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NUMERICAL MODELLING AND SIMULATION OF SHEET METAL CUTTING PROCESSES

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Abstract. *Material processing is a very important industrial sector. In order to guarantee high precision and quality of the products, reliable numerical simulation models are required. This contribution concerns the simulation of material cutting. As a benchmark example, a sheet metal is fixed by two clamping tools and the cutting process is controlled by a moving blade. The tools are modelled as linear elastic materials, and the sheet metal as elasto-plastic material with hardening. Main scope is the comparison of two simulation methods with respect to industrial application: (i) Coupled Eulerian-Lagrangian Finite Element Method and (ii) Coupled Lagrangian Finite Element and Smoothed Particle Analysis. Numerical simulation models for the two variants of the above benchmark example are implemented in the commercial code Abaqus. The numerical results of the two models are compared with respect to accuracy and numerical effort, and the advantages and disadvantages of the two methods are investigated. The implemented models for the cutting process and the materials can be applied to several other kinds of industrial material processing like stamping or punching.*

1 INTRODUCTION

Material processing is a very important industrial sector. In order to guarantee high precision and quality of the products, reliable numerical simulation models are required. This contribution concerns the simulation of cutting processes as part of a mechatronic system.

An example of a complex mechatronic system is an automatic panel bender in which complete products of sheet metal are fabricated. During production it is necessary to cut the panels causing high loads on the machine. To optimize the cutting process itself as well as the lifetime of the machine refined and reliable simulation models are required. It is the scope of this work to develop a simulation model for the cutting of the panel which can be adapted by measurement results.

Another example is the cutting of different kinds of material with a chain saw. On the one hand the dynamic behavior of the chain has influence on quality of the process, lifetime of the machine and noise emission. The load of the chain due to the cutting forces is a very important parameter in the system, but it is not possible to measure these forces directly, so that appropriate simulation models are required.

It is the scope of this work to investigate and compare two simulation methods for cutting. As a simple benchmark example, a sheet metal is fixed between two clamping tools and the cutting process is controlled by a moving blade. Two simulation strategies are compared:

First, the coupled Eulerian-Lagrangian Finite Element Method [1] is considered: The clamping and cutting tools are modelled by three-dimensional Lagrangian Finite Elements, and the sheet metal by three-dimensional Eulerian elements. The coupling of the elements is achieved by an appropriate contact formulation.

Secondly, the sheet is modeled by Smoothed Particles [2], a mesh-free discretization with Lagrangian formulation. Again, the tools are modelled by three-dimensional Lagrangian Finite Elements, and the coupling of the two models is realized by contact interaction.

Numerical simulation models for these two variants of the benchmark example are implemented in the powerful commercial code Abaqus [3]. The numerical results of the two methods are compared, and the advantages and disadvantages of the respective methods are investigated.

Finally, the results are compared to measurement on the automatic panel bender mentioned above. Because of differing dimensions of the sheet in the simulation model and on the real machine, only a qualitative comparison is possible which show a better correspondence of the measurements with the Smoothed Particle model than with the Coupled Euler-Lagrangian model.

2 SIMULATION METHODS

In this work two simulation methods are compared for modeling a cutting process. In both cases the clamping tools and the cutting blade are linear elastic bodies modeled by Lagrangian Finite Elements. During cutting large deformations arise in the sheet, and the material is divided. There are several strategies to handle this. One possibility is to use Lagrangian Finite elements for the sheet and an appropriate damage model. In this paper, two other methods are applied to model the sheet without definition of a damage model.

First, a coupled Eulerian-Lagrangian analysis (CEL) is studied, cf [1]. The sheet is modeled by Eulerian elements. In contrast to Lagrangian elements, the material flows through the mesh, and the mesh is fixed in space. This strategy is capable for modelling very large deformations. However, the shape of the deformed material cannot be resolved as good as with a Lagrangian formulation. The coupling of Lagrangian and Eulerian Elements has to be done by an appropriate contact formulation.

As a second strategy, the sheet is discretized by Smoothed Particles. Smothed Particles Hydrodynamics (SPH) is a meshfree Lagrangian method, [2]. With this method fluids as well as solids can be modelled. The material is divided into discrete particles which are interacting to each other within a defined area.

As mentioned before, it is not necessary to define a damage model for CEL and SPH. It is the scope of this work to compare the influence of the formulations on the behavior during cutting, and to find out the applicability for industrial purposes.

