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Effect of the cutting speed on the chip morphology and the cutting forces

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ABSTRACT

Purpose: The aim of this research is to make a first experimental analysis of the effect of the cutting speed on the chip morphology, and of the cutting forces in the orthogonal turning process of the titanium alloys Ti-6Al-4V.

Design/methodology/approach: The methodology has consisted of proving a series of parameters combinations: f, feed rate, Vc, cutting speeds are explored in a range from 50 to 250 m/min, and is analyzing the different types of chips and the evolution cutting forces appeared during each one them, and determined the analytical model of plastic deformation ratio.

Findings: Tests achieved have shown three main types of chips: Continuous chip at 50 m/min, Flow chip for speeds ranging around 100 m/min, and Shear localized chip starting from the transition speed of 125 m/min and above. The modification of the mechanism of chip formation is associated with the appearance of shearing instability. Chip segmentation by shear localisation is an important process which is observed within a certain range of cutting speeds. This phenomenon might be desirable in reducing the level of the cutting forces by improving chip's evacuation.

Research limitations/implications: A possible future work would be the development of a general the phenomenal of the thermo mechanical of the cutting high speed machining. The behavior is of the thermo – visco – plastic studies are planed in the future.

Practical implications: The relationship found between high speed machining and chip morphology and the cutting forces and work piece surface finish has an important practical implication since it allows selecting the best cutting condition combination from the points of view both the security and the economy for the established requirements in each case. Results are of great importance in for aerospace, biomedical and automotive industry.

Originality/value: The paper is original since the bibliographical review has allowed testing that, although works about these themes exist, none approaches the problem like it has been made in work.

Keywords: Cutting speed; Chip morphology; Cutting forces; Adiabatic shear banding; Titanium alloy

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MANUFACTURING AND PROCESSING OF ENGINEERING MATERIALS

1. Introduction

Titanium alloys have been widely used in the aerospace, biomedical, automotive and petroleum industries because of their good strength-to-weight ratio and superior corrosion resistance. However, it is very difficult to machine them due to their poor machinability. In 1955, Siekmann [1] pointed out that “machining of titanium and its alloys would always be a problem, no matter what techniques are employed to transform this metal into chips”.

Cutting of titanium alloys has always been a topic of great interest for industrial production (companies aeronautic, automotive, orthopaedic…) and scientific research worldwide. Titanium alloys are regarded as extremely difficult to cut materials due to their several inherent properties.

It has been observed that the chip morphology under different cutting speed is different. This is predominantly due to the changes in crack initiation and propagation as well as changes in flow localization in the cutting zone.

Chip segmentation by shear localization is an important process which is observed in a certain range of cutting velocities [2]. This phenomenon might be desirable in reducing the level of the cutting forces and by improving chip’s evacuation. The process of chip segmentation in titanium alloys was analyzed by Komanduri et al. (1981) [3], Bayoumi and Xie [4] have studied the effect of the cutting conditions on the formation of shear bands in Titanium alloy.

In this paper, an experimental study of localized shearing and chip serration is carried out for orthogonal cutting in a range of cutting speeds from 50 to 250 m/min. The influence of the cutting speed and of the feed rates on the level of cutting forces and on the shear band morphology is analyzed. The Ti–6Al–4V has been chosen as the workpiece.

2. Experiment procedures

2.1. Workpiece materials

Titanium alloys have are known for their application in biomedical devices, such as hip prosthesis and bone plates, since many decades, in the aerospace, automotive and petroleum industries because of their good strength-to-weight ratio and superior corrosion resistance. Among all titanium alloys, Ti–6Al–4V is the most widely used. Thus it has been chosen as the workpiece material in this study. Its nominal composition (wt %) and mechanical properties are shown in Tables 1 and 2, respectively [5,6].

2.2. Testing conditions

Generally speaking, to study the cutting phenomenon, we suppose we are in the simplest case of orthogonal cutting: the cutting edge of the tool is perpendicular to the plan defined by the feed-rate direction and that of the cutting speed (Vc). It is actually a pseudo-plan problem. We suppose that the untouched surface has been obtained beforehand without any superficial layer change, and that the removed material layer, or feed-rate (f), is thick compared to the dimensions of the crystal so that the manufactured material can be considered as statistically homogeneous. On one hand, we suppose that it is isotropic by compensation, that is to say exempted from preferential crystalline orientations and from fibrous macrostructure. On the other hand, we consider the tool as excessively rigid.

