Chapter 6
Modeling and Simulation

The use of simulations in the field of machining is generally based on the combination of numerical methods or on the algorithmic geometry with the manufacturing processes, which are dealt with in this book. Therefore, not only the input data of the simulation, but also and especially the underlying models are crucial for the value and the expressiveness of the simulation.

On the other hand, the computer aided methods offer the possibility to calculate data in many variations and in speeds and resolutions, which would be unthinkable without them. The resulting consequences are opportunities for new models, which avoid previously necessary simplifications and therefore have a considerably increased significance. It should not be forgotten however, that despite the striking and illustrative moving pictures simulations always imitate reality—based on the view of reality filtered by the models. Before a conclusion on the basis of simulation results, it is therefore necessary to examine the applicability of the used models to each situation and to verify it, if necessary, by means of real experiments. So, the target of a simulation must always be to apply and to understand a model by the systematic running through numerous variants.

When executing a simulation, one has to distinguish between the time represented by the simulation—the **simulation time**—and the time actually required for the necessary calculations—the **real time**. These times are identical only in the rarest cases. If one examines, for example, how much material in one rotation of a milling cutter with a speed of 6.000 $\min^{-1}$ is removed, the simulation time for this is a one-hundredth second, regardless of what real time has passed in the meantime.

Two essential approaches are followed in the field of simulation of machining processes, which differ in their objectives and their degrees of detailing. Geometric simulation of material removal or **kinematic simulation** determines the shape of the removed area on the workpiece in discrete time steps and from this, the particular shape of the workpiece. Modern systems of computer aided process planning *(Computer Aided Manufacturing, CAM)* often contain simple variants of such simulations to visualize and to check the planned machining processes. In addition, specialized, commercial systems are offered to provide virtual images of

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machine tools including kinematics, control and simulation of material removal. The objective of these systems is also the visualization and verification of process planning to date. In more recent times however, the determined geometric information is more frequently used to calculate technological quantities, such as process forces or temperatures.

The kinematic simulation distinguishes itself through the ability to map complex tool and workpiece shapes and is also able to model complicated movements of the components involved.

In contrast, the numerical simulation of machining processes is based on the **Finite Element Method (FEM**) or the **Molecular Dynamics (MD)**. These approaches consider the operations in a much more detailed way, but cover a much smaller time interval and a smaller geometric range because of this. At this, the calculation for a single cutting pass may take up to several days. It is obvious that the choice of an appropriate simulation approach depends on the objective of the desired research. Thus, for any kind of application one must proceed according to the principle: as detailed as necessary but with as little effort as possible.

6.1 Kinematic Simulation

Geometric models of workpiece and tool as well as the description of the performed movement are prerequisite to pattern the removal of material on the workpiece by a computer. Appropriate formats to describe the form of the involved components can be found in the area of **Computer Aided Design (CAD**). In fact, these formats are already used in the planning of the machining processes by means of CAM and are suitable as input data for the simulation. It is an obvious method to pattern the shape of a machined work piece in a simulation, to modify the existing CAD model of the workpiece in the initial state by the continuous application of geometric cutting operations with the tool and to adjust it to the progress of the machining process. Basically, this can be done through the same mechanisms used in the CAD. But in most cases it makes sense to use a customized model on the objective. Here, the simulation time is divided into intervals that are considered only approximately, but are short enough to look at the respective change precisely enough. Since only the state at the beginning and the end of the time interval is considered for the calculation, we talk about time steps or **time discretization**.

Two essential criteria for the suitability of a model for a specific application are the expected calculation time and the memory consumption. Subsequently, it is not the absolute magnitude for a concrete simulation which is important, but the performance of the model with a growing degree of detailing. Depending on the model, the necessary storage requirement may grow by eight times by decreasing the maximal error to half (doubling in each space direction) or not increase at all. The same applies to the required computation time.

Direct interactive input or the existing NC code for programming the machine can be used for the description of movements, depending on the complexity. Within the simulation this format is transformed into the resulting movement of the tool relative to the workpiece. Both the model of the workpiece as of the tool consist of points, edges, faces and bodies, each described related to a local coordinate system. For cutters, the zero point is usually set to the top, with orientation of the Z axis along the rotation axis and is called tool coordinate system. The local coordinate system of the workpiece is called workpiece coordinate system. To describe the position of a component it is sufficient to set the position and orientation of the local coordinate system (Fig. 6.1). This is done by a spatial transformation matrix that describes the image of each point or vector in the target coordinate system. To represent a movement, such a matrix is set for each time *t*.

In case the NC program for the machine tool is used as input data, a mathematical model of the machine kinematics and a replica of the machine control must be used to calculate the actual motion to calculate the transformation matrix. The task of the machine control is to implement the described movements in the real machine. To work around the thus occurring physical restrictions, it is necessary to make modifications to the trajectories. A sudden change of direction is replaced, for example, with fillets, because the acceleration of the physical machine axes is limited. In addition, a machine deviates from the ideal path because of compliances and vibrations. The investigation of these deviations is often the target of the performed simulations. The more influences have to be patterned, the higher the necessary effort. Moreover, the objective of kinematic simulation is often focused

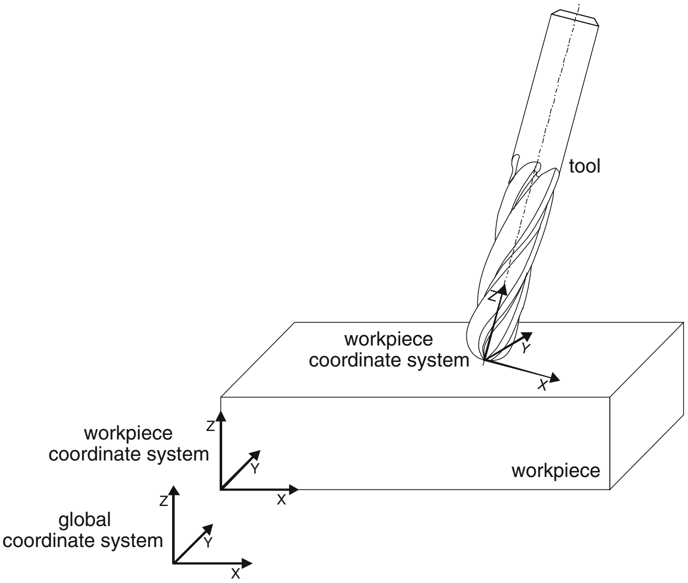


Fig. 6.1 Image of movements by transformation of the local tool coordinate system

on the use of the results in other simulations that mimic the behavior of the machine [WEI08, DEN06]. At this point, however, only the functionality of the calculations of the workpiece shape at every moment is to be described. Therefore, a given description of the motion function is assumed below.

