INFLUENCE OF TOOL WEAR CONDITION ON TOOL VIBRATIONS

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Abstract: The paper presents a segment of research results concerned with the identification of the influence of chip segmentation process during the turning process and the “free” segment of the vibration acceleration signal specter aiming at the creation and laboratory verification of the proposed method for recognizing tool wear condition in turning. There is a comparative survey of the oscillations calculated by utilizing the finite element method (FEM) and the measured vibrations of the cutting system elements during the machining operation. The analysis of the microscopic structure of the chip generated in the turning process is employed to determine the chip segmentation frequency and the agreement with the measured system vibrations. The aim of the paper is to prove that there exists a dominant influence of the chip formation process in the high-frequency specter segment with the neglectable participation of the proper higher frequencies of the cutting system.

Key Words: Tool wear, FEM modeling, vibration, chip

1. INTRODUCTION

The sources of vibrations appearing on a tool are of diverse origin, while their causes can be classified into deterministic and non-deterministic. Among the deterministic ones are: material deformation, friction of the tool and workpiece and chip separation. Their main feature is the inherent nonlinearity, having as a consequence the appearance of self-induced vibrations in the cutting process [1].

The increased loads lead to the pass over the material elastic point, which can be observed in the leap into the plastic deformation zone and material failure. In the process, the accumulated energy that appears impulsively each time the lamella shearing process occurs i.e. a chip is being formed, is released. This can be explained by the fact that in the material that has the crystal structure, the micro crack occurs during the crystal breakage and it rapidly moves creating the material failure i.e. breaking the inter-crystal connections and releasing the energy. These short-term individual events induce the elastic-viscous element structure of the workpiece system that generates vibrations in a wide frequency specter [2].

The friction on the contact areas between the tool and the workpiece creates the “stick-slip” effect. This effect introduces the aperiodic oscillatory induction into the workpiece system, which, same as in the case of the formation of chip segmentation can be observed as a set of discrete energy impulses inducing the elements of the workpiece system in the wide frequency specter as well.

2. CHIP SEGMENTATION PROCESS

Segmented appearance of chip lamellas comprises of two phases in which the workpiece material is plastically deformed in front of the tool causing the material convexes on the free chip surface. The result of the material deformation in the process of chip segmentation occurrence is composed of the moderately deformed chip segments separated by detached narrow band with the intensive material deformation. The described model of chip segmentation is presented in Figure 1 [3].

One of the important induction mechanisms causing the vibrations in the machining process is the creation of chip lamellas. In their research, Cotterell and Byrne [3] have determined the frequency of the occurrence of a lamella \( f_{seg} \) by analyzing the video material with chip formation. The frequency of chip segmentation formation linearly increases with the increase of the cutting speed, and decreases with the increase in depth. Chip frequency can occur in the range from 3.8 kHz to 250 kHz in hard material turning [4, 2], leading to great variations in the frequency of forces in a tool. The influence of chip segmentation onto the tool wear and processed surface quality has not yet been explained in detail, although it has been determined that it influences the intensity of force in the cutting process and the tool condition [5, 9]. Crater wear and wear band are the primary processes in tool wear with the cutting speed in the range between 50-800 m/min [6].

Lamella formation in the cutting process is characterized by their occurrence frequency. The frequency of chip segmentation formation can be calculated on the basis of the lamella formation steps \( p \), cutting depth (thickness of the undeformed chip part) \( h \), height of the deformed chip part \( h_{de} \) and cutting speed \( v_c \), applying the expression:
Based on the expression (1), one can observe that the increase of the thickness of the undeformed chip leads to the decrease in the lamella formation frequency which is directly observed in the decrease of the chip deformation coefficient [1, 2].

\[ f_{lam} = \frac{v_{ch} \cdot h_{ch}}{h \cdot p_c} = \frac{v_{ch}}{\lambda \cdot p_c} \]  

(1)

The relation 2 comprises parameters linked to the tool cutting geometry and technological parameters speed, feed and depth of cutting. On that basis, it can be concluded that the lamella formation frequency is directly proportional to the machining speed and feed, and indirectly proportional to the depth. The increase in the cutting speed directly influences the chip segmentation formation frequency, the increase in the energy that is reflected in the intensified heat release and the decrease in lamella steps; in a word, the overall wear dynamics is being increased. In the performed experimental research with the plate made of hard metal and the cutting speed range between 200 and 250 m/min, the frequencies of the chip segmentation were around 8 – 100 kHz. The area of the lamella formation frequencies, based on the mathematical calculations following the Bähre formula, approximates the measured frequencies of the tool handle oscillations, i.e. its natural frequencies, between 8.5 kHz and 88 kHz.

