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Casting Manufacturing of Cylindrical Preforms Made of Low Alloy Steels

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Abstract

The manufacturing of complex drivetrain components made of steel requires multi-stage manufacturing processes, resulting in long processing times and high costs. Forged parts get their final geometry after multi-stage forming operations. One approach to shorten such process chains is close contour casting of steel preforms and a single subsequent forming step to achieve high strength properties similar to those of multi-stage forged parts. Since the application of precision forging using cast steel preforms has been studied insufficiently up to now, the manufacturing of cylindrical preforms made of the low-alloy heat-treatable steel G42CrMo4 by sand casting was investigated. Using casting simulations, suitable casting parameters for the finished casting systems were identified and nearly pore-free preforms were achieved. Depending on the casting system, metallographic investigations revealed different fractions of bainite in the microstructure of the casted preforms. Subsequently, the cylinders were deformed in upsetting experiments by which the remaining porosity could be eliminated. The numerical casting simulation was combined with a forming simulation to model the reduction in porosity and to allow the prediction of the densification behavior in further research employing more complex geometries.

Keywords: sand casting; casting and forging simulation; G42CrMo4; reduction in porosity

1. Introduction

Steel casting is employed for workpieces with high requirements regarding strength and forming capacity [1,2]. Compared to other materials, cast steel components are characterized by their large variety of grades. This allows for the adjustment of properties such as strength, wear and corrosion resistance and operating temperatures. A big advantage of casting is the possibility to realize complex geometries [2]. Good mechanical properties can be achieved by a controlled cooling of the melt and a subsequent heat treatment [3]. These can be further improved by forming the cast part. For large steel parts, open die forging is employed to close remaining pores and to homogenize the microstructure. The forging of smaller parts directly after casting is up to now only established for aluminum grades [4].

Basic studies on the combined casting/forging technology of steel parts are from the 1980s [5,6]. In order to be able to use these approaches for precision forging, the cast preforms must comply with the smallest possible dimensional and mass tolerances [7,8]. However, steels tend to form pores during solidification, which must be taken into account in the design of the mold. While designing a casting mold, suitable gate geometries and the use of feeders are needed. It is also important that the mold dissipates the resulting gases to the outside, which are formed during the casting. Compared to gray cast iron, the volume shrinkage is about twice as high (between 1.5 % and 3 %) [9] and causes stresses in the material that can be removed by annealing the cast component. This is why most cast steel components are delivered in heat-treated condition.

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2. Development of casting System

2.1. Theoretical approaches

The close contour casting of steel parts for a subsequent forging of drivetrain components offers the potential to significantly shorten the conventional manufacturing process by reducing the number of forging steps. Sand casting can be chosen as a casting method because it is cost-effective, features low investments and is relatively simple to carry out. The casting of such preforms requires that the components' shape must be filled as quickly as possible in order to prevent early solidification; additionally, a low porosity in the parts has to be ensured by a suited casting system.

A systematic approach for the design and dimensioning of a suitable casting system for cast steel in sand molds is not clearly described in literature [10,11]. The basic models must therefore be designed and worked out based on the gate and feeder technology for cast iron. To simplify the geometry, cylindrical preforms of 44 mm in diameter and 75 mm in length were selected. For the design of the total casting system, the calculation of the runner cross section in the system is used. This cross section must be greater than the sum of all gate surfaces. The casting time and the friction loss factor are important for calculating the runner cross section. These can be taken from empirical diagrams of *Cabannes et al.* [12].

The CAD program SolidWorks was used to design all system components, such as pouring basin, sprue, runners, gates and cylindrical castings. To evaluate and determine suitable casting parameters (casting temperature and casting time) for the different designs, the filling of the system with molten steel was simulated by means of MAGMASOFT®. The mesh partitioning method of this casting process simulation software is the finite volume method (FVM). The amount of elements in the material volume was set to approximately 10^7. The temperature of the sand mold was set to 23 °C and the initial temperature of the steel to 1680 °C. The heat transfer coefficient between the melt and the sand mold of 940 W/(m^2 K) was chosen according to the internal MAGMASOFT® database as well as the temperature dependent material properties.

For the design and position of the cast components, different variants exist. It should be noted that in some systems, the distance to reach the castings is shorter, which can prevent early solidification in the runner. However, such systems tend to feature high turbulence in the melt and thus might have a higher amount of oxide inclusions. If the runners are designed longer, a laminar flow of the melt during filling will be possible. However, early solidification might occur [13,14].

