Simulation of the circular sawing process

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1 Abstract

Machining processes are characterized by high dynamic and states of deformation. With the use of simulation technology different machining processes have been analyzed and have shown reliable results. However, the simulation of sawing process has been carried out in very few cases. In order to analyze the saw processes and identify process optimization potentials, the present work contains the results of finite-element (FE) simulations of circular saw processes designed in LS-Dyna. The effects of the variation of the cutting speed and tooth feed on the process forces, temperature development and the chip formation, are shown by the results of these simulations.

2 Introduction - Simulation of machining processes

2.1 Basic models in the simulation of machining processes

The specific material deformation states caused by high thermal and mechanical loads of machining processes can be estimated with numerical approaches, such as the finite-element (FE), Smoothed Particle-Hydrodynamics method (SPH) and the Element-Free-Galerkin method (EFG). The diverse numerical approaches offer the possibility of predicting temperature, material flow and reactive forces within a machining process. The influence of the tool geometry and process parameters such as the cutting depth or the cutting speed, have been well examined with the aim of optimizing machining processes [1, 2].

Machining simulations require the implementation of thermomechanical material models to describe the material deformation in combination with a material separation method [4]. The material models must describe high plastic deformation under the effects of high temperature and deformation rates. Studies in metal cutting processes have shown that strains (ε) > 50%, deformation rates ($d\varepsilon/dt$) < 100 1/s and temperatures (T) of over to 300°C, are usual [4, 6]. Therefore, flow stress curves must be described in dependence of the strain (ε), the strain rate ($d\varepsilon/dt$) and the temperature (T). The strong dependencies between these variables for such material models are only visible through special measurement procedures [6]. A generalized material model developed for process with high deformation, strain rates and temperatures is the Johnson-Cook-Model, which describes the stress in dependence to these three variables [8, 9].

Beside the specific material models for high deformation, the material separation belongs to the main properties of machining processes [4]. In order to separate material and form the chip out of the work piece on a simulation, different material separation methods can be used. Among these methods, the use of failure criteria for the deletion of elements, remeshing or node separation techniques can be suitable. Additionally the various mesh free methods can be used in order to model the material separation [4, 5, 6].

2.2 Modeling of machining processes

Most studies have used orthogonal cutting simulation to analyze the machining processes. Experimental measurements on turning operations have shown a good agreement concerning the process forces, temperature and chip formations with these simulations. Therefore further simulations of the turning, drilling and milling processes have been performed in order to develop the process from the process inside. Multiple influences of the cutting geometries and process parameters on the tool and the work pieces have been identified by different studies [2].

The influence of simulation parameters has been also analyzed. In these sense, the selection of the mesh size and the failure strain affects the resulting of the cutting forces. The examination of *Vilumsen* and *Fauerholdt* of an orthogonal cutting process with LS-Dyna lead to the result, that the use of a fine mesh reduces the fluctuations of the cutting force [5]. Since the conditions for the material failure in machining are uncertain, the value of the failure strain in simulations must be mostly adjusted during the design of the simulations. The study of *Vilumsen* and *Fauerholdt* concluded that the cutting force increases with the increase of the value of the failure strain, while its reduction leads to a decrease of chip size [5]. *Vazquez* analyzed the properties and robustness of the Finite-Element-Method (FEM), the Smoothed Particle-Hydrodynamics method (SPH) and the Element-Free-Galeerkin method (EFG) for the simulation of orthogonal cutting process in LS-Dyna [4]. Here the SPH and the EFG represent the mesh free methods. Although the use of the same material model and the boundary conditions for each numerical method, different chip formations and process forces were estimated. The SPH-Method shows advantages concerning the use of time and memory resources however the chip formation has been estimated in this study as unrealistic. Additional practical advantages and disadvantages on the custom of the models for machining have been reported also in this study, however no real experimentation was carried on and it is uncertain to determine which of the methods is more precise compared to reality.

