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Procedia CIRP 31 (2015) 88 – 93

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15th CIRP Conference on Modelling of Machining Operations

Novel approach for 3D Simulation of a Cutting Process with Adaptive Remeshing Technique

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Abstract

This paper presents an approach of a 3D cutting simulation with a continuous adaptive remeshing technique. Such a method allows the investigation of cutting processes without losing precious information. Furthermore, the developed 3D remeshing technique represents a possibility to investigate the effects caused by the secondary cutting edge in detail for more complex cutting processes. When a 3D model is built up to simulate the cutting process, an accurate meshing of the workpiece and the cutting edge is applied, which means that a large number of elements is generated. The presented remeshing method is applied only locally at regions, where distorted elements are located. This leads to a significant reduction of the calculation times compared to other remeshing techniques.

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Keywords: Finite element method (FEM); Simulation; Cutting

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1. Intruduction

The continuous efforts in the last years enabled to investigate cutting processes in detail, considering complex material mechanisms. Most of the investigations are based on 2D FEM techniques and improved especially for orthogonal cutting, considering only the main cutting edge. For example, studies on friction model, coefficient of friction [1], or values of the parameters in a flow stress model [2] using a FEM cutting simulation were presented. In [3] the recent advances in modelling of metal machining processes were presented. Some simulation techniques like FE-, analytical, empirical and hybrid modelling were compared with their capabilities and limitations. In some current publications 3D FEM models of cutting processes like drilling are presented [4]. Although the models are an advancement, especially for the identification of the effects acting at the secondary cutting edge, the investigation of complex material mechanisms is impossible due to coarse meshes or simplified separating methods. Most of the simplifications normally lead to losses of information. A more complex technique is the continuous remeshing, which is an established technique for 2D simulation of orthogonal cutting processes with very high accuracy. In this paper a novel approach for simulating a 3D cutting process considering the secondary cutting edge is presented. Due to the large deformation in the material a continuous remeshing method was developed. Because of the expected high calculation time in 3D simulations, the development of the remeshing method was first used for 2D cutting simulations. Despite this simplification the 2D perspective allows a clear description of the used methods. Furthermore, the remeshing method was developed in such a way, that it can be easily adapted to 3D simulation models. For the detection of the distorted elements in the simulation model the following indicators were used:

- Face corner angle of the element
- Aspect ratio of the length of every edge in each element [5]
- Deformation degree of the element

During broaching, which can be designated as process with relatively simple kinematic properties, the parts are produced with only one translational movement of the tool. This manufacturing process has been considered for the investigations in this paper. With the developed remeshing method, sample simulations were run to determine the influence of the secondary cutting edge while broaching. Furthermore, the residual stresses caused by the cutting edge can be simulated.

Peer-review under responsibility of the International Scientific Committee of the “15th Conference on Modelling of Machining Operations
doi:10.1016/j.procir.2015.03.022

2. Simulation method

2.1. Existing methods

In the simulation of the cutting process high deformations in the cutting zone during the separation of the material are expected. Such deformations lead to a high number of distorted elements in the used mesh and therefore, to low accuracy of the results. For simulation of the material separation during cutting, deletion of elements or separation of nodes are well known methods (Figure 1). These methods are accompanied by loss of information in the simulation model, which lowers the accuracy of the results. Furthermore, a damage (failure) model has to be defined for calculating the critical values, when and where elements should be deleted or the nodes have to be separated. The choice of the parameters in the failure model is crucial to model the material separation, because the deletion of the elements or the separation of the nodes should be executed not too early but also not too late [6, 7].

