QUALITY PREDICTION THROUGH COMBINED SIMULATION OF INGOT CASTING AND FORGING

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ABSTRACT

Many quality problems in forged steel products have their origin in the ingot casting process. Defects like shrinkage, porosity, segregation, non-metallic inclusions and cracks are initiated during teeming of the liquid steel, but their position and severity are also affected by the material flow during forming operations. Process simulation tools for both casting and forming processes are available and used daily for analysing and optimizing the quality and productivity of each process. These two worlds of simulation have only rarely been brought together. There is a clear need for a through-process methodology to predict possible defects and to optimize the whole process chain, such that the best possible quality and the lowest reject rate is obtained. Here, information about the shrinkage cavity, internal porosity and macrosegregation in a cast steel ingot from casting process simulation are transferred as input for the simulation of the subsequent cogging process. The results of the cogging simulation clearly show how the forming process affects the size and shape of the as-cast shrinkage and segregation or can show if internal porosity can be closed by material flow.

KEYWORDS

process chain, ingot casting simulation, forging simulation, cogging, coupled simulation, shrinkage, macrosegregation

INTRODUCTION

The final quality of forged steel products is the result of a series of production process steps. After steelmaking, the molten metal is tapped from a ladle and poured into a mould, where it solidifies and cools. The solidified ingot is then brought to its semi-finished shape through a series of reheating and forging steps. Each individual step in this process chain influences the final product quality. Many defects in forged or hot rolled products originate from the casting process.

Simulation is the state-of-art tool to investigate, understand and predict the effects of production processes on product quality. For the two main parts of the process, ingot casting on one hand and forging on the other, dedicated simulation solutions are available. These simulation tools each benefit from years of development and experience in application in their particular field. Casting process simulation is today applied in many production plants to predict and optimize the properties of an as-cast product. The simulation of forming processes is a well-established tool for process design and optimization, including forging. Simulation enables virtual trials with nearly unlimited observation possibilities.

Using casting process simulation, it is possible to teem, solidify and cool an ingot in a virtual casting process to predict e.g. shrinkage, centre-line porosity, segregation, inclusions, residual stresses and cracks that originate during casting. With forming simulation it is possible to conduct virtual hot, cold, bulk, sheet and incremental forming processes, including heating and cooling stages, to predict the shape of the part, the process forces and the resulting material properties. Typically these are temperatures, strains and stresses, but increasingly also material damage, phase constitution and grain size are predicted using simulation. Additionally, with forming simulation, die wear and die stresses can be analysed.

1. QUALITY PREDICTION FROM CASTING TO THE FINAL PART

Until today, the worlds of simulation of these two processes have only very rarely been brought together, although there is significant necessity to do so. The origin of many defects in forged or hot rolled products can be found in the casting process. The quality of the as-cast ingot is the starting point for all the subsequent reheating and deformation steps and therefore plays a decisive role in the product quality. Defects in the ingot like centre-line shrinkage or segregation are affected by the forging process. For example, the severity of porosities may be decreased e.g. by closing voids during forging. At a minimum, the position of local defects in the semi-finished product is affected by the material flow during the deformation. Inclusions or residual stresses remaining in the ingot after casting may have a detrimental impact on the product quality when the ingot is exposed to intensive deformation.

In this paper, the authors illustrate how casting and forging simulation can be combined to visualize and understand the influence of as-cast defects on forged steel product quality. The simulated properties of the as-cast ingot from a casting process simulation are transferred in a simple process to a subsequent forging or rolling simulation. Here, the position and extent of defects in the semi-finished product are predicted – at the same time, the effect of the deformation on the severity of defects is considered.

As part of this analysis, the shape of the shrinkage cavity at the top of the ingot as predicting by the casting simulation is also considered in the subsequent forming simulation.

2. CASTING PROCESS SIMULATION

Casting process simulation has been successfully applied in foundries for over 30 years. During this time, the simulation of casting processes has experienced significant further and continuous development [1]. In particular, the simulation of steel casting is a field with a long tradition for the application of simulation. Today, casting process simulation is established as a part of daily working routines to predict casting quality in many production plants.

