Oscillations of Cutting Tool as a Useful Effect in Turning and Drilling

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Abstract **– The paper presents the fixtures with movably mounted turning and drilling cutting tools. The fixtures were developed on the principle of oscillating tooltip similar to the principle of the ultrasonic vibration-assisted machining process. However, presented fixtures do not need an electricity source and utilize mainly forced and self-excited oscillations. In general, the tool vibrations during the cutting process are recognized as a negative phenomenon as it causes a shortening of the tool life and worsens the roughness of the machined surfaces. However, a deeper understanding of the cutting process proposes possible positive effects of tool vibration in terms of chip shapes, flank wear, chip volume coefficient, and quality of the machined surface. Experimentally obtained dependence of mentioned quantities is provided in the paper.**

Keywords **– fixture, tooltip, drill, wear, chip shape.**

1. Introduction

The cutting process is well-known as a dynamic process. Cutting force during chip removal varies considerably due to the inhomogeneity of the material being machined [1], [2], [3].

DOI: 10.18421/TEM114-13
https://doi.org/10.18421/TEM114-13

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Received: 10 August 2022.
Revised: 17 September 2022.
Accepted: 27 September 2022.
Published: 25 November 2022.

A question can be asked if the vibrations generated while machining cannot be used to improve the process of chip removal. Each part of the lathe, milling, and drilling machines is deformable and subjected to cutting force of dynamic character. This is the main reason why the oscillations occur.

The interesting part of the presented paper is the oscillations of the tool which is the least stiff element of the system. The actual tool position can be determined by the analysis of the oscillations. If it is taken into account that the cutting force always involves a dynamic component, a new approach utilizing the decreased rigidity of the technological machine/cutting tool/tool holder/workpiece system can be developed and shown in the paper.

The oscillations described in the sub-system tool-workpiece can be included in the category of forced oscillations which are evoked dynamically by a variation of cutting force while cutting. However, during the process of machining, the oscillations which are characterised as self-excited are generated [4], [5]. The self-oscillations are a result of variable friction in the tool face and the chip contact surface and of the periodical slides inside the chip. In the case of the formation of the self-oscillations, they can be considered secondary influences because they have much smaller amplitudes than forced oscillations. During steady machining, the change of cut cross-section evoking the self-oscillations occurs only minimally. However, during the finishing cutting, the self-oscillations are necessary to be considered because they can cause problems leading to the worsening of the quality of the machined surface and other output characteristics of the machining process.

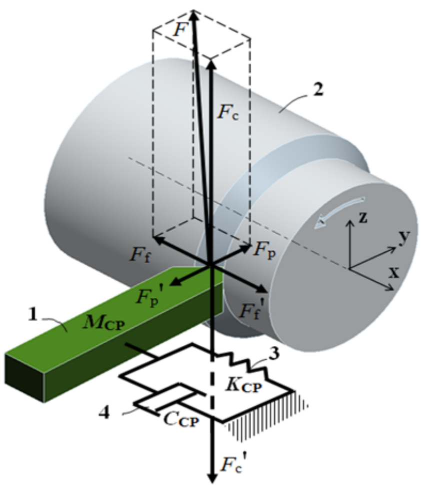
The goal of ultrasonic vibration machining is micro-level high-frequency vibration of the tip of the cutting tool to make the interaction of the tool and the workpiece an intermittent process. The principle is described in [6]. The interaction of tool-workpiece is non-monotonic at the microscopic level. The chip is therefore easier to separate and machining forces are reduced. At present, when special metal alloys, composite materials preferably in the aerospace industry [7] need to be machined, ultrasonic vibration-assisted machining is a well-known approach for making the effectivity of conventional machining very high. However, it is a machining process that needs an additional energy source for generating the high-frequency vibrations of the cutting tooltip. The analysis of chip morphology, cutting forces, and stability of the orthogonal cutting process is made numerically by [8], however, the roughness is not evaluated. A vibratory tool holder was developed also for vibration-assisted drilling and its performance is analysed experimentally and numerically in [9].

