Finite Element Modeling of High Speed Machining Processes

Arno Behrens, Bert Westhoff
Manufacturing Laboratory
University of the Federal Armed Forces, Hamburg, Germany

ABSTRACT

The Finite Element Method (FEM) can be applied on high speed machining processes to get a better understanding of the chip formation process. Furthermore, modeling such high speed cutting processes can reveal useful information which cannot be measured directly during the machining process (e.g. temperature distribution, stress over cutting edge) and which can be used to optimize tool wear as well as the entire machining process. In this paper the important aspects of a model are discussed. The procedure and requirements for establishing a high quality model for high speed milling is presented. Finally, the experimental results of an orthogonal cutting process are compared with an initial 2D FEM model.

INTRODUCTION

Over the past decades metal cutting mechanics were the subject of many research publications. The problem which is inherited with metal cutting mechanics is the highly localized chip formation process. The way the chip is formed has an decisive influence on the entire machining process. It determines the finish of the machined workpiece surface and is responsible for the cutting forces, cutting temperatures, and also tool wear. From this point of view, the chip formation is regarded as the core of the process. The formation of the chip occurs in a fairly small zone under extremely high velocity. This nature of the process makes it quite difficult to conduct precise measurements on the chip formation in order to understand and get a better understanding of the chip formation mechanism.

Therefore, attempts have often been made to describe the chip formation by either analytic or non-analytic models in order to understand the dependencies of different parameters [1]. Due to its universal capability, the Finite Element Method can be efficiently used to establish complex models to examine the chip formation process.

BENEFITS

Often the question arises what chip formation models are good for. First, these models are basically established to get a better understanding of the chip formation mechanism itself. Due to the tremendous difficulties which occur in attempting to measure temperatures, strain rates, stress distributions etc. during the process, modeling the chip formation offers new possibilities to have a closer look at it.

Second, the model reveals values that cannot be measured directly within the process. E.g. a model can deliver a temperature distribution across the chip thickness, but in an experiment the temperature can only be measured at the chip‘s outer surface.

Third, with a model the interaction of tool and chip can be examined.

Fourth, if a valid model exists, the model can be used to vary certain material or process parameters, e.g. heat conductivity or specific heat, of the workpiece and of the tool respectively. One the one hand, this may help to design materials or tools which are more suitable for machining operations, and on the other hand this procedure can be used to find new optimized tool geometries.

Also, due the complexity and the number of influences within a machining processes, it is important to notice that modeling chip formation processes has always be closely accompanied by an experimental verification. This is the only way to determine the quality of an model and to find out the critical factor of the model which have to be improved.

PROCEDURE

The objective of establishing a cutting model is actually a full 3D model of a chip formation process for milling operations such as high speed milling. Due to a lack of reliable experimental data (e.g. temperature distribution across the chip/tool interface) for those cases, the model has to be developed step by step with increasing complexity. The chosen procedure is to begin with a 2D model. This 2D model has the advantage of relatively good comparability to accurate experimental data obtained in orthogonal cutting test. In these kind of tests temperature distribution, cutting forces, contact length, chip thickness, and even stress distributions on the chip/tool interface can be measured and used for comparison with results obtained in 2D FEM simulations.

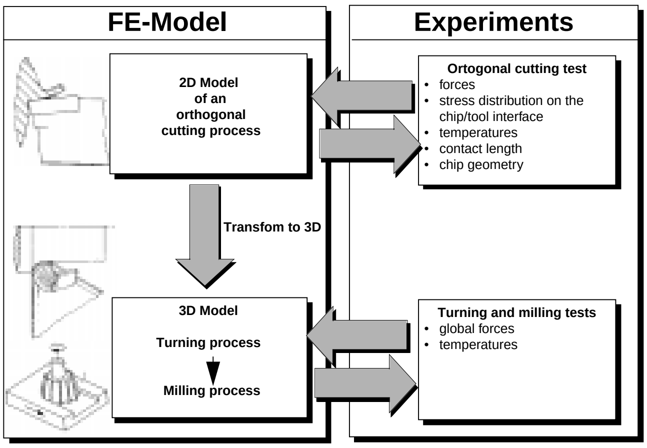

Figure 1. Procedure to establish a 3D model including continuous experimental verification

If the 2D model delivers accurate results with respect to the experiments, the next step of the procedure is the transformation of the 2D model to a 3D model. This model is first used to perform simulations of turning operations such as oblique turning actions which are also tightly related to adequate cutting tests.

In the final step (Figure 1) the model is used to simulate the chip formation of high speed milling operations.

