Implementation of an open-die forging process for large hollow shafts for wind power plants with respect to an optimized microstructure

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To realize large wind power plants in an economically feasible way, it is necessary to identify potential for lightweight design of the generator hollow-shafts, which are commonly produced by casting. The weight of these shafts can significantly be reduced by producing them by open-die forging, since the forming of the material leads to a higher strength, which allows to reduce the wall thickness noticeable. This paper describes the development and implementation of a forging process for hollow shafts with respect to an optimized microstructure. To numerically investigate this process, a realistic finite element simulation model was developed in a first step. The kinematic of the tools has been implemented authentically to provide a realistic material flow and process conditions. Additionally, a material model for the steel 42CrMo4 was integrated into the simulation model to predict the resulting microstructure. Using the implemented FE model, the forging process was optimized manually to achieve a homogeneous and fine-grained microstructure. The optimization was based upon a variation of different forging parameters and the sequence of forging steps. In the next step, a forging on laboratorial scale was performed to validate the simulation model. For this purpose, after forging, specimens from the hollow shaft were evaluated by metallography to determine the final grain size. A comparison of the results with the numerical simulation showed a general agreement of the measured grain size with the numerically calculated grain size. Based upon these results, the process model was transferred to an FE model with an industrial scale. By this it was possible to analyze the transferability of the used FE model regarding the assumptions about the kinematics and the sequence of the forging steps. A numerical investigation of the industrial process proved the scalability of the process to an industrial relevant geometry.

Keywords: Open-die forging - Microstructure - Process optimization

INTRODUCTION

Initial Situation

During the last years the importance of alternative energy sources like wind energy has risen constantly. To meet with the further anticipated demand for renewable energy, the importance of wind energy will be growing even more as this currently is the cheapest and most effective renewable energy source [1]. A higher energy production by wind power plants cannot only be achieved by setting up additional wind parks, but also by an increase in the performance and by this the size of newly built plants.

This requires larger machine parts, like rotors, shafts, gears and generators, leading to higher requirements for the tower's construction. To cope with these aspects, the reduction of the nacelle's weight at the top of the tower offers a good opportunity. One approach is to replace the commonly cast generator shaft by a forged hollow shaft with excellent mechanical properties. In comparison to a cast hollow shaft, a forged shaft could offer a higher strength and therefore would allow reducing the wall thickness significantly. Recker et al. [2] estimated that producing the hollow shaft by open-die forging could allow a weight reduction of up to 60% compared to a cast hollow shaft.

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State of the Art

Open-die forging is mainly used for the production of high quality parts in low quantities. These parts are applied for highly loaded purposes in large machines like generator shafts or rolls. Hollow parts like rings are usually forged by applying an upper-die and a mandrel. Usually, this kinematic is used for forging rings and intends to increase the diameter. For the production of a hollow shaft, which has a much higher length and smaller diameter, the main challenge is to ensure a sufficient axial material stretching. The longitudinal material flow is predominantly achieved by improving the tool's shape and the process kinematics [3]. The best axial stretching can be realized using concave or v-shaped dies. However, two concave dies are lacking flexibility during the process according to the forgeable diameter as the shape of the dies limits the possible workpiece geometries. Two v-shaped dies are disadvantageous for the process handling, since this tool combination impedes the loosening and extracting of the mandrel after a forging heat. Based upon numerical investigations and literature review [4], the combination of a flat and a v-shaped die proved best to realize a sufficient axial stretching.

Motivation and Scope

The overall objective of the investigation presented in this paper is the optimization of the open-die forging process for hollow shafts with respect to an optimized microstructure and transferring the results to an industrially relevant geometry.

As a first step, the main focus was the development of a simulation model for the forging of a 150 kg workpiece under consideration of the kinematic and tool geometry. The second main objective consisted of optimizations of the microstructural properties meant to ensure the final product's high mechanical strength. This requires a homogeneously distributed, fine grain size along the workpiece, which is likewise supported by a homogeneous strain. So a manual optimization through variation of the bite ratio and height reduction was performed. To verify the results from the numerical simulation, especially in terms of microstructural evolution, forging of a 150 kg workpiece was performed at the IBF. The corresponding results from the experiment were used to validate the numerical simulation model according to the microstructural evolution, tool geometry and kinematics. Based upon the validated simulation model, in a third step, the process was transferred to an industrially relevant geometry by numerical investigation.

