An Innovate Approach to Automated Simulation of Full 3D Ring Rolling Process and Other Incremental Forming Processes

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As the setting of ring rolling processes is influenced by a lot of parameters, the need to optimize conditions using forming simulation is growing with the constantly raising demands to shorten the time to market and to simultaneously reduce the development costs. Especially for huge workpieces or workpieces made out of expensive alloys experiments are no longer an adequate base for process setting and optimization. This paper focuses on an aspect of the simulation of ring rolling and other incremental forming processes often neglected in the discussion of the required models: Frequently these processes are not driven by predefined kinematics but controlled by tricky algorithms based on in-process information and feedback. For industrial relevant simulations this closed-loop process control of the real machine needs to be implemented enabling to use - and thus to optimize - the same setting parameters in simulation and reality. An innovative, already implemented approach to include this process control into automated simulations of all kind of incremental forming processes is presented. All control algorithms are integrated into the Finite Element Solver thus time consuming switching between post processing and solution phase of the analysis is avoided and in time feedback and control is enabled within each increment which leads to stable and fast simulations with results very close to the reality. Mostly ring rolling is used to demonstrate the efficiency of the current approach, but additional examples such as cogging processes are given, too.

Keywords: ring rolling, incremental forming, forming simulation, finite element method, closed-loop process control

Introduction

Ring rolling processes are widely used in industry because they are an effective method to produce ring shaped parts with a small cross section compared to the overall dimensions.

Even with the ring rolling machine and thus the basic kinematics are given, the setting of a rolling process is influenced by a lot of parameters and may be difficult to control. Initially the ring growth velocity – the increase of the ring diameter per unit time – may be limited by the machine power or stiffness. After this a high ring growth velocity ensures an effective process. At the end of the process a calibration phase may be needed to achieve the ring roundness and the desired cross section. During the whole process the rotation of the ring with minimum slip and a stable movement of the ring center must be achieved.

Modern ring rolling machines use sophisticated in-process measurement and closed-loop control to maintain a stable and effective process based on higher-order settings like the desired ring growth velocity. But these higher-order settings still need to be found, verified and optimized. Additionally further development of the control algorithm of the machine may be desired. With the constantly raising demands to shorten the time to market and to simultaneously reduce the development costs, shop-floor testing is no longer adequate.

Thus there is a growing need for forming simulation of ring rolling processes. The use of ring rolling simulation was limited in the past. This was due to the excessive calculation times of the needed 3d models and the required huge number of calculation increments to reflect the incremental process characteristics. Additionally the complex kinematics and the demanding contact conditions are a challenge for the simulation.

In [1] a summary of research activities to enable fast and accurate ring rolling simulations is given. One approach for this is to use dynamic explicit finite element simulations, e.g. [2]. But generally this approach is known for its limited accuracy of calculated residual stresses and process forces when mass scaling is used to achieve computational efficiency, compare [3].

V. Hehl [4] stresses the difficulties of finite element ring rolling simulations as reason for his development of a modular system for fast microstructure evaluation. He points out that for finite element simulations the kinematics, thus the changing speeds and feeds, need to be considered very accurately.

Requirements on Ring Rolling Simulation

The requirements on the ring rolling simulation can be separated into two groups:

1) General requirements on the model to achieve realistic simulations based on the movement of the rolls.
2) Requirements regarding in-process measurement and closed-loop control to avoid the need to predefine all movements and to enable process control based on higher-order settings similar to the real machine control.

This paper focuses on the second group of requirements and how they are met.

Model Set-up for Ring Rolling Simulation

The commercial software simufact.forming is used for the simulations presented in this paper. The software uses customized versions of the finite element solver MSC.Marc and of the finite volume solver MSC.Dytran. For ring rolling the implicit finite element method is used.

The solver allows rigid body movements, thus the ring can be rotated and there is no need to move the rolls around the ring. Elastic-plastic material behavior is used in fully mechanical-thermal coupled analysis which enables to include the calibration phase in the simulation. Volume

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constancy is not predefined but results form the accurate modeling of the physics. Contact and friction calculation, including the release of nodes that leave a roll, is stable.