3. FREQUENCY OF THE CHIP SEGMENTATION FORMATION

Most researches in material processing are directed towards the chip formation mechanism and tool wear characterization. Significant for the research in the tool wear effects and chip formation morphology are also cutting conditions. It has been observed that the alteration in the tool wear degree and cutting conditions alters the shape of the occurring chip lamellas [6].

Tool wear, cutting process parameters and their influence on the chip appearance and shape have been monitored in the experimental research. The shape of the chip has been measured by a microscope depending on the tool wear degree, in diverse cutting conditions (cutting speed, feed and cutting depth). During the processing, the vibrations on the tool handle have also been measured, while the segmentation frequency has been calculated on the basis of the measured parameters for the chip cross section in an electronic microscope.

Figure 2 presents the chip cross section, on an electronic microscope, in the worn tool processing. Figure 3 presents the morphology of the sawtooth chip with characteristic dimensions: lamella step (p_{sb}), height of the continual (compressed) chip part (h_c'), height of lamella shearing (d_c), shearing zone band (\delta_{sb}), angle in the direction of the initial crack (\Phi_{seg}) and angle of the free lamella part (\rho_{seg}) [5].

Based on the processed results of the experimental research, the following conclusions can be drawn as a result of monitoring the chip morphology and tool wear.
condition:

- The medium value of the segmentation of the free chip part (lamella step) ($p_c$) and the height of the free part (tooth) ($p_{to}$) are increased with the increase of tool wear.
- Segmentation step, distance between lamellas ($p_c$), increases with the cutting speed.
- Height of the continual chip part ($h'_c$) is greater with a new tool.
- Segmentation frequency increases with the increase in the cutting speed and decreases with the increase of tool wear degree.

The research in the chip segmentation formation contributes to determining chip segmentation formation mechanisms, as well as defining the most suitable processing technology [6]. The crater increase on a front tool surface has a very significant influence on the chip segmentation formation mechanism, same as on the frequency of lamella formation and chip shape.

Crater wear directly influences the basic initial structure of chip segmentation formation that always tends to have the character of a continual indefinite chip. Rear chip side in an extremely formed crater leads to the beginning of the occurrence of layers on the tool cutting edge.

4. MODELLING THE DYNAMIC TOOL BEHAVIOUR

Within the research, the dynamic behavior of a turning knife has been analyzed by applying the FEM - finite element method, [8].

FEM model of knife handle and tool insert had 5940 degrees of freedom (DOF) and it is formed as one two-part model. All DOFs for the support part of the handle have been removed, while the loads responding to cutting loads are set as parallel to the long axis of tool (Figure 4). Model is built by use of nine-node heterosis thick shell FE (from steel) and special link FE in connection between handle and cutting knife (hard material) parts.

![Fig. 4 FEM model of the handle/knife device](image)

The analysis of the dynamic behavior of a turning knife generates a very important a priori feeding set which can be utilized for building a neural-fuzzy system for the intelligent recognition of the tool wear condition [9]. The presence of the tool’s natural frequencies in the upper part of the specter, in the concrete example over 15 kHz, presents a problem in monitoring the tool wear condition, since this is the part of the specter where the frequencies occurring in the process of the chip segmentation formation are also situated. In such a “deformed figure”, the monitoring of the chip formation process by analyzing the adjoining frequency content will be significantly harder, if not even disabled. Presumptive information on the dynamic behavior of the tool can be utilized for separating the specter part that is not contaminated and whose monitoring can, with high precision, establish an unambiguous correlation between tool condition and tool vibration signal measured by an adequate sensor.

It is important to note that, due to the features of the tool carrier and other elements of the workpiece system linked to the mass, their influence on the dynamic behavior of the workpiece system measured on the tool handle is not critical. The frequencies of these elements are situated in the lower specter part which is significantly distant from the specter part where the frequencies generating the chip formation process are situated. Hence, the dynamic behavior analysis of the mechanical structure of the workpiece system is limited only to the tool behavior analysis.

