RESEARCH ARTICLE

From casting to forging—The combined simulation for a steel component

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Abstract
In the aluminum sector as well as in the manufacture of semi-finished products, there are numerous industrial examples for combinations of casting and forming processes. In the past, the processes usually were considered separately. However, with the development of digital technologies, it has recently become possible to jointly simulate casting and forging processes and set up continuous process simulations. In the manufacturing of steel components, such a combination is not known industrially. The present paper describes a forged steel component based on a cast preform. To predict the expected properties, the necessary simulations were linked, whereby the focus of the investigations is on the principle feasibility and methodology of such a combination. Based on the conditions assumed in the simulations, test components were manufactured. The simulation results, especially voids and porosity were compared with the real components. In addition, the microstructure of the components was investigated. Approaches for further investigations and the improvement of the combined simulation are presented.

KEYWORDS
cast preforms, cast forging, continuous process chain simulation, die forging

1 | INTRODUCTION

The combination of casting and forging is an innovative manufacturing method to bring together the best from both well-established technologies. The approach combines the main advantage of casting, that is, complex geometry generation, with the best of forging, that is, high strength and robust mechanical properties. Simultaneously, a reduction of material usage and a shortening of production steps becomes possible by this process combination. Furthermore, the forging process can be used to minimize or eliminate defects resulting from the casting process such as blowholes or pores. In order to achieve these advantages the combination of both disciplines would be necessary at the product development phase. It is the very aim of the present paper to meet this demand by linking and evaluating the simulations of both process types.

In the field of non-ferrous metals, preferably aluminum and its alloys, the processes are already closely linked for the production of automotive components. Perrier et al describe a process flow, based on a casting/forging process
(Cobapress™) for the weight reduction in aluminum alloy wheels without considering the simulations or their linking. Zhenglong and Qi show a combined process of squeeze casting and forging for improving the quality of control arms. They investigate the application of cast aluminum alloys by use of combined software for the prediction of component properties and comparison with wrought alloys. Also for magnesium, the changes in the properties of a cast body as the result of subsequent forming were investigated. Aiming to improve the forgeability of semi-continuously cast AZ70 magnesium alloy, Wang et al describe a technology using superplastic forming that not only avoids complicated material preparation but also enables the use of cast blanks. In contrast to non-ferrous metals, the main contribution of this paper is the focus on steel. It presents a practical example and validation of such a continuous process environment where casting and forging simulation and processes are effectively implemented. The description of a linked simulation of the sub-processes for steel component design is not known.

Conversely, in the field of alloy steel manufacturing process, only a few industrial applications are reported and very little information on the process combination of casting and forging for the manufacturing of steel components are available in the literature. This is mainly due to the significantly higher temperature required during hot steel forming, resulting in problems for tool life and the part quality, which are similar to the semi-solid forming of steel. Furthermore, investigations are known to solve problems in blocking the material flow in pure forging by producing a cast preform for closed die forging, whereby the presented solution is based on the production of different castings to investigate the form filling during forging without simulative linking. Another approach for combining casting and forging is related to the development of partially forged components of ductile cast iron with adapted properties. Practical forging trials at different degrees of forging and at different temperatures and the following tensile tests were carried out for comparison with tensile tests on only cast test bars. In order to predict the component properties while avoiding extensive tests, a simulative combination of both individual processes, as presented in this paper, is necessary.

Both, casting and forging have well developed but separated tools for the simulation of the processes for form filling and solidification and, respectively, forming and material flow. When considering components produced in this combination, it is essential to transfer the relevant results of the casting simulation to the forging simulation and to observe them further. So far, the benefit of linked simulation is only investigated in the field of manufacturing of semi-finished products such as blooms or bars. The authors describe the reuse of results of a casting analysis for incremental forging simulation. This repeated change in forming direction combined with a high degree of forming facilitates the closing of existing casting defects like pores and shrinking blowholes. Recent research by the company Tubacex (Spain) with a new ingot design to meet high quality requirements deals with the comparison of different manufacturing strategies, blooming and forging. Each of the manufacturing routes begins with the casting operation of a 6.3 tons stainless steel ingot. The application of the process combination casting – forging for the production of steel components with only one forming step makes it even more important to predict the expected component properties using linked simulations. The authors do not know further current investigations in this field.

