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Experimental Analysis of the Cutting Process and Chip Formation at High Speed Machining

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Résumé. Un nouveau dispositif expérimental a été conçu, permettant de reproduire la coupe orthogonale à grande vitesse. Il est ainsi possible d'étudier les effets d'une grande vitesse de coupe sur la fragmentation du copeau et sur les efforts de coupe. Ces grandes vitesses de coupe sont obtenues grâce à un canon à gaz qui propulse l'éprouvette, à une vitesse très supérieure à celle obtenue avec des machines conventionnelles (environ 100 m/s). Des observations microscopiques des copeaux et une classification systématique ont permis d'affiner l'analyse des effets de l'augmentation de la vitesse de coupe et des différentes conditions de coupe.

Abstract. A new experimental device has been designed to reproduce the orthogonal cutting process at very high speed. Thus, it is possible to study especially the effects of the very high cutting speed on the chip segmentation and on the cutting forces. High cutting speeds are obtained with an air gun that launches the workpiece at velocities much higher than those obtained in conventional machining (up to 100 m/s). Microscopic observations of chips and systematic classification have contributed to analyze the consequences of the cutting conditions.

1. INTRODUCTION

The mechanics of orthogonal metal cutting have been investigated by many authors, especially in the field of high speed machining (H.S.M.). Advantages expected from H.S.M. are among others, an increase of productivity, the ability of machining many advanced materials such as titanium or hardened alloy steels. Other desirable effects are chip segmentation, a better state of surface and the occurrence of adiabatic shear band essentially, in the aim of reducing the cutting forces.

Numerous studies have been published concerning either the analytical modeling of orthogonal cutting [1 - 6], the numerical simulation of high speed cutting [7], the study of adiabatic shear banding [8], or the mechanics of chip segmentation [9 - 13].

To obtain results in a wide range of speeds, a new experimental set up has been designed [14], whose principle is based upon the Hopkinson tube technique. This device allows real orthogonal cutting, under quasi-stationary conditions, with velocities up to 100 m/s.

The purpose of this paper is to present first results obtained with that experimental procedure. Experiments have been driven on a middle steel (medium carbon steel), for velocities ranging from 7 m/s to 100 m/s and for different rake angles (-5, 0, 5 degrees). The cutting forces were measured and the chips were collected and analyzed from a morphological point of view. The results show the predominant influence of the cutting speed and of the rake angle on the process, especially on the eventual occurrence of a shear band or on the chip segmentation. One of the principal feature put in evidence is the correlation between the chip segmentation and the level of the cutting forces.

2. EXPERIMENTAL SET UP

The experimental machining device is schematically presented figure 1. It is based on the Hopkinson tube method for the measurement of the cutting forces [15]. A workpiece is fixed on a projectile launched by an air gun which allows a precise control and a wide range of velocities. The projectile is then guided in the launch tube for an optimal precision of the trajectory (0.015 mm in the lateral position) and to ensure that no rotation of the projectile may occur. At the exit of the launch tube, the workpiece impacts on two tools symmetrically mounted on a transmitter Hopkinson tube. Thus two machinings are processed at the same time for the symmetry of the process. Finally the projectile is guided, inside the transmitter tube to a shock absorber. This set up is more precisely detailed in reference [14].

