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On the influence of work material microstructure on chip formation, cutting forces and acoustic emission when machining Ti-6Al-4V

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Abstract

The influence of heat treatment of work material on chip formation, when machining Ti-6Al-4V, was studied through microstructural investigation of chips, as well as response on cutting forces and acoustic emission. Three different microstructures were investigated; equiaxed, bimodal and Widmanstätten. It is well known that machining of titanium produces shear localized chips at all industrially practical cutting speeds and feed rates, however there is also a transition from aperiodic to periodic saw-tooth chip formation. The feed rate was varied at constant cutting speed to study this transition from aperiodic to periodic saw-tooth chips in the three microstructures. Face turning cutting tests were used when sensor signals were collected. The results from this investigation stress the importance to consider work material microstructure when studying the chip formation process, and its impact on cutting forces and acoustic emission, when machining Ti-6Al-4V.

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Keywords: Machinability; Microstructure; Titanium; Acoustic Emission

1. Introduction

Titanium alloys are known to be difficult to machine at all but very low cutting speeds, i.e. less than 1 m/s in cutting speed [1]. This is believed to be connected to the highly localized shear bands found in titanium chips, which also gives them their characteristic saw-tooth appearance. These bands are believed to be caused by thermoplastic instability, which occurs when thermal softening is higher than the competing strain hardening during deformation. Due to the poor thermal properties of titanium, these bands form at low deformation rates [1-3]. Preheating of work material in front of the primary shear zone plays an important role as well, hence the uncut chip thickness will also affect when localization sets in, where an increase will favor formation of bands [4]. This means that there exists a transition where continuous chips become localized, when either cutting speed or feed rate is increased.

Nomenclature

AE	Acoustic Emission
AE_{RMS}	Root mean square of AE signal
AC	Air cooled
a_p	Depth of Cut
f	Feed rate
s	Standard deviation
v_c	Cutting speed

Many different sensors can be applied when it comes to monitoring cutting processes. One of them is acoustic emission (AE), which detects small surface waves generated during machining [5]. Sources of these waves include friction, dislocation movement, chip breakage, phase transformations, fracture etc. Since the sensor is designed to react to surface waves of very high frequency (100-900 kHz) it is relatively insensitive to

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structural vibrations. However, the high frequency demands high data acquisition rates which make it common to apply a root mean square (RMS) filter with a predefined time constant, which drastically lowers the required sample rate.

The acoustic emission has also proved useful when it comes to detecting the transition from continuous type of chips to saw-tooth when machining hardened steels [6]. The change in chip morphology has been reported to result in an increase of two orders of magnitude in the root mean square energy of the AE signal (AE_{rms}). When the technique was applied to study the transition of Titanium 6Al-4V chips the same drastic effect was not seen [7]. The emission was instead attributed to the presence of welding between the tool and chip at higher cutting speeds (>30 m/min), compared to hardened steel where no welding was found, the dominant source then being catastrophic failure within the primary shear zone. The authors found that localized chips were produced at all speeds and feed rates tested, but that the chips produced at low speed and feed were 'aperiodic' in nature. This aperiodic "saw-tooth" chip is characterized by having small protrusions on the free surface, which has not been fully developed to reach throughout the chip width, thus not having 'periodic' localizations re-occurring.

The influence of heat treatment of Titanium 6Al-4V has been studied to some extent in literature, where beta-annealed has been shown to result in increased cutting forces as well as accelerated tool wear compared to mill annealed, as forged and duplex annealed material [8]. However, the influence of heat treatment on both acoustic emission and chip formation has not been studied to the authors' knowledge. This study aims at investigating different microstructures influence on chip morphology, cutting forces and acoustic emission.