To describe the spatial shape of tool and workpiece a suitable computer internal format is necessary, a so-called volume model. Regardless of the numerous data formats known from CAD, the methods of representation can be divided into three classes. *Volumetric models* apply small, easy-to-describe, contiguous, but not intersecting cells to combine these to a comprehensive model. In *connection models*, spatial objects such as spheres, cuboids, cylinders etc., which can be described by formulas, are combined by Boolean operations, i.e. by aggregation, penetration, or difference of the respective enclosed subset of the Cartesian space. In the *boundary representation model* (*B*–Rep), the objects are described by the enclosing and adjacent surfaces [STR06]. These can be complex parameterized surfaces as well as a large number of triangles. For the simulation of material removal, different partly specialized variants of these classes are considered, which shall be described below.

6.1.1 Representation of the Workpiece

Before commenting on the representation of the requirements of the workpiece, a look should be taken at the requirements from the user's perspective. The requirements depend—as already mentioned—on the objectives of the planned investigations. Therefore, the following questions, according to which the models need to be evaluated, must be asked before selecting a model.

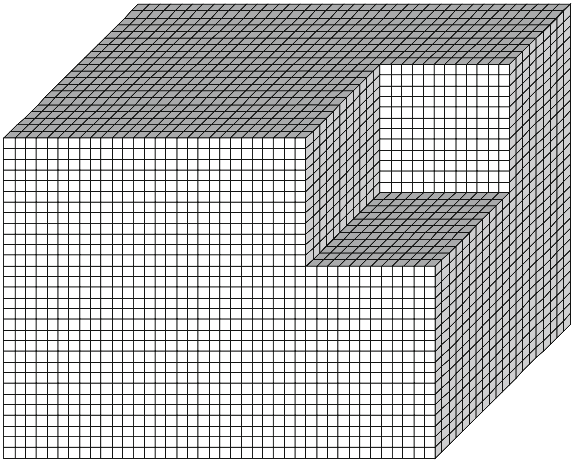
1. *What accuracy is the shape of the workpiece to be determined with*? The answer to this question influences not only the choice of the model as such—but using an approximated shape—the number of elements or the resolution of elements as well. Depending on the application, it can be sufficient to meet only a statement of the moment of contact between workpiece and tool or—on the other hand—to calculate the exact surface with high resolution. Higher accuracy typically results in a higher demand for disk space and adversely affects the speed of the simulation.
2. *Is the entire workpiece or only a detail considered*? Sometimes not the machining of the whole workpiece is of interest. Furthermore, possibly only one side of the workpiece has to be analyzed with high accuracy.
3. *What time resolution and what time interval will be investigated*? As already with the delineation of the kinematic simulation against FEM and MD, this question plays a role here as well. In general, a higher time resolution results in a longer calculation time. The memory requirement for the model does not increase, but more output data is generated.

4. *What real time has the simulation been performed in*? It is to be checked whether there are time restrictions for the duration of the calculations. This is especially the case for simulations, which run parallel to the real process to get additional information or to interfere by feedback control. In simulations for checking purposes of NC programs, it is naturally desirable to wait for the result only as shortly as possible.
5. *What kind of motion of the tool is expected and what does that mean for the generated shape?* A 3-axis milling process is limited in most cases from the outset on the surface of one side of a box. Choosing a suitable model can improve the value of the simulation or reduces the consumption of resources. The same applies to many processes that are composed of translational and rotatory movements. In particular, this can mean that the workpiece is rotationally symmetrical, at least in ideal shape, for example, in a turning or circular grinding process.
6. *How shall the resulting geometric data be further processed*? Depending on the aim of a geometrical simulation and specific processes different information shall be identified. This can be, for example, forces, temperatures, etc. The input data for the used technological calculations must be generated as simply as possible and with little losses from the simulation results. Under certain circumstances, they should be input data for other simulations. Conversely, the results of other simulations are the input data for the applied material removal model. For some applications, even a continuous exchange between different simulation systems is carried out to illustrate dynamic effects. The data exchange then heavily influences the choice of workpiece model.

6.1.1.1 Voxel Models

A *voxel model* is the simplest form of a volumetric representation of spatial objects. It is similar to bitmap formats for graphics. A discrete image of the workpiece is generated by three dimensional elements of small cuboids (building blocks) (Fig. 6.2). The blocks are called *Voxel,* an artificial word for volume element (in some references also volumetric pixel). Since a voxel has only two states, that is to say “material existing” and “no material existing”, it requires only one bit of memory. The location of a voxel is defined by the position in a three-dimensional matrix. At best, the accuracy of a voxel is given by the smallest mesh spacing and at worst by the length of the space diagonal of the voxel. As three-dimensional data fields are used, the memory requirement increases to third power, i.e. in doubling the resolution of any main direction the eightfold amount of memory is required. Thus, for a cube of 200 mm edge length and a mesh spacing of 0.1 mm a storage allocation of 1 Gigabyte is needed ($2{,}000^3$ Bit). The huge storage consumption of the voxel model can be weakened by a flexible variation of the resolution in different domains of the workpiece—for example by a so called octree structure—though this significantly increases the complexity of the calculations.

Fig. 6.2 Schematic view of a voxel model



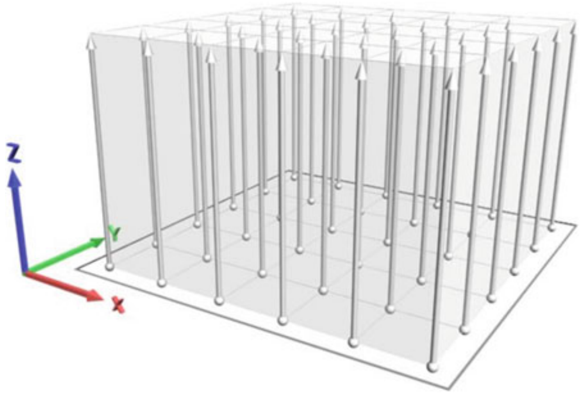
Overall, it is worth noting that voxel models are quickly applicable due to their simplicity and reach a very high computational speed at low resolutions. However, with an increasing number of voxels this procedure quickly reaches its limits.

