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Surface quality after broaching with variable cutting thickness

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Abstract

During machining, new surfaces are generated. Depending on the machining process, different qualities of surfaces are produced. After broaching, a high surface quality is expected. However, the quality can be influenced by vibrations of the machine structure which leads to varying cutting thicknesses and thus to low surface qualities. The influence of variable cutting thicknesses during machining was investigated experimentally and by means of simulations. Dynamic changes in cutting thickness were considered as geometrical profiles on the uncut surfaces. Process forces were measured during the experiments and the roughness before and after broaching with one tooth was evaluated. The residual stresses in the workpiece surfaces were simulated with an already validated model of orthogonal machining using a self-implemented re-meshing method.

Keywords: Roughness; Cutting; Residual stress; Broaching

1. Introduction

In the production of metal components, the quality of the machined parts is influenced by many factors such as the manufacturing process, the machine structure, tools, cutting conditions etc. One very effective manufacturing process in mass production is broaching. Here, the components are produced with only one linear motion of the broach and the cutting teeth are in contact with the workpiece one after the other. When the machine structure vibrates, the broach is vibrating as well, which leads to an additional motion of the teeth. This motion results in poor waviness profiles and poor roughness of the machined surface. Such a poor quality of the surface causes a variation of the cutting conditions for the next tooth. Therefore, the previous tooth affects the cutting conditions of the next one in terms of cutting thickness.

The interactions between the machine and process were investigated and discussed in many published studies [1, 2, 3, 4]. Zhang published in [5] some numerical investigations on broaching without considering the effects of the process-machine-interactions. In previous works, Schulze [6, 7 and 8] presented a numerical investigation of broaching with variable cutting thickness and variable rake angle. In these investigations it was shown that the cutting force reaches a stationary value after a while when the new cutting thickness is achieved. This was explained by the changes of the angle between the shear plane and the cutting direction. In [9], an analytical approach for the prediction of the shear angle was presented which was compared to the simulated shear angle in [8]. A relationship between the shear plane angle, friction angle (the angle between the chip/tool resultant force direction and the normal vector to the rake face of the tool), the rake angle and a strain hardening exponent was presented in [10]. Childs [11] developed a 2D-simulation model based on [10] for the investigation of metal cutting processes for orthogonal cuts. In [12], the influence of the friction angle on the shear plane was numerically investigated. The influence of variable cutting thickness on surface quality in terms of residual stresses was not investigated up to now.

2. Setups of the experiments and simulations

This paper presents experimental and simulative investigations of the changing cutting thickness during broaching. In the first phase, broaching experiments

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were conducted by varying the cutting thickness with an inclination of the cut surface relative to the cutting direction. Different cutting thicknesses and cutting velocities were applied. For the experiments the workpiece was the moving part instead of the broach, the broach was fixed stationary. The obtained parameters were the process forces, the roughness of the machined surface and high-speed-recordings of the process during broaching. In the second phase, the simulations with variable cutting thickness were carried out. The outputs such as shear angles were compared to the experimentally obtained data.

2.1. Experiment

Three different output parameters were obtained during the experiments: the process forces, high-speed-recording of the process in micro scale and the resulting roughness/waviness of the machined surfaces. For the measurement of the process forces, a measurement platform was built into the machine. The recording of the cutting process took place during broaching. Two approaches for the implementation of the high-speed-camera were possible. The first one was to move the camera with the broach, where the broach was moving and the workpiece was stationary. In this case, the vibration of the broach will affected severely the recordings of the process. The second one was more promising and therefore was applied here. In that case, the broach was stationary and the workpiece was moving (Fig. 1). The high-speed-camera was attached to the machine structure and was able to record the entire process. For the recordings, a lens with a maximum zoom of 8 times at a distance of 2 mm was used, so that the deformation zone of the workpiece can be observed on the recorded pictures. The roughness and waviness of the machined surface were measured with a perthometer.

