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Numerical Investigations on Changes of the Main Shear Plane while Broaching

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Abstract

The quality of broached components can be influenced by different factors, such as am-bient temperatures, human factors or vibrations of the machine structure induced by process-machine-interactions. These vibrations are normally initiated by changing pro-cess forces, which are mainly caused by cutting thickness or rake angle variations. Broached components are produced within one motion of the broach along the surface of the work piece, where multiple teeth in a row are in contact. The variation of the cutting thickness results from a wavy profile on the surface generated by the previous cut-ting process or the previous tooth. When the cutting thickness changes during the process, the rake angle varies, too.

In some further published works, the changing cutting thickness and the changing rake angle during broaching were investigated by means of machining simulations with the result that the process forces are still adjusting after the cutting thickness and the rake angle have already reached a stable value. The adjustment of the shear plane on the new cutting conditions is mentioned as the main reason. This paper presents some deeper investigations on this effect. Therefore, 2D machining simulations for different cutting thicknesses and cutting velocities are performed. The investigations show tendencies for the still adjusting shear plane after changing the cutting thickness or the rake angle during the cutting process. Finally, the simulation results are validated with experimentally observed data.

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Keywords: Cutting, Force; Cutting tool; Work piece; Finite element method (FEM); Simulation

1. Introduction

In reality, vibrations of machine structures during broaching result in low quality of the produced components. These vibrations are caused mainly by changes of cutting parameters, which lead to a variation of process forces. In [1] an approach for the simulation of broaching to predict process forces is presented. Here the effects caused by the interactions between process and machine are neglected. Different investigations on process-machine-interactions are presented in [2], but there is no publication where the broaching process is investigated. The topic of this work is a numerical research of the changes of some cutting parameters like cutting thickness and rake angle during the process in means of 2D cutting simulations. The 2D cutting simulation is based on a remeshing method, which may be applied anytime when necessary.

During the variation of the process parameter cutting thickness or the rake angle, mechanical changes occur in the work piece, for example changes in the temperature field or in the shear plane. The shear plane is the plane between the tip of the cutting tooth and the uncut surface in front of the chip. The angle between the shear plane and the uncut surface is called shear angle. Changes in cutting conditions induce a variation of the shear angle. Normally, the angle between the shear plane and the surface of the work piece has a constant value under different cutting conditions. Therefore, when changes in the cutting conditions occur, the shear angle has to be adjusted to the new conditions. In [3, 4] it is mentioned that the shear angle is still adjusting when the cutting conditions are already constant, which can be noticed in

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the curve characteristics of the specific cutting forces. This paper presents some numerical investigations on the adjustment of the shear angle when a new cutting thickness or rake angle has been applied during the cutting process. First the influences on the shear angle will be investigated by simulating the variable cutting thickness and afterwards by simulating the variable rake angle. The variable cutting thickness is implemented in two different ways: 1) as a geometry profile on the machined surface; 2) emersion and immersion of the tooth from and into the work piece. In both cases, the change of the cutting thickness was 15 µm. The variable rake angle is realized with a rotational motion of the cutting tooth around the tip of the tooth.

2. Broaching

Broaching is a highly efficient metal cutting process in mass production. Parts with high quality are produced by broaching. Broached parts are produced within one motion of the broach along the surface of the work piece where multiple teeth in a row are in contact. The important geometrical properties of the broach are presented in Figure 1, such as rake angle γ and cutting thickness h. In literature, broaching is divided into two types: internal and external broaching. In this paper, the external broaching is numerically investigated by means of an orthogonal cut.

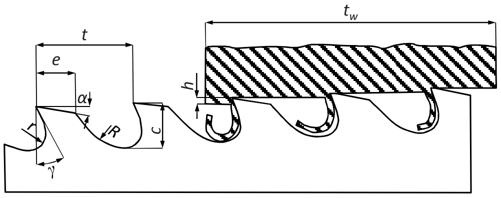

Figure 1: Broaching tool [5]

When vibration on the broach occurs, the cutting thickness will change its value during the process and the cutting tooth will leave a wavy profile on the machined surface (Figure 2b). This in turn will cause that the next tooth will also experience variable cutting thickness (Figure 2a). In [3, 4], the investigation of different changing rates of the cutting thickness was presented. In both cases, the two different approaches for the implementation of the variable cutting thickness were used during the simulations.

On the other hand, the rake angle will be changed due to the vibrations of the broach. These changes are caused by the rotational motion of the broach around a point in itself. If the changes of the rake angle are implemented as a rotation of the tooth around a point in the broach, the variable rake angle will be accompanied by a changing cutting thickness, too. This is the reason for applying a second option for the consideration of the variable rake angle in the simulation. The changes in the angle will be realized by a rotational motion of the tooth around a point on its tip. The rake angle changes its value due to the tooth's inclination caused by its rotation. In order to obtain a more detailed investigation, different inclination rates are implemented.