Table 1.
Chemical composition of Ti–6Al–4V (wt %)

Content	Composition (wt %)
C	0.05
Fe	0.09
N	0.01
O	-
Al	6.15
V	4.40
H	0.005
Ti	Balance

Table 2.
Physical properties of Ti–6Al–4V alloy

Hardness (HRC)	Density (g/cm^3)	Re (MPa)	Rm (MPa)	Thermal conductivity (W/m°K)
36	4.43	910	1000	7.3 TA

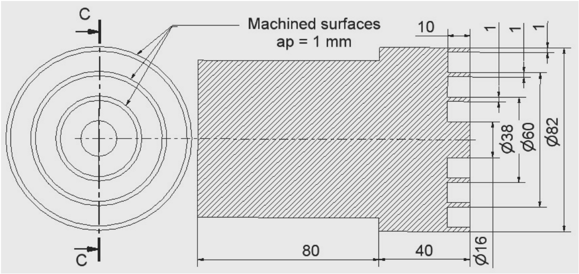

Fig. 1. Workpiece used in orthogonal cutting.

The cutting speeds used during the tests range from 50 to 250 m/min. The choice of the speed interval is made taking into account the classification of the HSM and according to the capacity of the used machine-tool. Along with these series of cutting tests, samples of chips on every set of tests are taken to make their metallographic close examinations. From a practical point of view, tests prove that the machining of flexible workpieces such as pipes is unsteady whatever the cutting parameters are (Figure 1). However, it is possible to rehabilitate the steady machining on stiff workpieces presenting some frontal gorges by using a machine with a digital system equipped with a device that measures the cutting forces [7,8].

The following cutting conditions were employed in this investigation:

- Dry cutting
- Cutting speed: from 50 to 250 m/min
- Depth of cut: $a_p = 1$mm
- Feed rate: f = 0.1 et 0,2 mm/rev
- Tool designation: Sandvik TNMG 16 04 08 PM 4005
- Tool geometry: direction angle $\kappa_r = 90°$, inclination edge angle $\lambda_s = 0°$, rake angle $\gamma_0 = - 6°$, edge radius $r\varepsilon = 0.8$ mm
- Tool coating : $T_iN + Al_2O_3 + T_i$ [C,N]

3. Types of chips

The study of chip formation began in the 1930s and 1940s, based on the work of Taylor [9] and Mallock [10]. Since then, various Scientifics research worldwide of the industrial production, (companies aeronautic, automotive, orthopaedic…) have made different chip classifications, depending microstructure, cutting speed, feed rate, depth of cut, angle of the cut, etc. [11-20].

In order to analyze the chip morphology completely, the chips must be cross-sectioned, polished, etched in 4% nitric acid in ethyl alcohol and examined under a microscope SEM.

Figure 2 presents the main chip types observed in the study turning of the titanium alloy at different cutting speed Vc. Continuous chips at Vc = 50 m/min (Figure 2a) are considered to be non oscillatory material flow in witch profiles of chip proprieties.

Figure 2b shows a segmented chip that is a continuous chip in witch shear zones appear aperiodically and chip thickness varies with time. Some authors [4] explain that this type of chip morphology appears due stick-slip oscillation and damage in the shear zone [13],

Figure 2c-d (Vc = 175 - 250 m/min), shows a serrated or shear localized chips and characterized them as oscillatory material flow.

4. Morphology and characteristic of the chip

The comparative survey of chips obtained for the different cutting speeds permitted us to come out with some properties that favour the instantaneous shearing. The mechanism of chip formation at a high speed is different from that obtained in conventional machining. We have noticed that when we increase the cutting speed, at a certain level of speed, the shearing appears for the case of the material at hand [4]. Our immediate aim here is to determine at what speed the change of the chip shape appears and at the same time to understand the phenomenon itself. According to the achieved experiments, we notice that Ti-6Al-4V in annealed state shows a saw-type chip starting from the speed of 100 m/min. Below this speed, there is a flow chip. We can deduce that a speed of transition exists beyond which the chip shows bands localizing the stress together with saw-tooth chip type with a metallurgical change.

