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Process chain optimization through digital twin technology with casting process simulation in the BMWI research project "SiPro"

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Digital simulation technology today makes is easily possible to carry out three-dimensional process simulation of the entire continuous casting process. State-of-art simulation tools provide quantitative insights into flow, solidification and stress formation. This includes the entire process, from the tundish and the flow into the mold to the solidifying strand that is withdrawn through the secondary cooling zones. Recent developments in modelling of electromagnetic stirring (EMS) and its impact on the flow behaviour as well as a thermomechanical coupling with simulation of stress development in the strand can also be considered.

The classical use of simulation solutions has evolved to approaches focusing on the optimization of the complete process. Statistical tools such as virtual Design of Experiments allow the performance of systematic virtual experimentation covering the complete process window. In this manner, expensive and energy intensive experimental trials can be avoided and replaced with the digital twin technology of MAGMA CC.

A simulation-based optimization of the process chain to save energy, resources and costs is the main focus in the BMWI project “SiPro”. The degree of digitalization in steelworks and subsequent steel processing companies is increasing significantly, which consequently amplifies the importance of identifying significant process parameters and investigating the effect of parameter changes. Important information about the quality, productivity and energy saving potential of process alternatives can be investigated through virtual experiments. Based on this knowledge, the optimized casting processes are both cost- and energy-efficient, as well as robust with respect to final product quality and its sensitivity to process variations.

By using MAGMA CC and through the development of new interfaces, it is also possible to connect and integrate separated simulation approaches and close the virtual process chain, to include subsequent forming and forging simulations up to the final product performance.

The results are shown for pilot and industrial scale examples of billets and bloom casters. The objective is to realize the full cost and energy saving potential, reduce CO_2 emissions as well as improve quality by using digital twin technology during production.

KEYWORDS: VIRTUAL EXPERIMENTATION – CONTINUOUS CASTING – DIGITALIZATION – DIGITAL TWIN – ELECTROMAGNETIC STIRRING – PROCESS OPTIMIZATION

Introduction

The "SiPro" project focuses on developing simulation-based methods to optimize process chains in steel mills and processing companies, aiming to save energy and resources while enhancing digitalization. By building on the capabilities of MAGMASOFT® for casting process simulation, the project seeks to optimize process chains, reduce energy consumption, and minimize scrap. The integration of

MAGMASOFT® with new interfaces unifies previously separate simulation approaches ("island solutions"), allowing the identification of optimization potentials across all stages of production. This holistic approach is designed to achieve energy savings and significantly reduce CO_2 emissions throughout the manufacturing process.

To meet the ambitious goals of energy and resource efficiency in metallic goods production, the project aims to numerically set up and optimize the process chains of primary and secondary forming for industrially relevant production routes. By equipping each process stage with advanced measurement technology, the project not only facilitates the digitization of individual processes running in parallel but also enables the validation of simulation results. The development of a corresponding simulation interface allows for seamless data transfer between individual simulation programs, enabling comprehensive evaluations to identify and optimize potential weak points in the entire process.

This paper presents an example of a digital twin, showcasing the integrated coupling of continuous casting simulation in MAGMASOFT® with forging simulation in Simufact. This approach highlights potential strategies to reduce CO_2 emissions and increase energy efficiency, with particular attention given to the microstructural characteristics of the investigated material. Segregations, defects, and other microstructural features are modeled within the casting simulation and seamlessly transferred to subsequent forming simulations, ensuring a robust analysis of material behavior and process optimization.

Reference Case

This paper illustrates the approach using a common process chain for a ring rolling process as a reference case. The process begins with the continuous casting of steel at the Georgsmarienhütte Holding GmbH (GMH) facility. After casting, the billet is cut and then undergoes open die forging and subsequent ring rolling at Rosswag GmbH. Figure 1 provides a brief overview of the considered case.

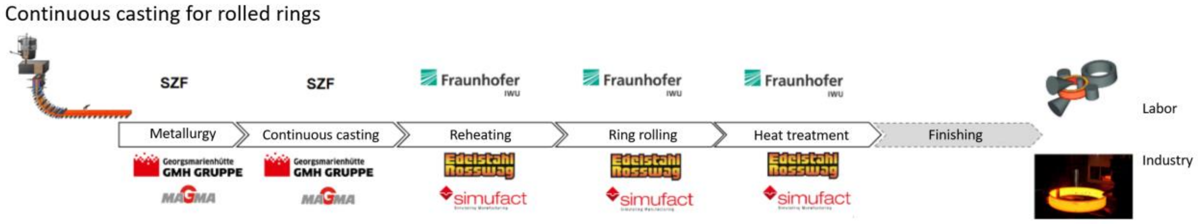

Fig. 1. The reference case of the ring production process route, including the participating organizations and the simulation tools.