Eulerian approaches have been also used for machining simulation with LS-Dyna. *Raczy* compared the effectiveness of the hydrodynamic material against the Johnson-Cook material model with use of an orthogonal cut [7]. This study deviations of 13% in relation to the experimental measured cutting force with the use of the hydrodynamic material model. When using the material model “Johnson Cook”, the cutting force is even 21% higher. A good agreement between the simulated and experimental results of the chip shapes was also achieved by this study.

Although circular saw processes are high-productive machining processes, simulations of the circular saw processes have been not found in literature sources.

3 The circular saw process

In circular saw processes material is separated by the action of several cutting teeth in the tool. Circular saws are characterized by a high number of geometric defined cutting teeth in comparison to any other machining tool. Either with a circular or a linear cutting kinematic, sawing processes are used for the cutting of sheets and profile tubes, the perforation of sheets, or for the machining of grooves and slots on components.

Figure 3.1 shows standard geometrical parameters, which characterize sawing blades [3]. In accordance to the material to be sawed, the form and separation of the cutting teeth must be selected. Next to the geometrical characteristics of the cutting tools, the process parameters play a very important role for the quality of the machining process as well. The cutting geometries and process parameters define the conditions of the process, which finally determine the surface quality after the processing and the integrity of the cutting tool.

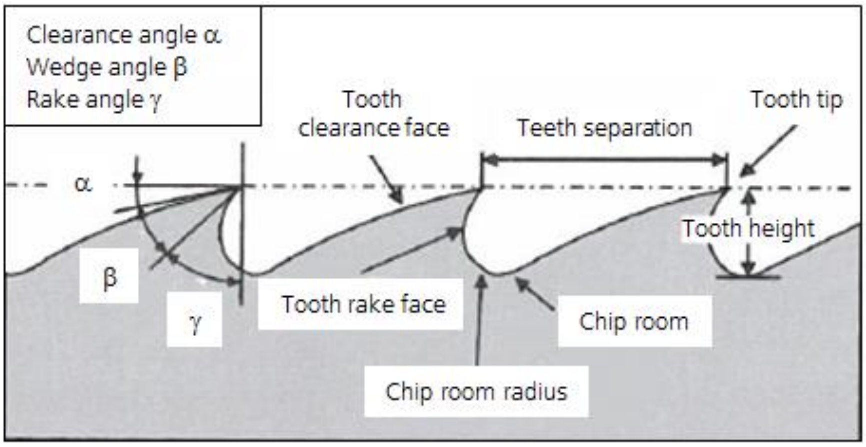


Fig. 3.1: Geometrical parameters in the cutting teeth of saw blades [3]

4 The effect of cutting speed and tooth feed on the machining processes

The cutting speed (v_c) and the tooth feed (f_z) are parameters to be selected in accordance to the economical and quality requirements. Both influence the surface quality on the work piece, the forces and temperature present in the process and also the the tool service life [10]. Machining tests on aluminum and steel have shown that the increase of the cutting speed reduces the surface roughness [10]. However, high cutting speeds induce as well the formation of unfavorable chip shapes and also the reduction of the service life of the tool [11]. This reduction of the tool service life can be related to the higher temperatures at the chip, the chip area, the minor flank, the cutting edge and in the work piece when machining with high cutting speed. This effect has been shown in both experimental tests and in FEM-Simulations [12, 13, 14].