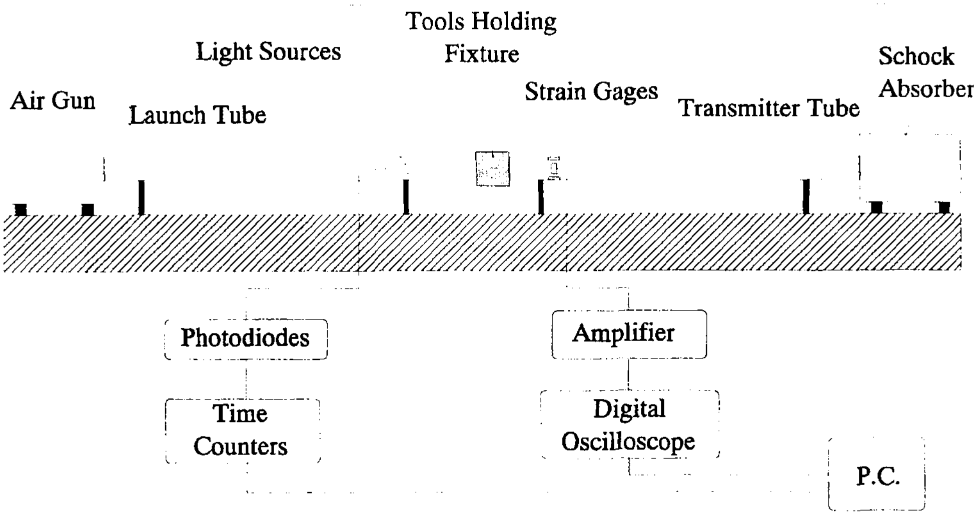


Figure 1 : Schematic description of the experimental set up.

A set of strain gages is fixed on the transmitter tube at a distance long enough from the head of the tube to ensure that stresses are uniform through its cross section. This set permits the measurement of the longitudinal cutting force.

The velocity of the projectile is measured just at the exit of the launch tube by the mean of a set of three sources of light, photodiodes and time counters.

Specimens used for the cutting test were obtained after machining from rectangular bars. They are themselves rectangular and have the following dimensions : 5 or 10 mm in the cutting direction, 45 and 10 mm in the orthogonal directions. The distance between the tools was measured before each test. The depth of cut, approximately kept equal to 0.3 mm, was checked by measuring the size of the workpiece before and after the test.

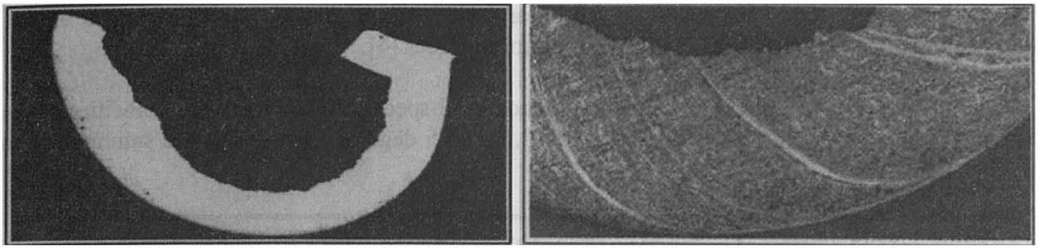
The two chips formed were collected after each experiment, observed by optical microscope and measured.

3. RESULTS AND ANALYSIS

The aim of the tests was, first, to establish if any correlation may be deduced between the very high speeds and the geometrical aspect of the chip. As for instance, discontinuous chips are generally wished for a better comfort of machining, among other advantages, it was important to focus on that problem.

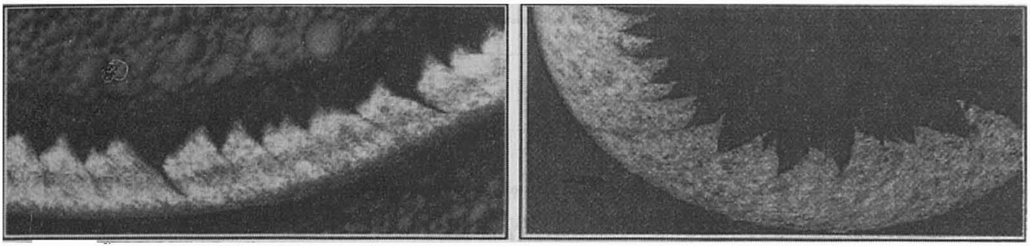
The measurement of the shear angle is possible as the machining is instantaneously stopped by pulling out of the chip from the specimen before the end of the process. Finally the chips have been observed through an optical microscope and we could measure the characteristic length of the chip waves or segments and eventually the thickness of the shear band. So, a quantitative approach could be attempted to explain the evolution of the cutting forces in a large range of velocities.

