FEA MODELING OF ORTHOGONAL CUTTING OF STEEL: A REVIEW

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Abstract

Orthogonal cutting is probably the most studied machining operation for metals. Its simulation with the Finite Element Analysis (FEA) method is of paramount academic interest. 2D models, and to a lesser extent 3D models, have been developed to predict cutting forces, chip formation, heat generation and temperature fields, residual stress distribution and tool wear. This paper first presents a brief review of scientific literature with focus on FEA modelling of the orthogonal cutting process for steels. Following, emphasis is put on the building blocks of the simulation model, such as the formulation of the mechanical problem, the material constitutive model, the friction models and damage laws.

Keywords: Finite Element Method (FEM), orthogonal turning, chip.

1 INTRODUCTION

In early work, the chip forming process was generally investigated on a merely experimental basis due to insufficient computer power and undeveloped simulation algorithms. Given the small size of the chip and possibly high speeds involved in the process, experimental observations are however difficult to perform. Computer simulations based on FEA have seen increased attention in the last two decades because they also offer the possibility to reduce the cost of experimental research. Advancements in remeshing procedures and damage models has brought the accuracy of FEA metal cutting simulations to a higher level. Amongst the most popular commercial software used at present are Abaqus^{TM} (Standard, Explicit), Deform (2D, 3D), LS-DYNA and MARC. An accurate simulation makes detailed examination of physical phenomena possible. Simulation of orthogonal cutting allows for example to evaluate the chip forming process and to predict chip shapes which are dependent on several material and process parameters. FEA based modelling and simulation of machining processes furthermore allows to predict physical parameters such as temperature and residual stress distribution, but it can also provide information regarding the integrity of the machined surface and cutting tools.

The aim of this work is to briefly review published FEA modelling studies and elaborate on their characteristic components, possibilities, restrictions and challenges. To restrict the body of literature, emphasis is put on the orthogonal cutting process and its application to steels.

2 LITERATURE SURVEY

Lo Casto et al [6] evaluated cutting temperatures in ceramic tools during turning of C40 steel based on experiments and finite element simulations.

Özel and Altan [12] predicted the flow stress of P20 mold steel at high deformation rates and temperatures, and the friction at the chip-tool interface, by matching FEA simulated values with experimentally measured cutting forces.

McClain et al. [7] analysed the normal and shear stress distributions on the rake face of a cutting tool during orthogonal machining of tool steel. Simulated distributions closely resemble split tool dynamometer measurements performed by other researchers. The shear stress distributions are consistent with results which are generally accepted in the field (plateau near the tool tip at the seized or sticking zone, followed by sharp drop off in the sliding region). The normal stress distributions also display a plateaued region of high normal stress strongly influenced by the feed distance.

Guo and Yen [4] studied the discontinuous chip forming mechanisms in hard machining of AISI4340. They concluded that the discontinuous chip is due to the internal crack initiation and extension in front of the tool and meeting with the surface crack, and that adiabatic shearing plays an important role.

Arrazola and Özel [2] performed 3D FEA modelling of precision hard turning of AISI52100 steel and investigated the effects of chamfered edge geometry. Because the complicated chip shape is difficult to predict, they presented a hybrid approach for the FEA simulations. In their approach, initially a manual remeshing stage is performed and finally an arbitrary Lagrangian-Eulerian step with Eulerian boundaries is used to reach the steady state condition.

Tawfiq and Shahab [16] investigated the effect of tool edge radius on the stress distributions at the tool rake face, cutting forces and tool-chip contact length during orthogonal machining of AISI1008. The optimum value of tool edge radius, i.e. corresponding to a minimum value of effective stress, was found to be 0.05 mm.

Umbrello et al [18] performed a sensitivity study about the influence of the constants used in the Johnson-Cook's material constitutive equation on the forces, temperatures, chip morphology and residual stresses in the machined components of AISI316L steel. The best results were found for a set of material constants which were identified through machining tests and cutting force measurements.

Özel and Zeren [11, 13, 14] used FEA modelling to investigate the influence of tool edge roundness on residual stresses, temperature and resultant surface properties for high speed machining of AISI1045 and AISI4340 steel and for Ti6AlV4. They demonstrated that ALE simulation approach (without remeshing and without using a chip separation criterion) results in better predictions for machining induced stresses.