In most cases, simulation is applied to optimize the production process. Proposed lay-outs for mould, feeders, cooling chills, the gating system and various process parameters are input into the simulation program. Afterwards, virtual casting processes are carried out in order to determine potential risks for defects and to predict material properties. The casting process can be visualized and analysed in a much more intensive and cost-saving way than would be possible with “real” experiments. Temperatures, metal velocities, flowing particles, reoxidation inclusions as well as the solidification process, potential defects and also material properties can be analysed. With the simulation software MAGMA[5], ingot quality can be predicted with a view towards various aspects – shrinkage, porosities, macrosegregation, cleanliness, and cracks [2]. Parameters of the casting process can be modified to explore possibilities for limiting defects and, if not completely eliminate them, to minimize their number and severity, Further, measures to increase the yield and productivity of the casting process, such as reducing hot top size, extending mould lifetime, efficient use of insulation, etc. can be investigated. To provide an example, fig.1 shows the temperatures at one particular point of time during teeming of a 90 t ingot.

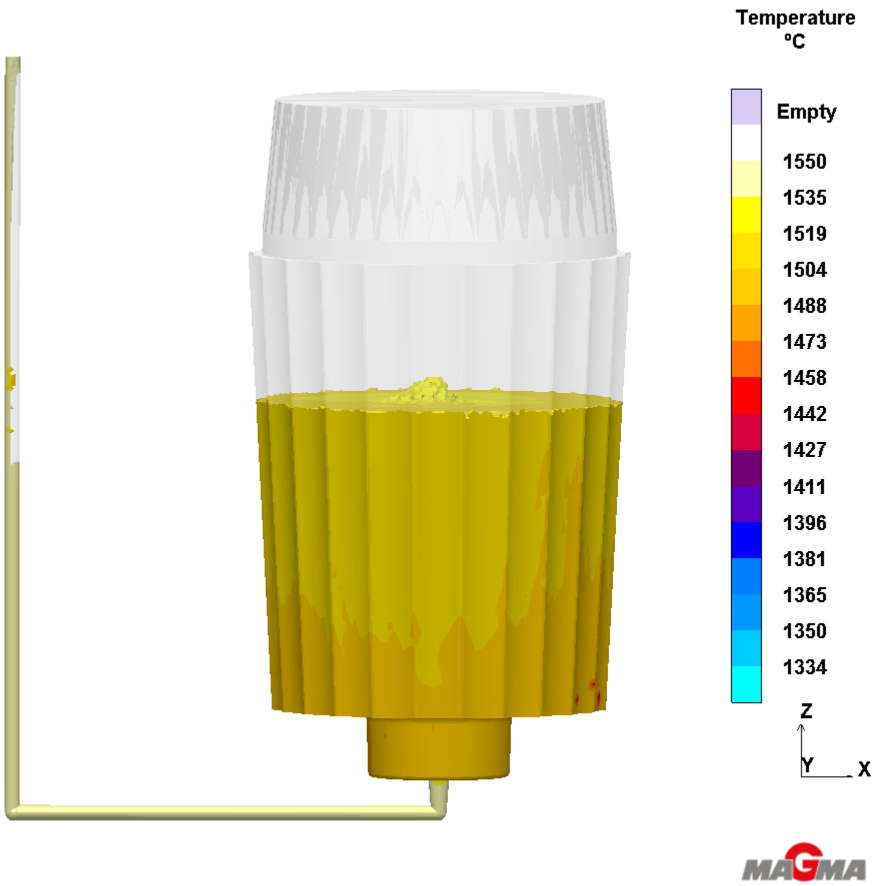


Fig.1: Simulated temperatures after 15 minutes of teeming

3. SEAMLESS RESULT TRANSFER FROM CASTING TO FORGING SIMULATION

For the simulation of the different processes of a process chain – like casting, forging, heat treatment, machining and simulation of the loads in the final part specialized software packages are frequently used individually for each process step. These software tools are tailored to the characteristic and the typical issues related to the particular process simulated. The transfer of simulation results from one of these software packages to another, to be used there as starting point, is an often discussed bottleneck of closed process chain simulations. The main issues are not the different used file formats - it can be a considerable effort to convert one into another, but once the detailed specifications are available that is typically a straight forward task. Process simulations always use elements, meshes and symmetry conditions fit to the specific process. The simulations may be explicit or implicit. Thus, in most cases remapping is needed when results are transferred from one simulation to another. But, again, this can be solved using state of the art technology.