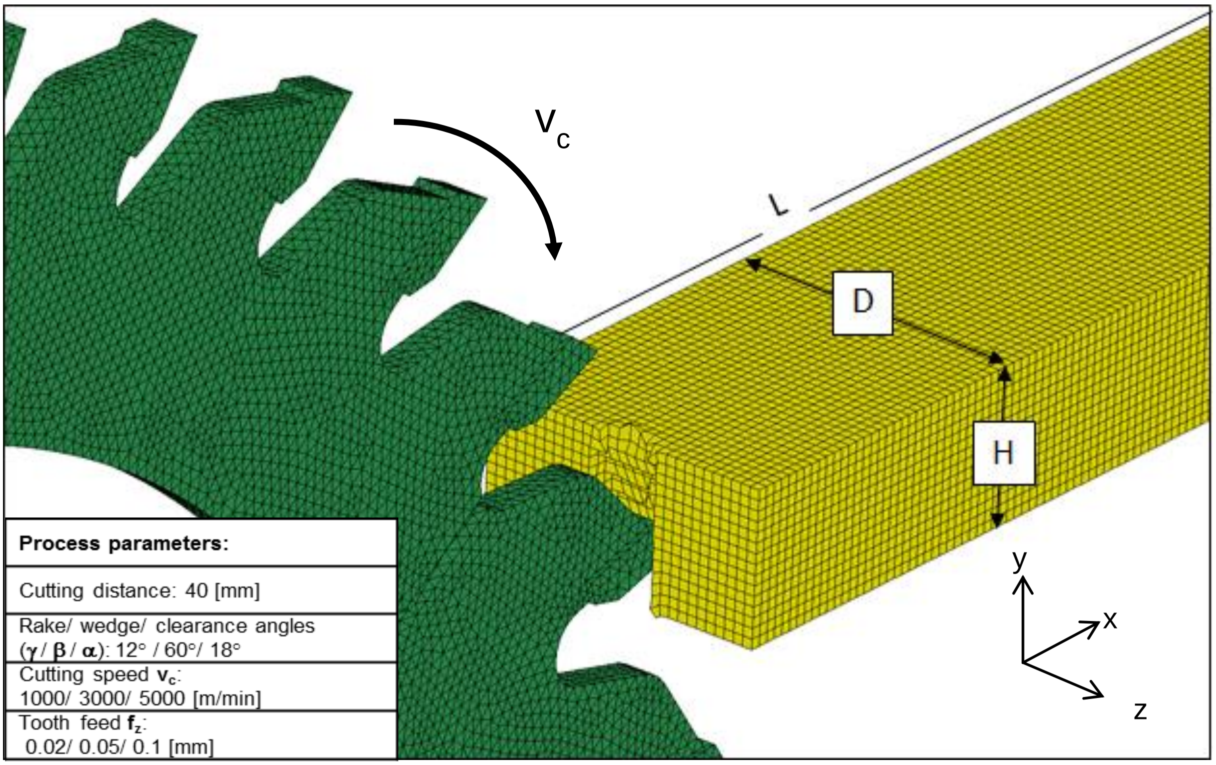
A positive effect on the use of high cutting speed is a drop of the cutting components, the cutting force F_c and the feed force F_z in machining. This effect has been documented in studies based on experimental tests [15]. Nevertheless simulation results have not been able to clearly show this effect [13, 14].

Since the feed f and the feed per tooth f_z influence the chip formation. They determine the room for material compression and the chip thickness. A high feed per tooth leads to more material compression, which dependent on the material structure induces in several cases a favorable chip breakage [11].

The same as with the cutting speed the increase of the feed has also shown an increase of the process temperature. This effect becomes clearer at higher cutting depths [12]. Also the forces in machining increase with the increase of the feed. This has been observed in both by experimental tests and by FEM simulations [11, 13].

5 Construction of the models

In order to analyze the effectiveness of simulations of sawing processes in LS-Dyna, FE-models have been designed. The effects of the variation of process parameters cutting speed v_c, and tooth feed f_z, have been analyzed and compared to results in literature. The figure 5.1 illustrates the general FE-model for the circular sawing used in the analysis. Table 1 contains data about the implemented materials and properties of the FE-model in LS-Dyna. The figure 5.2 shows the FE-model of the orthogonal cutting process derived from the circular sawing process. In contrast to the circular sawing simulation, the orthogonal cutting model performs a thermal calculation. Table 2 summarizes the general properties of the orthogonal cutting model.