List et al [5] studied the interface temperature and its effect on crater wear of uncoated carbide tool in high speed machining of AISI1018. An important issue of their model refers to the thermal transfer with dynamical frictional condition at the tool-chip interface. A polynomial law is used to describe the thermal softening of the maximum shear stress in the tool-workpiece interface.

Guo et Liu [3] performed a 3D finite element analysis of the hard turning of AISI52100 steels with PCBN cutting tools. They proposed an improved friction model to characterize the tool-chip interface. The sticking region instead of the sliding region on the tool-chip interface is found to be a dominant factor. It is also concluded that the ductile failure mode is a robust chip separation criterion.

Zouhar and Piska [20] studied the effects of rake angle and tool edge radius variations on cutting forces, stress, strain and temperature for AISI1045 steel. The main effect for an increase of cutting force was related to the rake angle. The higher rake angle caused higher chip thickness and higher shear angle.

3 FINITE ELEMENT ANALYSIS: LAGRANGIAN, EULERIAN AND ALE

FEA modelling requires an appropriate formulation of a mechanical problem. The general purpose software Abaqus^{TM} offers the possibility of three kinds of formulations: Lagrangian, Eulerian and Arbitrary Lagrangian-Eulerian. A brief discussion of these formulations follows and is based on [20].

In the **Lagrangian** formulation the mesh is attached to the workpiece and both deform together. There is no material flow between elements. This approach is useful for problems with moderately large deformations but relatively low distortions. Compared to the Eulerian method, the Lagrangian method is faster in calculations because the transport of material through the mesh is not calculated. However, it requires a criterion for the separation of the undeformed chip from the workpiece. For metal cutting simulations, the Lagrangian formulation is most suitable because the chip is generated from the incipient stage to a steady state form. The chip does not have to be predetermined; it is being developed during the course of the simulation of the cutting process as a function of the physical deformation process, machining parameters, and material properties. Disadvantage of the Lagrangian method is the increased time step or the stability loss when the elements are excessively distorted. In this last case, the accuracy can be improved by conducting a remeshing. These remeshing schemes are however computationally expensive.

In the **Eulerian** formulation the mesh is stationary and the material flows through the finite element mesh. The unknown material variables are calculated at preset locations as the material flows through the mesh. Distortion problems will not occur using the Eulerian approach and adaptive meshing algorithms are not necessary. It is therefore very well suited for very large deformation problems. A disadvantage of the Eulerian mesh is the high time consumption because a fine mesh is required to capture the material response. The main drawback for machining simulations is that the chip shape must be defined before the simulation. A chip separation criterion is not necessary.

A purely Lagrangian approach or a purely Eulerian approach have clear shortcomings. To combine the best features of both approaches, the **Arbitrary Lagrangian-Eulerian (ALE)** formulation has been developed. It is an extension of the Lagrangian formulation that, with additional computational steps, moves the mesh with the deformed material, modifies the mesh to preserve good quality, and remaps the solution from the old mesh into the new mesh. It is a very effective alternative for the simulation of large deformation problems.

As an illustration two geometrical models with indication of the boundary conditions for the 2D FEA of orthogonal cutting are presented in Figure 1. Plane strain conditions and ALE formulation are assumed in these models. The tools are considered as rigid bodies.