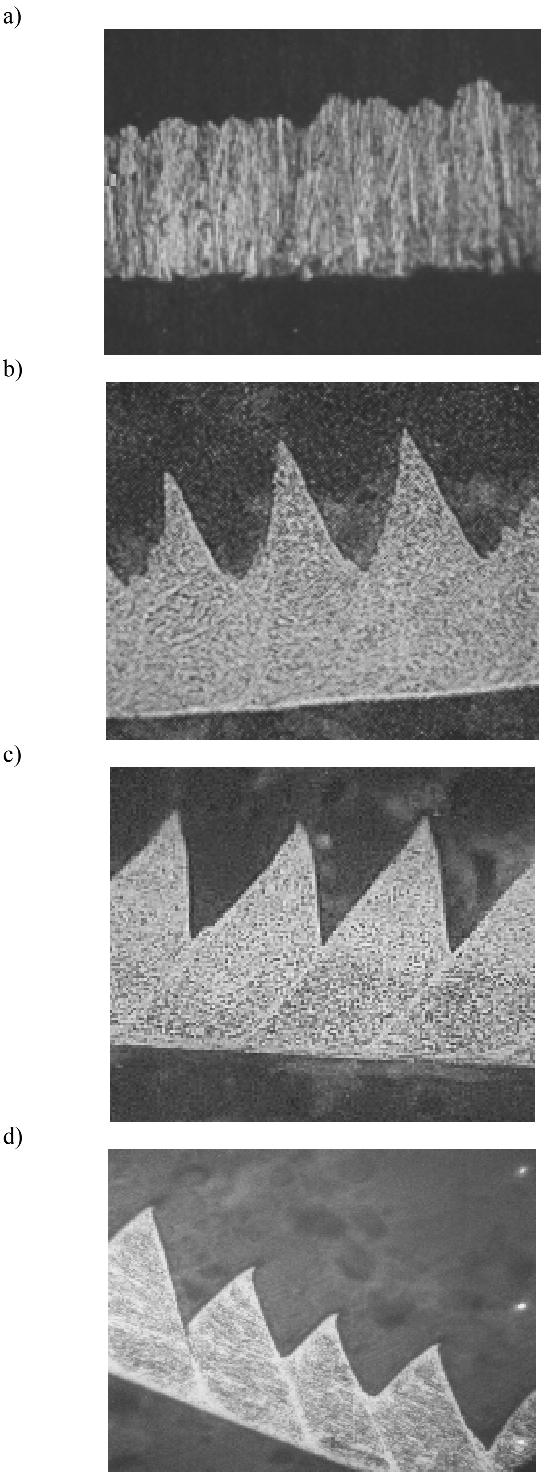

Fig. 2. SEM micrograph of the different chip types produced during a orthogonal turning operation: (a) continuous, Vc = 50 m/min (b) segmented, Vc = 100 m/min (c,d) serrated or sheared localized, Vc = 175 - 250 m/min

The appearance of strips is explained according to the cycle of autocatalytic ruination. From a local increase of deformation due to a defect in the structure, there is a local increase of the workpiece temperature due to the plastic work (see Figure 3). If the time of loading is short, the increase of temperature thus created decreases the flow stress of the work material by thermal softening. That's what favours again the deformation; the separation by adiabatic shearing and the evacuation of the chip on the tool rake face.

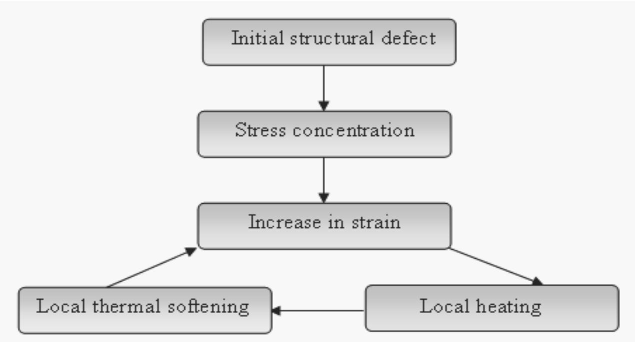

Fig. 3. Cyclic plastic deformation

This process described by C. Zenner and J.H. Hollomon appears like a plastic instability of the deformation. When the cutting speed increases, the created type of chip evolves from the flow chip toward the adiabatic shearing chip (ASC) (see Figure 4). This modification of the mechanism of chip formation is associated with the appearance of shearing instability. This instability has for origin a divergence between the thermal tempering and the dynamic tempering of the work material. The result is that, considering the chip morphology, three areas are well defined: lower cutting speeds corresponds to a shear formation area and above a transitional zone, higher cutting speeds constitute a shear localized deformation area, which is also the high speed machining (HSM) domain [7,17,18]. This mechanism is defined by precise laws of the material behaviour that takes into account the strain hardening, the sensitivity to the strain rate and the thermal softening. The work material behaviour is supposed to be isotropic and of Von Mises type; it can be in the following constitutive form:

