

Increasing Sustainability in Open-Die Forging by Means of Process Adaption and Innovation

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Abstract. Climate change is progressing rapidly, posing severe risks to the environment and making sustainability and circularity key challenges for future industrial development. Greenhouse gas emissions are largely driven by human activities within industrialized societies, requiring adaptation at individual, societal, and industrial levels. Metal forming technologies can contribute significantly to this transformation by improving material efficiency, process efficiency, product efficiency, and circularity. Material efficiency is particularly important, as material production accounts for the largest share of industrial emissions. Process efficiency offers a high leverage effect, due to the large production volumes in forming process chains, while product efficiency reduces energy consumption during usage and enhances the performance of energy generation systems. Circularity supports sustainability by extending material lifecycles through reuse and recycling, thereby avoiding energy-intensive primary production. This paper presents an overview of exemplary sustainability contributions in metal forming process chains. For open-die forging, it can, for example, be shown, that digital twins, virtual reality-based operator training and real-time assistance systems are measures to improve material and process efficiency. A circularity approach for open-die forging is presented, with a remanufacturing concept for large shafts based on re-forging end-of-life components, in order to heal fatigue-related damage by forming. Increased material, process and product efficiency is demonstrated by a use case study of forging hollow rotor shafts for wind turbines. Whereas, the hollow-forging allows for weight reduction in the rotor component and thus enables higher power density of the generator, thinner tower designs and reduced logistic costs. Additionally, the use of an innovative air-hardening ductile (AHD) steel can eliminate the energy-intensive heat treatment in the process chain.

Introduction

Climate change is progressing at a rapid pace [1], causing severe hazards for our living environment and making sustainability and circularity key challenges for our future. Greenhouse gas emissions are primarily caused by human influence and the industrialized society. According to Allwood et al. [1], 78% of the global greenhouse gas emissions (GHG) originate from energy generation and process emissions. Out of that, 35% is generated by industry. Therefore, every individual, the society and the industry need to adapt. Within the industrial sector, 55 % of the emissions stem from material production and processing [1]. Whereas iron, steel and aluminum are among the most relevant materials [2, 3]. In addition to the general human influence, that emphasizes the strong role of the industry and the material processing in particular. Based on that, a high relevance and responsibility, but also saving potential, can be derived for the metal forming community. Thus, forming technology can make a significant impact regarding material efficiency, process efficiency, product efficiency and circularity, besides other contributions to this transformation.

Material efficiency is very important because the largest emissions in many relevant products, such as automotive steel body parts and aluminum beverage cans, come from material production [2]. **Process efficiency** is crucial because the huge production volumes in forming process chains enable

a large leverage effect. **Product efficiency** allows to reduce energy consumption during the usage phase and also to increase the efficiency of energy transformation systems, such as electric generators and drives. And **circularity** allows to reuse and recycle materials for as long as possible in order to avoid energy-intensive primary production.

In order to achieve an effective circular economy, technologies and business models must be adapted and redeveloped. The depiction in Fig. 1 shows an exemplary, generalized process chain from the steel production and processing, along the product usage, towards the end of product life and the final discarding.