In practice, exothermic feeders are widely used. They prevent early solidification of the melt in the feeder due to the exothermic reaction. During solidification and shrinkage this allows for a refilling of the casting parts. To remove the feeders easily after casting, breaker cores are used. These also consist of the exothermic material and are glued to the feeders.

2.2. Casting system

In the developed casting system depicted in Fig. 1, the filling of the cylindrical preforms occurs directly from the runner. To prevent melt splattering in the casting preforms, the sum of all contact surfaces between gates and castings is much larger than the cross section of the runner. A slanting design of the runner allows almost simultaneous filling of all castings. The cylinders are connected only at flat surfaces of gates and feeders. This is advantageous for the subsequent cutting process. A sprue well was included that reduces the turbulence of the melt before it flows in the runners. A laminar filling of the preforms is to be expected even for short casting times. However, in this system, the insufficient pressure of the pouring basin and sprue could cause the melt level to not rise to the highest point of the feeder. Hence, the pouring basin has to be completely filled.

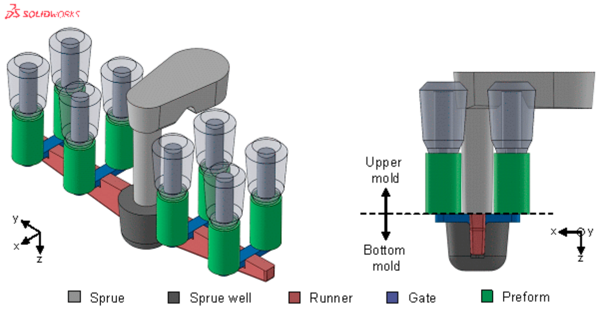

Fig. 1. CAD model of casting system.

3. Simulation parameters and experimental procedure

3.1. Casting

To prevent early solidification, the casting process must be as fast as possible and the casting temperature must not be too low. However, if the temperature is too high, the reactivity of the molten steel will increase. In addition, there is a risk of overheating during the melting process, which can damage the melting crucible. The mold should be filled with the low alloy tempered steel G42CrMo4 (material 1.7225). This steel has a solidus temperature of 1496 °C. Conventional melting crucibles are suitable for temperatures up to 1700 °C. Thus, casting temperatures between 1650 °C and 1700 °C and casting times between 8 s and 12 s were employed in the calculations.

All system components were manufactured by additive manufacturing (PLA 3-D printer) and put together in the casting model. Subsequently, bottom and upper sand molds were made using chemical binders and allowed to harden for about 48 hours. Finally, the casting model was removed from the sand and the complete sand mold was cast. The G42CrMo4 steel was molten in an induction tilt-pot furnace and heated to the casting temperature of 1680 °C. The temperature was monitored by a pyrometer. After achieving the casting temperature and a holding time of 3 minutes, the melt was poured within 10 seconds into the sand mold. After a cooling time of about 24 hours, the casting mold was removed and the system components separated from the castings. The density of all castings was determined using a density index scale. To identify possible casting defects, microsections were prepared from the casting preforms (cutting, grinding, polishing, etching with 2 % Nital) and the cast microstructure was analyzed by light microscopy. In addition, the chemical composition of the casting parts was measured by optical emission spectrometry (OES) and microhardness measurements were carried out.

3.2. Forging

The deformation of the cast specimens was carried out by upsetting experiments. The cylinders were heated for 30 min in a batch furnace to a forming temperature of 1200 °C. The temperature was verified by thermocouple measurements. Two flat dies were employed to apply the upsetting force. Their surfaces were lubricated by graphite spray (Fuchs Lubritech Con Traer G300). The height reduction of the cylindrical preforms was varied between 50 % and 78 %, corresponding to a global plastic strain of $\varphi = 0.7$ to $\varphi = 1.5$.

3.3. Forging simulation

The upsetting test was numerically investigated using Simufact.forming. The specimen's geometry and the distribution of the density after the casting simulation was imported from MAGMASOFT®. The import of the casting simulation results allowed for the analysis of the relative density, which can be used as an indicator for shrinkage holes that may have occurred during the casting process. The material is compressed by the upsetting test. The resulting stresses in the specimen close the shrinkage holes. This behavior can be characterized by the following equation 1:

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

The relative density ρ_r depends on the initial density ρ_0, the hydrostatic pressure σ_m (calculated within the simulation) and the hydrostatic pressure p_{max} which leads to a closing of the shrinkage holes. The value for p_{max} was determined iteratively based on the results of the experimental upsetting tests. The initial temperature of the specimen was 1200 °C. A combined friction model, consisting of the Coulomb friction model and the friction factor model, was used within the model. The friction coefficient μ = 0.08 was used for the Coulomb model. The friction coefficient m of the friction factor model was set to 0.1. The upsetting stopped at a global plastic strain of φ = 0.7, because at this value no pores could be detected in the experimental experiments. The model is depicted in Figure 5.