From the observation of the chips collected, a qualitative classification is first proposed, uniquely based on morphological criteria, without any consideration of the mechanism of chip formation.

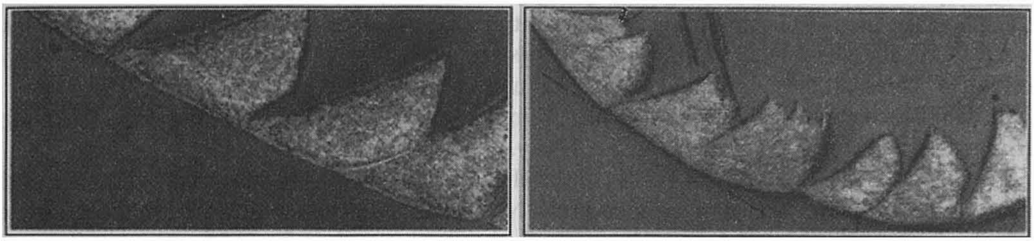


(a) Without shear band. *(b) With adiabatic shear band*

Continuous chips with smooth surface



Regular Wavy Chip without shear band : C-W-R-O *Regular Wavy Chip with shear band : C-W-R-X*



Regular Segmented chip with shear band : C-S-R-X *Regular Segmented Chip without shear band : C-S-R-O*

Figure 2 : Microscopic observations of different morphology of chips.

Four levels of classification are defined. The first level roughly separates the chips in continuous ones and not. The second level, concerning only the continuous chips, distributes them as smooth, wavy or segmented. The third level, valid for all the chips defines their regularity, and finally the fourth level is devoted to the occurrence, or not of an adiabatic shear band.

Level 1	CONTINUOUS (C)									DISCONTINUOUS (D)			
Level 2	Smooth (L)	Wavy (W)				Segmented (S)							
Level 3		Regular (R)		Irregular (I)		Regular (R)		Irregular (I)		Regular (R)		Irregular (I)	
Level 4		(O)	(X)	(O)	(X)	(O)	(X)	(O)	(X)	(O)	(X)	(O)	(X)

(X) : with shear band ; (O) : without shear band

Table 1

This classification is very similar to that proposed for instance by R. Komanduri and coworkers [9]. This qualitative analysis has been complemented by a quantitative one, through the measurement of different parameters. First, we measured the frequency of the segments or waves, which may be an important parameter for the explanation of the segmentation process that arises as the result of plastic instabilities, self excited vibrations, forced vibrations, stick-slip friction, or a combination of all these elements [9 - 12].

Secondly, we measured the width of the shear bands (when they occurred) which is one of the predominant parameters for the calculation of the cutting forces [4].

Experiments have been driven on medium carbon steel specimens in a range of velocities extending from 1 to 100 m/s, with 3 different rake angles : -5, 0 and 5 degrees. The results are summarized in the following table.

Cutting speed (m/s)	≈ 1			≈ 18			≈ 42			≈ 65		
Cut angle (°)	-5	0	5	-5	0	5	-5	0	5	-5	0	5
Type	C	C	C	C	C	C	C	C	C	D	C	C
Aspect	W	L	S	S	W	W	S	W	W	-	S	S
Regularity	I	-	R	I	I	I	R	I	I	R	I	I
Shear Band	O	O	O	X	X	O	X	X	O	X	X	O

Table 2

We may observe that the chips generally stay continuous, except at very high velocities, when the rake angle is negative. Concerning segmentation, it can be noted that at high velocities, the chips are segmented, for all rake angles. Thus, it may be extrapolated that for still higher velocities, even for positive rake angles, all the chips could be discontinuous.

No definitive conclusion may be deduced from the third element of classification, concerning the regularity, complementary experiments are necessary.