The schematic representation of the temperature throughout the process chain is shown in Figure 2. After casting, the billets were reheated to 1200°C. The forging process then began with a starting temperature of 1156°C, involving several key steps: upsetting to a height of 207mm, pressing and rounding corners, and subsequent punching, with precise measurements for each operation. A mandrel was used to achieve specific dimensions, including rounding to 470mm and final upsetting to 206mm. The process was completed in 5 minutes, resulting in a workpiece with dimensions of 480mm outer diameter, 150mm inner diameter, 207mm height, and a wall thickness of 164mm, with a final temperature of 955°C. Following the initial forging, a rolling process commenced after a second heating to 1123°C, during which the workpiece was rolled to rough dimensions as per the specified rolling data. The rolling process lasted 4 minutes, with a final temperature of 1063°C.

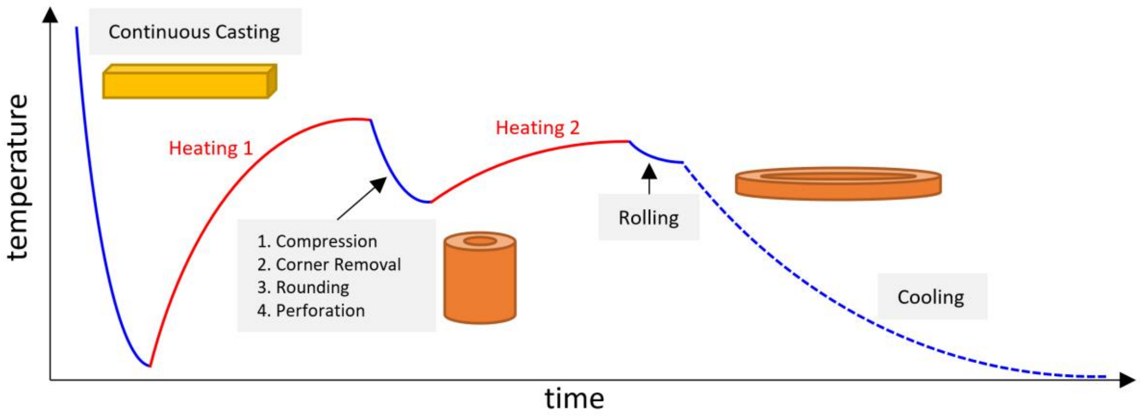

Fig. 2. The temperature profile and processing steps of the entire ring rolling process.

Numerical models description

The numerical simulations are performed using two software packages: MAGMASOFT® for the continuous casting process and Simufact Forming for the subsequent processing steps, including heating, forging and rolling.

Continuous Casting Simulation

The continuous casting simulation utilizes a 3D transient model based on the finite volume method (FVM) to calculate velocity and temperature fields within the strand as it is withdrawn, accounting for solidification and electromagnetic stirring (EMS) effects. The L-VEL turbulence model is employed to capture the flow dynamics, and temperature-dependent thermophysical properties, including variations with solid fraction, are incorporated into the model. Heat transfer coefficients are carefully configured to represent primary heat extraction in the mold and secondary cooling processes.

The electromagnetic field and resulting Lorentz forces are computed once due to the low magnetic Reynolds number. The electromagnetic field calculations are performed on a separate mesh, with the results interpolated onto the main grid used for fluid flow simulation. Detailed descriptions of the numerical model and its validation can be found in references [1] and [2].

In this study, the segregation computation models the transport of multiple chemical species during the continuous casting process, focusing on the formation of macrosegregation, a critical defect in continuous-cast steel that cannot be remedied by heat treatment. The model treats both liquid and solid phases, with no relative motion between them. Above the freezing temperature, equiaxed crystals are assumed to move with the liquid phase velocity. Below this temperature, both phases are constrained to the prescribed withdrawal velocity. The formulation is based on the work of Schneider and Beckermann [3], solving transport equations for each chemical element while accounting for both diffusion and convective transport.