The main challenge for the transfer of results is the meaning of the results themselves. Certain results are only meaningful in combination with a specific material model, which is again valid only for the specific application. For example, porosity may be a geometric result in one simulation, but a material property in the subsequent simulation. A clear concept for the handling of such impacts is needed when the transfer of results is designed.

In the current example, both of the software packages used for casting process (MAGMA[5]) and forging simulation (Simufact.forming) support the smooth and simple transfer of results from one package to the other. With the casting process simulation tool MAGMA[5] it is possible to map all predicted results from the casting process to any finite-element mesh. For a very quick transfer of data from MAGMA[5] to Simufact.forming, a file is produced from the casting simulation using the I-DEAS universal format. This information is imported as "geometry with results" into the forging simulation, where it can be flexibly used with the existing mesh from the casting simulation or with any new mesh tailored to the individual forging process. Standard remapping procedures are used where needed. In the present case, the porosity and the local concentration of specified elements (macrosegregation) are carried over from casting to forging as results. Additional results, like the temperature distribution, are possible extensions. During the import, the porosity is interpreted as a relative density, that later may be changed by the forging process based on a simplified powder material law as discussed below.

4. SIMULATION OF OPEN DIE FORGING

A typical cogging process was simulated using the ingot shown in fig. 1. The commercial software Simufact.forming was used for this utilizing the implicit finite element method. The solver allows rigid body movements, thus all movements of the work piece can be simulated realistically, and there is no need to shift movement into the dies. Elastic-plastic material behaviour was used in a fully mechanical-thermal coupled analysis with hexahedron elements, which is known to deliver most accurate material prediction.

The software contains a powerful kinematics module that enables the simulation of open die forging and ring rolling processes based on higher order settings and a closed-loop control within the solver [3, 4]. Several predefined controls are available and custom controls can be added. The standard cogging kinematics control was used for the presented simulation. This control enables the simple set-up of complex cogging simulations using higher order settings close to factory language. Several heats with several passes each can be defined. For each pass, the final height and translational and rotational movements have to be specified. Cogging in pull and push mode as well as in combined modes is possible using up to two manipulators with two grippers each, which can be additionally spring controlled. All positioning and clamping operations are included; transfer, cooling and heating can be activated before and after each heat. Based on this, all detailed movements are calculated in an internal closed-loop control considering the current status of the process and the current shape of the work piece.

To simulate the closing of the centre-line porosity from the casting process, a macroscopic approach was used. The porosity is described by the relative density of the material, which is changed during the forming process based on a simplified adapted material law using equation (1).

$$\rho_r = \rho_0 + \frac{1-\rho_0}{p_{\max}}\sigma_m , \qquad (1)$$

where ρ_r is the relative density, ρ_0 is the initial relative density, σ_m is the hydrostatic pressure obtained from the analysis and p_{max} is the maximum hydrostatic pressure needed to close all voids. Once the relative density reaches one, all voids are closed and the material is fully consolidated. The relative density is not reduced if the hydrostatic pressure decreases again in the process. The maximum hydrostatic pressure needed to close all voids is the only material parameter needed. It can be calibrated easily based on the simulation results. Additionally, a minimum hydrostatic pressure can be specified to include a minimum stress level needed before the voids start to close.

The built in default of the maximum hydrostatic pressure, which is the yield stress, has been used for the presented simulation. Like all macroscopic approaches, the implemented relative density model assumes that the initial porosity allows treating the material as homogeneous and that the effect of the voids on the material properties during hot forging can be neglected. A more detailed discussion of this model can be found in [4].

