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An interfacial zone evolutionary optimization method with manufacturing constraints for hybrid components

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A B S T R A C T

New multi-material manufacturing technologies demand the development of new mechanical design approaches, as seen in the production of hybrid components through Tailored Forming. Thereby, a new class of high-performance multi-material parts aiming for enhanced properties, such as lightweight properties, can be constructed and brings with it new challenges. The objective of this paper is to develop a method for finding the optimal material distribution for such multi-material components. Thereunto, Topology Optimization techniques were reviewed, focusing on the progress made on multi-materials and manufacturing constraints implementations. Following, a new method was developed and analyzed, called Interfacial Zone Evolutionary Optimization (IZEO), and here expanded for a multi-material approach. This method makes use of the Evolutionary Algorithms methodology to solve structural optimization problems and provides a flexible way to implement manufacturing constraints. Finally, some cases are presented, in which the developed tool was able to generate a multi-material and manufacturable high-performance design.

1. Introduction

The search for high-performance mechanical components is a constant search of the industry. With them, more reliable products can be designed, fewer energy requirements are needed, lower costs are achieved and the customer satisfaction is increased (Ullman, 2010). The reasons are unquestionable and that is why engineers from different fields have tried to achieve such ideal parts in order to make it possible (Fiebig et al., 2015). With the development of new manufacturing techniques, new opportunities arise, requiring a parallel development in design methodologies (ElMaraghy, Algeddawy, Azab, & Elmaraghy, 2012).

One of the ways to optimize the performance of a mechanical structure is by working on local specific properties in different parts of it by using multi-materials. This can bring great benefits, such as better stress distribution, greater hardness in contact points, thermic or electric isolation, and so on. Furthermore, cost properties can also be considered at this point, assuming that specific local properties require some extra cost, while other less important regions can be made of less expensive material. The use of multi-materials in the structure for these purposes and the connection between them present a current challenge for manufacturing techniques. One of these new technologies is Tailored Forming, a process chain in which two workpieces made of different metals can be joined to form one single hybrid component (Behrens et al., 2016; Behrens & Kosch, 2011a, 2011b). The research for this technology is the core of the Collaborative Research Center (CRC) 1153, placed in the Leibniz University Hannover, which the present study is a part of.

The design side of multi-material components is equally challenging and requires rigorous methods to achieve these high-performance functions, whereas the material distribution in the domain space is more complex than in classical design (ElMaraghy et al., 2012). Furthermore, as well as for mono-material components, the manufacturing constraints must be well known, so that a manufacturable geometry is created at this design stage (Vatanabe, Lippi, de Lima, Paulino, & Silva, 2016). So, the combination of the manufacturing constraints and design optimization methods must be performed together in order to achieve an optimal material distribution for a given problem. However, the conjunction of traditional topology optimization methods with these constraints is still not broadly available for common use (Roper, Li, Florea, Woischwill, & Kim, 2018).

The objective of this paper is the introduction of an alternative method for multi-material topology optimization of structure components, in which the implementation of manufacturing

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constraints can be done in a more practical and flexible way. This will bring great efficiency to the development process of such components by delivering optimized and ready-to-use designs, where no or very small adjustment has to be performed by the engineer before manufacture. Here, the focus is not the mathematical formulation of the optimization problem, but the development of a design method that uses a heuristic approach to generate practical application results. As examples, some possible geometric restrictions found in the manufacturing process are implemented here, taking also some restrictions seen in Tailored Forming.

2. Topology optimization

In this section, we present the state-of-the-art topology optimization techniques for our current issue. In this field, many different approaches were tried over the last decades, in order to find the optimal shape of a structure. The works of Bendsoe became the base for this theory, due to the development of the method known as SIMP (Solid Isotropic Material with Penalization) (Bendsoe & Kikuchi, 1988). With fast convergence capability and strong theoretical foundation, this method became the standard used in many commercial software packages for topology optimization. The classical optimization problem formulation is based on a minimization of compliance, with a volume restriction, as seen on its discrete form on Eq. (1):

$$\min \mathbf{f}^T\mathbf{u} \qquad (1)$$
$$\sum_{i=1}^{N} V_i x_i = V^*$$

where **f** is the applied load vector, **u** is the nodal displacement vector, N is the number of elements in the mesh, V_i is the volume of an individual element, x_i is the density of the element and our design variable, and V^* is the prescribed volume. Many alternatives and improved proposals for this method can be found in literature, as well as its expansion for a variety of different problems (Bendsøe & Sigmund, 1999; Bendsoe & Sigmund, 2004; Sigmund, 2001b). In the next sections, we will introduce the basic concepts of evolutionary algorithms, which are an alternative methodology to SIMP that served as a base for this study. Then, we focus on presenting the state-of-the-art topology optimization problems in two main areas of concern: multi-material optimization and the implementation of the manufacturing constraints.

2.1. Solution through evolutionary algorithms

A topology optimization solution methodology that has gained special attention is the use of evolutionary algorithms. In the early version of this method, called ESO (Evolutionary Structure Optimization) (Xie & Steven, 1993), the evolutionary process consisted of the deletion of material of the structure domain space iteratively according to stress, until the geometry reached the desired volume, as a way to maximize stiffness. Eq. (2) shows the threshold for this deletion:

$$\frac{\sigma_e^{VM}}{\sigma_{max}^{VM}} = RR_i \qquad (2)$$

where σ_e^{VM} is the Von Mises stress of the element, σ_{max}^{VM} is the maximum Von Mises stress of the structure, and RR_i is the rejection rate at the iteration i. The main problem of ESO is that this deletion was not recoverable, which lead to a premature deletion of some elements that could improve the performance on later stages of the evolution.

For that reason, it was desired that the evolution could happen in both directions to allow the process to also add material in some regions when necessary, which generated BESO (Bi-directional Structure Optimization) (Yang, Xie, Steven, & Querin, 1999). Since this methodology involves a complete removal of material, in the first versions of BESO, a filter had to be used in order to obtain a sensibility number for the void spaces. The soft-kill BESO version makes use of a very low density value for the void spaces, allowing the calculation of sensitivity numbers before the filtering step (Huang & Xie, 2009).

The main advantage seen in the use of evolutionary algorithms is the possibility to observe the evolution of the structure and its fields and, based on that, make coherent decisions in regard to the algorithm process. This ability allows a direct control of this evolution, which is a desirable characteristic for the implementation of restrictions.