For the ring rolling simulations a special ring mesher is used that produces a consistent mesh of hexahedron elements (**Figure 1**). For finite element analysis, hexahedron element is known to produce better results. To speed up the simulation the stabilizing effect of the rolling table can be replaced by a spring stabilizer that adds tilting stiffness to the model.

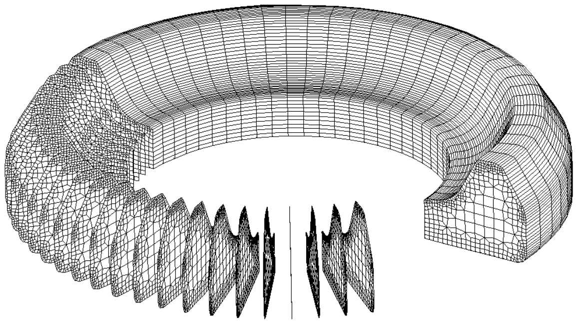

Figure 1. Finite element mesh produced automatically with ring mesher, partly as cross sections to show the principle.

The models contain the real kinematics, including skew-whiff axes and the separation between driven rolls and drag rolls. The drag rolls are rotated by friction and not modeled as not rotating frictionless cylinders. As far as it is predefined, the detailed movement of the rolls is used as input including multi-dimensional forward and backward movements.

As the loads and boundary conditions on the workpiece are not symmetric during ring rolling full 3d models have been used. Even in cases where symmetry perpendicular to the ring axis may be a reasonable assumption, symmetry should not be used because of the stabilizing effect of the symmetry plane that would suppress all tilting effects.

Integration of Closed-Loop Control in Simulation

Typically the translational and rotational velocities of the dies are used to calculate the finite element solution. But for most incremental forming processes the velocities are usually not pre-defined for the whole process. Within the real machine the current status –positions, dimensions, and forces – is continuously measured and used to calculate updated speeds and feeds using closed-loop control. For industrial relevant simulations of such processes the same control loop must be implemented in the simulation.

Positions, dimensions and forces are usually analyzed in the post-processing phase of a finite element analysis, whereas the definition of velocities is normally done in the pre-processing phase. In the controlled simulation of incremental forming processes this would lead to continuous ineffective jumping between the different phases and thus probably to a control loop only every couple of increments. To avoid this and to enable process control within each increment the whole control algorithm was integrated into the finite element solver, including the required measurement of positions, dimensions, forces and other status quantities (**Figure 2**).

During the solution phase the solver knows the current center positions and translational and rotational velocities of all rolls, which are modeled as rigid bodies, as well as the forces on them. Furthermore the bounding box dimensions of the deformable bodies can be queried. These and some more values can be accessed by user subroutines, which read input parameters, for example higher-order settings, form the input file. Based on this theses subroutines calculate the desired position, velocity or force for each rigid body. The calculated data is then used to control to the rigid body in the next calculation step. The result is a fast and robust closed-loop process control.

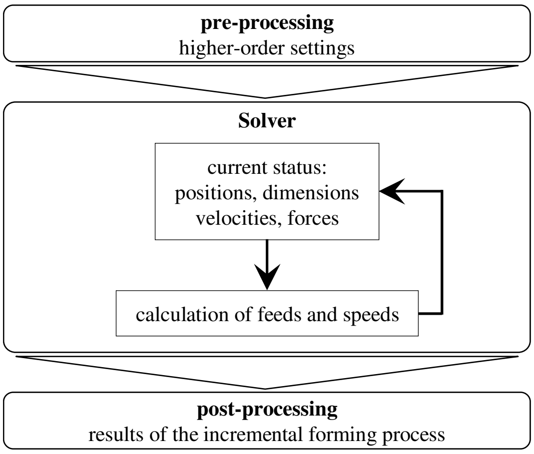

Figure 2. Closed-loop control within finite element solver.

On the one hand simufact.forming is shipped with a set of standard controls for the most common applications. On the other hand this approach can be used to implement special applications, for example to match a certain CNC control. Because these special applications are confidential only some standard controls can be presented here as examples to show the strength and effectiveness of this approach to model incremental forming processes.

