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AN INTUITIVE SOFTWARE SYSTEM FOR THE MODELLING OF THREE-DIMENSIONAL FEM TAPPING SIMULATIONS

Ekrem Oezkaya*, Till Haus and Dirk Biermann

Institute of Machining Technology, TU Dortmund, Dortmund 44227, Germany.

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***Corresponding Author**
Ekrem Oezkaya
Institute of Machining Technology, TU Dortmund, Dortmund 44227, Germany.

ABSTRACT

This paper presents the development of a software system, implementing user-friendly methods for creating, solving and evaluating three-dimensional tapping simulations without the necessity of large experience in the field of Finite-Element-Method (FEM) simulations. To process and solve tapping simulation models, external control of the commercial FEM software DEFORM 3D was realized, although an application programming interface does not exist. The novelty of this research study is the development of a control algorithm channel, to decouple simulation processing steps from DEFORM 3D and implement these in a developed simplified software system next to computing time reducing procedures. It could be shown that complex FEM simulations, which are typically allocated to research purposes, could be adapted for general industrial applications.

KEYWORDS: Finite Element Method (FEM); three-dimensional tapping simulation; software development; control algorithm channel; DEFORM 3D.

INTRODUCTION

The tapping process is one of the most complex cutting operations and the design of tool geometry varies widely with the experience of tool manufactures (Lorenz, 1980). Although tapping is a very common machining operation, it is one of the less comprehended cutting processes in practice till today (Armarego and Chen, 2002). A variety of different radial, axial and tangential forces occur, resulting from multiple engaging cutting edges with different forms. Tapping is an oblique cutting process and differs significantly form other machining processes such as turning, milling and drilling (Dogra et al., 2002b). The tapping process has not received much attention from research workers and the resulting torques and forces are not fully understood yet (Chen and Smith, 2011).

Step by step, material from the core drilling wall is removed by the cutting edges, until the last teeth of the tapping tool have fully cut the thread profile (Tengyun et al., 1999). The workpiece is conically formed due to the tool's angle of lead, while the cutting edges vertically move along a spiral course (Simmons et al., 2012). The tapping tool teeth following the chamfer length are used to calibrate and guide the tool in cutting direction. The geometry of the chamfer length specifies, whether the tool is usable for a certain application and influences the tool's performance (Figure 1). The occurring torque during the tapping process is generated via the chamfer length and increases due to the frictional torque of each tooth (Ahn et al., 2003). The determination of the total resulting forces, which generate the total torque, is therefore extremely difficult. Due the high complexity, the usage of simulations in the modern industry remains restrictive until today.

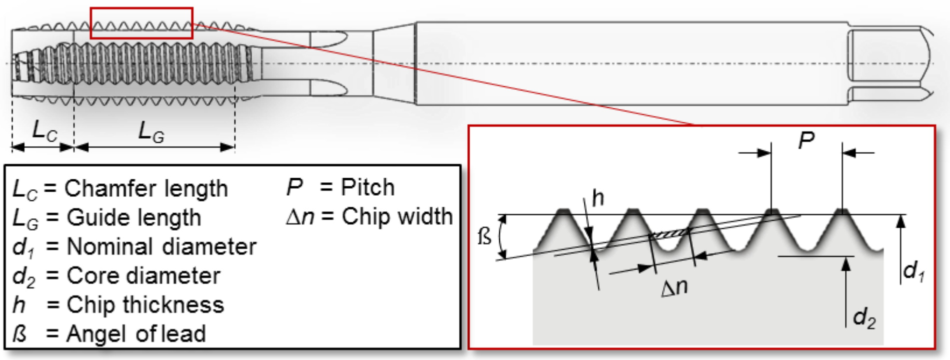


Fig. 1: Tapping tool with its geometrical properties.

In 1931, Pampel firstly systematically investigated female thread borers with flat and round thread profiles and observed, that tools with constant angles and larger core diameters have a linear dependence (Pampel, 1931). Stoewer also investigated the torque by means of an incision threading machine with three flutes and different chamfer length (Stoewer, 1932). This study found, that a higher the rake angle and a smaller number of flutes result in a higher torque, while in contrast to the tree-flute tools, the tapping tools with four flutes tended to clamping and breaking. Schröder analyzed the relation between the cutting force and the dimensions of the cross section and assumed, that the torque – provided that is a triangular threaded profile – increases in form of a parable. The findings obtained at that time were summarized by Schallbroch (Schallbroch, 1951). He showed, that the theoretical torque increases parabolically in calculations of triangular thread profiles and all the experimental measurements confirm these results, whereby the torque curve is strongly influenced by different factors. The findings of Schallbroch were extended in the nomogram by Stieber for prediction of torque (Stieber, 1955). Therefore, a tool performance evaluation could be possible as it is for turning, milling, drilling etc. for common materials and threads with a profile of 55° or 60°. Many influences such as the cutting angle, number of flutes, chamfer length, core diameter and length of the thread were unconsidered and therefore the nomogram does not have a high degree of scientific precision, but rather serves as a quick and fast overview.

Due to growing requirements, the tapping tool with pointed teeth was investigated in the chamfer length; the scientific investigation results were reported and summarized by Schmidt et al. (Schmidt et al., 1962). Additionally, Dürr reported on the geometrical system and the cutting properties of the tapping tool with pointed teeth in the chamfer length (Dürr, 1962). Based on these findings, Pietzsch dealt with the optimization of the new tool (Pietzsch, 1962). Due to the shortening of the cutting edges in the second half of the chamfer part, the load and thus also the total torque could be reduced and the chip removal improved.

Other researchers focused on the effect of force on each tooth. Thus the cutting forces were divided into cutting, feed and passive forces by Zielinski (Zielinski, 1964). According to Körsmeier, the important aspect, that the radial force is formed by the passive and the cutting force, was missed (Körsmeier, 1974). For the first time, Körsmeier investigated the geometrical relationships of tapping tools with positive and negative flutes on the thread dimensions of M12 to M30 (Körsmeier, 1974). In this way, the design angles of the cutting wedge could be calculated. A proportional relation to the static torque could also be derived and confirmed for the cutting torque. In studies of tapping tools with smaller dimensions, the boundary conditions change, so that further research is proposed. In this context, Hartkamp investigated both the formation of built-up edges and the influence of increased cutting speed and cooling lubricant during tapping (Hartkamp, 1977). Moreover, Hartkamp analyzed the process on the tool cutting edges and came to the solution, that the tool life can only be sensibly determined, when the interaction of material and tool has been thoroughly investigated (Hartkamp, 1978). The field tests were carried out by Mota et al. over three decades later and they noted, that the wear mechanisms are mainly caused by adhesion and abrasion (Mota et al., 2013). Armarego used his developed model called Unified Generalised Mechanics of Cutting Approach as a basis to get a deeper understanding of the cutting process, force and torque characteristics of straight flute machine tapping tools (Armarego and Chen, 2002). Under presupposed ideal conditions, Dogra et. al. developed a mechanistic model for calculating the cutting forces during tapping, by focusing on the process errors and borehole geometry (Dogra et al., 2002b). This model was incorporated into the methods described by Dogra et. al. (Dogra et al., 2002a). They found that the most common errors are the inconsistent adaptation of feed speed and thread pitch and that designs, which relieve the tooth flanks, increase the quality of the thread profile and the tool life. Based on this mechanistic model, Mezentsev et. al. developed a prediction model for the quality of the thread, by means of a detection and estimation method of disturbances in the tapping process (Mezentsev et al., 2002a). Mezentsev et. al. proposed a model-based method for tapping for error detection with respect to the torque and the radial forces (Mezentsev et al., 2002b). Another mechanistic model for the prediction of the torque and the axial force was developed by Cao and Sutherland (Cao and Sutherland, 2002). For the simulated prediction of the feed force and the torque during thread cutting, the general approach of Armarego (Armarego, 1998) provided the basic idea of deriving these from the orthogonal cutting data (Puzović and Kokotović, 2006). The importance and necessity of assessing the performance of the tapping process is elaborated in various literature references and is, amongst others, confirmed by the survey conducted by the the International Academy for Production Engineering (CIRP) in 1987 (Kahles, 1987). An extensive level of process understanding is required to control and optimize the various parameters of a complex manufacturing process, which has not yet been achieved in tapping.