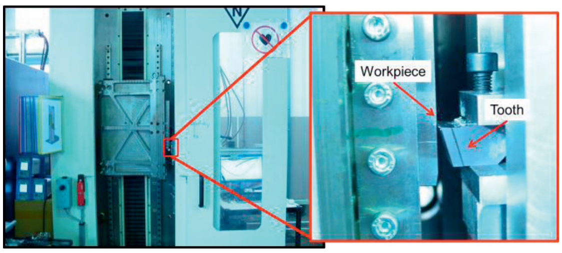

Fig. 1: Experimental setups

SAE 1045 in normalized state was used in all experiments. The variable cutting thickness was realized geometrically as 10° inclination at the workpiece (Fig. 2). The workpiece had a constant width of 7 mm for the realization of the orthogonal cut. Because of the large amount of data obtained in the experiments, a cut with just one tooth was investigated.

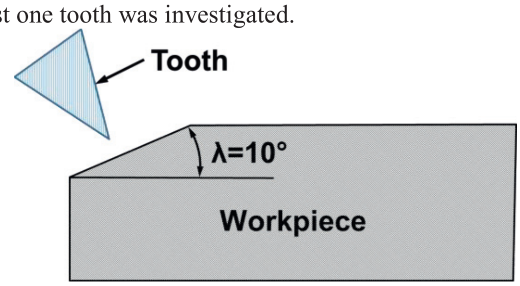

Fig. 2: Variable cutting thickness using 10° inclination at the workpiece

2.2. Simulation

The influences of the variable cutting thickness were investigated by means of 2D-cutting simulations using the finite element software ABAQUS. Identical workpiece geometries as in the experiments were used and the cutting velocity was varied between 20 m/min and 40 m/min. The elastic-plastic material behavior of SAE 1045 was considered and depends on the strain, strain rate and temperature. The implementation of the material behavior is discussed in more detail in [13]. Because of the high deformations in the shear zones, a self-designed continuous remeshing method was used in the simulations, which is presented in detail in [14]. The general approach of the continuous remeshing method is shown in Fig. 3. Coulomb's frictional model was implemented in the simulation with a constant friction coefficient (μ = 0.3) along the contact area.

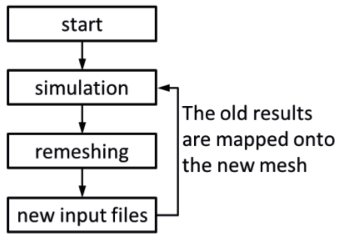

Fig. 3: Approach of the continuous remeshing method

3. Results and discussion

3.1. Roughness and process forces

In the following, the results from the experiments and the simulations will be presented and discussed. In Fig. 4, two areas are indicated with x_1 and x_2. In the first area x_1, the cutting thickness is changed from 0 to the end value in a given interval [20 µm – 40 µm]. Its length depends on the value of the cutting thickness. In area x_2 the cutting thickness has a constant value placed in the same varied interval [20 µm – 40 µm].

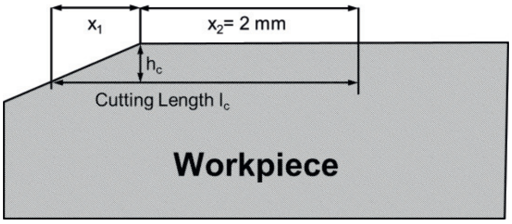

Fig. 4: Cutting thickness and cutting length

In Fig. 5, the specific process forces are plotted versus the cutting length. In this case the length of the workpiece is 300 mm whereby only the first 2 mm are of interest because afterwards the process forces are nearly in a steady state and no further changes of cutting thickness in cutting direction are implemented. In Fig. 5, the curve characteristics correspond to the geometry shown in Fig. 4. Here, the two areas are also shown. In the area x_2, the specific process forces are adjusting after the cutting thickness is already constant. This was first investigated by Schulze in [7, 8] in terms of 2D-cutting simulations. The curve characteristics of the specific process forces are calculated by means of a Fast Fourier Transformation filter (FFT filter) for better picturing of the experimental results. Fig. 6 shows the filtered curve characteristics of Fig. 5.