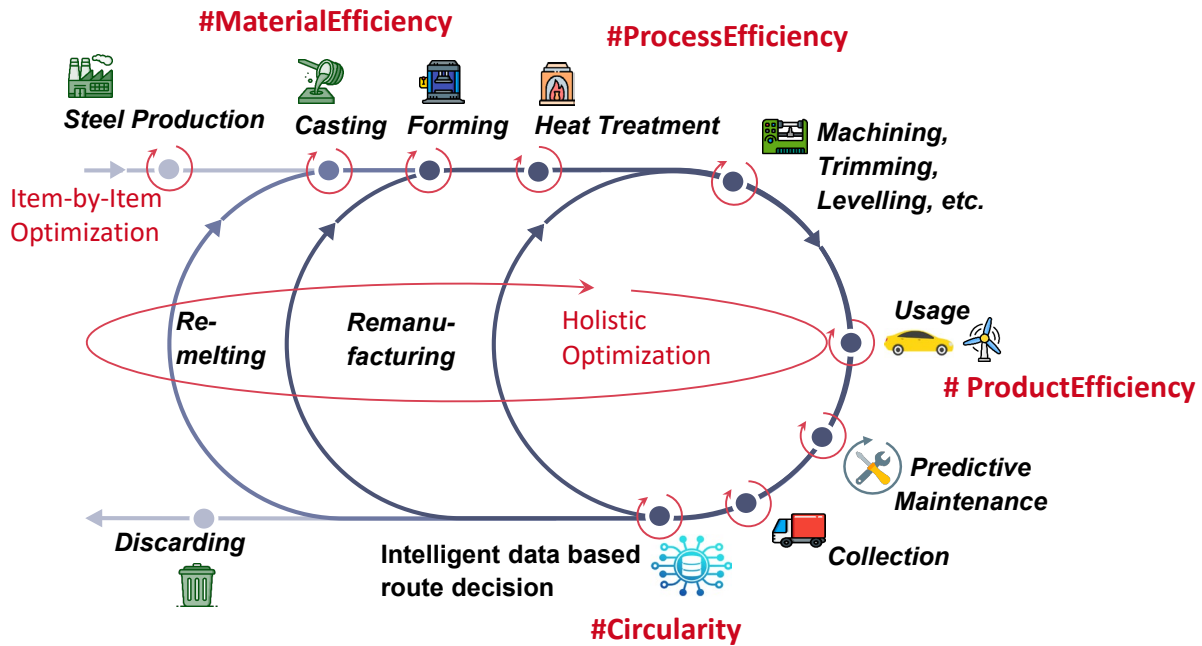


Fig. 1. Circularity Scenarios and holistic sustainability optimization of process chains.

After the production of a product an important sustainability goal is to keep it as long as possible in usage, e.g. supported by predictive maintenance. However, when the service life is finally no longer extendable, the product can be collected and discarded, which leads to the loss of the material and the energy invested in the product. Alternatively, the product can be kept in a circular material cycle, e.g. by re-melting the material or - even more energy-efficiently - by reworking or remanufacturing it. Remanufacturing can involve, for example, re-machining or even re-forming in order to improve material properties. Overall, it is therefore possible to re-enter the production cycle at different points. The decision which of these circular routes is most efficient and most sustainable as well as economic, can be very complex, but it can be strongly supported by data and digital twins. An intelligent data-based route decision can help to choose which circular path to take and how to design the new process route in detail. Digitalization methods in general are an important toolbox for substantial changes in the process routes towards sustainability and circularity, because they enable better holistic optimization (see Fig. 1) and allow for an adaptive response to fluctuations caused, e.g., by recycled materials.

This paper, therefore, aims to (i) structure sustainability contributions in metal forming routes for both sheet and bulk metal forming with four groups of improvement levers: **material efficiency**, **process efficiency**, **product efficiency** and **circularity** and (ii) to apply the four-lever framework more specifically on open-die forging and demonstrate a use case of hollow-forged wind turbine shafts.

The following paragraphs describe selected examples of specific potential sustainability contributions in metal forming routes to strengthen the four-lever framework.

Potentials for sheet and bulk metal forming routes in terms of efficiency and circularity:

Sheet metal forming process routes, starting from the liquid steel, followed by the rolling of sheets and the final component production are already widely optimized, mainly because of the

continuous, automated production and the extremely high production volumes. Nevertheless, there are still potentials and measures to further optimize these process routes and to shift them towards a circular production. And again, due to the high production volume, the overall potential to save material, energy and CO₂ is very high, even in terms of relatively small improvements.

In the following paragraph, some exemplary innovative examples will be discussed that can contribute towards further improvement of sustainability in the sheet metal forming route. The chosen examples are inspired by the research topics of the Institute of Metal Forming from RWTH Aachen University and serve to demonstrate the relevance and potential of the above-mentioned key measures, material efficiency, process efficiency, product efficiency and circularity.

The first example is the **strip casting process**, which is an integrated casting and rolling process, producing thin sheet material (usually 1 – 3 mm) in one step directly from liquid steel. Thus, it serves as an ultra-short process route for sheet metal production, compared to the conventional route, starting from continuous casting or thin-slab casting (see Fig. 2, right).