Although the FEM simulation is nowadays commonly applied to analyze and improve manufacturing processes by evaluating occurring forces, torques and temperatures, its usage remains restricted for the tapping process. Due to the complex tool geometry, the process cannot be described with a two-dimensional simulation model. A three-dimensional tapping simulation with commercial FEM software requires a great amount of experience in the field of FEM simulations and unreasonably large computing times, due to the complex tool geometry, since the entire chamfer length of the tapping tool has to be considered, to acquire a realistic torque value. For this reason, tool manufacturers develop new tapping tools in the conventional manner of executing numerous experimental field tests after producing according tool prototypes. In this paper, a novel developed FEM-based software system (FBS) is presented (Oezkaya, 2016), which creates the possibility to evaluate the performance of almost any tapping tool by determining and comparing relative torque values of the tapping processes. The influence of tool geometry modifications on the torque could be analyzed, so that the tapping tool could be optimized before the costly prototyping process. In this way, the number of experimental tests could be reduced, leading to decreased usage of engineering resources and development time, to sustainably support the tool construction process.

Motivation and approaches

The aim of this research study was the development of a robust software system with an according graphical user interface (GUI), suitable to create and evaluate three-dimensional tapping simulations in an intuitive way. In conventional commercial FEM software, various defining parameters, including properties for tool, workpiece, mesh, material, interactions and boundary conditions, have to be considered to create a realistic simulation model. To simplify this process, the required simulation parameters needed to be automatically provided by the FBS. The numerical solving of the simulation model is still carried out through a commercial FEM software, so that a control channel for the transfer of data between the FBS and the commercial FEM software had to be ensured.

The choice of a suitable FEM software is an important factor to ensure a high simulation quality, a large scope of analysis and correct simulation results, whereby the considered software characteristics are the available features (functions and function groups), available material models, as well as the utilized algorithms and solver techniques (Oezkaya, 2016). The most commonly used commercial FEM software codes for the simulation of metal forming are: DEFORM, Abaqus and AdvantEdge (Constantin et al., 2010; Gardner et al., 2005). Since DEFORM was especially developed to simulate complex three-dimensional forming and machining processes, this software presents a robust and potent FEM tool for this investigation (Gardner and Dornfeld, 2006; Oezel, 2009). Next to implied Lagrange calculations with iterative adaptive remeshing, the Euler-, Lagrange-, ALE and coupled Euler-Lagrange-formulation (CEL) can be used for meshing procedures. Benefits and disadvantages of DEFROM in comparison to AdvantEdge and ABAQUS are presented in (Constantin et al., 2010; Gardner et al., 2005). Due to these benefits, the new FEM-System was based on the DEFORM solver structure, although a typical application programming interface (API) to modify and execute DEFROM algorithms does not exist.

To facilitate the usage of FEM simulations within industrial applications like the tapping tool development process, the complex interactive structure of commercial FEM software needs to be simplified and automated. Since the graphical user interface (GUI) of DEFORM requires a large amount time of experience to perform the various user interaction and parameter modifications, a novel GUI was developed to realize a simplified process structure, including the automated execution of numerous DEFORM algorithms. The creation of a three-dimensional tapping simulation model was thereby implemented in an instructive way. Furthermore, the three-dimensional tapping tool and workpiece geometries, as well as the simulation results including the deformed workpiece geometry, were to be visualized within the GUI, to provide a clear illustration of the simulation process.

The lack of a typical API structure embedded within DEFORM, to easily and reproducibly execute and modify DEFORM algorithms, presented the main challenge for the development of the FBS. Typical API documentation usually includes the description of components such as class definitions, constructors, methods etc. and necessary processing steps can be retrieved by using an appropriate Dynamic Link Library (DLL). Since no comparable solution could be found within DEFORM, a control channel with specific control algorithms (CA-Channel) had to be developed (Figure 2).

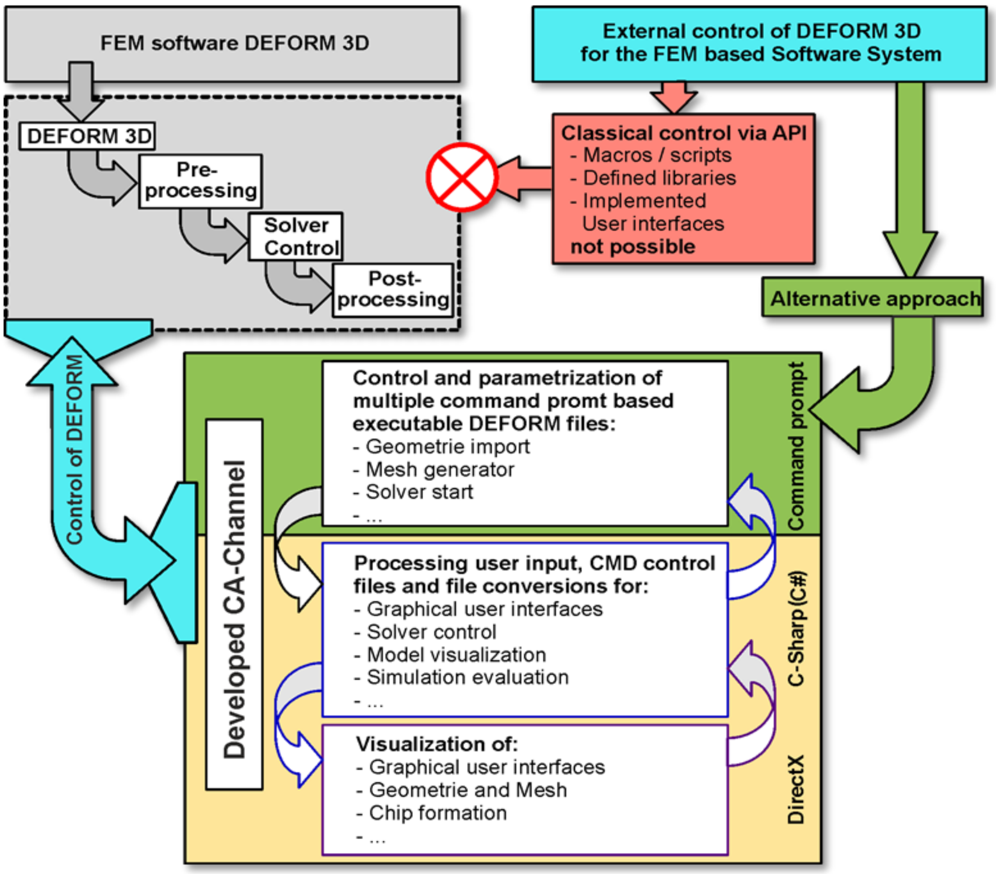


Fig. 2 Challenges and CA-Channel approach.

Another reason for the restrictive usage of 3D FEM simulations for the tapping process is the unacceptably high computing time due to the complex tool geometry, since the entire chamfer length of the tapping tool has to be considered to acquire a realistic torque value. To reduce the computing time of FEM machining simulations, tool and workpiece model simplifications are commonly applied, whereby symmetrical properties are used to decrease the complexity of the according geometry. Since the tapping tool consists of an asymmetrical and conical chamfer length, including various tool teeth, the entire chamfer length needs to be considered within the simulation, so that the computing time for a single tapping simulation using conventional FEM software can amount to several months. For these reasons, an innovative workpiece segmentation method (Oezkaya and Biermann, 2017), as well as a novel torque prediction method to estimate tool performance based on previous simulation results (Oezkaya and Biermann, 2018) were developed and validated in previous studies. These methods serve as the basis for the FBS, since acceptable computing times of approximately 170 h instead of the conventional 4320 h per simulation could be achieved.

Control Algorithm Channel (CA-Channel) development

To be able to implement and modify the necessary DEFORM algorithms and functions within the new FBS, a suitable alternative to the non-existing API had to be developed. It was possible to parameterize and execute several fundamental functions necessary for a three-dimensional tapping simulation, such as import of geometry, meshing procedures, database generation and solver start, decoupled from the DEFORM GUI. The according input and output data in form of text files could thereby be extracted and further processed. The developed CA-Channel is schematically illustrated in Figure 3, whereby the numerous interactions and file transfers between the separate control modules were reduced to the essential procedures.