Center Rolls. During radial axial ring rolling the ring is guided by one or two center rolls to maintain the desired position of the ring center. The center rolls themselves move on an arc with the position controlled by the current diameter of the ring or by other individual parameters (**Figure 3**). Thus the ring diameter needs to be determined continuously during the simulation and the updated position of the center rolls needs to be calculated and controlled. The diameter of the ring can either be determined by the bonding box of the ring or by the position of a spring loaded measurement roll. The later alternative is especially useful for profiled rings and allows to match the real measurement in the rolling machine. The center rolls are free rotating drag rolls.

Infeed Velocity. For some radial profile ring rolling processes additionally to the position of the center roll the infeed velocity of the main roll is controlled by the current ring diameter, including the switch to the calibration phase, as shown in **Figure 4**.

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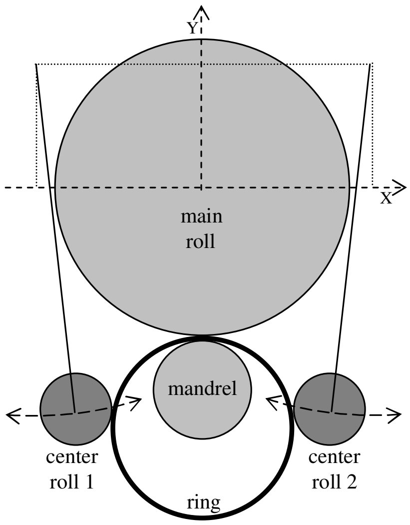

Figure 3. Path of center rolls during axial radial ring rolling, axial rolls omitted.

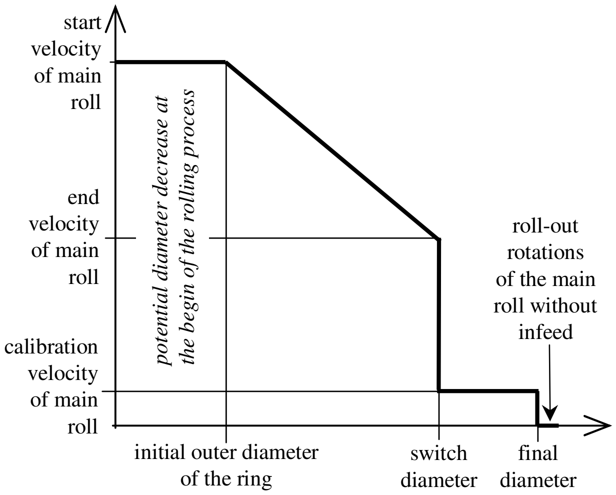

Figure 4. Infeed velocity of main roll depending on ring diameter for radial profile ring rolling.

Results of Ring Rolling Simulation

Center Rolls. Hot radial axial ring rolling of C60 steel is used as an example to demonstrate the accuracy of simufact.forming's standard control of the position of the center rolls for radial axial ring rolling. In this example the outer diameter of a ring with rectangular cross-section is increased by the factor 1.8 to 790 mm. **Figure 5** shows the model, **Figure 6** the temperature distribution at the end of the process.

The movements of mandrel and axial rolls and the rotation of the driven main roll and axial rolls were taken as input form the real process. The position of the center rolls was controlled by the current ring diameter thus that the center rolls are always just touching the ring. If desired, offsets can be specified to position the center rolls tighter or looser or to offset the center of the ring from the line through the centers of mandrel and main roll, which is useful for profiled rings.

Figure 7 compares the simulated path of the center rolls with their path in reality. It can be seen that simulation and reality are in good agreement. It should be noted that the real control strategy may have differed from the implemented control resulting in justified differences. The calculation time of the shown model was about three days on a standard workstation using only one CPU.