2.2. Multi-material optimization

Finding the best distribution of two or more materials in a design domain adds a considerable degree of complexity to optimization problems because the number of design variables gets higher. For more general formulations, the first proposed solutions can be seen in Sigmund (2001b). In these early-phase studies, it was made an adaptation of the standard SIMP to multi-materials with an equivalent penalization technique for all the materials involved, substantially increasing the number of design variables. An alternative interpolation method to reduce the number of design variables is seen in Zuo and Saitou (2017). Another method addressing the same problem is seen in Tavakoli and Mohseni (2014), where an approach called alternating active-phase is proposed. In this study, the multiphase problem is subdivided into a series of binary phase problems. An implementation using BESO was also shown in Huang and Xie (2009), where also an alternative sensibility criterion is presented to deal with multi-material. This was also implemented more recently in Ghabraie (2015), using a gradual procedure inspired by continuation approach. Although these improved techniques can generate good results, as shown in Meisel, Gaynor, Williams, and Guest (2013) and Park and Sutradhar (2015), the problem is mainly focused in a general formulation, where numerous materials are used and the process time must also be optimized.

Some other methods were also proposed, such as the use of a Phase field (Zhou & Wang, 2007) or Level-set (Guo, Zhang, & Zhong, 2014; Wang & Wang, 2004). However, more progress has to be made for the problem of multi-material optimization with the presence of strong manufacturing constraints, although works in this direction are seen in more recent publications (Kang, Wang, & Wang, 2016). Even with promising less limited new manufacturing technologies, such as additive manufacturing, the restrictions are still present and must be considered. This standard research has a fundamental importance in the field, but its applicability is still limited and the implementation with restrictions has to be further explored.

2.3. Manufacturing constraints

Commonly, optimization techniques are not performed by the same engineer that makes the design, maintaining these two processes as separated tasks. This fact tends to change in today's scenario, where both tasks would be performed by the same engineer through the use of more robust tools (Fiebig et al., 2015). Usually, the result of the topology optimization is taken as a first concept and, in a second stage, the actual and manufacturable structure is modeled, taking the concept previously generated as a basis. This leads to the addition and exclusion of material from the optimal shape that may lead to a loss of the optimal characteristics (Vatanabe et al., 2016).

In order to avoid this problem, it is agreed that a single and unified method must be used in the design stage. With this objective, some works have already proposed methods for the implementation of manufacturing constraints within the topology optimization process. Some results of this kind of implementation can be seen in the work of Zhou, Fleury, Shyy, Thomas, and Brennan (2002), where casting and extrusion manufacturing constraints are used in a commercial software. In Guest, Prévost, and Belytschko (2004) it is implemented the desired member-size control restriction on SIMP through the use of a density filter, generating the so-called pseudo-density. The combination of pseudo-density with projection and mapping techniques was more recently summarized in Vatanabe et al. (2016). This last work provided a unified approach to deal with this problem by a combination of many geometric restrictions for each manufacturing process, bringing flexibility to the method.

Other specific applications can be seen in the field of additive manufacturing (Aremu, Ashcroft, Hague, Wildman, & Tuck, 2010), where the suitability of BESO and SIMP for the implementation of manufacturing constraints was investigated. In Fiebig and Axmann (2011), an alternative topology optimization method based on BESO is proposed, where forging and casting restrictions were successfully implemented and the results were compared to commercial software results. In Sauthoff and Lachmayer (201) and Li, Gembarski, and Lachmayer (2018) a new design method where manufacturing constraints can be strongly defined through the use of design elements, called Generative Design Approach (GDA), is presented.

As seen, most of the scientific work performed was oriented to well-known manufacturing processes. Besides, no specific implementation has been done for multi-material designs, where a high number of manufacturing constraints are equally found in different stages of the process chain, as seen in Tailored Forming.

3. Interfacial zone evolutionary optimization

In order to create a multi-material method that can deal with manufacturing constraints, a new approach was first introduced in Siqueira, Mozgova, and Lachmayer (2017), called Interfacial Zone Evolutionary Optimization (IZEO). This method is based on evolutionary algorithms and presents two basic differences with the traditional BESO. Firstly, it restricts the structure evolution to a single surface, instead of the whole domain, allowing a better control of this evolution. The second one is that the ability of bi-directionality is given by steps in the evolution, where the mass is kept constant and the shape is adjusted by adding and removing material interchangeably. Similar to soft-kill BESO, this method uses a very low density value to get values for void sensitivity. The optimization problem is fundamentally the same one used for BESO, as seen in Eq. (1). The sensibility was initially calculated by compliance (Bendsoe & Kikuchi, 1988), as seen in Eq. (3):

$$\alpha_i = \frac{1}{2}\mathbf{u}_i^T\mathbf{K}_i\mathbf{u}_i; \quad i \in \Lambda \tag{3}$$

where α_i is the sensitivity of the element, $\mathbf{u}_i$ is the elemental nodal displacement vector, $\mathbf{K}_i$ is the stiffness matrix of the element, and Λ is the set of elements that belong to the allowable evolution surface. For its restricted and strong numerical approach, this method was presented as having a high potential for dealing with manufacturing constraints in multi-material problems (Siqueira & Lachmayer, 2018). In the next sections, we will look closely into the development of IZEO and its numerical implementation. Then, we provide a comparison of its performance with other methods. Finally, we present an expansion for multi-material and manufacturing constrained designs.

3.1. Interfacial zone restriction and Shape adjustment steps

Since the primary idea of IZEO is that the evolution happens only at the interface between the two materials, at the starting point the domain is completely filled with the material 1, while the material 2, whether void or not, grows from a single point into a bigger part of the domain by a material evolutionary rate (Fig. 1). This concept avoids big changes in topology, although it can't completely avoid the separation of material phases.

This concept was initially implemented with BESO, as a simple sensibility restriction. However, it generated a poor result, since the sensibility ordering made by BESO mixes the sensibility of both materials and executes the addition and removal simultaneously. So, for a same element of the interface, one material could be added at one side and removed from the other, separating phases and generating a big amount of undesirable check-board pattern.

As a form to avoid this problem, an intercalated change of material was proposed. Here, the removal or addition of material cannot happen at the same iteration, which excludes initially the ability of bi-directionality provided by BESO, approximating the technique to the original ESO. To provide this advantageous bi-directional ability to the interfacial zone evolution, a step-based method is used instead, where in predetermined points in evolution a phase called here shape adjustment takes place. For the shape adjustment step, the mass is held constant in a certain value and intercalated interactions of addition and removal take place until convergence. This allows the structure to homogenize the stress along the interfacial surface, as well as change the topology if required (Fig. 2), before the evolution process continues.

This shape adjustment step has a similarity with shape optimization methods, such as the net-based (Harzheim, 2008), whereas it tends to dissipate the stress. The step of shape adjustment will end when the geometry converges and no or small geometry change happens between the iterations. The user must, however, provide the frequency that this shape adjustment step will take place, which may influence the final result. By experience,

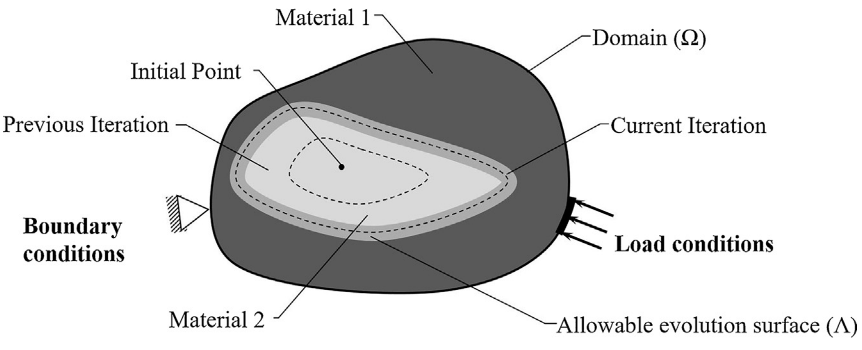


Fig. 1. Model representation of IZEO.

