Ann. For. Sci. 59 (2002) 857–865

DOI: 10.1051/forest:2002084

Original article

Towards high cutting speed in wood milling

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(Received 2 March 2001; accepted 16 November 2001)

Abstract – High cutting speed machining processes have been used for about 10 years for metals. This technology presents many advantages related to output and surface quality. For timber machining, commonly used velocities are already high. However, literature about cutting velocity function during a machining process is rare. Nevertheless, some published results have shown the effect of speed on chip formation. In order to perform experiments at high cutting speeds, we used a prototype model of a CN routing machine, which allowed us to conduct machining from 3 m s^{-1} to 62 m s^{-1}. Surface analysis was carried out by an optical roughness measurement device. The wood species studied is beech. Tests have been performed with constant chip thickness value.

wood / milling / cutting speed / surface quality

Résumé – Utilisation des grandes vitesses de coupe dans le fraisage du bois. Depuis une dizaine d'années, l'industrie des métaux a recours au procédé d'usinage à grande vitesse. Ses principaux avantages résident dans l'augmentation du débit matière ainsi que l'amélioration des surfaces usinées. Dans le domaine de l'usinage du bois, les vitesses de coupe sont déjà très élevées de telle sorte que les limites techniques sont pratiquement atteintes. Concernant la vitesse de coupe, peu d'informations existent sur son effet au cours du procédé d'usinage. Cependant, certains travaux traitent de l'effet de la vitesse sur le mode de formation du copeau. Afin d'analyser ce rôle de la vitesse, nous avons acquis une défonceuse à commande numérique permettant une gamme de vitesses de coupe de 3 m s^{-1} à 62 m s^{-1}. Une première série d'essais de contournage sur du hêtre, parallèlement et perpendiculairement au sens des fibres est présentée ici. Les surfaces obtenues sont analysées à l'aide d'un rugosimètre à capteur optique.

bois / défonçage / vitesse de coupe / état de surface

1. INTRODUCTION

The main goal of high-speed machining is to increase the output. In a context of economic competition, many of metal manufacturers have shown interest in high-speed machining process since the 70's. The question raised was how to increase the output while maintaining a good surface quality at the same time. As a matter of fact, cutting and feed speeds increase is often associated with poorer surface quality and higher power consumption. However, with some specific machining conditions and device, high cutting speed can lead to better surface quality and reduction of cutting forces. The first theoretical studies of Salomon [19] in 1930 had predicted a decrease in cutting forces and in cutting temperatures when velocity was above a critical rate for a given metallic material. The first NC high-speed machine appeared only in the early 70's. Nowadays, high speed machining is a research issue. Some of the most important concerns are the study of hard metals machining, the problem of cutting instability due to spindle, tool and/or work-piece vibrations. For wood machining, the common cutting speeds are 5 to 20 times higher than the classical cutting speeds for stells depending on the applied process. It's obvious that wood and metal are very different materials; their density ratio is about 10. Wood is strongly anisotropic and has very low thermal conductivity, whereas metal is isotropic and usually has high thermal conductivity. So, we have to be careful in the comparison of machining processes for metallic and wood materials.

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Nowadays, the behavior of many metallic materials such as steel, aluminum and cast iron under high speed machining process is relatively well known with regard to energy consumption, cutting forces and tool-piece interface temperature. Some results concerning composite materials have shown that high cutting speeds increase surface quality on glass and carbon fiber material [21]. However, in the field of wood, even if some results about the effect of cutting speed effects exist, there is no advanced study about surface quality resulting from a high-speed process in industrial conditions. It should be noted that there is no accurate definition of "high cutting speed" terminology in metals; a common criterion is for speeds 5 to 10 time higher than the conventional speeds. For example, conventional cutting speed is about 10 m s^{-1} for aluminum and 5 m s^{-1} for steel. In high-speed processes, cutting velocities reach about 60 m s^{-1} for aluminum and about 30 m s^{-1} for steel. For wood, the standard cutting speeds are already very high: for the softest wood species, a cutting speed about 60 m s^{-1} is normal and 40 m s^{-1} for the hardest wood species. In sawing process, a cutting speed of 70 m s^{-1} is not unusual. We could conclude that high cutting speeds are already involved in wood processing.

In the first part of this paper, we give a brief review of high cutting process for metals. Then, a state of the art review about cutting speed effect knowledge in wood machining is presented. In a third part, experimental results are presented and analyzed.