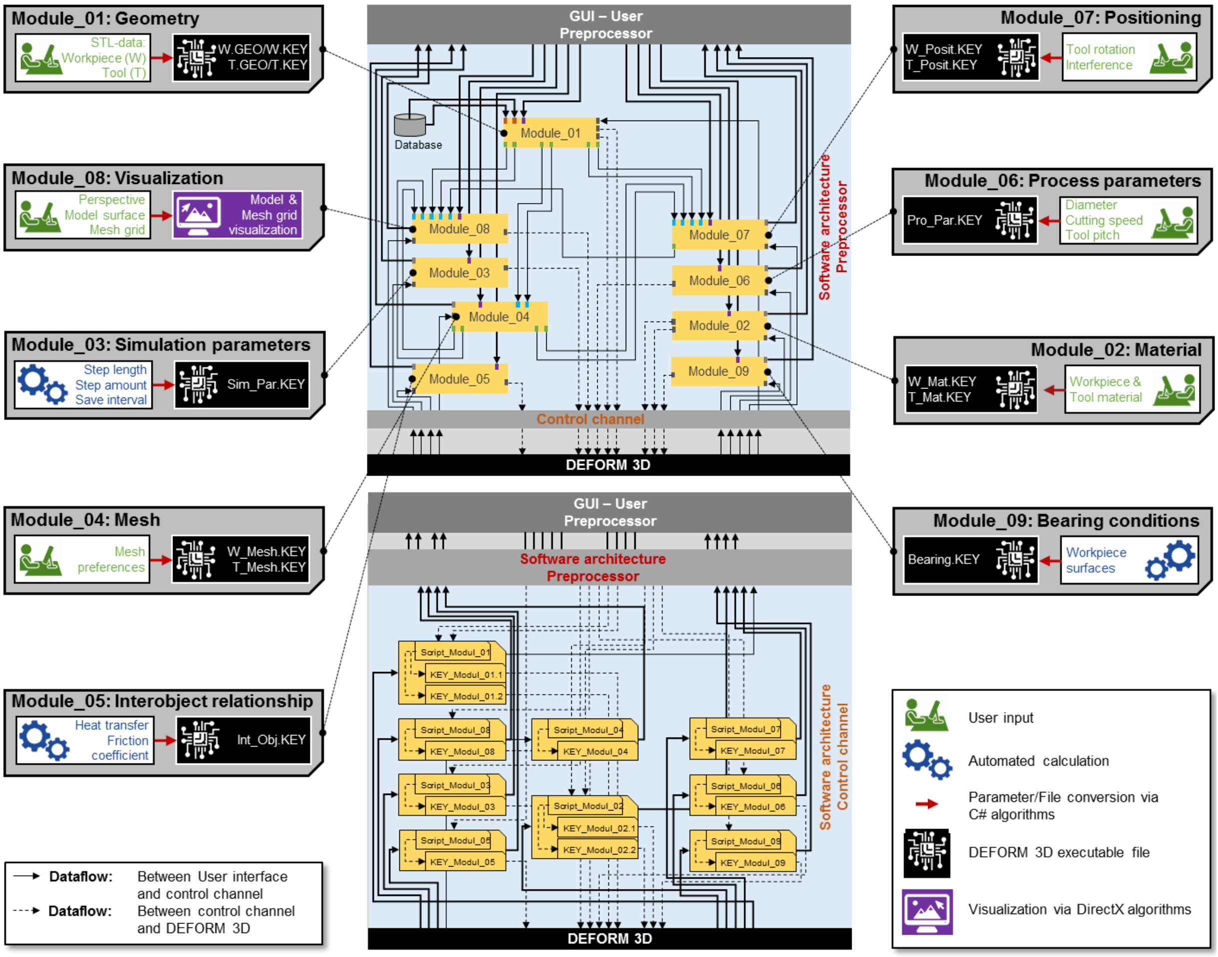


Fig. 3: Modules of the designed control channel with parameter and file interaction.

All control modules, as well as the actual software logic of the FBS were created in the programming language C#, whereby the according GUIs were implemented in the .NET platform using the object-oriented class library Windows Presentation Foundation (WPF) and programmed in Visual Studio with the declared manuscript language Extensible Application Markup Language (XAML). Moreover, the value converter Model-View-ViewModel (MVVM) was used for developing the GUIs. Due to the clear separation of competencies between the layout of the GUIs and software code, the performance of the concluding FBS was stable. Some of the developed procedures, functions, algorithms and file conversions are further described in the following passages.

Controlling CMD based executable files for decoupled data processing

As in any other software, functions and algorithms are parameterized and executed through according elements in the DEFORM GUI. When specific tasks, such as importing workpiece or tool geometries or generating a simulation database, are performed within the DEFORM

GUI, according command prompt (CMD) based executable files (.EXE) are executed in the background, which can be traced through the Windows process monitor. These CMD based programs could be executed by running the according files within the DEFORM installation folder. Key-Files, which contain task-relevant information in an DEFORM internal script-based programming language, are used as input and output data for the CMD based executable programs, whereby these Key-Files are usually saved in a hidden folder within the chosen user path. Suitable routines for the according .EXE - files, including correctly defined input files, input variables and CMD commands were developed for all necessary simulation tasks, which could thereby be decoupled from the DEFORM GUI. This procedure is further elaborated for the geometry import and mesh generation in an exemplary manner.

A 3D FEM simulation is generated on the basis of suitable tool and workpiece models. These models are usually provided in CAD file formats, such as the stereo-lithography (STL) format. When STL models are imported into the DEFORM GUI, a subroutine is performed in the background, whereby the STL file is converted into the internal DEFORM geometry format (GEO). This conversation process could be decoupled from the DEFORM GUI by parameterizing the according CMD based executable file, while user, tool model and workpiece model file path were defined as input variables (Figure 4 (a)). In this way, arbitrary STL models could be converted into the DEFORM internal GEO format and used for further simulation steps.

The meshing procedure could be decoupled from the DEFORM GUI in a similar manner. The mesh parameters like minimal element edge length and element size ration are automatically calculated from process parameters defined by the user and stored in a hidden input file, which serves as an input for the CMD based executable file for meshing, in addition to the tool and workpiece geometries in the GEO format. Subsequently, an output file in the KEY format containing the mesh coordinates is generated as presented in Figure 4 (b). Instead of a cylindrical workpiece model, a 15° circular volume segment in the height of the pitch was used, so that the number of necessary mesh elements could be reduced, concluding in a computing time reduction of approximately 96%. This segmentation approach was first proposed and validated in (Oezkaya and Biermann, 2017).

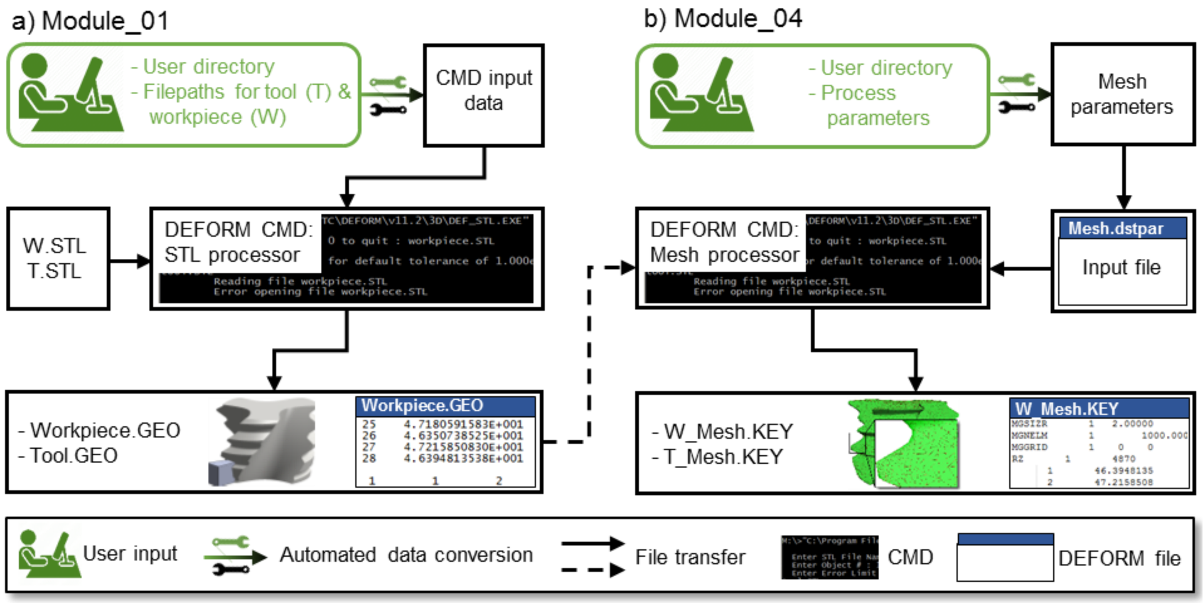


Fig. 4: Flow chart describing STL conversion [a)] and meshing procedure [b)].