METHODS AND PROCEDURE

Numerical Simulation Model

For correctly predicting the material flow and the microstructural evolution, a simulation model was implemented in Transvalor Forge 2011, whose boundary conditions and kinematics coincide with the forging conditions in reality. The general requirements on the process kinematic for a realistic simulation model are:

1. The upper flat die is moving in y-direction and performs the reduction of the material.
2. The lower v-shaped die is fixed in its position and not moved during the whole process.
3. The mandrel supports the hollow shaft during the process and is held by a manipulator. When the upper die presses in y-direction, the flexibly supported mandrel can move freely in all directions.

The grain size calculation was realized by implementing a microstructure model into the integrated calculation in Forge 2011, based on experiments at IBF and literature [5-8], which showed good accordance with the behavior of the used material.

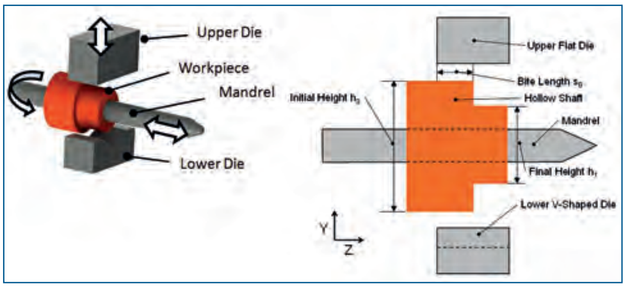

Fig. 1 - Process setup – hollow shaft forging

The numerical simulation of hollow shaft forging is more complex compared to conventional open-die forging due to positioning of the workpiece over a mandrel and the attachment of the mandrel to the manipulator. This setup and the long process time increases the complexity and calculation time of the simulation significantly. The simulation of the reference process described within the paper requires a calculation time of one week on a quad core Intel Xeon workstation. Furthermore, the handling of the workpiece in the simulation is impeded since in hollow shaft forging the workpiece is just indirectly positioned during the process. Sliding of the hollow shaft leads to an inexact positioning. Hence it is not possible to simulate the whole forging process in one simulation. The simulations needs to be interrupted after every pass to control the exact positioning and kinematic.

Chosen Strategy for Hollow Shaft Forging

Different parameters influence the forging of a hollow shaft. Firstly, the main influencing parameters are standard parameters for open-die forging, the height reduction ε_h and the bite ratio s_B/h_0, which describe the ratio of the contact length between die and workpiece and the initial height (here: initial diameter). The variable parameters are the direction of forging and the combination of forging strokes and rotations. According to the forging direction, two different possibilities exist. At first, the workpiece can be forged from the front of the mandrel towards the manipulator tong. After one rotation has been forged, the manipulator feed is executed and the next rotation is forged.

The second possibility consists of forging the opposite direction. As described before, after the forging of one

rotation, the manipulator feed is executed and the next rotation is forged.
Besides the forging direction, the combination of rotation and strokes can be varied as second possibility to mainly influence the forging process. The investigations described within this paper are based on the strategy to forge one rotation at first, translate the workpiece by the manipulator feed and forge the second rotation in the following step. Figure 2 visualizes this process principle. As shown in the top, the whole circumference of the hollow shaft is forged in the first step, which requires 10 strokes or a whole workpiece rotation. After each stroke, the mandrel is rotated by 90°, but just after the fifth stroke of each rotation the mandrel is once rotated by 45°.

