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Modelling of cutting induced surface phase transformations considering friction effects

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Abstract

Depending on machining process, machined material, cutting and tool parameters as well as the resulting heating and cooling rates the heat in cutting processes can lead to phase transformations in the work piece surface layer. This paper presents an approach to predict and analyze cutting induced phase transformations in surface layers. Therefore a 2D-FE-cutting simulation model has been developed for the steel 42CrMo4 (AISI4140). The model includes remeshing for the material separation and a material model considering short time austenization and transformation plasticity. To verify the simulations and to determine necessary input data, orthogonal turning experiments are done and furthermore a laboratory tribometer is used to measure the friction coefficient of the sliding pair between the hard metal cutting tool (WC-6Co) and the steel as a function of sliding speed and temperature.

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1. Introduction

Due to mechanical, thermal and chemical load cutting processes are responsible for the formation and characteristics of surface layers of machined work pieces. As the surface layers are the regions undergoing the highest loads during the time of use, their characteristics are determining the fields of application and the strength of work pieces. Besides thermal distortion or plastic deformation, phase

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transformations of the work piece material like white layers can be the result of the final cutting process [1]. Such phase transformations can be desired or not, in any case it has to be known if a cutting process yields to these processes and which characteristics are resulting in relation to certain boundary conditions like machining or tool parameters.

Phase transformations caused by cutting processes have been examined in research by a couple of authors with different approaches. In [2] the authors presented a list of authors who did detailed studies about phase transformations due to cutting processes. As an example of recent work, Caruso et al. presented a model to describe microstructural changes in hard turning using a hardness-based model and two empirical models [3]. Caruso’s simulation model predicts the grain size and the results were compared to data from literature. This comparison showed a good agreement and an increasing grain size with increasing cutting speed was stated. Ulutan et al. used an elastic-viscoplastic FE-model with temperature-dependent flow softening to examine the influence of friction on residual stresses resulting from the machining process [4]. The authors divided the cutting edge in regions with different friction conditions and determined friction coefficients according to these regions. With the use of this friction model the work piece surface integrity in 2D cutting simulations was calculated considering the resulting residual stresses. D’Urso et al examined the strain hardening of the steel AISI 304 due to orthogonal cutting [5]. The strain hardening was modeled by calculating the Vickers micro hardness. The simulated hardness in relation to the distance to the work piece surface showed a good agreement to experimental results.

It can be stated the existence of a big number of different approaches in the field of modeling machining induced phase transformations. Most approaches concentrate on results like residual stresses or the hardness of the work piece material. Even when effects like white layers are examined, only the results of the actual transformations e.g. the hardness of the material could be calculated and used to develop representing models.

More and detailed is the modeling of phase transformations based on the materials time-temperature-transformation behavior. With this method it can be calculated which phases exist in which region of a work piece providing a very detailed representation of a work pieces’ microstructure. In [2] Schulze et al. introduced the approach of combining such a model, existing for the laser hardening of the heat-treatable steel AISI 4140, with a 2D-FE-cutting simulation. In this paper results obtained with this modeling approach are presented and compared to experimental results. Additionally the friction between tool and work piece has been investigated experimentally and in the cutting simulation.

2. General Approach

The model is based on a 2D-FE-model of the orthogonal cutting process [2]. It is developed with the commercial code ABAQUS/Standard and consists of a full coupled thermo-mechanical analysis and user defined subroutines to provide the simulation of phase transformations. To verify the simulations, turning experiments are done. The approach aims to get very detailed information about the processes of phase transformations due to the cutting process and therefore about the local and temporal heat production and development during the machining process. Besides plastic deformation and cutting, friction has a big influence on the heat production and the resulting surface layer in cutting processes [6]. To consider this parameter, experimental tests are done using a laboratory tribometer to measure the friction coefficient of the sliding pair between the hard metal cutting tool (WC-6Co) and the work piece (42CrMo4). With the results of these friction experiments and the cutting simulation a model for the friction in cutting is developed as a function of sliding speed and temperature.
3. Experimental Set-up

3.1. Turning experiments

The turning experiments are done on a vertical turning center of the type INDEX V100. Turning inserts out of hard metal with a TiCn+Al2O3 (+TiN) coating and a tool holder SCLCR2020K12 from Walter are used in combination with a special device to provide the adjustability of rake and clearance angle. The following Table 1 and Fig. 1 contain the tool and process parameters and the experimental set-up.

Table 1: Tool and process parameters

| Parameter | Magnitude |
|-----------|-----------|
| Rake angle $\gamma$ [°] | 5 |
| Clearance angle $\alpha$ [°] | 2 |
| Cutting speed $v_c$ [m/min] | 75; 150; 300 |
| Feed rate $f$ [mm] | 0.05; 0.1; 0.15 |
| Radius of the cutting edge $r_0$ [µm] | 30 |
| Friction coefficient $\mu$ | 0.2 |

To provide orthogonal cutting conditions, bars are grooved in a cylindrical work piece. The work piece length is 100 mm, the outer diameter 70 mm. The bars have a width of 1.5 mm and between each bar there is a gap of 2 mm. The cutting edge of the tool is placed orthogonally to the bars to cut them off of the cylindrical work piece. Until now, no quick stop is used for the cutting experiments to get rid of the influence of the decreasing feed at the end of the turning process. This will be very important when the work pieces’ surface layers are examined. For the results presented in this paper, the experiments are only used to compare cutting forces and temperatures with results calculated in the FE-simulations. In the next step when the simulation of representative surfaces and their microstructure will be done, quick stop experiments will be conducted.

