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SOME INVESTIGATIONS ON THE COUNTER AND DOWN MILLING

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Abstract
Although the counter and down milling are well known and widely used in the woodworking industry, many aspects are not fully understood yet. New investigations were started on a CNC-router equipped with a three-component force measuring system and a LabView operating and evaluating program. The main task of these experiments was to clear the possible differences when rigid or vacuum clamping of the work piece is used. Further influencing factors such as cutting speed and feed speed were also investigated. The experimental results have shown that there are definite differences both in force relations and surface roughness parameters when either two rigid or vacuum clamping was used. The results of three different clamping modes produced different resultats. The stiffnest clamping on machine gave the smallest tangential and the largest radial force.

Key words: *Force, frequency of workpiece, cutting speed, milling, frequency of tool.*

INTRODUCTION

The mechanics of the cutting examines/analyses the interaction between the tool and the chip using the engineering mechanics. We take into consideration the mechanical properties of the material, if necessary the anisotropy, the viscoelastic and plastic properties as well. We look for connections between the forces and deformations, and the final goal is the determination of the cutting-force depending on the properties of the material and the tool. Our aim is as well that we explain the so far only observed phenomena with scientific background.
We confirm the theoretical results with experimental data. Where necessary, we give work-charts for the faster determination's aim of the wanted parameters.
In our present measuring series, researched poorly so far, the parameters of counter- and down-milling were investigated at different parameters especially the force relations and the difference between the three clamping methods.

THEORETICAL CONSIDERATIONS

Pneumatic clamping of workpiece
The most frequent clamping method for workpieces with flat surface is the fastening by a vacuum field. The vacuum pressure generates a vertical press-down force and the

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horizontal friction forces prevent the workpiece to shift in any direction. The vacuum pump generally allows a maximum vacuum pressure of 0.8 to 0.9 bar. The pressing force generated by the vacuum is.

$$F_v = p_v \cdot A$$

where p_v is the vacuum pressure and A is the effective area under pressure.

Applying a horizontal force, the workpiece clamped by vacuum on the machine table can be shifted. Shows the force and displacement relationships for a given workpiece is shown on Fig. 1.

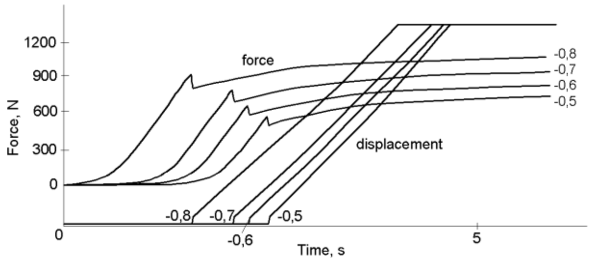

Fig. 1. Force requirement for shifting of a workpiece on the machine table (laminated particle board, A = 583 cm^2, at different vacuum values)

The horizontal force shifting the workpiece is a friction force and, therefore, the friction coefficient can be calculated:

$$F_h = \mu_0 \cdot F_v \quad \text{and}$$

$$F_h = \mu \cdot F_v$$

where μ_0 is the static friction coefficient for a resting body, and μ is the kinetic friction coefficient (body is in motion).

In Fig. 1. we can see that the static friction coefficient is slightly higher than the kinetic friction coefficient. After a given sliding distance, however, the kinetic friction coefficient slightly increases and it can surpass the static value. From practical point of view the static friction coefficient is definitive.
In order to calculate the friction coefficient, the vertical pressing force must be known. Apparently this is easily calculated from an equation given above, but the selection of the effective surface area under suction may cause some troubles. Special measurements have shown that the ratio of effective and actual surface area is depending on the shape and size of the workpiece and also on the vacuum value. Generally this ratio varies between 0.80 and 0.90 and the higher values are valid for larger workpieces and lower vacuum pressures.

