Numerical Investigation of the Changing Cutting Force Caused by the Effects of Process Machine Interaction While Broaching

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Abstract

During broaching, interactions between the process and the machine are inevitable and affect the process itself and the resulting work piece. To understand these effects profoundly, they have to be analyzed and investigated. One of these effects is the vibration of the cutting edge which results for example in a change in rake angle or cutting thickness during the cutting process. Therefore, the first part of this paper presents results of investigations concerning a variable cutting thickness and the second includes investigations of the variable rake angle during broaching, in both cases the effects on the cutting forces by means of two-dimensional (2D) cutting simulations.

1. Introduction

Production efficient and economically optimized metal cutting processes can be achieved with a better understanding of the process and of the effects which have an outside influence on the process caused by the machine such as vibration, temperature, etc. Therefore, all possible effects have to be investigated. This requires a great deal of time and resources which can be very expensive. In this paper, numerical investigations of the influences of machine vibration will be presented. For example, the vibration of the machine structure can result in a wavy profile on the machined surface (roughness) of the work piece. Other parameters that can be affected are the rake angle and the clearance angle. During broaching, the broach moves in a linear way and when machine vibrations occur, the cutting tooth will move orthogonal to the cutting direction. This results in a changing cutting thickness and rake/clearance angle.

This paper is structured in two main parts, 1) variable cutting thickness and 2) variable rake angle during broaching. In the first part, the results of the simulation model with a variable rake angle are presented. The investigations of the variable rake angle also include different inclination rates. In the second part, findings on the influence of the variable cutting thickness are shown. For this part, different inclination rates for the roughness profile and for the immersion of the tool into the work piece were investigated.

A 2D cutting simulation model was used for the two main objectives of this paper.

2. State of the art

There are many published studies on the effects of interactions between machine tools and processes [1, 2, 3, 4]. Krause and Brinksmeier present their results of experiments of diamond machining under consideration of unbalances in [5]. The results show that it is not the cutting force but the trust force which is affected by an unbalance. In [6], Brandt et al. deal with the possibility for the simulation of process machine interaction for ultra-precision turning. Eberhard et al. take the heat conduction into account in their study [7]. In contrast, Heisel et al. [8] investigate the influence of the thermo-
mechanical interaction between the work piece and the cutting tool. In [9], Uhlmann and Rasper present the dependence of the stability behavior of a milling process on different process parameters such as cutting speed and cutting depth. However, in the Priority Program 1180 “Prediction and Manipulation of Interaction between Structure and Process”, many metal cutting processes are investigated but very little work has been done in the field of broaching. Zhang and Chen investigated the chip formation of broaching by means of cutting simulations [10]. However, nobody has taken the possibility of variable cutting parameters during the process such as cutting thickness or rake/clearance angle into account in the simulations.

3. The broaching tool and its geometrical properties

All geometrical properties, such as cutting thickness \( h \), rake angle \( \gamma \), and clearance angle \( \alpha \) of the broach are shown in Fig. 1. In the specialized literature, broaching is distinguished into two types: internal and external broaching. In this paper, the external broaching is investigated by means of orthogonal cut.

Broaching and its simple dynamic properties are very suitable for the investigation of the effects caused by vibration of the machine structure. As aforementioned, if these machine structures vibrate, the broach will vibrate as well. This in turn will cause changes in the geometrical properties of each tooth relative to the work piece. For example, if the broach vibrates in direction of the work piece, the cutting thickness and the rake/clearance angle will vary. Multiple teeth are in contact with the work piece one after the other, so when the first tooth changes its cutting thickness (Fig. 2b), the second one also sees a variable cutting thickness; hence the formation of a surface profile (Fig. 2a). That is why different inclination rates (65 \( \mu \)m/ms, 130 \( \mu \)m/ms and 260 \( \mu \)m/ms) are applied for this investigation.

For both cases, two different approaches (see Fig. 2 a/b) are implemented in the simulation model and the cutting thickness changes by 15 \( \mu \)m during the simulation.

For the changing rake/clearance angle only one approach is applied, which is implied in Fig. 2c. The variation of the rake/clearance angle takes place around a point in the tool nose. This will not be accompanied by another effect such as changing cutting thickness which can be seen in the real cutting process.

4. Simulation model

The approaches in Fig. 2 are investigated by means of 2D cutting simulations using the finite element software ABAQUS. All work piece geometries were machined with the same cutting velocities of 90 m/min and have a constant theoretical width of 1 \( \mu \)m.