Vibration signals originating from the cutting process are difficult to be measure by direct methods, and they are technically and practically rather inaccessible for measuring in order to define the real influence. In the practical sense, what can be measured are the reactions of the overall system “tool-workpiece-machine” on the tool. In measuring, certain limitations occur in identifying and separating the induction mechanisms and transferring vibrations from other machine elements. It practically means that for certain processing operations only the phenomenological explanation is possible. Determining the precise content of the measured vibrations from the cutting process in the output sensor signal presents a very important task. Dominant influences of natural tool frequencies in the signal specter can be relatively precisely calculated by applying certain calculation methods. These calculations can greatly simplify the specter dismembering, which will be further explained and presented.

The analysis of the dynamic behavior of the turning knife handle, utilizing the finite element method, has an objective to determine natural frequencies and oscillation amplitudes of the knife handle in the machining process. Furthermore, the analysis by finite element method enables the establishment of connections between experimental research and certain models in the machining process linked to tool wear and cutting geometry alteration.

The analysis of vibration signals tends to identify the difference between natural and self-induced tool vibrations during the cutting operation and the entire system vibrations.

4.1 Natural tool oscillation frequencies

Figure 5 shows the comparative presentation of the calculated natural frequencies of the tool and the vibration acceleration signal specter obtained in experimental research for three cutting conditions. The calculated natural frequencies of the knife are presented by broken lines. Within the experimental research, apart
from the turning knife handle acceleration, the simultaneous measuring of the cutting forces has also been performed, and hence the turning knife has been fixed to a dynamometer whose rigidity is lower than the tool carrier rigidity.

The turning has been done on the lathe „POTISJE Ada“, type PH 45. Signal of vibration alternation and flank wear are recorded for every cutting pass.

The machining is done with combination of cutting speed and feed show in table 1. Combinations are selected in order to achieve progressive tool wear.

Table 1: Cutting parameters

<table>
<thead>
<tr>
<th>Material:</th>
<th>DIN 1.2343 hardened to HRC30</th>
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<tbody>
<tr>
<td>Workpiece diameter:</td>
<td>100 mm</td>
</tr>
<tr>
<td>Cutting speed:</td>
<td>170 m/min</td>
</tr>
<tr>
<td>Feed:</td>
<td>0.2 mm/rev</td>
</tr>
<tr>
<td>Tool type:</td>
<td>„Sandvik Coromant“ PTGNL tool holder cross-section, 20x20</td>
</tr>
<tr>
<td>Insert coated with</td>
<td>TNMG 110408 PGP, P15, PP-CORUN</td>
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Vibration alternation is measured using the accelerometer set up at the lateral tool side and oriented towards the longitudinal Workpiece axis.

![Fig. 5 Vibration signal spectres obtained in experimental research and calculated natural frequencies for tool oscillation utilizing the finite element method](image)

Based on the presented results, one can observe that almost all natural frequencies of tool oscillation are situated in the upper domain of the frequency specter. This confirms the feasibility of the adopted approach in modeling and analyzing the dynamic tool behavior. In this case, significant approximations in setting the model have not reduced the dominant vibration effects in the machining process.

For calculating the characteristic oscillation amplitudes of the knife handle, the method of harmonic analysis of oscillations has also been utilized. Harmonic analysis comprises the frequency range from 4 to 60 kHz. Figure 6 presents the amplitude frequency knife characteristics in the direction of the axes X, Y and Z. The analysis of the obtained results can argue that the oscillation amplitudes in the directions of the axes Y and Z are of the same size order in the larger number of natural frequencies, while they are significantly smaller in the direction of X axis, even at the frequency 46.6 kHz which presents the largest frequency in the direction of this axis.

![Fig. 6 Amplitude frequency characteristic of the knife in the directions of X, Y and Z axes](image)

Maximal amplitudes on the knife handle overlap with the places for setting the accelerators in experimental research. The mentioned natural frequencies entirely cover the part of the frequency range in which there are dominant components of induction generated by discontinuities during the chip segmentation formation.

5. CONCLUSION

In the range between 10 and 50 kHz there are a larger number of the tool’s natural frequencies, creating a space for the appearance of the resonance under the action of induced force generated by chip segmentation formation. The increase in the oscillation intensity induced by the tool resonance on a larger number of frequencies has a greater intensity and deforms the signal content occurring in the process of chip segmentation formation. This situation has been recognized in the experimental researches and the solution to this problem urges the necessity to develop methods and technologies for the work with higher frequency ranges, of over 50 or even over 200 kHz. Research on higher frequencies, where the signal content deformation derived from the chip
segmentation formation process is minimal, can be utilized to determine more precisely the trend of the frequency in chip segmentation process.

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7. REFERENCES