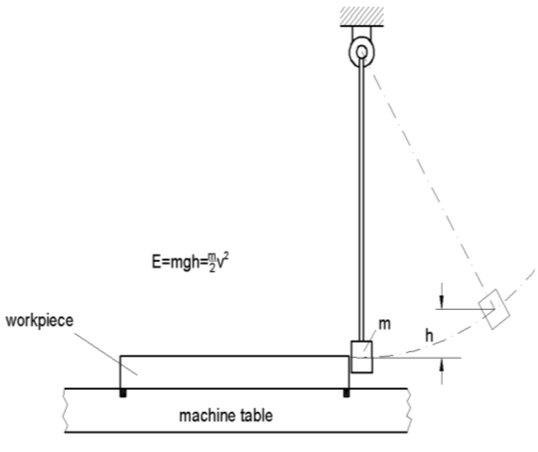

Fig. 2. Pendulum loading device

The dynamic behaviour of the clamped workpiece can be examined by impact forces accomplished by a pendulum loading device (Fig 2.).
Concerning an elastic material impacted by a mass, the impact characteristics such as the deformation, force, velocity and deceleration during the impact can also be calculated. Taking a linear force-deformation relationship in the form $F = B \cdot x$ then the maximum deformation is given by the energy equation:

$$mgh = \int_0^x F \cdot dx \qquad \text{and} \qquad x_{\max} = \sqrt{\frac{2mgh}{B}}$$

where B means the stiffness of the material, x is deformation :
Falling the mass onto the surface, the force is determined by the deceleration and, therefore, the following equation is valid

$$F = m \cdot a = B \cdot x \qquad \text{and} \qquad a = \frac{B \cdot x}{m}$$

After contacting the surface, the velocity of the pendulum mass decreases. At the beginning of the impact the approaching velocity is $v_0 = \sqrt{2gh}$ where h is the falling height (see Fig. 2.). As the deformation reached its maximum value, the velocity tends to zero.
The change in velocity can be calculated in the following way:

$$v_x \cdot dv = -a \cdot dx = -\frac{B}{m} x \cdot dx$$ after integration we have

$$\frac{v_x^2}{2} = -\frac{B}{m}\frac{x^2}{2} + C$$

The initial condition is taken as $x = 0 \rightarrow v_x = v_0$, therefore,

$$C = \frac{v_0^2}{2} \qquad \text{and further} \qquad v_x = \sqrt{v_0^2 - \frac{B}{m} x^2}$$

If the deformation x approaches its maximum value $x_{\max}$, then the velocity of the mass tends to zero. Using the last equation and keeping in mind that $v = dx/dt$ the impact duration can be determined: $\Delta t = \int_0^{x_{\max}} \frac{dx}{v_x} = \frac{\pi}{2}\sqrt{\frac{m}{B}} = \frac{\pi}{2}\frac{x_{\max}}{v_0}$

The maximum force is given by the following equation: $F_{\max} = Bx_{\max} = \sqrt{2Bmgh}$

In our case the above equations are valid if the counter-force is greater than the maximum impact force. If it is not the case, the impacted body will slide to a given distance and the surplus energy of the mass will be consumed by friction. It is important to note that a considerable part of the impact energy is converted into deformation and acceleration of the body. Theoretically, a pure elastic deformation does not consume energy and the impacting mass would be returned to its initial position.

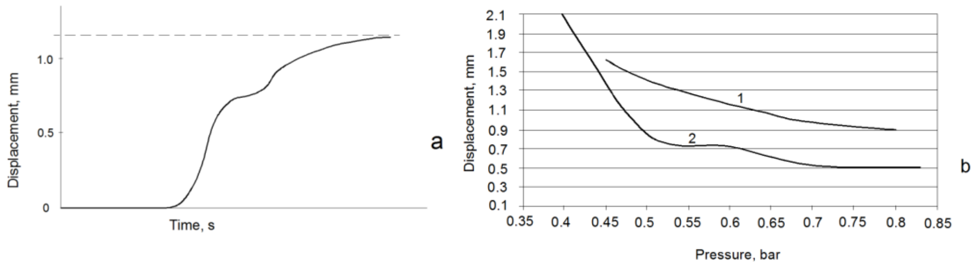

Fig. 3 Displacement of an oak specimen under impact load (a); and displacement of oak (1) and chipboard (2) specimens as a function of clamping pressure (b).
Impact mass 7.8 kg, drop height 7.5 cm, clamping vacuum 0.6 bar, *A* = 583 cm^2

The displacement of an oak specimen during impact loading is shown in Fig 3. The impacting mass was 10×10×10 cm, 7.8 kg and a drop height of 7.5 cm. The impact energy is 5.74 Nm and the impact speed is 1.21 m/s. The friction force of the specimen was appr. 700N. Friction energy of 0.812 Nm was consumed over a sliding distance of 1.16 mm and this amount is only 14 % of the total impact energy.