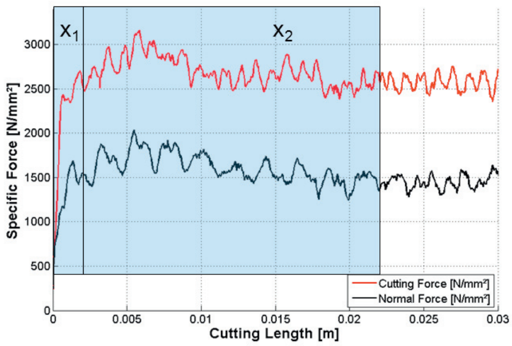

Fig. 5: Specific process forces versus the cutting length

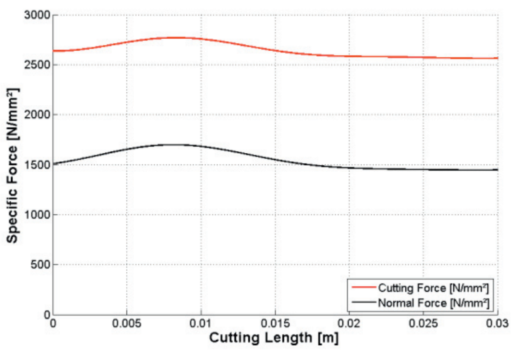

Fig. 6: FFT filtered Specific process forces

In Fig. 7, the roughness Ra is shown for different cutting thicknesses at constant cutting velocity (17 m/min). The roughness is measured in area x_1. When the tooth comes in contact with the workpiece, the minimum cutting thickness is not reached and the tool is just ploughing the surface. As soon as the cutting thickness is larger than the minimum needed value for chip formation, the real cutting process begins. The ploughing explains the high quality of the measured roughness in area x_1 (Fig. 7). The averaged values of the measured roughness are nearly the same for the cutting thicknesses of 20 µm and 30 µm. For the highest investigated cutting thickness (40 µm) the roughness is significantly higher (0.17 µm). In Fig. 8 the roughnesses within area x_2 are presented for the same experiments. Within this area the measured roughnesses are much higher than in area x_1. The variance of the measured points increases with rising cutting thickness. This is most likely caused by a combination of the kinematics of the machine structure and the changing cutting conditions.

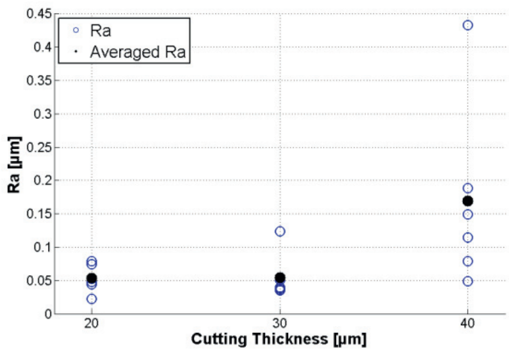

Fig. 7: Roughness Ra measured in area x_1

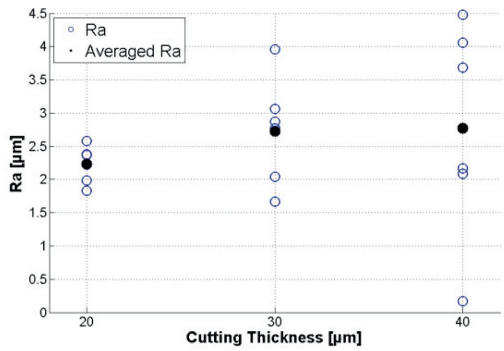

Fig. 8: Roughness Ra measured in area x_2

Fig. 9 shows the roughness profiles of area x_1 and x_2 for a cutting thickness of 20 µm and two different velocities (5 m/min and 17 m/min). At a cutting thickness of 20 µm the x_1-area has a length of 0.11 mm.

As mentioned before, the surface quality of this area is very high because of the ploughing effect. Within the first 0.5 mm of the second area the quality of the machined surface is also relatively high. After this point, the quality of the surface is decreasing which can be explained by the material separation and the additional vibration of the machine structure that can be observed in Fig. 9.

