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Finite element modelling of thin chip removal process

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Abstract. Micro milling is a continuously spreading, and therefore heavily researched technology. In this subject plenty of publications are highlighting the fact that there are many issues, which still has to be solved. Micro milling realizes thin chip removal process. In this paper 2D finite element simulation was performed to investigate the characteristics of small sized chip formation. Results of micro milling experiments were analysed too. This paper presents the results regarding effects of the cutting parameters (cutting speed, feed per tooth) on cutting temperature and machining forces at 2D finite element. Results based on different material models were compared with each other too.

1. Introduction

Nowadays, the role of miniaturization is becoming higher in many areas of our lives, but the production of these components requires the application of advanced technologies. One of the most important ones is micro milling, which typically produces structures between 1-999 μm on a wide range of materials. Such components are required for example in military industry, space technology, production of electrical components and in medical sciences.

Micro milling can be considered as transformation of conventional sized milling into the size range, which is less than 1 mm. Although the tool geometry and the kinematic system at micro end milling are actually the same, as that of conventional milling, there are many differences, which are originating from the size reduction. All these phenomena can be summarized as size effect.

Due to the size reduction, the effect of the tool edge radius is not negligible, because its size is comparable with the chip thickness. According to Aramcharoen and Mativenga [1], the ratio between the uncut chip thickness and the cutting tool edge radius is an important parameter in micro milling. Machining of hardened tool steel AISI H13 was investigated, and it was shown that the role of size effect is higher, if this ratio is less than one.

Other critical parameter considering the size effect is the minimum chip thickness (h_{min}). If the chip thickness is less than a critical value, there will be no material separation. The minimum value was considered by many researchers as a function of the cutting tool edge radius (r_β). De Oliveira et al. [2] investigated the ratio of h_{min}/r_β on AISI 1045, and it was found to be between 0.22 and 0.36. Cuba Ramos et al. [3] determined this ratio on AISI 1045 as 0.29, and Kang et al. [4] found a value of 0.3. Wu et al. [5] conducted finite element modelling in Deform FEM program and the results were validated micro turning experiments. The effect of the tool edge radius and the grain size were studied at a cutting speed of 314 mm/sec, the uncut chip thickness was 3 and 11 μm, and the cutting edge radius were 0, 2, 5, and 8 μm. Oxygen free copper with 20 and 60 μm grain size was investigated as workpiece material. It was found that the larger the cutting edge radius the larger the cutting force. Considering both factors, the effect of the grain size is more significant. The authors stated that the decreased grain size increases the forces and the specific energy. The chip formation requires the movement of the dislocations, but the grain boundaries block them. Smaller grain size will result in more grain boundaries, which have a more intensive blocking effect. It was also found that in the case of a 5 μm cutting edge radius, the shearing force will have a ratio of 45% of the cutting force, while the ploughing force will be 55% of the cutting force. Therefore the larger cutting tool edge radius generates larger differences.

Zhou et al. [6] predicted the cutting forces based on finite element modeling of orthogonal cutting on mirror die made of NAK 80, and the results were validated experimentally. The model has taken into account the tool trajectory, run-out, cutting edge radius, rake angle, mechanical and physical properties of the material, and the interaction between the cutting tool and the workpiece. The tool diameter was 0.4 mm, and cutting velocity was set in the range of v_c=12-36 m/min, and the uncut chip thickness was found to be between 0.1-1.2 μm. The largest von Mises stress (2000 MPa) raised in the secondary shear zone, the highest temperature was 210 °C. Based on the simulations the effect of the cutting speed on the forces is negligible in the investigated parameters range. Predicted and measured forces approached each other well.

Yang et al. [7] investigated the temperature distribution, effective stress and the cutting forces at various cutting edge radii in case of micro milling on Al2024-T6 material by means of numerical and experimental approaches. The tool diameter was 0.5 mm with a rake angle of 5° and with a clearance angle of 12°. The set parameters were as follows: n=22 282 rotation/min, a_p=10 μm, f_z=0.1 μm, and the cutting edge radius were 0, 3.2, 5 and 7 μm. The temperature decreased with the increasing of the cutting edge radius, the values for the above listed radii were 57.5, 51.5, 45.4 and 40.4 °C, respectively. The generated heat is concentrated to a small area at the contact point of the tool and the workpiece. In addition, effective stress has decreased, but the cutting forces have increased. The temperatures were slightly higher in the simulations than that of the experimental results, which can be explained by the fact that the tool edge radius increases during machining.

