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Computer-Aided Engineering Environment for Designing Tailored Forming Components

Tim Brockmöller *, Renan Siqueira, Paul C. Gembarski, Iryna Mozgova and Roland Lachmayer

Institute of Product Development, Leibniz University Hannover, An der Universität 1, 30823 Garbsen, Germany; siqueira@ipeg.uni-hannover.de (R.S.); gembarski@ipeg.uni-hannover.de (P.C.G.); mozgova@ipeg.uni-hannover.de (I.M.); lachmayer@ipeg.uni-hannover.de (R.L.)

* Correspondence: brockmoeller@ipeg.uni-hannover.de; Tel.: +49-0511-762-5340

Received: 29 October 2020; Accepted: 19 November 2020; Published: 27 November 2020



Abstract: The use of multi-material forming components makes it possible to produce components adapted to the respective requirements, which have advantages over mono-material components. The necessary consideration of an additional material increases the possible degrees of freedom in product and manufacturing process development. As a result, development becomes more complex and special expert knowledge is required. To counteract this, computer-aided engineering environments with knowledge-based tools are increasingly used. This article describes a computer-aided engineering environment (CAEE) that can be used to design hybrid forming components that are produced by tailored forming, a process chain developed in the Collaborative Research Center (CRC) 1153. The CAEE consists of a knowledge base, in which the knowledge necessary for the design of tailored forming parts, including manufacturer restrictions, is stored and made available. For the generation of rough and detailed design and for elaboration the following methods are used. The topology optimization method, Interfacial Zone Evolutionary Optimization (IZEO), which determines the material distribution. The design of optimized joining zone geometries, by robust design. The elaboration of the components by means of highly flexible computer-aided design (CAD) models, which are built according to the generative parametric design approach (GPDA).

Keywords: tailored forming; multi-material; IZEO; topology optimization; computer-aided engineering environment; GPDA; manufacturing restrictions

1. Introduction

The progress of manufacturing technologies tends to astonish observers. For example, at Leibniz University Hannover, the Collaborative Research Center (CRC) 1153, which is funded by the German research association, explores process chains for tailored forming [1]. Here, semi-finished hybrid workpieces, consisting of two different materials like steel and aluminum, are processed by forming, heat treatment and cutting technologies to produce high-performance multi-material parts [2,3].

Ashby and Cebon have shown that for special purposes, a multi-material design achieves superior performance than a conventional design [4]. Thinking of structural components like wheel carriers, rocker levers, or even pinion shafts, areas where high stiffness and wear resistance are needed can be made from steel, all other areas are made from aluminum [5]. So, from a design point of view, a new degree of freedom is introduced, which is the material distribution within the multi-material part. What initially appears to be an interesting avenue for leveraging even more efficiency of such parts results in higher complexity for the design since the material distribution generally influences the mechanical properties [6–9].

However, more than this, the complexity rises also from the manufacturing point of view [10]. The tailored forming technology requires production lines where many manufacturing steps follow each other, whose processes are linked and therefore precisely coordinated [11]. Setting up and running in a new product variant result in large efforts, especially when process windows need to be (re-)evaluated and the quality of semi-finished materials varies [12,13]. Thus, it is necessary for the designer to consider the available capabilities of manufacturing as early as possible since they restrict the possible solution space of the part geometry [14]. Examples, therefore, range from simple manufacturing restrictions like maximum traveling distances or hardening depths [15], over appropriate tolerances of dimensions, form and positioning to the consideration of design guidelines, as is discussed today as Design for Excellence (DfX) [16,17]. Here it also must be considered that both materials of a tailored forming part may differ in their processing, i.e., forming temperatures, cutting speed, etc., [18,19].

In order to avoid iterations during design, computer-aided engineering environments (CAEE) support the designer in making the right decisions, checking the design with respect to the solution space and finding the optimum between requirement fulfillment, capabilities and resulting production costs [15,20,21]. On the one hand, they include all necessary synthesis and analysis tools for a design task [5,22–24]. On the other hand, e.g., artificial intelligence technologies offer the possibility to process data from production, find patterns and formalize new manufacturing knowledge automatically [25–27]. Thus, such CAEE serve as a central information hub for all experts that are involved in the according to the design process [28–30].

Within the scope of this work, a CAEE is set up to reduce the uncertainties in the development of tailored forming components and to help ensure that they are adapted as optimally as possible to the respective use case. The CAEE has different tools that are used in different phases of the product development process. The manufacturing and process knowledge needed for the development is provided by the subprojects of the CRC 1153. Accordingly, the CAEE offers the possibility to extend the underlying knowledge base with new insights gained in the CRC 1153 and delivers rough as well as detailed designs of tailored forming components accordingly. Special consideration is given to the material distribution in the component as well as the implementation of the applicable manufacturing restrictions. The article is structured as follows. The second Section deals with the state of the art on the relevant topics of tailored forming, design theory and knowledge-based systems. Section 3.1 presents the methods and tools of the CAEE with which rough and detailed designs are implemented. In the following Section 4 these are implemented by means of corresponding examples. In the last two Sections 5 and 6 the contribution is summarized and a conclusion and an outlook to further research projects are given.

2. Research Background

2.1. Manufacturing Processes for Multi-Material Parts

The hybridization of semi-finished parts is a widely discussed and promising topic for raising the performance of structural components. In order to create a composite of different metallic materials, different methods are researched and applied in the industrial environment.

In explosive welding, two plate-shaped workpieces are joined together by a controlled explosion. The workpieces are welded at the joint surfaces without heat input by applying an abrupt force caused by the pressure wave generated by the detonation of explosives, preferably without filler metal [31,32]. Another family of production processes that is used to create hybrid semi-finished materials is additive manufacturing [33]. Different from this is a relatively new approach that combines two different materials in laser powder bed fusion processes [34]. All of these approaches have in common that an inter-metallic joining zone between both materials occurs.

With the hybrid forging developed by the Leiber company, non-plate shaped semi-finished products of steel and aluminum alloys can also be joined together. This approach does not aim at an

inter-metallic bonding of both materials [35]. In e.g., hybrid compound forging, this is different since a material joint is created using a soldering material [36].

In the CRC 1153 of Leibniz University Hannover, various process chains for the production of multi-material and formed solid components are being researched. The materials used are mainly aluminum (EN AW 6082) and steel alloys (20MnCr5, 41Cr4). The general process chain can be seen in Figure 1.

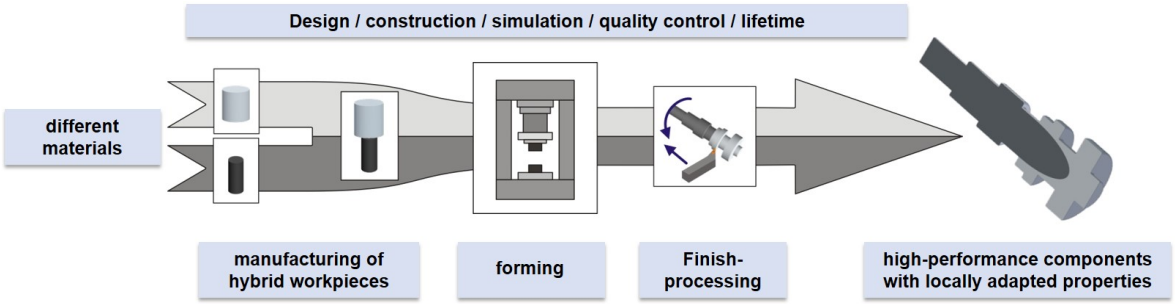


Figure 1. General tailored forming process chain, according to [2].