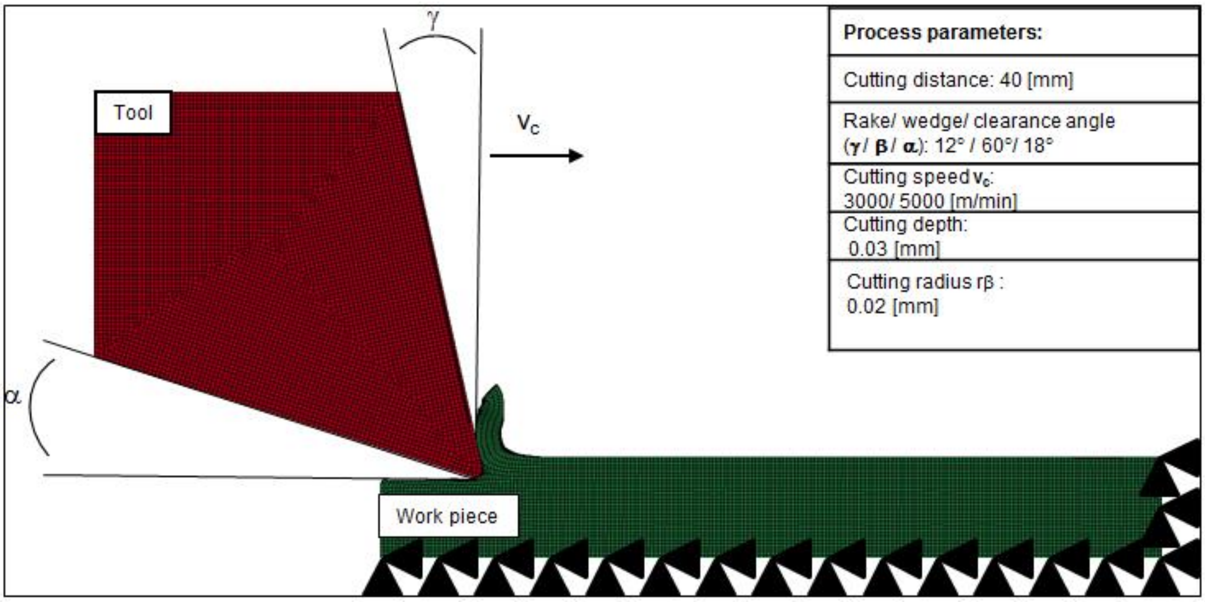


Process parameters:
Cutting distance: 40 [mm]
Rake/ wedge/ clearance angles (γ / β / α): 12° / 60°/ 18°
Cutting speed v_c: 1000/ 3000/ 5000 [m/min]
Tooth feed f_z: 0.02/ 0.05/ 0.1 [mm]

Fig. 5.1: Model design of the circular saw process in LS-Dyna

Table 1: Parameters in the simulation models of the circular saw process

Tool properties (Circular saw)	**FE-Model properties (Tool)**	**Work piece properties**	**FE-Model properties (Work piece)**
Tool dimensions (DxW): 200x3.2 [mm]	Number of Elements: 70000	Work piece dimensions (HxLxW): 10x100x20 [mm]	Number of Elements: 60000
Tool material: **Tungsten carbid (WC)**	Material model: **Rigid**	Work piece material: **Al 6061**	Material models: **Johnson Cook**
Number of teeth: 36	Element type: **Shell**		Element type: **Solid**
	Interface conditions:	Contact: **Eroding Surface to Surface**	Sliding friction coefficient: **μ = 0.1**



Process parameters:
Cutting distance: 40 [mm]
Rake/ wedge/ clearance angle (**γ**/ **β**/ **α**): 12° / 60°/ 18°
Cutting speed v_c: 3000/ 5000 [m/min]
Cutting depth: 0.03 [mm]
Cutting radius rβ : 0.02 [mm]