Pratap et al. [8] studied the cutting forces, the temperature and the stress distribution on Ti-6Al-4V material by finite element method, taking into account the effect of cutting speed, feed rate, uncut chip thickness, and cutting edge radius. The simulated results were validated by micro milling experiments. The diameter of the tool was 0.4 mm, the spindle rotational speed was chosen in the range of 15 000–35 000 rpm, the feed per tooth was set the range of 1 to 5 μm, and the depth of cut was 30 μm. At v_c=31,425 m/min, f_z=1 μm and a_p=30 μm the maximum stress (2467 MPa) was generated in the primary shear zone, which can be explained by the size effect. The maximum calculated temperature was as high as 845.3 °C. The cutting forces increased with the intensity of the cutting process, which could be caused by the growth of the cutting edge radius caused by high cutting temperature and accelerated wear accordingly.

Afazov et al. [9] investigated the micro milling process on AISI 4340 by experimental and finite element methods. According to the suggestion, novel force model factors should have been taken into account, which directly affect the chip formation, such as tool run-out, cutting edge radius, cutting speed, cutting tool geometry, and the workpiece preheating. It has been found that preheating of the workpiece material to 600 °C resulted in a higher stability limit due to the softening and the decrease of the cutting forces. Considering the tool geometry, the authors stated that an increase of the rake angle from 0° to 8° creates larger force components, while the stability limits will be lower.

2. Aims and circumstances

The main aim of this research is the better understanding of the micro milling process by studying the generated temperatures and forces during the cutting process. 2D finite element simulations were performed by Deform software. The chip formation phenomenon has been studied very close to the shear zone. The practical investigation of real material flow and temperature distribution is very complicated because of the limited size of the process. Finite element simulations were used by many researchers to investigate the cutting processes [8, 10].

The geometry applied in the simulations was based on a two flutes carbide end milling cutter produced by Magafor. The diameter of the tool is 0.3 mm. The geometric characteristics are as follows:

rake angle (γ) is 35°, clearance angle (α) is 20°, and helix angle (λ) is 30°. Based on the scanning electron microscopic images the cutting edge radius in the simulation was set to 3 μm. Machining of AISI 1045 was analyzed by means of finite element simulation. Based on the material model available in Deform software the material properties at room temperature are as follows: E=212 000 MPa, thermal conductivity is 41.7 W/(m·K), the thermal expansion is $1.19\cdot10^{-5}$ m/°C, which are changing with the temperature. The Poisson ratio is 0.3. The tool material is WC and the properties are as follows: E=650 000 MPa, Poisson ratio is 0.25, thermal conductivity is 59 W/(m·K) and the thermal expansion is $5\cdot10^{-6}$ m/°C. In case of carbide material the values are not changing with the temperature. Special material behaviors of chip removal process, such as intensive deformation and high strain rate require the application of visco-plastic models. Three different material models were applied and evaluated to make a comparison: Oxley's equation [11], Johnson-Cook constitutive equation [12], and a material model based on the flow stress data originated from the researchers of Engineering Research Centre (ERC) of Ohio State University [13]. Considering our previous investigation, the Oxley's equation provides the best approximation of the practical values in the case of normalized AISI 1045 steel [14]. Shear friction coefficient was fixed at 0,6 based on other studies [5, 15]. Two additional meshing windows were applied on the workpiece with even smaller element sizes (e.g. 0.5 μm), to ensure the appropriate mesh density in the near of the chip formation. The effect of the mesh size was investigated too.

In this study, the effects of two factors were investigated, such as cutting speed and feed per tooth. The levels of the experimental design are shown in the Table 1. The minimum chip thickness was taken into consideration at determination of the experimental values of feed per tooth. Systematic series of finite element simulation was carried out based on the full factorial design of experiments (DoE) method, which is often used during the scientific researches [16, 17, 18].