3 SIMULATION MODELS OF THE CUTTING PROCESS

The set-up of the simulation model is shown in Figure 1. A sheet metal of 4 mm thickness and 6 mm width is fixed by an upper and a lower clamping tool. The cutting process is controlled by a blade with 6° inclination. It moves downwards with a cutting speed of 0.5 m/s, which is a common average cutting velocity in blanking processes due to [4]. The cutting clearance is 0.1 mm. In both simulation models the clamping tools and the blade are discretized by Lagrangian elements with an edge length of approximately 0.5 mm.

Figure 1a) shows the SPH model. The sheet is discretized by Smoothed Particles. In the unloaded, initial state the particles are evenly spread at intervals of 0.25 mm in each spatial direction.

The CEL model is presented in Figure 1b) and 1c). Subplot c) shows the clamping tools, the blade and the complete Eulerian mesh with an element size of 0.25 mm. The material of the sheet metal can move and deform only within the region that is covered by the Eulerian mesh [3]. Material that leaves the mesh is no longer taken into account within the simulation. In the initial state most of the Eulerian mesh is void. Only the red region shown in Figure 1b is occupied by material. During the cutting process a chip is generated and displaced by the blade. Because of the relatively large volume needed to preserve the chip from leaving the model space the number of Eulerian Finite elements is much higher than the number of Smoothed Particles.

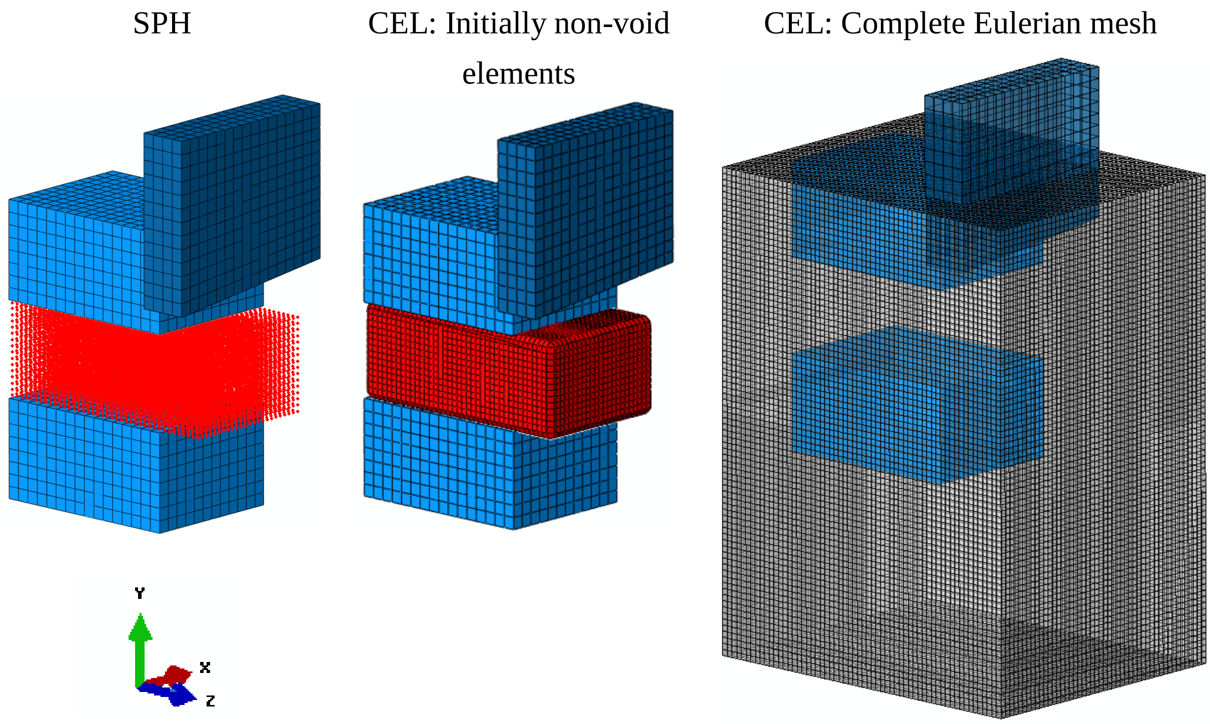

Figure 1: Simulation models: a) SPH, b) CEL: non-void region, b) CEL: Complete mesh

Both models contain 3904 linear Lagrangian Elements of type C3D8R. In the first model the metal is modelled by 15360 Smoothed Particles whereas in the second model the Eulerian domain consists of 230400 elements of type EC3D8R.