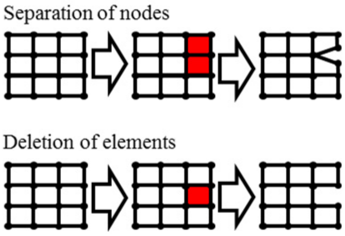

Figure 1: Methods for simulating of material separation

The presented method for the separation of the material is the continuous remeshing. In conjunction with machining this method was presented by Ceretti et. al. [6], where two techniques were compared; the remeshing and the deletion of elements. The remeshing technique is more accurate than the deletion of elements, but accompanied by longer calculation times because of the remeshing step. The longer calculation times are caused by the additional step for the detection of the distorted elements and the generation of a new mesh. The remeshing technique can be realized by two different approaches (adaptive and stationary). In the stationary approach the areas with different element sizes are defined by the user at the begin of the simulation. The stationary remeshing technique was successfully used for investigations of the tool wear during machining of Ti-6Al-4V [8]. The adaptive remeshing technique is defined by floating remeshing areas. A new mesh will only be generated in interesting areas (e.g. areas with high gradients of temperature, strain or stress). Holtermann et al. used in [9] an adaptive remeshing technique for the simulation of single grain grinding, which was first presented by Hortig in [10]. In most cases with adaptive remeshing state variables like strain rates or temperatures are taken as criteria for remeshing or refinement of the workpiece mesh. As a result material behavior or chip formation type influences remeshing. As mentioned before, the remeshing criteria in this research are only geometrical properties of the elements in the mesh, which makes the developed technique material independent.

2.2. Adaptive Remeshing Method

For the implementation of the remeshing method in the model the simulation has to be customized, because the used software doesn’t have a module for remeshing during the simulation. A summary of the important steps during the remeshing of the geometry is given in Figure 2. After the defined cutting length is reached, the element quality is checked and if any distortions in the mesh are found, a remeshing module will generate a new mesh without distorted elements. The mapping of the old results on the new mesh is realized by local interpolation in the solver of *ABAQUS*. If the whole geometry is remeshed as done with a stationary remeshing technique, larger deviations in the results are observed during the mapping step caused by the interpolation. With the presented method the deviations caused by the mapping is reduced by the local remeshing.

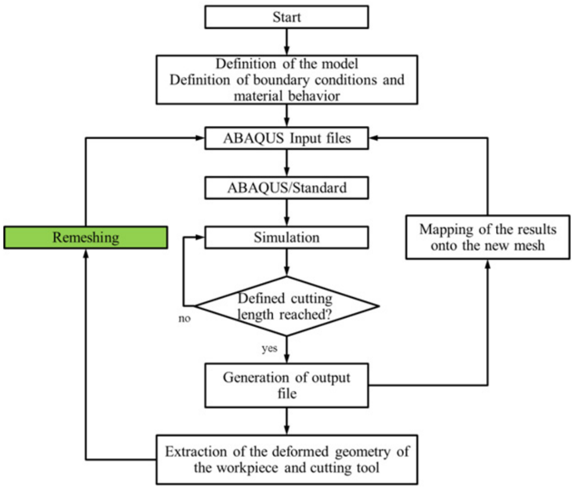

Figure 2: Flow chart of the customized FE-simulation for remeshing module, according to [11]