In the first step, a so-called hybrid semi-finished product is produced. Two mono-material semi-finished products are joined together by friction welding [37,38], ultrasonic-assisted laser beam welding [39], deposition welding [40] or composite rod extrusion (LACE (LACE = Lateral Angular Co-Extrusion) process) [41]. The hybrid semi-finished product is then shaped in a forming process. Here, cross wedge rolling [42], impact extrusion [43] and drop forging [40] are investigated. Both materials are formed during the process step and thus form an intermetallic compound. The process differs here, for example, from hybrid forging, in which the materials are not joined before forming and only one material is formed. In the end, heat treatment processes follow in order to be able to influence the component's mechanical properties [44] and the component is finished by machining [19]. The manufacturing process relevant for this article consists of the process steps friction welding, impact extrusion and machining. As the heat treatment processes only influence the component properties, but not the geometric shape, these are not considered.

Rotary friction welding is suitable for welding different materials that cannot be joined by other welding processes [45]. For friction welding of hybrid components, various investigations have been carried out in the CRC 1153 in which the strengths of steel–steel alloy combinations have been analyzed [46], also in comparison to US laser beam welding [45]. In addition, the strengths of steel–aluminum alloy combinations at different temperatures have been investigated [47]. Furthermore, it has been explored how different geometries (different cone angles in the semi-finished steel product), properties of the surfaces and temperatures also affect the strength of the composite [37].

Impact extrusion is a metal forming process in which a semi-finished workpiece is pressed through a die to obtain a product with a smaller cross-sectional area. These are differentiated according to the direction of material flow and the geometry of the formed product. The process used here is called forward rod extrusion [48]. In connection with extrusion, SFB 1153 has developed heating strategies for inhomogeneous heating, since the required forming temperature is different for each material. In addition, it is investigated how the shape and strength of the joining zone can be influenced by impact extrusion so that the strength of the composite is increased. The first concepts for impact extrusion and inhomogeneous heating by induction can be found in [2,49]. In Goldstein et al. 2017 the simulative results of heating are validated by experimental tests on steel–aluminum semi-finished products (20MnCr5, EN AW 6082) [48]. Based on these results, the joining zone geometries and properties of manufactured components are investigated in [18], which are then optimized in [43] by adjustments in the forming process. In addition, it has been shown that forming can improve the strength of the joining zone of components (41Cr4, C22.8) produced by US laser beam welding [50].

Besides pure shaping, machining is used to manipulate the properties of the surfaces of hybrid components [51,52]. However, these aspects are not yet relevant for the current state of the CAEE. Behrens et al. 2019 illustrate the entire product development and manufacturing process from the creation of the joining zone geometry, joining, forming and heat treatment to the finished machined component [11]. Figure 2 illustrates the manufacturing process.

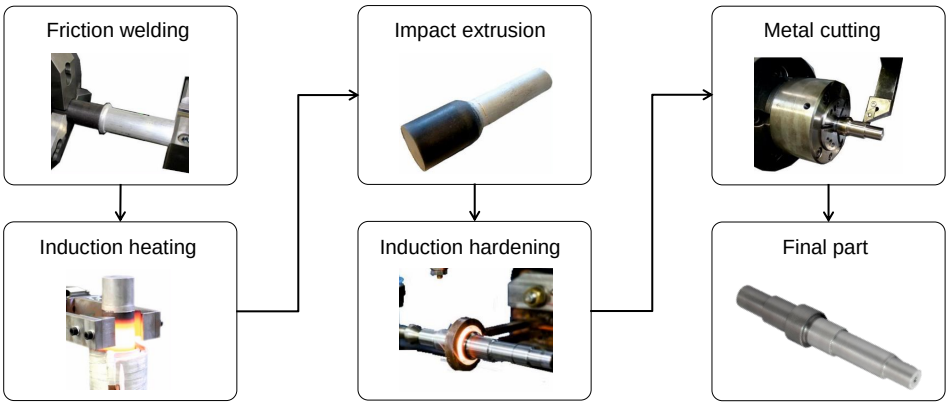


Figure 2. Process chain for the production of a hybrid shaft by tailored forming [11].

2.2. Computer-Aided Engineering Environments

The development of technical products follows well-known process models that are either of a sequential or networked nature [53]. As an example, the process according to Pahl and Beitz divides the development process into four phases which are task clarification, concept determination, embodiment design and detailed design [54]. Another example is Suh's approach of Axiomatic Design where customer requirements are translated into functional requirements, design parameters and process variables for manufacturing [12]. The translation is achieved with design matrices and is thus strictly formalized [14]. Usually, the processes allow iterations and zig-zagging through the phases, as requirements are sharpened and new knowledge is created continuously while the design team converges the solution space against the final design [55].

In modern product development, independently from the process, the application of software tools for synthesis and analysis of design artefacts is state of the art for many disciplines [56]. Beside these, such computer-aided engineering environments (CAEE) comprise product data management and collaboration support systems that allow for coordination of large teams as well as formalizing and communicating knowledge between all relevant stakeholders [15,57]. A very central tool for mechanical engineering is still the computer-aided design (CAD) system for defining e.g., product shape and production information [58,59]. Over time, these CAD systems have developed from tools for 2D line drawing to powerful parametric 3D design systems where a designer is able to modify his parts and assemblies simply by changing values of e.g., dimensions for lengths and adding or deleting features [60]. Hereby, it has to be considered that only a part of the product's characteristics may be modeled directly, like geometry, material, or surface quality. e.g., stress distribution is a resulting property that is influenced by the characteristics and thus modeled indirectly which leads to synthesis-analysis loops during development [61].

Two lines of development stand representative for the progress in CAEE implementation. First, knowledge-based engineering and design systems use formal, explicit knowledge that has been integrated into the according to synthesis and analysis systems [62–66]. As an example, knowledge-based CAD uses dimensioning formulae, design rules, spreadsheet integration and intelligent templates to automate routine design tasks [67,68]. Exemplary works from this line of development describe CAEE for fixture design [30,69,70], automotive and aircraft engineering [67,71] or mechanical and plant engineering [20,72–74]. In Sauthoff 2017, the automatic configuration and optimization of structural components from automotive engineering are proposed, integrating a

knowledge-based design system and an evolutionary optimization algorithm [75]. All of these works have in common that a more or less closed solution space of predetermined designs is modeled. The resulting artefact description is usually of high quality and corresponds to detailed design.

As the second line of development, computational design synthesis systems rely on a more informal and implicit formulation of knowledge in order to design an artefact [59]. Their aim is more to capture the laws-of-creation of how a design artefact is developed. The consequence is that computational design systems commonly deliver more abstract artefact descriptions which have to be reengineered e.g. into parametric CAD [76]. An example of this is 3D topology optimization that considers manufacturing restrictions [6]. Other works from this line include the synthesis of additively manufactured parts using object-oriented programming, CAD and parametric optimization [21] or the design and optimization of mechanical engineering parts using CAD and multi-agent systems [27].

3. Computer-Aided Engineering Environment for Tailored Forming Parts

In order to design a tailored forming part, both lines of development make a contribution. The determination of the material distribution is more subject to computational design synthesis as laws-of-creation, therefore, may be formulated, independently from distinct geometry. Especially the design of the joining zone necessitates a formal representation that considers the restrictions of the later manufacturing processes precisely. Thus we propose a CAEE that uses both approaches for the respecting phases of the development of tailored forming parts.

The basic structure of the CAEE is shown in Figure 3. It essentially consists of four different areas. Three of the areas represent the product development process and provide tools for potential determination (1), for the creation of the rough design (2), and for the generation of the embodiment design or elaboration (3). The fourth area is the knowledge base (4), in which the expertise required for development is stored. The focus of this paper is on the areas (2), (3) and partly (4). Further information on area (1) can be found in [5,77] and is not part of this paper.