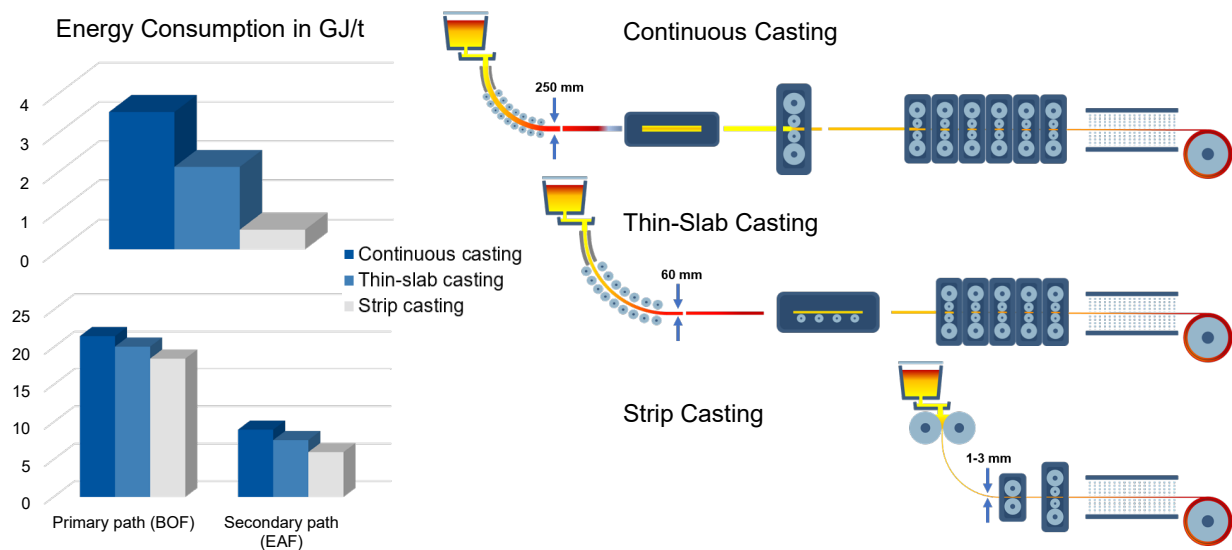


Fig. 2. Comparison of energy consumption for continuous casting, thin slab casting, and strip casting (left, top); Comparison of blast furnace route with electric arc furnace route (left, bottom); Comparison of process chain length (right) [4,5].

The comparison of the energy consumption between the conventional process routes and the strip casting route shows a significant advantage of strip casting, when looking at the route from liquid steel till hot rolled strips (see Fig 2, left, top). Considering also the reduced process scrap in an ultra-short process route, strip casting has a huge potential in terms of *material efficiency* and *process efficiency*.

When adding the steel production to the energy assessment, the differences between the process routes however look relatively smaller (see Fig. 2, left, bottom). Nevertheless, the comparison between primary production of steel using basic oxygen furnace (BOF) and secondary production using electric arc furnace (EAF) depicts a huge energy saving potential for the secondary route.

This leads to the second main advantage of the strip casting process route, which is a perfect enabler for recycling-based *circularity* in metal production. The production volume of typical strip casting lines is very suitable for a flexible and decentralized strip production with scrap as a major material source. Additionally, the high cooling rates in the solidification phase of the process (up to approximately 1000 K/s) are very advantageous for tackling tramp elements in the recycling route of aluminum and steel [6]. Furthermore, the process conditions including high cooling rates, the avoidance of slab reheating and extensive high-temperature exposure are very advantageous for the recycling of steels with high copper contents originated from recycling. The process conditions help to reduce copper segregation as well as oxidation-driven copper enrichment at the steel-scale interface and thus largely avoid liquid copper formation and weakening of the material. By producing near-net-shape strips directly from liquid steel, the necessary hot rolling effort is drastically reduced.

This additionally allows for largely surpassing the problem of damage due to copper-induced embrittlement (Hot Shortness) in the hot rolling [3, 7].

Another potential advantage of strip casting, which is also based primarily on the high cooling rates and reduced rolling effort, lies in the production of special, high-alloyed materials. Previous studies have demonstrated that the high cooling rates strongly influence microstructure evolution, texture development and downstream processability. For high-silicon electrical steels, it is known that an increased silicon content increases the electric efficiency of the electric drives using these sheets. The optimum silicon content for electrical efficiency is 6.5 wt.% (weight percent). However, the brittleness of these alloys increases dramatically with rising silicon content, which means that alloys with a silicon content greater than 3.5 wt.% cannot be produced using conventional industrial process routes. Strip casting has shown that high cooling rates, near-net-shape casting, and low rolling effort enable the production of electrical strips with 4.5 wt.% [8] and 6.0 wt.% [9] silicon. These examples demonstrate the potential of strip casting to improve *product efficiency*.