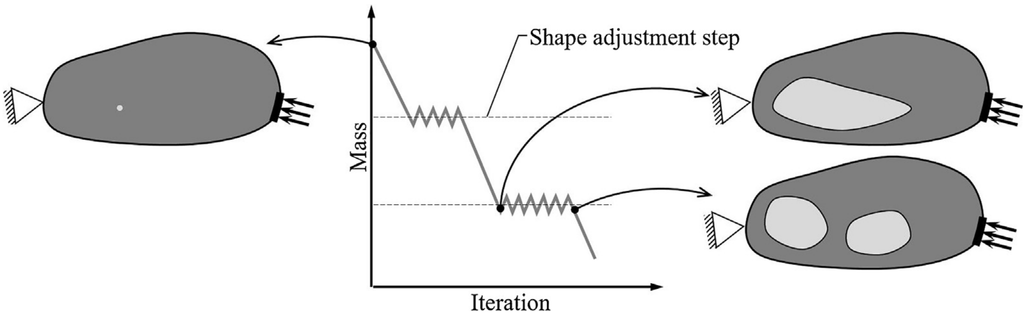


Fig. 2. Illustration showing the shape adjustment steps in a model for minimization of mass.

it is seen that for this frequency, a value between 5% and 10% of mass change demonstrated a good performance in cases where minimization of weight was the objective function, being assured that it is always bigger than the material evolutionary rate. Next, to facilitate understanding, we define the two types of steps:

- material 1/2 evolutionary rate (er_{12}): is the rate of change between material 1 and 2 in every iteration.
- shape adjustment step (S_a): is the process that occurs in some points of the evolution, where the mass is kept around a constant value.

To validate this so-called bi-direction ability, this approach was implemented within the code provided in Sigmund (2001a). A comparison was then made for the problem of a mono-material MBB beam, using the traditional ESO, soft-kill BESO and the implemented approach of steps adjustment with ESO, as seen in Fig. 3. The final compliance value is indicated by C in the figure.

As seen, there is a strong similarity between the results of soft-kill BESO and the approach with adjustment steps, confirming the bi-directional ability. The final compliance value for the soft-kill BESO and the altered ESO, as seen in Fig. 3, were approximately the same and lower than the one seen for the original ESO. The number of iterations was also similar. It is important to remember that both methods require an extra parameter to control the bi-directional ability.

3.2. Bi-material IZEO

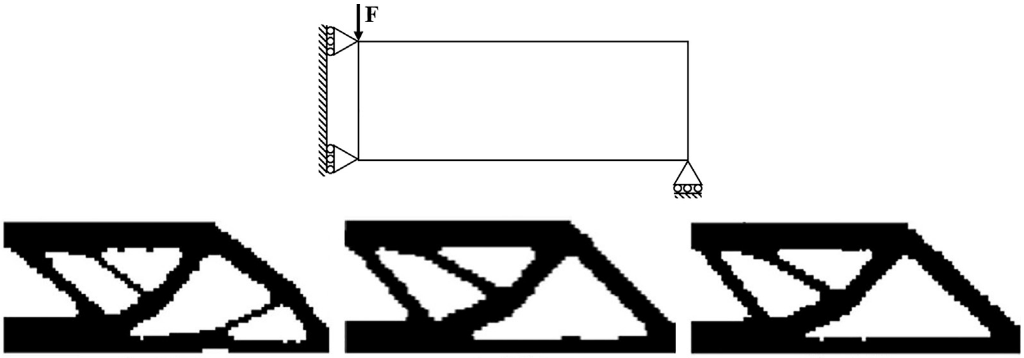
With the use of the interfacial zone restriction with the bi-directional ability provided by the shape adjustment steps, the first version of IZEO was constructed. This first version can deal with two distinct materials, but since this approach is the same for a material/void formulation, it cannot be named yet as a multi-material method. Fig. 4 presents the flowchart for the bi-material IZEO, showing the most relevant steps in the program.

One last point that has to be commented on is the position of the initial point of the material 2 (see Fig. 1), which must be specified at the initialization. The position of this point can be calculated as the lowest sensibility element in an initial trial. However, since the development of this method is connected to manufacturing constraints, this initial point can also be chosen by the user according to the desired manufacturing process. As an example, we present the result for a bi-material MBB beam using IZEO in Fig. 5, with the initial point defined as the lowest sensibility element (right upper corner of the beam).

The result seen here has a strong similarity with the result presented in Huang and Xie (2010) for the same problem. This is not always the case since here the use of the interfacial restriction with the filters tends to generate simpler solutions. Despite the use here of compliance sensibility, it is also presented in Siqueira et al. (2017) a stress approach that generated good results when using a strength restriction. Although this stress approach will not be discussed in the present study, it will be used in some of the next examples.

3.3. Multi-material IZEO

As discussed in the last section, the bi-material IZEO can only perform classical mono-material problems and specific bi-material problems where no void is used. Although this approach without using a void material can generate already relevant results, having a fixed domain (Ω) is not effective when looking for optimal shapes. So, in the current work, we want to implement



C = 127,0
(a)

C =123,2
(b)

C =123,2
(c)

Fig. 3. MBB beam with 40x100 mesh and volume constraint of 50%: (a) ESO; (b) Soft-kill BESO; (c) ESO with shape adjustment steps ($S_a = 5\%$ in volume). All simulations use er_{12} as 0.25% in volume and a sensibility filter radius of 4 elements.