Continuous Casting process description. The continuous casting process is simulated in a comprehensive 3D framework that incorporates fluid mechanics of the liquid phase, heat transfer in both solid and liquid phases, and latent heat release during solidification. The simulation focuses on the C45 alloy, with thermophysical parameters generated using JMatPro®. Key process parameters are as follows:

Parameter	**Value**
Casting Format	250×250 mm^2
Pouring Temperature	1523 °C
Casting Speed	1000 mm/min
Superheat	35 °C
M-EMS	On

Cooling is defined as primary (2000 W/m²K in the mold) and secondary water cooling, which varies from 400 to 1000 W/m²K depending on the zone.

The finite volume mesh comprises 447,573 cells. The process time for a 30 m long strand is 30 minutes. Thermal simulation requires approximately 4 hours, while stress calculations take about 2 days and 10 hours (using 16 cores), and segregation simulations take 1 day and 22 hours (also using 16 cores).

Data transfer

A special interface using the so-called.m2s file format facilitates the transfer of temperature, microporosity, stress, and segregation results from MAGMASOFT® to Simufact Forming.

Forming Simulation

Following continuous casting, all subsequent processes are simulated using Simufact Forming, a software designed for metal forming process simulations, where the heating, forging and rolling processes are considered for this study. Simufact Forming offers two solver technologies: the implicit finite element solver (FE) and the explicit finite volume solver (FV). Since the FV solver is only used for flash forging processes, in this case the complete model was built using the FE solver. The finite element solver is an extended version of the MARC solver from MSC.Software Corporation. The FEM is a numerical method that solves differential equations in a continuum described by a finite element mesh. A mesh consists of many elements of different shapes that are connected to one another by nodes. This means that the stiffness method used in MARC relates forces and displacements to the stiffness of the overall system. Thus, in general, a forming process is determined by nonlinear equations. The following nonlinear effects are considered in MARC:

- Material nonlinearities
- Geometric nonlinearities
- Structural nonlinearities

Material nonlinearities consider the fact that the material properties are a function of temperature, plasticity, deformation rate, porosity, etc. The material can therefore experience elastic or elastic-plastic deformations. The geometric nonlinearities arise with large deformations and/or rotations. The structural nonlinearities (so-called boundary conditions) make it possible to map the contact between the workpiece and the die, to represent the friction behavior and complex movements (machine movements). To solve the nonlinear system, MARC proceeds incrementally, which means that many increments are required for a forming simulation. Using the Lagrange approximation, the deformation of the workpiece can be described by the change in shape of the mesh. In addition, the Newton-Raphson method is used to solve the nonlinear equations. For the modeling of open die forging in combination with ring rolling, the imported continuous casting section is meshed with tetrahedral elements, as these allow for easy meshing of even complex structures (thread cavities). Due to the size of the imported section, the element edge length is 9 mm, with the area of the thread shrinkage cavity being meshed more finely, resulting in an initial number of elements of 364303. Due to the strong deformation of the elements, adaptive remeshing is activated, which automatically creates a new, as undistorted as possible mesh on the surface of the old mesh according to defined criteria.

All tools used are modeled as rigid bodies with heat conduction. All relevant process parameters were adopted according to the real tests:

Parameter	**Value**
Tool temperature	150 °C
Press speed	86 mm/s
Friction	$\mu = 0.18, m = 0.3$

Results

Continuous Casting Simulation

One key result of the continuous casting simulation is the temperature distribution within the casting machine and the strand. Figure 3a displays the 3D temperature field of a single simulated strand, among several parallel cast strands. The simulation accounts for the SEN and water-cooled mold and support rolls. Figure 3b shows the temperature profile at the surface center along the strand length. The initial casting temperature of 1523°C decreases to 1100°C in the mold, then reheats to 1250°C. The strand is subsequently cooled by sprayed water and later undergoes passive cooling, approaching 800°C almost linearly. The simulation results closely match measured temperatures at 11.2 m and 20.95 m, demonstrating good agreement.