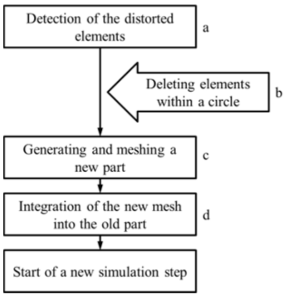

Figure 3: Description of the remeshing part in Figure 2

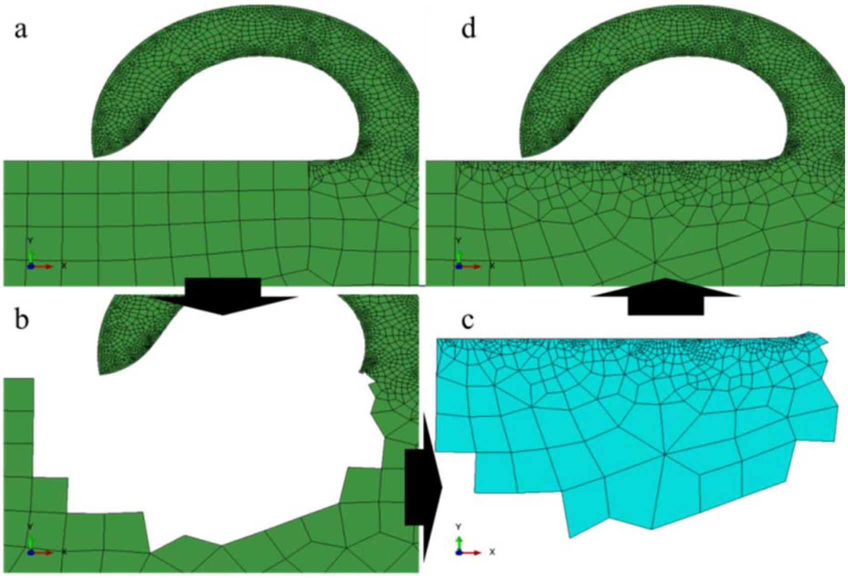

Figure 4: Remeshing steps

To the remeshing step four stages contain. The remeshing module is described in Figure 3 and presented graphically in Figure 4a-d. In Figure 4 the mesh quality is checked and the distorted elements are detected. A radius of a circle, which depends on the length of the element edges, is defined at the begin of the simulation. To achieve the new, non-distorted elements, the mesh around the detected element within the circle is deleted (Figure 4b). Then, a new part is generated with the geometrical properties of the deleted mesh. The new part is meshed with non-distorted elements (Figure 4c) and integrated into the old mesh (Figure 4d). The next step of the simulation is run with the new mesh. The presented remeshing method is also transferred into the 3D cutting simulation. A description of the transfer of the remeshing technique will not be described in this paper.

The quality of the mesh is assessed by the following criteria (Figure 5):

- Face corner angle of the element θ [5]
- Aspect ratio of the length of the element edges $\frac{l_n}{l_{n-1}}$ [5]
- Deformation degree of the element D

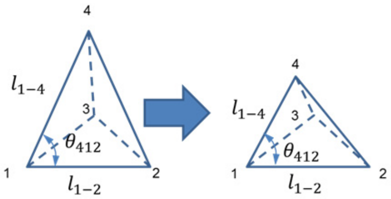

Figure 5: Tetragonal element before (undeformed) and after (deformed) the simulation step

The first criterion depends on the face corner angles θ. If one of the element face corner angles is larger than 150° or smaller than 15° as suggested by the manual of ABAQUS, the element is classified as distorted. The second criterion was solely used in the 3D cutting simulation, because in 2D, the face corner angle made it redundant, when triangular elements were used. When using remeshing in 3D modelling the element number increases drastically compared to 2D modelling, this leads to higher calculation times for the remeshing step. To reduce high calculation times, a third criterion (deformation degree D_θ) was developed for estimating the mesh quality. The deformation degree is defined for the face corner angle in Equation (1) and for the length in Equation (2).

$$D_\theta = \prod_{i=1}^{n} \frac{\theta_i}{\theta_i^{un}} \tag{1}$$

$$D_l = \prod_{i=1}^{n} \frac{l_i}{l_i^{un}} \tag{2}$$

In Equation 1, n is the number of face corner angles, θ_i and θ_i^{un} are the face corner angles at the current increment and at the begin of the simulation respectively. In Equation (2) the deformation degree for calculating the product of ratio of the length of every element edge at the begin l_i^{un} and at the end of the simulation l_i is presented. Before the simulation step is run, the mesh is nearly free of distorted elements, which allows the comparison of the element properties at the begin and at the end of the simulation. Figure 6 shows the deformation degree, dependent on the simulation increment for four different examples. Each example describes the deformation behavior of the considered element. Both dashed curve characteristics represent a highly deformed element, which will be classified as distorted, if the element properties are not in the defined interval of the face corner angle.