The specimen on the machine table is also supported by the elastic rubber which exerts an additional resistance only after a given deformation. Therefore, the displacement curve shows a wavy character.

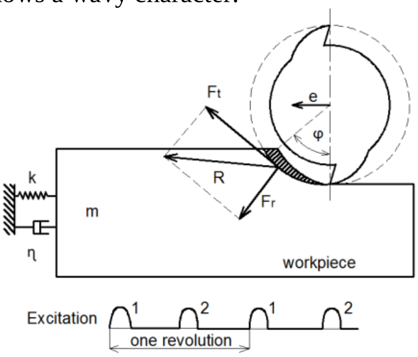

Fig. 4 Excitation of a workpiece by periodic cutting forces

Softwood species, and particle board, suffer more deformation and absorb more energy. This means less surplus energy and less displacement, which was verified experimentally (Fig. 4).

The pneumatic clamping of a workpiece cannot be regarded as a rigid clamping method and the workpiece is often inclined to vibrate. Especially small workpieces tend to have forced vibrations due to the excitation of the cutting force (Fig. 4). The governing equation of motion has the following general form:

$$m\frac{d^2y}{dt^2}+k\cdot x+\eta\cdot\dot{y}=P(t)$$

where *P(t)* is the excitation force.

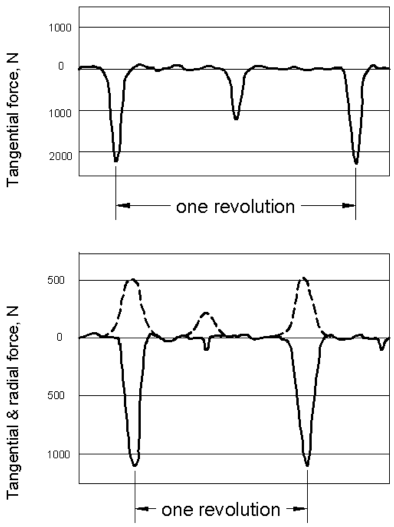

Fig. 5 Unequal tooth feed and cutting force due to workpiece vibration clamped on a CNC-router and using a tool with two cutting edges. Upper Figure: *n* = 3,000 rpm, feed speed 5 m/min, cutting depth 1 mm. Bottom Figure: *n* = 6,000 rpm, feed speed 5 m/min, cutting depth 1 mm

Resonance occurs if the natural frequency of the workpiece equals the force excitation frequency or its multiple. A typical feature of this phenomenon is the unequal tooth feed and cutting force on the individual cutting edges, as shown in Fig. 5.

In the first case the feed per revolution is large enough (e_n = 1.67 mm) and the displacement of the workpiece in the same direction to the approaching cutting edge can only halve the tooth feed. In the second case the feed per revolution is 0.83 mm and the second cutting edge has practically no tooth feed. The edge is in contact with the workpiece which is indicated by the radial force. To avoid resonance, the frequency of rotation should be changed. If every second cutting edge fails to cut, the surface will generally show a wavy character similar to wash boarding.

Here again an important condition for instability that the tooth passage frequency ($f_t = nz/60$) is slightly higher than the natural frequency of the workpiece. The expected band width of resonance is some 4-5 % related to the resonance frequency of the workpiece.

MATERIAL AND METHODS

In our case we would like to represent dynamic effort as a function of time. We used a special measurement system for this goal. Measurements based on personal computer can be realized with products offered by the National Instruments. The National Instruments, LabVIEW is a graphically programmable development environment, with which measuring-, process controlling applications can be made.
The measuring system is adapted for the implementation of various measurements and during the cutting we can measure the dynamic impacts. In the case of vacuum- and rigid clamping, measure and compare the originated forces. For the cutting, we have used straight edged removable hard metal tipped cutter. We have done the force measurement in the case of a 20 mm beech wood panel on one side. It is common among the measurements that we have done conventional milling along x direction in every case. In the case of comparison investigation, we have done the milling between 6000 and 12000 revolutions by cutting depths (1 mm) with four different feeding (from 5 to 12 m/min).
We applied three types of clampings, rigid clamping screwed to a metal base, semi-rigid clamping screwed to an MDF sheet, and normal vacuum clamping.