In the **rolling process** chain, either after strip casting or after continuous casting, respectively thin-slab casting, there is significant potential for optimization through the use of digital twins of the material and processes. For example, fast process models [10] and digital twins [11] can be used to adapt processes in the event of process deviations in order to maintain quality and avoid rejected products, which in turn increases *material efficiency* and *process efficiency*. Furthermore, digital twins and process adaptation can also be used in the long term to respond effectively to greater fluctuations in input material in the process chains, triggered by high recycling rates [12]. This shows a strong potential for *circularity*. Further potentials for *material efficiency* can be found in the reduction of edge scrap in heavy plate rolling, which is still very pronounced [13]. Regarding *product efficiency*, the rolling processes can contribute by an increased damage control [14].

In the final **sheet metal forming** the highest potential for *material efficiency* and *product efficiency* can be found in lightweight design concepts. New potentials in lightweight design can be exploited primarily through process innovations, such as in architecture and design applications through the combination of stretch forming and incremental sheet metal forming (ISF) [15], and in automotive components through gas-based aluminum hot sheet metal forming [16]. Additionally, gas-based aluminum forming can also increase material efficiency and product efficiency by reducing damage evolution in the process [17]. Finally, the re-manufacturing of end-of-life components with flexible sheet metal forming processes such as ISF [18] can contribute to *circularity*.

Compared to many **bulk metal forming process routes**, the sheet metal forming routes are already on a rather mature level regarding efficiency and sustainability, which is mainly due to the high production volume and automation. However, the previous paragraphs have shown promising further potentials. Many bulk metal forming processes are less automated and optimized, due to the lower production volumes and high part variations, like in open-die forging. However, there is great potential due to the large quantities of material and process energy involved. In open-die forging the process optimization can be significantly advanced using digital twins of the material and the process. Virtual reality training of operators [19] and a real-time assistance system for the process [20] allow for a minimization of scrap, tolerances and trim as well as near-net-shape production, e.g. curved components [21]. These measures all contribute to increased *material efficiency* and *process efficiency*. Another concept related to large shafts can make a significant contribution to *circularity*. The conceptual idea is a remanufacturing approach for large shafts, which involves the healing of fatigue-related damage by the re-forging of end-of-life shafts and strongly relies on digital twins of material and process.

A further option to increase *material efficiency* and *process efficiency*, as well as *product efficiency*, can exemplarily be demonstrated by the forging of hollow shafts for wind turbines, which enables material and weight savings and increases the efficiency of energy generation by higher power density. The use case of hollow shafts for wind turbines will be explained in more detail in the following chapters.

Motivation for the Use Case Wind Turbines

The transition towards sustainable energy systems imposes increasing performance and efficiency demands on wind turbines. Key drivetrain components must be designed to reduce material and energy consumption during manufacturing while enabling higher power densities. The rotor shaft, which absorbs cyclic bending loads and transfers torque from the rotor to the gearbox, plays a central role in this context.

Conventional manufacturing routes face inherent drawbacks: cast rotor shafts offer high geometric flexibility but exhibit comparatively low mechanical strength. Solid-forged shafts provide significantly higher strength but require extensive machining and large material input, resulting in high economic and environmental burdens.

A common research project of the Center for Wind Power Drives, the Steel Institute and the Institute of Metal Forming at the RWTH Aachen University addresses these challenges by investigating the potential of directly hollow-forged rotor shafts made from air-hardening ductile steel (AHD-steel). This approach combines the mechanical benefits of forged steels with the geometric flexibility of hollow sections and eliminates the need for energy-intensive quench-and-temper heat treatment. By enhancing *material efficiency* and *process efficiency*, i.e., reducing process-related energy consumption, the project contributes to lowering the environmental footprint of drivetrain components for wind turbines.