6.1.1.2 Dexel Models

A very similar approach to the voxel model, the so called *dexel model,* represents the particular height of the top and the bottom of the workpiece on a two-dimensional matrix of equidistant, discrete X and Y positions. The resulting small rods at the matrix position are called dexel (depth element) [WEI02]. This is graphically similar to rectangular-arranged parallel pins on a board that are cut by the process (Fig. 6.3).

There is no material, so apparently not a pin for the case that the height values for both sides are identical.

Fig. 6.3 Dexel model of a block



The limitation of one dexel per position results in a constraint of the representability of any spatial object. In the direction of the dexels, no gap in the material is allowed. This can be avoided by an extension with a locally variable number of dexels, however it leads to higher memory consumption and a more complex data structure.

Compared with voxel models dexel models have the advantage that the memory requirements grow only by the second power. In addition, the accuracy in the dexel direction is much higher, because the height values can be represented with floating point accuracy instead of integer values. Any point on a surface approximately perpendicular to the direction of the pins can be very accurately determined by interpolation between the height values of adjacent grid points. But if the considered direction is on the level of the grid matrix, no higher accuracy is reached than by the voxel model. For a generally applicable material removal model it is not satisfying, if the computational accuracy relies strongly on the considered direction. This difficulty can be avoided by building up a specific dexel field for each main axis of the Cartesian workpiece coordinate system. However, this approach has the disadvantage that for further processing, for example, for visualization, three redundant data sets must be combined to a total model, a procedure which is quite elaborate.

The storage requirement of the example already used with the voxel model of a cube with 2,000 elements per direction is—implying single floating point accuracy (32 bits) in the three spatial directions—at $2{,}000^2$ elements à 192 bits, which results in 96 Mb. Even with a more complex representation of the dexel and for this magnitude of workpiece and this resolution, a considerable lower memory requirement is to be expected than with the voxel model.

6.1.1.3 Polyhedron Model

Polyhedron models belong to the group of boundary surface models, i.e. a body is completely described by its surface. In the case of the polyhedral model, this surface consists only of flat polygons (facets), covering the surface to be represented with a maximal deviation, which has to be specified in advance (Fig. 6.4). To insure a consistent function the surface has to be closed, i.e. must not have openings or gaps.

Explained descriptively, this means that the described area is “waterproof”. To achieve this, the data structure for the model is often built as a hierarchical tree of bodies, surfaces, edges and nodal points. A surface is described within this tree by references to the boundary edges. These consist of references to start and end nodes. With multiple references to common elements, the risk of gaps is reduced and the testability of consistency of the model is eased. Two adjacent surfaces, for example, reference the same edge. To simplify graphic representations and the computer operations with the described bodies a normal vector is assigned to any surface, which points out of the body.

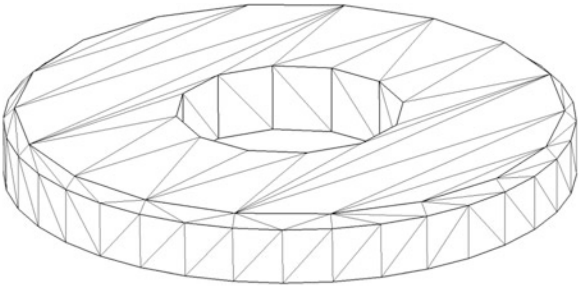


Fig. 6.4 Polyhedron model using triangles

Cut operations between bodies can be reduced in the polyhedral model to a number of cut operations between the facets of both bodies in contact. Separated by the traverses of the two surfaces of the bodies, four or more shell fragments are generated, which are joined according to the operation to the resulting body. In practical use, one often does without polyhedrons with more than three corners or sides respectively. This reduces the number of different configurations to be distinguished while intersecting. Elements with more corners can easily be decomposed into triangles.

The computational accuracy of the polyhedron model depends on the accuracy of the approximation. To carry out cutting operations it is somewhat difficult to identify two identical points as such, since identical coordinates do not exist—only two very close values because of calculation errors. This is avoided by introducing a threshold value, which defines two points below a minimal distance as being identical. However, for unfavorable configurations inconsistent data may occur, which have to be avoided either by case discrimination or corrected after subsequent review.

The computational time required for a cutting operation depends on the number of faces of the participating bodies. A doubling of the number of surfaces quadruples the number of necessary comparisons. The memory requirement is not directly predictable as is the case with the volumetric models. The example of the cube with an edge length of 200 mm can easily be represented as a polyhedron model—a cube is actually already described by the six sides with polyhedrons, namely squares. Only diagonals in the sides must be inserted for a representation with triangular surfaces. The resulting representation of the cube is in every respect mathematically correct and without errors and always requires the same memory space, regardless of the size of the cube. The more complex the shape of a workpiece, the larger the number of flats necessary. With this, a disadvantage of the polyhedron model becomes evident. By using each intersection operation with the tool normally more polyhedrons are added than removed. So the memory requirement grows with the progression of the simulation. The benefit of this approach is that locally very different accuracies can be created according to the needs in different areas of the workpiece.

6.1.1.4 CSG Models (Constraint Solid Geometry)

CSG models [WEI08] are formed by applying set operations on a basic set of simply describable spatial elements, the so called primitives, and are thus part of the link models. In contrast to the previously described models, the intersection operation is not carried out at the time of definition but the used bodies and operations are stored (Fig. 6.5). The data storage is carried out as a binary tree, whose leaves are formed by the individual primitives and its nodes by the respective set operation. In this structure, a cutting operation is very easy to add, as occurs in machining processes. In addition, the resulting shape of the workpiece is described exactly and analytically, depending on the accuracy of representation of the basic elements. During further processing, for example, for the graphical visualization or for the calculation of process variables, the tree of operations must however be analyzed again each time and converted into another model, because CSG models are only suitable for direct usage to a very limited extent. The cube, which has already been used as an example several times, creates a tree with a single node in the CSG model.

The tree grows with the number of operations. By that, the memory requirement and the calculation time grow for further evaluation. The storage of the cutting operation itself, however, can take place very quickly.