The present work combines casting and forging simulation and investigates the behavior of forged steel components from a cast preform under the assumption that only one forming step is required to achieve the final dimension. The first overview about the principle of direct combination of casting and forging simulation for steel components, given at the annual congress of the German Academic Association for Production Technology (WGP) in 2019 in Hamburg, was extended by metallographic investigations. A short description of the simulation of the single processes is followed by the introduction into the combined simulation of casting and forging in Section 3. In this section, the method for the linking used by the authors is presented. Hereafter, a comparison with conventional processes as well as a comparison of the simulation results with real components are shown. Furthermore, the microstructural properties of real components manufactured by this process route are investigated and evaluated. Finally, in Section 5, the potential and risks of combined process route for steel parts are discussed.

2 | PRELIMINARY INVESTIGATIONS

2.1 | Demonstration part

The starting point of the investigations was to improve a shift fork, previously produced as a sheet metal assembly, with regard to component properties and mechanical characteristics. Furthermore, complexly shaped elements should be integrated. A benchmark test was carried out for different technologies with regard to costs, functionality, number of single parts and process steps. In summary, the combination of casting and forging was selected as the most suitable alternative
manufacturing method with the challenge to link both simulations. In preparation of the combined simulation of the process chain, the individual processes are simulated in the conventional way. These simulations are used to check the generally feasibility and serve as the basis for manufacturing by conventional routes. For the combined method, a material has to be selected that can be easily processed both in terms of casting and forging. Historically, not only have the casting and forging technologies developed independently of each other, but the materials available have also been adapted to the respective application and the associated technologies.

In consultation with casting and forming experts, 42CrMo4 steel grade was selected and corresponding material data were taken from the data base JMatPro. The geometry of the investigated part is shown in Figure 1.

2.2 | Simulation of the separate processes

As the forging die determines the final shape, the design of the forging process is done first. To minimize the tooling costs and material consumption for the trials a simplified two-stage hot forging process is configured. This process based on a bent and welded round material and is simulated using both SIMUFAC® and FORGE NxT® software. Subsequently, the second stage of this simulated forging process is also used to insert the cast preform into it.

First simulations to determine the sequence of two stages as a forged part show critical areas with folds in which forging errors frequently occur. However, the design as a defect-free forged part requires an increased material input. The preform and a detail of the die for forging simulation is shown in Figure 2.

The casting model of the shift fork was developed and simulated in cooperation with the Foundry Institute of the TU Bergakademie Freiberg in MAGMASOFT®. To avoid additional surface defects, the cast model must be easy to insert into the finishing stage of the forging die. The reduction in width dimensions is compensated by additions in the forming direction. Due to a better utilization of the mould and a simpler feeding system, a quadruple mould is designed in preparation of the experimental part of the investigations. Figure 3 shows the models with the pins for the mould boxes as the basis of the upper and lower boxes of the mould for the casting process. The casting process was also simulated to verify general feasibility. No casting optimization of the component was done, since the focus of the investigation was on simulation and verification of the process combination.

The casting simulation shows a very different temperature profile during the solidification (Figure 4 left). In the consequence, large deviations in the solidification of narrow and compact areas are the result. Therefore, blowholes can occur inside the part (Figure 4 right), which have to be investigated more closely. If subsequent forging or mechanical processing cannot eliminate these blowholes, their effects on the functionality of the component must be checked.

FIGURE 1 Demonstration part selected for investigation (critical areas are highlighted)

FIGURE 2 Lower forging die with preform (right) and intermediate form (left)
The simulation of the individual processes was used to determine the final geometries in the sub steps and to ensure the general feasibility. In the following, the setup of a combined simulation can be started.