Process optimization

Generally, the bite ratio (quotient of the bite length and initial height of the workpiece – s_B/h_0) and the height reduction ε_h can be identified as the forging parameters, which most decisively influence the strain distribution and grain size. Therefore to optimize the process parameters for hollow shaft forging, numerical studies of different bite ratios (0.3, 0.5, 0.7) and height reductions (10%, 20%) were performed and the resulting equivalent plastic strain and average austenitic grain size were analyzed. The optimization was performed for a hollow cylinder with a diameter of 240 mm at an initial temperature of 1200 °C. For the forging on a laboratorial scale, this corresponds to the geometry for the middle steps of the hollow shaft.
As due to the long simulation time the process could not be optimized completely, three different process routes were used to investigate the process optimization. The optimization was performed for the forging of two rotations, each for one and two passes. The equivalent strain and the grain size according to the optimization are evaluated along three lines at half of the wall thickness, each 120° distributed over the circumference, see Figure 3.
Table 1 summarizes the influence of the bite ratio, height reduction and number of forging steps on the strain distribution in the workpiece. An increase of the bite ratio from 0.3 to 0.7 leads to an average increase of strain of 26% for one pass and 50% for two passes at half of the wall thickness. The standard deviation of the strain distribution can be reduced by 46% for one and by 14% for two passes and thus mainly increases the strain homogeneity. Similar effects can be observed for a higher height reduction.

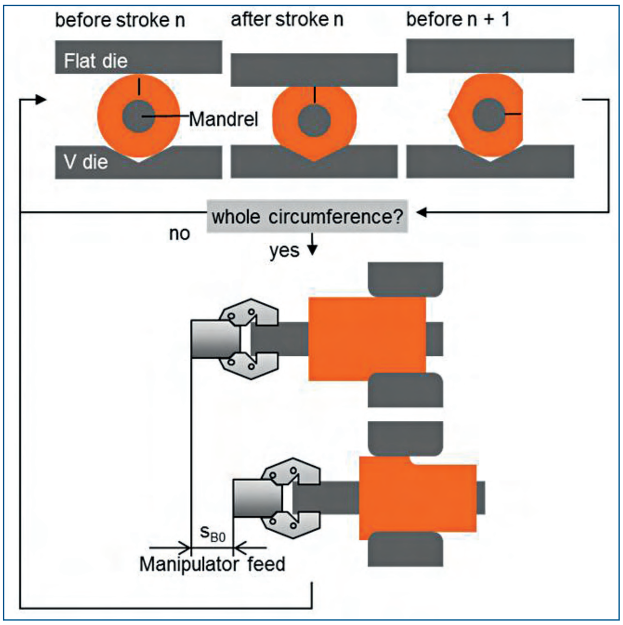

Fig. 2 - Strategy for the forging of one rotation [2]

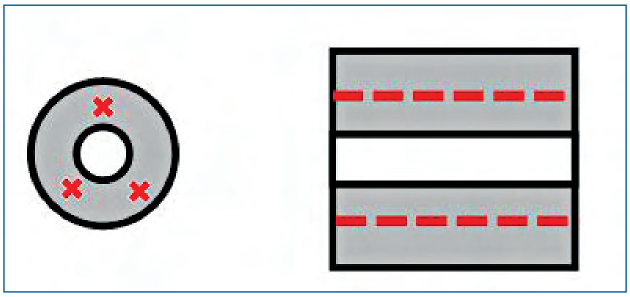

Fig. 3 - Points for evaluation of strain and grain size distribution

So for the optimization of the strain, a higher bite ratio and height reduction should be preferred to achieve the intended results.
The grain size as second optimization objective is mainly influenced by the temperature, strain and strain rate. Since the minimum warm forming temperature for 42CrMo4 is 850°C, the workpiece temperature should not drop below this point. So to allow a long enough time frame for forging the initial temperature is set to 1200°C.