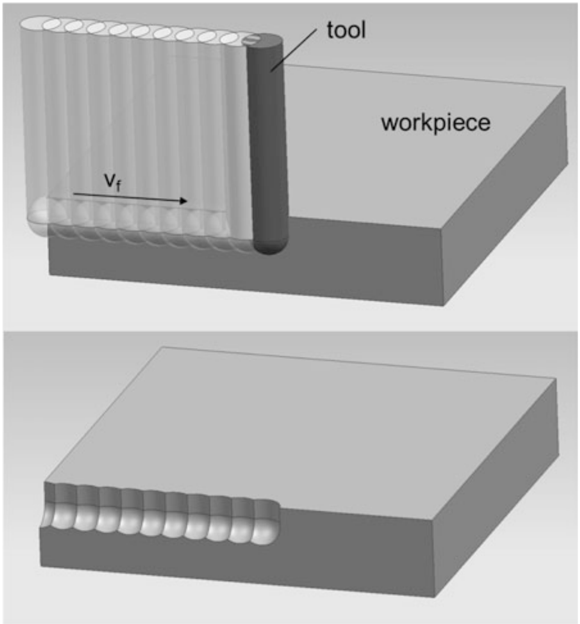


Fig. 6.5 CSG model of a ball end milling process (*upper*), resulting workpiece shape (*lower*)

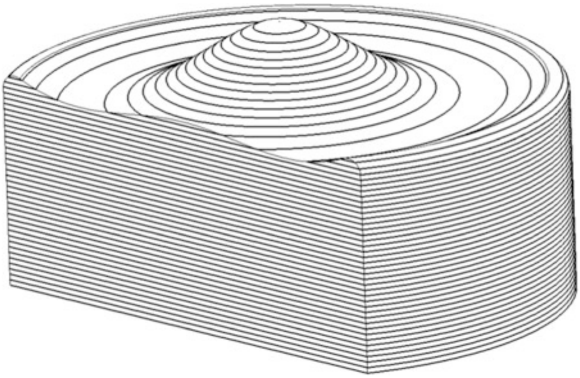


Fig. 6.6 Level curve model

6.1.1.5 Level Curve Model

Another model based on boundary representation is the *level curve model* (Fig. 6.6) [DEN07]. Similar to the depiction of landscape surveys in maps the workpiece is usually sliced with parallel planes, commonly parallel to one of the coordinate planes, and the intersection line is stored as a two-dimensional model. The intersectional line can be created either as polygon with appropriate constraint for the maximum deviation or as analytic description by parametric curves. In the case of polygonal lines one obtains a special case of a polygon model, because the nodal points of adjacent planes easily add to triangles. To intersect the represented workpiece with a tool it is sufficient to determine the section of the tool in the respective plane and to intersect the resulting section line with the respective level curve. This operation can be carried out much more easily than with the general polyhedron model since it is a two-dimensional intersection operation.

Another advantage of the level curve model is the lower effort for the reusing of the results. The volume removed during one time step is split into elements by the planes, which are limited by parallel planes in one direction, which simplifies further calculations.

6.1.2 Tool Model

Each of the described models for the workpiece is designed to be modified by a suitable model of the tool by geometric intersection operations. The model applied for the tool is not necessarily built up in the same way as the workpiece. In fact, it is of benefit to use a specific tool model, depending on the situation which is adapted on machining the workpiece model.

At this, it has to be especially observed that using a workpiece model with analytically described shape the advantage of high accuracy is nullified by discretized tool models. As a whole, it is necessary to adapt the accuracy of the tool model on the accuracy of the workpiece representation. The same applies to the choice of the temporal resolution.

Still it is often useful to make simplifications for the tool model depending on the objective of the simulation. For most applications with rotating tools it is sufficient to look at the tool body resulting from the rotation as the movement of individual cutting edges is not considered in the time steps of the simulation. Therefore, CAD models of the real tool with a detailed representation of the discrete cutting edges are not applied. Instead, the tools are often specified via the contour curve of the rotational body. A representation with seven parameters is shown in ISO3592, which most of the milling tools can be specified by [ISO3592].

Despite the reduction of the tools on their rotational body, the rotational direction and speed or the concrete shape of the cutting edges can incidentally be reconsidered for the evaluation of the results.

Regardless of the used format or the level of detail of the tool model, for the intersection of the workpiece model not the tool model at a specific moment has to be considered but the space passed through by the tool—the trace—even at very high temporal resolving discretization. Therefore, a so-called swept volume has to be created from the tool model and the data of the applied movement by a further operation. This is especially not trivial for tool motions, which are combined by translational and rotational motions. However, for many models algorithms already exist, which can produce trace volumes.

Another important consideration when choosing a suitable tool model is the convexity. In the calculation of intersections between tool and workpiece, most of the procedures consider only the visible area of the tool surface from different views and make the intersection by this tool model. If there are undercuts in the considered view, i.e. the ray in line of the view would penetrate the material more than once, the hidden domain would not be recognized. This case can occur, for example, when grinding with a profiled grinding wheel (Fig. 6.7), with cup wheels or for the detailed examination of milling processes including specific cutting edges. Not only because of this, it is important to be familiar with the functionality of the models and the respective algorithms for the design of a kinematic simulation.

6.1.3 Determination of Process Values

So far it has been described how the shape of the removed material can be determined for a predefined time interval on the basis of purely geometric considerations. The input data of the analytical methods, as described in previous chapters contain no detailed information of the shape of the removed material, but have to make generalizations. In contrast, the simulation offers the possibility to determine a representation of the actual shape of the material removed per time step. On the one hand, this requires the obtained data to be processed for further

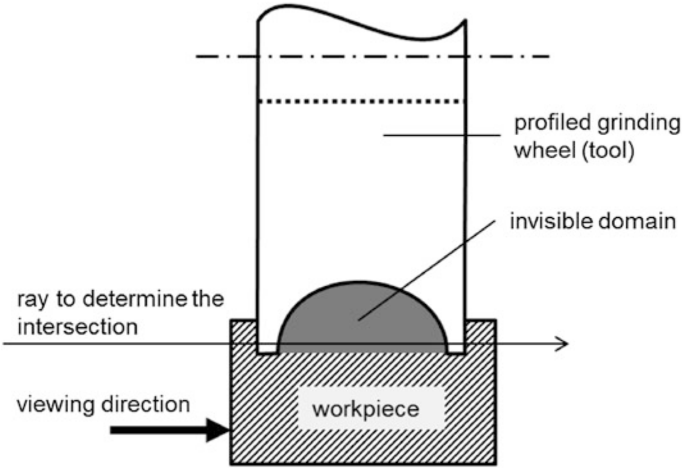


Fig. 6.7 Considering concave domains in the tool model

use and on the other hand, this offers the possibility to get a much more detailed picture of the ongoing process by integrating knowledge of other process parameters.