Starting with a convergence study with different mesh refinements, it turned out that a reliable distribution of contact forces between sheet metal and cutting blade are obtained with a ratio of 1:2 concerning the element size of the cutting tool and the sheet metal.

It is assumed that the clamping and cutting tools are much harder that the work piece and perform only small deformations during the cutting process. Therefore the tools are modeled as linear elastic material, characterized by Young's modulus E=210000 N/mm² and Poisson's ratio ν = 0.3. The same model is used to model the sheet's material in the linear elastic range. After exceeding the yield stress, plastic strains occur. In the following we assume isotropic hardening according to v.Mises yield function. In the first step, a very simple flow curve as shown in **Figure 2** is taken into account. The figure shows the Cauchy stress as a function of the plastic strain (Hencky strain).

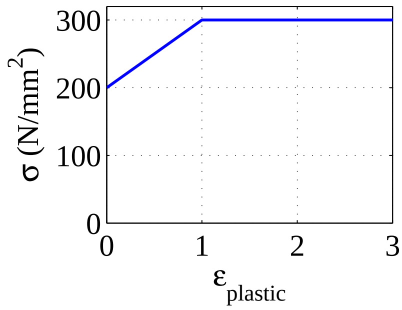

Figure 2: Stress-strain relationship in the applied model of isotropic hardening

For the chosen mesh refinement the simulation time for both models is approximatively equal. However, in case of a 20 % finer mesh of all components, the computation time of the CEL model becomes more than twice compared to the SPH model.

4 EVALUATION OF THE SIMULATION RESULTS

First the stresses in the chip as well as the shape of the chips will be regarded. Afterwards the stress distribution in the cutting tools will be examined. At last the cutting forces are discussed and qualitatively compared to experimental results.

When comparing the distribution of the v.Mises stresses in the sheet metal during the cutting process there is a high level of consistency between the two models. This is exemplified for the beginning of the cutting at the time 3.95 ms in Figure 3.

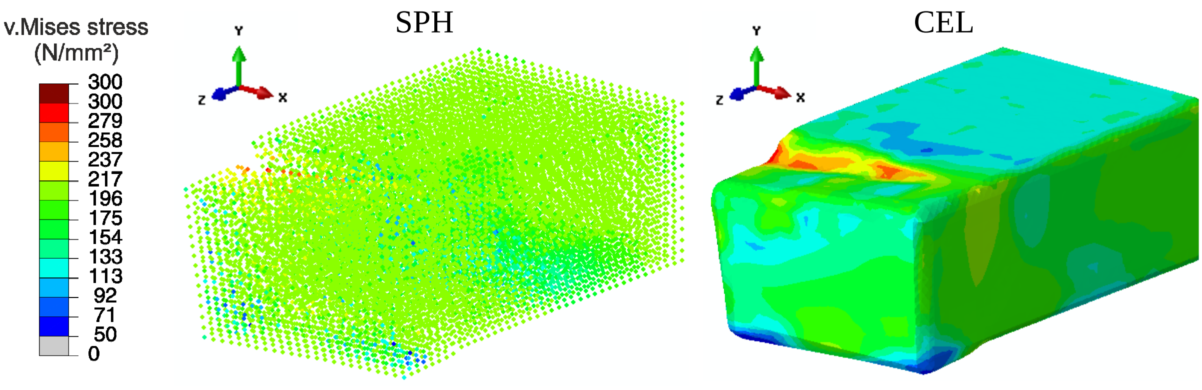

Figure 3: Distribution of v.Mises stresses in the sheet metal at the beginning of the cutting process

Figure 4 shows the shape of the chip at time 9.79 ms. At that time the sheet metal has already been highly deformed, i.e. almost cut off. On the one hand there is a high resemblance concerning the shape as well as the size of the flakes in the two models. On the other hand there are qualitative differences in the region of the cutting surface. In the model that uses SPH there is contact between the sheet metal and the blade almost across the whole cutting surface. In contrast in the CEL model the cutting surface touches the blade only in a small region at the bottom. This effect is a result of the Eulerian formulation: The Eulerian elements interacting with the blade are partially void.