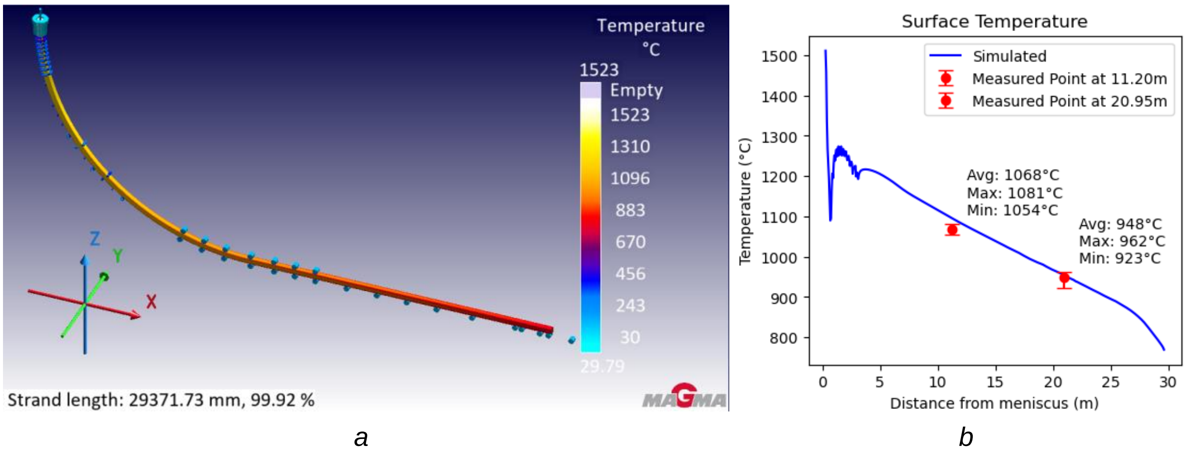

Fig. 3. Temperature results in continuous casting. a - 3D temperature field. b - temperature profile along the strand length

Macrosegregation is another important aspect evaluated in the continuous casting process. Figure 4 illustrates the carbon segregation in the cast billet. The results indicate that during the initial solidification stages, carbon-poor regions form on the surface of the strand. The central region of the billet maintains a relatively uniform carbon concentration of 0.44%, with no centerline segregation observed. These findings are supported by measurements from the GMH steel mill. Stress results, which are essential for the subsequent forming simulation, are shown in Figure 5. The Von Mises stress distribution in the cast strand reveals a maximum stress of 35 MPa, predominantly located at the outer regions and corners of the strand, while the center exhibits lower stress levels.

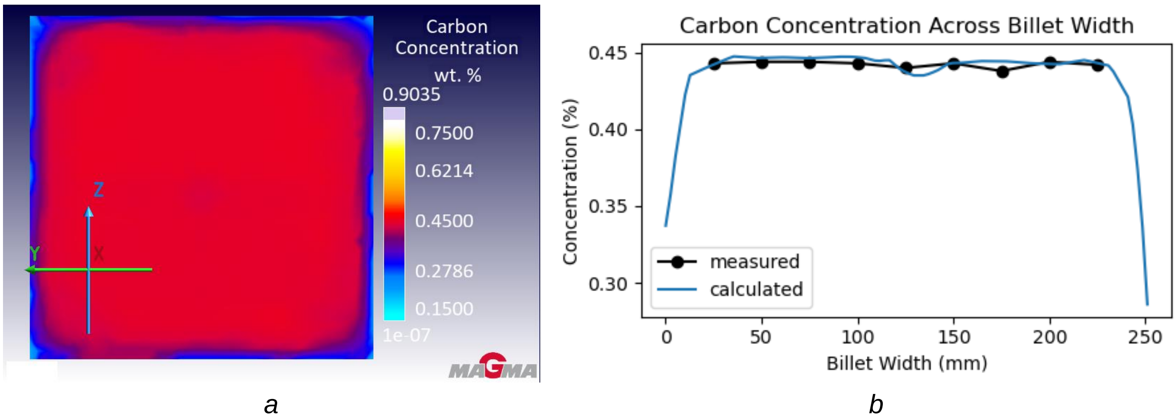

Fig. 4. Carbon concentration in the cast billet. a – cross-section of the billet.; b – Carbon concentration plot along the billet width.