Some of the most important geometric input data in cutting are the cross section of the undeformed chip, the contact area between tool and workpiece and the removed volume per time unit. Especially for variable engagement conditions, the considered domain can be divided into smaller parts so as to be able to determine these values with higher precision. The different procedures for the calculation of other parameters, such as process forces, can then be applied separately, each with adapted parameters in the partial domains. As a consequence the parameters varying locally in practice such as the cutting speed, can be taken into better account.

As an example of an application to determine the shape of the undeformed chip cross section, a coupling of the calculated forces to a simulation of dynamic vibration behavior of the used machine tool shall be discussed. The objective is to simulate the stability behavior for the groove milling and to determine the influence on the workpiece surface by this effect. Due to the process force action the tool is deflected and pushed aside, which again influences the engagement of the tool and leads to varying forces. In connection with the vibration behavior of the machine dynamic effects are caused, which appear as irregularities on the surface of the workpiece.

To determine the forces under the varying engagement conditions purely analytic considerations are not sufficient. Also, a simplification of the material removal process by a mere intersection of the rotational body of the tool with the workpiece does not deliver a sufficient temporal resolution of the force course. In fact, it is necessary to include the position of the specific cutting edges of the cutter into the simulation and to compute the force course for the rotating tool. Figure 6.8

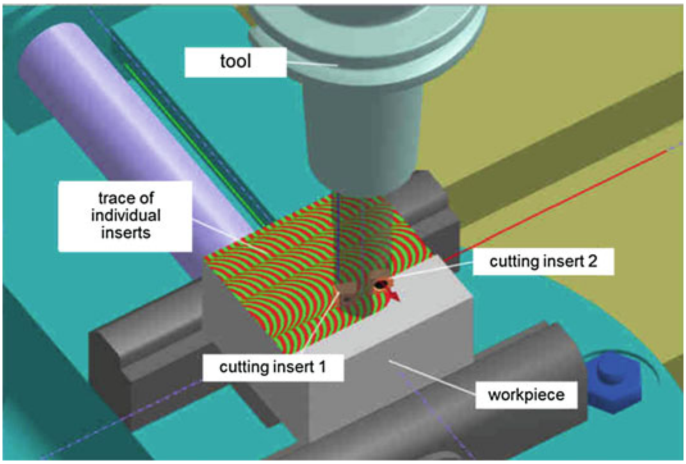


Fig. 6.8 Simulation of the material removal of single inserts in the rotating tool system

shows the material removal of two cutting edges of a torus milling cutter. The domains machined by both edges are colored differently to illustrate the areas processed by the two cutting edges.

To calculate the cutting forces for the process conditions of each time step, the geometric shape of the machined range is first determined from the used part model. It corresponds to the intersection of the trace body of the tool from the start to the end position of the current time step with the shape of the workpiece before the start time. It should be noted that each time interval contains an interval in the rotational movement of the milling cutter too. The time steps have to be taken small enough to be able to neglect the chord error resulting from building the trace body. In the application, a maximum increment of 10° of the tool rotation has proved to be suitable.

In the next step, the cross section of the undeformed chip is determined from the resulting volume element. The hereby relevant information for each particular point is the position in the reference system stretched from the milling cutter axis and the radius. Therefore, a projection of the body is taken in the space of the cylinder coordinates of these axes on the plane spanned by the radius and the tool axis.

The so resulting surface is decomposed into partial areas and for these the respective part of the force components are calculated (see Chap. 4).[1] The sum of the fractions results in the force component to be determined (Fig. 6.9).

Another application example, where less the cross section but rather the contact area between tool and workpiece plays a decisive role, is the adjustment of

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[1] In the presented example a semi empirical force model introduced by Altintas was used to determine the forces. See also [ALT00].

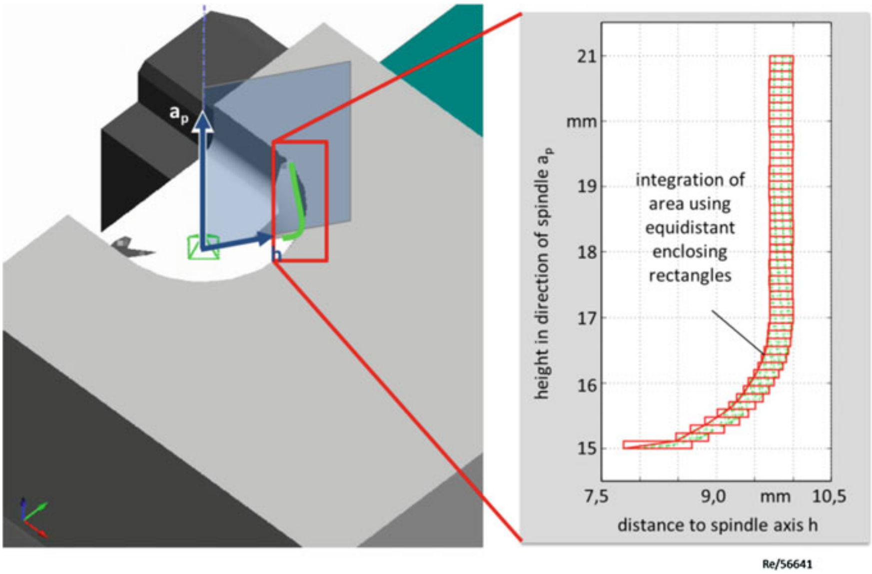
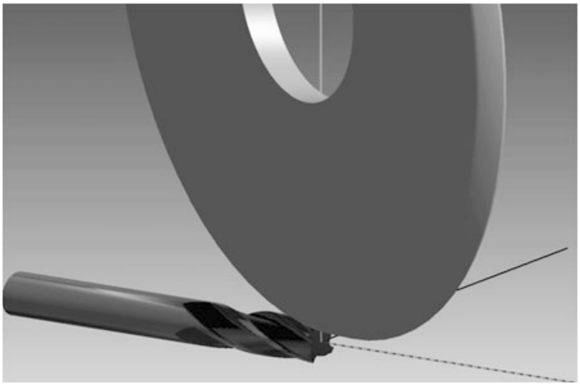


Fig. 6.9 Computation of the cutting forces by the cross section of the undeformed chip from the simulation

grinding processes for the manufacturing of milling cutters and drills of tungsten carbide [DEN08]. The flute in the workpiece—in this case the milling cutter or the drill—are produced by a profiled grinding wheel, which moves on several helix trajectories around the cylindrical workpiece (Fig. 6.10). Due to the hard material and the aimed high metal removal rate high process forces arise. This results in deviations of the set shape—as in the first example—in this case, however, by deflection of the workpiece. If the kind and size of this deflection is known, the error can be compensated by adapting the depth of the wheel.