Fig.6 Rigid clamping with steel plate

Fig.7 Semi-rigid clamping screwed to an MDF sheet

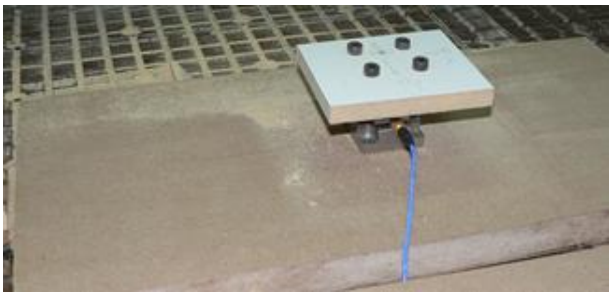

Fig.8 Flexible vacuum clamping

RESULTS

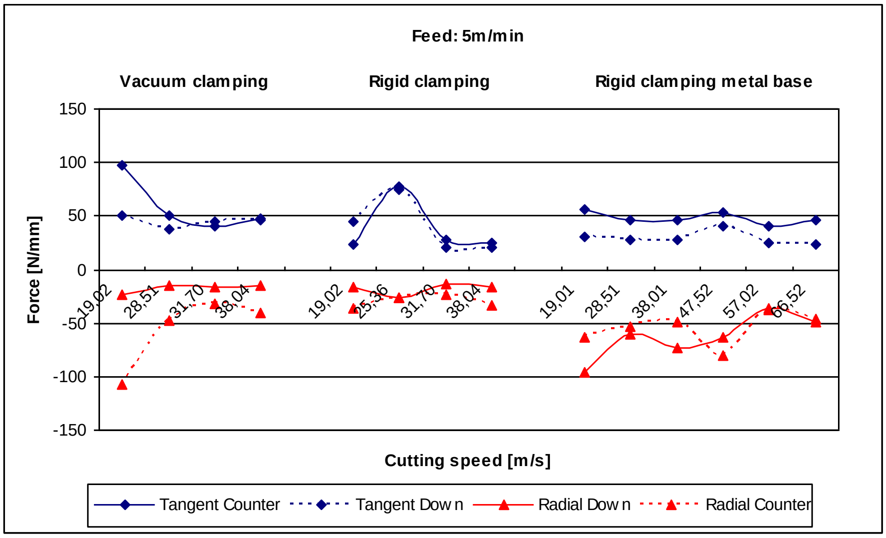

Fig 9. Tangential and radial forces in as a function of clamping varieties and cutting speed.

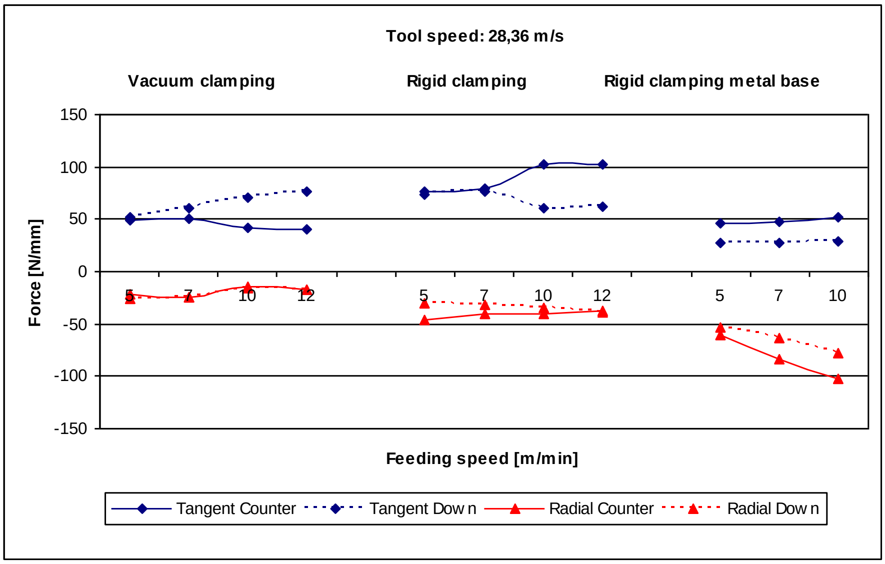

Fig 10. Tangential and radial forces in the capture of clamping varieties and feed speed.

Based on figure 9 and figure 10 it can be said that the the metal based clamping is the most rigid, which affects the vibration frequency of the system. The possibility of displacement is the lowest of all, the forces thus increased in radial direction. This direction points inwards of the timber, and forces to deformation. Tangential force is reduced in this case. The split is generated in this direction. As a result of the rigid clamp, this split is the best, the chip separates quickly, thus the cutting edge is no longer pushes the wood significantly, the measurable force is reducing. Forces represented by feed components can be observed in case of counter forces. In case of counter milling this component is added to the measured tangetial force component while in case of one-way milling it does not play a role.