### 3 | COMBINED PROCESS SIMULATION

The development of the combination of casting and forging simulation aims at the minimization of information loss in the simulation models and the data transfer and provides the basis for further investigations. The optimization of the individual processes and the process combination are not the focus of the current work. The interface from MAGMASOFT® to the forming simulation SIMUFAC® at this stage of the project was under development. Therefore, the combined process simulation was carried out using the software tools THERCAST® and FORGE®, provided by the French manufacturer Transvalor S.A. Due to the development of the software by the same company, an interface for data transfer without loss of model parameters exists. The repeat of the simulation with MAGMASOFT® and SIMUFAC® and the comparison with the results of the corresponding software are in progress.

Furthermore, the following assumptions and conditions are necessary at this stage in the development:

- Blowholes or porosity have their origin in the solidification. The influence of gas porosity is not considered.
- The influence of varying the friction conditions in the forging process was not investigated.
The determination, fine-tuning, and combination of the initial parameters values for mold filling and solidification like cast temperature and time, mould material, cross-section of feeder system and others is decisive for the reproduction of the real process by the simulations. Even though a large number of settings, also for the cooling or heating systems, the arrangement of the feeder system but also the adjustments on the casting geometry, can be quickly considered, it depends on the experience of the operator to define the appropriate combinations of parameters.

Real manufactured components are used to evaluate the simulation results. It will not be further investigated whether the closing of the blowholes is based only on compaction or on fusing the grain boundaries in the microstructure.

### 3.1 Casting simulation

For the casting simulation, the injection system and feeders (see Figure 3) are added to the model. They will be removed later prior to the forging process.

The basic settings and the material data set were taken over from the single process. The boundary conditions for the simulation of the casting process were defined as follows:

- casting time: 12 s
- casting temperature: 1650°C
- cooling time in the mould: 10 h
- mould material: sand mould.

The casting simulation is based on a finite element model which contains elements and nodes. The evaluation of different criteria (Niyama, Yamanaka, etc.) during the simulation describes the component quality. Since these criteria are not usually used in a forging simulation, but must be considered further when combining the processes, parameters with the same name are used which can be evaluated in the forging simulation. The Porosity_Transfer_of_Parameters_(Niyama) describes the Niyama criterion, and so forth.

In order to simulate the process from the casting to solidification the following parameters are used:

- Porosity_Transfer_of_Parameters_(Niyama)
- Porosity_Transfer_of_Parameters_(Shrinkage) and
- Porosity_Transfer_of_Parameters_(Yamanaka).

These parameters use either elements (Shrinkage, Yamanaka) or nodes (Niyama) of the mesh-file and describe thermal (Niyama) as well as mechanical (Yamanaka) aspects like porosity, shrinkage or stress, and crack formation. The relevance of these parameters for a following forming simulation is also highlighted in References 8,12.

Figure 5 shows the surface porosity as a result of casting simulation compared to a cast part. For the evaluation of the expected distribution of porosity on the surface, the Niyama parameter is used. This parameter indicates the areas with increased tendency to form pores, but not the size of the pores.

### 3.2 Forging simulation

As described above, the model has to be adapted for the forging simulation. The feeder system of the casting model, which is disturbing in the next step, is removed by a trimming operation in FORGE®. The boundary conditions for the simulation of the forging process were defined as follows:

- die temperature: 250°C
- coefficient of friction: 0.4 (Coulomb friction limited Tresca)
- rigid tools.
No further adjustments of the mesh from casting to forging are made, so that the resulting mesh of the casting simulation is the initial mesh state for the forging simulation. The forging simulation starts with a heating step up to 1200°C. This step is used to compare shrinkage from casting with expansion during heating and shows a good correlation between both simulation models. The reheated cast preform is inserted into the finishing die of the developed two-stage forging process.

The behavior of originally existing blowholes and porosities is mainly dominated by the effective strain in the component areas. In this specific example, the effective strain reaches values between 0.3 and 1 (Figure 6).