$$\tau = \tau(\gamma, \dot{\gamma}, T) \tag{1}$$

where τ is the shear stress, γ the shear strain, $\dot{\gamma}$ the strain rate and T the temperature.

The behaviour is of the thermo-visco-plastic type; a well-adapted differential relation has been suggested by [7] in the plastic zone specified by the subscript *"pl"*:

$$d\tau = \left(\frac{\partial \tau}{\partial \gamma_{pl}}\right)_{\dot{\gamma}_{pl},T} d\gamma_{pl} + \left(\frac{\partial \tau}{\partial \dot{\gamma}_{pl}}\right)_{\gamma_{pl},T} d\dot{\gamma}_{pl} + \left(\frac{\partial \tau}{\partial T}\right)_{\gamma_{pl},\dot{\gamma}_{pl}} dT \tag{2}$$

A solution from the constitutive law can be expressed by the equation (3) in which the coefficients τ_0, k, γ_0, a, p, D are deduced from specific torsion tests.

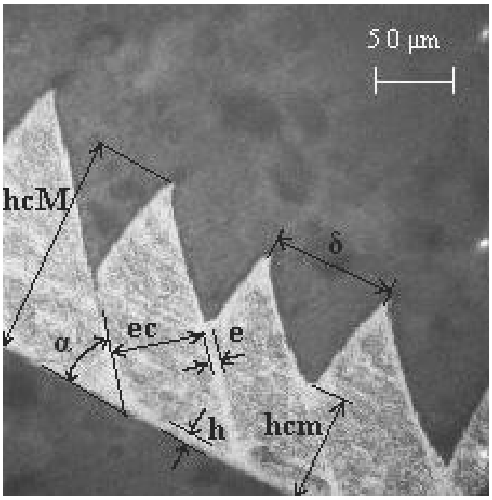

Fig. 4. Adiabatic shear band in a chip ASC of titanium alloy Ti-6Al-4V, obtained by orthogonal cutting at the velocity Vc = 250 m/min

$$\tau = \tau_0 \left[k + \mathrm{Ln}\left(1 + \frac{\gamma_{pl}}{\gamma_0}\right) \right] (1 - aT) \left[1 + \left(\frac{\dot{\gamma}_{pl}}{D}\right)^{1/p} \right] \tag{3}$$

with a>0

The requirements of the work material beyond the elastic limits are accompanied by a temperature elevation within the workpiece. The higher the strain rate, the more elevated is the temperature. Therefore the adiabatic phenomenon results in an evolution of the temperature in accordance with the energetic balance given by the following expression:

$$\frac{\partial T}{\partial t} = \frac{\beta}{\rho . c} \tau \dot{\gamma}_{pl} \tag{4}$$

in which β is the heat plastic-work coefficient estimated to about 0.9, ρ is the density (Kg/m^3), C is the specific heat (J.Kg^{-1}.°C^{-1}).

The two laws (3) and (4) are the basic laws able to characterise the machinability of Ti–6Al–4V alloy. Finally, the geometry of the adiabatic shearing chip ASC is different from that of the flow chip.

5. Analytic modelling of plastic deformation ratio

The most convenient ways to determine that the machining conditions are perfect are based on the close examination of the chip. Indeed, there is a cause-effect relationship between the cutting aspects and the requirements needed by the tool to assure the chip formation.

Cutting in the HSM causes a deformation with an increase of chip thickness (h_c) (maximal chip thickness h_cM, and minimal chip thickness h_cm), (see Figure 4) in relationship with the feed rate (f). This deformation depends on the cutting speed evolution and defined by the thickness coefficient (Kr) is given by equation (5):

$$Kr = \frac{h_c}{f} \tag{5}$$

After the experimental study and the application of experimental design method, we have obtained the analytic expression (6) of the plastic deformation coefficient Kr which depends on the cutting speed (Vc) and the feed rate (f). With this equation we can calculate the analytic value of Kr for different cutting speeds and a constant value of feed rate f; either f = 0,1 mm/rev or f = 0,2 mm/rev. After the determination of the plastic deformation values for different cutting speeds, we can draw the analytic curve and compare with the experimental values carried out (see Figure 5).