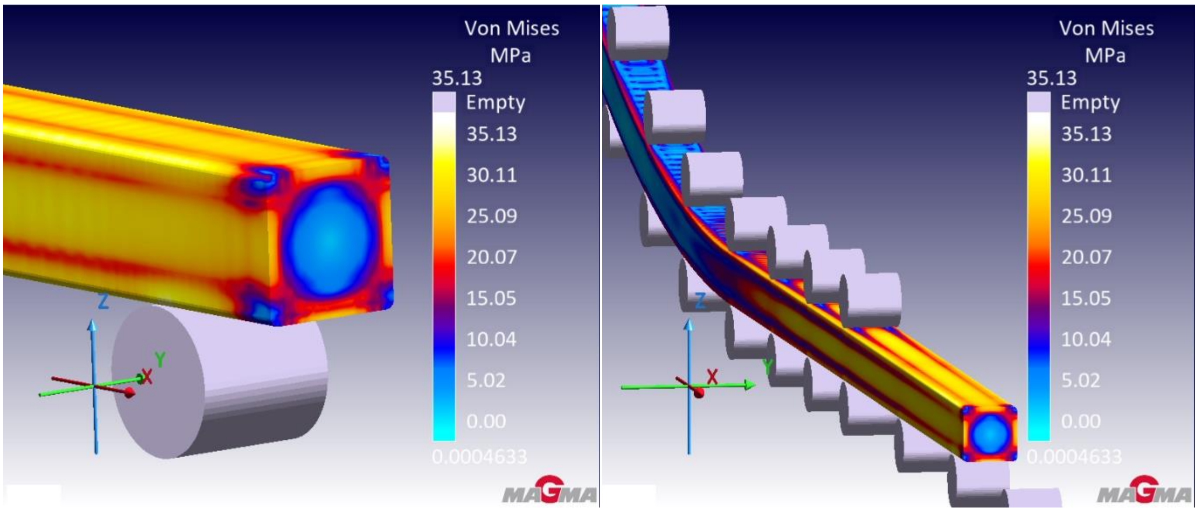

Fig. 5. Von Mises stresses in the cast strand.

Microporosity criteria were evaluated based on temperature gradients and cooling rates. Figure 6 presents the microporosity prediction for a 556 mm long billet, which will be used for further forging and rolling simulations. The main finding is significant centerline porosity, exceeding 0.56%, while the rest of the cast material exhibits negligible microporosity.

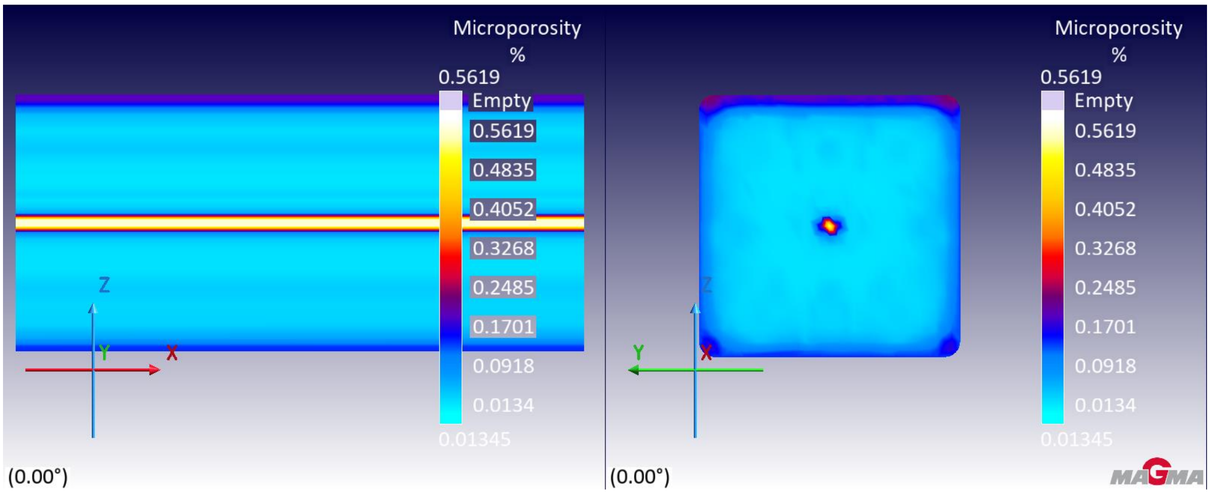

Fig. 6. Microporosity prediction in the 556 mm long billet.

Forming Simulation

Ring rolling itself is a very flexible forming process that can be used to produce a wide range of different rings (varying diameters, wall thicknesses and heights) on a single machine. However, the upstream process of open-die forging must also be considered for a consistent process analysis. With this upstream forging operation, rolled blanks tailored to the application are produced, potential defects in the semi-finished product are closed and the microstructural prerequisites for further processing in the material using forming technology are created [4].