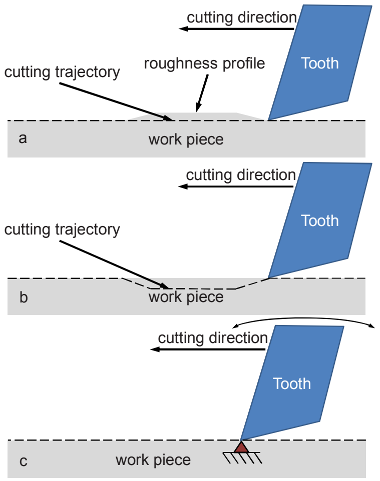

Figure 2: Cutting trajectory of the cutting tooth

3. Simulation model

The different approaches for the implementation of the variable cutting parameters were presented in the previous chapter. The influences of these parameters on the specific forces are investigated numerically by means of 2D cutting simulations using the finite element software *ABAQUS*. For the different investigations, cutting velocities between 60 m/min and 90 m/min were simulated and the work piece had a constant theoretical width of 1 µm.

The material behavior of the work piece (SAE 1045) was implemented in a subroutine as function of strain, strain rate and temperature. The subroutine is called at each simulation point and the material properties are calculated under the new cutting conditions [6]. These dependencies of the material are described in more detail by Weber and Autenrieth in [7].

During the simulation of the cutting process, high mesh deformations occur in the material separation zone. The available methods in ABAQUS for the separation of the material lead to a loss of information due to the deletion of element or nodes, for example. In [6, 7], Schulze and Autenrieth present a self-designed continuous remeshing routine which avoids any loss of information in the results. In Figure 3, the scheme of the continuous remeshing routine is presented. At the beginning, the cutting simulation is divided into smaller sub-simulations. After each sub-simulation, the routine is called and the work piece geometry is extracted and new input files are generated. Before the next sub-simulation is started, the old results are mapped onto the new input files. The Coulomb friction model was considered with a time-independent constant friction coefficient in each simulation.

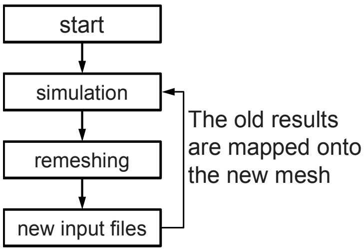

Figure 3: Approach of the continuous remeshing method

4. Simulation results and discussion

4.1. Comparison of the cutting forces between simulation and experiment

In Figure 4, the specific cutting force resulting from the simulation with constant cutting parameters are compared to the experimentally obtained data for three different cutting thicknesses. The simulation results are showing very good agreement with the experimental data. The maximum deviation of nearly 18 % from the experimental results is observed in simulations with a cutting thickness of 20 μm.

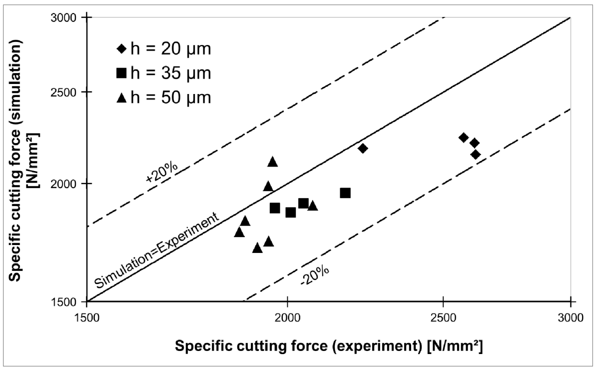

Figure 4: Comparison of the cutting forces between simulation and experiment for different cutting velocities

4.2. Variable cutting thickness

The variable cutting thickness caused by the vibration of the machine structure is accompanied by some changes in the value of the rake angle. When the tooth immerses into or emerges from the work piece, the theoretical value of the rake angle is varied due to the new cutting trajectory of the tooth tip (Figure 2b). If a tooth rotation is implemented into the simulation along with the variable cutting thickness, it would prevent the additional variation of the rake angle, but it will not correspond to the real process. For this reason, the variable rake angle was investigated separately. For the following simulation results and discussions, the variable cutting thickness was implemented without an additional rotation of the tooth.