During the turning experiments the cutting forces and temperatures are detected. To measure the cutting forces, the tool holder is fixed on a KISTLER force plate of the type 9257B, providing the detection of forces in the three directions X, Y and Z.

The temperature measurement is done using a two color pyrometer and fiber optics, leading the radiation of the cutting zone to the pyrometer. Micro electrical discharge machining is used to get holes with a diameter of 0.3 mm into the cutting inserts to introduce the fiber optics.

3.2. Tribometer experiments

The friction coefficient of the WC-6Co/steel tribo couple, which is a necessary input data for the simulations, is measured as a function of sliding speed and temperature using a laboratory tribometer of...
the type PLINT TE92HS. The ball-on-disc tests are run under unlubricated, unidirectional sliding conditions with a normal load of 60 N in laboratory atmosphere with a relative humidity of 50%. There are carried out two different types of experiments: (a) tests, which run for 300 s at constant sliding speeds of 1.25, 2.5 and 5.0 m/s and (b) load cycle tests with a sliding speed increasing from 0 m/s to 5 m/s within 5 s (Fig. 2). The WC-6Co balls (d = 15 mm) are used with the as delivered polished surfaces whereas the 42CrMo4 steel discs are ground in a way so that the scratch marks are perpendicular to the sliding direction during the tribological tests. During the experiments normal load, sliding speed, friction coefficient as well as the temperature of the steel disc and the hard metal ball are continuously measured and recorded. Furthermore the worn surfaces are examined with a scanning electron microscope after the tests.

![Diagram of tribological model system and test parameters for load cycle tests](image1)

**Fig. 2** Schematic description of the tribological model system and test parameters for the load cycle tests

4. **FE-Cutting-Simulation**

The FE-simulation model of the cutting process was already presented in [2]. The work piece is modeled as a rectangular plane body with a length of 1000 µm and a height of 600 µm. It is moved into the X direction to get in contact with the tool and at the work piece bottom the boundary conditions in Y direction are fixed. To provide stock removal, all the rest of the work piece body can move in X and Y direction. The work piece and the tool both are meshed with 4-node bilinear displacement and temperature elements (CPE4T). The tool is defined as a rigid body and the heat transfer between the two partners is defined assuming perfect contact. Surface film conditions enable heat transfer due to radiation.

To model the disconnection of the work piece material, a self-made remeshing routine [7] has been implemented. The work piece material and the kinetics of the phase transformations are defined by a user based subroutine including the latent heat by a Taylor-Quinney-Factor. In this subroutine the austenization and the retransformation to bainite or ferrite/perlite is modeled using a modified approach of Avrami, the formation of martensite is modeled using an approach of Koistinen and Marburger. Transformation plasticity is modeled using the approach of Greenwood and Johnson [8]. In this model the austenization temperature depends on the heating rate and therefore is not described by a single temperature. The influence of strains concerning the austenization is not considered.

The calculations are done on a high performance computer.

5. **Results**

5.1. **Comparison of turning experiments and FE-cutting simulations**

The comparison of the results of the FE-cutting simulations and the turning experiments shows a good agreement concerning the qualitative development of the cutting force in relation to varied feeds and cutting speeds (Fig. 3). The forces increase with increasing feed and have decreasing tendency for
increasing cutting speeds. The simulated forces are about 20 percent lower than the measured forces. This underestimation is caused by several reasons. One reason is the chosen friction coefficient of 0.2. First simulations with a higher coefficient of 0.35 at the cutting speed \( v_c = 300 \text{ m/min} \) show a tendency to better agreement with the experimental results.

Besides deformation caused heating friction is decisive for the resulting temperatures and possible phase transformations in the cutting process. Regarding the cutting temperatures the cutting simulation showed the expected results. Fig. 4 shows the temperatures in the contact zone of tool and work piece during orthogonal cutting for the friction coefficients 0.2 (a) and 0.35 (b). With the higher coefficient the maximum temperature on the rake face amounts 740 °C, with the lower coefficient of 0.2 the maximum amounts 710 °C. Besides the maximum temperature there is also a displacement of the hottest regions around the cutting edge. The higher \( \mu \) leads to a second zone with maximum temperatures near the clearance surface which affects the maximum temperatures at the work piece surface and therefore gains importance concerning phase transformations in the surface layer of the work piece.

As a result of the high temperatures the implemented model calculates the transformation of the work piece microstructure during the cutting process. Fig. 4 (c) presents the transformation of work piece
material in the chip flowing over the hot rake face. In fact the colored region represents a zone of austenization during the cutting process. Although the transformed region is quite small it can be shown where the first transformations occur. In the further development of the simulation this transformations can also take place in the work piece itself depending on the temperature development at the cutting edge. Due to the early state of the cutting simulation with implemented phase transformation the formation of martensite cannot be presented yet. Experimental results of phase transformations due to the cutting process had been demonstrated in [2].

Results of the tribological experiments show a decreasing friction coefficient of the WC-6Co/steel sliding pair with both increasing sliding speed and temperature. The collected experimental data will used as input data for further simulations whose results will be verified by detailed metallographic examinations of the microstructural changes within the machined surfaces.

6. Discussion

It has been shown, that the presented FE-cutting simulation model shows good agreement with experimental turning experiments. The influence of the friction was shown by the resulting maximum temperatures and temperature fields. The current model is able to calculate austenization during the cutting process. Further simulations will be done to examine the transformation in the work piece surface layer considering the processes of cooling down and retransformation. Additional experiments are necessary to quantify the temperatures during the turning process and to do metallographic pictures of the machined work pieces.

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