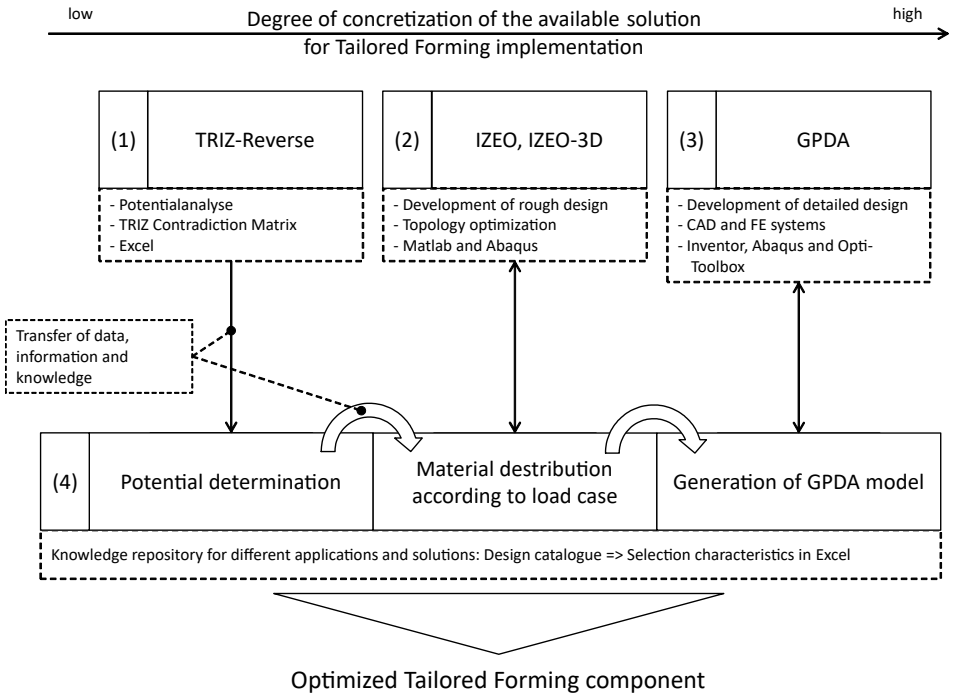


Figure 3. Structure of the computer-aided engineering environment (CAEE) for tailored forming.

3.1. Rough Design by Interfacial Zone Evolutionary Optimization

The Interfacial Zone Evolutionary Optimization (IZEO), developed in [78], is a method able to deal with the specific challenges of the present study since it can solve general multi-material problems

that have the presence of strong manufacturing restrictions. As recommended in [79], taking these restrictions into account in an early phase of the design process avoids the loss of the optimized properties when these are applied later.

The working principle of IZEO can be visualized in Figure 4. This method is based on evolutionary optimization algorithms, such as the Bidirectional Evolutionary Structure Optimization (BESO) [80], where the domain is discretized into elements and the material of the elements are changed iteratively, following a sensitivity function. The primary difference in IZEO is how these changes occur, which is limited to the interfacial zone between the different materials.

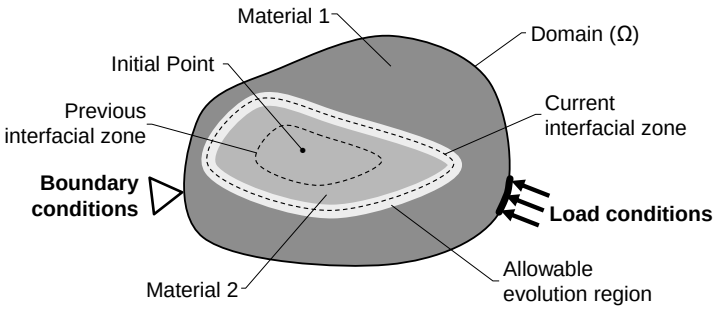


Figure 4. Model representation of the interfacial evolutionary process [81].

This strategy allows the implementation of a variety of manufacturing restrictions [81]. Following the theory proposed in [79], each manufacturing technique can be modeled as a combination of geometric constraints, as shown in Figure 5. IZEO follows the same principle, allowing the designer to apply different constraints at the same time.

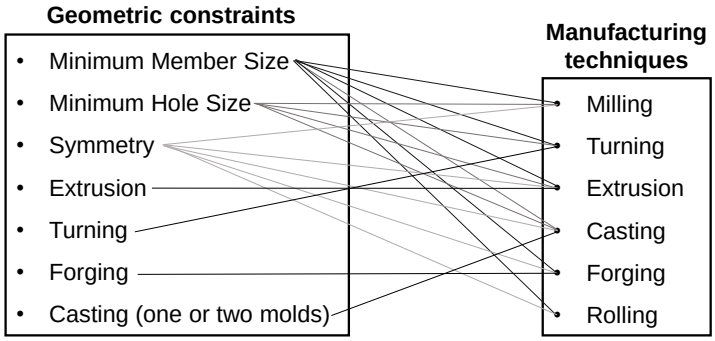
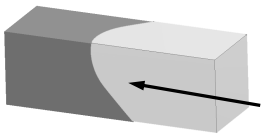
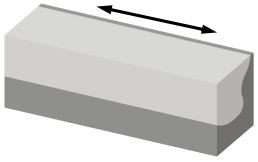
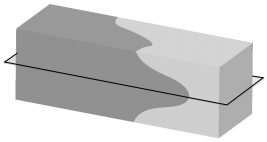


Figure 5. Relationship between geometric constraints and manufacturing techniques [79].

The constraints shown in Figure 5 can be also serialized in the simulation, which works as a prioritization from the first one applied until the last one. This is in accordance with typical manufacturing process-chains, where many restrictions are applied in different stages of the process. For multi-material processes, this also allows different constraints for the connections between the materials and the component body. This way, with the inclusion of all necessary geometric constraints, a general approach can be implemented to attend to the specific challenges inherent to a manufacturing process and generate optimized conceptual designs.

In the current study, the implementation of IZEO was extended for a 3D environment, differently from previous works. This was implemented in the FE-software Abaqus, using its scripting capabilities in Python. Therefore, the full IZEO program was implemented with Python, using the solving capabilities of the FE-software. In this case, the implementation of the manufacturing restrictions described in [81] was made following the same concepts, but considering the third dimension and a higher degree-of-freedom to control them. Table 1 presents the implemented geometric constraints and the respective control parameters.

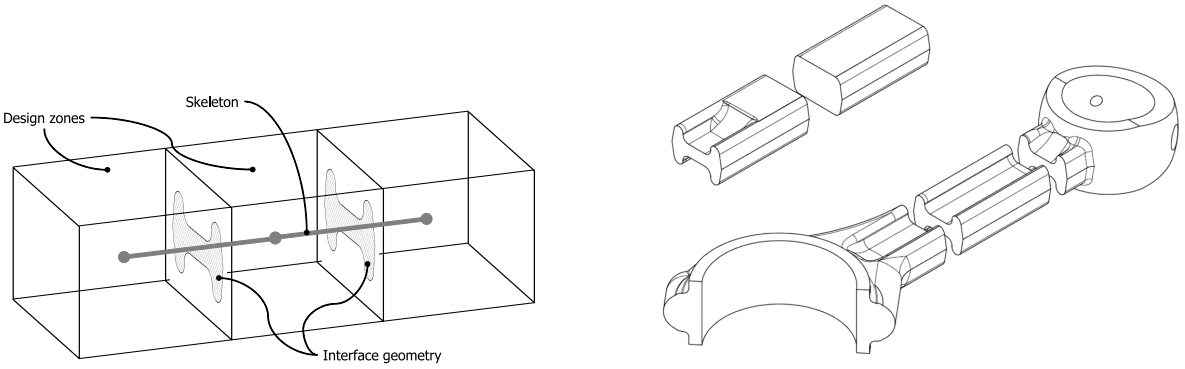
Table 1. Table with the implemented Interfacial Zone Evolutionary Optimization (IZEO) geometric constraints.