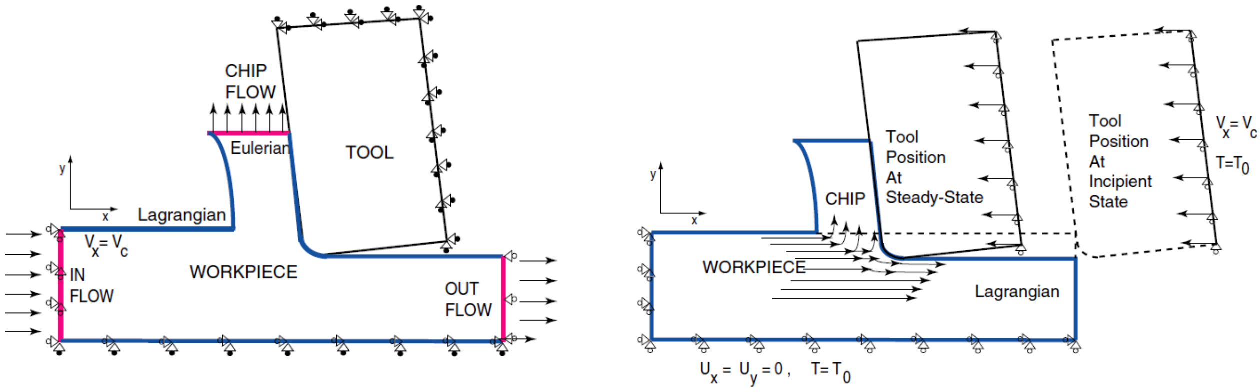

Figure 1. Finite element model for ALE formulation with: a) Eulerian and Lagrangian boundary conditions (with predefined chip) [11, 14], and b) pure Lagrangian boundary conditions [14].

Model (a) requires a predefined chip geometry. The chip surfaces are defined with Lagrangian boundary conditions and the chip upper surface is defined with an Eulerian boundary condition. Therefore, the chip flow is bound at a vertical position. However, the chip thickness and the chip-tool contact length gradually settle to their final size with the change in the deformation conditions as the cutting reaches its steady-state [11, 14]. In model (b) an ALE scheme with pure Lagrangian boundaries and kinematic penalty conditions between tool and workpiece is used. This model allows to simulate chip formation.

4 WORKPIECE MATERIAL CONSTITUTIVE MODEL

Material properties are essential inputs for an FEA simulation of a machining process. To represent the constitutive behaviour of the workpiece material under specific cutting conditions, it is necessary to have an accurate and reliable flow stress model that is capable of representing hardening, strain rate hardening and thermal softening. The Johnson-Cook material model was developed in the 1980's to study dynamic events and it is favored in problems of fast deformations and large strain, e.g. simulations of machining [20]. The model proposed by Johnson and Cook describes the equivalent flow stress, $\bar{\sigma}$, of the material as a product of strain, strain rate and temperature effects as given in Equation 1.

$$\bar{\sigma} = [A + B(\bar{\varepsilon})^n]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \quad (1)$$

In the first term of this model, the parameter *A* is the initial yield strength of the material at room temperature and a strain rate of 1/s, *B* is the hardening modulus, *n* is the work hardening exponent and $\bar{\varepsilon}$ represents the equivalent plastic strain. In the second term, *C* is the strain rate sensitivity; the strain rate $\dot{\bar{\varepsilon}}$ is normalized with a reference strain rate $\dot{\bar{\varepsilon}}_0$ (equal to 1/s). The temperature term in the Johnson-Cook model includes a thermal softening coefficient, *m*, the room temperature, T_{room}, and melting temperature, T_{melt}. The flow stress reduces to zero at a working temperature equal to the melting temperature of the work material.

The Johnson-Cook model provides a good fit for the mechanical behavior of metals, it is numerically robust and can easily be used in FEA models. In general, the parameters *A*, *B*, *C*, *n* and *m* of the model are fitted to the data obtained by several material tests conducted at low strains and strain rates and at room temperature as well as split Hopkinson pressure bar (SHPB) tests at strain rates up to 1000/s and at temperatures up to 600 °C [13]. Many researchers used the Johnson-Cook model as constitutive equation in FEA modeling of orthogonal machining (see Table 1). Remarkable differences between values cited for the same material type can be observed. These are most probably related to specific material and test conditions.

Table 1. An overview of Johnson-Cook model parameters for different steels.

Steel	Ref.	*A* (MPa)	*B* (MPa)	*n*	*C*	*m*
Tool steel	[7]	391.3	723.9	0.3067	0.1144	0.9276
AISI H13	[8]	6.54	0.89	0.15	0.014	0.113
AISI 316L	[18]	305	1161	0.61	0.01	0.517
		305	441	0.1	0.057	1.041
AISI 1018	[5]	520	269	0.282	0.0476	0.053
AISI 1035	[10]	490	600	0.21	0.015	0.6
AISI 1045	[13]	553.1	600.8	0.234	0.013	1.00
AISI 1045	[11]	451.6	819.5	0.1736	0.0000009	1.0955
AISI 4340	[9]	950.0	725.0	0.375	0.015	0.625
AISI 4340	[11,14]	792	510	0.26	0.014	1.03
AISI 4340	[15]	1150	739	0.26	0.014	1.03
AISI 52100	[2]	2482.4	1498.5	0.19	0.027	0.66

5 FRICTION MODELING

Friction on the tool-chip interface is a major input which determines the output of the FEA simulations. Key issue is the variation of tangential and normal stresses at the tool rake face. Zorev modelled the normal stresses at the tool rake face with a power law distribution, decreasing with distance to zero at the end of the tool/chip contact length (see Figure 2). He observed that two regions, a sliding and sticking region, exist simultaneously on the tool rake face when machining under dry conditions. The shear stresses are considered to be proportional to the normal stresses (Coulomb friction) at low values of normal stress (sliding region), and reach a constant maximum τ_{max} value near the tool tip (sticking region).

