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DEVELOPMENT OF A TOPOLOGY OPTIMIZATION METHOD FOR TAILORED FORMING MULTI-MATERIAL DESIGN

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Abstract. *With new technologies for manufacturing of mechanical parts, new design approaches must be developed to attend specific requirements. Tailored Forming is a process chain with the objective of creating hybrid solid components by using semi-finished work-pieces. This opens a vast range of possibilities for mechanical design, as well as lighter or load-adjusted components, or different material properties in different regions. Thus, one of main concerns in this new methodology is on how the joining zone between the two metals should be designed, since it brings an infinite number of possibilities. With the objective of finding the optimal shapes, topology optimization methods have been widely investigated in last decades. Furthermore, multi-material methods have been proposed, but mostly with too generic approaches, bringing difficulties for its practical use. Another point of concern is about the objective function, where most of these studies have been focused only on compliance minimization. For that reason, the aim of this study is the evaluation of different methods and techniques that can be used in Tailored Forming design. Then, a new method called here Interfacial Zone Evolutionary Optimization (IZEO) is proposed, where the design update happens only at the joining surface. Its main implementation points consist in a material exchange rule and steps of shape adjustment. As result, the algorithm written was able to generate satisfactory results and will be an advantageous approach for dealing with manufacturing constraints.*

Keywords: *Tailored Forming, Topology Optimization, Multi materials, Lightweight*

1. INTRODUCTION

The design of mechanical components is in constant renovation. The search for optimized and high performance parts is always a goal of the industry, in order to improve product quality, reduce energy requirements and reduce costs and increase sales. Such affirmative is very evident in electronic industry, for example, where chips become always smaller and more powerful, leading to lighter and smaller devices with much greater performance. In the world of mechanical structures this is not different. The pursuit of lighter materials or components with a longer life cycle is one of the industry main focus, as mentioned by Fiebig *et al.* (2015).

However, the improvement of these properties is constantly restricted by the available manufacturing technology. With the rise of new methods, such as new forming techniques and additive manufacturing, new opportunities in design raise, where restrictions seen before are no longer present. This is the focus of the Collaborative Research Group - SBF 1153, that researches about a new forming technique, named Tailored Forming, that makes possible the construction of a component using two different metals (Behrens, B. et Al., 2015). This opens a completely new range of possibilities in design, bringing benefits such as lighter weight, longer life-cycle and local specific properties. Figure 1 presents a component using this concept.

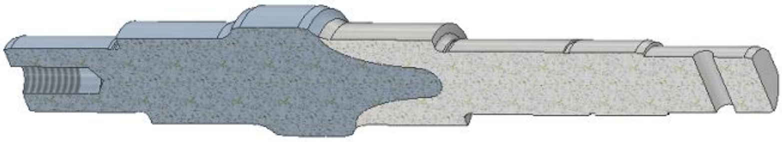

Figure 1. Concept of a shaft made of two materials, through Tailored Forming.

In order to analyze how this technique could be used, selecting the potential candidates, the work of Brockmoeller *et al.* (2017) raise a method that can make this identification. Based on his approach, there are different contradictions in design that must be considered when selecting a candidate. We focus here mainly at the components with weight contradiction, which are the ones where a reduction of weight is wanted, prejudicing stiffness or strength. These are components submitted to a load and due to the nonlinearities present in such model, the design with multiple material becomes critical.

So, after selecting a potential candidate, the design process must start. Although the development of Tailored Forming is still on-going, it is important to be in the vanguard of design guidelines for such a method. There are basically three challenges in design that this technique implies: design with multi-material, stress-based design and manufacturing constraints. The first one is an intrinsic characteristic of Tailored Forming, since it is based in the use of two different metals. The second challenge arises when Topology Optimization tools must be implemented. The different stress field in each material cannot be neglected and its implementation brings challenges that will be discussed further in this article. The third one is about the own Tailored Forming manufacturing constraints, that must be obviously taken in consideration.

With that in mind, a right methodology of design must be chosen and executed. The use of parametric optimization techniques appears as a first option, due to its practical way to implement manufacturing constraints (Harzheim, 2008). However, to use such a method, a basic concept must be created, which may be plausible for the class of components where only local properties are required, but not for our case of interest, where the optimal materials distribution is completely unknown. For that reason, it is needed a method that presents this best distribution of two materials in a component domain in order to achieve a desired property. So, the first design question is: where to set each material at the component?