Geometric Constraint	Definition	Control Parameters	Representation
Minimum member size	Level of detail in the manufacturing process	Minimum size	
Uni/Bidirectional growth	Unidirectional access of the manufacturing tools or serial connection of materials	Vector of growth direction	
Extrusion	Extrusion direction in the manufacturing	Vector of extrusion direction	
Planar symmetry	Symmetry imposed by the processes	Point and normal vector to the plane	

It can be observed that with the inclusion of the control parameters, the implementation of geometric constraints adds new degrees of freedom to the generation of optimized solutions. Naturally, these restrictions will be selected according to the chosen manufacturing process. Ideally, the optimization should be performed several times with a variation of these constraints, in order to find the most suitable geometry and manufacturing process at the same time. In this case, not only the control parameters (radius, points and vectors), would be varied, but also different combinations of the constraints, simulating different process chains. Since the current study is focused on tailored forming, only the constraints related to the proposed process are here investigated.

3.2. Detailed Design Using the Generative Parametric Design Approach

A CAD-centric KBE environment was proposed by Sauthoff for the automatic configuration and optimization of structural components in mechanical engineering [75]. It combines a CAD modeling strategy called generative parametric design approach (GDPA) with knowledge integration and an evolutionary optimization algorithm. In order to achieve the necessary flexibility, the CAD model of a structural component is divided into several design zones which are linked by a common skeleton (Figure 6a). For each design zone, independent CAD models are implemented as so-called design elements that reflect parts of the structural component and may be understood as generic parametric templates (Figure 6b). In such a design element, all relevant design knowledge, like dimensioning, design rules or manufacturing restrictions, are stored [65]. The top-level assembly of the component is implemented in such a way that adjacent design zones communicate with each other and exchange interface parameters. The design elements can be replaced with other design elements that are also approved for the design zone, as required. When now a control parameter of the skeleton or general requirements for the structural component change, this is propagated through all design elements that check themselves for consistency, technical correctness and violation of restrictions. The result is that highly flexible models are created which can be rebuilt without errors even after topological changes [82]. If a sufficient library of generic and task-specific design elements exists, a large solution space of structural components like vehicle chassis or bodies, is available [83].



(**a**) (**b**)

Figure 6. Generative parametric design approach (GPDA) model of a connection rod: (**a**) skeleton and interfaces, (**b**) computer-aided design (CAD) model, according to [84].

Due to the flexible model structure, it is possible to optimize the shape of the GPDA models in automated synthesis-analysis loops. According to Sauthoff, the CAD system is coupled with an FE system via an optimization program, the so-called Opti-Toolbox. The Opti-Toolbox generates several component variants on the basis of e.g., evolutionary algorithms by automatically adjusting the parameters in the GPDA model and exchanging design elements. These are then analyzed in the FE system and the results are evaluated by the Opti-Toolbox. If the requirements are not met, further component variants are generated. This loop is repeated until the requirements are met [75]. Figure 7 shows the schematic structure of the GPDA engineering environment.

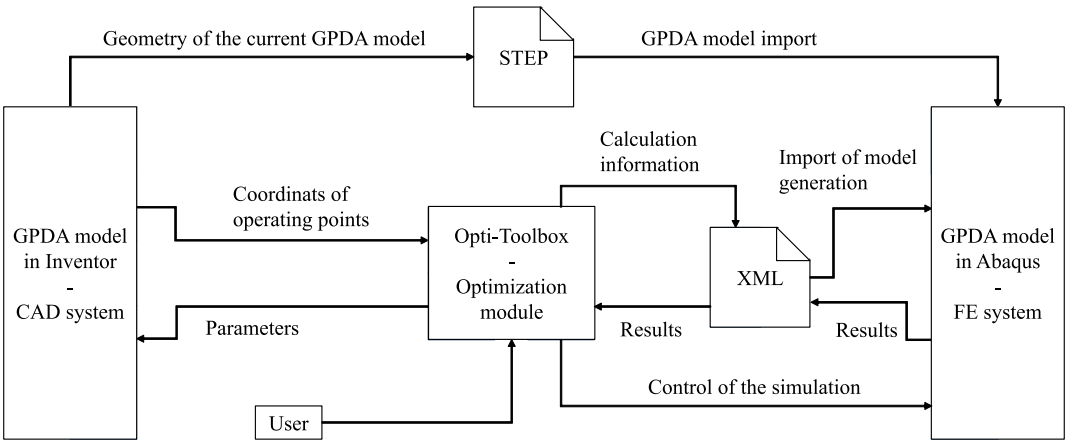


Figure 7. Schematic structure of the GPDA engineering Environment [83].

4. Implementation for Shaft-Like Tailored Forming Parts

A hybrid demonstrator shaft developed in CRC 1153 is used as an application example. The shaft is manufactured by the above-described manufacturing processes of friction welding, impact extrusion and machining. The material combination under consideration and 41Cr4 and EN AW-6082, whose properties are given in Table 2. The objective function is to generate a component that is as light as possible with sufficient strength.

Table 2. Material properties.

Material	Density	Yield Stress	Ultimate Stress
Steel (41Cr4)	7.85 $\frac{g}{cm^3}$	660 MPa	1020 MPa
Aluminum (EN AW-6082)	2.70 $\frac{g}{cm^3}$	280 MPa	385 MPa

Figure 8 shows the load and boundary conditions considered in this example. Furthermore, the represented geometry describes the boundaries of the domain in which the optimization is allowed to take place. The absolute values for force and torque were set to generate a global safety factor of 1 when the shaft is completely made of steel and the proportion between them was set to generate 15% of maximal stress through the bending and the rest through the torsion.

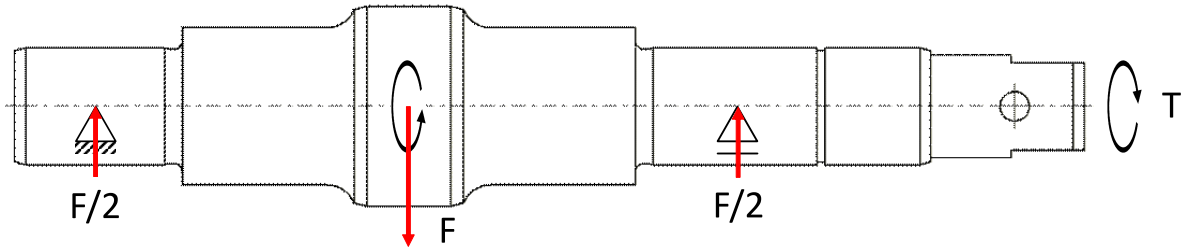
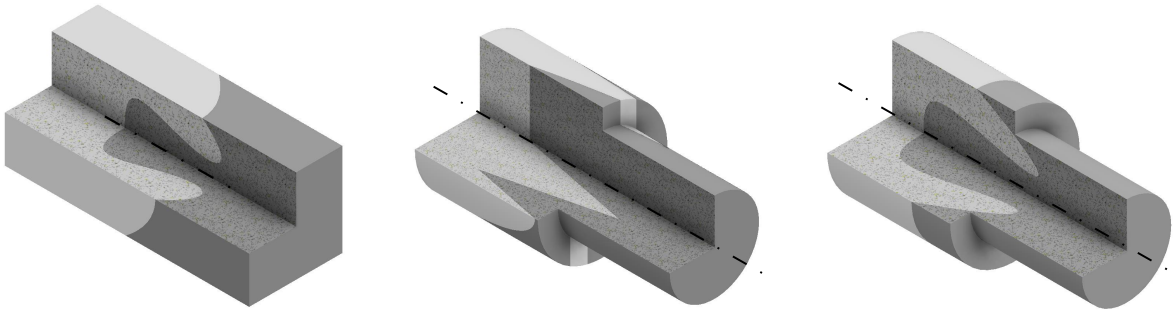


Figure 8. Domain with load and boundary conditions of the shaft for the 3D optimization.