The simulated fictitious process consists of three heats with a total of 23 passes, all in pull mode, with different rotations leading to a total of 459 blows. The maximum diameter of the ingot is reduced from 2.5 m to 1.4 m, simultaneously the length increases form 4.5 m to 12.5 m. The simulation uses about 50,000 hexahedron elements with automated remeshing. To precisely include the mechanical and thermal interactions of the work piece not only with the saddles but also with the manipulators, a single, uniform mesh with elastic-plastic material was used for the whole work piece. Fig. 2 gives an impression of the simulation model.

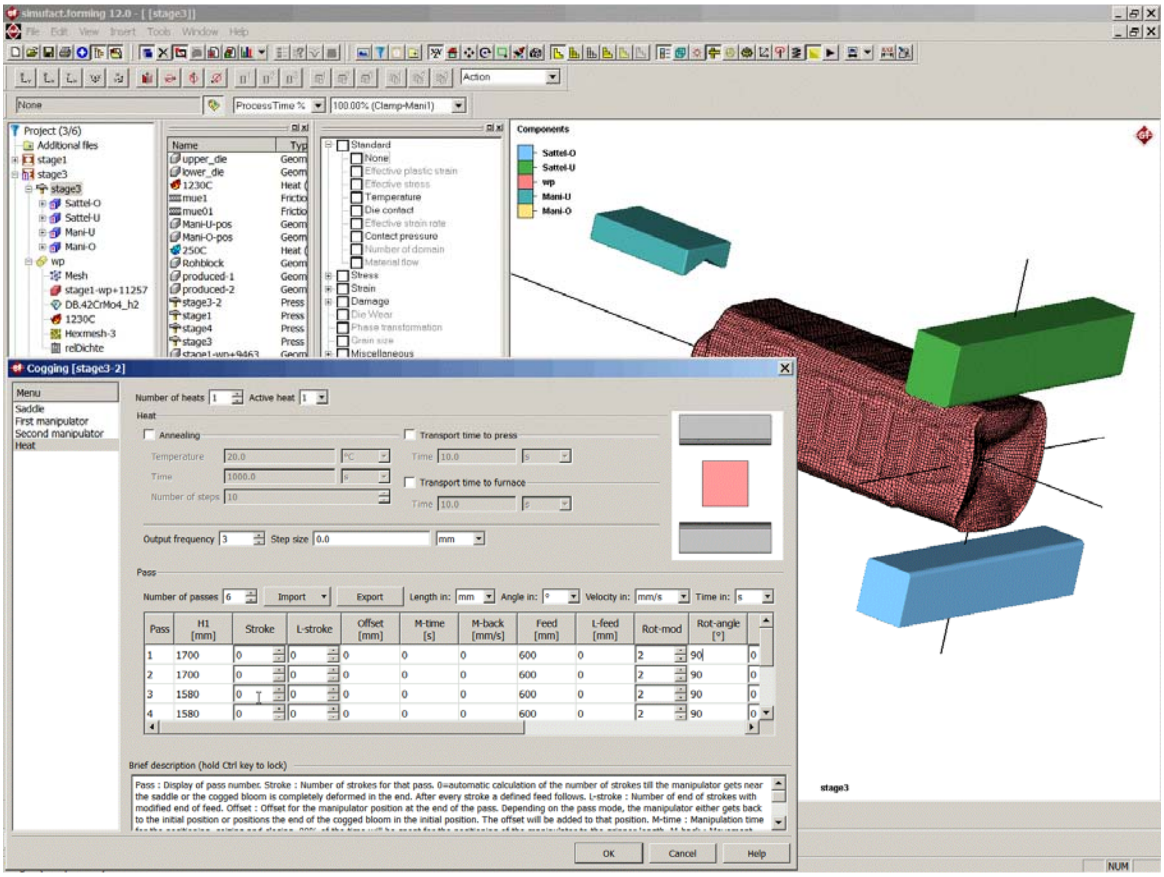


Fig. 2: The model of the cogging simulation

5. QUALITY PREDICTION BY PROCESS SIMULATION

Shrinkage and Porosities

The specific solidification pattern of ingots leads to a characteristic shrinkage appearance in the cast ingot, see fig. 3. There is always a shrinkage cavity in the hot top, but it has to be assured that this primary shrinkage does not extend into the work piece. To minimize the shrinkage cavity and thus the size of the hot top, means an increase in the process yield. During the forging process, the remaining shrinkage cavity is deformed together with the work piece. The forming simulation tracks this deformation