State of the Art for the Use Case Wind Turbines

Wind energy plays a crucial role in renewable electricity generation and is central to achieving global climate objectives. The growing demand for wind energy is reflected in the ongoing development toward turbines with higher power ratings [22]. However, further increases in turbine size are limited by logistical challenges related to transport, installation, and space requirements. As a result, research efforts increasingly focus on reducing the levelized cost of energy and enhancing the power density of the drivetrain. One approach is the application of lightweight design concepts to drivetrain components.

Rotor shafts in wind turbines are inherently hollow to allow electrical cabling for the pitch control system. Currently, there are two established manufacturing routes: Casted and solid forged shafts [23]. Cast shafts must be oversized due to their comparatively low strength, while drilled solid-forged shafts offer higher strength but incur significant material waste and require extensive machining, followed by costly quench-and-temper heat treatment. This contradicts current sustainability goals, as large volumes of steel must be cast, forged, and subsequently removed.

Directly hollow-forged shafts are typically manufactured by upsetting the heated ingot, followed by piercing [24]. For that, the ingot is first brought to forging temperature and oriented in the axial direction under the press. During upsetting, the height of the block is substantially reduced, causing complete deformation and initiating recrystallization, which improves the material properties [24]. Additionally, higher total strains can subsequently be introduced in the cogging process, also benefiting the mechanical performance. After upsetting, a solid mandrel is driven into the block in multiple steps to pierce it, displacing material outward and creating the hollow core [25].

The subsequent cogging of the pierced blank occurs over several hundred strokes using a mandrel held by a manipulator. During this stage, the hollow shaft obtains its final geometry and material properties, making the design of the forging strategy critical. Previous studies have shown that strategies employing two forming tools and a movable mandrel achieve significantly larger elongations while minimizing undesired increases in inner diameter [26]. Besides conventional free-forging parameters such as reduction ratio and bite ratio, the saddle geometry also strongly influences the material flow. V-saddles are particularly effective in maximizing elongation [25].

In stepped hollow shafts or those with flanges, such as wind turbine rotor shafts, special attention must be paid to regions with large radial thickness. Prior work suggested one-sided upsetting in closed dies to form the flange, though this reduces the inner diameter, requires a dedicated die for each shaft type, and limits process flexibility [27].

Following forging, machining and heat treatment are normally required to achieve the final mechanical properties, both of which contribute to significant energy consumption. Newly developed air-hardening ductile steels (AHD-steels) provide a potential solution, as they transform during air cooling after forging, eliminating the need for quench-and-temper treatment. Compared to conventional QT-steels, AHD-steels can also provide improved static and cyclic material properties. However, their applicability to large wall thicknesses must be investigated, because the transformation requires maintaining a critical cooling rate. Previous studies on small components demonstrated substantial CO₂ reductions, highlighting their relevance for sustainable manufacturing [28].

Objective for the Use Case Wind Turbines

The objective is to demonstrate that rotor shafts for wind turbines can be directly hollow-forged from AHD-steel to enable lightweight design and increased power density. Beyond geometric manufacturability, it must be shown that this method offers economic advantages compared to conventional processes. A key factor is the reduction of required input material through targeted control of the material flow [29]. Additionally, the critical cooling rate of AHD-steel must be maintained even in areas of the shaft with large wall thickness to ensure full hardening.

Procedures and Methods for the Use Case Wind Turbines

An implicit finite element simulation model of the hollow-forging process was developed in FORGE NxT 4.0. The model includes a flat upper saddle, a V-shaped lower saddle, the workpiece, forging mandrel, and manipulator.

An adaptive tetrahedral finite element mesh comprising more than 22,800 elements was employed, with local refinement in the forming zones to accurately resolve large strain gradients and complex material flow behavior. The material response was described using a thermo-viscoplastic constitutive model based on tabulated flow stress data as a function of temperature and strain rate. Thermal conductivity was implemented via temperature-dependent coefficients, while density, specific heat capacity, emissivity, and the linear thermal expansion coefficient were treated as constant parameters. Frictional interactions were modeled using a combined Coulomb friction law with a limiting shear stress criterion. For the tool–workpiece interfaces, a friction coefficient of $\mu=0.4$ and a shear yield limit of 0.8 were applied, whereas the lubricated mandrel–workpiece contact was characterized by a reduced friction coefficient of $\mu=0.15$ and a shear yield limit of 0.3. Heat transfer between the workpiece and the forming tools was represented by a heat transfer coefficient of 10,000 W/m²·K, while heat exchange with the surrounding air was modeled using a coefficient of 15 W/m²·K. Throughout the model development, particular emphasis was placed on an accurate representation of the manipulator kinematics and the complex interactions with the forming tools, as these factors were identified to have a decisive influence on the resulting material flow. The numerical model was developed in close cooperation with the simulation software provider and industrial forging companies, ensuring that the implemented boundary conditions and process assumptions reflect state-of-the-art industrial practice and expert knowledge.