4.1. Expansion of Geometric Constraints

With the geometric constraints described in Table 1 and the idea of a combination of constraints from Figure 5, a great variety of processes can already be simulated. However, for the current application, two constraints were added: rotational symmetry and radial growth.

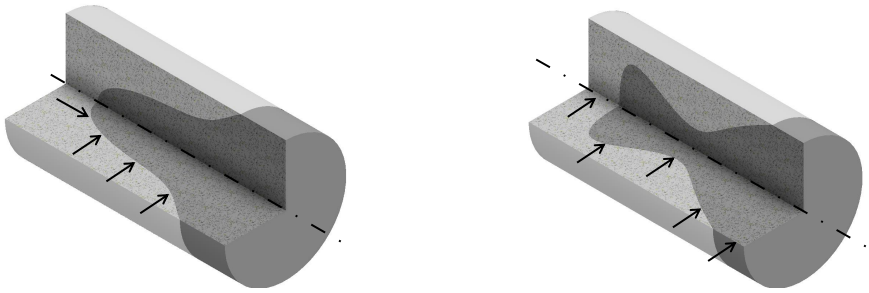
Rotational symmetry is self-explained, being related to components that are subjected to processes such as rolling or turning. Two control parameters are necessary: initial and final coordinates of the symmetry line. In the case of multi-materials, this constraint can be applied not only to the component body as a whole, but also separately to the connection between the two materials. IZEO allows these possible configurations, as presented in Figure 9. This restriction was implemented using the same principle of planar symmetry presented in [81], where the sensitivity of all elements present in the rotational curve are averaged.



(**a**) (**b**) (**c**)

Figure 9. Rotational symmetry applied to: (**a**) joining zone only; (**b**) component body only; (**c**) both joining zone and component body.

Radial growth is a special constraint present in tailored forming. In the manufacturing of rotational symmetric components, the possible processes do not allow the presence of the softer material inside the harder material. Due to thermal properties, the harder material always flows inside the softer material. This translates to the optimization method as a special type of "unidirectional growth" constraint, where the direction is not linear, but radial coming from outside, similar to what is seen in a turning machine (Figure 10). Therefore, the same as rotational symmetry, the initial and final coordinates of the center-line are required as control parameters.



(**a**) (**b**)

Figure 10. Rotational symmetric components with joining zone constrained by: (**a**) radial growth only; (**b**) radial and unidirectional growth.

This radial growth is not only important because of the thermal effects of the multi-material connection, but it also describes the main restriction involved in the manufacture of shafts during turning in a mono-material approach.

4.2. IZEO and Robust Design for Tailored Forming

The model described was submitted to IZEO with the following constraints: minimum member size (3 mm), unidirectional growth (same direction of the aluminum in the friction welding), rotational symmetry and radial growth (aligned to the axis of the shaft). Since the outer geometry of the shaft should remain unchangeable and the addition of aluminum will tend to reduce the strength of the shaft, it was set as the objective function a safety factor of 50% the value for a shaft made entirely of steel. The last interactions are presented in Figure 11.

During implementation, it became clear that design and manufacturing process development need to be aligned towards a common objective. The information exchange between the two fields is commonly of a sequential nature. Thus, an additional information exchange platform for continuous improvement was created to prevent from losing the knowledge acquired in past interactions.

For that purpose, the use of Knowledge-Based Engineering (KBE) tools are necessary for the creation of this common interface between design and manufacturing processes, and for the operationalization of both, as proposed in [85]. Therefore, an adaptation of a case-based reasoning (CBR) cycle was proposed, where the decision-making process is supported by a unified information management system. This method makes use of parametric models to analyze the information generated on both sides, compare them and suggest innovative design solutions based on new specifications and previous experiences. The topology optimization result will serve as the first input in the construction of this parametric model. Thereby, both design and manufacturing research can be performed in parallel, exchanging information in a continuous way and enhancing the system with its use.

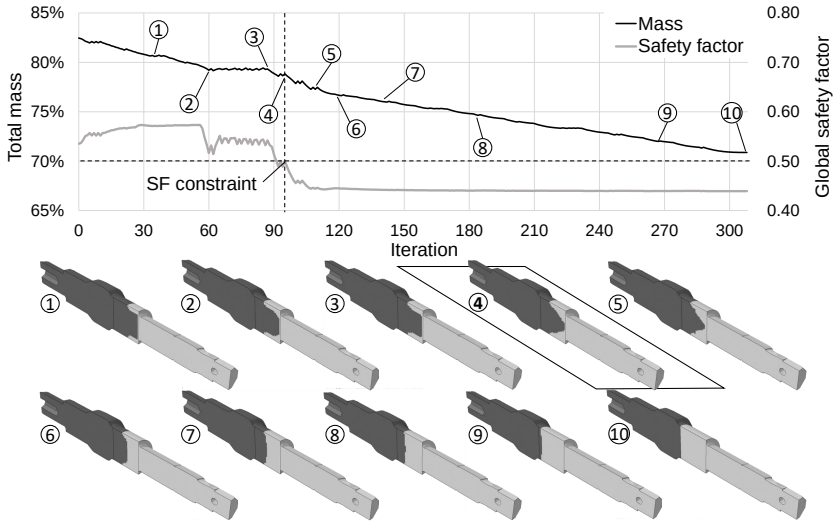


Figure 11. Optimization evolution for the tailored forming shaft model with IZEO.

With the results obtained with IZEO, a parametric model of the joining zone was constructed for the submission in the adapted CBR. With different parametric models and parameters, a large number of variations were simulated. Figure 12 shows a graph where the two objectives are set at both axes and every variation is represented as a point in the space. A Pareto front of optimal solutions can be easily recognized, where the simulations close to this curve are considered optimal solutions.

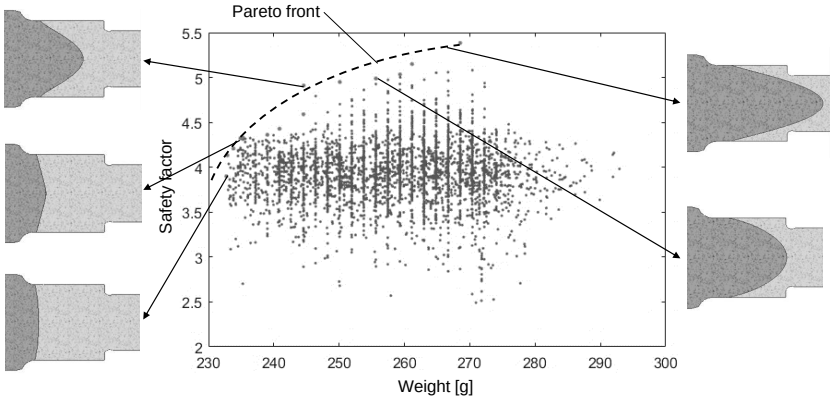


Figure 12. Plot of every parametric simulation over safety factor and weight, where a Pareto front is observed.