ε_h/Number of Passes	Parameter	Bite ratio (s_B/h_0)		
		0.3	0.5	0.7
10% / one pass	$\bar{\varepsilon} \pm \sigma_\varepsilon$	0.46 ± 0.13	0.56 ± 0.13	0.58 ± 0.07
20% / one pass	$\bar{\varepsilon} \pm \sigma_\varepsilon$	0.54 ± 0.11	0.97 ± 0.14	1.03 ± 0.13
10% / two passes	$\bar{\varepsilon} \pm \sigma_\varepsilon$	0.75 ± 0.25	1.03 ± 0.14	1.13 ± 0.14

Table 1 - Influence of bite ratio, height reduction and forging steps on the equivalent plastic strain distribution (average and standard deviation)

Properties optimization	Parameter	Bite ratio		
		0.3	0.5	0.7
10% / one pass	$\bar{d} \pm \sigma_d$	86 ± 21 µm	56 ± 21 µm	55 ± 20 µm
20% / one pass	$\bar{d} \pm \sigma_d$	82 ± 31 µm	49 ± 16 µm	40 ± 16 µm
10% / two passes	$\bar{d} \pm \sigma_d$	63 ± 17 µm	47 ± 17 µm	30 ± 6 µm

Table 2 - Influence of parameters on average austenitic grain size (average and standard deviation), initial grain size 200 µm

Therefore, a variation of the temperature to optimize the microstructure is nearly impossible as always the maximum temperature of 1200°C has to be chosen for the beginning of the forging process. The strain rate results from the tool speed of 40 mm/s and the geometry of the work piece. Table 2 visualizes the influence of the forging parameters on the average austenitic grain size evolution during the forging process. It can be concluded that a large bite ratio in combination with a high height reduction is preferred to yield a fine grained and homogeneous microstructure.
From this case study, a process route with a higher bite ratio and a sufficiently height reduction should be preferred to both optimize the strain distribution and microstructure in the hollow shaft. Furthermore, the numerical simulations proved that a height reduction of 20% and more leads to an increase of the inner diameter and deviations from the intended shape. Therefore, the height reduction during the process should be lower than a value of 20%.
Besides a small and homogeneous microstructure along the workpiece, likewise a homogeneous distribution over the cross-section is preferred. As example, Figure 4 shows the grain size distribution after the forging of one rotation. It can be concluded that the chosen forging strategy is advantageous to achieve a homogeneous strain distribution over the cross-section. The strong deviation in two points is probably caused by numeric irregularities and disagrees with the general distribution at the cross section.

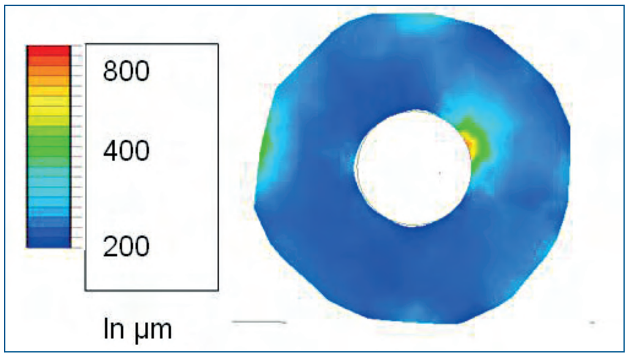

Fig. 4 - Exemplary grain size distribution at the cross section

Reference forging process
The reference forging process was used to validate the numerical simulation model and in particular the microstructure calculation. Therefore the process was designed such that an inhomogeneous grain size distribution should be obtained in the final workpiece to validate the microstructure calculation on a preferably wide range. For that purpose, sections with different outer diameters were forged using different reductions in diameter and varying reheating conditions. The geometry for the laboratorial forging was limited by the maximum possible length of 490 mm and a weight of 150 kg for the initial workpiece. The development of the shape of the

