679. Cutting tool vibration in the metal cutting process

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Abstract. Research of machining dynamics have long history in manufacturing processes with consideration of cutting interruption, intermittency and coupled interaction between the tool and workpiece. It gives better understanding of the underlying physics of material removal. The complex motions in cutting dynamics are mainly caused by discontinuities, including chip and tool-workpiece seizure as well as complex stick–slip motion. Through the application of discontinuous system theory, a comprehensive understanding of the grazing phenomena is induced by the boundary of frictional-velocity and the loss of contact between the tool and workpiece are discussed. Significant insights are to control machine-tool vibration and to develop tool wear free machine-tool concept. The experiment on the stainless steel machining is presented in the paper and generation of machine tool vibrations and the associated cutting dynamics is considered.

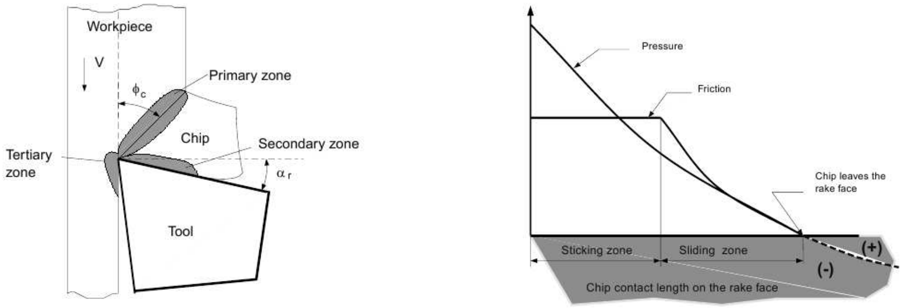
Keywords: metal cutting, vibrations, cutting tool.

Introduction

The final shapes of most mechanical parts are obtained by machining operations. Deformation processes such as forging and rolling are mostly followed by metal removing operations in order to achieve parts with desired shapes, dimensions and surface finish quality. The machining operations can be classified into cutting and grinding processes. The cutting operations are used to remove material from the blank. The subsequent grinding operations provide a good surface finish and precise part dimensions. The most common cutting operations are turning, milling, and drilling followed by special operations such as boring, broaching, honing and shaping. However, all cutting operations share the same principles of mechanics, but their geometry and kinematics may be different. The mechanics of cutting and the specific analysis for a variety of machining operations and tool geometries are not widely covered in this text [1].

Mechanics of orthogonal cutting and vibrations in metal cutting

Although the most common cutting operations are three dimensional and geometrically complex, the simple case of two-dimensional orthogonal cutting is used to explain the general mechanics of metal removal. In orthogonal cutting, the material is removed by a cutting edge which is perpendicular to the direction of relative tool–workpiece motion. The mechanics of more complex three-dimensional oblique cutting operations are usually evaluated by geometrical and kinematic transformation models and applied to the orthogonal cutting process. The orthogonal cutting resembles a shaping process with a straight tool, whose cutting edge is perpendicular to the cutting velocity (V). A metal chip with a width of cut (b) and depth of cut (h) is sheared away from the workpiece. In orthogonal cutting, the cutting is assumed to be uniform along the cutting edge; therefore it is a two-dimensional plane strain deformation process without side spreading of the material. Hence, the cutting forces are exerted only in the directions of velocity and uncut chip thickness, which are called tangential (F_t) and feed forces (F_f). However, in oblique cutting, the cutting edge is oriented with an inclination angle (i) and the additional third force acts in the radial direction (F_r). There are three deformation zones in the cutting process as shown in the cross-sectional view of the orthogonal cutting (see Fig. 1. a). As the edge of the tool penetrates into the workpiece, the material ahead of the tool is sheared over the primary shear zone to form a chip. The sheared material, the chip, partially deforms and moves along the rake face of the tool, which is called the secondary deformation zone. The friction area (Fig. 1. b), where the flank of the tool rubs the newly machined surface, is called the tertiary zone. The chip initially sticks to the rake face of the tool, which is called the sticking region. The friction stress is approximately equal to the yield shear stress of the material at the sticking zone where the chip moves over a material stuck on the rake face of the tool. The chip stops sticking and starts sliding over the rake face with a constant sliding friction coefficient. The chip leaves the tool, losing contact with the rake face of the tool. The length of the contact zone depends on the cutting speed, tool geometry, and material properties. There are basically two types of assumptions in the analysis of the primary shear zone [2, 3].