Modification of the tool-holder with the aim to break the chip was developed in [10]. The standard tool holder was equipped with an external chip breaking system for dry machining. The chip breaking system does not need external source of electricity, however, it is designed only for chip breaking, and the material cutting process is not influenced.

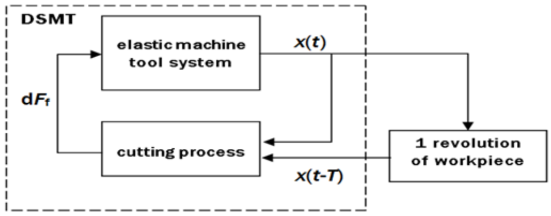
The principle of vibrating material removing „tool“ is used in the case of the water jet. The pulsating water jet provides more effective erosion performance in disintegrating rock or metal surfaces compared to the continuous water jet. The additional change from a continuous water jet to pulsating one makes the water jet be utilized for more manufacturing applications [11], [12].

1.1. Turning System and Oscillations

The machining process evokes vibration phenomena causing irregularity of generated vibrations manifesting, mainly, in tool wear and surface roughness. Three components of vibrations are mainly simplified in a single degree of freedom system of orthogonal turning process with a flexible tool and relatively rigid workpiece. The inertia force, damping force, spring force, and the cutting force in the feed direction are forces in a mechanical system.



(a)



(b)

Figure 1. (a) Scheme of cutting tool within the machine-tool system; 1 – tool, 2 – workpiece, 3 – stiffness, 4 – damping, F_f, F_p , F_c is axial, radial, and tangential force, respectively,(b) dynamic system of machine tool (DSMT), cutting process (CP)

If it is supposed that the force of the spring is smaller than the friction force of the chip F_f on the tool face, the tool will move to the right and together with the chip, and the relative speed between the tool face and the chip is zero. When both forces are balanced, the tool starts moving back. As the friction coefficient will be considerably smaller when the tool and chip move than when there is relative inaction, the force F_t decreases, and the tool moves to the left into a balanced position by the influence of the spring. That process repeats. Because the tool can be considered to be a deformable element of the machining system, which performs elementary movements (oscillations) along the direction of the workpiece axis, these oscillations will occur practically always, even in cases where we consider the cutting force to be relatively constant. It means the cutting force has a mean value that evokes static deformation and a dynamic element, which evokes system vibrations.

Let consider the parts of the cutting tool holder as deformable and all other components of the machine-tool system as rigid ones. Moreover, let suppose that the cutting tool oscillates axially, in the direction of the feed where the axial force F_f works. Fig. 1a shows a rheological scheme of that single degree of freedom oscillation system. Fig. 1b shows a schema of a dynamic system of the machine tool. A differential formula (1) (according to [13]) describes dynamic behaviour single degree of freedom system. The right side of formula (1) is the increment of the feed force component generated in cutting process (Fig. 1b):

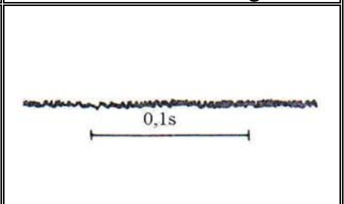
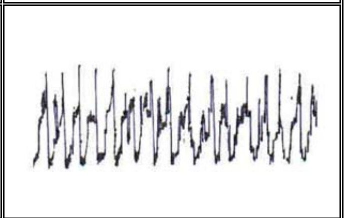
$$\begin{aligned} M_{\mathrm{MTS}}\,\ddot{x}(t)+C_{\mathrm{MTS}}\,\dot{x}(t)+K_{\mathrm{MTS}}\,x(t)= \\ =-K_{\mathrm{CP}}[x(t)-x(t-T)]-C_{\mathrm{CP}}\,x(t) \end{aligned} \tag{1}$$

where M_{MTS}, C_{MTS}, and K_{MTS} is mass, damping, and stiffness of machine tool system (MTS), respectively, K_{CP} is stiffness of the cutting process, $x(t\text{-}T)$ is tool displacement relative to the workpiece in the present and previous revolution of the workpiece, C_{CP} is damping of the cutting process and T is period of workpiece revolution.