It should be mentioned that in both models the contour plots of the metal sheets provide less significant results than the ones of the cutting tools which are modeled by Lagrangian Finite elements. Because of the discrete arrangement of the Smoothed Particles they do not provide exact information of the free boundaries of the material.

Within the CEL method the free boundaries of the material-filled regions in the Eulerian mesh are estimated based on the material volume fractions [3], which is the ratio of void and filled material within an element.

In the next step the distribution of the v.Mises stresses in the cutting tools is compared. Figure 4 shows a high level of consistency in the distribution of the stresses. However there are higher magnitudes in the v.Mises stresses in the model with CEL elements.

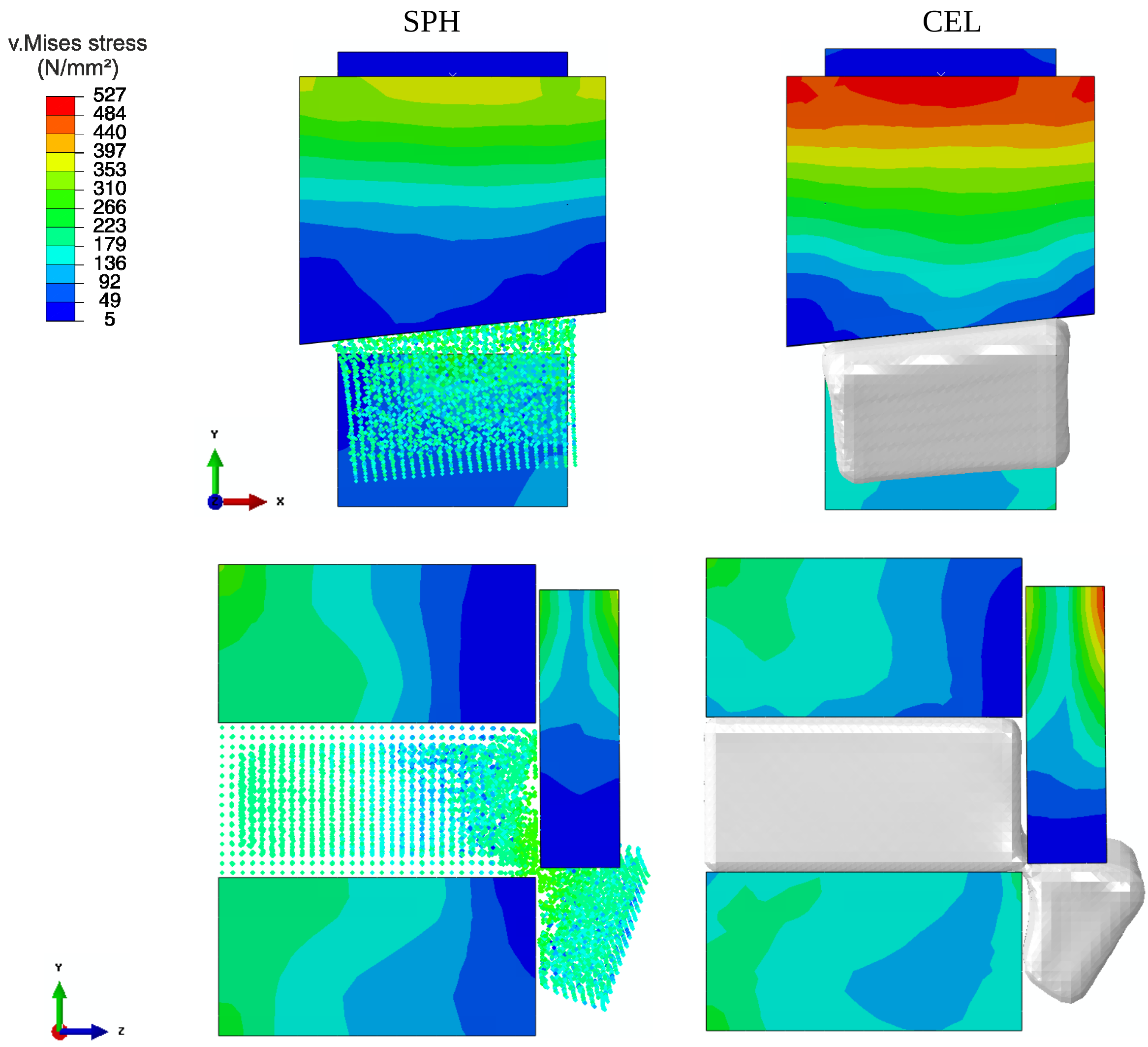

Figure 4: Distribution of the v.Mises stresses in the cutting tools and shape of the chip

This is also reflected by the magnitude of the contact pressure on the blade shown in Figure 5 at time 3.08 ms. It is higher in the CEL model than in the SPH model. The distribution of the contact pressure especially on the upper clamping tool shows high similarity for both methods.