A first analysis of the results of the fourth level of classification shows that the occurrence of shear bands is favored by a diminution of the rake angle. No shear band has been observed in the experiments, with a rake angle of 5°, at any velocity.

On the other hand, an increase of the velocity has the same effect. At the lowest studied velocity, no shear band is present, confirming the idea that the cutting speed is a dominant factor in the process of initiation of adiabatic shear bands.

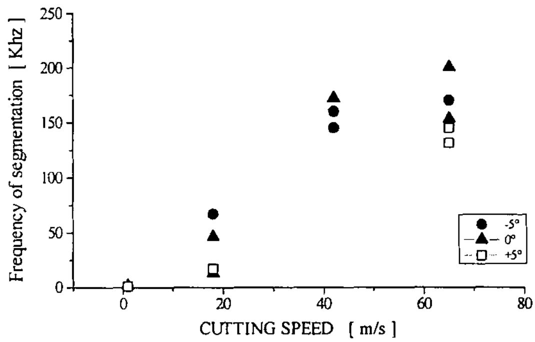


Figure 3 : Frequency of segmentation.

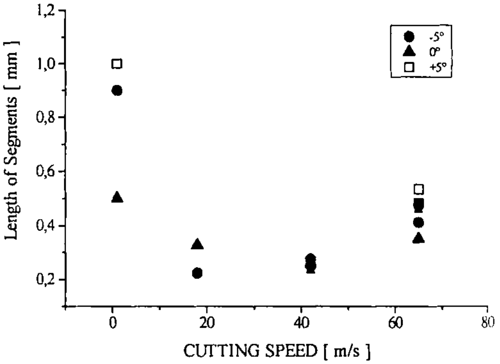


Figure 4 : Average lengths of segments (or waves).

Figures 3 and 4 show the evolution of the segments frequency with the velocity. As the velocity grows up, the characteristic lengths of segments (figure 4) decrease, reach a common value of about 0.25 mm, independent of the rake angle, and finally, for higher velocities, tend to grow up slowly. This minimal value is attained for a velocity of about 35 m/s. Other authors have also observed an increase of the frequency with velocity, and a tendency for that frequency to reach an asymptotic value, generally associated to natural frequencies of the structure [10 - 11].

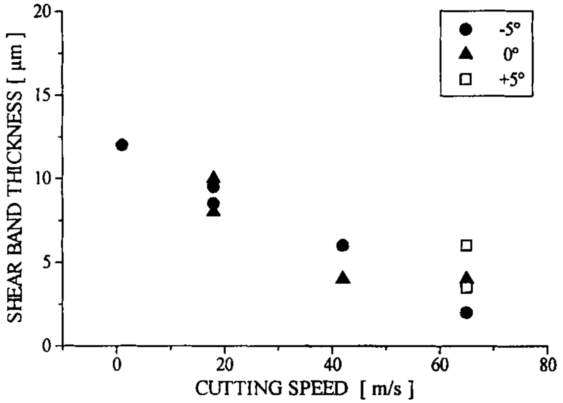


Figure 5 : Width of the Adiabatic Shear Band

Finally, when it occurred, we measured the width of the adiabatic shear band as presented in figure 5. Globally, we observe a decrease of the width of the shear bands with the velocity.

It is of interest to compare the previous morphological observations to the measured cutting forces, figure 6.