2. HIGH CUTTING SPEED PROCESS IN METALS

2.1. Presentation

It has been noted in the introduction that the main goal of high-speed machining is to increase the productivity. A great material removal requires high feed speed. At the same time, spindle rotational speed (thus cutting speed) has to be increased in order to maintain a reasonable feed rate. The main fact when cutting speed increases is the decrease of cutting forces as shown in *figure 1*. At high speed, a new type of chip formation is involved [10, 21, 24]. During chip formation, an adiabatic shearing process is observed: most of caloric energy (80%) created by chip formation is located in the shear plane and then evacuated by the chip [27]. As a result, the material becomes softer in the shear plane area and this leads to a decrease in cutting forces. At the same time, chips become more fragmented with increase of speed. It is a great concern in machining process like turning where chip rolling up at the tip of the tool has to be avoided [11]. Another great advantage of high cutting speed process is the better quality of generated surface. In some cases, the finishing stage can be curtailed. The better surface quality is mainly due to the decrease in cutting forces, which may be explained by the adiabatic cutting phenomenon. It should be noted that smaller depths of cut are used in high-speed machining. Thus, very high cutting and feed speeds are required. As a result, the material removal rate is increased to about 5 times and the machining time and cost are reduced by about 2 and 1.5 times respectively [13]. The main applications of high cutting speed processes are milling, turning and grinding. Nowadays, one of the main focuses of high-speed processes is the modeling and prediction of cutting instability. As a matter of fact, for a set of given stiffness and damping characteristics of tool/spindle and work-piece, regenerative vibrations can occur [2, 25]. These regenerative vibrations also called chatter could lead to a rough surface, acceleration of tool wear and possible damage at the spindle. In some cases, for a given process, it is useful to design machine structure, spindle and tool with specific dynamic parameters in order to avoid chatter.

2.2. Technical requirements

In a rotational process such as milling, the technology meets difficulties linked to machine dynamic behavior, tool balance and attachment. As a matter of fact, for high rotation rates (above 20000 rpm), milling operation imposes severe conditions on spindle, bearings and machine stiffness. Quality of feed drive, piece clamping and tool attachment have also to be considered. This way, in addition to safety requirements, the aim is to reduce vibrations at spindle nose while

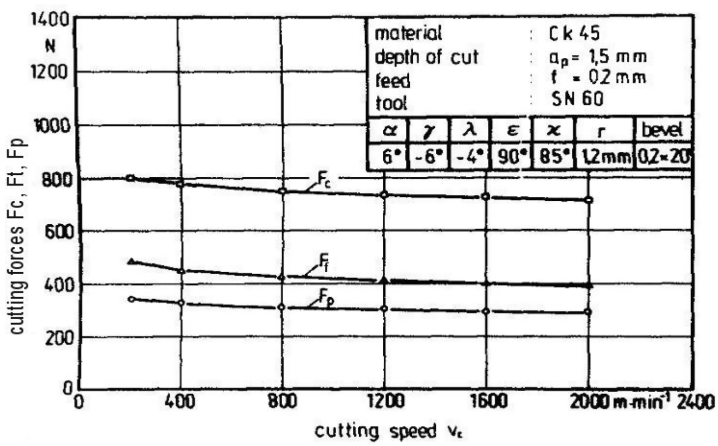


Figure 1. Cutting forces function of cutting speed [28].

cutting. As a result, the best attention will be given in the choice of machine structure, spindle and tool.

3. HIGH CUTTING SPEED IN WOOD MACHINING

3.1. Introduction

In the field of wood, although if some results about cutting speed exist for some processes, there is no advanced study about surface quality resulting from high-speed machining process in industrial conditions. In this part, we review the state-of-art in the matter of wood machining speeds and about known effects of deformation speed during mechanical trials.

3.2. Cutting speed effect

There are diverse opinions regarding the effect of cutting speed during machining processes. Some researchers found that cutting speed has no effect on surface quality and cutting forces for a large range of speed. Others found that cutting speed has a slight effect depending on process conditions.