To evaluate the cast parameters like porosity, shrinkage, or crack formation in the forging simulation, it is necessary to implement them as user-defined variables in the simulation model. In this manner, the results from cast simulation will be embedded and can be checked during forging simulation. The simulation shows the changes of the porosity from casting to forging (Figure 7) by using the Niyama-Parameter. The porosity parameter of the casting simulation (Niyama criterion) allows to transfer the result from THERCAST® to FORGE®. The porosity parameter of the forging simulation (Porosity Risk Niyama) describes the behavior of the pores during forming. Thus, it is possible based on the local stresses and deformations to evaluate whether the pores are closed or not.

Furthermore, the forging simulation suggests, that blowholes from casting can be closed during forming. Forging errors in form filling as described in chapter 2.2 do not occur. Other topics such as accuracy, warpage, and so forth, are not reflected because not in the focus of the work.

Figure 4 in Section 2.2 shows blowholes inside the part. With a combined simulation, their behavior during forming can be considered in more detail. Figure 8 shows two simulation stages during the forging process at different forming die positions $h$. Closing the press by 6.8 mm results in a significant reduction of blowhole sizes.

First attempts to combine casting and forging simulation indicate good results. As in the individual processes, errors can be detected early in the combined simulation and the process chain can be adapted. The calculation of a large number of variants is possible without costs for the production of test samples.
FIGURE 7  Risk of porosity (orange – high; blue – small; left: after casting simulation, right: after forging simulation)

FIGURE 8  Blowhole during forging simulation

FIGURE 9  External porosity of the cast part (middle) and after forging (right)

4  COMPARISON OF THE COMBINED SIMULATION WITH TEST SAMPLES

For a better classification of the results, the combined simulation is supplemented by prototypical manufacturing of test samples. Some parts were cast according to the specifications of the simulation. These parts are forged in the second stage of the test tool. On the test parts, only a complete mould filling is taken into account. Since geometric properties such as dimensional accuracy or distortion are not in the focus of investigations, they are not further evaluated. In the following, it is considered how the statements of the simulation are reflected in the real components. A basis of comparison for further investigations is created.

Changes in the porosity between casting and forming as shown in Figure 7 are recognizable on real parts (Figure 9). The improvement of the cast surface by closing the pores during forging is visible.

Figure 10 shows the different cross-sections used to cut samples out of the cast and forged part. The comparison of experimental samples of cast and forged parts demonstrates that forged parts are free of visible blowholes, while in cast parts blowholes in different cross-sections are visible (Figure 11). The detailed analysis of forged parts shows in the peripheral zone the formation of crack-like structures (Figure 12 right and Figure 13). These oxide inclusions can have various causes.
FIGURE 10  Cross-section on cast and forged part

FIGURE 11  Cross-section planes for metallographic investigations (left: cast part, right: forged part)

FIGURE 12  Blowholes in cross-section 1 (left: cast part, right: forged part)

FIGURE 13  Oxide inclusion on the peripheral area
It is assumed that these structures form when larger pores are not compacted completely due to insufficient forming if the effective strain is too small. Otherwise, during cooling and reheating of cast part depending on temperature and environment steel tends to scale formation. Such particles of scale can be forged into the surface. For a precise evaluation, it is necessary to examine more closely the different effective strain in a defined area as well as the type and extent of reheating before forging.

Initial investigations of microstructure regarding grain size and segregations visualize the changes from cast to forged part. The microstructure of both the cast and forged state is an intermediate stage structure, which is partially coarser and needle-shaped. In areas of segregation, the cementite is present in a needle-like arrangement. Figures 14 and 15 show the respective microstructures of a sample near the surface and a sample in the middle of cross-section 1 of Figure 10. Figure 16 depicts the segregation zones of cast and forged samples. The changes in the microstructure are due to transformation processes during reheating as well as the subsequent forming. The combination of casting and forging simulation with microstructure evolution makes the simulations more predictive and flexible. Such a step is planned for further projects.