Fig. 5.2: Model design of the orthogonal cutting process in LS-Dyna

Table 2: Parameters in the simulation models of the orthogonal cutting process

Tool properties (Circular saw)	**FE-Model properties (Tool)**	**Work piece properties**	**FE-Model properties (Work piece)**
Tool dimensions (W): 0.3 [mm]	Number of Elements: 360000	Work piece dimensions (HxLxW): 0.13x1x0.3 [mm]	Number of Elements: 325000
Tool material: **Tungsten carbid (WC)**	Material model: **Rigid**	Work piece material: **Al 6061**	Material models: **Johnson Cook / Thermal isotropic**
	Element type: **Solid**		Element type: **Solid**
	Interface conditions:	Contact: **Eroding Surface to Surface**	Sliding friction coefficient: **μ = 0.1**

6 Simulation results

The effect of four cutting teeth impacting the work piece over the force components F_x and F_y has been plotted in figure 6.1. The simulation results show that the lowest cutting speed v_c presents as well the lowest mechanical loading conditions. Further relationships affecting the process forces are not clearly visible out of the selected time scale. However fluctuations of the process forces have been noticed. In this sense it is presumed that the contact conditions and tooth positions inside the material removal process affect the both force components. This aspect in combination with the relative coarse elements in the model and the failure method implemented condition the observed fluctuations of the forces components.

In the same way variations of the tooth feed f_z under a constant cutting speed (v_c = 5000 m/min) have been plotted in figure 6.2. The diagrams show as well that the lowest tool loading takes place when the lowest tooth feed (f_z =0.02 mm) is used. This aspect has been expected and is in good agreement with the results in other studies. This effect however cannot be clearly seen when increasing from 0.05 to 0.1 mm. It is assumed that this model deficiency could be improved with the use of finer mesh elements in the work piece. The consideration of thermal effects should also support material softening allowing lower force fluctuation on the process forces.

Since the temperature calculation was not implemented on the circular sawing models, the effect of the cutting speed for the process temperature has been shown in the orthogonal cut. The figure 6.3 shows acceptable chip formations expected from such cutting operations. The expected increase of temperature at the cutting edge of the tool with the increase of the cutting speed has been also captured by the simulations. The maximal temperature has been identified at the cutting edge in both of the presented models. There is no real increase of the temperature in the chip with the increase of the cutting speed. A validation of these calculations results in relation to real process must still take in order to optimize the simulations.