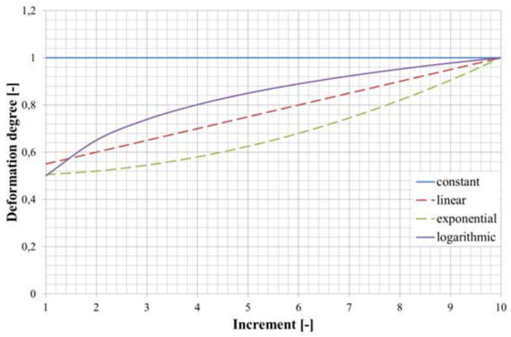

Figure 6: Deformation Degree during the Simulation

With D_θ the deformation scale of each element can be calculated and additionally it can be predicted, if the element will experience high deformations in the next step/simulation, which can be observed for example in Figure 6. The non-dashed curve characteristics in Figure 6 are examples for elements, for which the deformation degree at the end of the simulation is nearly constant. In this case such elements can have a low quality. For an accurate simulation the face corner angle should not be lower than 5° or higher than 170° [5]. These parameters can be adjusted for large cutting lengths. Elements with low quality and constant deformation degree will not be considered in the remeshing step, because, with high probability, they will not experience any load or displacement in the next step. Therefore, these elements will not be deformed any longer and their geometrical properties will remain unchanged. Such elements are not taken into account any more, when the remeshing step is started, which lowers the calculation times for the remeshing in the simulation.

Additionally to the remeshing steps in 3D cutting simulation in Figure 7 two elements are highlighted white and red. The first one (marked red) has a deformation degree just as the dashed lines show in Figure 6 (no constant deformation degree during the simulation step) and it has to be remeshed before the next simulation is started. The white marked element is not considered as a distorted element, because it has a nearly constant deformation degree, which means, that this element will not experience any deformations at the moment.

With the presented remeshing technique 3D cutting simulations are run to estimate the influence of different radii of the secondary cutting edge. The workpiece material is implemented as elastic-plastic behavior of SAE 1045, where the flow stress is a function of the plastic strain, strain rate and temperature in the workpiece. Furthermore, the Coulomb friction model was implemented with a time-independent constant friction coefficient of 0.3 in each simulation.

3. Simulation results and discussion

First, with the presented model, where the adaptive remeshing method is implemented, 2D cutting simulations with different cutting thicknesses were run. The results were compared to cutting simulations, where the remeshing regions were defined at the begin of the calculations. In the second step 3D machining simulations were carried out to determine the influence of different roundings of the secondary cutting edge. The material model used in the cutting simulation was validated in [12] regarding process forces and additionally in [13] regarding residual stresses after the cutting process. Therefore, comparing these results with them of the adaptive remeshing technique conforms as verification of the model.