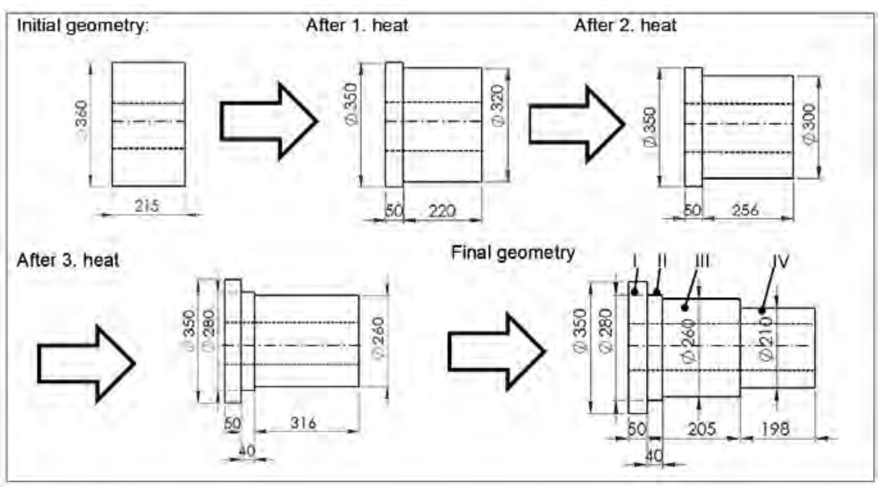

Fig. 5 - Geometry in different stages of the reference process, all dimensions in mm

workpiece during forging is shown in Figure 5.
The forging was performed using a 6.3 MN hydraulic press and a 6-axis forging robot. The workpiece was initially heated to 1200 °C and the tool speed was set to 40 mm/s.

RESULTS

Results of the forging process

Comparing the final shape, material flow and especially the grain size of the experiment to the numerical simulation allows judging the quality of the simulation model. In this context, the validation of a simulated grain size by metallographic analysis is limited since only the final state can be investigated. So it is not possible to analyze the grain size evolution during intermediate steps of the forging process.
Figure 6 visualizes the results of the metallographic analysis. Generally, the microstructure is only investigated in one single center point per step and could possibly vary due to different conditions in a step. The metallographic analysis shows that in the largest step (I) the microstructure is just partially recrystallized and shows still similarities to the initial microstructure. This effect results from the low strain, which just has been imposed by the 10 mm diameter reduction during the first pass. In the other three

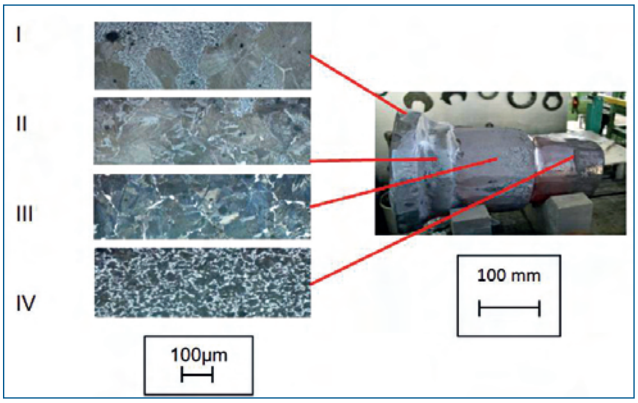

Fig. 6 - Exemplary results of microstructure investigation for each step

steps of the shaft, the effect of the higher strain clearly becomes visible as the grain size becomes smaller in a fully recrystallized microstructure. Under consideration of the measuring error, the average austenitic grain size for each step is decreasing from 142 μm in step I to 37 μm for step IV with the smallest diameter. The general expectation from the optimization, that a higher strain leads to a finer

Step	1*	2	3	4
Metallography	142 ± 89 μm	102 ± 21 μm	110 ± 38 μm	37 ± 14 μm
Simulation	167 μm	163 μm	84 μm	6 μm
Absolute Deviation in Percent	17,6%	59,8%	23,6%	83%

* The high standard deviation is resulting from the occurrence of non-recrystallized grains.

Table 3 - Comparison of numerical and real grain size

grain size and recrystallized microstructure, is fulfilled.
According to the numerical calculation, during the reheating process, the grain size increases rapidly up to approx. 500 μm due to grain growth, whereas the dynamic and static recrystallization phenomena during and after a strain increment result in a reduction of grain size. Considering the standard deviation of the metallographic grain size measurements, the grain sizes show roughly the same tendency as summarized in Table 3.
A correlation between the strain and the grain size can generally be observed, showing that a higher strain leads to a finer grain size in the workpiece. However, this needs always to be regarded in relation to the process history, since significant grain growth can appear during a necessary reheating process. For this kind of process, an exact prediction of microstructure proves as difficult due to the long process time and the semi-empirical modelling of the microstructure evolution. Nevertheless, the microstructure calculation reproduces the influences on microstructure during forging in a satisfying way.