together with the overall shape of the work piece. As can be seen in fig. 3, even a small initial shrinkage cavity can lead to a considerable effected area at the end of the cogging process. With the simulation, different cogging strategies can be evaluated easily to minimize this effect.

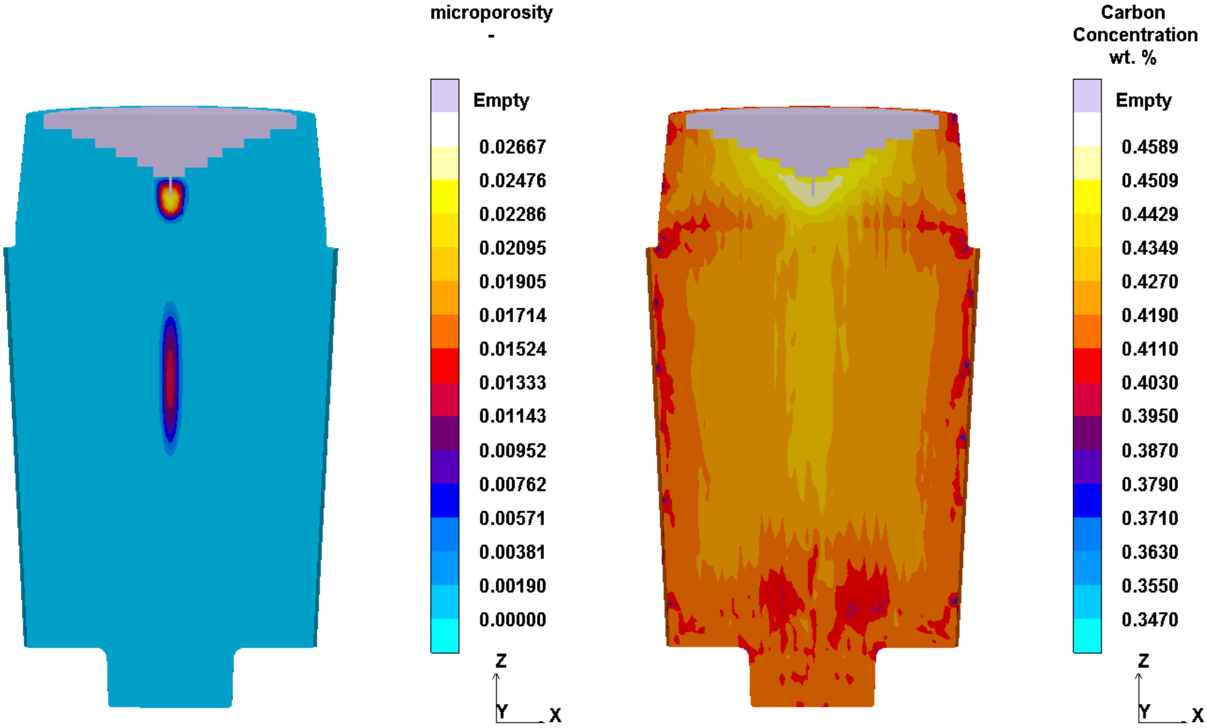
Fig. 3: Shrinkage cavity at the beginning of the cogging process (as predicted by the casting process simulation) (left) and at the end (right)

In many cases, problems with centre-line porosity are reported. This porosity is small in comparison to the hot top shrinkage cavity and is found along a line in the centre of the block, as shown by the casting simulation results in fig. 4 (left). Porosities in ingot casting are influenced by various factors like insulating powder, hot top insulation, hot top geometry, ingot height and diameter (H/D), ingot taper and so on. Depending on the size and position of porosities, it is possible to close them in subsequent hot forming processes, like forging, cogging or rolling [5]. In order to be successful in this, the hydrostatic pressure in the area of the voids needs to be high enough; this may require an adapted process design. The main influencing parameters in this process are the die geometry and the applied feeds and speeds.