In 1950, Liska [12] showed that the strength in compression parallel to the grain and in flexure increased by 8 percent for every 10-fold increase in testing speed. McKenzie [15] was also interested in speed effect with velocities between 0.2 mm s^{-1} and 6.3 m s^{-1}. He found no significant effect on surface quality and on cutting forces. For Kivimaa as well, in a 0–90 process, an increase in cutting speed from 2.5 m s^{-1} to 50 m s^{-1} has no effect on cutting forces [9]. Under high deformation speeds, free water contained in cells has to be evacuated from the maximum stress area to adjacent areas. So, water brings viscosity behavior to wood material. The result is an apparent increase in rigidity through Young's modulus. This is known as the Maxwell effect. Because of this free-water effect, it may be useful to focus on green wood machining involved in sawing and veneer cutting. For the latter, with green wood, Thibaut [23] observed a decrease of friction coefficient when the cutting speed was increased; Marchal [14] and Mothe [17] have shown greater cutting forces values on rake and clearance faces with increasing cutting speeds. According to Mothe, this increase can be attributed to Maxwell effect. From 1 m s^{-1} in veneer cutting, the viscoelastic behavior of wood leads to cut refusal [5, 7]. Chardin [3] did some experiments about cutting speed effects in sawing. The author observed better chip evacuation at higher speeds and thus, less heating of the saw blade. From a turning experiment, McKenzie evaluated the force variation in the cutting direction when cutting speed was increased from 15 m s^{-1} to 150 m s^{-1} [15]. According to McKenzie, because of speed changes, an additional amount of force due to acceleration has to be taken into account: this additional force is almost proportional to the square of the cutting speed and can be assimilated to an inertia force component of chip on the rake face. As a result, the higher the speed is, the greater acceleration component is. However, for turning and sawing, cutting speed contribution on total forces seems to be low and, in any cases, is less than 10% [4, 7]. About surface quality, many authors agree that higher cutting speed gives better surface quality. The common explanation is that the force increase, previously discussed, acts as if the wood piece stiffness has been increased. As a result, fibers severance is cleaner and surface quality is improved.

Inoue and Mori [8] have shown interesting results about cutting velocity effect on fracture. They found the four types of chip described by Franz [7], the occurrence of which depends on the cutting speeds. More over, the compressive strain in the chip decreases with increase in cutting speed. In an orthogonal to the grain cutting experiment, Ohta and Kawasaki [18] described several types of fractures. A transversal cutting process has been conducted with velocities going from 5 m s^{-1} to 70 m s^{-1}. For the lowest velocities, the test piece was deflected and no chip is removed. From 10 m s^{-1}, the "breakage type" often occurred (a split from rebate to the test-piece embedding). Above 60 m s^{-1}, the cutting process produced good chips with no deep splits. A numerical simulation by the Extended Distinct Element Method has confirmed these experimental results [20].

In studies concerning milling processes some experimentation problems need to be addressed [29]. If rotation rate is the only variable while keeping the feed speed constant, the feed per tooth would vary. This would lead to variable chip thickness and thus variable surface quality. In order to observe the effect of cutting speed in milling process, chip thickness has to remain constant. In case of milling, feed rate, f_z, is obtained by the equation, $f_z = \dfrac{V_f}{N \times Z}$. For a small cutting depth, the mean chip thickness is given by Schlessinger equation: $e_m = \dfrac{V_f}{N \times Z} \times \sqrt{\dfrac{H}{D}}$ with V_f = feed speed, N = rotation speed, Z = number of teeth, H = cutting depth, D = tool diameter. As our goal is an evaluation of the cutting speed effect only, it's worth setting all parameters such as feed per tooth, depth of cut, therefore chip thickness to fixed values. As a consequence it will be necessary to lead experiments by increasing rotational and feed speeds with the same rate.

At this point, according to results from literature, it seems that cutting speed could play a role in a machining process. The question of its significance still remains. We can already raise an important point; the possible effect of speed can be linked to transformations of mechanical properties of wood during the process. On the other hand, it may be the whole machining device and testpiece which behave in a different way when speed increases. In this case, that involves a study that integrates the dynamic behaviour of the device. This way, both scales, that is to say wood in the area of the edge and machining device have to be considered. For metal cutting, Touratier [26] has developed a numerical model of orthogonal cutting which integrates microscopic, i.e. in the area of edge, and macroscopic scales, i.e. dynamic of structure. The comparison between experimental and numerical results shows a good prediction of cutting forces and chip geometry. A similar model should be conducted for woodcutting in order to predict chip formation and flow and effect of cutting speed. In the following part an experiment is conducted. The aim is to show an effect, or not, of cutting speed on surface quality.

4. EXPERIMENTATION

4.1. High speed NC router machine

A Dubus 3 axis NC Routing Machine was used to confirm presence or non-presence, of a speed effect on wood cutting for a large range of cutting speeds (see *figure 2*). The Dubus machine has a Fisher spindle (N_{max} = 24 000 rpm; P_{max} = 24 kW) and the maximum feed speeds is 45 m min^{-1} for X and Y axis.