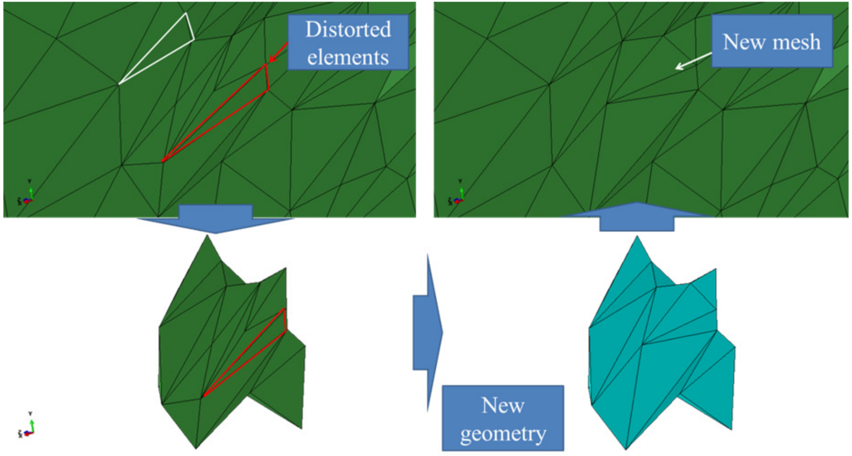

Figure 7: Remeshing steps during 3D cutting simulation

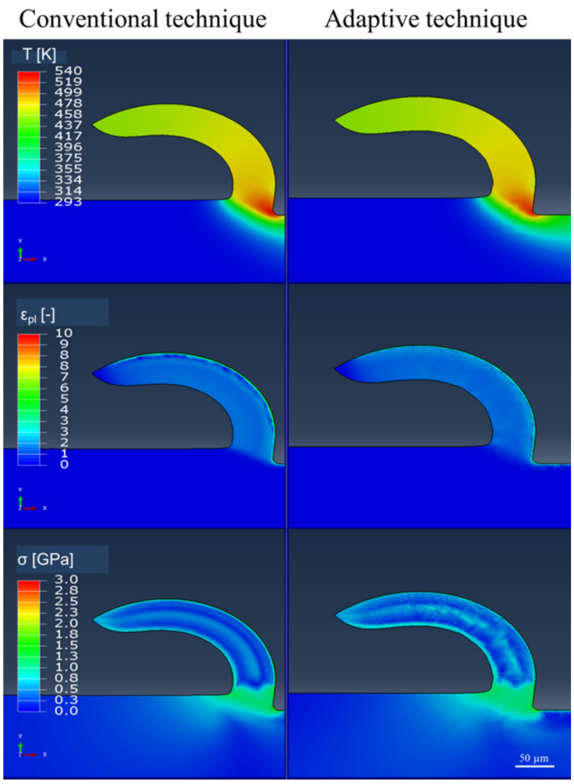

Figure 8: Comparison of results from simulation with the adaptive remeshing with the stationary remeshing

In Figure 8 the results from 2D cutting simulations are presented. On the left hand side the results from simulations with stationary remeshing technique are shown. For the comparison of the results of this method with the results of the adaptive remeshing method, the frames are taken at the same time and cutting length after the temperature reached a stationary state. In both cases 20 µm cutting thickness and cutting velocity of 90 m/min were implemented. The comparison between the stationary and adaptive remeshing is made with regard to temperature field, stresses and plastic deformations and shows a very good agreement.

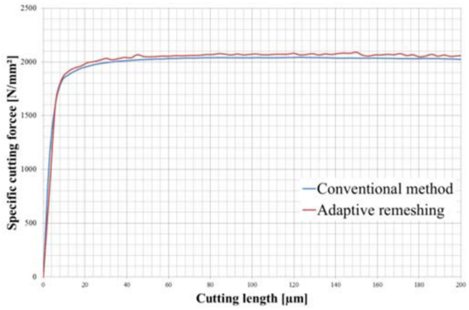

Figure 9: Specific cutting forces from simulation with a conventional and adaptive remeshing

In Figure 9 the specific cutting forces from simulations with and without adaptive remeshing are presented. The curve characteristics show good agreement (deviation in the stationary state is acceptable). The calculation time for the simulation with stationary remeshing method was about 36 hours. For the same cutting length the simulation with adaptive remeshing needed only about 7 hours. This reduction of the calculation time can be explained by the differences in the mesh, which is shown in Figure 10. The adaptive remeshing is implemented to make the mesh coarse for calculating the process forces and parallel to save calculation times. Such optimization is made in the conventional remeshing method, but it still takes longer time for one simulation than with the adaptive remeshing. The remeshing algorithm can be adopted with finer mesh for investigating the residual stresses or the main shear plane after cutting. The reduction of calculation time is a remarkable progress within the field of cutting simulation.