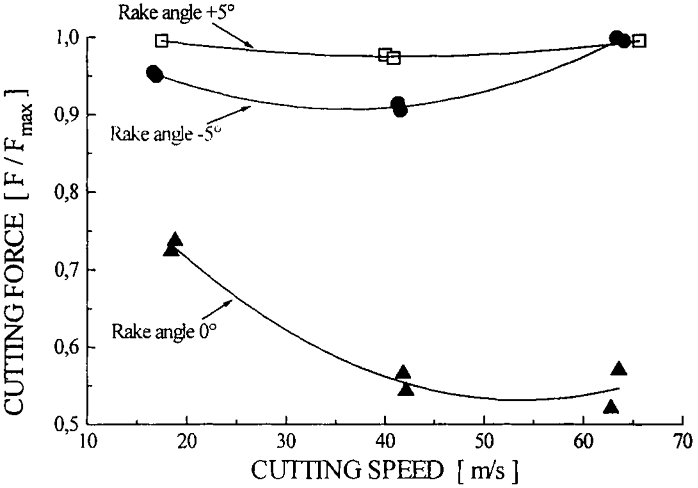


Figure 6 : Longitudinal cutting forces as function of cutting speed.

For any value of the rake angle, the cutting forces first decrease with the velocity, as generally observed [10 - 13]. However, they reach a minimal value at a critical velocity. Above this velocity, the cutting forces grow up. It must be pointed out that this critical velocity was also observed in the curves representing the evolutions of the segment length, demonstrating a correlation between this morphological parameter and the cutting force measured.

Secondly, an analysis of the results of figure 6, shows the strong effect of the rake angle on the level of the cutting force. As the rake angle diminishes, the pressure and the friction force at the tool-workpiece interface grows up and thus the cutting force ought to grow up too. However, the diminution of the rake angle favors the occurrence of a shear band, as may be seen in table 2, thus drastically decreasing the corresponding cutting forces. This explains the drop of the cutting force when the rake angle varies from 5° to 0°. The further increase of the cutting force when the rake angle decreases from 0° to -5° may be attributed to the increase of the frictional forces at the tool interface.

4. CONCLUSION

A new experimental device has been designed which allows the study of orthogonal cutting for a large range of velocities (from 1 to 100 m/sec). The effect of high speed on the chip morphology and on the cutting forces has been studied in the case of a medium carbon steel.

The results obtained show that the evolution of the cutting force, in terms of rake angle and cutting velocities, can be correlated to morphological aspects.

References

[1] Pomey J., *Mec. Mat. Elect*, **256,** (1971), 8-36.
[2] Merchant M.E. , *Journal Applied Phys.*, **16,** (1945), 367-418.
[3] Hastings W.F., Mathew P., Oxley P.L.B., *Proc. R. Soc. Lond.*, **371,** (1980), 569-587.
[4] Oxley P.L.B., Mechanics of Machining, An Analytical Approach to Assessing Machinibility, (Ellis Horwood Limited Publishers, 1989), Chichester England.
[5] Molinari A., Dudzinski D., *C.R.Acad. Sci. Paris*, **315 (II),** (1992), 399-405.
[6] Dudzinski D., Molinari A., *Int. J. Mech, Sci*, **39**, n°4, (1997), 369-389.
[7] Marusich T.D., Ortiz M., *Int. J. Num. Methods Engrg,* 38 (1995) 3675-3694.
[8] Bodin L., Thesis of University of Metz, (1996).
[9] Komanduri, R., Brown, R.H, *J. Eng. Ind.* ,**103**, (1981), 33-51.
[10] Komanduri, R., Schroeder,T., Hazra, J., Von Turkovich, B.F., Flom, D.G., *J. Eng. Ind.* ,**104**, (1982), 121-131.
[11] Komanduri R., High-Speed Machining, (eds Komanduri, R., Subramanian K., Von Turkovich B.F., (1984).
[12] Sullivan, K.F., Wright, P.K., Smith, P.D., *Metals Tech.*, **181**, (1978), 181-189.
[13] Kottenstette J.P., Recht, R.F., Proceedings, Tenth North American Manufacturing Research Conference, Trans. Society of Manufacturing Engineers, (1982), 263-270.
[14] Sutter G., Molinari A., Faure L., Klepaczko J.R., Dudzinski D., *Journal of Engineering for Industry*, (1997). (to appear)
[15] Klepaczko J.R., *Int. J. Impact Engng,* **15,** (1994), 25-39.