Casting process simulation can be applied to optimize the casting process to prevent porosity from being formed. If its presence is inevitable, it is of importance to transfer information about the size and position of the porosity to the forming simulation. There, it is possible to determine the process parameters that are required to close the porosity and thus to ensure the required quality and to maximize the yield of the final product. Fig. 5 shows how the centre-line porosity is removed during a - simulated - cogging process.

Macrosegregation

Segregation is an inhomogeneity of the concentrations of alloying elements and impurities in the steel. Most alloying elements are more soluble in the liquid phase than in the solid phase. Thus, as the metal solidifies, alloying elements in the mushy zone (solidifying liquid-solid mixture) are rejected from the growing solid dendrites into the neighbouring interdendritic liquid. This liquid becomes increasingly enriched with alloying elements as solidification proceeds. On the scale of the dendrites (tens to hundreds of microns), segregation results in a non-uniform solute distribution in and between the dendrite arms. This is termed *microsegregation.*



MAGMA

Fig. 4: Typical appearance of the shrinkage cavity and the centreline porosity in a cast ingot (left) and Carbon segregation (right) – the light / yellow areas indicate positive segregation, the red areas are the areas of negative segregation

The movement of liquid melt or the liquid-solid mixture during solidification leads to a redistribution of these micro-scale concentration differences over larger areas up to the scale of the whole ingot or parts of it. The resulting inhomogeneities in concentration are called *macrosegregation*. The dominant mechanism for moving the liquid melt is thermo-solutal convective flow. This flow is driven by local differences in temperature and chemistry that affect the local density of the melt. In addition, the growing mushy zone provides a resistance against the melt flow which increases with increasing solid-fraction.

Macrosegregation can result in a cast ingot with regions having a composition quite different from the nominal value, either being higher (positive segregation) or lower (negative segregation). A state-of-the art model to simulate thermo-solutal convection and macrosegregation is described in [6]. This model has proven to give good results in application to heavy ingots [7]. Segregation can lead to locally lower material properties. The locally chemistry variations can lead to a different thermochemical behaviour, e.g. when it comes to forming precipitates or local hot spots that induce shrinkage porosities.