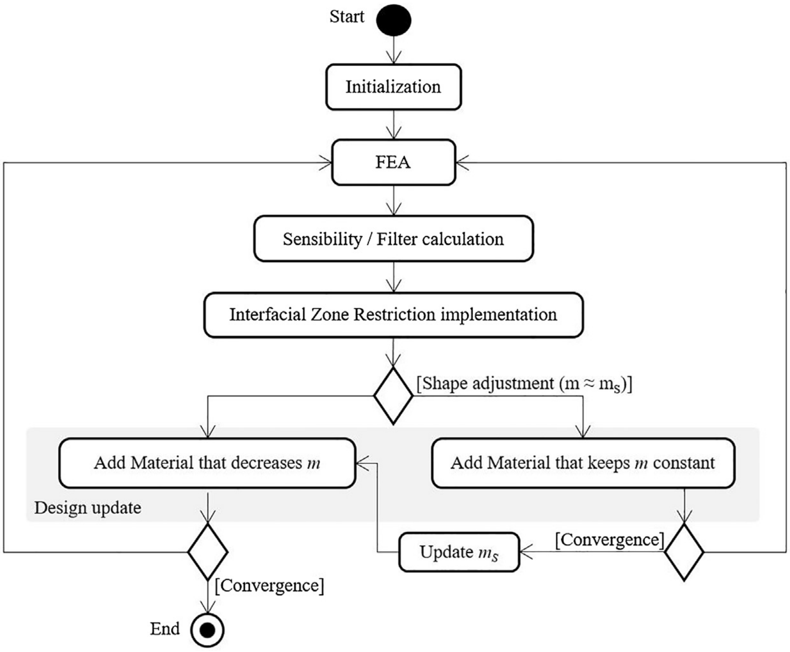


Fig. 4. Simplified flowchart of IZEO for two material designs, where m is the mass and m_S is the mass where the shape adjustment occurs.

Fig. 5. Design of a MBB beam using IZEO (30 × 90 mesh; mass constraint of 50%; elasticity $E_2 = 0.34 \times E_1; er_{12} = 0.2\%$ in volume; $S_a = 10\%$ in mass).

an approach that deals with three materials, meaning two actual materials and void space.

The use of a higher number of materials increases considerably the complexity of the problem. In our case, that means the presence of a second interfacial zone for the growth of the third material. For the solution of this problem, we use a similar approach showed in Park and Sutradhar (2015), where the problem is decomposed in two binary sub-cycles. That means that in the internal cycle, the algorithm optimizes the distribution between material 1 and 2, while in an external cycle, the optimization is made between the material 3 and the whole group of materials 1 and 2 as one common phase (Fig. 6).

In the first optimization step with materials 1 and 2, the right proportion between both is achieved. Then, the increase of material 3 is made in a very small step, to avoid divergence problems. After the first addition of material 3, the optimization between material 1 and 2 becomes faster, whereas it will be just an adjustment to reach again the right proportion. Step by step, the material 3 is added and, when all the proportions desired for the three materials is achieved, the system converges to a solution.

The blocks of optimization are described as IZEO in Fig. 4, because it uses the same criteria, although it has to be slightly adapted for the multi-material approach. In a bi-material with a void case, the method consists on finding the best bi-material distribution in the domain and, progressively, start to take out material of the structure. For this case, Fig. 7 presents the result achieved for the MBB beam, as an evaluation test. Here we used as the material evolutionary rate two different values for each cycle: one for the change between material 1 and 2 and the other for the change between the materials (1 + 2) and the material 3. Instead of having this value based on the volume of the structure, good results were obtained by defining this values as a fraction of the interfacial zone. The initial point for the growth of material 3 is taken to be the whole external surface, allowing it to grow at any point of this region.

A requirement of this approach is the equivalency between the sensibility of the different materials, whereas the addition of the third material happens at materials 1 and 2 at the same time. In this case, for example, the use of Von Mises stress as sensibility for a strength approach would be inappropriate, requiring the use of a safety factor field.

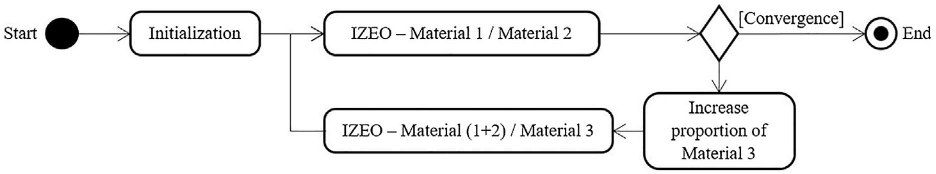
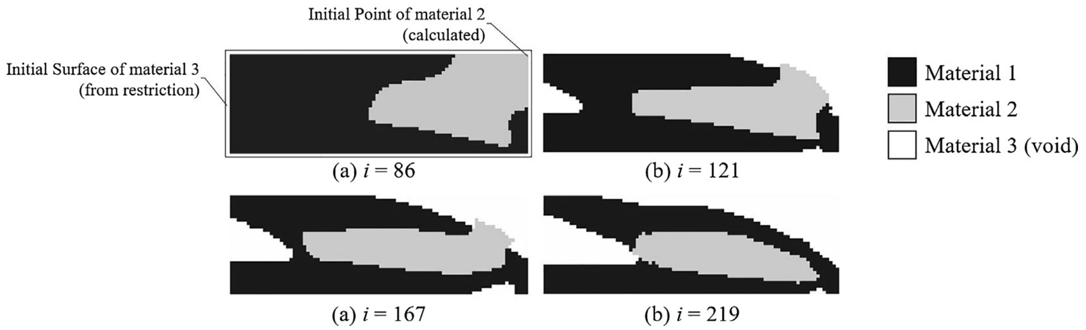


Fig. 6. Flowchart showing the adaptation of IZEO for multi-materials.



(a) $i = 86$ (b) $i = 121$

(a) $i = 167$ (b) $i = 219$

Fig. 7. MBB beam with multi-material IZEO in different iteration stages i (30×90 mesh; final volume proportion: $v_1 = 0.47, v_2 = 0.23, v_3 = 0.3$; elasticity: $E_1 = 1, E_2 = 0.34, E_3 = 0.001$; $er_{12} = 50\%$ and $er_{(12)3} = 5\%$ of the interfacial region; $S_a = 10\%$ in mass; sensibility filter radius: 3 elements).

The second cycle is also bi-directional, allowing material 3 to change back to 1 or 2, depending on which one is the closest neighbor (in cases of a draw, material 1 is taken). The high number of materials implies a higher number of control parameters, such as the two evolutionary rates and the proportion of each material in the final structure. All these parameters can have a strong influence in the final result, requiring an expertise of the user to deal with them. This can be shown in Fig. 8, where we compare our result with an equivalent design generated by the alternating active-phase algorithm (Tavakoli & Mohseni, 2014), an approach that uses SIMP as solution generation method. It was seen that both final designs are influenced by the control parameters, but with a standard configuration, the alternating active-phase algorithm presented a similar concept nevertheless, although it allows the presence of intermediate densities.

In the next section, the manufacturing constraints will be investigated. Since we have a multi-step optimization, we will also have a multi-step restriction process related to each of the optimization blocks. In order words, that means that different constraints can be used in the different steps, which is a meaningful benefit of the method.

3.4. Manufacturing constraints

Differently from past proposed multi-material methodologies, the present one was designed from the start to ease the implementation of the geometric restrictions of the manufacturing process. It will be shown that for most cases, these restrictions can be made by a simple deletion of certain elements from the allowable evolutionary surface.

Firstly, it has to be understood what these constraints are. In most manufacturing technologies, these constraints can be translated into geometric restrictions. That means that for a certain technology, only a group of geometric solutions is possible (Gembarski, Brockmoeller, & Lachmayer, 2016). However, many of these processes contain complex restrictions, requiring multiple geometric restrictions to describe it. The work presented in Vatanabe et al. (2016) shows the relation of some well-known manufacturing constraints with different geometric restrictions. The present work makes use of a similar approach in order to achieve flexibility.