Table 1. Experimental design

Factors	Levels
v_c (m/min)	30, 60, 90, 120, 150
f_z (μm/tooth)	1, 3, 5, 8

At 2D simulations orthogonal cutting process is examined actually, where there are basically two important directions, as shown in the Figure 1. Direction of the cutting force is parallel to the machined surface. The perpendicular direction to the surface of the machined workpiece is the direction of the

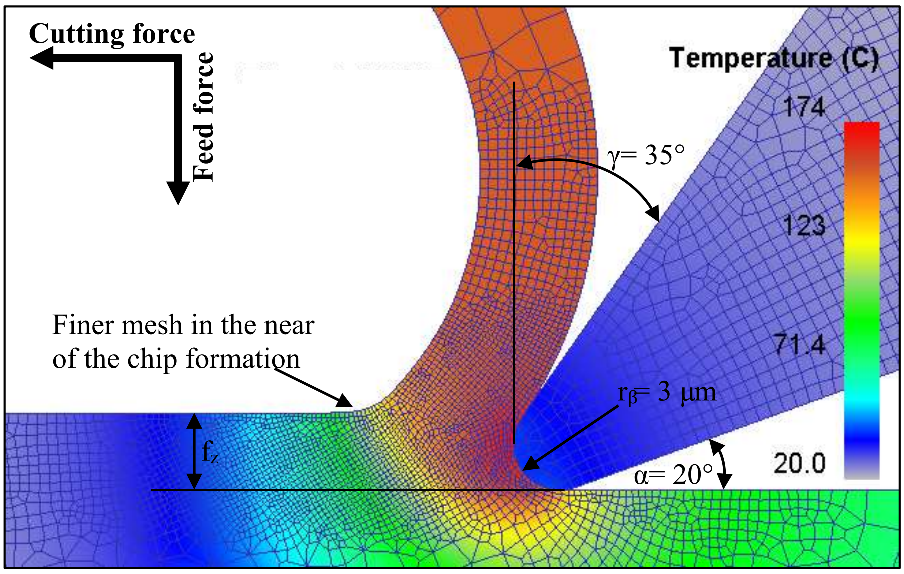

Figure 1. 2D finite element model of thin chip removal process

passive force, which can be considered as feed force in the case of milling process. There are some simplifications in the 2D simulations compared to the real milling process. E.g. the chip thickness was constant during the simulation, and it corresponds to the maximum thickness of the material layer removed by one edge of a micro end milling cutter. Other important difference lays in the width of the chip, which is influenced by the setting of the depth of cut. It is considered to have a unit thickness. In the paper the feed force was analysed and discussed too, because it has a great importance if the chip thickness is less than the critical value. In that case, the tool can pass through the material several times without chip removal, which can cause local hardening. Although, no parameter was chosen below the minimal chip thickness in this paper, but a worn tool can change the ratio of cutting edge radius and chip thickness in real life, so a given feed per tooth value can be shifted to the non-preferable range.

3. Results and discussion

3.1. Tool temperature

The temperature has a great importance, as it affects the tool wear and the cutting force [9]. The temperature of the tool was investigated in detail by means of finite element simulation of thin chip removal process. Figure 2. shows the characteristic change of the temperature value in any point of the tool, which is in physical contact with the machined workpiece. It can be seen that the temperature changing rate is much higher at the starting point of the cutting than in the later position of the tool tip. The cutting length of 0.45 mm corresponds approximately to a half rotation of the tool in the case of an