The process sequence of Rosswag GmbH served as a reference for the desired continuous process chain. This consists of a multi-stage open die forging process, preform production and subsequent ring rolling. For exact process mapping, the complete system parameters, the process kinematics, and the process parameters were therefore first recorded by measurement and then implemented in a corresponding simulation model of the "Simufact.Forming" software.

Using the .m2s interface between MAGMASOFT® and Simufact Forming, it was possible to import the results of the first production step, continuous casting, directly into the forming simulation. Once the appropriate import parameters have been selected, the geometry can be used as the initial workpiece. The advantage of the interface is that, among other things, casting-related defects (thread shrinkage cavities) in the material are transferred. The figure below shows the imported continuous casting material.

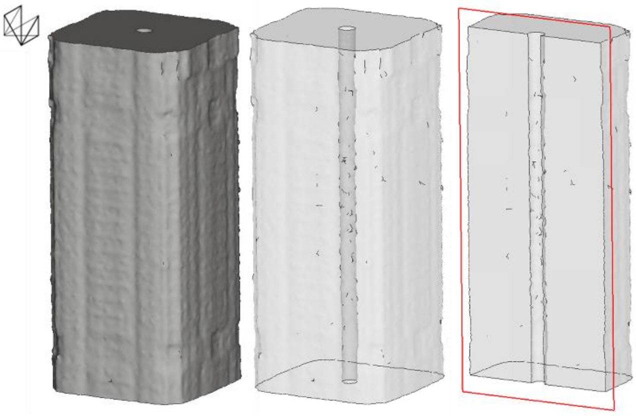

Fig.7 Continuous cast billet from MAGMASOFT® imported as the starting point for forming simulation, including centerline microporosity from the continuous casting process.

The exact start temperature for the forming process was realized via an additional simulation step "furnace heating". To achive consistency between the real process and and the process simulation, not only was this heating considered, but intermediate operations such as transport and holding times were also integrated into the process sequence. This makes it possible to track the temperature curve in the component over the entire process. In addition to the degree of forming, the forming temperature is the decisive process variable that influences the development of the microstructure and thus holds potential for optimization as a control variable for the overall process.

The initial form for ring rolling is open-die forged on a 1000 T press. The process is as follows:

- Upsetting
- Pressing away corners
- Rounding (approx. 20 strokes)
- Upsetting
- Rounding (approx. 25 strokes)
- Upsetting and punching

The calculation time for upsetting is 2 hours, a single rounding stroke takes only 30 mins, so that after 10 hours or 13 hours the results can be transferred to the next forming stage.

In addition to the result variables of temperature and equivalent plastic strain, the main focus was placed on the "development" of the thread shrinkage cavity in the center of the component. The following figure 8 illustrates the influence of the "upsetting" forming stage on the shrinkage cavity geometry. The exact display of a void as a volume element in the simulation model offers further optimization potential. In this way, forming processes can be optimized so that the sequence and degree of forming of individual forming steps can be optimized in order to effectively close cavities etc. in the component.

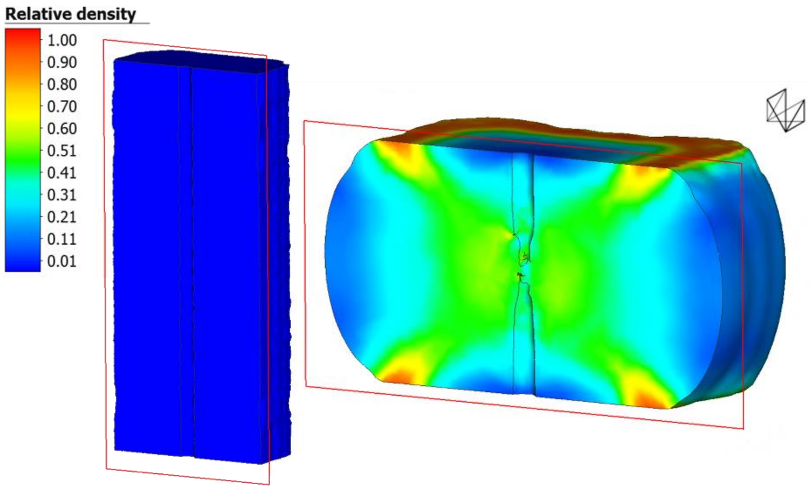

Fig.8 Forming of the continuous casting section and deformation of the thread shrinkage cavity.