2. Experimental

2.1. Work material

A 129 mm diameter bar from a single batch of material was cut into 25 mm thick discs. One disc was used in the 'as received' condition which had an equiaxed alpha microstructure with almost no beta phase present. The first heat treatment was a duplex heat treatment that resulted in a bimodal microstructure, i.e. consisting of both equiaxed alpha and transformed beta. The second heat treatment held the disc high above the beta-transus temperature to give excessive grain growth, ending in a Widmanstätten structure [9]. Figure 1 shows the microstructures achieved after the heat treatments, summarized in Table 1 together with their hardness. A load of 30 kg was used during the Vickers hardness testing, with 25 indents per heat treatment.

Table 1. Investigated microstructures

Heat treatment	Microstructure	Hardness (HV_{30}±s)
As received	Equiaxed	319±6
950°C 30min + AC	Bimodal	324±10
1110°C 30min + AC	Widmanstätten	335±12

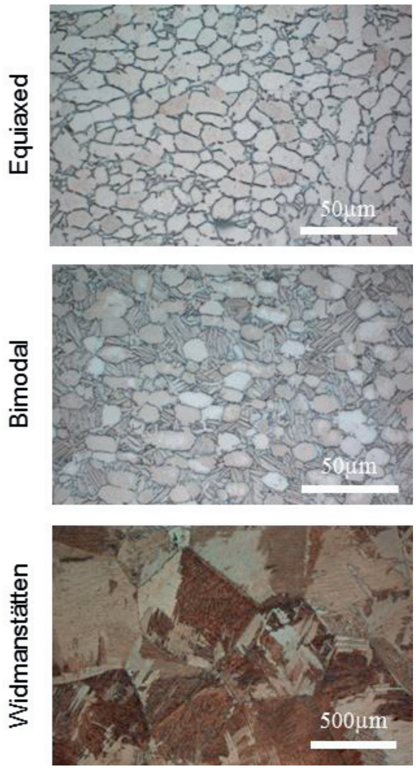


Fig. 1. Microstructure of heat treated discs.

2.2. Machining

All machining was performed on a EMCO 365 CNC lathe, with mineral oil based emulsion Hysol XF, with a concentration of 8%, applied.

The inserts used were uncoated standard cemented carbides without chip breaker (Sandvik Coromant TCMW16T304-H13A) with a 0.4 mm nose radius, 0° rake angle and 91° entering angle.

Turning was performed at 60 m/min cutting speed with a feed rate of 0.05 - 0.15 mm/revolution and 2 mm depth of cut, see Table 2.

Each test was run twice, with a new cutting edge every time.

Table 2. Cutting Parameters

Cutting Speed, v_c (m/min)	60
Feed rate, f (mm/rev)	0.05, 0.10, 0.15
Depth of Cut, a_p (mm)	2

A Kistler Type 9257A three component dynamometer was used for force measurement during the experiments. For the acquisition of AE_{RMS} a Kistler AE sensor type 8152B221 with amplifier type 5125 was used, with a bandpass between 50-200 kHz and a time constant of 0.12 ms for the RMS filter. All signals were sampled at 20 kS/s.

3. Results and discussion

3.1. Chip Morphology

When the chips were investigated the equiaxed and bimodal microstructures were found to be almost identical at each feed rate, bimodal is shown in Figure 2 together with Widmanstätten. Both equiaxed and bimodal showed a smooth chip with small protrusions, close to continuous, but still aperiodic, at 0.05 mm/min. When feed rate was increased to 0.10 mm/min more localized deformation was evident, showing signs of increased periodic localized deformation. At 0.15 mm/min the chips are highly localized, or fully periodic.