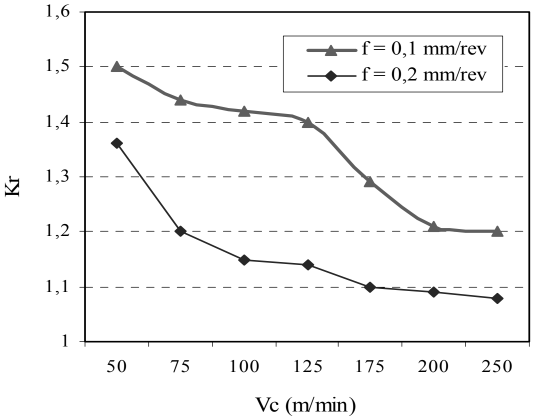

Fig. 5. Deformation ratio evolution in terms of the cutting speed and the feed rate

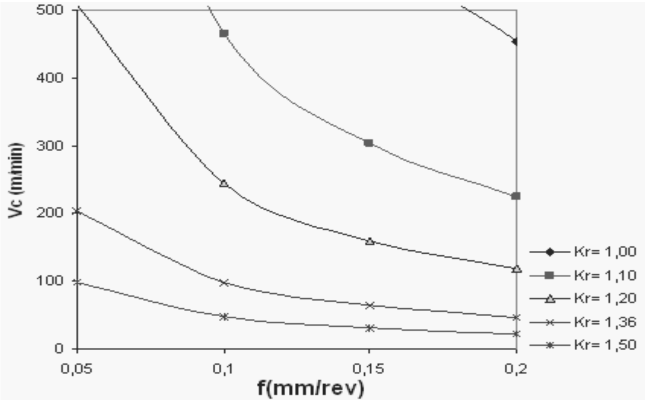

Fig. 6. Iso-answers curves of Vc in terms of the cutting speed and the feed rate

According to the analytic model, the variation of Kr in step with the cutting speed Vc is in decrease. In fact, if we increase the cutting speed, the value of the thickness ratio decreases. After this study, we can draw the iso-answers curves of Kr in step with the feed rate and the cutting speed (Figure 6);
According to the model Kr = f (Vc, f):

$$Kr = 1{,}826 f^{-0{,}143} Vc^{-0{,}136} \tag{6}$$

We can be able to write the expression of Vc:

$$Vc = 83{,}56\, Kr^{-7{,}35} f^{-1{,}05} \tag{7}$$

This experimental modeling permits to get the optimum choice of the cutting speed and feed rate from the obtained analytic equation. The result optimization is defined by the iso-answers curves which permit to fix and to optimize the experimental conditions which give the answer value; these curves are very useful to find the experimental domain region.

6. The evolution of the cutting force in terms of the cutting speed

The knowledge of the cutting force is the basis of the necessary power to the cut assessment. In order to know the mechanical output of a machine - tool, it is important to know what is the cutting power taken by the tool and therefore to have information on the cutting forces. The value of the cutting forces also serves to dimension the organs of machines and to foresee the deformations of the pieces. It takes part in the precision of machining, in the conditions of auto - excited vibrations apparition and indirectly, in the formation of the topographic state and the integrity of surface (internal constraints of traction compression, layers…). Finally, the cutting forces being in relation with the mechanical properties of the material in the chip formation process are susceptible to provide information on the machinability of the material and the Couple Workpiece Tool, CWT [18-20]. Generally a complete CWT is realized when, for a given cutting process, it is necessary to determine ranges of cutting parameters for achieving a given quality criteria or cost function.