By measuring each forming operation, both the geometries formed in the FE model and the resulting temperatures were compared (Figure 9).

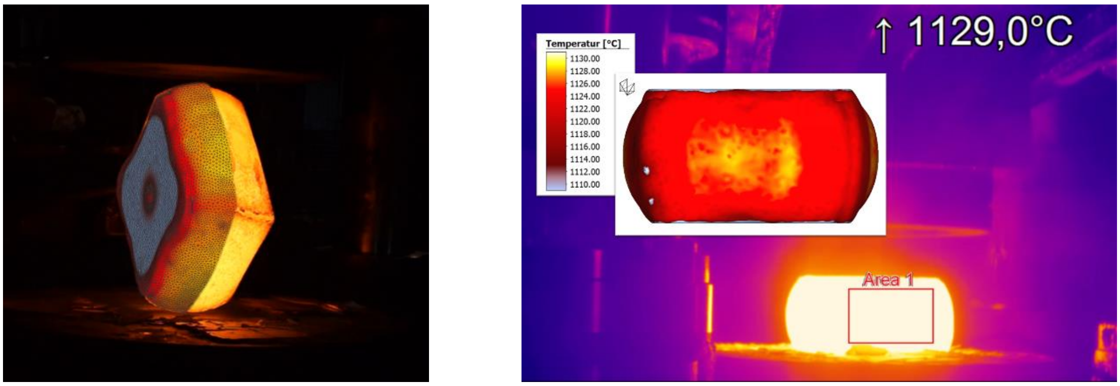

Fig.9 Comparison of the geometry and of the temperatures during the forming process.

To compare the geometries, the simulation result was superimposed over the corresponding process section in addition to a measurement in the FE software for better visualization. In addition to the almost exact geometry formation, an almost identical temperature curve could be simulated. The temperature measurement using a thermal imaging camera in the real process could be confirmed in the identical range of the FE simulation (Figure 9) by means of a value query. On average, the temperature in the simulation is only 15 K higher than the measured values of the real process.

For the final rolling process, the starting temperature of the ring blank was set at 1123°C, analogous to the series process. An overview of the ring rolling model according to the system from Rosswag GmbH is shown in figure 10.

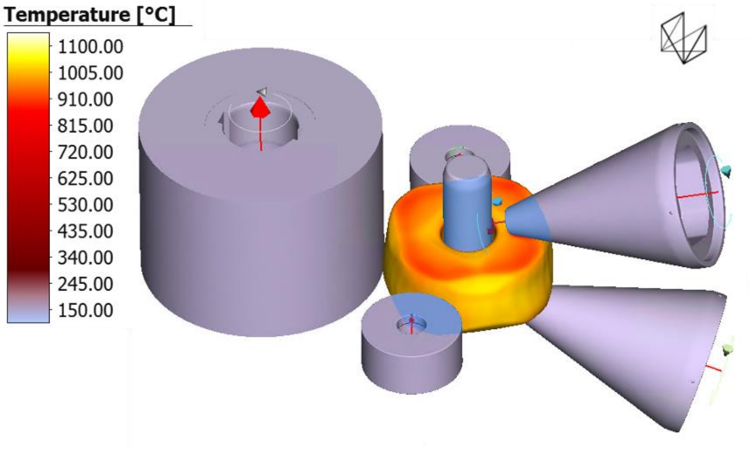

Fig. 10 Temperature of the ring during rolling simulation.

Conclusion

This study presents a comprehensive simulation of a seamless ring production chain, encompassing continuous casting, heating, forging, and final rolling stages. The validation process included comparisons with temperature and concentration measurements at various steps of the production chain. The specially developed .m2s interface for transferring information from continuous casting to the forming simulation proved instrumental in simulating such complex production chains and can be adapted for different casting-forming combinations. This tool holds significant promise for evaluating and optimizing the energy efficiency of the entire production process.

A thorough analysis of current reference processes is crucial for optimizing process chains through simulation, enabling energy and resource conservation. Accurate understanding of energy utilization or loss is essential for formulating effective recommendations. Combining extensive experience in open-die forging with advanced simulation systems will allow for quantifying potential savings, with a focus on the final product and its properties. For instance, utilizing residual casting heat could eliminate a heating stage, while simulation could reveal that certain forming curves are achieved earlier in the process, reducing the number of required forming steps.

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