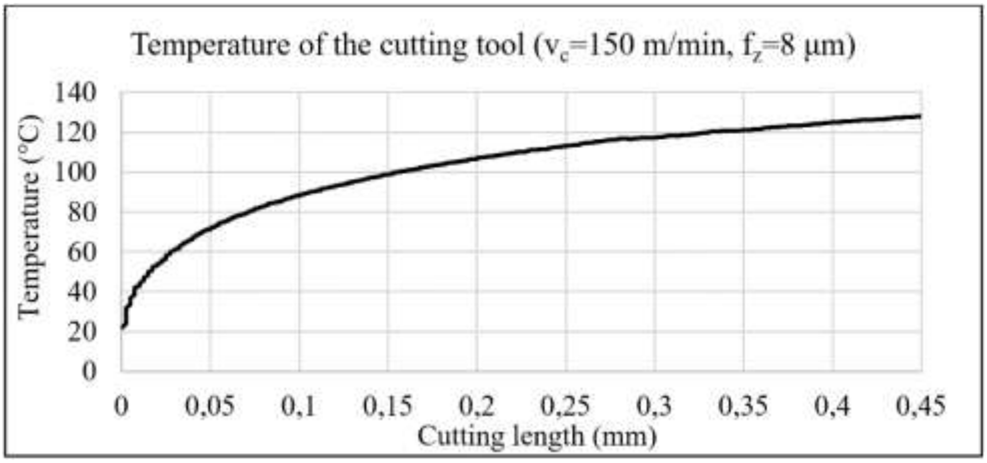

Figure 2. Finite element simulated temperature of the cutting tool

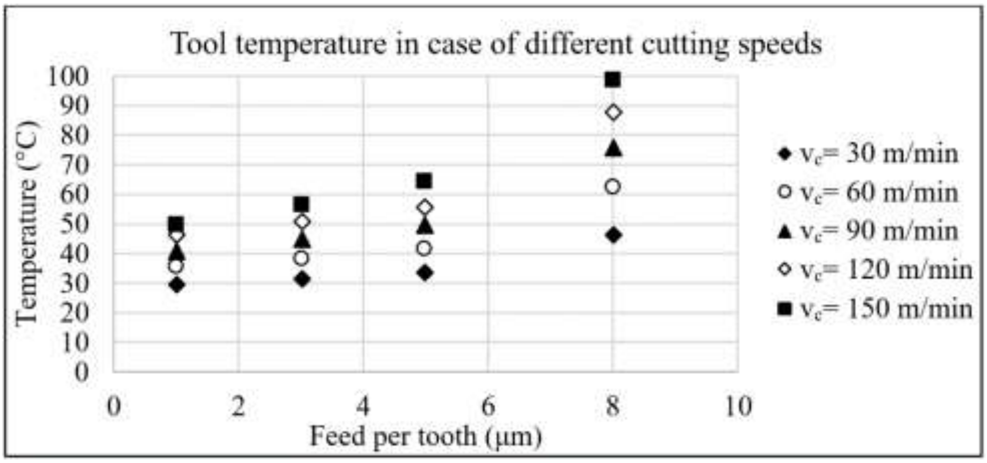

Figure 3. Effect of the cutting parameters on the simulated tool temperature

end milling cutter with a diameter of 0.3 mm, which means the full impact of one edge. The tool temperature at thin chip removal process can be evaluated as quite low, similar to the results of other researchers [7]. It must be taken into account that there is no continuous chip formation during the end milling process. In the case of full groove milling, there is a half rotation for the cooling of one edge of the tool.

Large number of simulations were performed regarding the tool temperature. Figure 3. shows the temperature values as a function of feed per tooth at different cutting velocities after a cutting length of 0.15 mm. It can be seen that the larger the feed per tooth, and the larger the cutting velocity the larger the temperature.

If mesh size of the model is decreased, higher temperature values were calculated.

3.2. Machining forces

The cutting force and passive force were examined by means of finite element simulation too. Because of the simplification of the 2D model the passive force component corresponds to the feed force in the case of milling process. It was found that a larger cutting speed slightly reduces the cutting force in the investigated parameter range, which is consistent with the conventional size milling, where the cutting velocity has a weak effect on the main cutting force [19]. However, the effect of the feed per tooth is more significant (see Figure 4.). The simulated cutting forces are relatively high, nearly one order of magnitude higher than our experimental results (e.g. ~1 N vs. ~10 N). The reason of that may be the difference between the 2D simulation and the actual kinematic of milling process. E.g. the chip cross section is not taken into consideration by the 2D. The width of the chip (depth of cut) can not be defined in this case, although it has great importance on the forces.