To answer that question, topology optimization techniques will be discussed in following sections. Different approaches can be used to find this optimal material distribution and get most of its advantages.

1.1 Topology Optimization

Topology Optimization (TO) techniques have a high potential for use with multi-material scenarios. Although it can lead to the best possible result on how to make the design, it normally faces difficulties when it must be used with manufacturing constraints, in contradiction to Parametric Optimization. Here, the suitability of this tool for Tailored Forming will be investigated.

Optimization of structures is a topic that has been actively researched in past decades. These methods are normally implemented in conjunction to the Finite Element Method (FEM), where a space domain is set and a required amount of material is distributed in order to achieve the global minimum of an objective function. The most traditional theory about it was proposed by Bendsoe and Kikuchi (1988), where a strong mathematically formulated theory is presented. In this method, the stiffness (or compliance) is the objective function and the volume is the constraint. It makes use of density as design variable, allowing it to assume values between 0 and 1. The intermediate values are then discouraged by the introduction of a penalization function to describe the relation between the elasticity and density (Bendsoe and Sigmund, 2004).

This method is known as SIMP (Solid Isotropic Material with Penalization) and became very popular in subsequent research, allowing simplistic implementation approaches (Sigmund, 2001a). Another strong characteristic of it is the capacity of fast convergence, requiring very few iterations and saving computer requirement. Wherefore, this is today the most consolidated technique, used in most commercial softwares available, such as TOSCA (Tosca, 2014). The method has been also expanded and improved constantly, such as in (Zhou *et al.*, 2002), (Bendsoe and Sigmund, 2004) and (Zhou *et al.*, 2001). Still today many research is made around it, as for Additive Manufacturing (Ferguson *et al.*, 2016), multi-materials (Zuo and Saitou, 2017), vibration problems (Zargham *et al.*, 2016) and also for optimization of thermal components (Li *et al.*, 2017).

Although SIMP has been largely used with success, it faces some problems. The solution is guaranteed to be the global optimum only for convex problems, such as compliance (Rozvany, 2009). Furthermore, design by compliance is only one of the criteria normally used. Another critical factor commonly used is strength, as in designs based on a safety factor or with fatigue concern. This implies in a stress-based objective function, which is a singular problem that requires special techniques to be solved, as seen in the work of Duysinx and Bendsøe (1998). What is largely used today by the industry is the use of shape optimization techniques after a topology optimization step is performed (Harzheim, 2008), which is a highly heuristic and inefficient method, since these subsequent changes can make the component loose the optimal properties (Vatanabe *et al.*, 2016). The second big problem of SIMP is related to the called *grey zones* generated in result, which have no physical meaning, unless composite materials can be used (Osanov and Guest, 2016).

In contrast to SIMP, another group of methods gained relevance: the Evolutionary Algorithms. Its first use was called ESO (Evolutionary Structure Optimization) and it was based on an erase of material in the domain, step by step, guided by the areas with low Von Mises stress (Huang and Xie, 2010). Many improvements were also made for this method, such as compliance sensibility, soft-kill theories and the ability of a bi-directional evolution, producing the state-of-art of this technique, called BESO (Bi-directional ESO) (Radman, 2013). This methods became more popular due to its clear physical meaning (Fiebig *et al.*, 2015), ease of implementation and also possibility to implement in commercial FEM software (Zuo and Xie, 2015).

For stress-based criteria, although the original ESO used the stress field to find and delete inefficient use of material, it is still equivalent to the stiffness criteria (Li *et al.*, 1999). Proof of that is that in many cases the results are very similar to the ones found with SIMP (Huang and Xie, 2010). So, as well as SIMP, the method is normally used in conjunctions with stress constraints, instead of a stress objective function (Bendsoe and Sigmund, 2004). A critic disadvantage of evolutionary algorithms is also the high computational demand required, which is probably why commercial softwares still rejects the method. However, despite BESO being criticized and qualified sometimes as highly heuristic (Rozvany, 2009), most of past and recent research has shown the great potential of the method (Cazacu and Grama, 2014). In the present research, it is also seen a great advantage of it, due to its meaningful physical approach, making it easier to make adaptations based on the results achieved during the evolutionary process.