An elastic-plastic material behavior is considered for the material of the work piece (SEA 1045 in normalized state). This is implemented as a function, which is described more in detail by Weber and Autenrieth in [12], of strain, strain rate, and temperature in a user subroutine which is called up at each increment in the simulation and calculates the new material properties [13] under the new cutting conditions.

Because of the high mesh deformation, a self-designed continuous remeshing subroutine is used for the separation of the material in the simulation model which was introduced by Schulze and Autenrieth in [14, 15]. In Fig. 3, the scheme of a self-designed continuous remeshing method is shown. Each cutting simulation is divided in short sub-simulations. At the end of each sub-simulation, the subroutine is called up and new input files are generated. Then the old results are mapped onto the new input files with the start of the new sub-simulation.

In each simulation, the Coulomb friction model was included with a time-independent constant friction coefficient along the contact surfaces.
5. Simulation results

5.1. Comparison of the cutting forces between simulation and experiment

In [16], the used cutting simulation was compared to the experimentally obtained data. The minimum and maximum deviations of the specific cutting forces from the experimental results on cutting thickness were approximately 2% and 18% (Fig. 4, 20 μm), respectively. In simulations with an initial cutting thickness of 35 μm, the specific cutting force deviated from the experimentally obtained data by a minimum of 4% and a maximum of 10%. Overall, the simulations show accuracy compared to the experimentally achieved data.

5.2. Variable cutting thickness

Fig. 5 shows the specific cutting force predicted by simulation under variable cutting thickness and two different initial cutting thicknesses. The influence of the different inclination rates on the cutting forces can be observed in the curve characteristics.

Fig. 6 shows the specific cutting forces obtained from simulation with the tool immersing into the work piece. The initial cutting thickness affects the curve characteristics. This will be discussed in more detail in the following chapter.

5.3. Variable rake angle

The curve characteristics of the specific cutting force from simulation under variable rake angle are presented in Fig. 7. The initial rake angle in all simulations was 3.52°, the same as in the experiments for validation of
the simulations with a constant rake angle. The differences in the specific cutting force can be observed in the curve characteristics, which will also be discussed in the following section.

6. Discussion

As mentioned in [16] the specific cutting force is still adjusting after changes in the cutting thickness. The same was obtained in simulation with variable rake angle. In the following, these effects will further be elaborated.

6.1. Variable cutting thickness

After the cutting tooth enters the work piece, assumed that no additional outside influences occur, the cutting force reaches a constant value. If for instance the cutting thickness changes, naturally the cutting force must change as well. The changes in the specific cutting force can be seen in Fig. 5 and Fig. 6. For more details see Fig. 8, which is the closer view of Fig. 7, where the cutting thicknesses reach its new constant value. Here, the x-axis is normalized with the cutting length needed for reaching its stationary value. This is necessary for a better illustration of the results. On the y-axis the specific cutting force is normalized with the value obtained in simulation with constant cutting thickness of 50 μm.

As can be seen in Fig. 8, the simulated and theoretically calculated cutting forces at the beginning of constant thickness have unequal values for the three different inclination rates but diverges toward the end of the simulation. As mentioned in [16], the shear angle changes with a variation of the cutting thickness as well. For this reason, similar to the cutting forces, it can be deduced that the shear angles will take a longer time to change to a new value. The main cause for the changing shear angle is the variation of the rake angle. When the cutting thickness is changed, the tooth moves along the cutting trajectory as shown in Fig. 2. This means that the rake angle changes relative to the cutting surface along the changes in the cutting thickness as well. This dependency of the cutting force on the shear angle can be confirmed with the theoretically calculated curves in Fig. 8. The specific cutting force has the largest value in the model with inclination rate of 65 μm/ms and the smallest where the inclination rate is 260 μm/ms. This tendency can be observed in the simulated curve characteristics.

Fig. 9. Effect of different immersion rates on the shear angle φ for the variation of the cutting thickness

In Fig. 9, frames from simulation with different immersion rates for the variation of the cutting thickness are presented. The pictures are taken exactly after the cutting thickness reached 50 μm. The value of the shear angle increases with an increasing immersion rate. This means that the material needs some time to adjust to the new cutting conditions. In Fig. 8, the cutting force obtained by simulation with an immersion rate of 65 μm/ms has a value already near the constant value at the beginning of the constant cutting thickness parameter. Here the simulation is done with constant cutting thickness of 50 μm. In the same simulation (Fig. 9), the shear angle φ has the smallest value (29.8°) but the shear angle obtained by simulation with a constant cutting thickness of 50 μm is 27°. This may explain the different specific cutting force values in Fig. 8.