4. Results

The casting simulations showed that the best casting results are achieved with a casting temperature of 1680 ° C and a casting time of 10 s. A sectional view of the calculated distributions of temperature and porosity is shown in Fig. 2 a) and b). The most important parameters that determine the casting quality are the residual temperature and porosity after filling.

As shown by the simulation results, an elongated, vertical pore close to the feeder neck is predicted (see Fig. 2 c). The density measurements after casting (between 7.6 g/cm^3 and 7.7 g/cm^3) showed a deviation from the density of low alloy steel 1.7225 in the as-delivered condition of 7.85 g/cm^3.

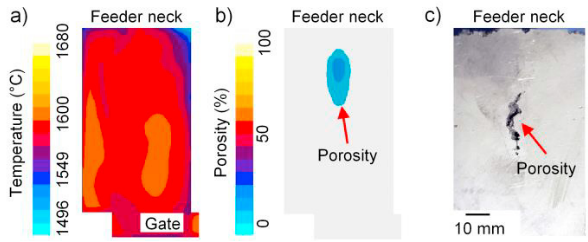

Fig. 2. a) Simulated temperature, b) simulated porosity distribution and c) resulting porosity after filling.

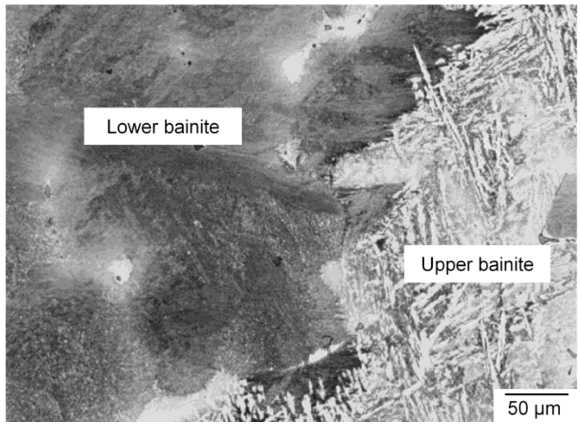

Fig. 3. Etched microstructure of casting preforms with different fractions of bainite.

The initially slightly increased content of carbon of 0.52 ma.-% decreased by approx. 25 % during melting and casting. As a result, the chemical composition of the cast preforms corresponded to the values according to DIN EN 10293 for G42CrMo4.

The light micrographs of the etched cross sections of the preforms showed a bainitic microstructure (see Fig. 3). However, the microstructure reveals different fractions of bainite (lower and upper bainite). The microhardness measurements resulted in an average value of about 340 HV1 with lower values for upper bainite than for lower bainite.

The subsequent upsetting of the cast cylinders lead to a closing of the pores. Mechanical testing indicated material properties were comparable to the reference material after a deformation of φ = 0.7 or more. Figure 4 shows metallographic image of the etched microstructure after forging at 1200 °C and a plastic strain of 1.5. It features a homogeneous structure of upper bainite comparable to conventionally hot rolled reference material after upsetting.

The results of the simulation of the upsetting test are demonstrated in Figure 5 (a). The initial distribution of the relative density was imported from the casting simulation. In the marked area, the initial density is equal to 0.51, which indicates a shrinkage hole. Figure 5 (b) represents the distribution of the plastic strain after the forming process. In the area of the shrinkage hole, a plastic strain of 0.7 was achieved after the upsetting test.

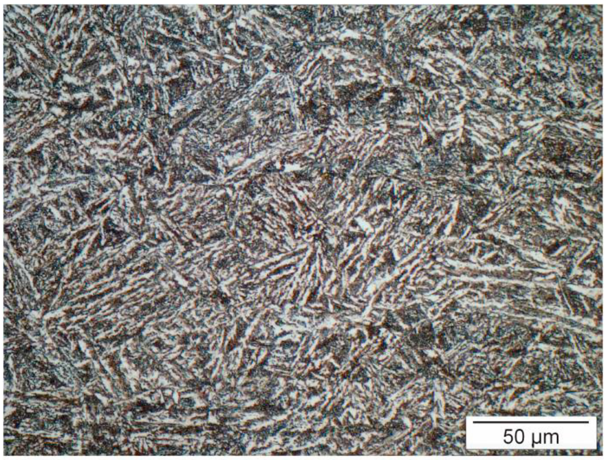

Fig. 4. As-forged and etched microstructure of the preforms after upsetting.