In other words, it is implemented in this step is a range of geometric restrictions that can describe the manufacturing process results. Multi-material manufacturing processes, such as Tailored Forming (Behrens et al., 2016), present even a multi-layer constraint. Since the component undergoes a process chain, different processes of this chain present different manufacturing constraints, creating this so-called multi-layer constraint. As mentioned in the last section, in our method distinct restrictions can be used at the multi-material interface and at the interface of the component with the void space, being an advantageous realistic approach to describe this multi-layer constraint.

A few geometric restrictions were implemented here, named: symmetry, minimum member size, unidirectional growth, and single phases. Each of them requires a different implementation and, for that reason, will be explained next in more details. Other constraints, such as some specific from Tailored Forming, were also implemented, but since they use the same numerical approach, they will be further not described.

3.4.1. Symmetry

Manufacturing processes that generate symmetric geometries are common in the industry and its implementation can be made in a considerable simple manner. For that, considering that a symmetry line is specified in the domain, the sensibility at the two sides of this line must be mirrored, so that the growth of the second material happens symmetrically. In such a manner, an equal sensibility value must be found for every pair of elements that stands in the equivalent opposite side of the symmetry line (Fig. 9). This mirroring effect can be made in two manners: calculating the average or the maximum sensibility of every pair and replicating this value for both. It is seen that the average is suitable for compliance problems, while the use of maximum value is suitable for stress approaches.

Although this restriction is not really required in fully symmetric components, where the FE analysis can be simply reduced to a partial problem, this restriction can be also partially or locally implemented, generating more relevant results for complicated structures.

C = 191,5
(a)

C =187,1
(b)

Fig. 8. Comparison between MBB design with IZEO and alternating active-phase algorithm. Both simulations present the same mesh, elasticity values, and volume fractions.

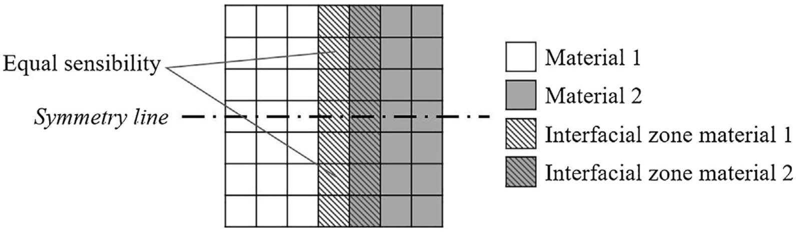


Fig. 9. Scheme showing the numerical description of the symmetry constraint.

3.4.2. Minimum member size

This constraint is a common and desired constraint in topology optimization problems, whereas it avoids the creation of very thin structures. The solution used here for this restriction was proposed in Guest et al. (2004), where a q-norm filter for the densities is applied (Fig. 10).

The use of filters was not yet mentioned in this paper because of this constraint. This is an important step in topology optimization problems because it avoids mesh-dependent results and checkboard patterns (Bendsoe & Sigmund, 2004). Its use here works equally against these problems, besides the restrictive behavior. Eq. (4) shows how the filtered density is calculated using a q-norm filter:

$$\rho_i = \left(\sum_{j\in\Phi_k} d_j^q\right)^{\frac{1}{q}} \tag{4}$$

where ρ is the filtered density, i is the element index, Φ_k is the region inside a chosen radius from the element, d is the real density, and q is a user parameter. In this work, q is normally taken as 1, which makes the filter equivalent to an average value of the region. The radius value that describes the region Φ_k is the parameter that allows the user to control the minimum member size.

3.4.3. Unidirectional growth

This constraint is present in a large number of manufacturing processes. That is related to the fact that certain geometries are manufactured by a unilateral access to the raw material. As a matter of fact, many manufacturing processes can have their restrictions described by a combination of this constraint, such as forging or stamping.

In the case of multi-material components, this represents a type of construction that involves two workpieces that have to be serially connected. So, instead of calling it as an extrusion constraint, as it is normally called for mono-materials, we call it here unidirectional growth, because our second material will be allowed to grow in only one direction. The implementation of this constraint consists of an exclusion of the sensibility of elements that provide a growth in a different direction than the one specified, as shown in Fig. 11.

As seen in the picture, some elements of the interfacial zone are excluded from the allowable evolution area for changing of material 1 to 2. Due to this numerical approach, the principle used in this constraint is highly flexible and can be used for many different cases.

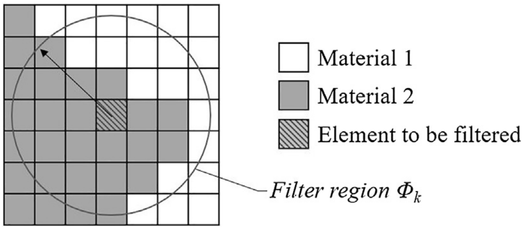


Fig. 10. Scheme showing the filtered region of one element.

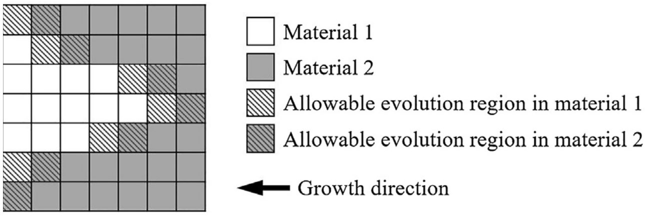


Fig. 11. Scheme showing the numerical description of the unidirectional growth restriction.

3.4.4. Continuous phases

The last constraint described here also uses a numerical description, but more elaborated than the one seen in unidirectional growth. It is related to the fact that a final geometry should have only two separated continuous phases, one for each material. This continuous phase means that there is no continuity interruption in the domain for each of the materials. As mentioned earlier, the use of an interfacial constraint in IZEO tends to avoid this problem but doesn't exclude it. During the evolution, one of the phases might separate the continuous phase of the other material and sometimes that is not desirable.

To avoid this from happening, a radial search around every element of the interfacial zone is made to detect if the change of material in this element may lead to a separation of phases or not. If the second material is detected in the opposite side of the radius, the change of material in this element is blocked (Fig. 12).

In Fig. 12, the element under analysis has a proximity with another phase and its change to material 1 has a potential to separate the phases of material 2. For that reason, this element will be excluded from the allowable evolution surface. This restriction is controlled by the radius where this search is made, which represents the minimal member size allowable before this blockage takes place. For that reason, the same radius used for the Minimum Member Size restriction can be used here.