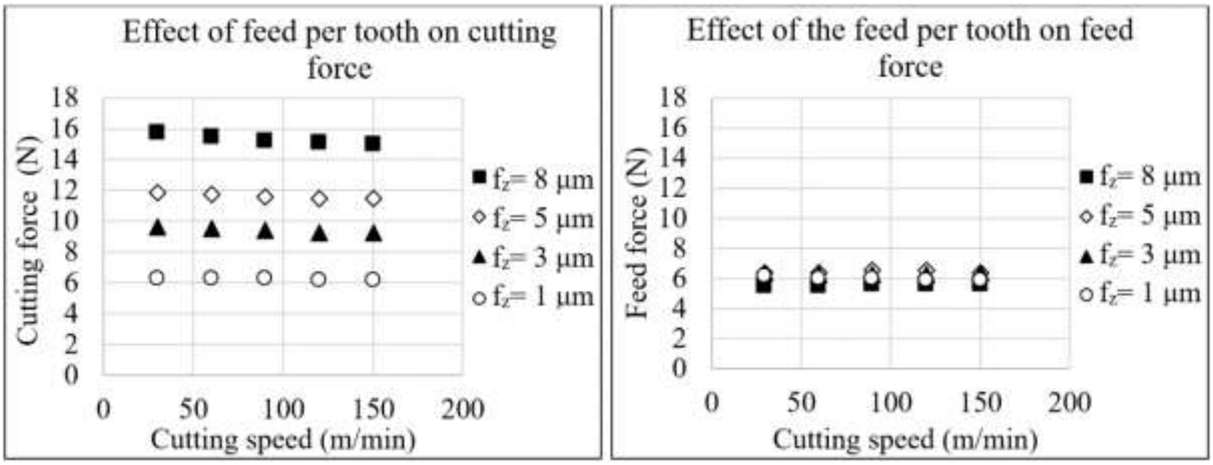

Figure 4. Effect of the cutting parameters on the simulated cutting force and feed force

As a result of the simulations the values of the passive force varied within a relatively small range (see Figure 4.), the minimum value was 5.48 N, and the maximum value was 6.5 N at f_z=8 μm and f_z=5 μm, respectively. The ratio of F_f/F_c is also examined. It can be stated that this ratio decreases, if feed per tooth is set larger. In the case of f_z=1 μm the ratio is as high as 0.95, at f_z=3 μm it is 0.67, if f_z=5 μm is set, it will be 0.55, and in the case of f_z=8 μm the ratio is found to be 0.36.

Three different material models were applied and evaluated. At v_c=120 m/min and f_z=3 μm the Oxley's model provided F_c=9.31 N, F_f=6.3 N, the Johnson-Cook model resulted in F_c=9.36 N, F_f=6.36 N, and the ERC model led to F_c=10.33 N, F_f=5.58 N. It can be seen that the results of Oxley's and Johnson-Cook models are very close to each other.

It was observed that in the case of finer mesh size the cutting force (in X direction) is increased, and the feed force (in Y direction) is decreased. The deviation of the results decreased significantly at smaller mesh size.

4. Conclusions

The demand for better understanding of the micro milling process initiated performing 2D finite element simulation, which was carried out by means of Deform software. In this phase of research AISI 1045 material was investigated. The cutting temperatures and forces close to the cutting zone were studied in detail. Full groove milling experiments were also performed to make a comparison between the theoretical and practical results.

Based on the finite element calculation the temperature of the tool during the cutting process is slightly low, which increases by both the increasing feed per tooth and the cutting speed.

The cutting speed has a small effect on the cutting force in the examined parameter range. There is a slight reduction of the values, if cutting speed increases. There is a general observation considering the cutting force values determined by FEM simulation. The results are located above the measured values by an order of magnitude. The reason can be the 2D simplification of the model, where the width of the chip is considered as unity.

The passive force (which is the feed force in case of milling) change is small in the investigated parameter range. Considering the four feed per tooth values (1, 3, 5 and 8 μm), the highest passive force value belongs to f_z=5 μm, and the lowest one to f_z=8 μm. The F_f/F_c ratio decreased from ~0.95 to ~0.36 with increasing feed per tooth.

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