Using this model, the entire process chain, from raw ingot (raw block) to finished hollow-forged preform (raw part), was simulated over multiple heats, including all reheating steps (see Fig. 3). The process begins with initial cogging of the polygonal casting block, followed by upsetting and piercing. The main hollow-forging sequence consists of three heats and more than 380 strokes, resulting in the raw hollow shaft.

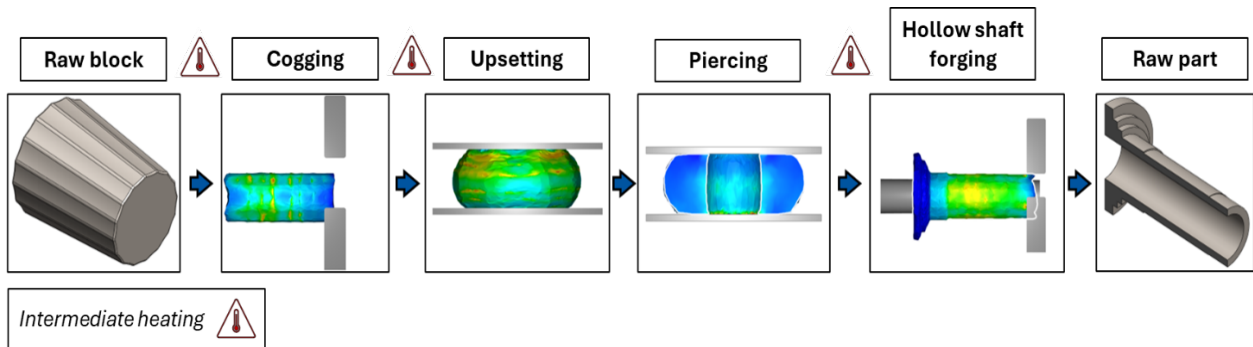


Fig. 3. Simulated process chain for hollow forging, including reheating.

Results and Evaluation for the Use Case Wind Turbines

Simulation results revealed that the initially designed forging sequence led to a pronounced conical formation of the flange, which was directly associated with excessive axial material flow and, consequently, a substantial surplus of material in the flange region (see Fig. 4a)). This outcome was identified as incompatible with the targeted improvements in material and energy efficiency. To address this issue, the axial allowances of the forging geometry were systematically reduced, and the resulting material flow was analyzed in detail to assess whether the required cross-sectional geometry could still be accommodated within the final forged shape.

These analyses showed that a nominal flange width corresponding to the geometric width of the target geometry led to an instability in the flange region: Once a critical wall thickness was undershot, the flange exhibited buckling toward the manipulator, preventing full die filling and thus resulting in a deviation from the target geometry (see Fig. 4b)).