a) b)

Fig. 1. a) Deformation zones and distribution of load on the rake face. b) The tool experiences compression stress under the chip contact zone (−) and tensile stresses (+) after the chip leaves the tool

The prediction of temperature distribution at the tool–chip interface is very important in determining the maximum speed that gives the most optimal material removal rate without excessive tool wear. The binding materials within the cutting tools may be weakened or diffused to the moving chip material at their critical diffusion or melting temperature limits. The fundamental machinability study requires the identification of a maximum cutting speed value that corresponds to the critical temperature limit where the tool wears rapidly. By using the approximate solutions summarized above, one can select a cutting speed that would correspond to a tool–chip interface temperature (T_{int}) that lies just below the diffusion and melting limits of materials present in a specific cutting tool.

Machine tool vibrations play an important role on machining performance. Excessive vibrations increase tool wear, are cause of poor surface finish, and may damage the spindle bearings. The workpiece, cutting tool and machine form are sophisticated system with complicated dynamic characteristics. The reactive forces from the workpiece are transmitted to the machine. The cutting tool receives its cutting forces from the machine. Under certain operating conditions, the structural system may pass through heightened vibrations. The presence of vibrations results in poor surface finish, cutting-edge damage and irritating noise. It is, therefore, very important to study the causes and control all types of free and forced vibrations due to interaction between the cutting process and the machine tool structure.

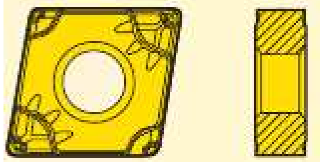
Machine tools are complex structures consisting of mass points and therefore infinite degrees of freedom. The cutting forces can be resolved into steady or constant component and time-dependent dynamic component. The steady component of cutting forces along with dead loads can cause static deflections in the elastic workpiece tool-machine system. These deflections disturb orientation and motion of tool relative to workpiece. Cutting load in the point of application have changes with time and hence the deflection. The machine tool must have static stiffness to resist the constant loads of the system.

The dynamic component of forces cause dynamic deflection or vibration in the machine-tool-workpiece system, which produce dimensional, shape and finish imperfections and endanger the life of cutting tool and machine by fatigue and impact loading. Therefore the machine tools must be designed to be dynamically rigid. In addition, it should be dynamically stable and amplitude of vibration should go on decreasing and system must return to its equilibrium position in short time. The machining performance will suffer if the machine tool has insufficient static stiffness, dynamic rigidity and stability [4, 5].

Experimental parameters, cutting tool and experimental results

The aim of the experiment is to study the machining parameters and machined surface, directly the surface roughness and tool wear, cutting tool vibrations, chip forming process and control the cutting forces in machining process. Cutting temperature in metal cutting is one of the most crucial problems, especially in dry (without cooling) machining process. In our experiment K-type chromel-alumel thermocouple was placed inside of cutting insert and it gave us opportunity to control the temperature field in the cutting tool. Nowadays the computer modeling programs which use finite element method (FEM) analysis, such as ABAQUS, Third Wave AdvantEdge can solve this problem. What in fact was done in cooperation with Helsinki University of Technology [6]. The FEM of cutting temperature distribution field in the cutting tool and material a shown in the Fig. 2. The cutting temperature in the cutting zone was between 1100 and 1300 °C. This was received by the direct measuring and with the FEM modeling. For our three factor experiment was chosen stainless steel 420 (12 % Chromium) with high chromium content, because high chromium content steel have unstable chip forming process and variation of chip length was from optimal size (a) to continuous (b) (Fig. 3). Modern coated turning insert TNMG 160412-MF5 (MF5 chip breaker description and geometry are shown in the Table 1), TP3500 with cutting edge radius 0.8 mm, lathe 16K20. Experimental machine is shown in Fig. 4. Machining parameter combinations (Table 2) are chosen, to study the increased cutting speed and the result of this increment (cutting speed was increased by 25% from the recommended one): feed - 0,1 mm/rpm and 0,35 mm/rpm; cutting depth is 0,5 mm; cutting speed 273 m/min., and 341 m/min. The chosen chip breaker MF5, for medium/finishing turning with TP3500 coating, two holders with cutting edge angle φ = 90º and φ = 60º. The main advantage of the MF5 chip breaker is that the opened and high positive design reduce cutting forces and give us the opportunity to use higher cutting speed. This, in turn gives: low cutting forces - higher cutting speed; increased speed capability - higher productivity; traditional medium - finishing inserts perform well at ordinary speeds, but fail early when the speed is increased. During metal cutting on the lathe three cutting forces take place in this process. As a result of so high-speed metal cutting vibrations are induced as well. They are successfully measured by the digital vibrometer VM6360. Received values of the cutting tool displacement are shown in Fig. 5. Received machined surface average values are shown in Fig. 6. Cutting tool wear result is shown in Fig. 7.