In Fig. 10 the specific cutting force from simulation with and without variable cutting thickness is presented. For this diagram the immersion rate of 195 μm/ms as in [16] was implemented. Here the cutting thickness changes twice during the simulation: 1) the tooth immerses into the work piece (h=35 μm), 2) the tooth
emerges from the work piece \((h=20 \, \mu m)\). As aforementioned the cutting force is still adjusting due to the changes of the shear angle even after the cutting thickness reaches a constant value. In the first marked point \((\phi = 31.7^\circ)\) in Fig. 10) the cutting thickness reaches first its new value of 35 \(\mu m\), but the specific cutting force is approximately 6% smaller than the stable state cutting force taken in simulation with constant cutting thickness of 35 \(\mu m\). In the second point \((\phi = 23.2^\circ)\) in Fig. 10) the cutting thickness reaches to 20 \(\mu m\). In this case the specific cutting force is approximately 17% higher than its value in simulation with \(h = 20 \, \mu m\). This can be explained with the different cutting conditions, which cause the variation of the shear angle. During the immersion of the tooth into the work piece, the rake angle decreases fictitiously, which leads to higher value of the shear angle. In the other case, where the cutting thickness changes back to 20 \(\mu m\) the rake angle increases and causes smaller shear angles, which induces higher cutting forces.

6.2. Variable rake/clearance angle

In this chapter, the results obtained by simulation under variable rake angle are specified. As mentioned earlier, the cutting force is changing due to mechanistic factors if, for instance a variable rake angle is applied. Here, the same effect on the specific cutting force as in the simulations with a variable cutting thickness is observed. The cutting force is still changing even after the rake angle reached the new value.

Fig. 11 shows five different areas (0-1; 1-2; 2-3; 3-4; 4-5). These areas represent parts of simulations with different constant rake angles or where the rake angle has been varied. Each time step is normalized with the time, which is needed to reach the next area. This is done in order to better illustrate the effect of the different inclination rates.

A further illustration of the still adjusting cutting force when no outside influences occur in the area (4-5) is shown in Fig. 12. Here, the still adjusting cutting force after the rake angle was changed back to 3.52° can be seen. The smallest inclination rate at the beginning of the area shows the smallest value of the cutting force. Two other curve characteristics are approximately 140 N/mm² higher at the same simulation point. This effect can be explained by the time and the mechanical conditions in the work piece. In the simulation with an inclination rate of 35.2°/ms, the time for the new conditions to adjust (Fig. 13) is considered sufficient. The resulting shear angle in simulations with a constant rake angle of 0° and 3.52° is approximately 23° and 25.6° respectively. Therefore, during the change of the rake angle back from 0° to 3.52°, the shear angle has to increase to a value of
In Fig. 13, the shear angles of the three presented inclination rates are depicted. The angle between the shear plane and the surface of the work piece in the simulation with an inclination rate of 35.2°/ms is 25.2°, which is nearly 25.6° as the value in the simulation with constant rake angle. In the simulation with an inclination rate of 352°/ms the shear angle is 24°; therefore, it requires more time to adjust to the new cutting conditions and to reach the value of 25.6°.

7. Conclusions

The first part of the presented study included some investigations of the influence of variable cutting thickness during the simulation of the cutting force. Different approaches were applied for the implementation of the variation of the cutting thickness. A compressed version of [16] was given. This work was concentrating on the investigation of different immersion rates of the tool. The different immersion rates have no significant influence on the cutting force but on the curve characteristics of the cutting force. An explanation of this effect was given with the changing angle between the shear plane and the work piece surface in the material. Another effect, which was observed during the simulation, was the different specific cutting force after the immersion and emersion of the tooth. This is caused by the different cutting conditions and fictitiously changing rake angle.

The second part of this paper focused on the variable rake/clearance angle. Three different changing rates have been investigated and it can be concluded, that the angle between the shear plane and the work piece surface is still changing even after the rake angle reaches a constant value. This causes changes in the value of the cutting force. A stationary state of the cutting force is achieved after the shear angle reaches its stable state and it reaches the value obtained by simulation with a constant rake angle during the process. The dependency of the cutting force on the shear angle will be a topic in future papers.

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