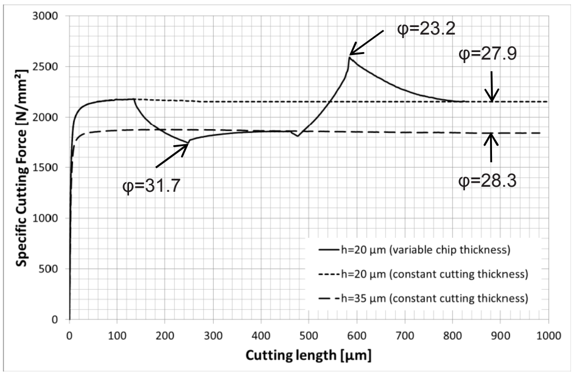

Figure 5: Specific cutting forces k_c during the cutting simulations with an immersion of the tool into the work piece (initial cutting thickness 20 μm)

In Figure 5, the specific cutting force is plotted over the cutting length. The curve characteristics are taken form simulations with constant cutting thickness (20 μm and 35 μm) and with variable cutting thickness (initial cutting thickness of 20 μm). The applied approach for the implementation of the variable cutting thickness is presented in Figure 2b (emersion or immersion of the tooth from or into the work piece). In Figure 5, the values of the shear angle (angle between the shear plane and the uncut surface of the work piece) at different simulation points are also shown. The shear angle changes its value during the variation of the cutting thickness. When the cutting thickness has reached constant level the angle is still adjusting which influences the value of the specific cutting force. Also the areas can be seen where the cutting thickness changes. Figure 5 shows both of the areas in which the cutting thickness is already constant but the specific cutting force is still adjusting. By comparing these areas, it can be concluded that the cutting length for reaching a stationary state of the specific force is nearly the same for the emersion from the work piece and immersion into the work piece. In [8], Delonnoy used a relationship between the specific cutting force depending on the maximum shear stress, the cutting thickness, and the shear angle. This relationship was briefly discussed in [3] and the tendencies were theoretically calculated. The simulated specific cutting forces are in good agreement with them.

In Figure 6, the specific cutting force is plotted over the cutting length from simulation with different immersion depths (5 µm, 10 µm and 15 µm) but the same immersion rate. The diagram shows, that, the specific cutting force has nearly the same deviation of 5 % (nearly 100 N/mm²) as the specific cutting force at the end of the simulation, once the cutting thickness has reached constant level. The cutting length needed for the adjustment of the cutting force is different for the three cases. This can be explained by means of Figure 7. Here, the shear planes from simulations with a different immersion depth, but the same immersion rates are shown. The frames are taken when the cutting thickness remains constant and correlate to Figure 6. As expected, the shear angle is different in the three simulations at this point. Furthermore, the length of the shear plane is not the same for the three cases, which is caused by the different immersion depths. This explains the different cutting lengths needed for the adjustment of the specific cutting force.

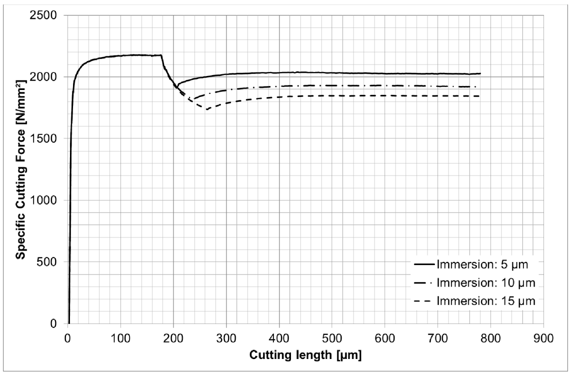

Figure 6: Specific cutting forces k_c during the cutting simulations with different immersions of the tool into the work piece (initial cutting thickness 20 µm)

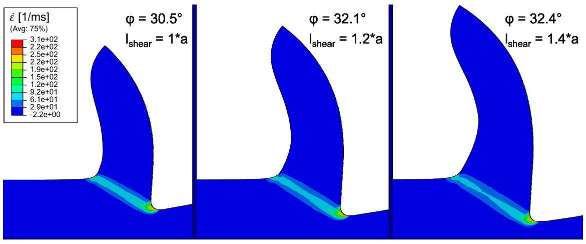

Figure 7: Shear plane in three different cutting depths

Figure 8 depicts the different cutting lengths needed for reaching the stationary state of the cutting force in the simulation with variable cutting thickness and variable rake angle by cutting velocities between 30 m/min and 90 m/min. The new constant value of the cutting force is reached after applying higher cutting velocities at shorter cutting lengths. Such effect can be explained with Figure 9 and Figure 10. In Figure 9, two frames of the simulation with variable cutting thickness and cutting velocities of 60 m/min (right) and 90 m/min (left) are shown. The state variable of these frames is material softening induced by temperature variation. For a cutting velocity of 90 m/min the material softening in the pre-compression area is slightly higher than in the simulation with a cutting velocity of 60 m/min. This influences the motion of the shear plane and particularly the changes of the shear angle.