MODEL OF AN ORTHOGONAL CUTTING PROCESS

INTRODUCTION

Figure 2 pictures schematically the different zones which have an important influence within chip formation. Zone 1 is known as the primary shear zone in which the material is subjected to a major shearing deformation. Due to high friction in the tool/chip interface the chip is also sheared in the secondary shear zone (zone 2). The material separation takes place in the area close to the tool tip (zone 3) which is supposed to be highly pressurized. The newly generated surface is also slightly sheared by the clearance face of the tool which contacts it in zone 4. Further, a general material pre-deformation is assumed in an area which is shown in Figure 2 as zone 5.

MATERIAL PROPERTIES

The properties of the workpiece material have a tremendous influence on the chip formation [9]. For example, the material's flow stress determines the range of the cutting force because the major part of the energy is used for plastic deformation within the shear zone. Therefore, these material properties have to be determined for the computer simulation. The flow stress depends on strain, stress, and temperature. We use for the initial model material data for a 0.18% carbon steel as follows [3, 4]:

$$\sigma_Y = A_0(T)\left(\frac{\dot{\varepsilon}}{1000}\right)^{0,\,0195}\varepsilon^{0,\,21} \qquad \text{Eq. 1}$$

where $A_0(T) = 1394\exp(-0,\,00118T) + \ldots$

$$\ldots + 339\exp[-0,\,0000184B^2] \qquad \text{Eq. 2}$$

with $B = T + \left(-943 + 23,\,5\ln\left(\frac{\dot{\varepsilon}}{1000}\right)\right)$ Eq. 3

ε is the engineering strain, $\dot{\varepsilon}$ the engineering strain rate, and T the absolute temperature.

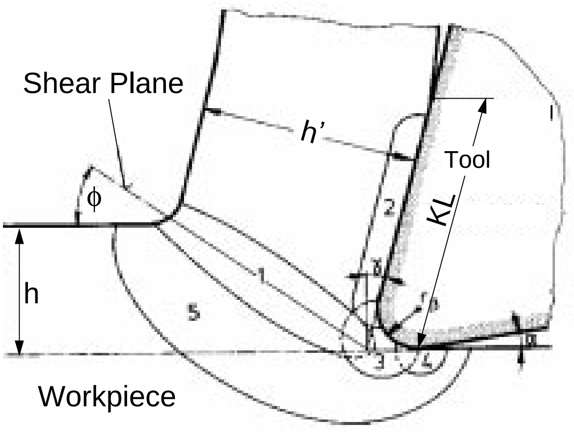

Figure 2. Section trough the cutting area and resultant chip, showing the deformation zones [2]

FRICTION

Friction in the chip/tool also has an important influence on the chip formation process. As shown in Figure 2, due to high friction the deformed material is sheared in the secondary zone. Furthermore, friction determines the contact length.

Concerning the model, it must be determined how friction in the interface is to be modeled. In this case, the shear friction model (Eq. 1) is used to describe friction due to chip/tool interaction and its shear friction factor m (τ_i is the shear friction stress in the interface, τ_Y is the shear yield stress) is seen to be constant across the interface area.

$$\tau_i = m\tau_Y \qquad \text{Eq. 4}$$

For metal cutting problems, Coulomb's friction model is not the most appropriate model as the material is highly deformed and under locally high hydrostatic pressure which would lead to an overestimated shear friction stress far beyond the local yield shear stress. Later when a good working model exists, the friction must be described in more detail by a variable friction coefficient across the tool rake face. Further, it is assumed that no coolant or lubricant is used throughout the process.

MATERIAL SEPARATION

During the machining process a new workpiece surface is generated. The generation of a new surface is one of the characteristics of the process which also needs to be part of the FEM simulation. Because FEM models are based on a finite element mesh which discretize the materials volume (in the here applied Langrange formulation), the material separation model must be closely related to the mesh.

Generally, two questions have to be answered to conduct a material separation in an FEM simulation. First, it has to be determined when the material failure occurs (separation criterion), and second, how this separation is obtained by the model. Further, it can be said that material separation in machining operations has the advantage that the tool geometry and its movement already determine the area of the workpiece where the material separates. Operations in simulations, such as finding a crack path, can be used but do not have to be used because the „crack“ path is approximately known.