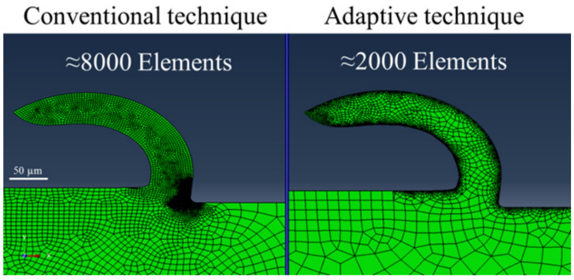

Figure 10: Comparing the mesh from the two approaches

In Figure 11 the results from 3D cutting simulations are presented. In the simulations two different rounding radii of the secondary cutting edge (3 µm and 15 µm) were implemented. The comparison of temperatures inside the chip shows significant differences, which leads to larger softening of the material in the chip and therefore to lower stresses for the 15 µm rounding.

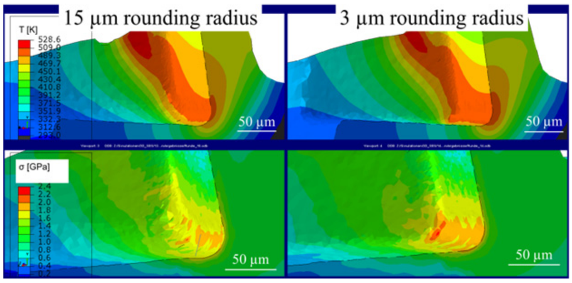

Figure 11: Temperature and stress fields from 3D cutting simulations with different rounding radius of the secondary cutting edge

To compare the 3D cutting simulation to the 2D simulation a model was developed with the boundary conditions for the cross direction of the machined material and without considering the secondary cutting edge. The simulation results are presented in Figure 12, right side. In Figure 12, left side the movement of the material in cross direction was allowed.

All frames in Figure 12 were taken at the same simulation progress (cutting length of 250 µm). The differences of the chip formation can be observed. The chip formation, where the boundary condition in the cross direction were implied, is build up after 50-60 µm cutting length. The results from the simulation without additional boundary conditions show that the chip is formed after at least 200 µm. This can be explained by the materials capability to flow sidewards. After the first contact of the cutting edge with the workpiece the material is compressed in all three directions (cutting, normal and passive direction). The chip formation depends on the ratio of the primary cutting edge radius and the cutting thickness. For the simulations in this paper this ratio is 3/4. The further influence of the ratio r_β/h will be analyzed in future work.

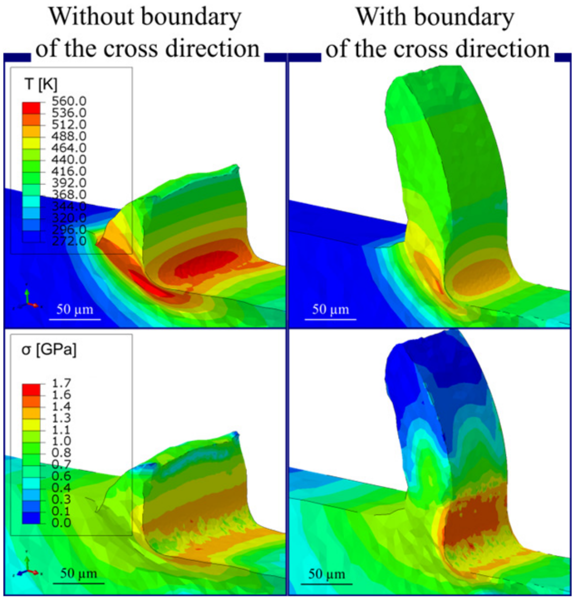

Figure 12: Orthogonal cut without secondary edge

4. Conclusions

In this paper an adaptive remeshing technique for 2D and 3D cutting simulations was presented. Because of the high calculation times the deformation degrees of the mesh-elements was introduced, which decreased tremendous the calculation times for the remeshing. With the developed method 2D and 3D cutting simulations were run. The 2D results are compared to the stationary remeshing method. Furthermore, the curve characteristics of cutting force taken during the simulations with both remeshing techniques are in good agreement. With the 2D adaptive remeshing technique a significant reduction of the calculation time of the cutting simulation was achieved. Results of the 3D cutting simulation with the developed adaptive remeshing technique were presented, where different rounding of the secondary cutting edge was implemented. The results show the differences in the temperature and the stresses in the workpieces. Furthermore, the cutting process in orthogonal cut was simulated with two different boundary conditions for the cross direction. At first the material was capable to flow sidewards and in the second simulation the cross direction was pinned, so that it can be compared to the 2D cutting simulation. The differences of the chip formation were shortly discussed. The possible cause is the ratio between the radius of the primary cutting edge and the cutting thickness, which will be investigated in detail in future works.