2. Cutting Force Variation and Chip Shape

A positive aspect of tool or workpiece oscillation is the formation of suitable, i.e., not ribbon chips. We made the tests of that relationship. The tests were conducted in sense of Komanduri's experiments [14] to prove the relation between the frequency of cutting force value change and the frequency of the chip breaking. Table 1 provides the different chip shapes and corresponding time records of cutting force, e.g. in the second row, the chip breaking frequency is 90Hz and the cutting force frequency is111Hz (cutting force is 472N).

Table 1. Cutting force variation and chip shape

Chip shape	Time record of cutting force
	
	

3. Experimental Tests

The main idea in design of the presented fixtures was to allow a tool tip-controlled oscillation by releasing one degree of freedom. The fixed tool became movable in one direction. The process of tool oscillation is controlled by cutting force.

3.1. Fixture with a Movable Turning Tool

The force of cutting resistance is a source of oscillations of a movable turning tool fixture (Fig. 2). The point of action of that force is situated with eccentricity from the axis of the roller bearings 1. The eccentricity of the point where the cutting resistance force acting causes small rotational movement controlled by springs 3. The one free rotation degree of freedom is allowed. During the turning process, the value of the force of cutting resistance is not the same due to the ferrite and perlite material structure. Both steel phases are of different hardness and they are one of the sources of the force dynamic component. The springs return the turning tool to the initial position and the process is repeated. The oscillation amplitude is controlled by springs.

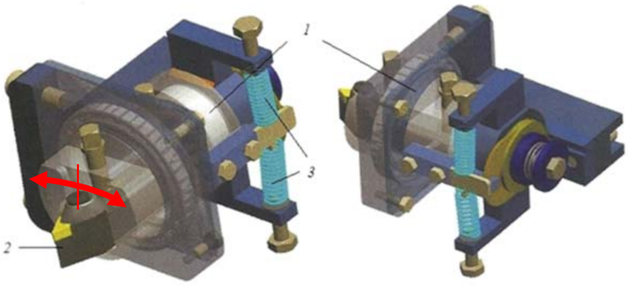


Figure 2. The virtual 3D CAD model of fixture with movable turning tool – design 1 (1 – roller bearings, 2 – turning tool, 3 – springs)

In stand 1 in Fig. 5, there is a pin 2 with a movable face disk placed on roller bearings 3. A turning tool 5 is mounted and fixed by screws 4. The tooltip is in the axis of the pin 2 rotation and also in the axis of the workpiece. The face disk 2 is secured by adjustable springs 6 against free rotation. Alternatively, there is a rod *7* with a movable weights balance in the back part to adjust the frequency.

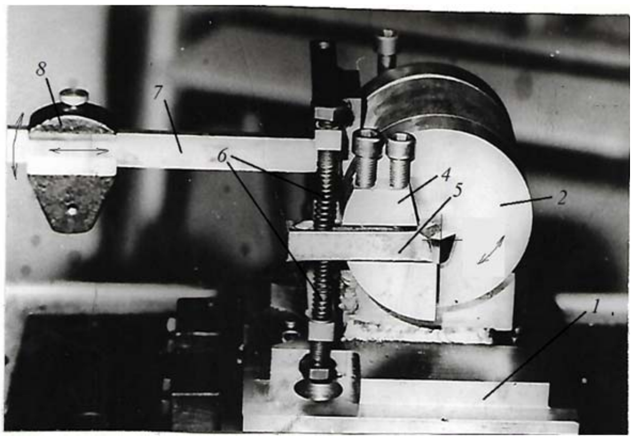


Figure 3. Fixture with movable turning tool – design 2; 1 –stand, 2 – pin with movable face disc, 3 – roller bearings, 4 – clamp, 5 – turning tool, 6 – springs, 7 – rod, 8 – movable weights balance

3.1.1. Results – turning

Table 2 provides the comparison of the chips shapes turned by un-movably (fixed) and movably mounted turning tool in the fixture design described in Fig. 3 for six values of depth of cut a_p.