The machine structure has been strengthened in order to increase its stiffness to avoid vibrations.

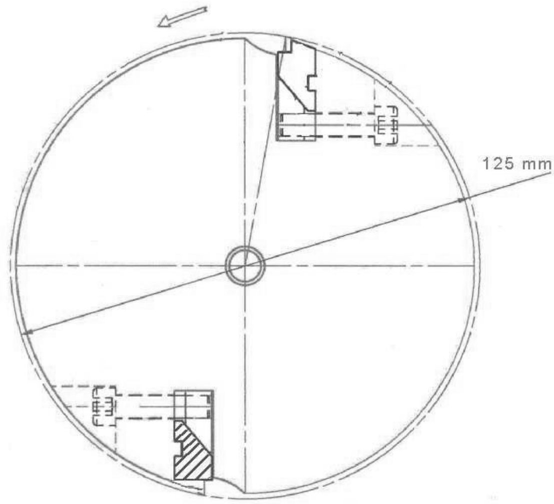


Figure 3. Single tooth tool-holder. The removed tooth has been replaced by an equal weight steel piece (hatched area)

4.2. Tests conditions

The conducted process was a milling operation in beech with a large range of cutting speed values and a constant chip thickness value. In a first experiment, we used a 4 teeth, 16 mm-diameter tool. That kind of tool might present a run-out default. As a result, the amount of material removed by each tooth is not the same along a tool round. That is why a one-tooth tool has been preferred. A 125 mm-diameter tool holder has been employed with a unique straight edge insert (see *figure 3*). As the tool-holder was originally set with 2 inserts, the first step was to remove one and then, balance the tool-holder by the addition of an equivalent mass. Rake and clearance angles were 10 degrees. The width and depth of cut were respectively 15 mm and 2 mm. Two cutting directions have been examined: longitudinal (90–0) and transversal (90–90) (see *figure 4*). The oven-dry state (≈ 0%) and water saturated (55% moisture contents) have been both considered. For safety reasons and because of the large diameter of the tool, the maximum applicable rotational speed was 10 000 rpm. The minimum rotation rate was 500 rpm. Both up-milling and down-milling processes have been examined.

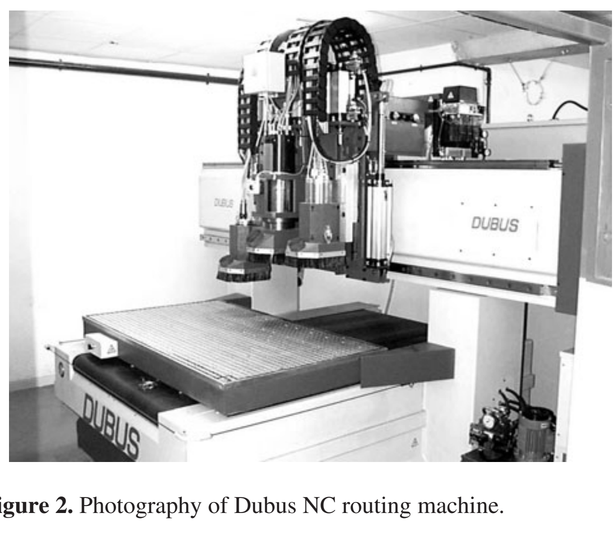


Figure 2. Photography of Dubus NC routing machine.

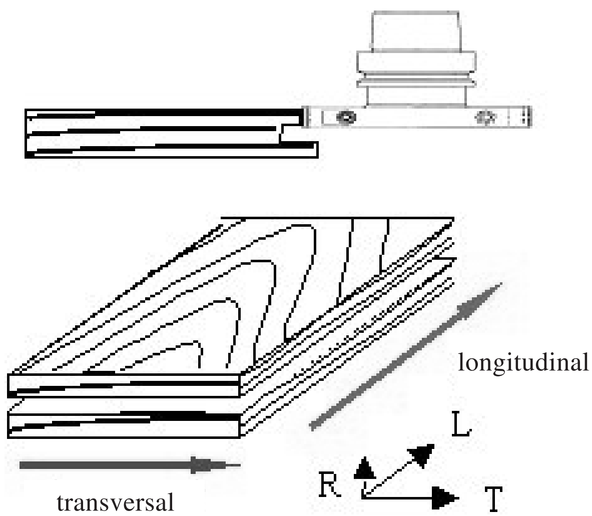


Figure 4. Wood piece shape and cutting directions. Annual rings are orthogonal to the longitudinal side of the piece.