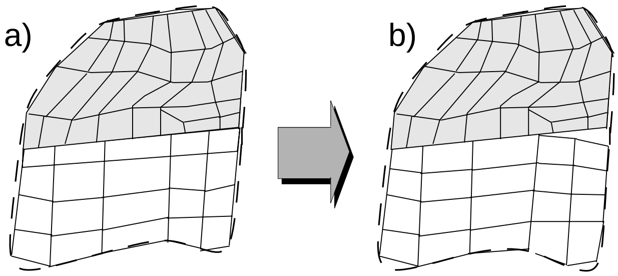

Figure 3. Contact detachment technique

There are two types of separation criteria: one group is integrated into „geometrical“ criteria, which means separation is detected based on geometric parameters (e.g. distance tool tip to mesh node), and the other group is „physical“ criteria, which are derived from physical measures such as stresses, strains, energy, etc. [5].

Furthermore, there is a variety of different methods to model the material failure in an FEM model. Techniques like element elimination [6] and node splitting [7] can be applied. Another method is a separation technique based on contact detachment [8]. Figure 3 illustrates this process: two bodies are „glued“ at the area where separation occurs. Strains, stresses, and heat fluxes can be transferred from one body to the other as long as they are glued together. Fulfilling a certain criterion, nodes are detached from the other surface. Applying this method on the orthogonal cutting process, two bodies are defined for the workpiece. One represents the chip volume removed from the workpiece, the other body is the volume which remains. The chip volume which is subjected to a severe deformation ending up with a very distorted mesh can be remeshed automatically without any major problems.

DYNAMIC EFFECTS

Dynamic effects, in this context, means the influence of forces or stresses on the process created by inertia of masses, may be also have to be taken into account. Especially in high speed machining it is possible that dynamic effects play an important role. They can increase the stress within the shear zone or chip/tool interface which might influence the process. Usually in high speed machining a smaller cutting depth is used than with conventional cutting speeds. The model allows taking dynamic effects into account so that it is possible to use FEM to conduct research on the importance of the dynamic influences.

CHIP SEGMENTATION

In a number of machining processes a chip segmentation can occur during the process. The segmentation is due to adiabatic shear bands. In these bands, a localized shear increases the temperature in the shear plane which again decreases the shear stress in the plane[10]. But, like the dynamic effects, it is not definitely clear whether they have a tremendous influence on the important process parameters such as cutting force and temperature distribution. The present model does not take chip segmentation into account yet because this segmentation is not easy to model. Basically, the same problems are present as with the material separation except that the path of the shear bands is unknown. First, it has to be determined when adiabatic shear bands exist, and second the FEM mesh has to be modified adequately. The second factor is the major problem, which is the reason that this is not implied in the current work.

HEAT TRANSFER

Heat transfer occurs in the contact area between chip and tool and at surfaces exposed to the environment. Due to the short time of the formation process, heat transfer by radiation and convection is neglected in the first assumptions. Only the heat transfer between tool and chip is taken into account with a constant heat transfer coefficient h which is needed to determine the flux $\dot{q}$:

$$\dot{q} = h(T - T_{tool}) \qquad \text{Eq. 5}$$

where T is the local chip temperate and T_{tool} represents the local tool temperature.

TOOL AND TOOL TIP

During the cutting process the tool is heated up and deflected by high stresses even if it has a higher strength than the workpiece material. For the first analysis the tool can be considered to be rigid without any deflections. Further, in the real process the tool tip contacts the workpiece‘s newly generated surface and „slides“ over it. It is also a difficult problem to describe this „sliding“ within the model. The radius of the tool tip certainly has an influence on the chip formation process as well as non-perfect tool tip geometries from tool wear.

SIMULATION RESULTS

MODEL SETUP

The setup of the model used in the analysis is shown in Figure 4. The material failure is represented by the contact detachment technique. As shown in Figure 3, a full model based on this technique consists of two bodies, the chip volume and the remaining workpiece volume which are „glued“ to each as other shown in Figure 4(i). In this analysis, the remaining volume is replaced by a straight rigid line where the chip volume is glued (Figure 4(ii)).

The rake angle γ used in the analysis is chosen to be 0° because the same rake angle is used in the experiments. The cutting depth of 0.1mm used in the experiments is the same as in the simulation. The material properties are derived from Eq. 1 to 3 for a 0.18% carbon steel [3,4] to attempt to describe material properties of the C15 steel. However, properties may vary due to different microstructures and heat treatment. The friction factor m was chosen to be 0.4 and constant across the tool face. Heat exchange between tool and chip was also taken into account in the analysis although the process is almost adiabatic. Therefore, a heat transfer coefficient of about 20,000 W/m^2K was defined which is about the same size of coefficients for hot forging processes. Tool temperature is considered to remain constant at $200^\circ C$, but as mentioned before, due to the adiabatic character of the process, this parameter does not have a decisive influence. If not otherwise described, the analysis is conducted quasi-static which means that inertia effects are neglected.