The meshing procedure could be carried out with minimized user input, since the necessary mesh parameters could automatically be calculated from the tapping tool diameter and chip thickness. These described routines, as well as similar CMD procedures for all other necessary simulation tasks, were implemented within the FBS using according C# algorithms, whereby variable input file paths and parameters could be defined by the user as required.

Process and simulation parameter conversion

One of the benefits of DEFORM is the existing extensive material database. Material parameters are defined in the DEFORM internal script-based programming language within a dedicated Key-File for each accounted material, which is exemplary illustrated for the tool material tungsten carbide in Figure 5 (a). The script-based commands, containing the task-relevant information within the Key-Files, are referred to as Key-Words and are documented in the DEFORM user manual. From the developed FBS, the user could choose a tool and workpiece material, whereby the according Key-Files would then automatically be selected, modified into the correct format and used for further processing.

In a similar manner, process and simulation parameters like cutting speed, rotational speed or simulation time steps could be defined as Key-Words and stored within a generated Key-File. Therefore, suitable functions had to be developed for each relevant process and simulation parameter, to convert the parameter into an according Key-Word, which could later be processed by the DEFORM solver (Fig. 5 (b)). These conversion functions were implemented within the FBS using according C# algorithms to transform the process and simulation parameters specified by the user into DEFORM Key-Data.

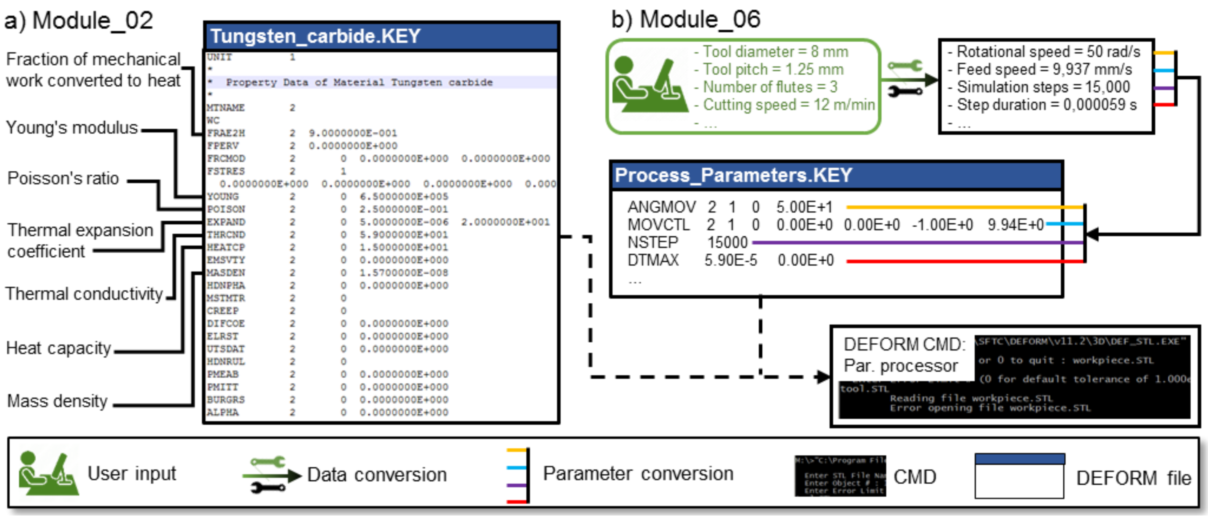


Fig. 5: Exemplary material Key-File [a)] and parameter conversion procedure [b)].

Automated model positioning and fixed support conditions

To ensure correct simulation starting conditions, the tool needs to be positioned in a suitable engagement situation, while correctly defined support conditions are required for the workpiece model. The horizontal tool positioning could be carried out by defining a congruent axis within the tool and workpiece model. The DEFORM internal intersection method was used to position the tool vertically, by executing the CMD procedure decoupled from the GUI in the described manner.

The selection of surfaces and subsequent definition of fixed support conditions is typically carried out through mouse interactions within the DEFORM GUI. Since these mouse interactions cannot be performed without opening the DEFORM GUI, a workaround was developed for the FBS. A distance function in dependence to the workpiece diameter was developed to select all mesh nodes of the outer workpiece surface, as well as the bottom workpiece surface and parameterized with C# algorithms (Figure 6). These surfaces could then be defined as fixed supports by defining the velocity of the according mesh nodes as zero in all three Cartesian coordinate directions. The mesh nodes fulfilling the distance criteria could subsequently be stored in a new Key-File with according fixed support definitions, using suitable parameter modification and conversion.

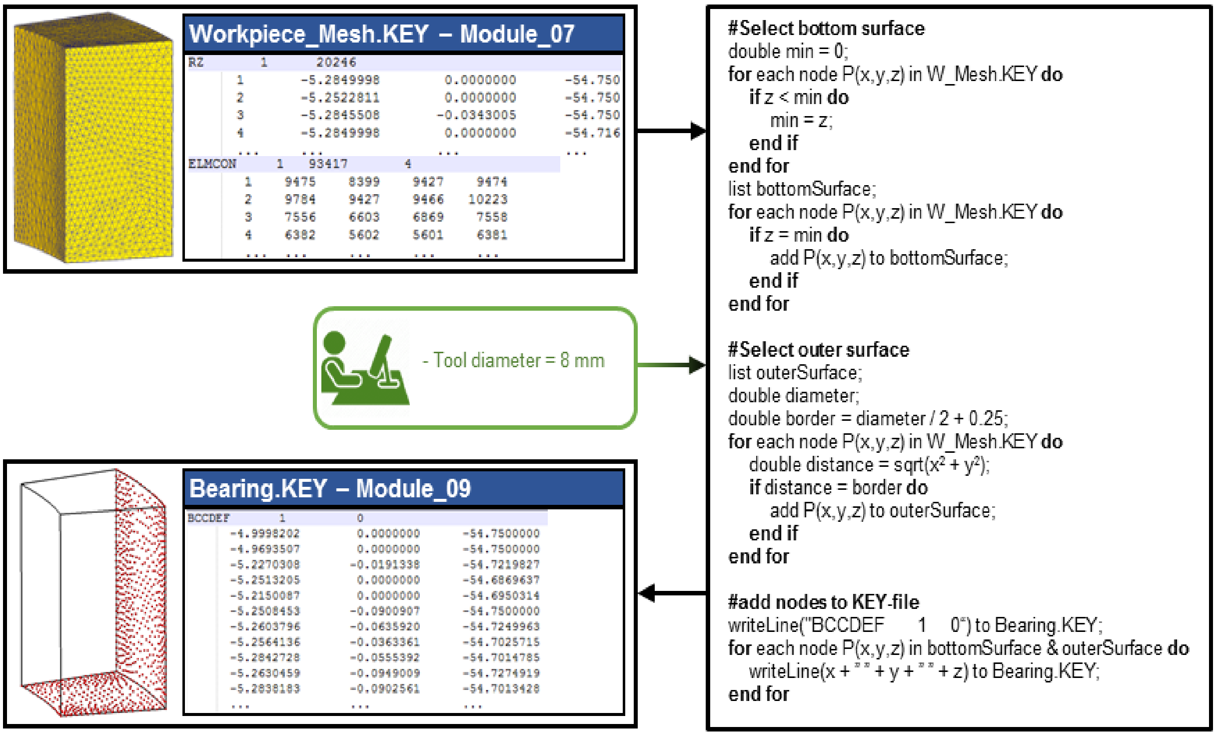


Fig. 6: Fixed support conditions through surface selection with illustrative C# code.