4.3. Test pieces preparation

We have used rectangular test pieces that were 200 mm long and 40 mm thick. A rebate along both sides of the wood-piece has been profiled in order to work only with tool periphery. The longitudinal machined side has been shaped in such a way to minimise tearing between annual rings. As a consequence, the longitudinal side was orthogonal to the annual rings and longitudinal process was performed in R, L plane (see *figure 4*).

4.4. Testing progress

The milling operation has been programmed on a numerical control NUM 1060. As said previously, keeping chip thickness set to constant value involves a constant rate between feed speed, V_f and rotation rate, N. Mean chip thickness, e_m, has been set at 0.2 mm. This value is expected to give a good quality surface. According to Schlessinger equation, we find that $\frac{V_f}{N}$ ratio has to be equal to 1 (where V_f in mm min^{-1} and N in rpm). Five sets of rotational speed/feed speed have been tested. They are presented in *table I*. As explained previously, the feed per tooth f_z and thus, chip thickness e_m are maintained constant.

As a result, 8 testpiece patterns have been tested (up- and down-milling, dry and water saturated, longitudinal and transversal cutting directions). At each time, 5 cutting speeds have been experimented. That 40 cutting experiments were repeated 4 times. Thus, the total number of experimentations is 160.

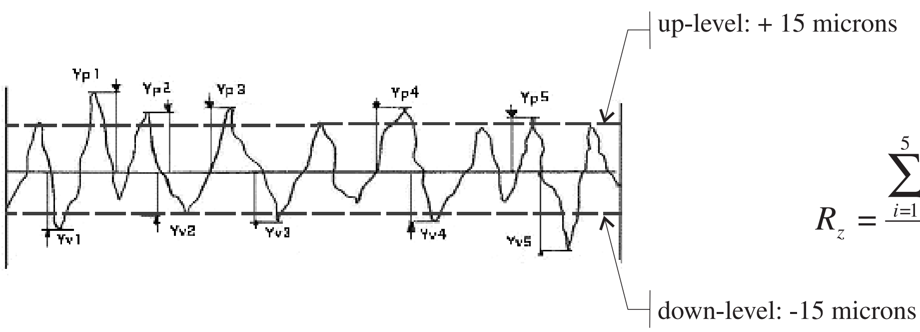
Table I. Experimented rotational and feed speeds. Feed per tooth and chip thickness values remain constant.

No	N (tr min^{-1})	V_c (m s^{-1})	V_f (mm min^{-1})	f_z (mm)	e_m (mm)
V1	500	3.27	800	1.6	0.2
V2	1500	9.81	2400	1.6	0.2
V3	4000	26.17	6400	1.6	0.2
V4	6500	42.52	10400	1.6	0.2
V5	9500	62.15	15200	1.6	0.2

4.5. Surface quality measurement

A roughness surface characterization has been conducted just after the milling process. We used a Mahr© optical roughness device in order to give an appreciation of surface quality. One of the main advantages of this technology is that there is no mechanical interaction between the sensor of device and the observed surface. The objective focuses the laser beam on the test-piece surface. The light reflected by the surface is assessed by the objective and directed to a focus detector. A linear motor moves the objective so that the laser beam is always correctly focused on the test-piece surface. Laser roughness measurement device has been used in the past by Lemaster and De Vries for sawn surface qualification [6].

For each longitudinal cut surface, parallel profiles were acquired by displacement of the laser beam in fiber direction. For transversal surfaces, profiles were chosen as close as possible to tangential direction. The number of profiles is 17 with a pitch of 0.5 mm. From each individual profile, the arithmetic roughness parameter R_z, the software has computed Abbot curve components A_1 and A_2 [1]. According to Mothe [16], R_z is a relevant surface quality parameter. A_1 and A_2 are respectively the area of peaks and valleys per millimeter of profile; the peaks density RP_c (15;–15) has been also analyzed. If we consider the mean line of the profile, we can define an up-level line located 15 microns above the mean line and a low-level at 15 microns below the mean line. RP_c (15;–15) is the number of peaks-valleys which go beyond the up- and low-level lines (see *figures 5* and *6*). These parameters are defined by the ISO 13565 standard [22]. Then, for each surface, the averages of the 17 roughness parameter values have been computed. Finally, as each cutting conditions is repeated 4 times, we have 4 average values for R_z, A_1, A_2 and RP_c (15,–15). The results are presented in the following section.



$$R_z = \frac{\sum_{i=1}^{5} Y_{Pi} + \sum_{i=1}^{5} Y_{Vi}}{5}$$

Figure 5. Surface profile with mean line and up– and down-level lines. R_z is the average of the five highest peaks and the five lowest valleys.