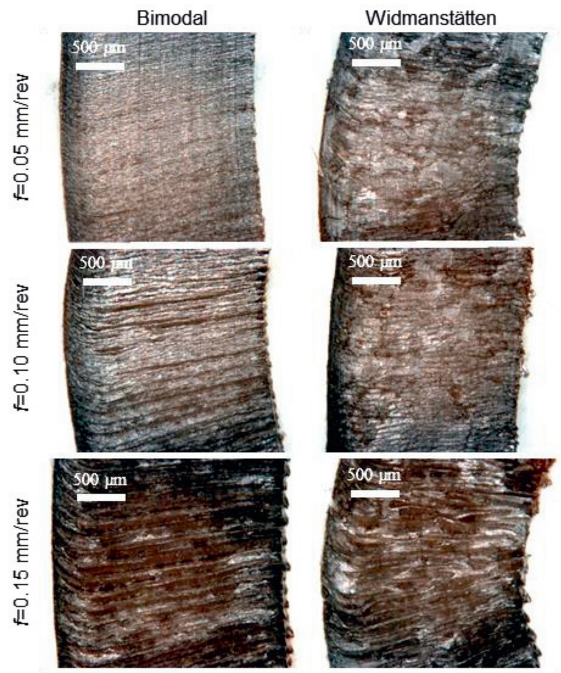


Fig. 2. Chip morphology of bimodal and Widmanstätten microstructures.

The Widmanstätten microstructure resulted in chips somewhat different from the two others, with an aperiodic appearance kept to some degree even at 0.15 mm/rev, as evident in Figure 2 and 3. Both coarse and fine protrusions can be found at all feeds. Etched cross sections of chips are presented in Figure 4, where similarity between equiaxed and bimodal microstructures is evident.

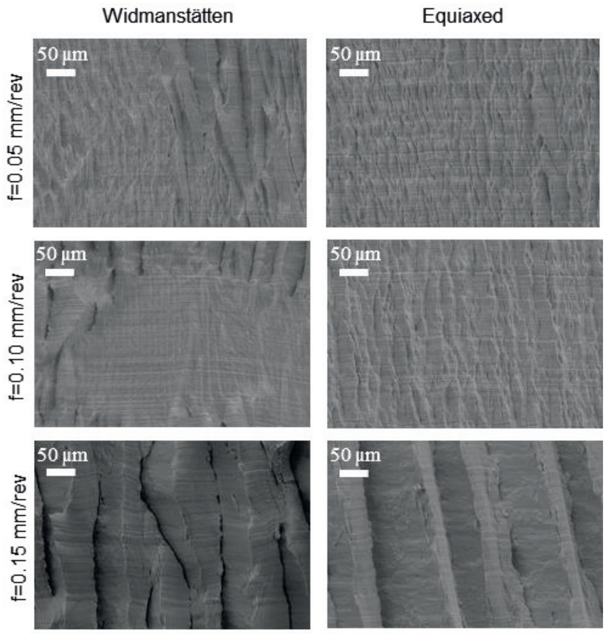


Fig. 3. SEM micrographs of the free surface of chips in the Widmanstätten and equiaxed microstructures.

Shear bands can be seen in all three chips. The Widmanstätten structure shows two interesting areas in Figure 4, one where the lamellae are perpendicular to the shear band (a) and one where it’s parallel (b). The one perpendicular seems more locally deformed, with a very distinct shear band, whereas the parallel seems to have more evenly distributed deformation. This might be explained by the anisotropy of the lamellar colonies [10]. It’s also worth noting that the size of lamellae colonies is on the same order of magnitude as the uncut chip thickness, even at 0.15 mm/min in feed rate. The influence of varying directional properties on the cutting process is sometimes referred to as ‘anisotropic machining’ [11]. This would explain the inhomogenous deformation found at all feed rates, and shows that not only transition from a continuous chip to a periodic one results in ‘aperiodic’ chips, it can also be caused by anisotropic properties in the work material.