Solver options and simulation evaluation

The Key-Data resulting from the execution of the above described functions and routines could be combined into a coherent DEFORM database with an according CMD based executable program, whereby the various Key-Files could be imported and processed. Subsequently, the simulation could be started with a CMD command addressing the DEFORM solver module. All CMD functions, including the database generation as well as the simulation calculations are performed in the background, without further required user interactions. During the numerical calculations of the solver module, the simulation status could be monitored through a log file, which is created and updated by the DEFORM solver module. During the simulation, the calculated simulation steps, including information about occurring forces, stresses, deformations and temperatures are continuously added to the generated database located inside of the chosen user directory. The assessment of the simulation results could in conclusion be carried out in the Postprocessor of the FBS.

Model visualization

To visualize the tool and workpiece geometry and mesh nodes during simulation preparation, as well as the chip formation for simulation evaluation, several DirectX based algorithms were utilized to create a three-dimensional graphical illustration of the desired elements. Conversion procedures to transform geometry and mesh data from the DEFORM GEO and

Key format into a file format displayable by standard DirectX modules were developed and implemented in the FBS.

The DEFORM geometry file format (GEO) is quite similar to the Wavefront geometry definition file format (OBJ), which is generally supported by 3D graphics applications. In this case, the open source 3D library Helix Toolkit was used, since it supports the visualization of models in the OBJ format. Thereby, each vertex is defined with three according coordinates in a line starting with the letter *v*, while triangular face elements can subsequently be defined by referring to the indexes of three vertices in a line starting with the letter *f*. The three-dimensional tool and workpiece model could be converted from the standard STL format into the DEFORM GEO format subsequently be converted into the OBJ format, which could then be displayed in an according DirectX window within the designed GUI.

In contrast, the visualization of the mesh nodes and edges could not be realized through common file conversion procedures, since the generated tetrahedral mesh grid significantly differs from the typical triangular face elements of standard three-dimensional geometry models. Therefore, suitable algorithms to highlight the mesh network on top of the workpiece and tool model were developed and integrated within the visualization procedures. After a mesh generation generated tetrahedral mesh grid with the according number of mesh nodes and edges is stored in a KEY-file. Thereby, each mesh nodes is defined with three according Cartesian coordinates, while a mesh element is subsequently defined by referring to the indexes of four vertices. With an according software routine, the four edges and nodes of a mesh element could be connected with a cuboid of defined thickness and highlighted with an according coloring function. The resulting three-dimensional mesh grid visualization could subsequently be displayed on top of the according surface models within the DirectX window of the GUI, as illustrated in Figure 7 with illustrative C# software code using the tool model as an example.

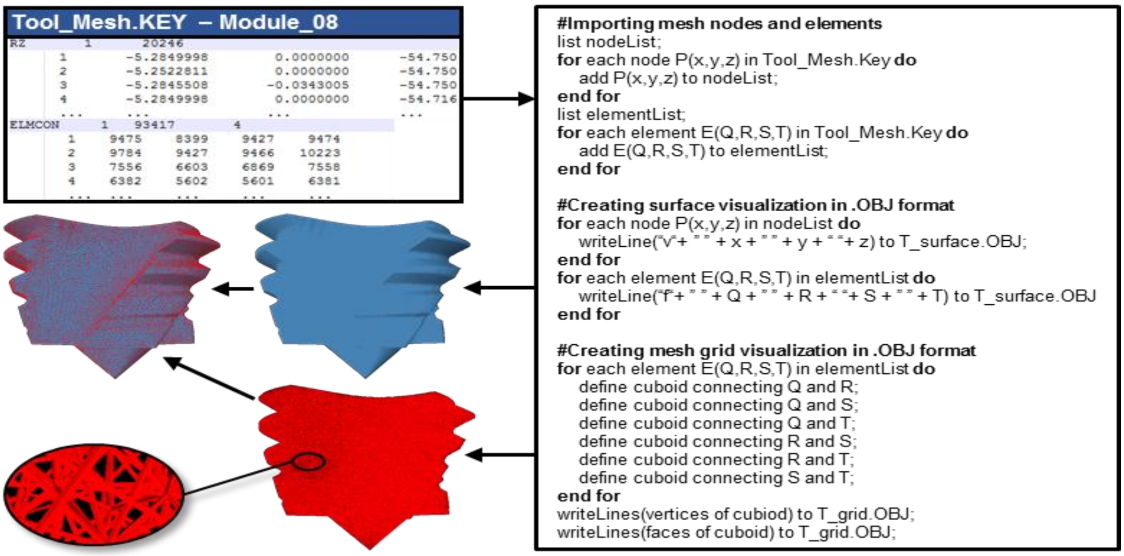


Fig. 7: Surface and mesh grid visualization with simplified C# code.

RESULTS

In the following passages, the resulting software system with its GUIs, as well as the implemented simplified simulation model generation procedures are described. Thereby a helical fluted M8 tapping tool is used as an illustrative example, which is in conclusion validated with according experimental investigations, although tapping processes with arbitrary tool types and sizes could be simulated and evaluated with the FBS. The UML class diagram of the resulting software structure is presented in Figure 8.

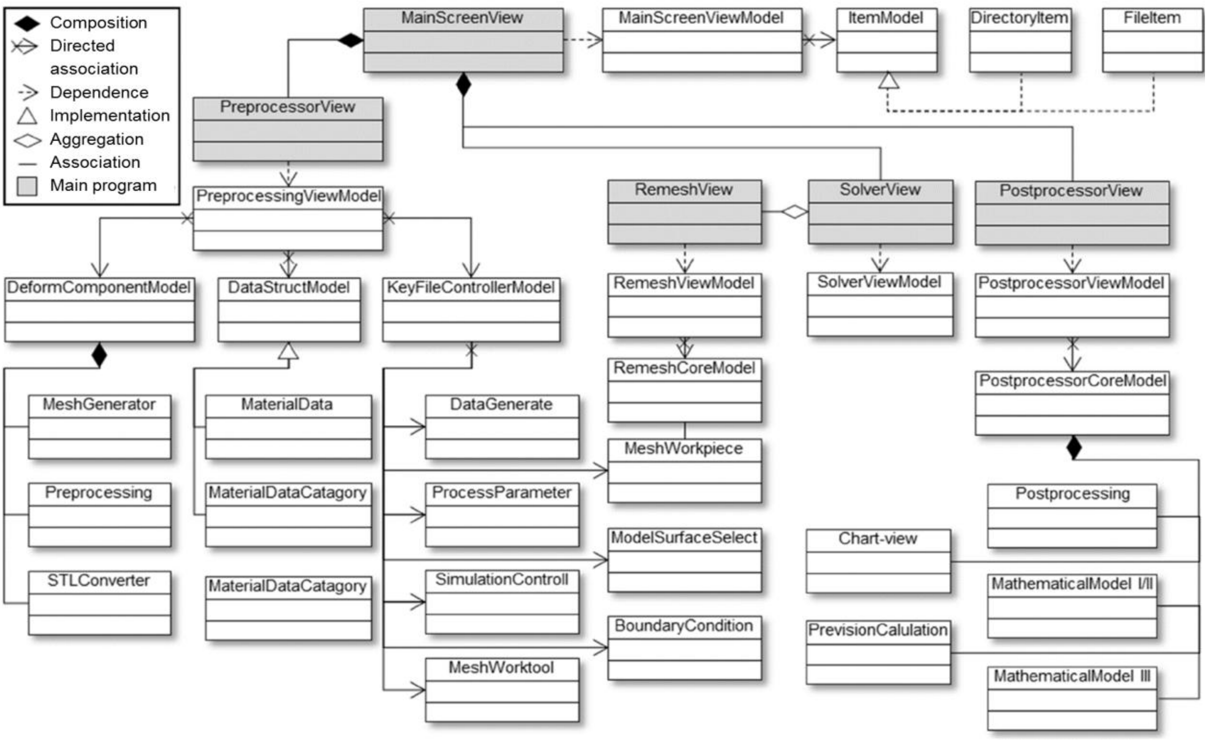


Fig. 8: Surface and mesh grid visualization with simplified C# code.

Intuitive Graphical User Interface

The GUI of the FBS was developed following the structure of the simulation development process. The FBS was divided into three GUI elements for general tasks, simulation preparation and simulation evaluation. In the development phase, the main focus was laid on simplified user interactions and user requirements in a functional and appealing environment. After software initialization, the user is prompted to select a user path in the Main GUI of the FBS, which was designed in the familiar Windows desktop environment (Figure 9). Subsequently, the user is granted access to all but only the options, which are needed for the preparation of a three-dimensional tapping simulation, while the implemented active help supports the user of the FBS during all operations with simple and self-descriptive dialogs.