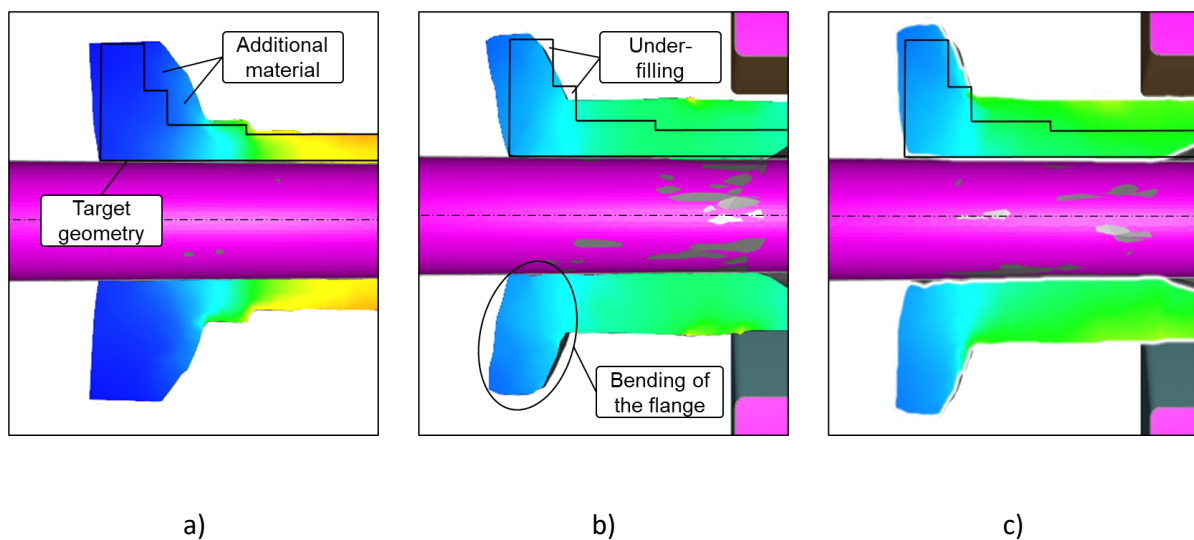


Fig. 4. Cross-section of the hollow shaft after forging the flange area: a) Original dimensions, b) reduced dimensions, c) adapted forging strategy.

An adapted process route successfully resolved this issue: after forming the flange in the first heat, the forging ingot is removed from the mandrel, aligned axially under the press, and axially upset using simple flat dies until the flange is fully realigned. The use of simple die geometries eliminates the need for dedicated dies and maintains process flexibility.

The procedure is shown in Fig. 5.

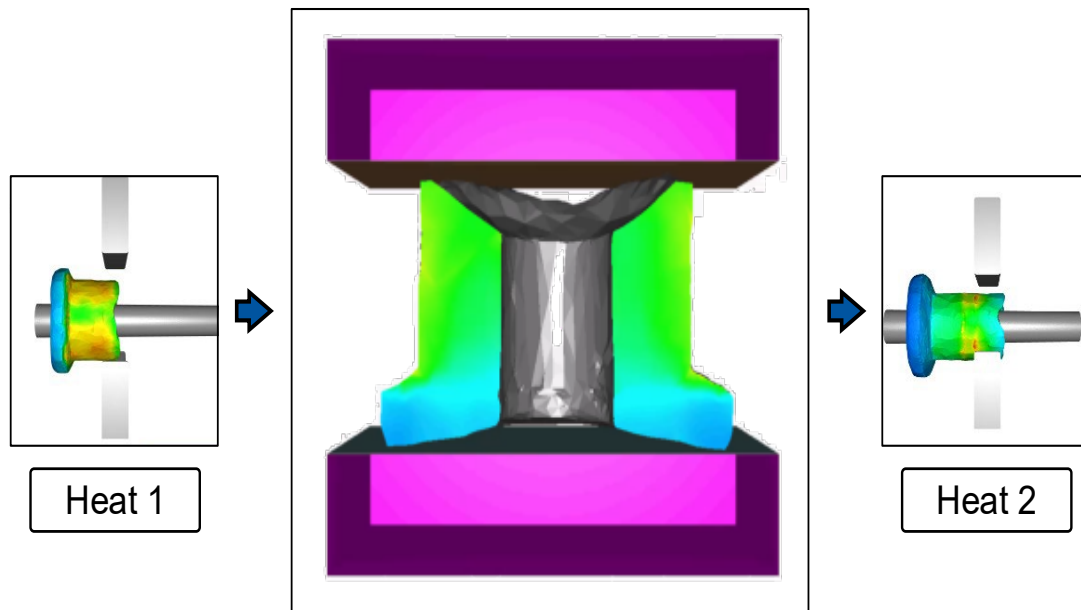


Fig. 5. Adapted process chain with intermediate upsetting of the ingot.

With this adapted strategy, the material mass of the forged part was reduced from approx. 27 t to 22.4 t, yielding a 17 % material saving based on process optimization. This directly reduces the required ingot mass and thus enhances both economic and ecological performance.