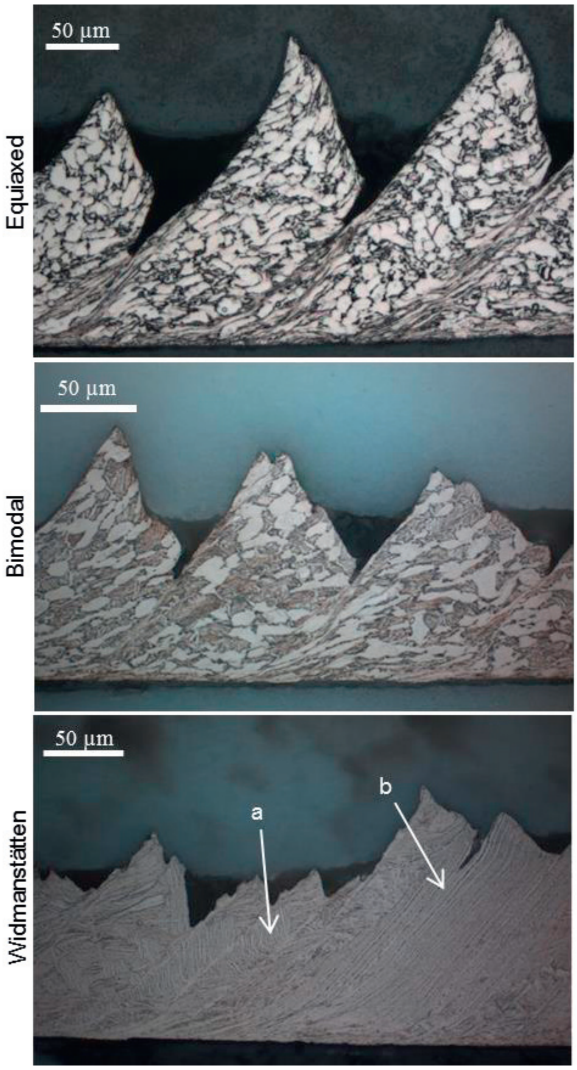


Fig. 4. Etched cross section of chips showing shear localization (f = 0.1mm/rev). Arrows indicating lamellar structure perpendicular to shear bands (a) and parallel to shear bands (b).

Figure 5 shows SEM micrographs of both the free and the tool side of chips in fully periodic chips in the equiaxed microstructure. Ductile shear fracture can be seen on both sides. The distance between the fracture surfaces on the tool side is equal to the distance between localized segments seen on the free surface, and clearly shows that welding is occurring between chip and tool during formation of segments. Redeposited work material can also be seen between the fracture surfaces on the tool side of chip. This welding between chip and tool was only observed at the highest feed rate for the equiaxed and bimodal microstructures, whereas it could be found to some degree even at 0.10 mm/rev for the Widmanstätten.

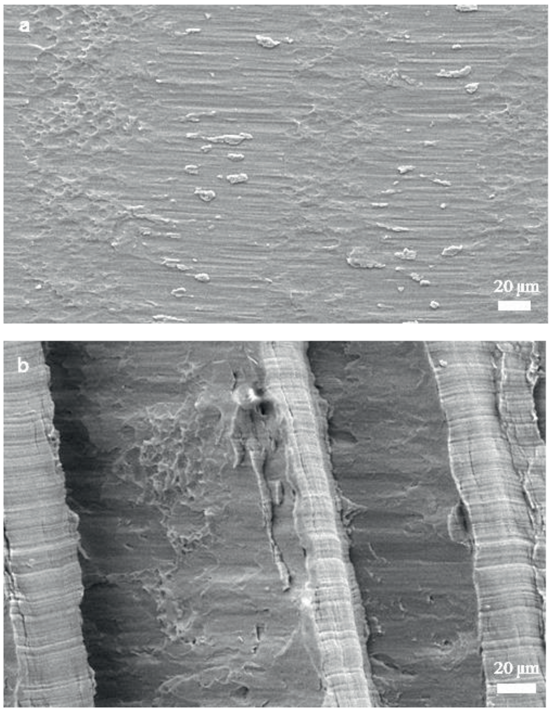


Fig. 5. SEM micrograph of the tool side of chips showing repeated ductile shear fracture (a) and the free surface of chips showing ductile shear fracture between segments (b) in the equiaxed microstructure at a feed rate of 0.15mm/rev.