It can be seen that if the tool is mounted movably, a considerable improvement of chip shape within the whole range of the used depths of cut occurs. A tool oscillation around the axis passing through the tooltip is enabled. The tooltip stays in the same position, however, the position of cutting edges (working angle of cutting edge setting is being changed) changes during oscillation. This leads to the change of the direction of the chip leaving and its shaping.

Table 2. Dependence of chip shape on the cut depth a_p during turning by fixed and movable turning tools

a_p	0.3	0.5	0.8
fixed tool			
movable tool			
a_p	1	1.5	2
fixed tool			
movable tool			

Long-term tests of turning have been performed with design 2 (Fig. 3). Fig. 4 presents the resulting dependence of the flank wear *VB* on machining time τ_c when turning with a static tool (fixed by screws) and a movably mounted tool with a free degree of freedom limited by springs.

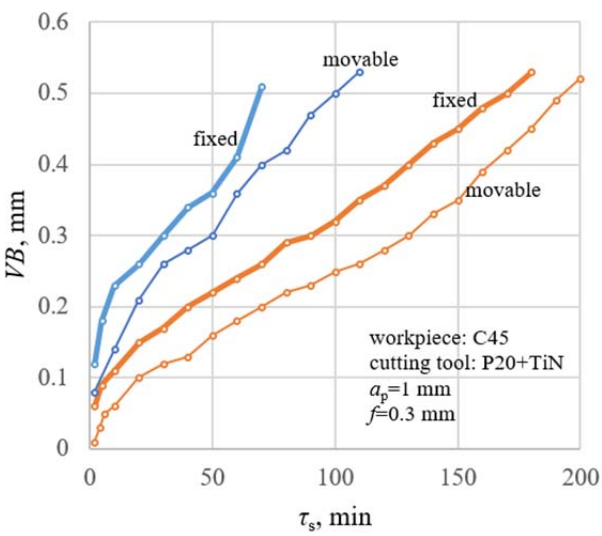
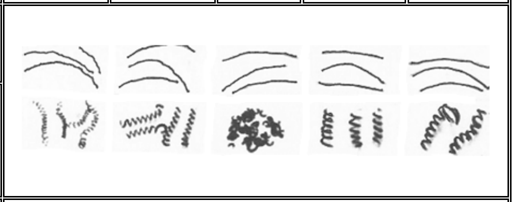
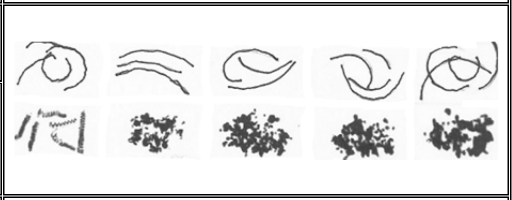
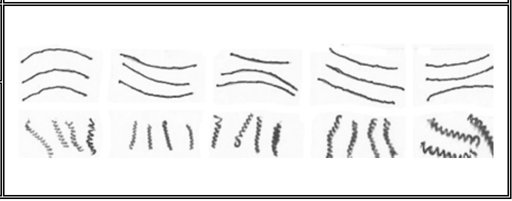


Figure 4. Flank wear of a fixed (thin line) and movable (bold line) turning tool (orange for cutting speed v_c=50 m.min^{-1} and blue for v_c=100 m.min^{-1})

The source of the increase in the tool life can be seen in the fact that the working geometry ($\lambda_s;\alpha_n$) of the tool partially changes during turning. The tool can change position caused by increased cutting force, the face angle increases and it can be said that the tool is "floating" in engagement in the path of least resistance.

The change of face angle and the cross-section of the chip influence the shape of the leaving chip. Table 3 shows that this influence is significant. The chips are of suitable shaped (not ribbon) within the whole range of used depths of cut a_p from 0.5 to 1.5mm in all tested materials, i.e. C45 – low carbon steel, 100CrMn6 – chrome bearing steel, and 12NiCr6 – stainless steel.