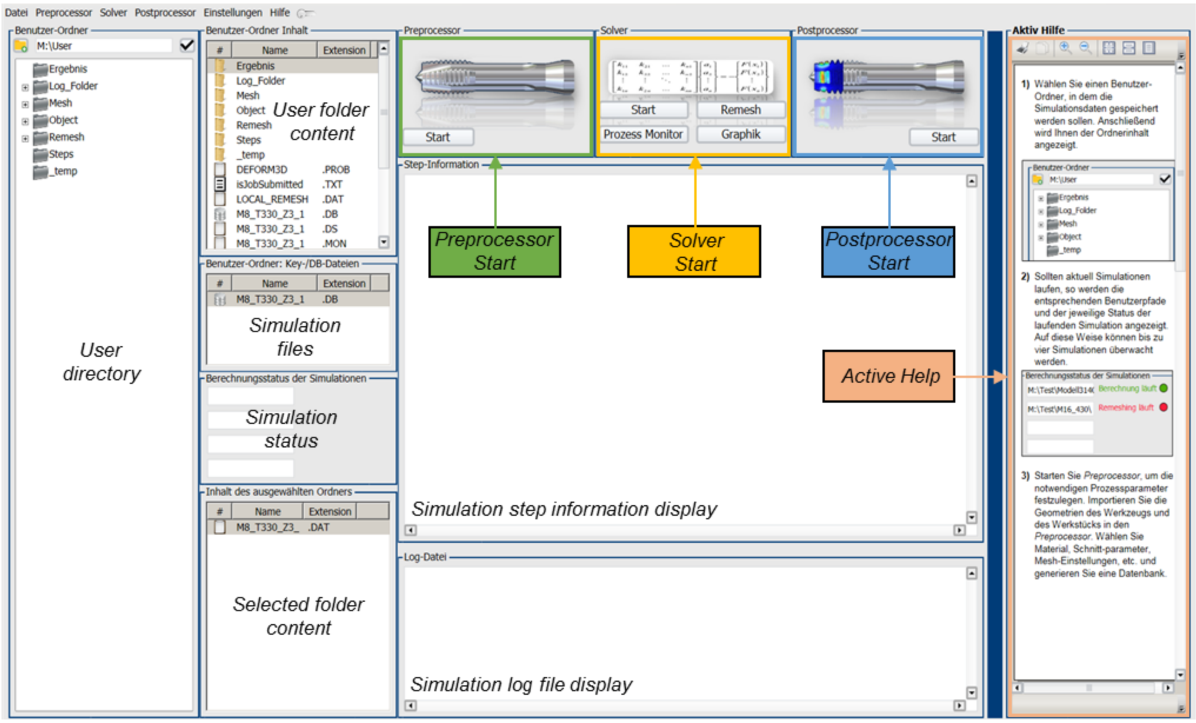


Fig. 9: Main GUI.

The Preprocessor GUI can be started after a valid user path has been selected or generated. It is divided into several tabs for file input, parameter modification and execution of software routines, next to a DirectX window for model visualization purposes, as well as an active help section. Input data is converted into key-data in the declared script language using according algorithms and is continuously interchanged with DEFORM for further processing. The necessary simulation preparation steps are clustered in several tabs within the GUI of the Preprocessor, while the imported geometries and generated mesh grids are subsequently displayed in the DirectX window and can be viewed from different perspectives via according user interactions (Figure 10). As in all other GUI windows of the FBS, an active help section is included in the Preprocessor to support the user during the simulation preparation phase.

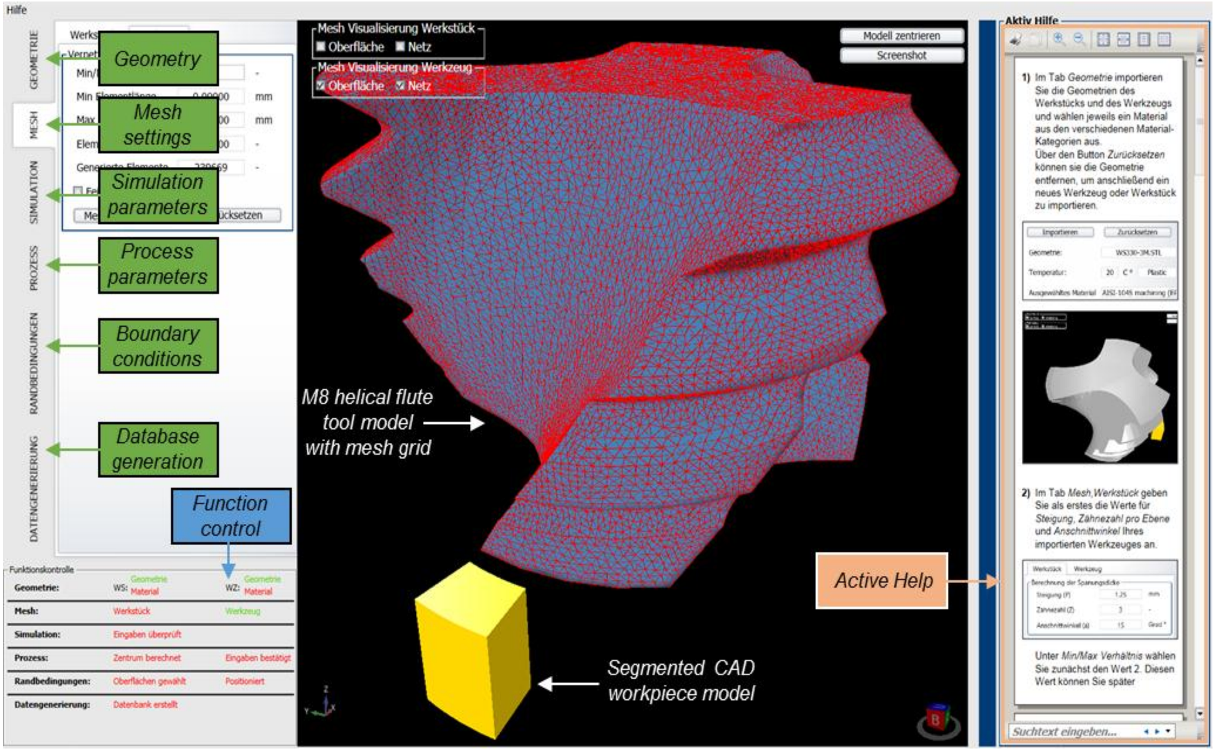


Fig. 10: Process steps in the Preprocessor GUI.

In the first tab (geometry), the 3D geometries of tool and workpiece models can be imported and material properties can be defined, whereby the according subroutines are automatically executed in the background. Amongst other parameters, the choice of a correct minimum element edge length is an important criterion when meshing (second tab), to be able to reach convergence during numerical calculation and is automatically calculated without further user interactions. In the third tab (simulation parameters), the number and increment of simulation steps are automatically determined considering rotational speed, minimum element edge length and cutting speed. Additional parameters like the heat transport coefficient and suitable parameters of friction define the interactive relationship of the objects workpiece and tool. In the fourth tab, process parameters are defined. Using the input of the rotational speed and pitch, the feed speed is calculated automatically. Tool rotation is defined about the z-axis. Since a congruent axis is defined for the tool and workpiece models, the tool positioning as well as the determination of the center of rotation can be carried out accordingly. Additionally, the user is able to initialize the definition of suitable boundary conditions, whereby the described subroutine is executed. After the tool model is automatically positioned in z-direction, the user is able to initialize a rotation of the tool around the z-axis as required, so that the teeth of the tapping tool are in the correct engagement situation, while these positioning movements are traceable through the visualization window. Using controls of the last tab (data generation), all input data will be converted and stored in a DEFORM database. A function control implemented in the Preprocessor GUI verifies, that all input data is continuously sent to DEFORM and validates plausibility of sent and received data. Therefore, an additional response code for communication with the FEM-based software system has been programmed for all the tabs included in the Preprocessor. Using this response code, value limits are checked after data generation, so that the updated information can be evaluated for its accuracy.