3.2. Cutting forces and acoustic emission

The main cutting force show an increase with feed rate as expected, there is however no obvious difference between the heat treatments, see Figure 6.

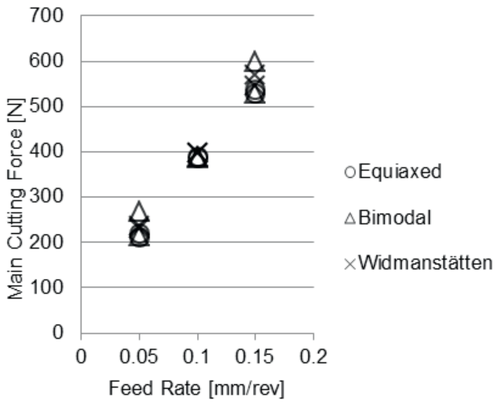
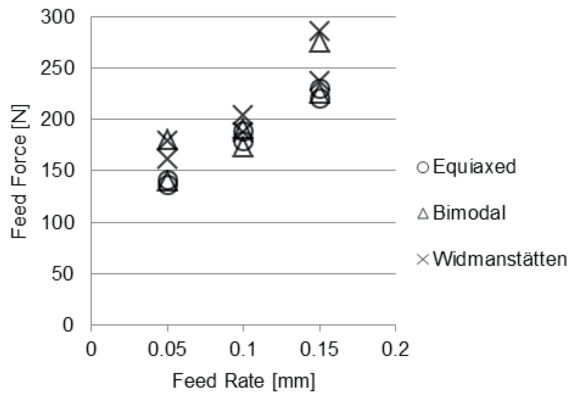


Fig. 6. Main cutting force results.

The scatter in feed forces and passive forces makes it impossible to distinguish between the different heat treatments, see Figure 7.

(a)



(b)

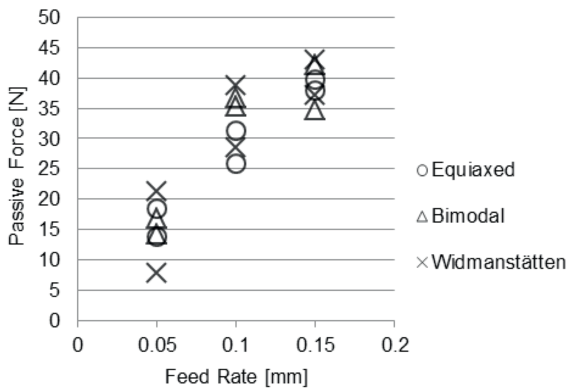


Fig. 7. Feed (a) and passive (b) force results.

The variation in AE_{RMS} is remarkably low within heat treatments, considering the variation in feed forces, see Figure 8. One possible explanation of this is that the feed and passive forces are highly sensitive to both nose and edge radius variations. Although all inserts came from the same batch, deviations in geometry can have high impact on both passive and feed forces. The reason why the scatter is not reflected in the AE_{RMS} would be explained if the welding to the tool is the dominant source of emission as proposed by Barry and Byrne [5]. However, it does not explain the gradual increase in AE_{RMS} with feed rate for both bimodal and equiaxed microstructure, as welding was only observed at the highest feed rate. Instead, the emission seems to be related to the gradual transition from low localized deformation at 0.05 to highly localized at 0.15 mm/rev. The emission seems to be correlated to the size of segments. This could explain why Widmanstätten show high levels of acoustic emission even at low feed rate, where thick segment formation occurs even at 0.05 mm/rev, as seen in Figure 2 and 3.

These results show that microstructure should not be overlooked when influence of cutting parameters on both chip formation and acoustic emission is studied, when machining Ti-6Al-4V.