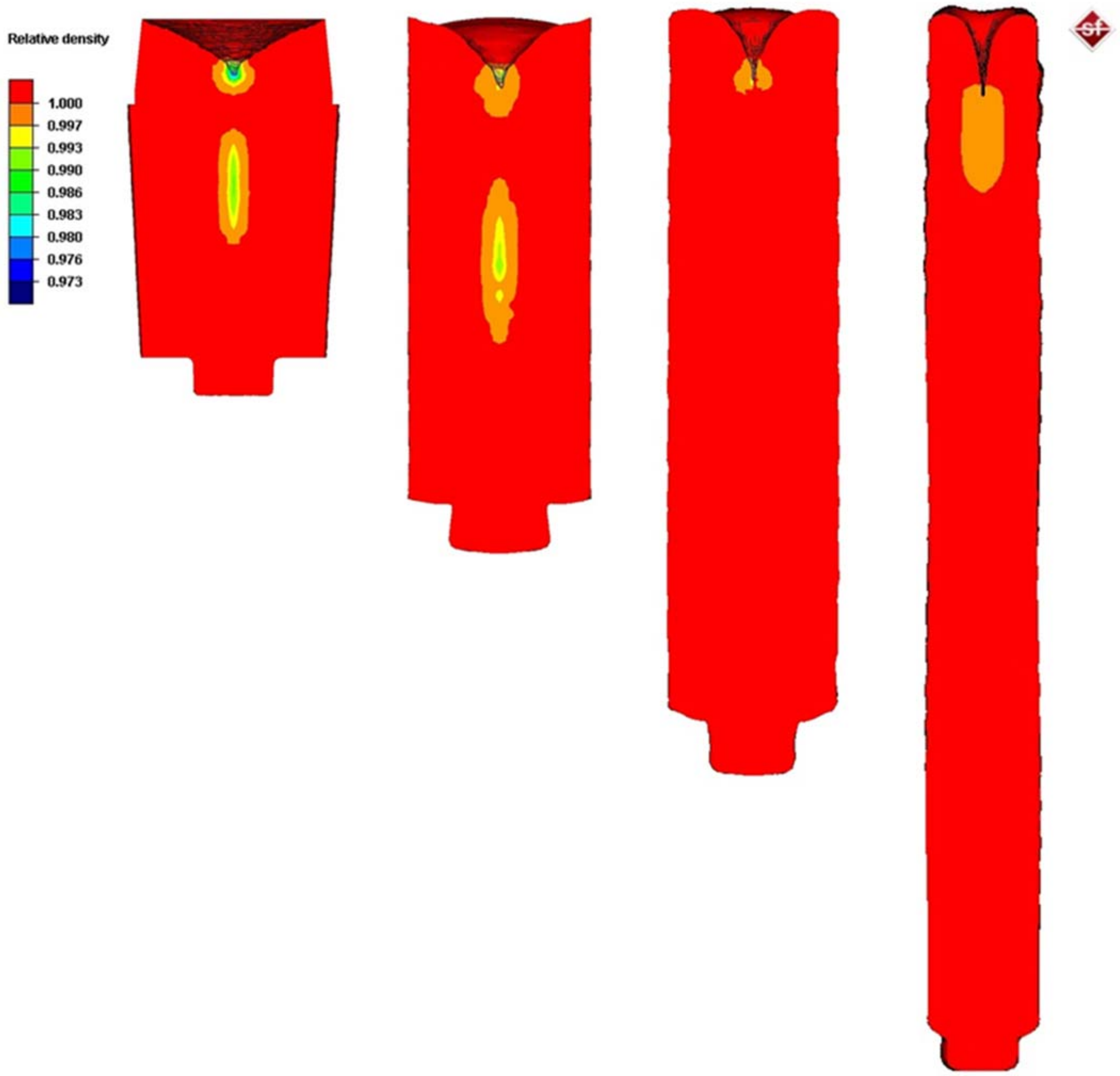


Fig. 5: Development of the porosity during cogging
(geometric dimensions not to scale)

Casting process simulation delivers the distribution of the concentrations of all relevant elements in the steel chemistry as they are to be expected in the cast ingot, fig. 3 (right). If this information is transferred to the forming simulation, the changes of the distribution of the concentrations due to the material flow during the forging operations can be analysed and the expected local chemistry of the forged work piece can be predicted. This enables a judgement of the local quality and the yield of the final product, compare fig.6.

During the forging, cooling and reheating operations the local concentrations in the steel chemistry are not only influenced by the material flow but also by several diffusion effects. The simulation of these effects is an area of ongoing research. Simufact.forming supports this by its flexible data structure for handling material data. The material database considers the chemical composition and provides the infrastructure for phase dependent material properties [8], which are already used for phase transformation simulations. The implementation of diffusion and other defects during heating, forming and cooling is under development. Powerful user subroutines can be used to include application specific material laws to consider the specific effects.