The analytical view on geometric input values (see Sect. 12.7) ascribes grinding processes to surface grinding by transforming the individual values to

Fig. 6.10 Simulation of material removal in tool grinding



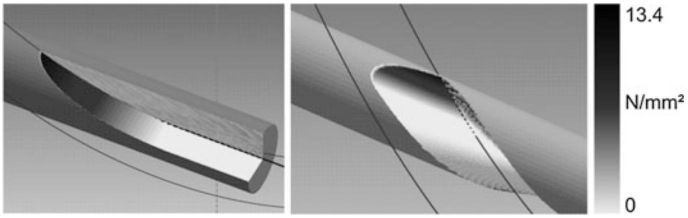


Fig. 6.11 Distribution of normal stresses on the contact area for straight (*left*) and helical flutes (*right*) determined by simulation

equivalent ones. For example, the equivalent radius r_{eq} or the equivalent chip thickness h_{eq}.

For this purpose, a generalization is made by replacing the actually locally varying values with average quantities. Since the axis of the grinding wheel is skewed against the feed direction, not only the cutting speed but also the contact length and the chip thickness vary over the contact area. Thus follows a non-uniform force distribution, which influences the deflection of the workpiece over time and position. An investigation by geometric simulation delivers the necessary data for a detailed consideration. For the evaluation the (not plane) contact area determined in the simulation is broken down into smaller fractions.

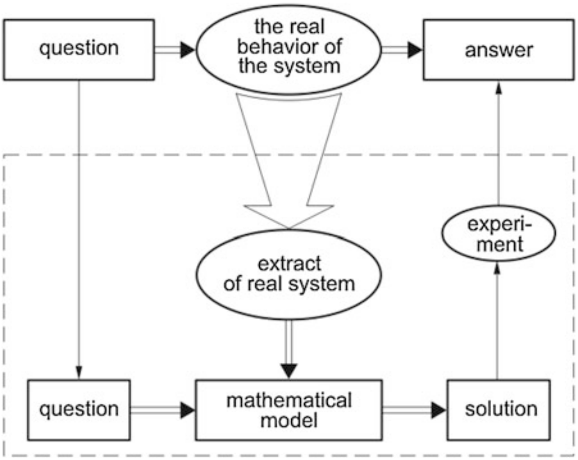
The removed volume in the specifically viewed time interval is assigned to each partial area by the calculated shape of the removed domain as determined in the first example. From this, the equivalent chip thickness h_{eq} and the equivalent chip width b_{eq} and the equivalent cross section $A_{eq} = b_{eq} \cdot h_{eq}$ can be determined respectively. These quantities are used for each partial area as input value for the calculation of the forces so as to obtain the normal stresses on the contact areas (Fig. 6.11).

With this distribution as input for a simulation of the deflection of the workpiece much more precise information about the defection can be derived. If the computation of the forces is coupled to a suitable model, dynamic effects can be patterned—similar to the first example [DEI10].

6.2 Numerical Simulation by FEM

With the upcoming of powerful computers simulations based on numerical calculations have become possible. All of them are also based on models, which represent the real behavior of the system to be analyzed only in abstractions (Fig. 6.12). However, one is more independent in the choice of the included effects—subject to the effort—than using the closed analytical methods. But it should be realized: these numerical simulations also have to be verified in experiments. The occasionally used term “numerical experiment” is therefore mistaken.

Fig. 6.12 General formulation of engineering tasks



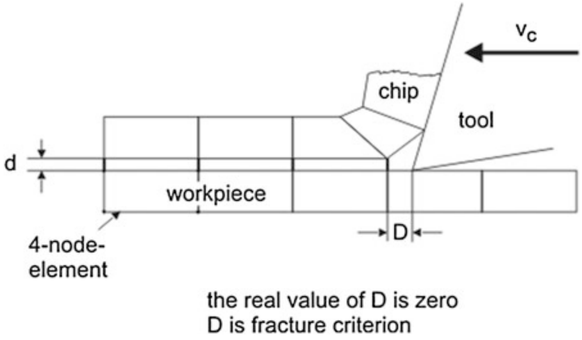
Among the numerical methods the Method of Finite Elements has been introduced in many fields of mechanics, thermodynamics and especially in continuum mechanics, as well as in the mechanics of large plastic deformations and for some years, also in cutting theory [STR90, MEI88].

FEM simulations are based on two fundamental principles, on the Lagrange- and the Euler-formulation. The Lagrange-formulation can be further distinguished into the implicit and the explicit mode. Simulations of cutting processes are run chiefly two dimensionally because of the high computing time. This approach corresponds to the orthogonal cutting.

A difficulty in the simulation of the cutting process after Lagrange is to pattern the extreme strain at the cutting edge. Two ways have been developed:.

In the implicit Lagrange's formulation (ILF), a parting line *d* is introduced (Fig. 6.13). A separation of the FE net is allowed only on this parting line. Chip and workpiece are represented by their own nets, which are connected until the actual separation by linking elements. The separation path is set as a parallel line to the workpiece surface on the height of the tool tip. Each linking element consists of two nodal points, which have the same coordinates, since the original length *d* is equal

Fig. 6.13 Presentation of the linking elements with a parting line in the ILF [ZHA94]



to zero. They have two states, the connection or the separation. These states are each subject to the distance D between the tool tip and the next element of the separation line. If D reaches a predefined value or less than that, the element is dissolved and chip and workpiece are separated. With the progression of the tool with cutting speed v_c the chip continues to be formed. The procedure of chip generation is considered purely geometrically. The influence of the cutting speed is hereby neglected. Initially, purely geometric sizes were adopted also in determining the timing of the network separation. Only later, material specific parameters (for instance maximal strain) were used as a separation criterion [LIN93].