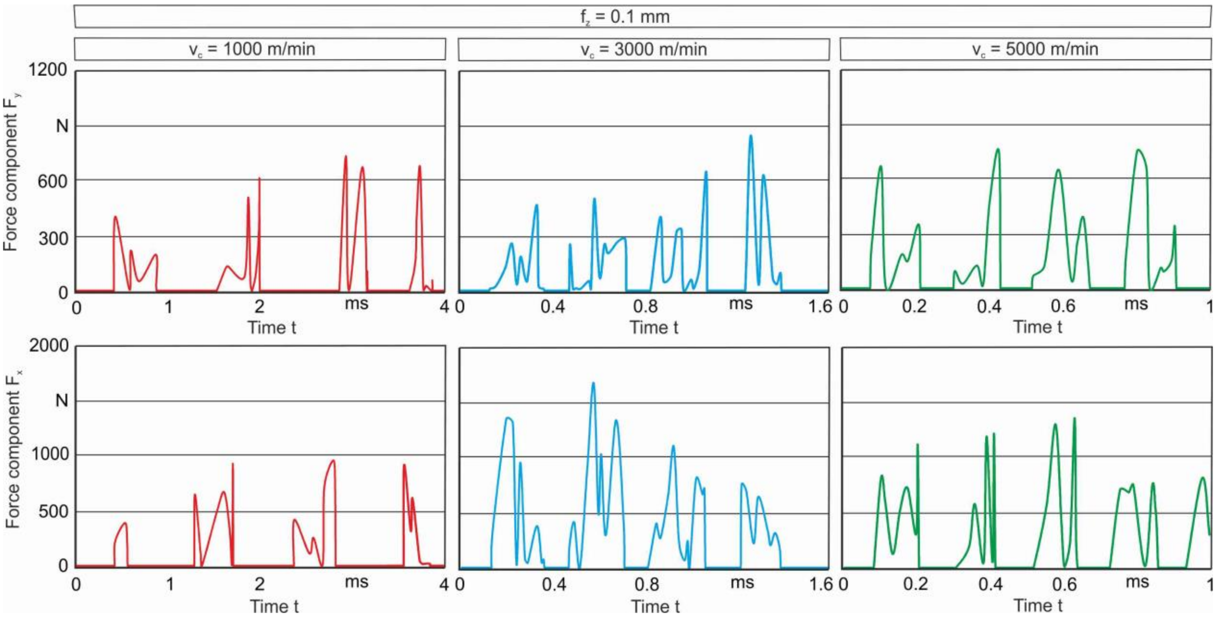


Fig. 6.1: Calculated force components of the circular sawing process on Al 6061 with variation of the cutting speed

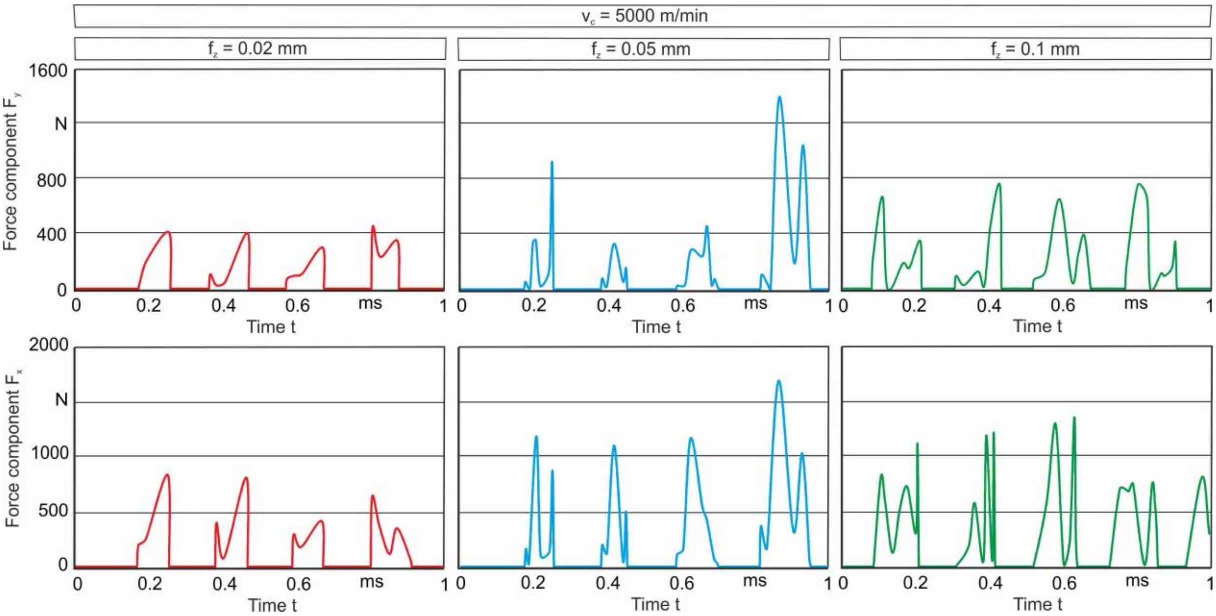


Fig. 6.2: Calculated force components of the circular sawing process of Al 6061 with variation of the cutting speed