Transfer to Industrial Scale

The verification of the simulation model showed in principle a satisfying accordance between the real process and the numerical model. Based upon this, the simulation

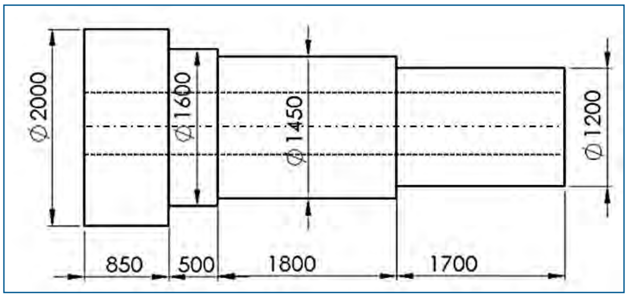

Fig. 7 - Industrial hollow shaft geometry, all dimensions in mm

is scaled to a 20 ton geometry (Figure 7), based on [9], in order to prove the process design on a large scale. A general difference between forging on laboratorial and industrial scale consists in the thermal development during the process. Due to the significantly larger volume and a smaller ratio of surface to volume, the workpiece cools down considerably slower. Therefore, the number of necessary heats can be reduced from four heats for the 150 kg part to just two heats for the 20 t part.

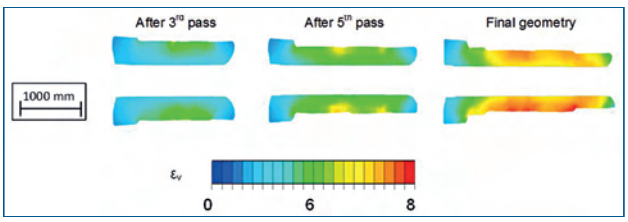

Fig. 8 - Strain evolution for a hollow shaft with an industrial geometry

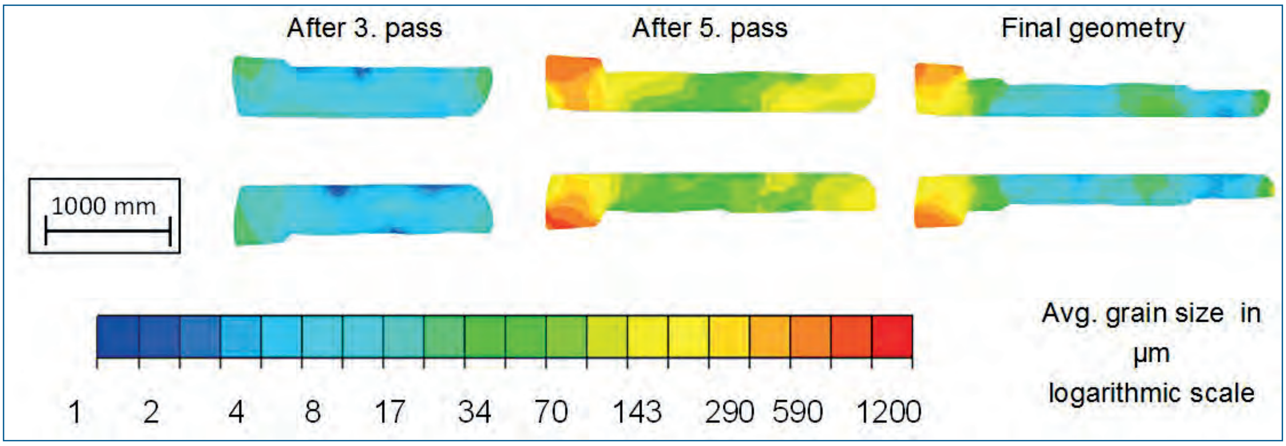

Fig. 9 - Grain size evolution for a hollow shaft with an industrial geometry (Reheating after 3rd pass)