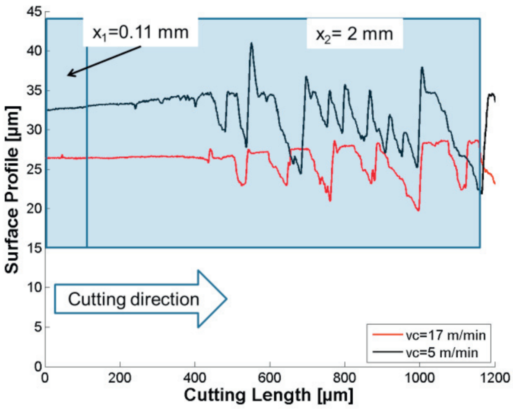

Fig. 9: Roughness measured after broaching with different cutting velocities

3.2. Residual stresses

To reach residual stresses after machining, the process has to be in a steady state, where the temperature, process forces and stresses have a constant value. After reaching the steady state, the tool has to be taken out of contact and the workpiece has to be cooled down, as shown in Fig. 10. Because the used machining simulation with the material SAE 1045 was already validated by Schulze [6, 7] regarding the specific process forces and by Autenrieth [13] in terms of residual stresses for a large range of process parameters, it can be used directly without a further validation. In Fig. 10, the stresses in cutting direction are presented. The position in area x_1, where the residual stresses are selected from, is also shown in this figure.

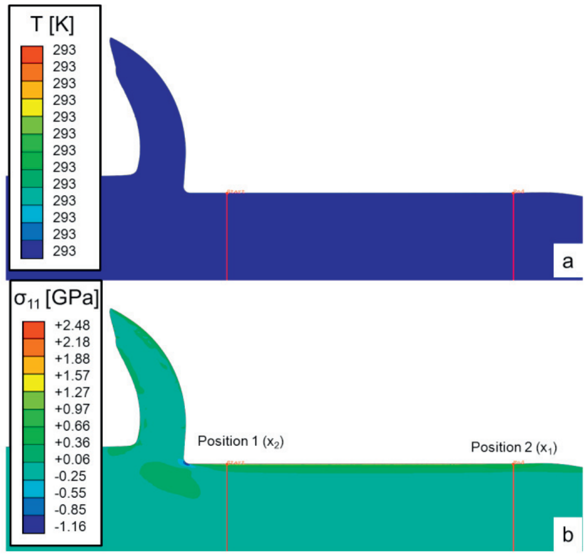

Fig. 10: Simulation results: a) temperature after reaching a stationary state; b) residual stresses in cutting direction

In Fig. 11, the simulated residual stresses in cutting direction are presented. The used process parameters are cutting thickness h = 20 µm and cutting velocity v_c = 17 m/min. The residual stresses at two different positions (area x_1 and x_2) are compared with the results of a simulation with constant cutting thickness (conventional simulation). As the graph clearly indicates, the curve characteristics of the first 10 µm depth are sharply changing from positive to negative values. The minima of the curves taken in area x_2 and the conventional simulation have nearly the same values. In area x_1 the curve characteristics are completely different for the conventional simulation and the simulation with variable cutting thickness. The depth of the minimum residual stress values with variable cutting thickness is at 20 µm and for the constant cutting thickness at 27 µm depth.

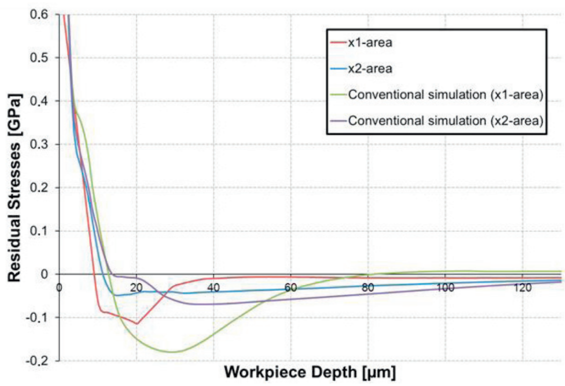

Fig. 11: Residual stresses in the both areas (x_1 and x_2)

3.3. Main shear plane

In [6, 7], the simulation results with varying cutting thickness were presented. It was shown that the angle between the cutting direction and the shear plane (shear angle) changes with the variation of the cutting thickness. A possibility to measure the shear angle and the shear plane would be a quick stop test, where the cutting tooth is decelerated from the actual cutting velocity down to zero. This enables measuring the shear plane with a microscope independent of the machine structure and tool. Due to the quick stop and the related deceleration of the tooth, the cutting conditions are changing. Therefore, the influences of variable cutting thicknesses on the shear plane cannot be investigated. Another possibility to observe the shear plane is the approach used in the experiments. In the experimental investigations, the main shear plane is filmed with a high-speed-camera during the process. An example is presented in Fig. 12, on the right side.