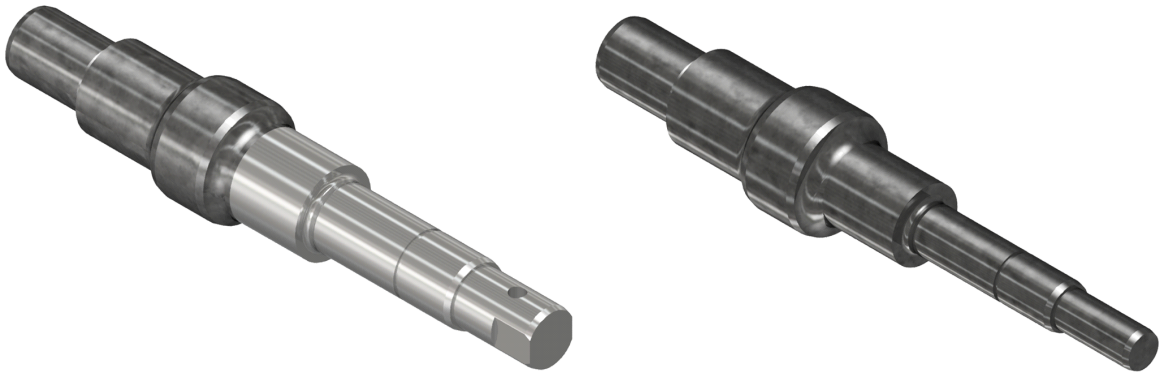
With the completion of the CBR cycle, the best candidates for manufacturing can be selected and submitted to the process chain of tailored forming. In this way, the process learns on every cycle while more optimized solutions are being generated.

For validation purposes, various joining zone geometries were examined in test bench trials, e.g., on the torsion test bench, and compared with the simulation results. Subsequently, the parameters were adjusted so that the simulation provides an adequate representation of the manufactured components [6].

4.3. Intermediate Results

The comparison with a mono-material shaft cannot be straightforward executed, since multi-materials are intrinsically connected to more requirements, but it serves to show the potential of the technology for lightweight. This potential, however, is also connected to some of the geometric restrictions imposed, such as the allowable size of the component. Figure 13 makes a

comparison between the multi-material design achieved and an equivalent mono-material shaft with the same requirements for strength and wear, considering a life-span of 1 billion cycles.



(**a**) (**b**)

Figure 13. Shaft design for same requirements, where a reduction of 11% in weight is seen for the multi-material shaft (**a**) in comparison to the mono-material one (**b**).

4.4. GPDA for Tailored Forming

In the GPDA implementation for tailored forming, the design elements are carriers of the knowledge that gives the design its shape. In addition, a design catalog [86,87] of the CAEE controls the GPDA models and serves as a superordinate knowledge base. Depending on the application and load case, the knowledge in the catalog determines which skeleton and which design elements should form the basis for the development of the tailored forming component. The more knowledge is available in concrete form, the better the selected starting point and the lower the effort required for subsequent optimization. The design catalog does not consist of a single catalog, but of a general main catalog that refers to concrete detail catalogs. The connection of the catalogs is shown in Figure 14.

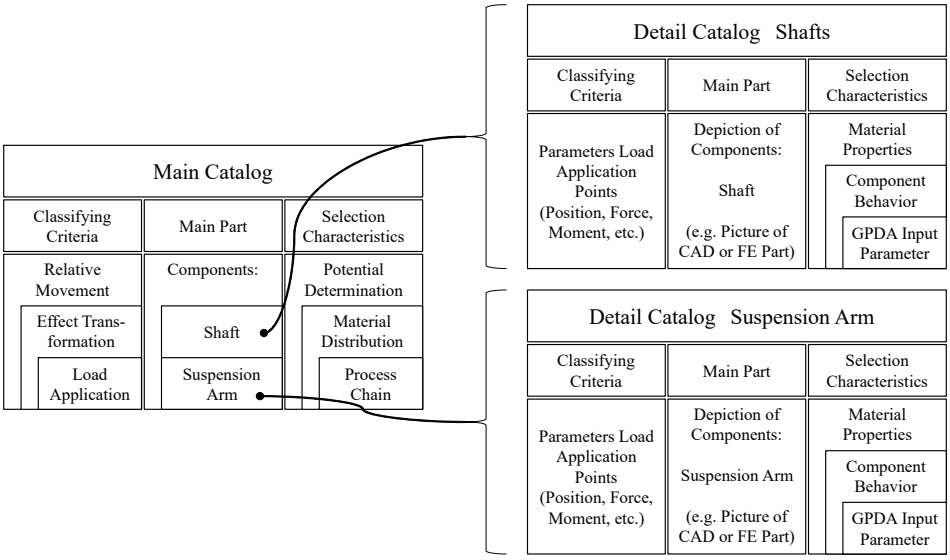
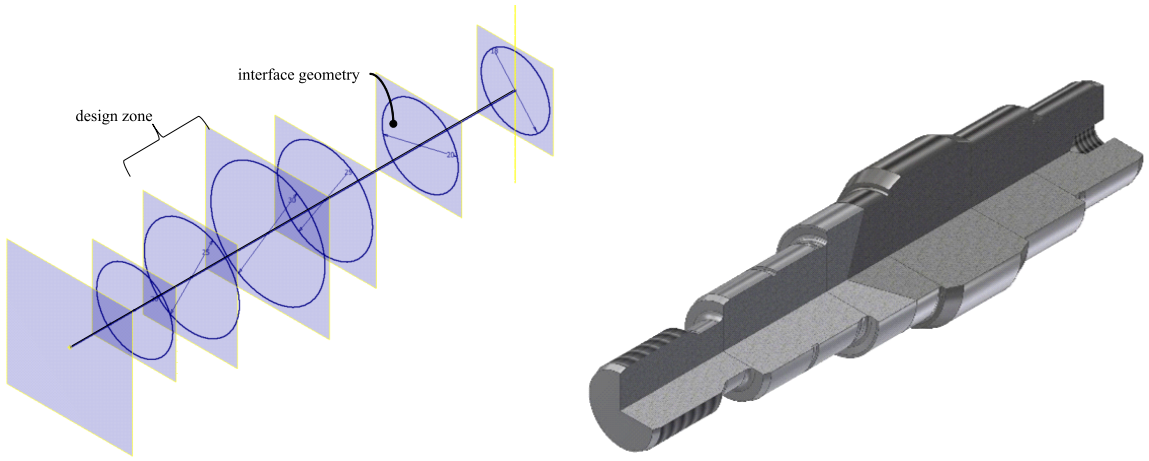


Figure 14. Structure of design catalogs.

Different component types and the corresponding general application and load cases are defined in the main catalog. It shows how a tailored forming implementation for conventional mono-material parts can look like, e.g., by showing the general material distribution according to IZEO. The main catalog also provides the skeleton and thus the basic structure for the GPDA model. For each case in the main catalog, there is a detailed catalog in which concrete characteristics are derived from the general case. Here, concrete values have been assigned to the parameters that describe the load cases

and geometry characteristics. In addition, the resulting and relevant component properties such as max. deformation or stress are also stored.

The structure of the GPDA model of the shaft is shown in Figure 15 The skeleton consists of an axis on which the interface geometries are defined. Along the axis, there is a design zone between the interfaces in which the design elements are attached. The design elements are defined in such a way that they represent exactly one shaft step. The leading diameter of each design element is defined by the interface geometry of the skeleton.



(**a**) (**b**)

Figure 15. Skeleton (**a**) and CAD model (**b**) of tailored foming shafts.

The design elements contain the concrete knowledge of geometry and take into account the manufacturing restrictions and design guidelines. Figure 16 shows, for example, how the relief grooves required on a shaft are implemented in the model. The dimensions of the relief grooves depend directly on the leading diameter of the shaft shoulder and are described according to DIN 509 in Table 3 [88]. Furthermore, the shape of the relief grooves can vary depending on the application. In the case of a relief groove of type F, the definition goes beyond the limits of the design element, so that the geometry in the adjacent element must adapt accordingly. For this case, parameters are already stored in the adjacent design element, which are then filled accordingly via the skeleton. These parameters are suppressed for relief grooves of the type E that do not extend beyond the design zone.