In the explicit Lagrange's formulation (ELF), the equations of motion are integrated directly and explicitly. No global stiffness matrix is used in contrast to the implicit methods, where the FEM solution via the stiffness matrix is achieved. The stresses are directly calculated in the integration from the element stresses after each single time step. The advantage of this formulation is that no separation line has to be defined. To find the location of material separation in the model the maximal stresses are compared with a maximum value in a dedicated routine at every nodal point of the FE net—when this value is exceeded a separation by doubling the nodal points is carried out. Here, it becomes obvious that the strain energy density is a realistic criterion for the nodal point separation [MEI88].

The third possibility of simulation is a consideration according to the Euler-formulation, in which the structure to be investigated is viewed as a controlled volume. In this approach, the nodal points are stationary and not fixed to the physical material of the investigated structure. This has the advantage that the net can be intensely refined at the tool tip, where the highest stress and strain gradients occur as is necessary for a sufficient accuracy. It is important that there is no separation criterion in the Euler formulation in this method, since the stresses and velocities in the workpiece are calculated as a function of the spatial position and not as a function of the individual material particle. Given that the chip geometry in the Euler's representation is not known from the beginning and the material properties are partly dependent on the strain rate and on the changing temperature, the equations for the cutting model have to be solved iteratively [STR90] (Fig. 6.14).

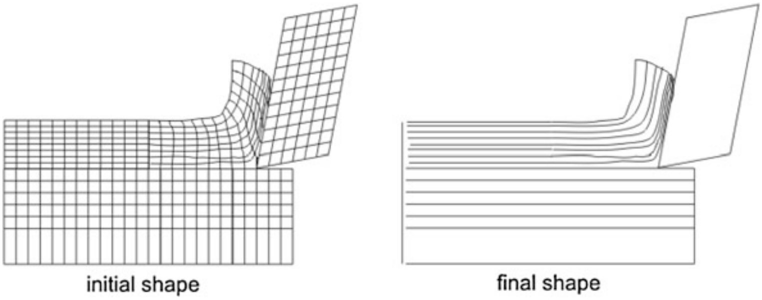


Fig. 6.14 Start and end contour of the Euler model, iteratively determined

A comparison of the different formulations shows:
Properties of the Euler formulation:

- visco-plastic flow process,
- no separation criterion necessary,
- forces and temperatures at the contact of tool-workpiece are realistically represented,
- a locally fixed net is applied, whose boundaries have to be known in advance,
- only stationary processes can be represented, i.e. no lamination or shear localizations,
- there are no extreme distortions in the cutting edge domain so that a constant computation mesh can be used.

Properties of the Lagrange formulation:

- elastic–plastic starting procedure,
- separation criterion necessary,
- at the cutting edge, extreme distortions of the net occur, which make remeshing necessary,
- chip geometry during or immediately after the chip generation results from the simulation and does not need to be provided in advance,
- transient processes can be patterned, i.e. the simulation is not limited to pure chip flow processes. This is especially interesting for shear localizations at chip compression or for the representation of segmented processes and variable cross section of undeformed chips,
- Lagrange simulations are considerably more complex than Euler computations because of the necessary remeshing and the link to material spots. However, they offer the chance to recognize material inhomogeneities in the first place, which is interesting especially in micro domains.

Most of the FE models described in literature are based on the Lagrange-formulation. Combinations of Lagrange and Euler formulations have been developed, which want to combine the advantages of both kinds of calculation [STR90].

During the FE analysis, considerable deformations of the net structure occur. Geometrically heavily distorted elements have a low quality of results and can lead to an interruption of the calculation, if the Jacobi determinant of the displacement vector becomes negative [MAR98]. Especially in the contact domain, where generally large deformations take place, state variables may adopt unrealistic values because of the element distortions. Thus, wrongly larger state variables are obtained by these analyses with a distorted net than by using repeated remeshing. Therefore, for a realistic process simulation a robust automatic remeshing procedure is essential, which generates a new net according to predefined criteria without intervention of the user.

There are several FEM programs applicable to chip building simulations. From among these, the following programs are often applied: SFTC/Deform, MSC/Superform, Thirdwave AdvantEdge and ABAQUS. SFTC/Deform and MSC/

Superform are FEM programs to solve metal forming problems. ABAQUS is a FEM program to handle structure–mechanical, thermodynamic or acoustic problems. The above mentioned programs have to be adapted to cutting simulations. Third wave AdvantEdge was specifically configured for cutting simulations. The mentioned programs are based on the Lagrange's approach. They differ in software architecture, in programming and the use of different algorithms for the remeshing of strongly distorted material domains.

A characteristic problem of the simulation of chip building, which does not exist for metal forming problems, is the material separation. It is different in Lagrange's approaches:

- either the separation takes place alongside the element edges also providing the direction of separation by precisely these edges,
- or elements are removed from the net.

The example demonstrates the application of the FEM for chip formation processes, i.e. the deformations or the chip formation kinematic. Figure 6.15 shows the snapshot of a chip root simulated by FEM. A special advantage of the FEM is that by this method it is also possible to compute stress distributions and with that contact stresses, force and power requirements, heat fluxes, temperature distributions and in appropriate modeling, also alterations of surface layers, i.e. surface integrity effects.