When we used semi-rigid and vacuum clamping, the vibration of the system of the material and the holding down components -in case of some cutting speed- generated an excitation, that caused the apparent elimination of the forces on one cutting edge in case of two-edged milling tools, at the same time it caused an unexpected growth in the force of the operating cutting edge. This case couldn't be observed in oscillation on different cutting speed. The metal based sheet according to it's rigidity has shifted the vibration: frequency to higher values. The differences between the forces inducted by the cutting edges in case of milling on the resonance wasn't so high as in case of semi-rigid and vacuum clamping. The shift and the increase of the forces due to resonance can be observed on figure 11-12, and from the separate force-time diagram.

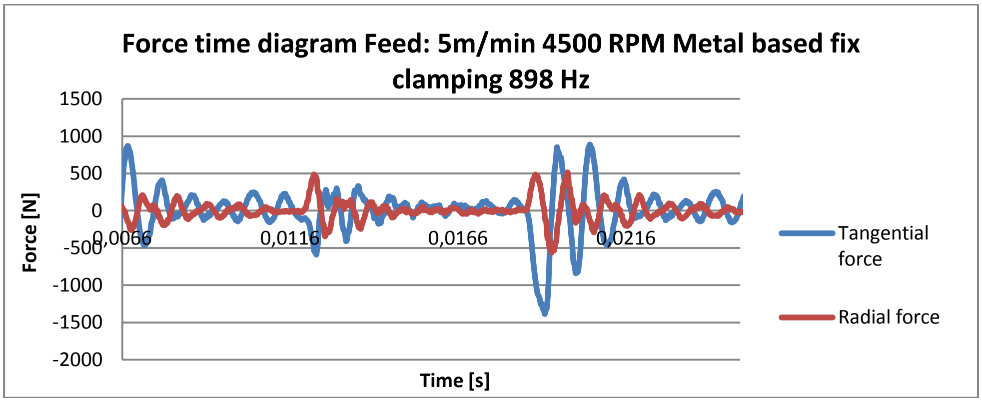

Fig 11. The self-oscillaton and the course of forces at rigid clampings

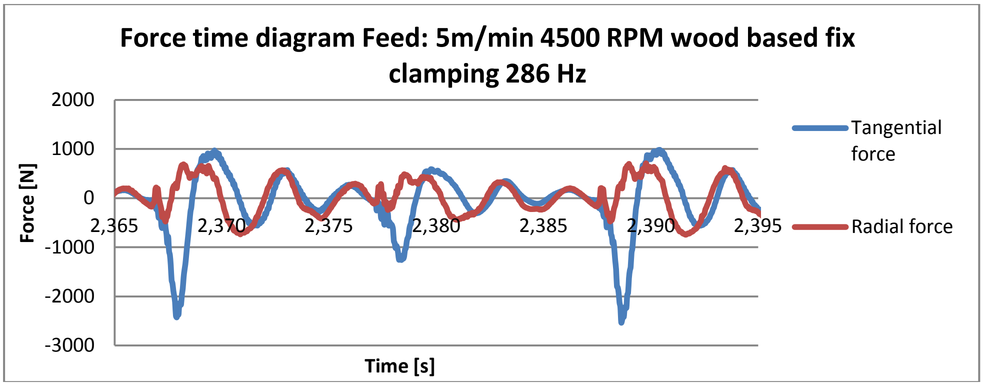

Fig.12. The self-oscillaton and the courde of forces at semi-rigid clampings

CONCLUSIONS

The correlations revealed create the basis for defining a well applicable method to determine the optimum cutting speed of the CNC router. According to the usual idea that increasing the cutting speed and feed speed indicates productivity growth can supplemented with the idea that -depending on the clamping- certain cutting speed ranges is denied by machining beacuse of the worthening of the surface quality and the increased loading of the machine.

The diagrams in terms of forces can also show minimum-places, that means at these speeds lower force is applied to the machine.

The method of speed selection is to define the self-oscillaton of clamped workpiece, thereafter the choise of the highest possible cutting speed that gives minimum force. At the same time, the tooth frequency of the given tool should be as far as possible from the natural frequency of clamped workpiece.

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