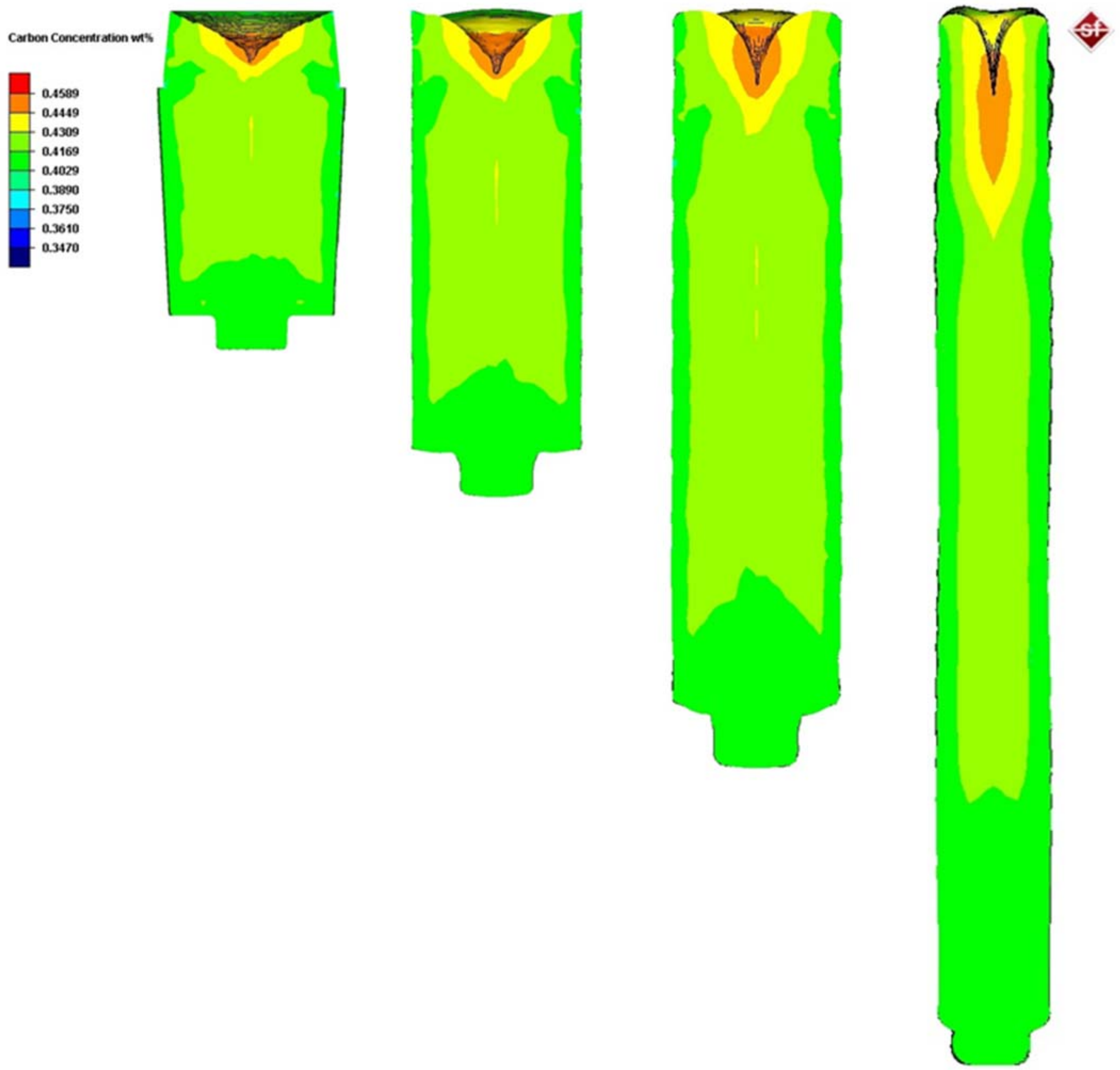


Fig. 6: Development of the carbon segregation during cogging
(geometric dimensions not to scale)

CONCLUSIONS

By coupling the simulation of a casting and of a cogging process, the extent and position of defects in a semi-finished product have been predicted. The defects from the casting process play a significant role for the quality of the deformed product – therefore, the coupled simulation gives valuable additional information. This information could be used to optimize both of the production processes - casting and forming. The production always has the target to use as much material as possible from one cast ingot – With the coupled simulation of casting and forming a powerful tool is given to perform this task.

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