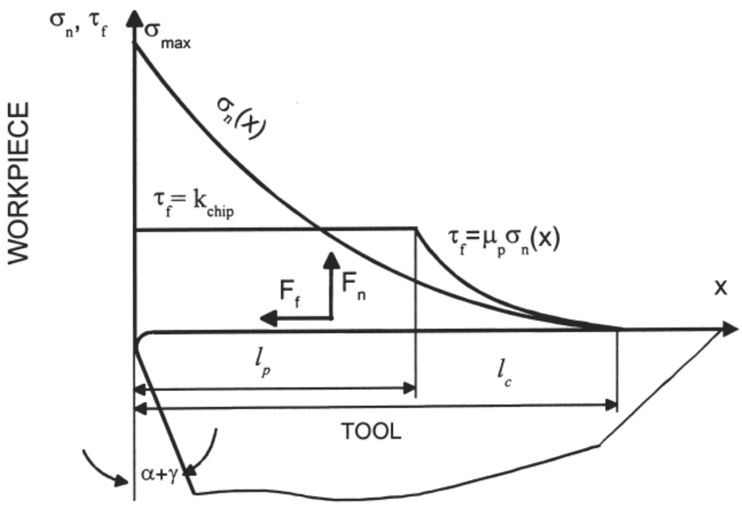

Figure 2. Normal and frictional stress distribution at the tool rake face [12].

The friction model can be mathematically expressed as:

$$\tau_f = \mu\sigma \quad when \quad \mu_p\sigma_n < \tau_{max} \tag{4}$$

$$\tau_f = \tau_{max} \quad when \quad \mu_p\sigma_n \geq \tau_{max} \tag{5}$$

where τ_f and σ_n are the tangential (or friction) stress and the normal stress on the tool-chip interface, μ_p is the friction coefficient and τ_{max} is a limit value for shear stress. The prevalent conditions at the chip-tool interface constrain the use of the empirical values of the coefficient of friction found from ordinary sliding test conditions. An estimation of the limit shear stress is $\sigma_y/\sqrt{3}$, where σ_y is the (temperature dependent) von Mises yield stress of the material [1].

Özel and Zeren [11] have made some modifications and improvements to Oxley's predictive analytical model (see Figure 3), by using orthogonal cutting experiments and an inverse solution of the model in order to determine the flow stress and friction conditions experienced in the range of high speed cutting [11, 13].

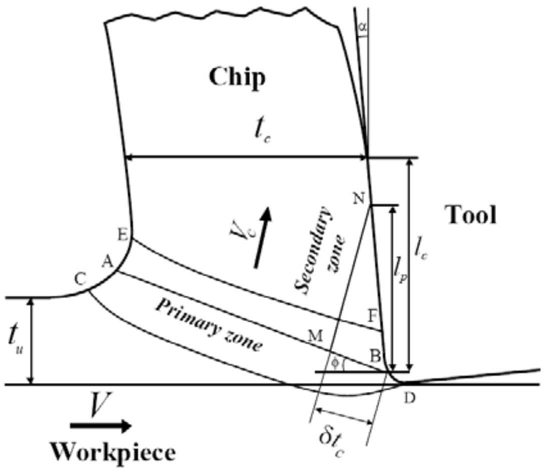

Figure 3. Parallel-sided shear zone model of Oxley [13].

6 MODELLING OF CHIP FORMATION

As discussed higher, a Lagrangian formulation requires a chip separation criterion. In a first approach, a node separation line between chip region and finished surface region is predefined (see Figure 4). For this area a condition of failure has to be created. In the study of McClain et al [7], a failure criterion based on normal and shear forces acting on the contact elements is used. The nodes connecting both regions will separate when the failure criterion is satisfied or when the distance between the tip of the tool and the connecting node is less than a specified distance criterion.