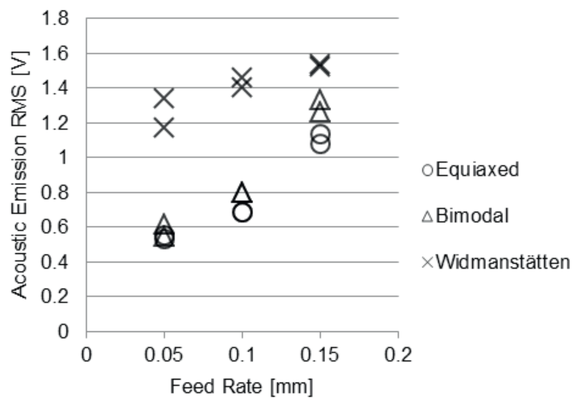


Fig. 8. Root mean square-filtered acoustic emission results.

4. Conclusions

The heat treatments were shown to influence the chip morphology, where equiaxed and bimodal microstructures showed a transition from aperiodic at 0.05 mm/rev, via aperiodic/periodic mixture at 0.10 mm/rev to full periodic saw-tooth at 0.15 mm/rev. The Widmanstätten showed more inhomogenous deformation, with presence of large lamellae even at the lowest feed rate.

There was no obvious difference in main cutting force between the different heat treatments, and the same was true for feed and passive force.

The acoustic emission root mean square energy doubled from 0.05 mm/rev in feed rate to 0.15 mm/rev for both equiaxed and bimodal microstructures, whereas the Widmanstätten was less affected by feed rate changes.

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References

[1] Komanduri, R., von Turkovich, BF., 1981. New Observations on the Mechanism of Chip Formation when Machining Titanium Alloys, Wear, 69, p.179.

[2] Komanduri, R., von Turkovich, BF., 1982. Some Clarifications on the Mechanism of Chip Formation when Machining Titanium Alloys, Wear, 76, p.15.

[3] Komanduri, R., Hou, ZB., 2002. On Thermoplastic Shear Instability in the Machining of a Titanium Alloy (Ti-6Al-4V), Metallurgical and materials Transaction A 2002, 33A, p. 2995.

[4] Burns, TJ., Davies, MA., 2002. On repeated adiabatic shear band formation during high-speed machining. International Journal of Plasticity, 18, p. 487.

[5] Teti, R,. Jemelniak, K., O'Donnel, G., Dornfeld, D., 2010. Advanced monitoring of machining operations, Annals of the CIRP 2010, 59, p. 717.

[6] Barry, J., Byrne, G., 2001. Study on acoustic emission in the machining of hardened steels, part 1: acoustic emission during saw-tooth chip formation. Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture, 215(11), p. 1549.

[7] Barry, J., Byrne, G., Lennon, D., 2001. Observations on Chip Formation and Acoustic Emission in Machining Ti-6Al-4V Alloy, International Journal of Machine Tools and Manufacture, 41, p. 1055.

[8] Armendia, M., Garay, A., Iriarte, LM, Belloso, J., Turner, S., Osborne, P., Arrazola, PJ, 2010. "The influence of Heat Treatment in the Machinability of Titanium Alloys: Ti6Al4V and Ti-5Al-4V-0.6Mo-0.4Fe (Ti54M)," 4th International Conference on High Performance Cutting.

[9] Lütjering, G., Williams, JC, 2007. "*Titanium*." 2nd ed. Berlin Heidelberg New York: Springer.

[10] Bieler, T., Nicolaou P., Semiatin S., 2005. An experimental and theoretical investigation of the effect of local colony orientations and misorientation on cavitation during hot working of Ti-6Al-4V, Metallurgical and Materials Transactions A, 36(1), p. 129.

[11] Dornfeld, D., Min, S., Takeuchi, Y., 2006. Recent Advances in Mechanical Micromachining, Annals of the CIRP, 55(2), p. 745.