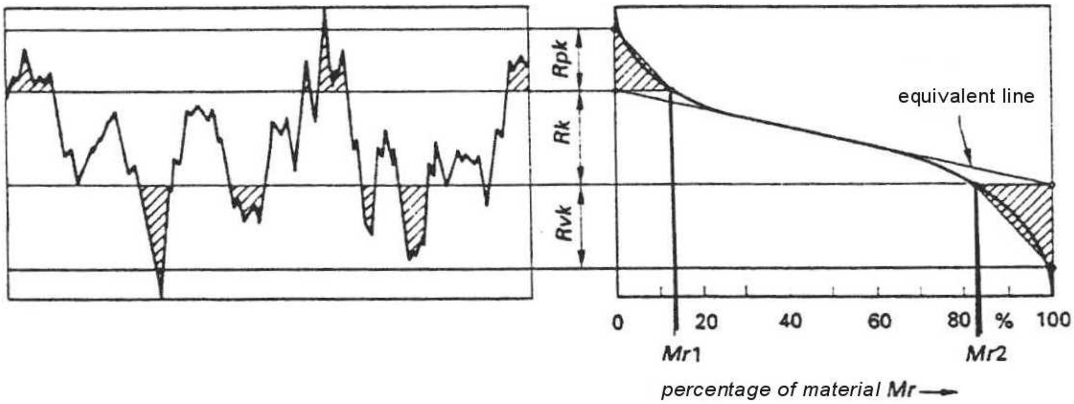


Figure 6. Abbot curve and peaks/valleys areas components. The plotted curve on the right is the heigh of a virtual cut versus the percentage of material.

4.6. Results

For each experimental condition repeated four times, roughness parameter values are plotted (see *figures 7* and *8*). We can first notice that for longitudinal direction speed effect is slight compared to transversal direction. The general trends when cutting speed rises are an increase in roughness values for up milling and a decrease for down milling. Second, we observe a strong variability of results for longitudinal surfaces. In the case of transversal surfaces, variability is lower especially for high cutting speeds. A variance analysis has been conducted in order to evaluate the relevance of cutting speed for each cutting condition (see *tables II* and *III*). For longitudinally machined pieces, Fisher test leads to a cutting speed effect that is not significant because of the strong measurements variability. This result may perhaps change with a higher number of repetitions (at least 10). But for transversally machined pieces and dry state, it appears that cutting speed becomes significant (10% error value). In this case, all roughness parameters are decreasing. Thus, the surface quality is better when cutting speed is increased. For transversally machined pieces and saturated state, increase of cutting speed leads to higher roughness parameters i.e. a worse surface quality. Let's notice that in this case cutting speed effect is relevant only for RP_c values. As a result, we can conclude that a cutting speed effect exists in transversal machining process and that water seems to play a significant part. Results show that the presence of water reverses the trend of speed effect. Water may change the mechanical behavior of wood close to cutting edge: it is possible to explain this by a brittle failure at dry state and a ductile failure at saturated state. The worse surfaces have been obtained for transversal, water-saturated pieces and down-milling process. For those pieces, because of deep checks, roughness measurements were impossible. Nevertheless, by visual evaluation, no cutting speed effect appears for water-saturated pieces/down-milling conditions.

Table II. Relevance analysis with Fisher test for longitudinal cutting direction.

Experimental conditions		Relevance (10%)	Effect of cutting speed on R_z, A_1, A_2, RPc(–15,15)
Up-milling	dry	NS	↗
	saturated	NS	↗
Down-milling	dry	NS	↘
	saturated	NS	↘

↗: increase of parameter value; ↘ : decrease of parameter value; NS: Not Significant; S: Significant.

Tables III. Relevance analysis with Fisher test for transversal cutting direction: (a) dry test-pieces; (b) water saturated test-pieces.

(a) Dry state

Fisher test	5%	10%	Effect of cutting speed on parameter value
R_z	S	S	↘
RPc (15;–15)	NS	S	↘
A_1	S	S	↘
A_2	S	S	↘

(b) Saturated state

Fisher test	5%	10%	Effect of cutting speed on parameter value
R_z	NS	NS	↗
RPc (15;–15)	S	S	↗
A_1	NS	NS	----
A_2	NS	NS	----

↗: increase of parameter value; ↘ : decrease of parameter value; NS: Not Significant; S: Significant.