Table 3. Relief groove parameters for shafts according to DIN 509 [88].

R1	f	t1	t2	D1
0.4	2	0.2	0.1	>3...18
0.8	2.5	0.3	0.2	>18...80
1.2	4	0.4	0.3	>80

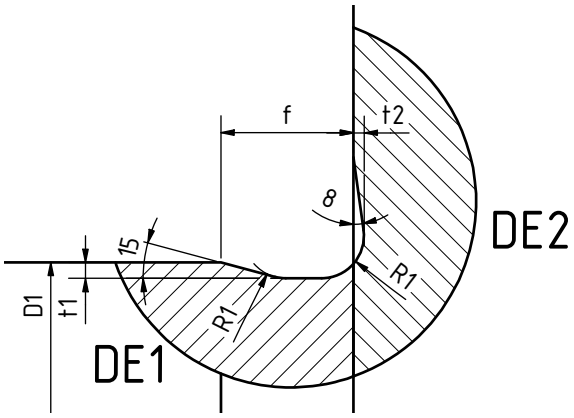
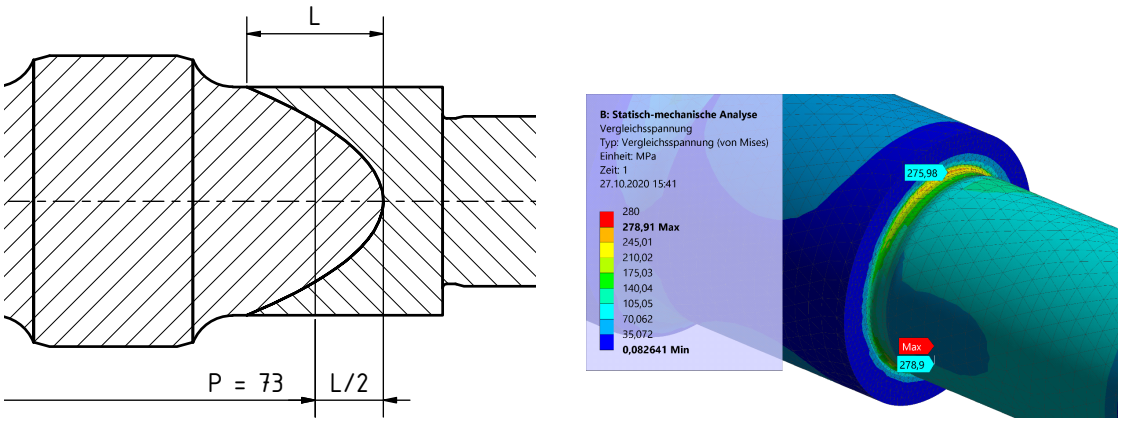


Figure 16. Parameters for a relief groove (type F) that extends over two design elements (DE1 and DE2).

4.5. Application Example of the GPDA: Model Adaptation in Case of Changes in Boundary Conditions

In the GPDA a load case of the shaft is considered as an example, where $F = 5.5$ kN and $T = 40$ Nm. For this load case, the joining zone position from the results of IZEO (Figure 11, result 5) and the shape from the results of CBR are used. In the GPDA model, the joining zone position is the distance from the left shaft end to the center of the joining zone area ($P = 73$ mm; Figure 17a). As can be seen in Figure 17b, the v. Mises stress does not exceed the yield strength of 280 MPa of the aluminum alloy in the relief groove under consideration, with an assumed safety factor of 1.



(**a**) (**b**)

Figure 17. (**a**) Joining zone position and (**b**) resulting v. Mises stresses (max. 278.9 $\frac{N}{mm^2}$) at $F = 5.5$ kN and $T = 40$ Nm.

If the force is increased at a constant torsional moment, the yield strength is exceeded. Figure 18 shows the case at $F = 8$ kN. To reduce the stresses, the position or geometry of the joining zone must now be adjusted. It is not possible to increase the diameter of the shaft on which the relief groove lies, because the bearing size is determined by the external connection dimensions.

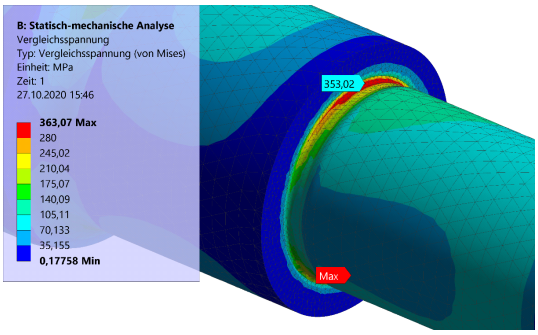
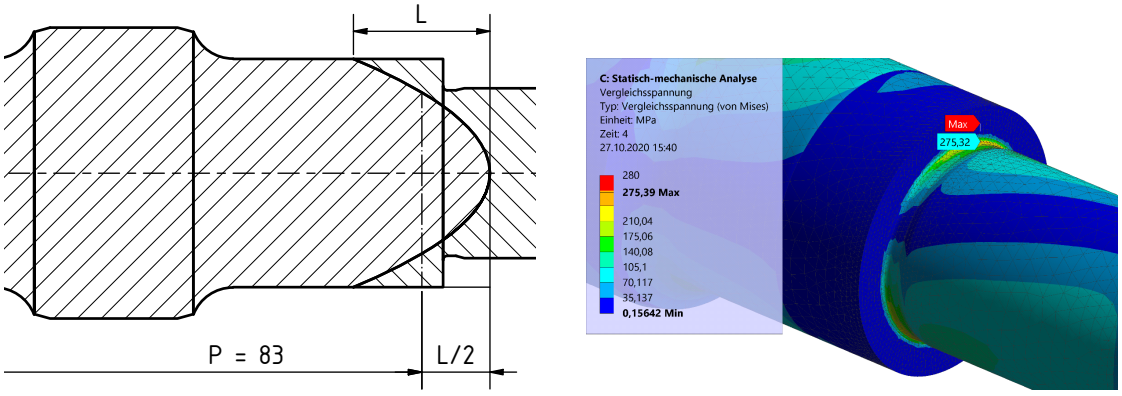


Figure 18. Exceeded yield strength (max. 363.07 $\frac{N}{mm^2}$) at a joining zone position of $P = 73$ mm at $F = 8$ kN and $T = 40$ Nm.

Therefore, the position of the joining zone is shifted 10 mm to the right to $P = 83$ mm in the following. The yield strength of the aluminum alloy is no longer exceeded in the undercut. Figure 19 shows the new joining zone position (a) and the resulting stresses (b).



(**a**) (**b**)

Figure 19. (**a**) Joining zone position (**b**) and resulting stresses (max. 375.39 $\frac{N}{mm^2}$) at $F = 8$ kN and $T = 40$ Nm.

Table 4 summarizes the individual results. By increasing the proportion of steel alloy in the component, the weight of the shaft increases from 245.61 g to 264.05 g.

Table 4. v. Mises Stress in the relief groove at different forces.

Position	v. Mises Stress at 5.5 kN	v. Mises Stress at 8 kN	Weight
73 mm	278.9 MPa	353.02 MPa	245.61 g
83 mm	–	275.39 MPa	264.05 g

In this case that the GPDA offers the possibility to move the joining zone over the boundaries of the individual design elements. This increases the proportion of steel and reduces the stresses in the undercut of the aluminum area. Because the model is designed according to the approach of the GPDA, it can be used to develop similar shafts that are exposed to similar load cases. Due to the flexible structure, which is based on the use of the design elements, parametric and topological changes can be made without much effort if they are necessary for another load case under different boundary conditions. The test bench trials required for validation are still pending.

