed for each individual depth of cut.The parameterforthe first two cutting depths (0.05 mm and 0.1 mm)increases with increasing cutting speed in the range between 80 m/min and 300 m/min. Forthe chips with cutting depth between 0.15 mm and 0.2 mm, d increases up to 80 m/min and remains almost constant at higher cutting speeds.At300 m/min d significantly decreases due to chip ignition.

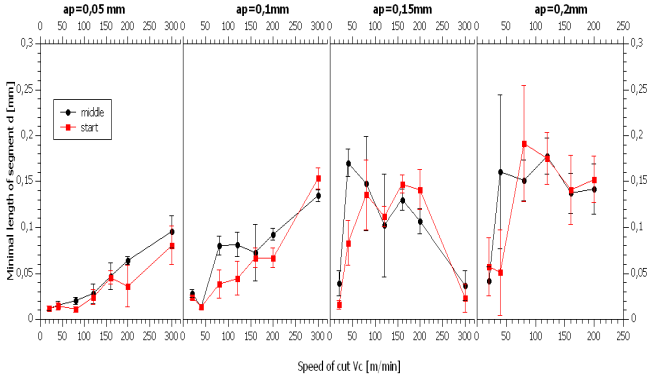


Fig. 6 Correlation between the sheared distanced and the cutting speed for different depths of cut, the red curve represents the begin of cut, the black curve is taken from the middle of the long chip

The Width of segments W shows a similar trend as described for the sheared distance. In our analysis we also estimatedthe widths of the primary shear zones. The average value was calculated from tenregions in the shear zoneas shown in figure 7.Figure 8 shows the correlation between the shear zone width and the machining conditions. For thefirst two depths of cut (0.05 mm and 0.1 mm) the average values increase with increasing cutting speed.For chips producedata depth of cut of 0.15 mm thewidth of the shear zones increases withincreasing cutting speedup to 200 m/min. Fora depth of cut of 0.2 mmthe parameter substantially increases with increasing cutting speed. In general, the shear zone width increases with increasing cutting depth which can be easily understood by the higher amount of deformation due to the increase in sheared distance.

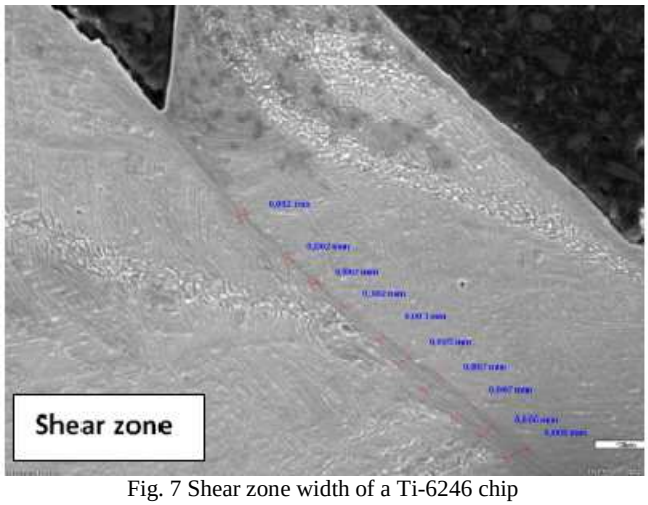


Fig. 7 Shear zone width of a Ti-6246 chip

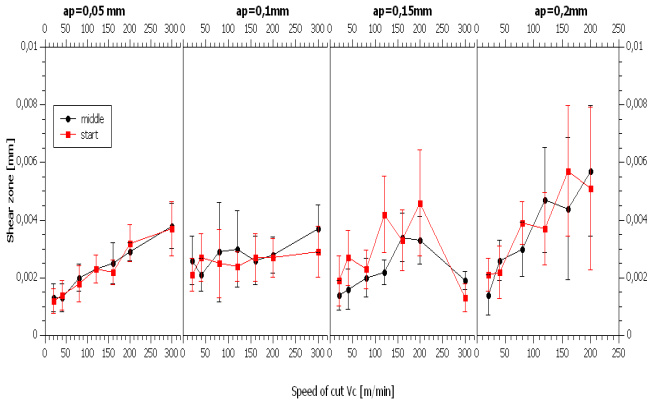


Fig. 8 Correlation between shear zone width and the machining conditions

SEM-EDX

Energy dispersive X-ray Spectroscopy (EDX) analysis on Ti-6246chips has been performed in order to seepossible changes in the phase composition in the material due to the cutting action performed.[7]

Figure 9shows an SEM image of a continuous chip (a_p: 0.05 mm, v_c: 20 m/min) together with line scan EDX. Based on the analysis we can say that segments and shear zones regions have the same chemical compositions at least within the detection limit of the detector used, see figure 10.A similar conclusion can be drawn for a fully segmented chip (a_p: 0.2 mm, v_c: 200 m/min), see figure 11.