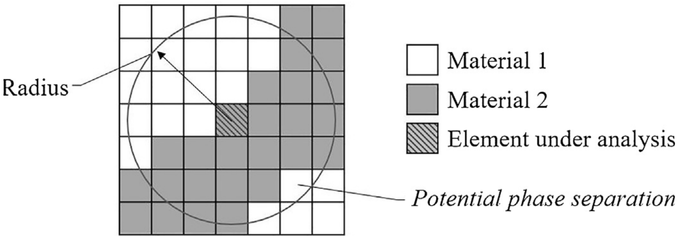


Fig. 12. Scheme showing how the potential for phase separation is made for the elements in the interfacial zone.

4. Application results

The numeric implementation was based on the open source code provided in Sigmund (2001a), using the software Matlab. We show here some classical cases, commonly seen in works of topology optimization, as well as the result for one specific component. These examples used different combinations of geometric restrictions to reach the desired result.

4.1. MBB beam

For this geometry, we show an example where three geometric restrictions were used, in order to test its performance. They were Minimum Member Size, Continuous Phases and Unidirectional Growth from left to the right (Fig. 13). The restriction for the void material phase was that it could grow only from the border of the whole component, without creating new holes. This illustrates a case where the manufacturing process chain goes through a serial connection between the two materials, followed by a machine or forming step, to set the final shape of the component.

This result resembles the one presented in Fig. 5, although this time some manufacturing constraints are observed. The design presents only two continuous phases and no structures thinner than what was specified, as desired. Both external shape and joining zone could be manufactured, according to the hypothesis created about the manufacturing process.

4.2. L-shaped beam

For this second classic problem of topology optimization, the same manufacturing constraints were used. So, the multi-material connection is here made by a vertical serial mounting, with a posterior forging or machining to give the component the final shape. To describe these constraints, it was used Unidirectional Growth from the under part at the multi-material level, and for the component level an outside contour restriction. The result of the evolution can be seen in Fig. 14.

The final result presents a reduction of 60% of the weight compared to the initial model. This is a stress concentration problem and the solution should contain a smoothing of the stress at the corner of the "L", which is achieved in our result (Fig. 15).

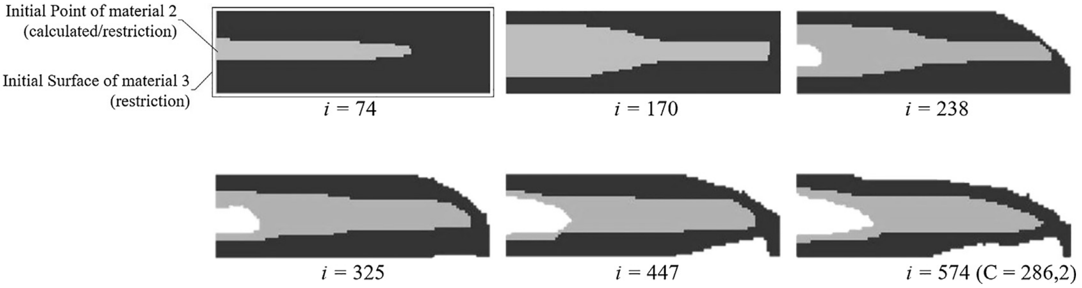


Fig. 13. MBB beam with multi-material IZEO and manufacturing constraints in different iteration stages i (30×90 mesh; final volume proportion: $v_1 = 0.3, v_2 = 0.2, v_3 = 0.5$; elasticity: $E_1 = 1, E_2 = 0.34, E_3 = 0.001$; $er_{12} = 70\%$ and $er_{(12)3} = 10\%$ of the interfacial region; $S_a = 10\%$ in mass; minimum member size radius: 5 elements).

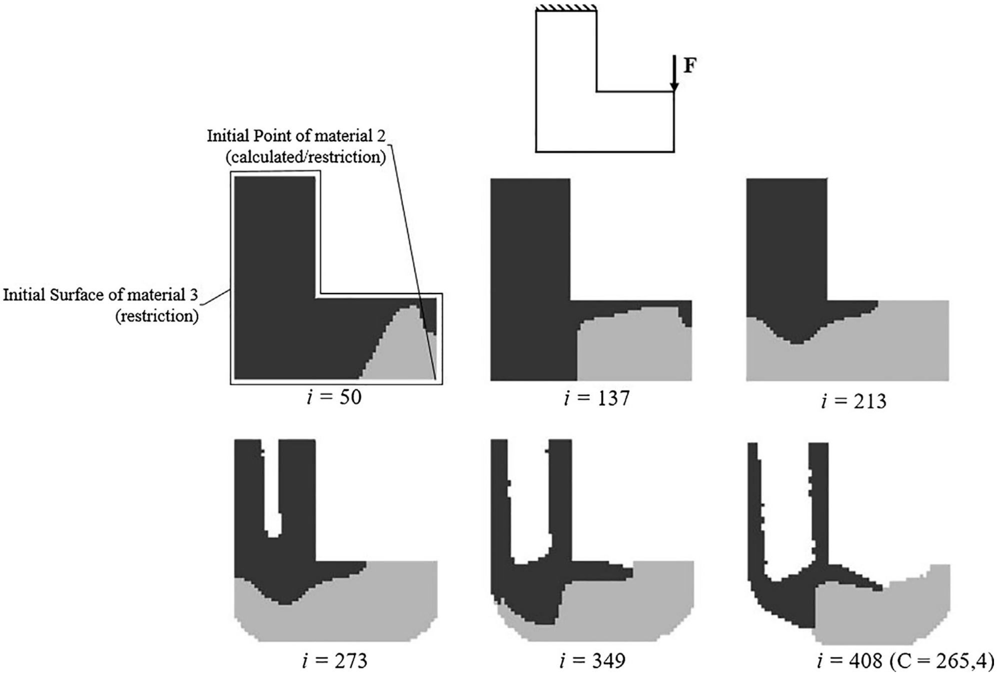


Fig. 14. L-shaped beam with multi-material IZEO and manufacturing constraints in different iteration stages i (60x60 mesh; volume proportion: $v_1 = 0.2, v_2 = 0.2, v_3 = 0.6$; elasticity: $E_1 = 1, E_2 = 0.34, E_3 = 0.001$; $er_{12} = 50\%$ and $er_{(12)3} = 5\%$ of the interfacial region; $S_a = 10\%$ in mass; minimum member size radius: 4 elements).

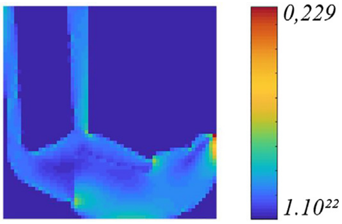


Fig. 15. Safety factor distribution of the optimized L-shaped beam (tensile strength: $\sigma_{U1} = 1, \sigma_{U2} = 0.31$).

The stress concentration at the node where the force is applied is an expected result. As it can be seen, the final design presents a satisfactory stress distribution, without any other stress concentration point and a uniform distribution of safety factor.