According to the strain distribution in a longitudinal section of the workpiece, as shown in Figure 8, the chosen forging strategy leads to a homogeneously and sufficient equivalent strain in the three smaller steps of the workpiece with values of ε_V>5 in average. Only in the first step (largest diameter), the average strain reaches a level of ε_V just above 2. Nevertheless, a homogeneously distributed average equivalent strain of 2 is sufficient to enable good mechanical properties.
Figure 9 visualizes the grain size distribution in a longitudinal section. The 2nd, 3rd and 4th step of the workpiece are showing a fine and homogeneously distributed grain size between 5 µm and 40 µm. In contrast, the largest step of the hollow shaft has a final grain size up to 1200 µm. The reason for this behavior is based on the chosen process sequence. The workpiece needs to be reheated to forging temperature of 1200 °C, after the temperature has dropped below the minimum forging temperature of 850°C. As the step I has already been forged in the first heat and is not forged any more after reheating, the resulting microstructure is mainly driven by grain growth, which leads to an enormously high grain size of up to 1200 µm. In contradiction the grain size of step II, III and IV is mainly influenced by the forging during the last heat. As shown in Figure 9, the forging on industrial scale results apart from step I in a more homogeneous grain size than the forging on laboratorial scale.

CONCLUSION

This paper proves by numerical simulation and experiments that open-die forging can generally be used for the process design of hollow shaft forging. The experimental forging of a 150 kg part based on numerical simulation studies showed that the developed kinematic and pass schedule are suitable.
The development of the experimental forging process was based on an optimization by variation in the numerical simulation. The optimization showed that high bite ratios of 0.7 and height reductions of 10-20% should be preferred for an optimized distribution of strain and grain size in the workpiece.
In order to validate the numerical simulation model, a 150 kg hollow shaft was forged and compared to an identically simulated numerical process. A comparison of the numerically predicted and the experimentally measured grain size showed a general accordance between both approaches. However, due to the long process time and the semi-empiric microstructure modelling in the numerical simulation, some uncertainties occurred, leading to an average deviation of 46% between the numerical and experimental results. Since in general the trend of the numerical simulation could be observed in the experiment, the results can be considered in principle as sufficient.
Based on this, the process design of the 150 kg shaft could be transferred to an industrial scale. A numerical investigation of the industrial process proved the scalability of the process to an industrial relevant geometry. Both in laboratorial and industrial scale, the grain size evolution is mainly influenced by grain growth. In the industrial scale, the resulting grain size distribution is much more homogeneous as less reheating steps are required and by that, the influence of grain growth on the grain size is reduced.

OUTLOOK

- The manual optimization presented in this paper only considers the optimization of few rotations and passes. To perform a more complex optimization, it is necessary to regard the whole process. Possible approaches are a fully automatic optimization through the variation of different process parameters or a pass-wise optimization based upon the main values for the investigation of the microstructure as strain, strain rate and temperature. As a fully automatic process optimization in numerical simulation is too complex regarding simulation time, a fast empirical calculation model could be implemented and used to optimize whole processes. First works to this direction for squared ingots are presented in [10].

- A further degree of freedom to influence the workpieces final properties is the initial geometry. By a variation of the height to diameter ratio, the geometrical and microstructural evolution are influenced significantly.
- The investigation of the grain size evolution showed that grain growth during reheating has the dominant influence on the final grain size. Therefore an optimization approach could be the adaption of the process route, so that in the final heat the whole workpiece is forged in order to reduce the large grain size after grain growth.
- While lowering the reheating temperature is not an option for the 150 kg workpiece, this might be a solution for the 20 ton ingot. As the numerical simulation is validated, it could be used to find the optimal reheating temperature.

ACKNOWLEDGEMENTS

The authors thank the Deutsche Forschungsgemeinschaft and CAPES for the financial support within the project “Forged hollow shafts for power plants” in the “Brazilian German Collaborative Research Initiative in Manufacturing Technology” (BRAGECRIM).

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