The first theories as those of Ernst and Merchant didn't take into account the cut speed in their analysis for the calculation of the efforts. Oxley [14], later, proposed a theory in which intervened the speed of deformation, and according to this survey, the strength of cut had to decrease since a slow speed until a moderate speed, then to increase again, following the material strain characteristics. The tests led thereafter to more elevated speeds put in evidence the apparition of the adiabatic shearing. The layers of slip that appear during the machining drag a reduction of the necessary mechanical constraint to the formation of the chip. The experimental design modelling has contributed to find the analytic model of the tangential effort Ft according to the cutting speed Vc and the feed rate f:

$$Ft = 5182,8 f^{0,93} Vc^{-0,25} \tag{8}$$

The Figure 7 shows that the analytic and the experimental curves of Ft (Vc) are nearly identical.

The variation of the cutting force according to the cutting speed is decreasing. The decrease at high cutting speed is essentially owed to the reduction of the rubbing chip - tool, limited by the stabilization of the temperature at high speeds.

At high cutting velocities the plastic deformation Kr decreases and the angle of shearing Φ increases (see Figure 8) permitting the reduction of the area or section of shearing (S1 and S2) (Figure 9) and therefore, of the cutting force.

However, when we amplify the cutting speed, the angle of shearing increase and the section will be reduced. The increase cutting speed at the same reduce a considerable the cutting force. The Figure 9 shows the evolution of the angle of shearing Φ and the section in the terms of the cutting speeds.

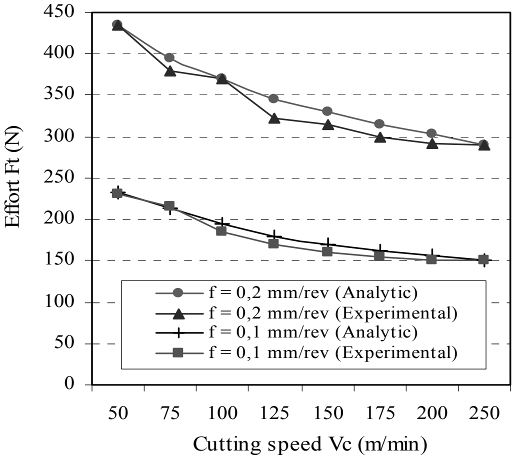

Fig. 7. The evolution of the cutting forces according to the cutting speed and the feed rate

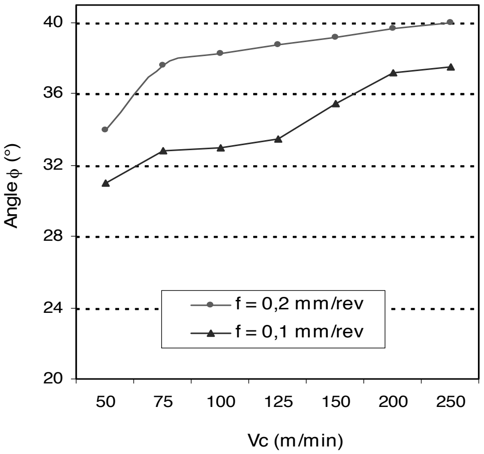

Fig. 8. The evolution of the angle of shearing according to the cutting speed and the feed rate

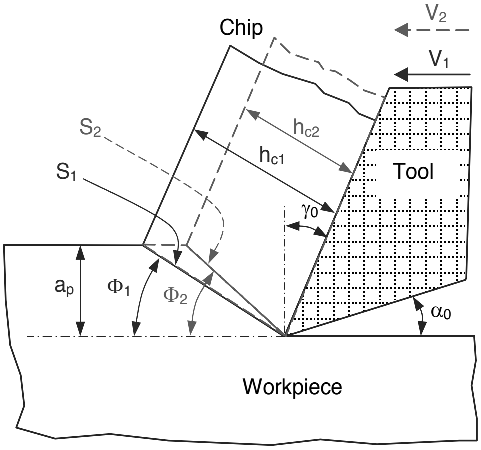

Fig. 9. Sections of chip (S_1) and (S_2) according to the cutting speeds (V_1) and (V_2)

7. Conclusions

The influence of the cutting speed and of the feed rate on the level of cutting forces and the chip morphology is analyzed for orthogonal cutting of Ti-6Al-4V in the range of cutting speeds Vc from 50 m/min to 250 m/min.

Tests achieved have shown three main types of chips:

- Continuous chip at 50 m/min,
- Flow chip for speeds ranging around 100 m/min,
- Shear localized chip starting from the transition speed of 125 m/min and above.