4.3. Rocker arm

As a real application example, we took into consideration some automobile components that are desired to be light and have a potential for Tailored Forming manufacturing (Brockmoeller, Gembarski, Mozgova, & Lachmayer, 2017). It was selected a rocker arm, a component located in the engine and responsible to transmit the motion from the cam lobes to the valves. Here, some shape restrictions take place at the face turned to the engine. Furthermore, since we wanted to compare a mono-material and a hybrid design, we used heuristically as the objective function the minimization of weight and as optimization constraint a certain safety factor. The load conditions, the initial design domain, and the final results are presented in Fig. 16. The direction of growth is also used here as a restriction and presented as an arrow on the illustration.

Due to the constraint implemented, both results present the same safety factor. The design made of aluminum and steel, however, shows a weight 21.7% lower than the one made only of steel. This is due to the identified potential of this material combination to deal with bending forces, as it is seen in the better distribution of safety factor (Fig. 17). As observed, this distribution becomes more uniform with the combination of these two materials.

4.4. Discussion

As seen in the results presented, there is a big difference between them and the topology optimization designs that are commonly achieved. Here, the designs are much simpler and closer to what forming processes can normally achieve. The manufacturing constraints specified were faithfully and satisfactory obeyed, whereas this is the main objective of the research.

Whereas every restriction requires one or more variable to control it, the models collect a high number of control parameters. The multi-material approach implies in more parameters, such as volume proportions and different evolution steps to control the sub-iterations. However, only the step values must stay in a specific range and be carefully adjusted to generate meaningful results. The rest of these parameters are directly connected to the final design and can be chosen according to final requirements, as the choice of the initial point, filter or material proportion, for example.

The last point to be discussed is about the processing time. One of the main disadvantages of evolutionary algorithms is the need for longer processing time (Querin, Young, Steven, & Xie, 2000), whereas methods using SIMP can achieve the optimal result within fewer iterations. The results presented took between one and two hours to be completed, which is considered long for a 2D implementation. However, this time can shrink with better processing capacities and an optimized programming, not presenting a concern at this moment.

5. Conclusions

In this paper, a discussion over topology optimization capabilities was performed. The main focus was the use of manufacturing constraints, in order to unify the process of design and optimization for multi-materials components. For that, the new method called IZEO was used to deal with the difficulties faced with these challenges. The results obtained when no restrictions were implemented were satisfactory, reaching similar geometries to the ones seen with traditional well-known methods.

The method presented a potential for the implementation of constraints, as expected, with an intuitive programming and ability to solve strongly restricted problems. The validation of these

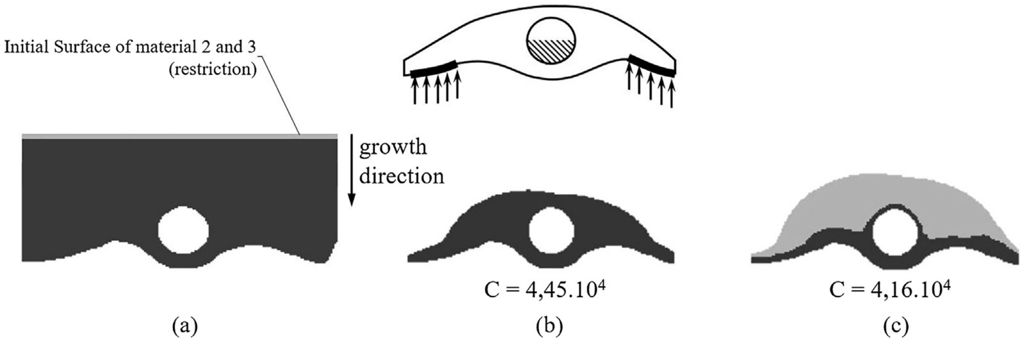


Fig. 16. Rocker Arm optimization: (a) Design domain; (b) Result for pure steel design; (c) Result for a design with same safety factor made of 70%v aluminum and 30%v steel. ($er_{12} = 70\%$ and $er_{(12)3} = 10\%$ of the interfacial region; $S_a = 10\%$ in mass; minimum member size radius: 6 elements).

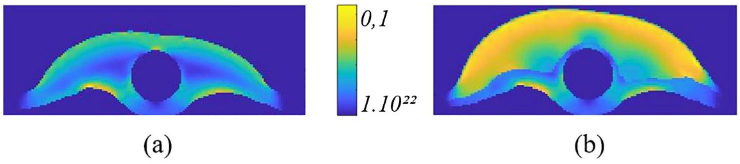


Fig. 17. Safety factor distributions of the optimized Rocker Arms: (a) Pure steel; (b) Steel and aluminum ($E_{steel} = 1; E_{alu} = 0.34; \sigma_{U,steel} = 1; \sigma_{U,alu} = 0.31$).

manufactured constraints results is a sensitive topic because their comparison with classical methods is not possible. However, it is validated here the fact that the specified manufacturing constraints were obeyed in the final results, as desired. Another important topic analyzed is the use of more convenient design properties for engineers, such as minimization of weight and safety factor constraint. Such an approach was heuristically implemented in the example of the Rocker Arm and generated a satisfactory result as well.

Despite all that, the proposed method is still in an early development phase and some other questions have to be investigated in more detail. The higher complexity of the model demands a high number of control parameters, requiring caution and experience from the user. Besides, other objective functions must be also introduced, such as for thermodynamics, vibration or cost problems, whereas the use of hybrid materials is not limited to lightweight applications. Finally, a 3D extension is certainly desired to generate more complex results. With all that into consideration, a balance for number and selection of control parameters represents a challenge and must be rationally planned, so that a reliable and practical method is achieved.

Thereby, we conclude that the results presented have great potential for solving the presented problem of hybrid component design, although further research is needed. However, specific restrictions can be already used to take into account specific manufacturing constraints and generate relevant optimized designs that can be manufactured. In this sense, the final objective must be the generation a robust, reliable and practical method, so that in future optimized components won't be just a cutting-edge technology, but the industry standard.

Conflicts of interest

There is no conflict of interest related to this work.

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References

Aremu, A., Ashcroft, I., Hague, R., Wildman, R., & Tuck, C. (2010). Suitability of SIMP and BESO topology optimization algorithms for additive manufacture. In *21st annual international solid freeform fabrication symposium (SFF)–An additive manufacturing conference* (pp. 679–692).

Behrens, B.-A., Bouguecha, A., Frischkorn, C., Huskic, A., Stakhieva, A., & Duran, D. (2016). Tailored forming technology for three-dimensional components: Approaches to heating and forming. In *5th International Conference on Thermomechanical Processing, 26-28. Oktober, Mailand, Italien.* .

Behrens, B.-A., & Kosch, K.-G. (2011a). Influence of different alloying elements on the intermetallic phase seam thickness of compound forged steel-aluminum parts. *Production Engineering, 5*(5), 517–522.

Behrens, B.-A., & Kosch, K.-G. (2011b). Production of strong steel-aluminum composites by formation of intermetallic phases in compound forging. *Steel Research International, 82*(11), 1261–1265.