A few other less grounded methods must be also mentioned here. One of them is the Soft-kill option (SKO), based on biological observations of nature structures (Baumgartner *et al.*, 1992). Beside this method being very interesting, for its unique approach by stress analysis, it became outdated due to the small interest given to it (Cazacu and Grama, 2014). However, despite being not explored, this method raises one of the great advantages of having components with a non-uniform structure: the uniform stress distribution. It shows how stronger materials should be positioned in high stress areas and propose a method to do so. Other promising techniques has been appeared also in last years, such as the use of level-set description optimization, in (Challis, 2010) and (Michailidis, 2014), or a Proportional Topology Optimization (PTO) (Biyikli and To, 2015). It can be noted that these new techniques have a strong correlation with the former methods, being only alternative ways to make the mathematical description of a physical problem.

Selecting the most suitable tool for the presented issue can become an extensive job, due to the high volume of research and improvement techniques already performed. Many comparisons can be found on the literature, such as in (Aremu *et al.*, 2010) and (Cazacu and Grama, 2014). SIMP has as main advantage the more robustness to reach global optima (Rozvany, 2009), but the scientific community has not agreed yet in what is the most suitable method. This choice is still dependent on its applicability, whenever is used for multi-material design, stress-based approaches or manufacturing constraints. For the Tailored Forming application, the present study focus on the first two.

1.2 Multi-Material design

The design with multiple materials adds a significant challenge to the design process. In respect to Topology Optimization techniques, the subject becomes even more relevant, due to its inherent complexity. Differently from the basic optimization methods, the research in this field has not been equally extensive and the results are much less solid.

One of the early proposals was made using SIMP (Sigmund, 2001b), where an equivalent penalization method using multi-material is presented, also showing the difficulties that it implies in the mathematical resolution. It showed, for example, how the number of design variables is increased by the numbers of materials. Other proposed methods were the use of alternating active-phase algorithm (Tavakoli and Mohseni, 2014), Phase field (Zhou and Wang, 2007) or Level-set, in (Wang and Wang, 2004) and (Guo *et al.*, 2014).

One characteristic in common of all the methods presented above is the high number of design variables, due to the use of more materials. The called ordered SIMP interpolation was proposed in (Zuo and Saitou, 2017), as a method to decrease the number of design variables and reduce computational time. It uses a unique design variable and an interpolation function to describe all needed materials. Another proposal to cover the high demand problem was presented by Tavakoli and Mohseni (2014), where the standard SIMP for multiple materials is used, but with an active-phase algorithm to reduce computational cost. This method was lately used in (Park and Sutradhar, 2015) for 3D structures, generating good results.

An approach using BESO was also presented in (Huang and Xie, 2009), where a completely different strain-energy criterion is showed for dealing with multi-material, using also a penalization parameter. In some recent works it is shown some actual implementations of the methods, as in (Meisel *et al.*, 2013), and as in (Mirzendehdel and Suresh, 2015) with the use of a Pareto-optimal approach.

What can be seen in all the methods cited is the great generalization that they try to apply to the problem of multi-materials. Systems with only two materials, considering no void, which has currently much greater applicability, are hardly given special attention. The algorithms are not even limited to applications with two materials and void. This approach only intensifies the complexity of the shapes already seen in Topology Optimization. With multi-materials, this issue raises to a higher level of difficulty, losing the practicality of the research in reality.

1.3 Stress-based Constraints

Dealing with multiple materials has another critical point, which is the choice of objective function and constraint. Since the materials have different elasticity and different strengths, the effects of stress cannot be neglected and this approach becomes a basic requirement.

The most common selection for objective function and constraint is, respectively, compliance and volume, as described by Bendsoe and Kikuchi (1988). Despite this compliance-volume selection being the preferable choice for its simpler resolution, it is not always the best choice and different arrangements should be also applicable to TO (Sui and Yi, 2013). In a big variety of cases, a maximum stress-volume or strength-mass choice is desirable, as in components where the stiffness is not an issue, but the life-cycle or safety (Nisbett and Budynas, 2014).

As well as for multi-material, the research of stress-based systems presents great challenge, due to its highly non-linear dependency on the design of the structure (Le *et al.*, 2010). Another reason for the difficulty of dealing with stress is that, differently from compliance, it is a local parameter (maximum stress) that has to be optimized.

An initial method using SIMP was proposed by Duysinx and Bendsøe (1998), where a Von Mises sensibility method is proposed with a relaxation method, to overcome singularity problems. An idea to overcome the local nature issue was also proposed (Duysinx and Sigmund, 1998), where it was used a p-norm function to approximate the maximum stress of the structure continuously. However, it has been seen in these works that the grey regions generated by SIMP cause problems when dealing with stress, due to its high non-linearity. Another idea to contour these problems can be seen in the work of Verbart *et al.* (2013), where a compliance optimization is made with a penalization of stress.