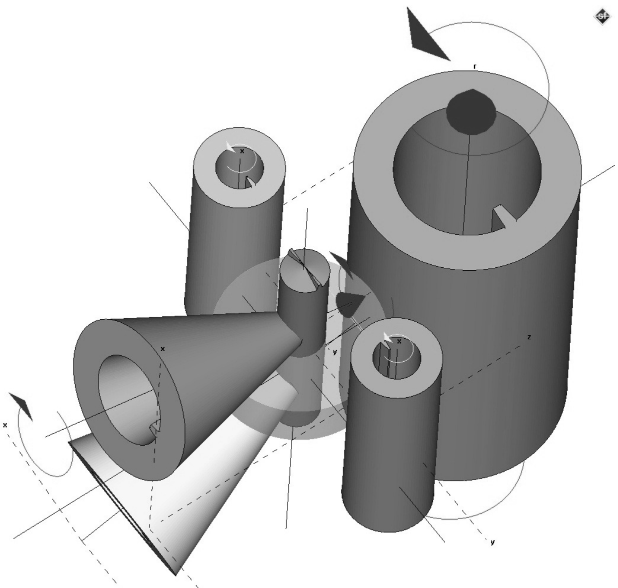

Figure 5. Radial axial ring rolling model, initial position.

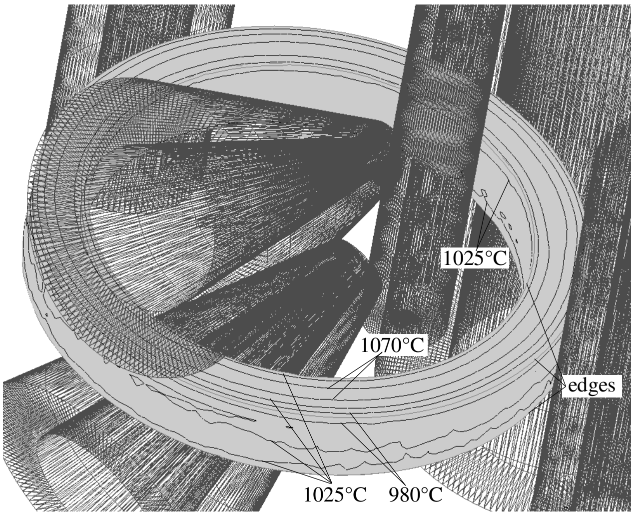

Figure 6. Temperature distribution at end of example process.

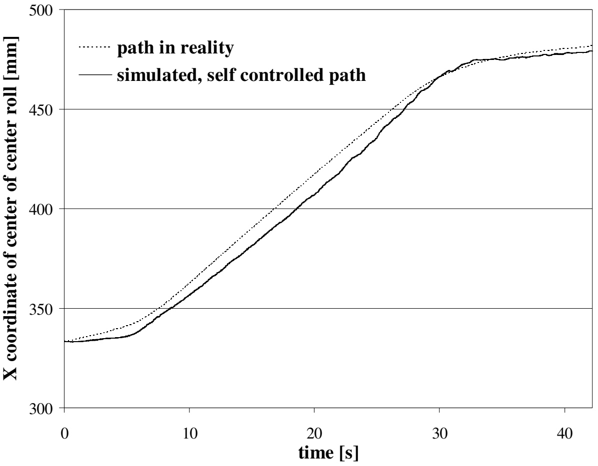

Figure 7. Path of center roll.

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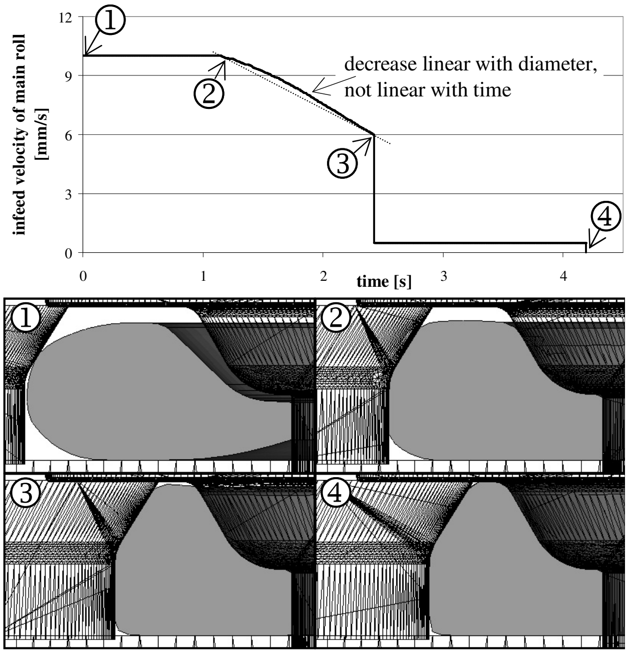
Infeed Velocity. Hot radial profile ring rolling of 42CrMo4 steel is used to demonstrate simufact.forming's standard control of the infeed velocity of the main roll. In this example mainly the profile of the ring is formed, the outer diameter is only slightly increased to 210 mm. The main roll is the only driven roll and rotates with constant frequency. Its movement was defined as function of the current ring diameter as described in Figure 4. This included the determination of the end of the process, too.