Acknowledgements

The authors gratefully acknowledge the support of the German Research Foundation (DFG: Deutsche Forschungsgemeinschaft). The authors appreciate the support and the grant of computational time by the Steinbuch Centre for Computing (SCC) on the high performance computers ic2 and hc3 at the Karlsruhe Institute of Technology (KIT).

References

[1] Bil, H.; Kılıç, S. E. & Tekkaya, A. E. (2004), „A comparison of orthogonal cutting data from experiments with three different finite element models“, *International Journal of Machine Tools and Manufacture*, Vol. 44, Nr. 9, pp. 933–944.

[2] Childs, T. H. C. (2009), „Modelling orthogonal machining of carbon steels. Part I: Strain hardening and yield delay effects“, *International Journal of Mechanical Sciences*, Vol. 51, Nr. 5, pp. 402–411.

[3] Arrazola, P. J.; Özel, T.; Umbrello, D.; Davies, M. & Jawahir, I. S. (2013), „Recent advances in modelling of metal machining processes“, *CIRP Annals - Manufacturing Technology*, Vol. 62, Nr. 2, pp. 695–718.

[4] Abouridouane, M.; Klocke, F.; Lung, D. & Adams, O. (2012), „A new 3D multiphase FE model for micro cutting ferritic-pearlitic carbon steels“, *CIRP Annals - Manufacturing Technology*, Vol. 61, Nr. 1, pp. 71–74.

[5] ABAQUS 6.12 manual, Simulia 2014

[6] Ceretti, E.; Fallböhmer, P.; Wu, W. T. & Altan, T. (1996), „Application of 2D FEM to chip formation in orthogonal cutting“, *Selected Papers on Metal Forming and Machining*, Vol. 59, 1–2, pp. 169–180.

[7] Ceretti, E.; Lucchi, M. & Altan, T. (1999), „FEM simulation of orthogonal cutting: serrated chip formation“, *Journal of Materials Processing Technology*, Vol. 95, 1–3, pp. 17–26.

[8] Schulze, V., Zanger, F., 2011, Development of a simulation model to investigate tool wear in Ti-6Al-4V alloy machining, 13th CIRP Conference on Modeling of Machining Operations (CIRP CMMO), 12.-13.05.2011, Sintra, Portugal.

[9] Holtermann, R.; Menzel, A.; Hortig, C. & Svendsen, B. (2011), „Towards the simulation of grinding processes – a thermoplastic single grain approach“, *PAMM*, Vol. 11, Nr. 1, S. 385–386.

[10] Hortig, C. & Svendsen, B. (2007), „Simulation of chip formation during high-speed cutting“, *Journal of Materials Processing Technology*, Vol. 186, 1–3, S. 66–76.

[11] Autenrieth H. Numerische Analyse der Mikrozerspanung am Beispiel von normalisiertem C45E. 2010, Dissertation.

[12] Schulze, V., Boev, N., Zanger, F., 2012, Simulation of metal cutting process with variable cutting thickness during broaching. 5th CIRP Conference on High Perfor-mance Cutting 2012, 4.6.2012-6.6.2012, Zürich, Schweiz, Procedia CIRP 1, 454-459.

[13] Weber, M., Autenrieth, H., Kotschenreuther, J., Gumbsch, P., Schulze, V., Löhe, D., Fleischer, J., 2008, Influence of Friction and Process Parameters on the Specific Cutting Force and Surface Characteristics in Micro-Cutting, Machining Science and Technology, 12, pp. 474–497