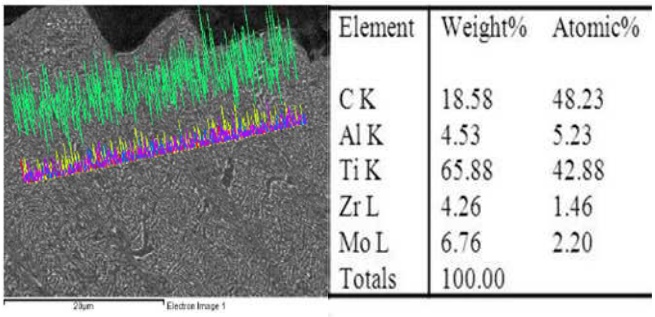


Fig. 9 Linear analyzes of a continuous chip (a_p: 0.05mm, v_c: 20 m/min). No changes in the local chemistry have been recorded

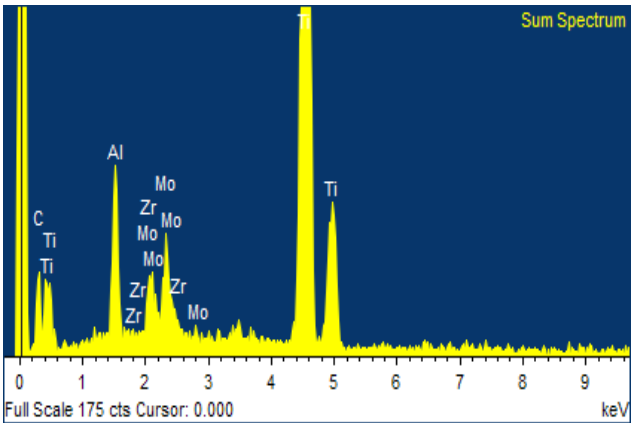
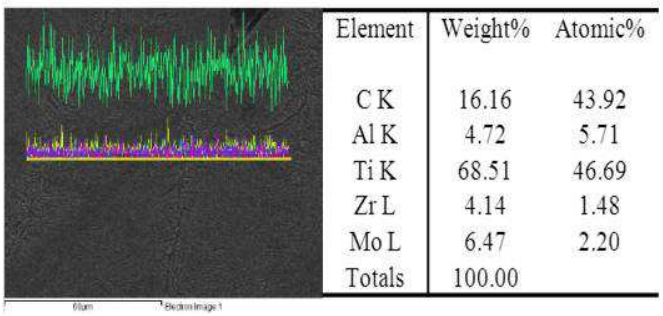


Fig. 10 Cumulated spectrum of the line scans presented in figure 9



Element	Weight%	Atomic%
C K	16.16	43.92
Al K	4.72	5.71
Ti K	68.51	46.69
Zr L	4.14	1.48
Mo L	6.47	2.20
Totals	100.00	

Fig. 11 Linear analyzes of a fully segmented chip (a_p: 0.2 mm, v_c: 200 m/min). No changes in the local chemistry have been recorded

IV. Conclusion

In this work,we analyzed geometry of Ti-6246 chips machined in a wide range of cutting conditions, namely a cutting depth between 0.05 mm and 0.2 mm and cutting speeds between 20 mm and 300 m/min. Depending on the machining conditions continuous, segmented or chips with mixed natureformed.In the continuous chips, formed at low depth of cuts (0.05 mm and 0.1 mm) and cutting speed up to 40m/min, segments are not visible because of the high density of zones of localized deformation. In segmented chips, formed at $a_p = 0.05$ mm above 120 m/min, $a_p = 0.1$ mm above 40 m/min and $a_p = 0.15$ mm and 0.2 mm above 20 m/min, segments areseparated by a nanostructured shear zone. Chips showing a mixture ofcontinuous and segmented regions were found at $a_p = 0.05$ mm at cutting speeds between 80 m/min to 120 m/min and at $a_p =$ 0.15 mm and 0.2 mm at the lowest speed of 20 m/min.

The geometry of the chips was described by fivemain geometrical parameters, namely, the maximal and minimal height h_{max}, h_{min}, the segments' shear angle Φ, the segment width W and the sheared distance d. Their dependenciesof the machining conditions were shown.

The chemical composition is homogeneous in the chips andcorresponds tothe chemical composition specified forthis alloy.Studies of the chemical composition of the shear zones and its boundarieswere performed indicating that the cutting action did not lead to any changes in the local chemistry of Ti-6246 alloy. As the chip formation process is now understood, the machining processes can be improved in a second step.

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