Table 3. Chip shapes obtained by fixed and movably mounted turning tool

Workpiece material	Tool	Cutting speed v_c = 120 m.min^{-1}, feed f = 0.2 mm				
		a_p (mm)				
		0.5	0.8	1	1.2	1.5
C45	fixed					
	movable					
100CrMn6	fixed					
	movable					
13NiCr6	fixed					
	movable					

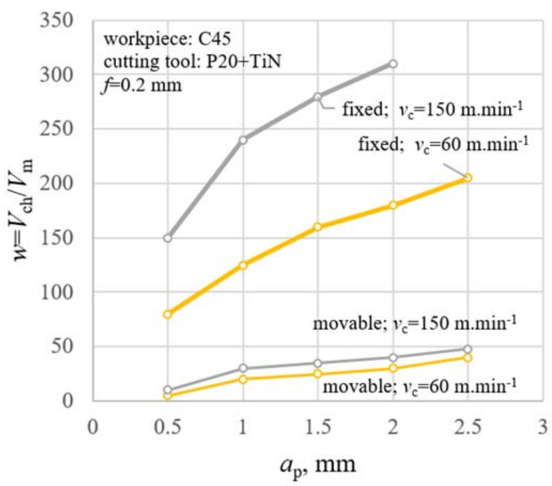


Figure 5. Experimental dependence of chip volume coefficient w

The suitable effect of the movably mounted turning tool is possible to confirm by a chip volume coefficient *w*. The coefficient is calculated as the ratio of the volume of freely laid chips V_{ch} and the volume of removed workpiece material V_m. Fig. 5 provides the experimentally found dependence $w = f(a_p;v_c)$ for both fixed and movably mounted turning tools. It can be seen that the influence of oscillation on chip shaping is substantial. In the whole range of tested cut depths a_p, the chip volume coefficient decreases and the chip is suitably shaped. Moreover, the another important effect of the additional tool oscillation is that a built-up edge is not formed.

The metallographic cut in Fig. 6 shows the moment of reducing the thickness of the chip when the tool is making an oscillation. Thus the discontinuous chip is formed.

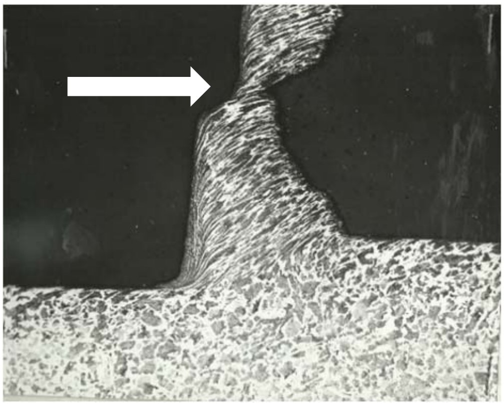


Figure 6. Metallographic cut of the chip of reduced thickness due to oscillation

3.2. Fixture with a Movable Drill

The oscillation can be used for the improvement of the turning process as it was presented above. The principle of a movably mounted cutting tool is applied to the drilling process. Fig. 7 provides the photo of the fixture with a movable drill. The rotational angle is limited by springs 4.

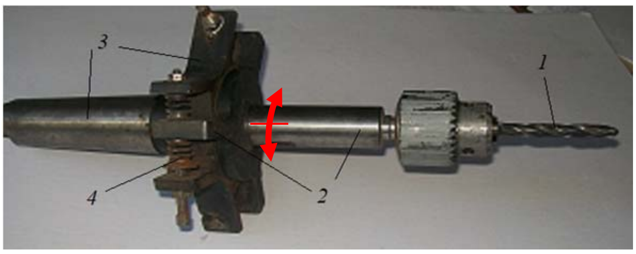


Figure 7. Fixture with movably mounted drill (1 – drill, 2 – shaft, 3 – fixture, 4 – springs)

Drill 1 is fixed in the head mounted on shaft 2. Both parts of the fixture are connected by adjustable springs 4 which enable adjustment of the pressing tangential force in order to make the drill oscillate when the dynamic component of force acts.

3.2.1. Results – drilling

It means that during drilling, the torque non-harmonic drill oscillations are generated and it leads to the chip breaking and machined surface quality change. The quality of the machined surface at different rotational speeds *n* of drilling and drill diameter is provided in Fig. 8.

It is obvious that if the tool is released in one degree of freedom that is limited, the improvement of the quality of the machined surface is obtained. It can be explained by the alternating change of drill circumference speed and elimination of the built-up edge formation on the cutting wedge.