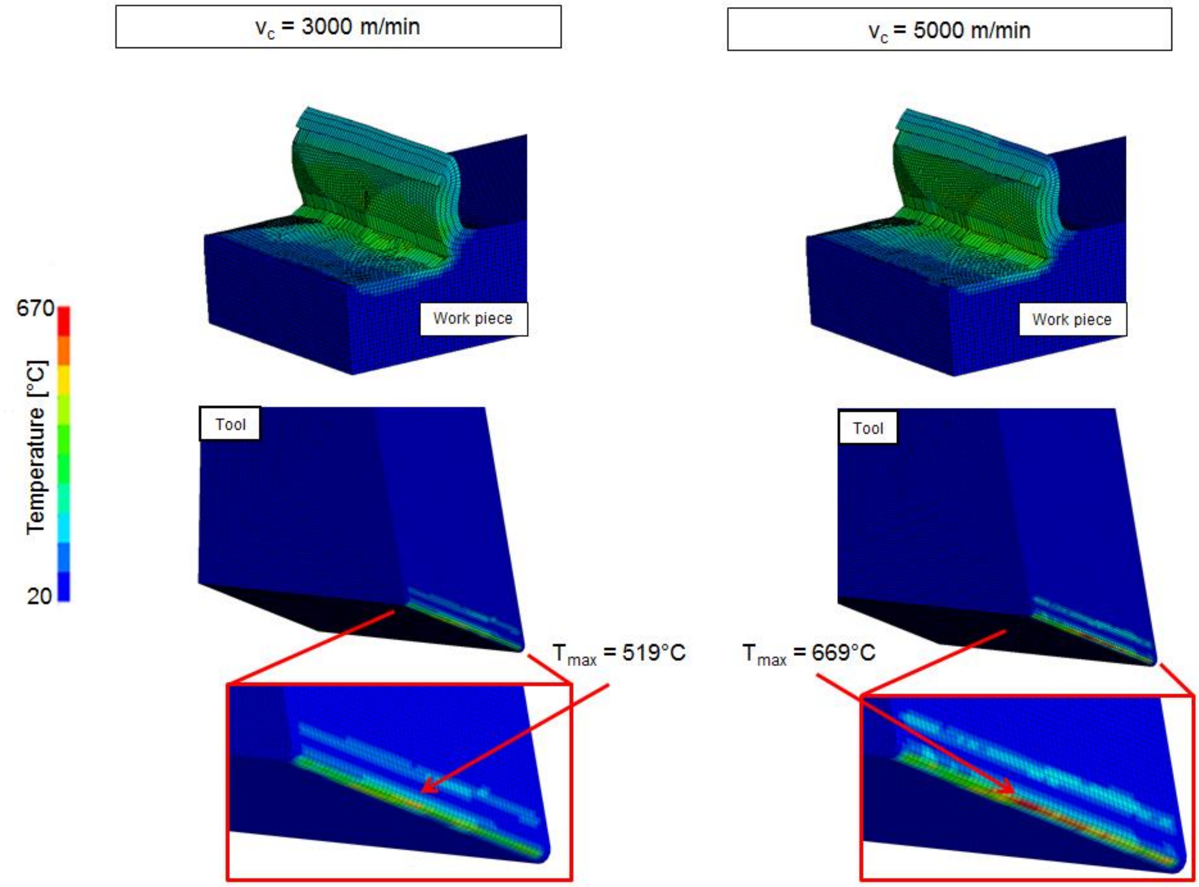


Fig. 6.3: Calculated maximal temperature in the orthogonal cutting process on Al 6061 with variation of the cutting speed

7 Conclusions and outlook

The present study has shown concepts for the FE-simulation of the circular sawing process on aluminum alloy Al 6061 with the software LS-Dyna. Some of the basic thermal and mechanical effects of machining operations have been reproduced with use of these simulation models. The further optimization of these models shall show higher accuracy on the results.

In order to show a more realistic dependence between the process temperature in the cutting zone due to variations of the cutting speed and the feed, further models should integrate circular sawing process with the thermal calculations. In the same way statements about the chip formation in dependence to these parameters can be expected, reflecting additional the thermomechanical effects out of such models. The presented process simulations aim a wide replacement of extended empirical testing during the development of cutting tools and the optimization of machining processes.

8 Literature

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