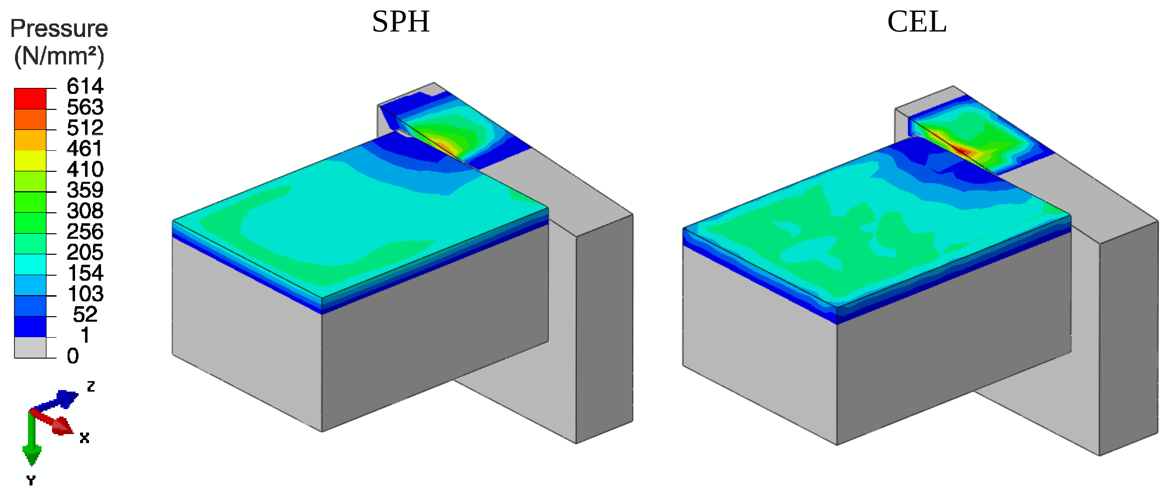

Figure 5: Contact pressure on blade and upper tool

Figure 6 shows the resulting forces that occur at the clamping of the blade in the cutting direction. For both methods the beginning of the cut is characterized by a steep rise of the blade forces. The maximum force in the CEL solution is approximatively 25 % higher than the one of the SPH method. The material is cut off after a time of 12.4 ms. After that point of time higher friction forces at the cutting surface can be found in the case of SPH than in the case of CEL which is resembled in the blade forces.

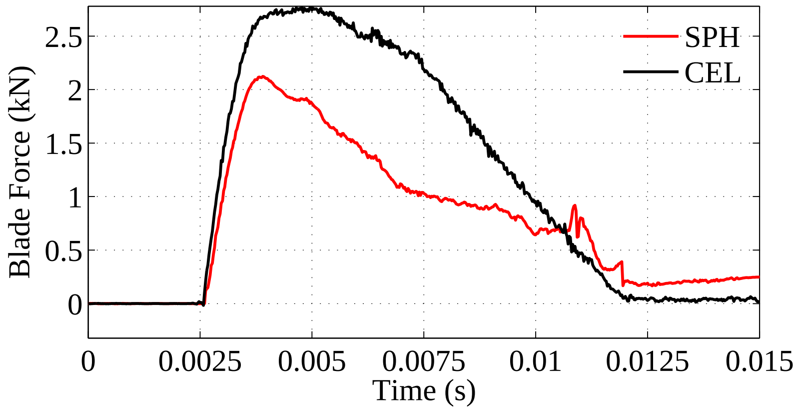

Figure 6: Blade forces in vertical direction

4.1 Comparison with measurements

Finally, the simulation results are compared to measurements performed on a Salvagnini automatic panel bender. A direct comparison of forces is not possible yet because of differing configurations in the simulation model and the experiment concerning dimensions of the sheet, tools and trajectories. It is the planned next step to adapt the simulation model to the configuration of the real machine. However, a qualitative comparison is already possible.