Table 1. Chosen chip breaker and its description

	MF5	Chip breaker intended for medium finishing of steel and stainless steel at high feeds. Very easy cutting and open geometry. Machining range: f = 0,1–0,8 mm/rev, a_p = 0,2–2,7 mm.

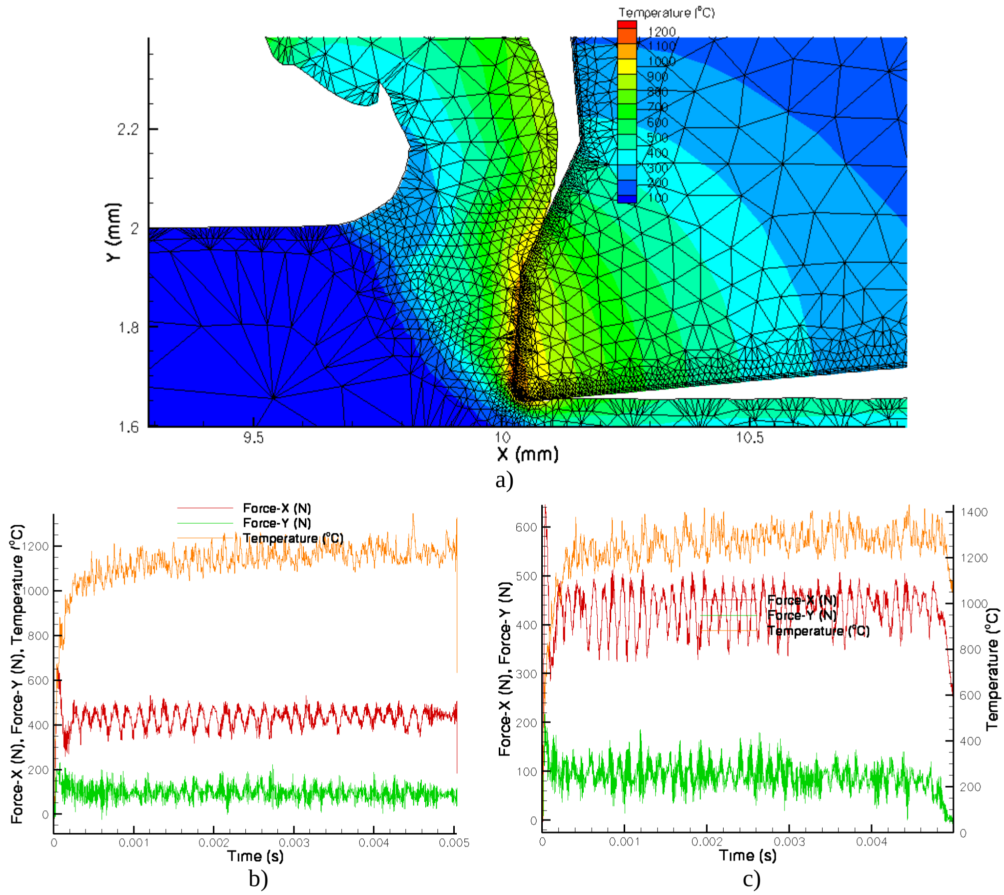


Fig. 2. FEM temperature fields distribution (a) modeling results of the 420 stainless steel cutting process. Cutting temperature and cutting forces graphs on cutting speed 273 m/min (b) and 341 (c)