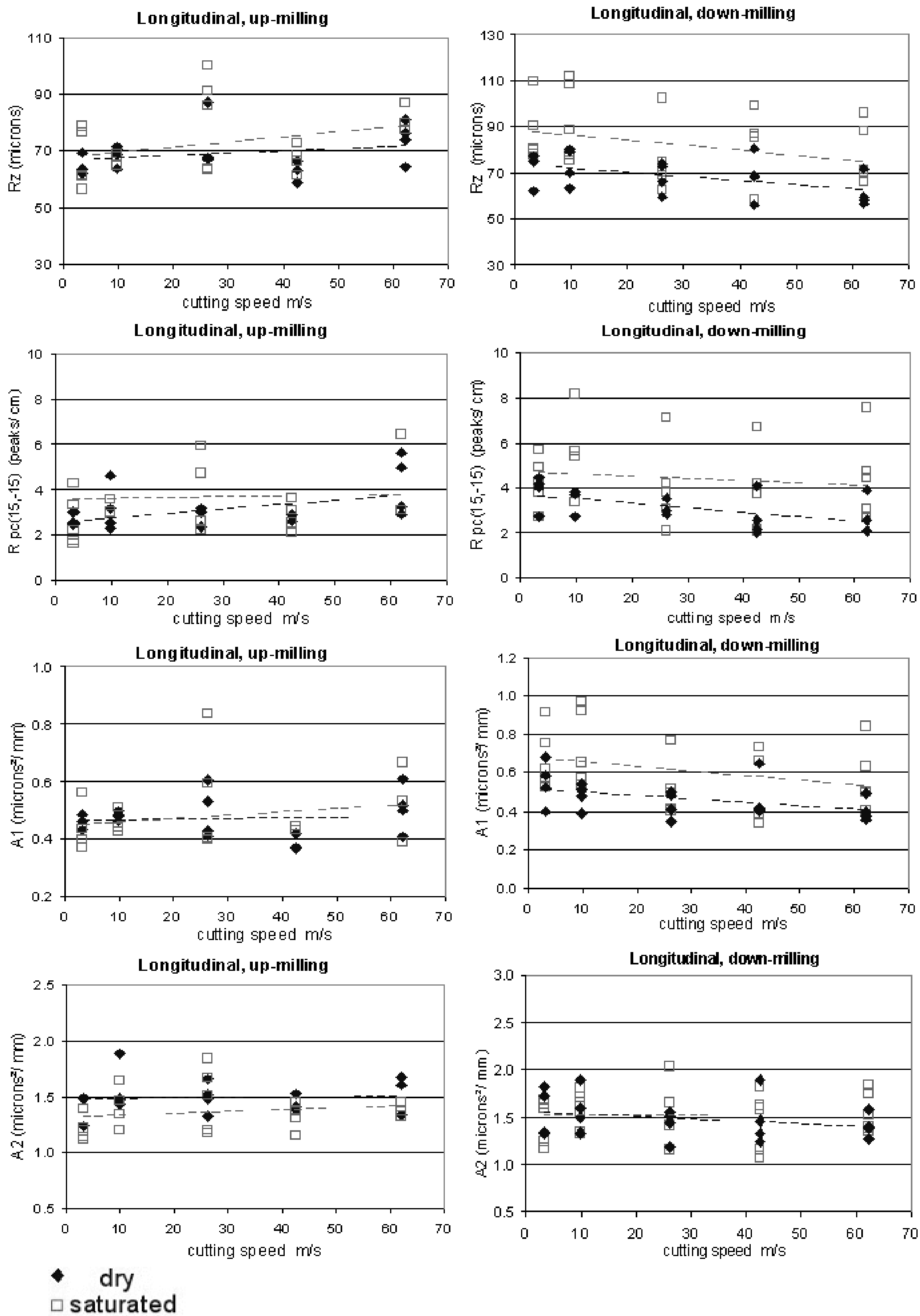


Figure 7. Roughness results for longitudinal cutting.