However, for the current predesign, the hollow-forged shaft requires 26.5 t AHD steel as input material, which is 24 % more material than needed for the cast shaft (EN-GJS-400-18-LT). This is due to the conservative forging surcharges (allowance) that have been assumed (160 % in total for forging, compared to 32 % for casting). In order to get towards costs for forging that are comparable to casting, the total forging surcharges need to be reduced from currently 160 % to around 50 % of the final shaft mass.

Nevertheless, the resulting rotor shaft made of hollow-forged AHD steel has a mass of 10.2 t, which is 37 % lower than the cast shaft with 16.2 t. Thus, the final weight saving in the product has already been demonstrated successfully and enables higher power density of the generator, thinner tower designs and reduced logistic costs. [29]

Cooling simulations further showed that, due to reduced flange dimensions, the thickest sections achieve the critical cooling rate required for proper air hardening. Comparison with experimentally determined CCT diagrams confirms that full transformation is expected, supporting the suitability of AHD-steel for large forged geometries like hollow rotor shafts for WEA.

Conclusion and Outlook

In the introduction, the paper has presented exemplary potentials for the improvement of sustainability and suggested to structure sustainability contributions in metal forming routes with four groups of improvement levers: *material efficiency*, *process efficiency*, *product efficiency* and *circularity*. The four-lever structure together with specific examples from the field of open-die forging, mentioned in this paper, is shown in Fig. 6.

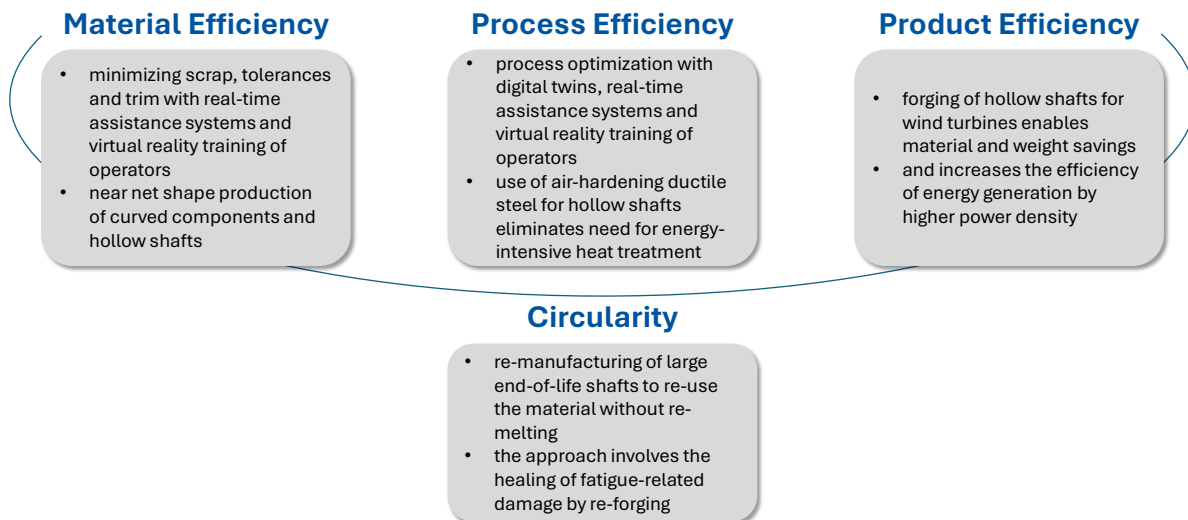


Fig. 6. Depiction of a four-level concept for sustainability contributions in metal forming routes and specific examples from open-die forging.

The use case presented in the main part of the paper demonstrates that hollow-forged rotor shafts made from air-hardening ductile steels offer substantial potential for material and CO₂ savings in wind turbine drivetrain manufacturing. A complete hollow-forging simulation model was established, enabling systematic reduction of excess material. An adapted forging process with intermediate upsetting achieves significant material efficiency without compromising manufacturability or cooling behavior.

Future work will focus on the further reduction of the forging surcharges and will demonstrate a proof-of-concept by forging representative shaft sections as well as the manufacture of a full demonstrator shaft for validation of the simulation model and testing on drivetrain test benches or pilot turbines.

These steps will further validate the industrial feasibility of AHD hollow-forged rotor shafts and support their adoption as a more sustainable alternative to current manufacturing routes.

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