The modification of the mechanism of chip formation is associated with the appearance of shearing instability. The instability that gives birth to the segmented chips emanates from a divergence between the thermal softening and the hardening caused by the tempering of the manufactured work material. This instability appears when the thermal tempering culminates at a certain point of the structure, thus creating the shearing strip. This type of chip appears when the cutting speed is low while the hardness of the work material is high.

Chip segmentation by shear localisation is an important process which is observed in certain range of cutting speeds. This phenomenon might be desirable in reducing the level of the cutting forces by improving chip's evacuation.

References

[1] H.J. Siekmann, How to machine titanium, Tool Engineer, 1955, 78-82.

[2] A. Molinari, C. Musquar, G. Sutter, Adiabatic shear banding in high speed machining of Ti-6Al-4V: experiments and modelling, International Journal of Plasticity 18 (2002) 443-459.

[3] R. Komanduri, R.H. Brown, The mechanics of chip segmentation in machining, Journal of Engineering for Industry 103 (1981) 33-51.

[4] A.E. Bayoumi, J.Q. Xie, Some metallurgical aspects of chip formation in cutting Ti–6Al–4V alloy, Materials Science and Engineering A190 (1995) 173.

[5] Z.G. Wang, Y.S. Wong, M. Rahman, High-speed milling of titanium alloys using binderless CBN tools, International Journal of Machine Tools & Manufacture 45 (2005) 105-114.

[6] J. Barry, G. Byrne, D. Lennon, Observations on chip formation and acoustic emission in machining Ti-6Al-4V alloy, International Journal of Machine Tools & Manufacture 41 (2001) 1055-1070.

[7] M. Remadna, J.F. Rigal, Evolution during time of tool wear and cutting forces in the case of hard turning with CBN inserts, Journal of Materials Processing Technology 178 (2006) 67-75.

[8] A. Daymi, S. Ben Salem, B. Hadj Sassi, M. Boujelbene, S. Torbaty, Influence cutting speed on the chips formation in high speed turning of the titanium alloy, 9th International Research/Expert Conference TMT, Antalya, 2005.

[9] C.H. Che-Haron, A. Jawaid, The effect of machining on surface integrity of titanium alloy Ti–6% Al–4% V, Journal of Materials Processing Technology 166 (2005) 188-192.

[10] G. Byrne, D. Dornfeld, B. Denkena, Advancing cutting technology, Annals of CIRP 52/2 (2003) 483-507.

[11] W. Grzesik, T. Wanat, 'Surface finish generated in hard turning of quenched alloy steel parts using conventional and wiper ceramic inserts', International Journal of Machine Tools & Manufacture 46 (2006) 1988-1995.

[12] A. Vyas, M.C. Shaw, Mechanics of saw-tooth chip formation in metal cutting, Journal of Manufacturing Science and Engineering 121/2 (1999) 163-172.

[13] T. Mabrouki, J.F. Rigal, A contribution to a qualitative understanding of thermo-mechanical effects during chip formation in hard turning, Journal of Materials Processing Technology 176 (2006) 214-221.

[14] P.L.B. Oxley, The mechanics of machining: an analytical approach to assessing machinability, pub. Ellis Horwood LTD, 1989.

[15] J.A. Arsecularatne, On tool-chip interface stress distributions, ploughing force and size effect in machining, International Journal of Machine Tools & Manufacture 37 (1997) 885-899.

[16] G. Poulachon, A. Albert, M. Schluraff, I.S. Jawahir, An experimental investigation of work material microstructure effects on white layer formation in PCBN hard turning, International Journal of Machine Tools & Manufacture 45 (2005) 211-218.

[17] A. Salak, K. Vasilko, M. Selecka, H. Danninger, New short time face turning method for testing the machinability of PM steels, Journal of Materials Processing Technology 176 (2006) 26-69.

[18] I.S. Jawahir, C.A. Van Luttervelt, Recent Developments in Chip Control Research and Applications, Annals of the CIRP 42 (1993) 659-685.

[19] K.A. Venugopal, S. Paulb, A.B. Chattopadhyay, Growth of tool wear in turning of Ti-6Al-4V alloy under cryogenic cooling, Wear 262 (2007) 1071-1078.

[20] R.T. Coelhoa, Eu-G. Ngb, M.A. Elbestawi, Tool wear when turning hardened AISI 4340 with coated PCBN tools using finishing cutting conditions, International Journal of Machine Tools & Manufacture (2007) 263-272.