The combination of casting and forging simulation shows, that the properties of cast parts can be changed by a following forming step. To confirm these statements, real components were manufactured. The evaluation of the external

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**FIGURE 14** Cast part cross-section 1 (left: surface zone, right: middle zone)

**FIGURE 15** Forged part cross-section 1 (left: surface zone, right: middle zone)

**FIGURE 16** Segregation zone cross-section 1 (left: cast part, right: forged part)
and internal criteria like porosity, blowholes or microstructure confirms the results of the simulations. An improvement of the surface and microstructure has been verified. Taking into account the fact that shrinkage cavities are minimized during forming, the presented process combination may reduce the effort required for casting simulation. Effects on the structural-mechanical properties have not been considered during the work. They are the subject of future investigations as well as the connection of forming and structural-mechanical simulations. Thus, results from a forming simulation can directly influence the structural-mechanical design of components.

Compared to References 7,8, where the forming of the cast structure is done in multiple steps, the closing of pores and surface defects in only one forming step is to be considered more critically. Metallographic investigations indicate, that it occurs that possible defects such as wrinkling or the forging of scale cannot be corrected completely in the component and may lead to rejects. The same applies to the evaluation of segregations or inclusions in the component. In this field, further investigations are necessary.

5 | CONCLUSION AND OUTLOOK

With the aim to improve an existing shift fork a combined simulation of the casting and forging process of a steel component was developed. In advance, the individual processes were simulated for comparison. Subsequently, a combined simulation approach for casting and forging was implemented. It enables the transfer of the results from the casting simulation to the forging simulation without loss of information like porosity, shrinkage or stress, and crack formation.

For a better illustration of the purposes, all steps are summarized with their objectives and specifics.

- Simulation of forging step to define the preform used for finishing forging; Settings such as friction, meshing, heating, and so forth, depend on the component size and technological conditions for manufacturing. Used software: SIMUFAC® and FORGE®.
- Simulation of casting step to check the preform for forging and the generally feasibility; If necessary, both geometries have to be adapted. Used software: MAGMASOFT®
- Setup of combined simulation with casting (definition of parameters), reheating (check of conformity) and forging (evaluation of parameters); The definition of parameters and the transfer depend on the objectives of investigation and the available software. Used software: THERCAST® and FORGE®; Due to the further development of the interface during the project, the change of the software combination was necessary
- No optimizations have been made yet. Also, the influence of the meshing on the simulation results has not been investigated.
- Regional specifics (degree of application) should be taken into account when using the software.

The results simulated with the software combination THERCAST® and FORGE® show a good conformity with real components. As expected, an intermediate microstructure is formed after the forging step. The casting, as well as the forging process, can influence its formation.

In the example above, the use of cast preforms for subsequent forging results in material savings of more than 20% compared to forged only components. In order to be able to better estimate this value, investigations are currently running with another product for industrial use. For components from ship engines, cavities and holes are intentionally introduced in the cast preform and their behavior is analyzed in the course of the forging step. Since such geometry elements cannot be realized in the forging dies, significant material savings will be expected here as well.

Additionally to the present work, the behavior of segregations as well as grain sizes and grain shape can be predicted in the simulation by implementation of microstructure parameters. Further investigations to predict the structural properties and the expected microstructure of components manufactured in this combined way are in preparation. Also, the evaluation of mechanical and dynamic component properties is necessary to show the potential for improvements relative to the original component.

In general, the method presented in this paper can also be transferred to other materials like aluminum or titanium, when the material files are available in both, casting and forging software. The use of a cast preform for subsequent forging opens up new possibilities for shortening process chains and saving resources. With this technology, components with targeted property distributions adapted to the functions can be realized. By linking the required simulations without
loss of information, it is possible to predict the expected component properties. The direct linking of casting and forming simulation is one way to open new possibilities in the lightweight design of components.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT
The main data used to support the findings of this paper are included within the article. Further supplementary data are available from the corresponding author upon request.

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