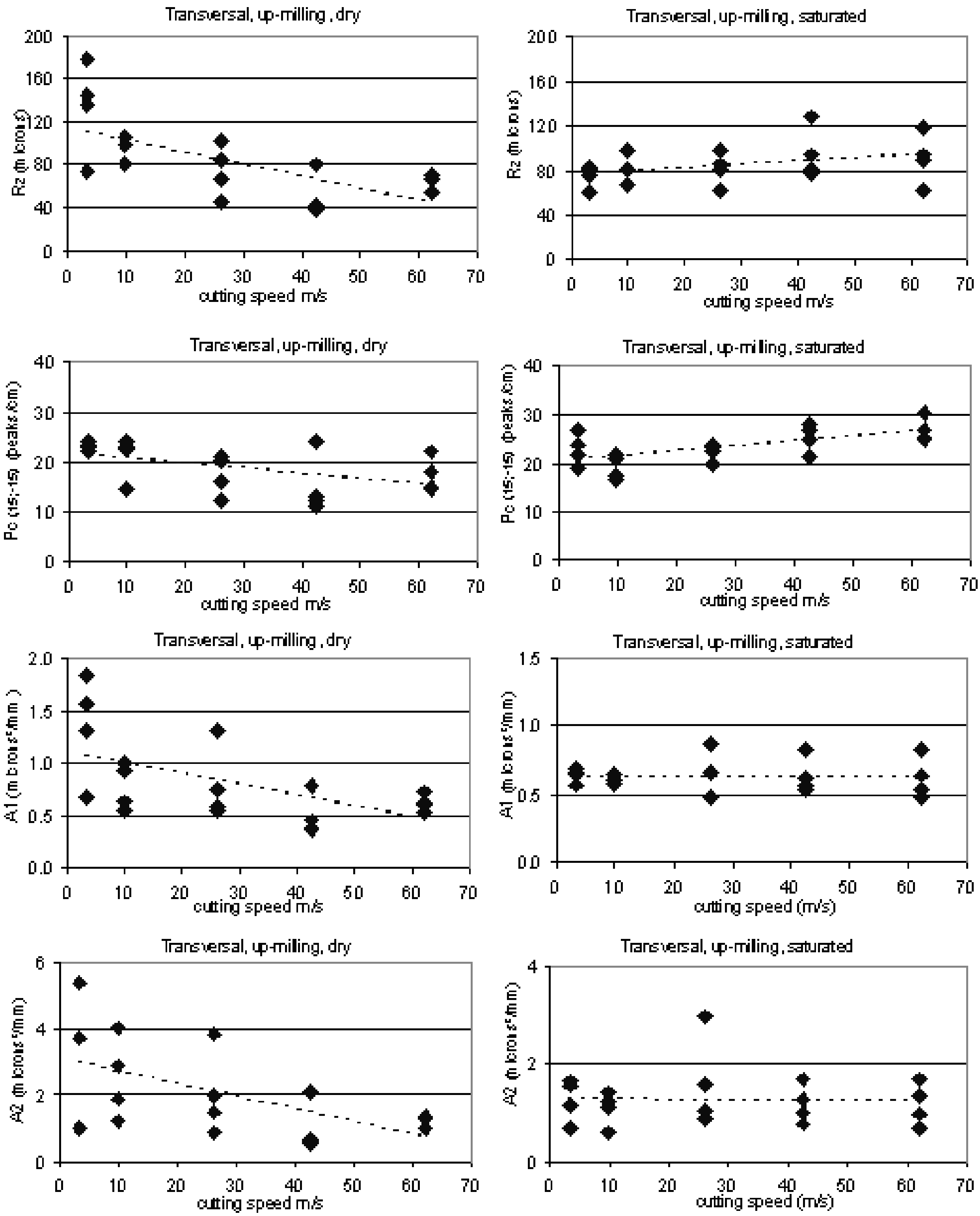


Figure 8. Roughness results for transversal cutting direction and up-milling process.

5. CONCLUSION

In this article, we have exposed the main advantages of high speed machining process in metal industry; increase in productive output and better surface quality lead to better productivity. In wood machining, literature results about cutting speed effect are rather fuzzy depending on the experimented process and measurements conditions. Here, we have conducted milling experiments with constant chip thickness and cutting speeds from 3 m s^{-1} to 62.2 m s^{-1}. A significant effect appears for transversally machined pieces especially for dry wood. In this case, an increase in cutting speed results in a better surface quality. We can also conclude with an interaction between cutting speed and water.

In the future, it would be useful to focus on an important issue in woodcutting with a similar approach as Ohta and Kawazaki [18]: flakes at extremities that might damage the wood piece in milling process. Another important point is the study of machining instability, which has been developed by Tlusty [25] for metal cutting. With well-known dynamic characteristics of the machine components, it becomes possible to avoid machining conditions where regenerative vibrations occur.

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