Figure 7 shows the measurement result for the resulting vertical force related to the maximum admissible force of the actuators. Three materials are investigated: two kinds of stainless steel with thickness 1.5 mm and almost the same nominal tensile strength $R_{m,}$ as well as mild steel with thickness 2 mm. The length of the sheets has been 260 mm. Figure 7 shows an increase of the force up to a maximum value. After reaching the first cut through the sheet on the first boundary, the force starts to decrease. Finally, the force drops rapidly when the cut is finished. It has turned out that for the two sheets of stainless steel with almost the same nominal tensile strength the measured force differs of about 15%.

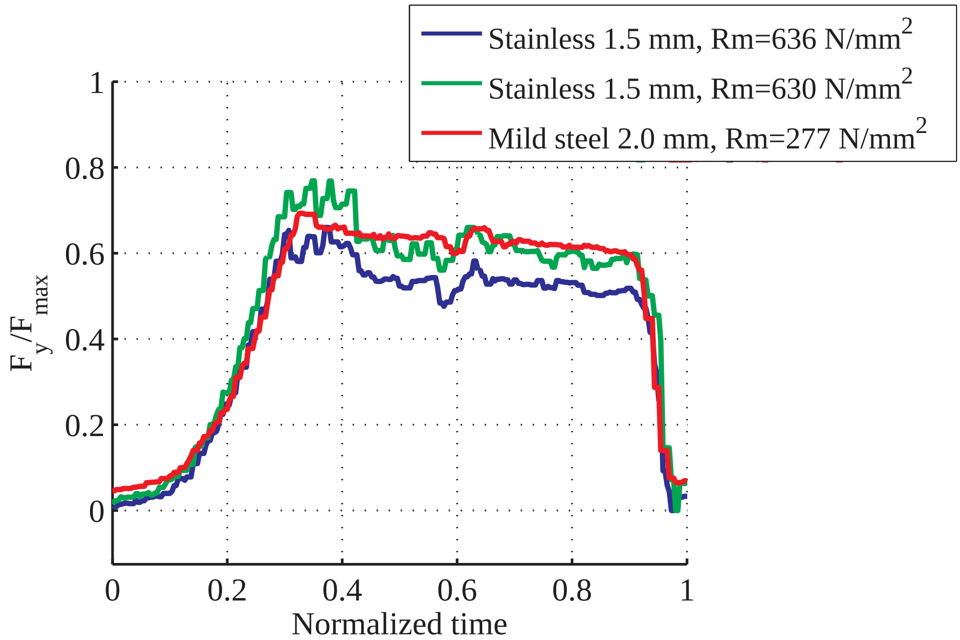

Figure 7: Measurement of resulting force in vertical direction

As mentioned above, only a qualitative comparison with the simulation results in Figure 6 is possible, because of different configurations of simulation model and experimental setup:

- Geometrical dimensions: Differing sheet length and thickness, differing tool geometries. Moreover the construction of the machine is far more complex than the simple simulation model. Elastic deformations have an influence on the measured forces,
- Different constitutive behavior: In the simulation models very a simple material behavior has been assumed as shown in Figure 2. On the other hand on the machine real materials with exponential flow curves have been cut. Thus, the decrease of the force after reaching the maximum value is less in the experiment than in the simulation.

The comparison shows the following qualitative coincidence of simulation and measurement:

- An increase of the force up to a maximum value
- A moderate decrease of the force after the first cut through the sheet.
- A rapid decrease at the end of the cut: This behavior is shown only in the SPH solution.
- The maximum forces in the two simulation models are differing of about 25%. In contrast on the machine differences of 15% for almost equal materials have been measured. Therefore the differences of the two simulation methods are in the same order of magnitude.

5 CONCLUSIONS

Two simulation methods have been compared for modelling cutting processes, i.e. CEL and SPH. Both methods are suitable to represent the main effects. Concerning the geometry of the cutting surface and the stress distribution in the cut material the methods show a good correspondence. Due to the differences of the formulations, the resulting forces do differ of about 25%. On the other hand, deviations in the same order of magnitude have been noticed in the experiment, comparing two kinds of stainless steel with almost the same tensile strength. The effect of rapid decrease of the resulting force at the end of the cut is only obtained in the SPH solution. The next planned steps are to adapt the simulation model to the experiment (geometry and constitutive relations) and to calibrate the parameters by measurements.

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