Subsequently, the simulation calculation can be started via the according Solver Control, which is accessible from the Main GUI. The calculation is executed in the background using the DEFORM solver module, while the simulation status, as well as a simulation log file is continuously displayed in the Main GUI for monitoring purposes. Should the calculation be interrupted due to a mesh convergence error, the user is notified and can start a manual remesh procedure through the function implemented within the Solver Control, whereby the remesh routine is executed according to the mesh grid generation.

An intuitive evaluation of the calculated simulation is possible in the Postprocessor GUI (Figure 11), since the user is able to import the simulation database of any finished tapping simulation.

Due to the workpiece segmentation, the tapping tool does not remain in constant contact to the workpiece during the simulation, resulting in a torque curve consisting of incoherent peaks. To accumulate the torque peaks into an evaluable torque course, the according validated mathematical functions were adapted and included in the FBS (Oezkaya and Biermann, 2017):

$$M_{total}(t) = \begin{cases} 0 \mid t = 0 \\ M_1 * \dfrac{t}{t_1} \;\Big|\; 0 < t < t_1 \\ \displaystyle\sum_{n=1}^{i} M_n \;\Big|\; t = t_i \\ \displaystyle\sum_{n=1}^{i} M_n + \left(\sum_{n=1}^{i+1} M_n - \sum_{n=1}^{i} M_n\right) * \left(\frac{t - t_i}{t_{i+1} - t_i}\right) \;\Big|\; t_i < t < t_{i+1} \end{cases} \quad (1)$$

Hereby, t corresponds to the simulation time, i represents the number of torque peaks, t_i is the time of the according torque peak and M is the torque value. The torque accumulation is automatically carried out in the background, without any required user input and the resulting torque curve is then displayed as a graph in a diagram side by side to results of further simulations, enabling the user to easily evaluate and rank the tapping tool performance and consider possible improvements.

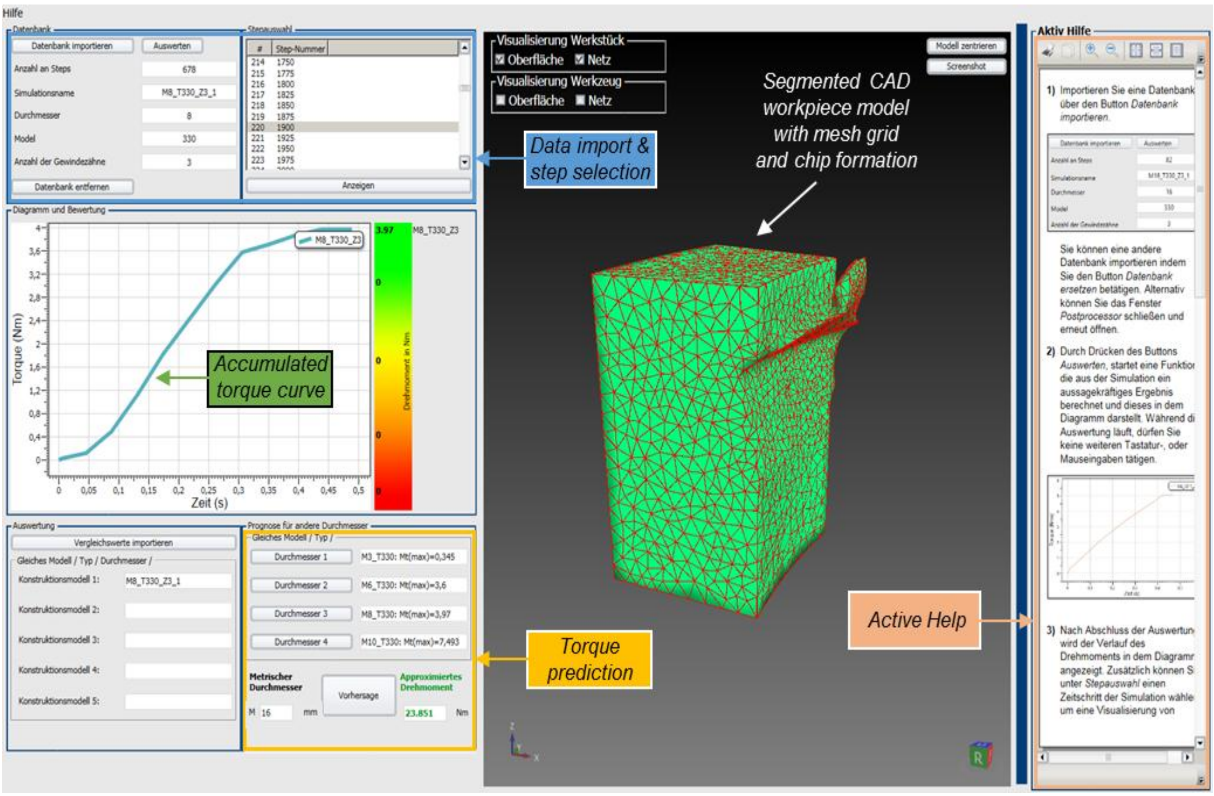


Fig. 11: Postprocessor GUI, including evaluated simulation results of a helical fluted M8 tapping tool.

Furthermore, a torque prediction method was implemented in the Postprocessor, so that the user is able to predict maximum torque values for further diameters, as soon as four simulations of the same tapping tool type with varying diameters have been carried out. Therefore, a parabolic dependency between the metrical tool diameter and the resulting maximal torque value could be used, to extrapolate a torque value out of four simulation results of the same tool type, which was proposed and validated in (Oezkaya and Biermann, 2018). With this function, the user of the FBS could choose any metrical diameter d_{pred} up to the geometrical transmission limit g, at which the tapping tool starts to consist out of ω = 4 flutes instead of ω = 3, and obtain an according predicted relative torque value $predM_{max}$, without having to perform an entire simulation routine for the desired diameter.

$$predM_{max} = M_{par}\left(d_{pred},\, setM_{aval},\, g,\, \omega\right) \mid d_{pred} \in \mathbb{N}\, whereby: \begin{cases} d_{pred} < g \; for \; d_4 < g \\ d_{pred} > g \; for \; d_1 > g \end{cases} \tag{2}$$

The parabolic regression curve M_{par} is dependent on the set of the already simulated and available torque curves $setM_{aval}$, whereby four simulation results, which were previously accumulated with equation 1, are considered:

$$M_{max}(d_i) = max(M^{\,i}_{total}) \mid M^{\,i}_{total} = available\; torque\; curve\; for\; d_i \tag{3}$$

$$M_{max}(d_i) \in setM_{aval} \mid i \in \mathbb{N},\, i \leq 4 \tag{4}$$

To acquire the parabolic regression curve, the available evaluated torque maxima were sorted by the size of metrical tool diameter, whereby all of the described processing steps were automated, concluding in a further simplified and user-friendly software structure.

$$d_1 < d_2 < d_3 < d_4 \mid d_4 < g \;\dot{\vee}\; d_1 > g \tag{5}$$

Next to the numerical evaluation procedures, a three-dimensional graphical visualization of the tapping simulation was implemented within the GUI of the Postprocessor to further illustrate the process conditions, workpiece deformation, chip formation and tool position. Thereby, the user could choose to display any desired simulation step included in the chosen simulation database. The chosen simulation step and the according model geometries and mesh grids, which are stored in the DEFORM database, would then be converted into a file format displayable within the DirectX window as described above.

Simplified simulation model generation and evaluation procedures

To provide an overview of the resulting simplified simulation model generation and evaluation, the example of a helical fluted M8 tapping tool is used. As described above, several necessary simulation parameters, including the chip thickness, minimal mesh element size, simulation step amount and heat transfer coefficients are automatically provided by the FBS, so that minimal user interactions and no in-depth knowledge of FEM simulation are required to prepare the tapping simulation. The simulation parameters for the three-dimensional M8 tapping simulation are listed in Table 1, whereby parameters that are provided by the FBS are highlighted in green.

Table 1: Simulation parameters and tapping tool and workpiece properties.