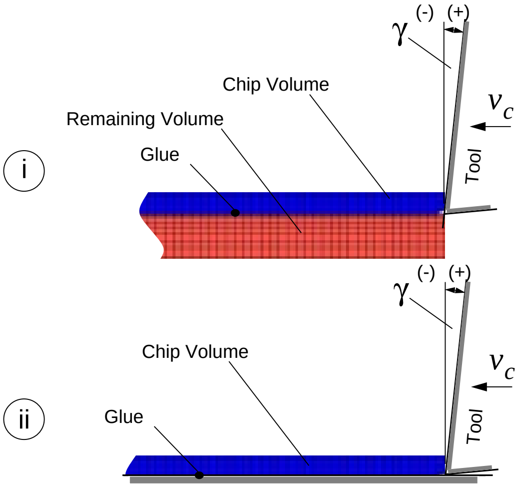

Figure 4. Model setup based on the contact detachment technique

CHIP FORMATION

A HSC analysis conducted with a cutting speed v_c of 4000 m/min was taken to compare the chip formation with experimental data. The chip geometry obtained by simulation is shown in Figure 5. The contact length KL measured in high speed orthogonal cutting tests can be compared to simulation results. The experiments showed that the contact length ranges from 0.22mm to 0.28mm which is a good correlation. Figure 6 presents the tool displacement versus the calculated cutting force per unit depth. The curve shows the beginning of the cut and a more or less constant region. The scatter-like appearance of the force results on the one hand from continuous remeshing during the process and on the other hand from contact detachments of certain nodes.

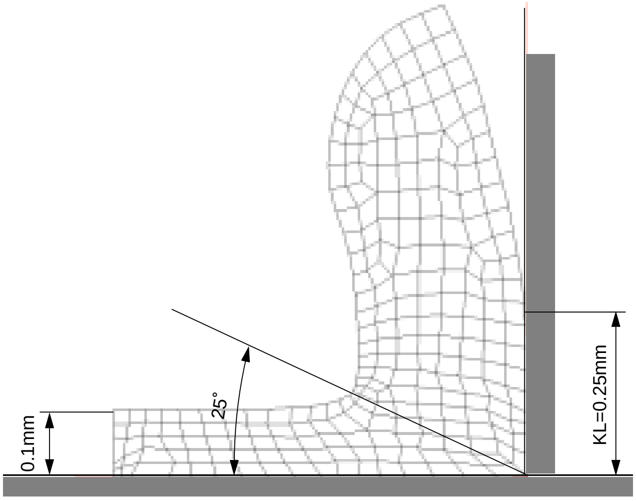

Figure 5. Calculated chip geometry at a cutting speed of 4000 m/min for a 0.18% carbon steel

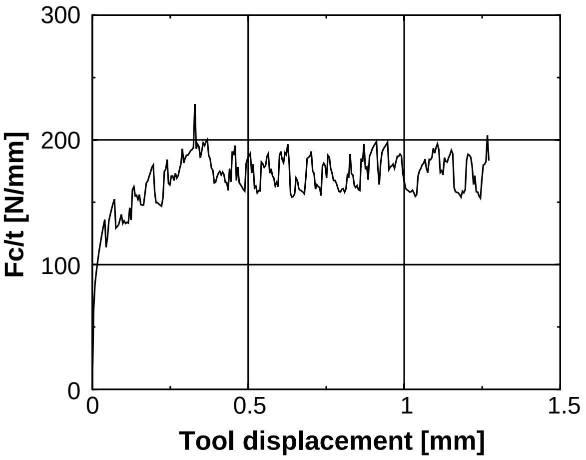

Figure 6. Tool displacement vs. cutting force at a cutting speed of 4000m/min (0,18% carbon steel)

COMPARISON TO EXPERIMENTS

In orthogonal high speed cutting experiments, cutting forces, temperatures, and the chip geometry have been measured. This data was used to compare to results of computer simulations. Figure 7 shows a microsection of the chip obtained in a quick stop test at 4000m/min. With the same scale, the outline of the simulated chip is transposed with the microsection. The result shows a good correlation with the contact length. Further, the side of the real chip that is not in contact with the tool exhibits segmentation which was not included in the model. The macroscopic formation of the calculated chip correlates well with the experimental.