The results shown in **Figure 8** illustrate how this control links the infeed velocity to the diameter and the form fill. The calculation time of the used model was about a day on a standard workstation using only one CPU.



① start of the process

② inner profile filled → ring diameter starts to increase → infeed velocity is reduced

③ profile nearly filled, ring switch diameter reached → calibration starts

④ end of the process

Figure 8. Infeed control for radial profile ring rolling.

Adaptation of Simulation Approach to Cogging

Cogging and radial forging are incremental forming processes that need in-process control, too, because the number of blows in each pass is usually not predefined but depends on the current length of the part. The principle and the architecture of the described closed-loop control can be used for this.

Simufact.forming's standard control for cogging and radial forging calculates not only the required number of blows in a pass but enables the input of comprehensive forging plans consisting of several heats and passes using standard forging nomenclature. All required movement and rotations are calculated during the simulation based on the current shape of the part. Heating and cooling processes can be included. **Figure 9** shows the temperature distribution during cold radial forging of a 9 kg pipe made of 16MnCr5 steel.

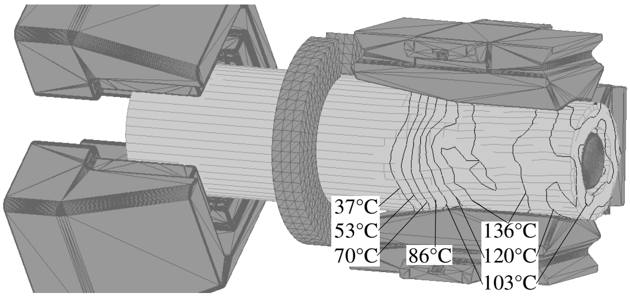


Figure 9. Temperature distribution in a radial forging process with four forging heads, front head masked out.

Conclusions

Ring rolling and other incremental forming processes are usually not driven by predefined kinematics but controlled based on in-process information. For industrial relevant simulations this closed-loop control needs to be implemented. An effective approach for this is to integrate the whole control algorithm, including the required measurement of positions, dimensions, forces and other status quantities, into the finite element solver. This way time consuming switching between pre-processing, solution and post-processing phase is avoided and control is enabled within each calculation increment.

This solver integrated closed-loop control enables real process optimization using the same higher-order settings in simulation and reality. Ring rolling, cogging and radial forging can be simulated efficiently using the standard controls of simufact.forming. But the concept and the open architecture enable the adaptation of closed-loop control to all kind of incremental forming processes. Further control algorithms are in development, partly in cooperation with machine manufactures to implement the same controls in simulation and in reality.

Ring rolling simulation can be combined with the simulation of the pre-forming and heat treatment operations to achieve the closed simulation of the whole process chain. Changes in the microstructure can be included in the simulation, too. With parallel computing using the domain decomposition method a considerable speed up of the simulations is possible.

References

[1] P. Groche, D. Fritsche, E.A. Tekkaya, J.M. Allwood, G. Hirt, R. Neugebauer: Incremental Bulk Metal Forming, CIRP Annals, 56-2 (2007), 635-656.

[2] M. Wang, H. Yang, Z.C. Sun, L.G. Guo: Analysis of coupled mechanical and thermal behaviors in hot rolling of large rings of titanium alloy using 3D dynamic explicit FEM, Journal of Materials Processing Technology, 209-7 (2009), 3384-3395.

[3] P. Pauskar: Finite Element Modelling of Incremental Forming Processes at The Timken Company, Workshop on Modelling of Incremental Bulk Forming Processes, Darmstadt, Germany, 2006.

[4] Hehl, A. v.: Thermomechanische Behandlung beim Ringwalzen – Modelle zur schnellen Simulation der Gefügeevolution, Dissertation RWTH Aachen, Shaker Verlag, Aachen 2010.

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