Tapping tool properties		**Workpiece properties**	
Tool diameter	M8 (d = 8 mm)	**Core hole diameter**	d_1 = 6.8 mm
Tool type	Uncoated helical flute tap	**Outer diameter**	$d_2 = d + 0.5$mm = 8.5 mm
Tooth pitch	P = 1.25 mm	**Height**	P + 0.25 mm = 1.5 mm
Chamfer length	$L_C = 3 \times P$ = 3.75 mm	**Chip thickness**	$h_{cu} = \left(\frac{P}{z_N}\right) sin(\beta)$ = 0.1078 mm
Chamfer angle	$ß = 15°$	**Heat transfer coefficient**	h_c = 45 W/m^2·K
Number of flutes	$\omega = 3$	**Threading depth**	3.75 mm
Cutting speed	v_c = 12 m/min		
Rotational speed	n = 477 1/min		
Feed speed	v_f = 9.9375 mm/s		
Material model	Johnson and Cook material model		
Material	cemented carbide	**Material**	AISI-1045
Mesh elements	200,000	**Mesh elements**	60,000
Maximal mesh element size	0.07189 mm	**Minimal mesh element size**	$ElmS_{min} = \left(\frac{h_{cu}}{5}\right)$ = 0.03595 mm
Object type	Rigid	**Object type**	Plastic

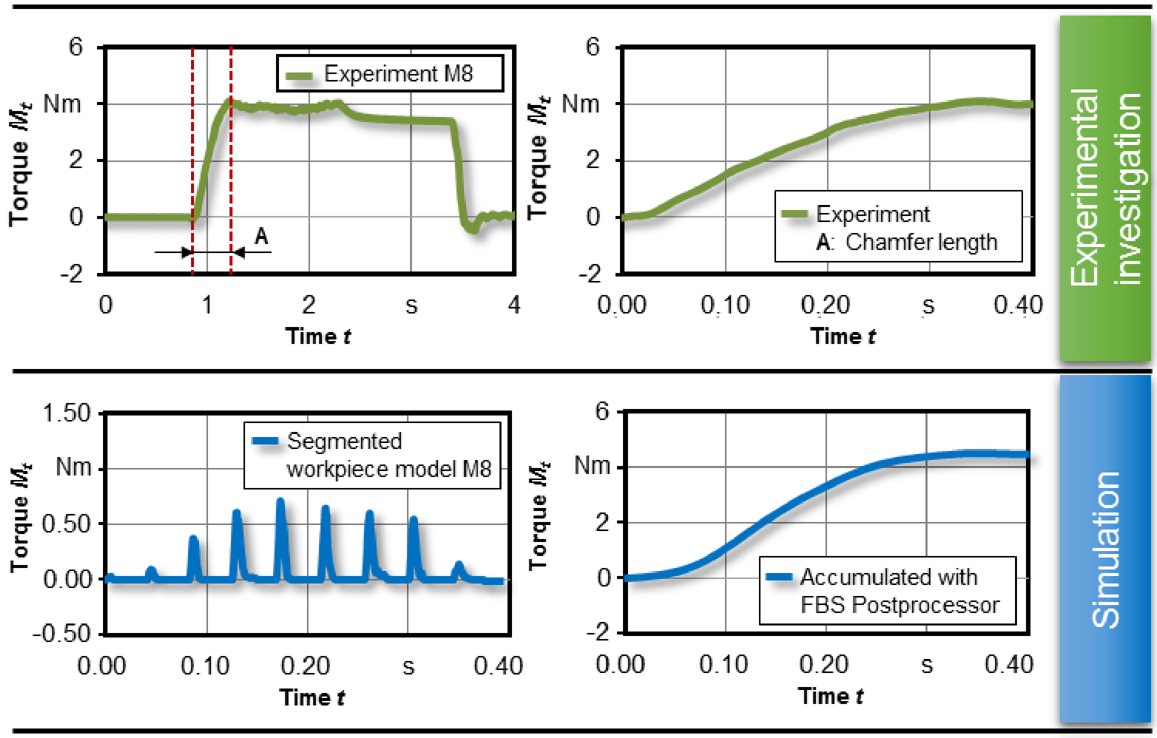
In contrast to conventional simulation model generation, the user only has to specify the geometrical tapping tool properties, the cutting speed v_c and choose materials for tool and workpiece, whereas all other necessary parameters including material parameters are automatically defined by the FBS. Additionally, all required user inputs are elaborated in the Active Help of the Preprocessor, concluding in a decreased simulation model generation effort by more than 50 % compared to the complex GUI of DEFORM.

After successful numerical calculations, a simple evaluation of the simulation results is possible in the Postprocessor, whereby the occurring torque over time is depicted in the diagram without further user interactions, which would be necessary within DEFORM. The torque is the most relevant process parameter for the evaluation of the tapping process, so that the according diagram is the essential part of the FBS Postprocessor GUI, as presented in

Figure 11 for the M8 tapping tool simulation. The occurring maximal torque values are automatically included within the corresponding colored scale, so that the conventionally time-consuming simulation evaluation procedures could be strongly simplified through the developed FBS, without compromising their significance. In this context, it should again be mentioned that execution of all methods described in this chapter would not have been possible without previously establishing external control over DEFORM.

The numerical results of the introduced simulation of the uncoated M8 tapping tool with helical flutes are not essential for the CA-Channel and software development methods described in this research paper, but included for the sake of completeness. The segmented torque course, which is automatically accumulated with the FBS Postprocessor is depicted and compared to according experimental investigations in Figure 12. Since the simulated tapping depth corresponded to the tool's chamfer length, the chamfer length also considered in the experimental study. The numerically determined torque course, which was accumulated in accordance to equation 1, shows good agreement to the experimental results, confirming the quality of the segmented simulation model.

With the results of three further simulations using the same tapping tool type with the diameters M3, M6 and M10, an extrapolation curve could automatically be generated. Afterwards, torque values for various other tool diameters could be determined, which is exemplary illustrated for the diameters M12, M14 and M16 and in conclusion compared to experimental and simulative values, showing overall good agreement. The relatively large deviation between 17.15 Nm (experimental) and 20.08 Nm (predicted) can be traced back to the model simplification procedures. Nevertheless, the predicted torque values could be used by too manufacturers to evaluate the tool performance tendency associated with the modification of design parameters. Further experimental and simulative studies were carried out in previous investigations (Oezkaya and Biermann, 2017; Oezkaya and Biermann, 2018) and are not included here, since the focus of this paper lies on the developed software system, CA-channel and procedure simplification.



	Experiment smoothed: chamfer length, max. torque	**Simulation smoothed:** accumulated, max. torque	**Torque prediction:** regression curve from simulation results: max. torque
M3	0.31 Nm	0.30 Nm	–
M6	1.64 Nm	1.67 Nm	–
M8	3.91 Nm	3.98 Nm	–
M10	6.56 Nm	6.57 Nm	–
M12	–	–	**10.28 Nm**
M14	–	–	**14.77 Nm**
M16	17.15 Nm	17.50 Nm	**20.08 Nm**

Comparison to prediction method

Fig. 12: Evaluation of numerically calculated values.

CONCLUSIONS

In this paper, a developed FEM-based software system for the intuitive modelling of three-dimensional tapping tool simulations is presented. In this context, the commercial FEM software DEFORM was externally controlled for the first time, although a typical application programming interface does not exist. Therefore, several software routines and algorithms were developed to decouple the necessary features from the DEFORM user interface and to implement these within a newly designed user environment. In addition, a three-dimensional graphical visualization of tool and workpiece models, as well as mesh grids, positioning and chip formation were included within the developed Preprocessor and Postprocessor.

Using the FBS, a tool design engineer could simulate the manufacturing process using various tapping tools and analyze the resulting relative torque values. By varying design parameters and comparing simulation results, a fast method to deduce optimal tool design parameters is provided, before tool prototypes are fabricated, so that many experimental field tests, resources and development time could be saved. The extensive amount of experience required for the preparation and execution of FEM simulations could be minimized by automating multiple parameter calculations and simplifying user interactions in an adequate style.

The here presented FBS is a novel research effort and represents first approaches, which increase the understanding of the tapping process and move forward the 3D modelling and simulation of complex manufacturing processes. It could be concluded that the external control of DEFORM is achievable, so that novel possibilities of creating software solutions to simplify the simulation model development, or automate extensive simulative studies based on DEFORM, exist. These possibilities should be exploited in future studies, since they present a high potential concerning a better process understanding and the implementation of FEM analysis in further areas of engineering without in-depth knowledge of simulative procedures.

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