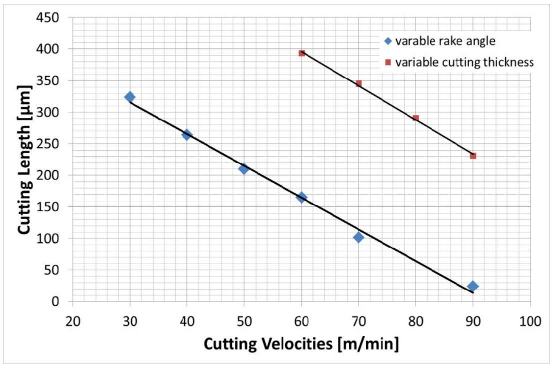

Figure 8: Cutting length needed for the adjustment of the shear angle after changing cutting parameters

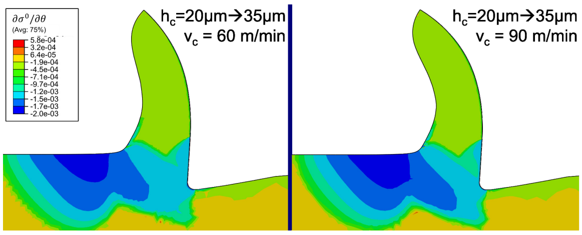

Figure 9: Temperature induced material softening during simulations with two different cutting velocities and variable cutting thickness

4.3. Variable rake angle

In Figure 10, frames from two different simulations (30 m/min and 90 m/min) are taken after the rake angle has been changed back to 3.52°, where the temperature induced material softening can be seen. Here the motion of the shear plane is also influenced by the cutting velocity, resulting particularly in changes of the shear angle. Another aspect is the different chip thickness which leads to different lengths of the shear plane. In the shear plane, the material hardness induced by the strain rate is nearly the same for all simulations but the size of these areas is different for each parameter combination. Figure 9 and Figure 10 lead to the conclusion that due to the temperature induced material softening the new constant value of the cutting force is reached faster. The softening of the material is caused by the higher temperature when higher cutting velocity is applied.

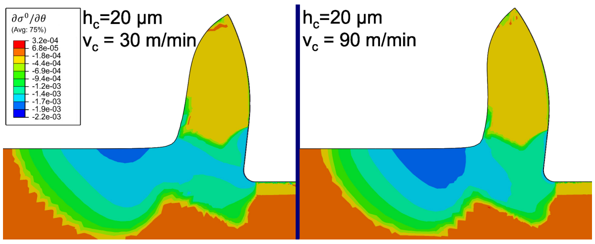

Figure 10: Temperature induced material softening during simulations with two different cutting velocities and variable rake angle

The shear plane was investigated experimentally in order to validate the simulation results. In Figure 11, the shear plane is shown by using the experimentally obtained data (left) and by using simulation. The cutting parameters were the same for both approaches, cutting velocity – 30 m/min and cutting thickness 20 µm. A possible approach for the experimental investigation of the shear plane is a quick stop of the broach. However, due to a quick stop of the broach, the cutting tooth decelerates from the initial cutting velocity to zero and the mechanical state of the shear plane would be changed. Such data cannot be used to validate the simulation results. The measurements of the shear angle took place in the machine during the process. This prevents deviations when a quick stop of the broach is implied. The measured shear angle was 19.4°, which is in very good agreement with the simulated data. In future works, a new measurement platform for the experimental investigations of the shear plane will be built up and the results will be presented in upcoming papers.

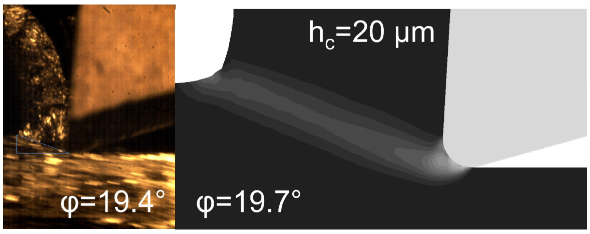

Figure 11: Shear angle experimentally measured and simulated

5. Conclusion

In the presented paper, numerical investigations on changes of the main shear plane while broaching are presented. When vibrations of the machine structure during the process occur, cutting parameters such as cutting thickness or rake angle will change, too. The presented research focuses on these changes, which cause a variation of the specific cutting force during the process. The different shear angles explained the adjustment of the specific cutting force after the application of new cutting conditions. Simulations with different cutting velocities were implemented. The results show that different cutting lengths are needed for the adjustment of the specific cutting forces, as depicted in Figure 8. With a higher velocity, the stationary state of the cutting force is reached faster. This can be explained by the characteristics of the uncut area in front of the chip. Different temperature induced softening is observed during the simulation with cutting velocities of 30 m/min, 60 m/min and 90 m/min. The validation of the simulation results is divided into two parts. In the first part, the simulated specific cutting forces are compared to the experimentally obtained data. In the second part, the shear planes (shear angle) are compared one to another during simulation and experiment. The simulated data are in good agreement with the data obtained from the experiments.

Acknowledgements

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