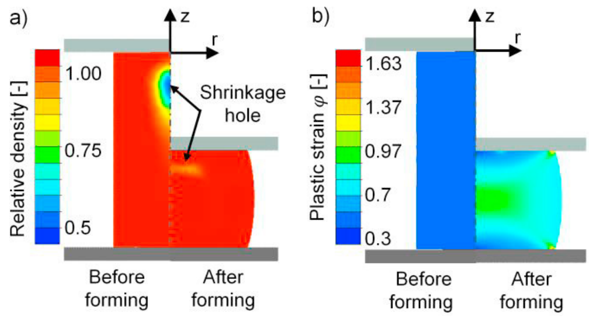

Fig. 5. a) Distribution of the relative density, b) plastic strain before and after the upsetting test.

The experimental tests showed that the shrinkage holes were completely closed for these process parameters. Subsequently, the hydrostatic pressure p_{max} was adjusted to 35 MPa, so that the relative density achieved a value of 0.99 at the end of the forming process. This information will be used in further simulations to developed an optimized process route to achieve components with zero shrinkage holes.

5. Discussion

Using the simulation software MAGMASOFT®, it was possible to identify a turbulence free melt flow during filling for selected casting parameters. The mold filling depended on whether the pouring stream first hit the pouring basin and then flows laminar in the sand form or (partially) directly hit the sprue and thus induced air into the mold. To comply with the exact casting time and casting position of the numerical simulation, the total casting process must be automated.

Both the simulation and the experimental results have shown that in the middle of the casting preform, an elongated shrinkage hole was present. This casting defect inside the cylinder with an irregular shape and rough walls mostly occurs in the thick-walled areas with large accumulation of material [13]. Thus, the casting core was the last position of solidification and the pore probably was a result of the high volume shrinkage of the steel [15]. Therefore, in further experiments, an exothermic feeder was used with an approx. 30 % larger feeder volume. The formation of pores in cast cylinders made of G42CrMo4 could almost be eliminated (see Fig. 6 a). In experiments using the unalloyed steel C45, the porosity could even be completely prevented (see Fig. 6 b). The closing behavior of the shrinkage holes in the upsetting simulation was successfully adjusted to the experimental observations, enabling process design for more complex parts in further investigations.

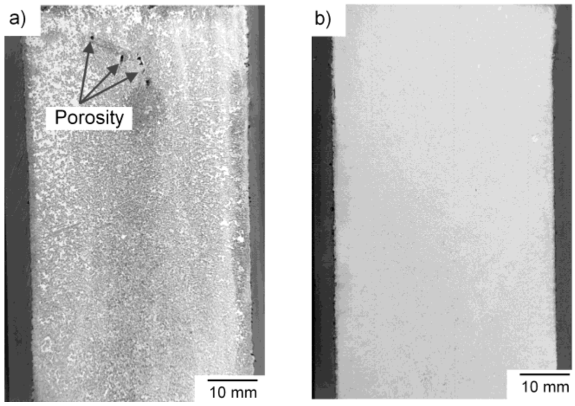

Fig. 6. Casting cylinders after longitudinal cutting: a) G42CrMo4 with lower porosity and b) C45 without visible porosity.

6. Summary

In the present study, the casting manufacturing of cylindrical preforms made of low alloy steels in a sand casting process was investigated. The most important scientific findings are the following:

- Using a casting simulation, suitable casting parameters were identified and the porosity in the casting system could be predicted. To eliminate or reduce the porosity, it was necessary to adjust the feeder technology.
- Use of larger feeders has significantly reduced pores formation in G42CrMo4 preforms. In the casting manufacturing of drivetrain components made of low alloy steels with a complex geometry, the exactly position of the feeders is very significant to filling the critical areas in casting parts.
- The manufactured preforms show good dimensional accuracy and allow subsequent forming processes.
- The simulation of casting and forging was successfully combined and the hydrostatic pressure p_{max} was derived from the experimental oberservations.

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