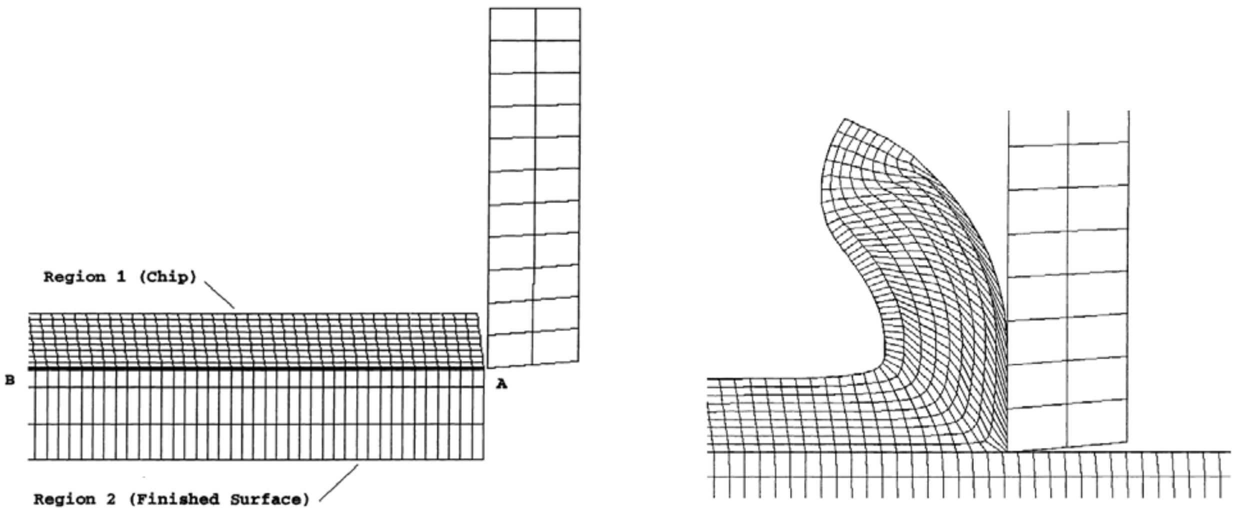

Figure 4. Left: Undeformed mesh with indication of node separation line (AB). Right: deformed mesh at steady-state cutting [7]

As a second approach, an element deletion method can be used. Ng and Aspinwall [8] simulated continuous and segmented chip formation for machining AISI H13 steel using element deletion approach. After achieving the Johnson-Cook damage criterion, failure of a mesh element is assumed to occur and the conditional link element A and B are removed from the computation (see Figure 5). This resembles the initiation or propagation of a crack. Johnson and Cook proposed a damage model (shear failure) that can be used as an integral part of the Johnson-Cook yield model. Damage is quantified as

$$D = \sum \frac{\Delta\bar{\varepsilon}}{\bar{\varepsilon}^f} \tag{2}$$

where $\Delta\bar{\varepsilon}$ is the increment of equivalent plastic strain during an integration step, and $\bar{\varepsilon}^f$ is the equivalent strain to fracture under the current conditions of stress triaxiality. Damage occurs when the damage parameter *D* is equal to or exceeds 1. According to the Johnson-Cook damage law, the general expression for the fracture strain is given by

$$\bar{\varepsilon}^f = \left(D_1 + D_2 exp D_3 \frac{\sigma_m}{\bar{\sigma}}\right)\left(1 + D_4 ln \frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\left[1 - D_5\left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \tag{3}$$

were $D_1 - D_5$ are damage parameters, σ_m is the average of the three normal stresses and $\bar{\sigma}$ is the von Mises equivalent stress [10].

A disadvantage of this method is mass deletion during solution. With large losses of material, the obtained results are suspicious.