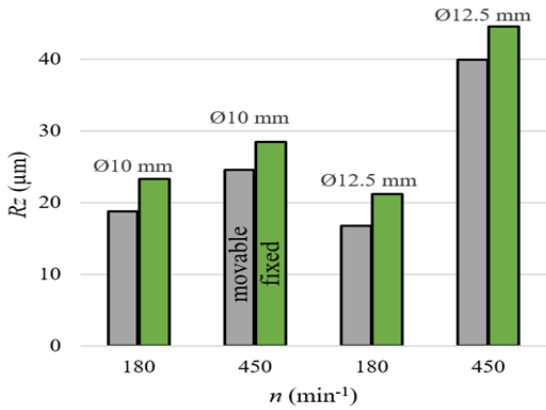
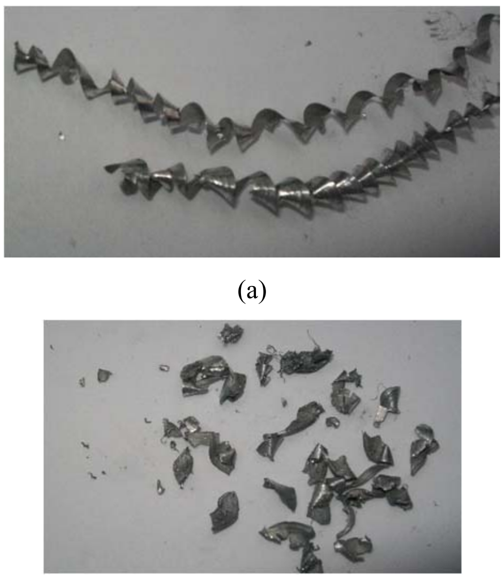


Figure 8. Maximum profile height Rz; material of drill: HS-18-01, workpiece material: Fe37B1FU

The chip shaping is an important effect of controlled tool oscillation. Fig. 9 shows chips formed at fixed and movable mounted drills. The considerable shortening of the chips is visible. The discontinuous chips go through drill grooves without any obstacles.



(a)

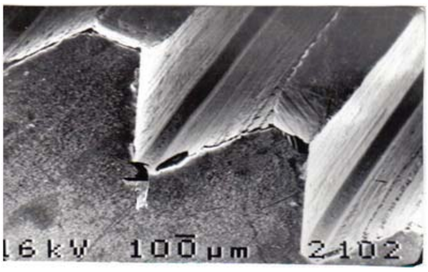
(b)

Figure 9. Chip shapes for fixed (a) and movable (b) drill; drill diameter 12.5mm, workpiece material steel: C45

3.2.2. Discussion

One of the other possibilities of using of the movable mounted cutting tool is the use of ultrasound oscillations of screw tap for cutting the thread into titanium alloy VT 3-1.

(a)



(b)

Figure 10. Thread profile formed by (a) classical and (b) ultrasound screw tap

Fig. 10a shows the surfaces of the thread cut by a classical tap. One can see tearing off material, matt, uneven surface of thread wall. It is the result of a high friction coefficient, i.e. intense adhesion between machined (titanium alloy) and cutting materials.

When high-intensity ultrasound is implemented into the tool, tremendous improvement in surface quality has occurred. The difference in surface quality is significant in Fig. 10.

4. Conclusion

The understanding of chip creation and machined surface quality as a dynamic process led to the release of one degree of tool freedom that evokes oscillation which influences the cutting process. The results are beneficial in terms of chip shaping, quality of machined surface, and cutting tool life. The following advantages are for movably mounted cutting tools: (a) suitable chip shapes with lower chip volume coefficient (85%), (b) flank wear reduction (about 20%), (c) longer machining time till determined flank wear (up to 60% depending on cutting velocity), (d) improvement of maximum profile height *Rz* about 30% when drilling. In comparison with firm fixation of the tool, a built-up edge is not formed when a flexible setting is used.

Acknowledgements

The authors want to thank the Slovak Research and Development Agency for supporting this research through grant no. APVV-18-0316.

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