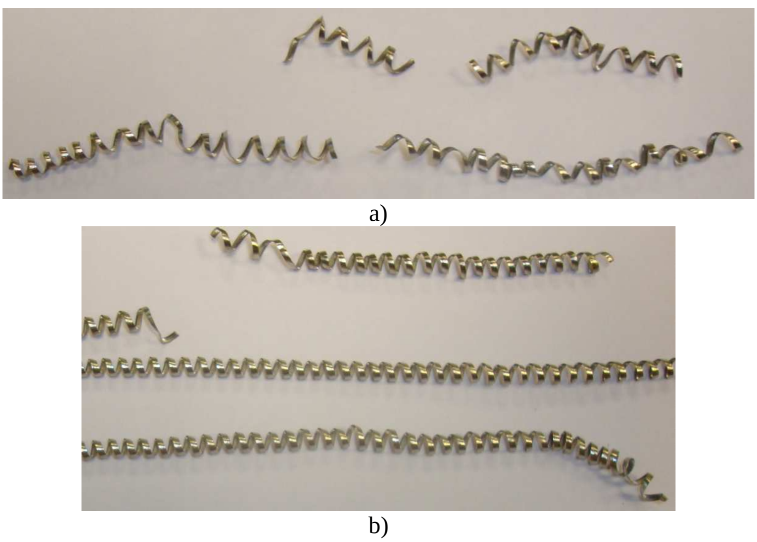


Fig. 3. Experimentally received chips

Table 2. Machining parameter combinations

Machining parameter combination Nr.	Cutting speed, m/min.	Feeding, mm/rev.	Cutting edge angle
1	341	0,1	60
2	341	0,35	60
3	273	0,1	60
4	273	0,35	60
5	341	0,1	90
6	341	0,35	90
7	273	0,1	90
8	273	0,35	90

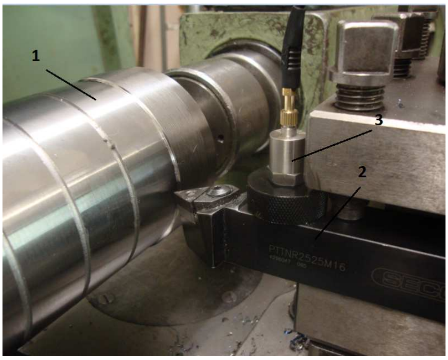


Fig. 4. Experimental test rig, 1- 420 Stainless Steel machined part, 2- cutting tool holder with the cutting insert, 3 – vibration accelerometer

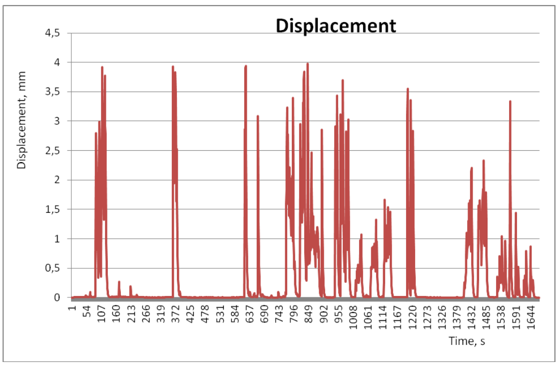


Fig. 5. Measured values of the cutting tool displacement obtained during testing

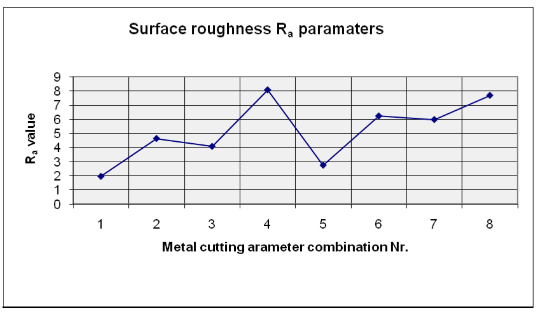


Fig. 6. Measured surface roughness values

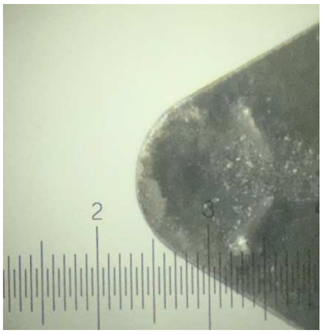


Fig. 7. Cutting tool wear

Conclusions

Obtained results of experiments demonstrate variation of surface roughness as a function of actual cutting parameters as well as variation of displacement of the cutting tool during combination type machining process. By using of increased cutting speed became known, that the cutting tool, that we use can give higher wear and toughness characteristics, as a result we checked and it is more than recommended from manufacturer. Although, the experiments revealed high values of tool wear, this does not leave affected the machining process, as we can see in the vibration of fixation and in the surface roughness results.

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