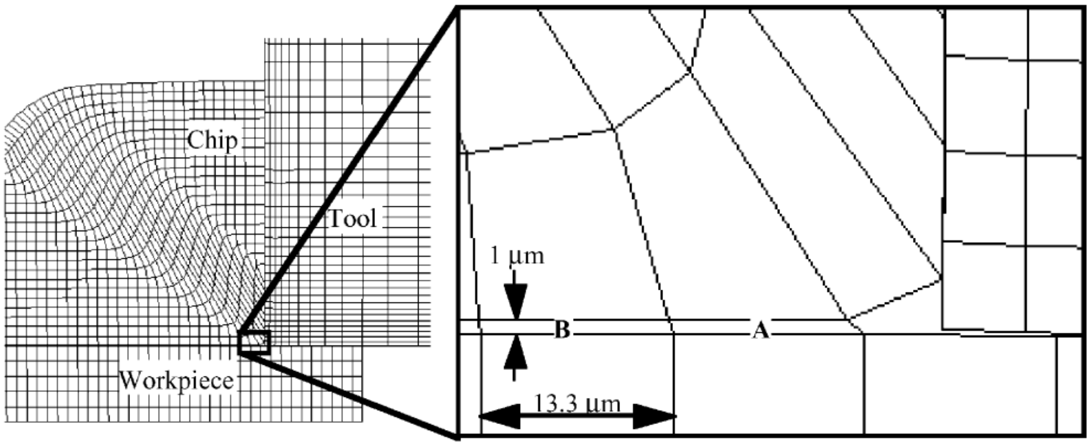

Figure 5. Link elements in the finite element model [8]

The criterion of equivalent plastic strain can be used as an alternative. It states that failure occurs when the equivalent plastic strain reaches a critical value, the equivalent strain to fracture.

Cockroft and Latham's criterion can be employed to predict the effect of tensile stress on the chip segmentation during orthogonal cutting. This criterion is expressed as:

$$\int_0^{\bar{\varepsilon}_f} \sigma_1 d\bar{\varepsilon} = D \tag{4}$$

where $\bar{\varepsilon}_f$ is the effective strain and σ_1 the maximum principal stress. When the damage parameter reaches the value one, chip segmentation starts. The element is deleted with all the parameters related to it, and subsequently the rough boundary produced by element deletion is smoothed by cutting out the considered rough angle and adding new points [17].

As a third approach, adaptive meshing can be used in an ALE formulation during crack propagation. A new mesh is created around the moving crack tip. It is critical that the parameters of adaptive meshing (intensity, frequency and sweeping) are fine tuned in order to simulate plastic over the edge of the tool. Because the chip formation is simulated via adaptive meshing, there is no need for a chip separation criterion. Özel and Zeren motivated the use of adaptive meshing criteria because they consider that the essential and desired attributes of continuum-based FEM models should be [14]:

(1) the work material model should satisfactorily represent elastic, plastic, and thermo-mechanical behaviour of the deformations observed during the machining process;

(2) the FEM model should not require chip separation criteria that highly deteriorate the physical process simulation around the tool cutting edge, especially in the presence of a dominant tool edge geometry, such as a round edge and/or a chamfered edge design;
(3) interfacial friction characteristics on the tool–chip and tool–work contacts should be modelled highly accurately in order to account for additional heat generation and stress developments due to friction. All parameters have to be obtained for the new mesh and it leads to long computation time [7,4,20].

7 HEAT TRANSFER

Heat transfer in the machining process take place primarily in the shear zone where the plastic work is converted in to heat and the chip-tool interface where frictional heat is generated. Some heat is lost to the environment through convection and some transferred to the outgoing chip and the cutting tool through conduction. Adiabatic analysis is typically used to simulate cutting processes. Adiabatic analysis assumes that no heat transfer occurs between surfaces of the workpiece, the chip, the cutting tool and the surrounding environment. The generated heat has no time to dissipate in the transient event such as a practical metal cutting process, so the energy loss to the environment can be neglected. The difference between the calculated temperature under adiabatic condition and the temperature from the actual process should be small.

8 CONCLUSIONS

The current work presented a brief review of several studies related to FEA modelling of orthogonal cutting of steels. A discussion is given on different analysis formulations such as Lagrangian, Eulerian and Arbitrary Lagrangian-Eulerian (ALE). The chip formation is simulated by assuming a predefined chip (Eulerian) or by using chip separation criteria and/or adaptive remeshing schemes (Lagrangian and ALE). The mechanical behaviour of the machined material is generally described by the Johnson-Cook model as it allows to incorporate the effects of strain hardening, strain rate hardening and temperature dependence. Friction at the tool-chip interface is described by a model that consists of a sticking and a sliding region. This overview can serve as a guide for the selection of the building blocks that are needed for the development of a proper FEA model for orthogonal turning.

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