As mentioned above, in the tests a cutting depth of 0.1mm was chosen. Further, the broad dimension of the cut was 2.0mm. With this data the measured cutting forces can be compared with the analysis. At a speed of 4000m/min the measured cutting forces are about 290N/mm. The forces obtained from the simulation are around 180-190N/mm (Figure 6). This great difference may result from different microstructures and heat treatments of the material. In upcoming experiments, material properties must be determined with the same material and same microstructure to overcome this difference. Further, the neglected radius of the cutting edge may also have an influence on the range of the cutting force and must be included in future models.

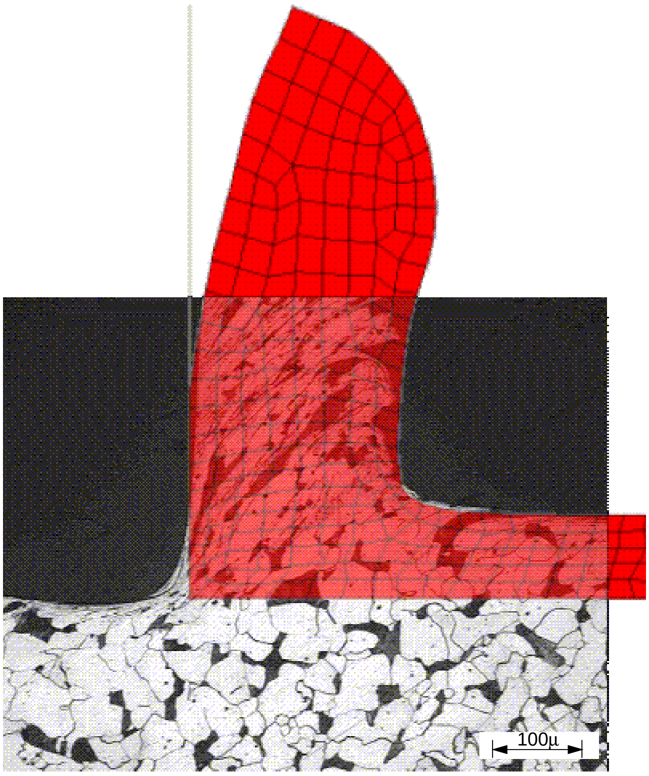

Figure 7. Comparison between simulated and real chip formation (C15 steel) at 4000 m/min. High speed cutting quick stop test were performed in cooperation with IFW, Hannover

DYNAMIC EFFECTS

To examine the influence of mass inertia effects the model was used to compare a quasi-static analysis (without inertia effects) with a dynamic analysis, taking these kinds of effects into account. The result of the comparison is shown in Figure 8 for a cutting speed at 1200m/min.The comparison shows that the rage of cutting forces seems to remain the same. The cutting forces predicted in a dynamic analysis seem to oscillate with fairly high amplitudes around the forces predicted in the quasi-static simulation. This oscillation is due to numerical problems using a rigid body within a dynamic analysis, but it shows that at that cutting speed the inertia effects seem not to influence the process tremendously.

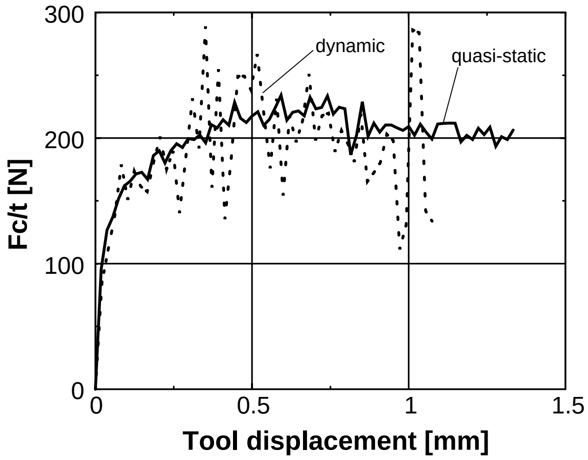

Figure 8. Cutting forces of quasi static analysis in comparison with a dynamic simulation

CONCLUSION

It has been shown that FEM models of high speed cutting processes can be quite useful for the understanding and exploration of the process itself and help finding out important dependencies. First results with an orthogonal cutting model in comparison with cutting tests show that even a simple model with a number of constraints can partly deliver reasonable results. However, the model has to be improved step by step. First, more reliable material data has to be determined to exclude effects from a mismatch of material properties. Further, the complexity of the simple 2D model has to be increased by introducing a discrete tool with a cutting edge radius. Next, the model has to be compared systematically to orthogonal cutting test to determine its quality and find out defects. Finally, the model can be transferred to a 3D model to study high speed machining processes such as milling.

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