Bendsoe, M. P., & Kikuchi, N. (1988). Generating optimal topologies in structural design using a homogenization method. *Computer Methods in Applied Mechanics and Engineering, 71*(2), 197–224.

Bendsøe, M. P., & Sigmund, O. (1999). Material interpolation schemes in topology optimization. *Archive of Applied Mechanics, 69*(9), 635–654.

Bendsoe, M. P., & Sigmund, O. (2004). *Topology optimization: Theory, methods and applications*. Springer.

Brockmoeller, T., Gembarski, P. C., Mozgova, I., & Lachmayer, R. (2017). Design catalog in a CAE environment for the illustration of tailored forming. In *59th Ilmenau scientific colloquium, Ilmenau, Germany.* .

ElMaraghy, H., Algeddawy, T., Azab, A., & Elmaraghy, W. (2012). Change in manufacturing – Research and industrial challenges. In H. A. ElMaraghy (Ed.), *enabling manufacturing competitiveness and economic sustainability* (pp. 2–9). Berlin, Heidelberg: Springer.

Fiebig, S., & Axmann, J. (2011). Combining nonlinear FEA simulations and manufacturing restrictions in a new discrete topology optimization method. In *Proc. of 9th world congress on structural and multidisciplinary optimization, Shizuoka, Japan.* .

Fiebig, S., Sellschopp, J., Manz, H., Vietor, T., Axmann, K., & Schumacher, A. (2015). Future challenges for topology optimization for the usage in automotive lightweight design technologies. In *Proc. of 11th world congress on structural and multidisciplinary optimization, Sydney, Australia.* .

Gembarski, P. C., Brockmoeller, B. S. T., & Lachmayer, R. (2016). Operationalization of manufacturing restrictions for Cad and KBE-systems. In *14th international design conference, Dubrovnik, Croatia.* .

Ghabraie, K. (2015). An improved soft-kill BESO algorithm for optimal distribution of single or multiple material phases. *Structural and Multidisciplinary Optimization, 52*(4), 773–790.

Guest, J. K., Prévost, J. H., & Belytschko, T. (2004). Achieving minimum length scale in topology optimization using nodal design variables and projection functions. *International Journal for Numerical Methods in Engineering, 61*(2), 238–254.

Guo, X., Zhang, W., & Zhong, W. (2014). Stress-related topology optimization of continuum structures involving multi-phase materials. *Computer Methods in Applied Mechanics and Engineering, 268*, 632–655.

Harzheim, L. (2008). *Strukturoptimierung: Grundlagen und Anwendungen. (German) (Structure Optimization: Fundamentals and Applications)*. Deutsch.

Huang, X., & Xie, Y. (2009). Bi-directional evolutionary topology optimization of continuum structures with one or multiple materials. *Computational Mechanics, 43*(3), 393–401.

Huang, X., & Xie, M. (2010). *Evolutionary topology optimization of continuum structures: Methods and applications*. John Wiley & Sons.

Kang, Z., Wang, Y., & Wang, Y. (2016). Structural topology optimization with minimum distance control of multiphase embedded components by level set method. *Computer Methods in Applied Mechanics and Engineering, 306*, 299–318.

Li, H., Gembarski, P. C., & Lachmayer, R. (2018). Template-based design for design co-creation. In *Proceedings of the 5th international conference on design creativity (ICDC2018), Bath, UK.* .

Meisel, N., Gaynor, A., Williams, C., & Guest, J. (2013). Multiple-material topology optimization of compliant mechanisms created via polyjet 3d printing. In *24th Annual international solid freeform fabrication symposium an additive manufacturing conference* (pp. 28).

Park, J., & Sutradhar, A. (2015). A multi-resolution method for 3d multi-material topology optimization. *Computer Methods in Applied Mechanics and Engineering, 285*, 571–586.

Querin, O., Young, V., Steven, G., & Xie, Y. (2000). Computational efficiency and validation of bi-directional evolutionary structural optimisation. *Computer Methods in Applied Mechanics and Engineering, 189*(2), 559–573.

Roper, S., Li, D., Florea, V., Woischwill, C., & Kim, I. Y. (2018). Multi-material topology optimization: A practical approach and application. In *WCX World Congress Experience*. SAE International.

Sauthoff, B., & Lachmayer, R. (201). Generative design approach for modelling of large design spaces. In *Proc. of 7th world conference on mass customization, personalization and co-creation (MCPC 2014), Aalborg, Denmark.* .

Sigmund, O. (2001a). A 99 line topology optimization code written in matlab. *Structural and Multidisciplinary Optimization, 21*(2), 120–127.

Sigmund, O. (2001b). Design of multiphysics actuators using topology optimization–part ii: Two-material structures. *Computer Methods in Applied Mechanics and Engineering, 190*(49), 6605–6627.

Siqueira, R., & Lachmayer, R. (2018). A manufacture constrained design methodology application for a tailored forming hybrid component. In *Tagung Faszination Hybrider Leichtbau, Braunschweig, Germany.* .

Siqueira, R., Mozgova, I., & Lachmayer, R. (2017). Development of a topology optimization method for tailored forming multi-material design. In *Proc. of 24th ABCM international congress of mechanical engineering, Curitiba, Brazil.* .

Tavakoli, R., & Mohseni, S. M. (2014). Alternating active-phase algorithm for multi material topology optimization problems: A 115-line matlab implementation. *Structural and Multidisciplinary Optimization, 49*, 621–642.

Ullman, D. G. (2010). *The mechanical design process: Part 1*. McGraw-Hill.

Vatanabe, S. L., Lippi, T. N., de Lima, C. R., Paulino, G. H., & Silva, E. C. (2016). Topology optimization with manufacturing constraints: A unified projection-based approach. *Advances in Engineering Software*, 100:97–112.

Wang, M. Y., & Wang, X. (2004). Color level sets: A multi-phase method for structural topology optimization with multiple materials. *Computer Methods in Applied Mechanics and Engineering, 193*(6), 469–496.

Xie, Y. M., & Steven, G. P. (1993). A simple evolutionary procedure for structural optimization. *Computers & Structures, 49*(5), 885–896.

Yang, X., Xie, Y., Steven, G., & Querin, O. (1999). Bidirectional evolutionary method for stiffness optimization. *AIAA Journal, 37*(11).

Zhou, M., Fleury, R., Shyy, Y.-K., Thomas, H., & Brennan, J. (2002). Progress in topology optimization with manufacturing constraints. In *Proceedings of the 9th AIAA MDO conference AIAA-2002-4901.* .

Zhou, S., & Wang, M. Y. (2007). Multimaterial structural topology optimization with a generalized Cahn–Hilliard model of multiphase transition. *Structural and Multidisciplinary Optimization, 33*(2), 89–111.

Zuo, W., & Saitou, K. (2017). Multi-material topology optimization using ordered simp interpolation. *Structural and Multidisciplinary Optimization, 55*(2), 477–491.

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