6.3 Molecular Dynamic Modeling

The previously mentioned considerations were made phenomenologically on isotropic and homogeneous material. In the meantime, it has become possible to handle deformation and also wear problems on molecular or atomic basis (molecular dynamics (MD), minimum potential simulation (MPT)) [IKA92]. The

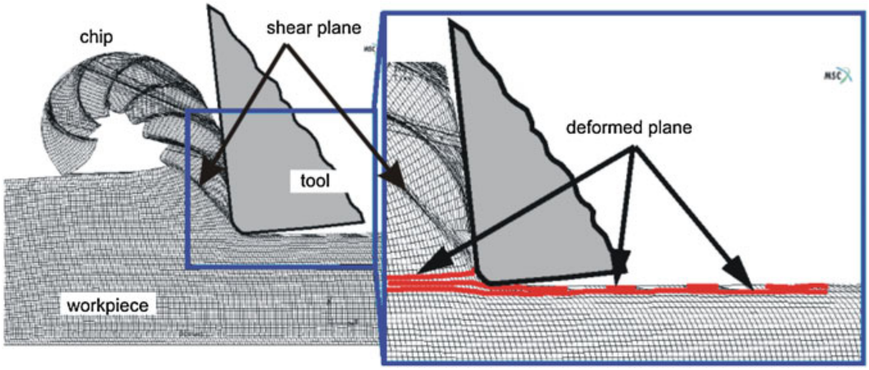


Fig. 6.15 Simulation of segmented chip formation

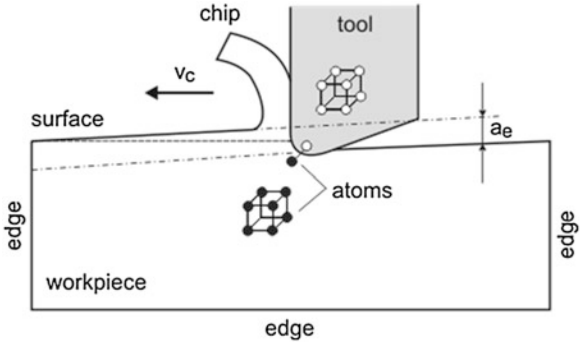


Fig. 6.16 Concept of cutting modeling by MD (acc. Rentsch)

interactions of atoms or molecules are modeled. Thus, mechanical and thermal states of an atomic lattice can be patterned.

Figure 6.16 shows the general concept of chip modeling by the MD method [REN95], Obviously, orthogonal cutting is assumed, which is indispensable for two-dimensional analyses. The material properties, the interactions between the components, the contact and interface conditions between cutting wedge, tool and chip, as well as the environmental properties have to be defined in the model. Furthermore, the boundary conditions inside the model (surface to the base material) and the system boundaries to the not-modeled surrounding are of interest. The core of the MD method is the particle-to-particle interaction. This interaction is described by the potential energy between the particles. Figure 6.17 shows the potential energy as a function of the atomic spacing and derivation for the distance. Rentsch points out that the pair function cannot represent technical metals properly. For this, models based on multi-body interactions are needed, which cannot be addressed in detail here [REN09].

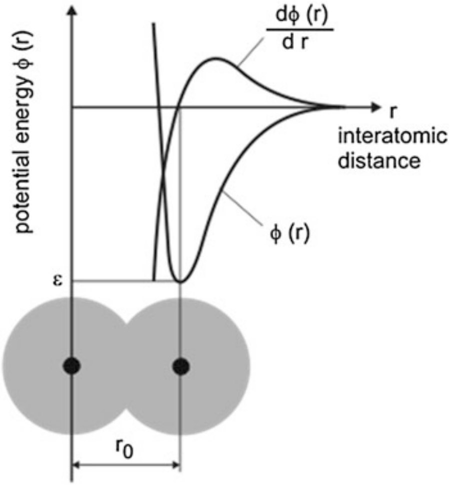


Fig. 6.17 Potential energy as function of atomic distance [REN09]

Cutting needs a relative motion between tool and workpiece, specified by the cutting speed v_c, which has to be introduced into the model. Furthermore, forces and moments introduced by the contact areas between tool and workpiece have to be supported by appropriate responses to avoid non-realistic movements of the system. Normally, the deformation process in front of the cutting edge is of interest. To limit the complexity the tool is mostly taken as rigid. In principle however, appropriate partial models can also be introduced to enable the simulation of wear caused by friction and thermal effects. Since energy is transformed into heat in the process, the temperature of the material increases. To maintain realistic conditions in the chip forming zone temperature controlling atoms are placed at the boundaries of the modeled body.

From the above it becomes obvious that these simulation calculations are very time consuming. Therefore, only limited sizes of volume or area can be modeled and simulated respectively. On the other hand, the volume must be large enough to keep artifacts negligible from the sides of the boundaries and as a consequence of elastic effects (Fig. 6.18).

However, with greater computing power this type of modeling can include the potential to pattern realistic scenarios of cutting. It is also interesting that approaches are pursued to combine MD models with FE models [HEI09]. Thereby, a part based on atomic view, considering local elastic and plastic deformations is complemented. A surrounding FE part takes care of elastic processes as it is indeed the case in the reality of cutting with a fading effect in the further surrounding of the effective point.

In any case, it was possible to show [REN09] that already today, the MD method is able to give interesting details on the deformation process in front of the cutting edge, on the thermal processes in the cutting zone and on the stress distribution in the workpiece material in micro machining in the nanometer regime of a crystalline material.

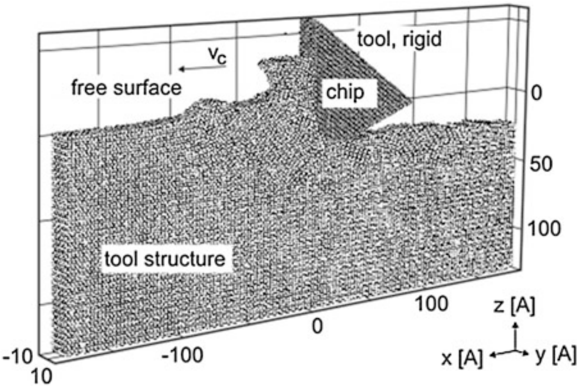


Fig. 6.18 MD simulation of orthogonal cutting according to Rentsch [REN95]

6.4 Questions

1. Explain the difference between simulation time and real time.
2. What considerations should precede the choice of models for the kinematic simulation?
3. How do the models for the representation of the workpiece differ for the simulation of the material removal?
4. Why is the adaptation of the tool model on the simulation target and the applied workpiece model important?
5. Explain the fundamental principles of the FEM.
6. What is implicit and what is explicit formulation?
7. Which principally different effects have to be considered in the FE simulation of cutting according to Lagrange compared to conventional forming processes as deep drawing or extrusion?
8. Why is a separation criterion not needed when using the Euler formulation?
9. Name typical problems of cutting which can be handled by FEM. Arrange these according to their complexity or the degree of difficulty.
10. Compare FEM and MD.
11. How is the interaction between atoms described in the MD method?

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