5. Discussion

All in all, it can be said that the computer-aided engineering environment has met the required expectations. On the basis of the given load cases and other boundary conditions like design space,

a tailored forming high-performance part was generated. In addition, the restrictions resulting from the manufacturing processes could be fully considered. Furthermore, the CBR system provides a platform for a data-driven development of tailored forming components.

Since the tailored forming process chain is novel, basic research is conducted in CRC 1153. In order to develop controllable manufacturing processes, in the beginning, only simple, rotationally symmetric components were investigated. For these components, the most robust results have been achieved and most knowledge about manufacturing restrictions is known. For these reasons, the shaft presented in this paper is the subject of the investigations on the creation of the CAEE. However, due to the existing load cases, the full tailored forming potential cannot be developed for shafts. Therefore, mirror-symmetric geometries such as rocker arms, which offer a higher tailored forming potential, are currently being investigated in CRC 1153 (Figure 20). Nevertheless, as shown in Section 4.5, there is also tailored forming potential for shafts under certain boundary conditions and these components are therefore also suitable for the development of the CAEE.

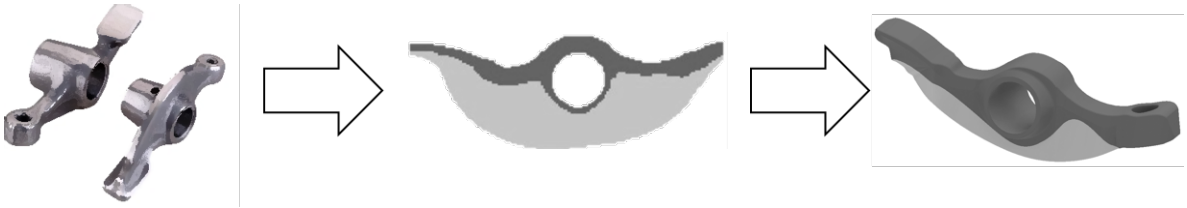


Figure 20. Rocker arm (**left**) and derived tailored forming component variants in IZEO (**center**) and CAD (**right**).

Furthermore, it should be noted that all simulations have been carried out with linear-elastic material behavior up to the yield strength, since this describes the limit in which a component can be used in practice. The joining zone is designed as a simple adhesive contact. Within the scope of CRC 1153, special finite elements are being developed that can simulate the material properties of the joining zone [89]. These are currently not yet included in the simulations described here, but will be added in the future.

In addition, test bench trials have been conducted to validate the strength of the joining zone geometries generated by IZEO and Robust Design. An optimized joining zone geometry helps the shaft to withstand higher loads. Analogy tests on simplified shafts have shown that a shaft with optimized joining zone geometry has nearly the same strength as a reference shaft made of the aluminum alloy. With a non-optimized geometry, the shaft fails in the area of the joining zone and the strength is reduced [6].

For future approaches to the development of CAEE, ontology-based approaches are probably more beneficial than the approaches presented in this paper. The ontology would serve as a mediator between the knowledge base and the instantiated CAD model. The result would be a model architecture in which e.g., the design elements could be used much more flexibly. Currently, the parameters of the design elements are hard-coded by the CAD system and are explicitly addressed so that they can practically only be used for a single or similar component.

The challenge with GPDA is that an enormous amount of work is required in advance to generate a functioning model. In order to ensure the modularity of the approach, great care is required in the generation of the skeleton, the interface geometries and the design elements. The creation of a model-free of errors within defined limits requires increased programming effort and a well-planned structure, especially at the beginning. Further degrees of freedom are added in the context of tailored forming by taking the joining zone into account, which must be defined both in the top-level assembly and in each design element. As shown in Figure 19a, the design elements must be controlled by the top-level assembly so that the joining zones form a smooth transition from design element to a design element. However, the work has also shown that the effort for embedding new design elements and new joining zone geometries is reduced the more the GPDA model is built up, since they can be

derived from the previously created design elements and can be integrated into the working top-level assembly relatively easily.

Furthermore, there is a significant difference in the programming effort required to implement formal, explicit and informal, implicit knowledge (see Section 2.2). While explicit knowledge can be implemented very easily, e.g., by means of table values and If-Then-Else queries, the translation effort for implicit knowledge is significantly higher and also ties up more computing capacity. However, as IZEO has shown, implementation is quite possible. In summary, it can be said that computer-aided methods can handle explicit knowledge very well, but there is still a need for research on the implementation of implicit knowledge.

6. Summary and Outlook

The desire for components that are always better adapted to external conditions than their predecessors leads to the technological advancement of the components, but also of the processes required for their manufacture. As a result, components and processes are becoming more and more complicated, so that the effort for planning, conception, design and elaboration is increasing. In some cases, components and process chains are already so complicated that the optimal solution is no longer readily apparent. When newer approaches, such as multi-material design, are added, the degrees of freedom to be considered increase even further. Especially in this case, systematic, computer-aided approaches are needed to meet the challenge of finding the best solution from an objective point of view. Therefore, modeling approaches and design methods are needed that take into account the manufacturing processes throughout the entire product development process.

The methodology presented in this work works as a framework to develop the technology of tailored forming further and generate continuously better solutions. As seen, the topology optimization method IZEO was able to handle dynamic manufacturing restrictions while optimizing the use of multi-materials. Additionally, different strategies for solution exploration were presented, such as CBR and GPDA, where the influence of manufacturing is direct. For these reasons, this design methodology is able to support this manufacturing technology to be further developed. This translates into first transfer projects for real industry applications that are being currently performed under the umbrella of the CRC 1153.

All in all, computer-aided engineering environments help to find the optimum shape for a component in order to derive the best possible manufacturing process. The stored knowledge base provides a clear and objective set of rules that can protect companies from undesirable developments. This provides a better starting point for the development of components and processes. Routine processes can also be automated, giving designers more room for creative work.

In further developments, additional non-rotationally symmetric components will be investigated and developed. For this purpose, complicated manufacturing restrictions have to be implemented for IZEO. The GPDA also needs skeletons and design elements with more complicated shapes and extended functionalities. For example, the skeleton will no longer be one-dimensional, but two or three dimensional. The design elements may have more than two neighboring elements. In order to better link product development with process development in the future, a transfer model is currently being worked on within the framework of CRC 1153, which will allow conclusions to be drawn about the upstream production stages. For this purpose, a GPDA model is currently being developed, which, depending on the manufacturing process, can map the individual stages of component production. In this case, the research results from the CRC will also serve as a basis.

Author Contributions: Conceptualization, R.S. and T.B.; methodology, R.S. and T.B.; software, R.S. and T.B.; validation, R.S., T.B. and P.C.G.; formal analysis, R.S. and T.B.; investigation, R.S. and T.B.; resources, R.L.; data curation, R.L.; writing—original draft preparation, R.S., T.B. and P.C.G.; writing—review and editing, T.B. and P.C.G.; visualization, R.S. and T.B.; supervision, P.C.G., I.M. and R.L.; project administration, P.C.G., I.M. and R.L.; funding acquisition, I.M. and R.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) grant number 252662854.

Acknowledgments: The results presented in this paper were obtained within the subproject C2 "Configuration and design of hybrid solids" of the Collaborative Research Center 1153 "Process chain to produce hybrid high performance components by Tailored Forming". The authors would like to thank the German Research Foundation (DFG) for the financial and organizational support of this project.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BESO	Bidirectional Evolutionary Structure Optimization
CAD	Computer-aided Design
CAEE	Computer-aided Engineering Environment
CBR	Case-based Reasoning
CPM	Characteristics-Properties Modeling
CRC	Collaborative Research Center
DfX	Design for X
GPDA	Generative Parametric Design Approach
IZEO	Interfacial Zone Evolutionary Optimization
KBE	Knowledge-based Engineering
LACE	Lateral Angular Co-Extrusion
PDD	Property-Driven Development

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