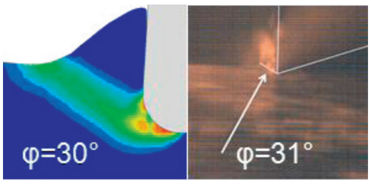

Fig. 12: Shear angle: simulation (left) and experiment (right)

Fig. 12 also shows the main shear plane calculated by the simulations (Fig. 12, left) that can be compared to the experiments (Fig. 12, right). The frames are taken nearly at the same time and at the same cutting length (at the beginning of the cutting process). The simulated shear angle is 30° and the experimentally measured one is 31°. The simulation is in good agreement with the experiments. The cutting edge rounding was kept constant, because its influence was not one of the primary aims within the research.

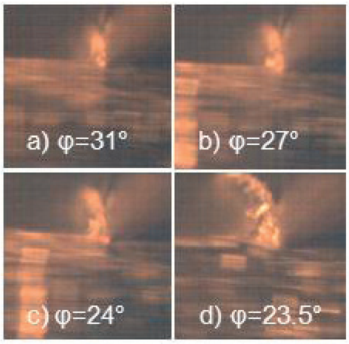

Fig. 13: Shear planes taken in different time steps during the experiments

The shear plane at different time steps during the process is shown in Fig. 13. In Fig. 13a, the cutting thickness is rising from zero to 20 µm. After the cutting thickness reaches the constant value (Fig. 13b), it remains constant (Fig. 13c and 13d). During the experiment the shear angle changes from 31° at the beginning of the process to 23.5°. The same results are obtained in the simulations, which are presented in Fig. 14.

4. Conclusions and outlook

The results of experimental investigations supported by FEM simulations of variable cutting thickness during broaching were shown. For the investigations the workpiece material SAE 1045 was used. The experimental investigations have shown that variable cutting thickness, caused by vibration of the machine structure, has an influence on the specific process forces and the quality of the machined surface. At the beginning of the cutting process (area x_1), the quality of the surface is very high. This was explained by the interaction of the cutting edge with the minimum cutting thickness and ploughing that takes place until the minimum cutting thickness is achieved and chip formation begins. The results of the FEM simulations have shown that a variable cutting thickness influences the residual stresses in cutting direction in area x_1. Further experimentally achieved results were shown. Using a high-speed-camera frames of the main shear plane, were filmed. The results were used for a further validation of the FEM simulations and it was shown, that varying cutting thicknesses during machining are influencing the shear angle. The results will further be used for an analytical model that describes the process forces depending on varying cutting thicknesses.

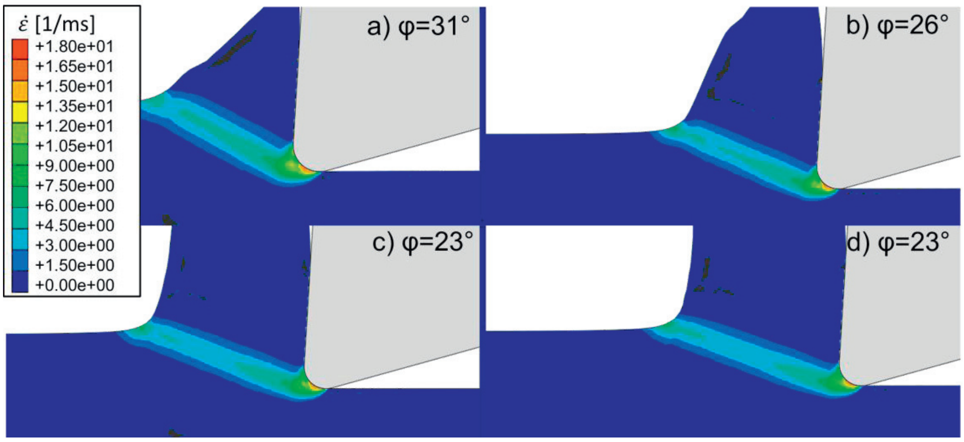

Fig. 14: Shear planes taken in different time steps during the simulations

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