The use of stress as constraint instead of objective function is also an alternative explored. This is the concept presented by Ramani (2011), where a pseudo-sensitivity approach is presented. However, this idea can be more easily implemented in Evolutionary Algorithms, where the volume is minimized step by step. This method was proposed by Fiebig and Axmann (2013), where the objective function is the minimization of volume, using some of the SKO concepts and a step-size controller.

As can be seen, despite all the comparisons between the different stress-based approaches (Le *et al.*, 2010), there is a lack of mathematical capability to deal with stress constraints. The high non-linear dependency of every element of the mesh with each other brings great difficulty to reach a decisive final solution. For that reason, heuristic approaches, such as the one seen in the work of Fiebig and Axmann (2013), play an important role today to generate practical stress-based solutions, where engineering knowledge can be prioritized in the programming over the mathematical assertiveness.

2. PROPOSED METHOD

In the present work, we have the view that the computational and analytic process developed for optimization should work as a tool to execute what the engineers have planned, and not be over formulated. That means that a full observation of the whole process and the interpretation of what is happening inside the component have here a decisive role. For this reason, the proposed method here is based on the Evolutionary Algorithm methodology. The main advantage seen by this choice, as mentioned, is this exactly opportunity to observe how the stress evolves during every iteration. This is a powerful tool that allows a quick in-time analysis about the significance of the result, supporting the decision making in the algorithm development. Within this principle, a method named here Interfacial Zone Evolutionary Optimization (IZEO) was developed.

2.1 Concept of IZEO

Firstly, some restrictions and hypothesis must be determined. A first point is that here only 2 materials will be considered, without a void space. The idea is to work with pre-existing single-material components, which has a certain geometry already defined, and then find out how both materials should be distributed. Since our focus are mechanical properties, we also assume that the material with lower Young's Modulus is also the one with lower strength. This is due to the interest of the project in achieving lighter components, with a combination, for example, between Steel and Aluminum. Therefore, this model focus on a future direct component replacement.

The key feature of IZEO is that the evolutionary process happens only at the interface between the two materials. In other words, the component starts the process fully made of one single material, but with one single point (or mesh element) made of the second material, and then, from this point, the second material starts to grow. This initial point can be rather calculated or chosen, as it will be shown in next sections. Figure 2 shows an example of structure for a given instant of the evolution process. The idea behind it is to facilitate future implementation of manufacturing constraints and maintain only two material phases in the process. Although this method still doesn't exclude the possibility of a separation of phases, it consists in a simplistic way to create plausible designs for future application with forming methods.

Another important guideline criteria goes around the stress field of the structure. Since we have a component made of two materials with different properties, including different strengths, it is necessary an analysis based on how much the stress in each material is close to its ultimate stress. That is equivalent of calculating the safety factor of every point of the structure, in order to find which material is closer to failure. Determining this material took a decisive role in the algorithm, which will be presented ahead.

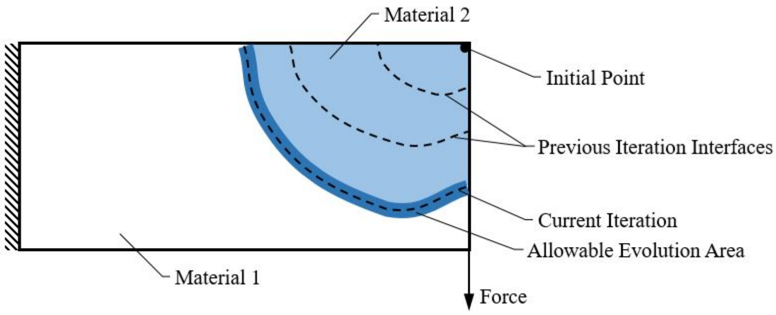

Figure 2. Concept of IZEO: Evolution process of the material topology happens only at the joining surface.

2.2 Problem Formulation

So, to deal with the stress issue in a practical way, our problem formulation uses as objective function the minimization of mass. The optimization problem is stated in Eq. (1).

$$\min_{\rho,E} m$$
$$m = \int_{\Omega} \rho(x)dx; \qquad \rho \in [\rho_1, \rho_2], x \in \Omega$$
$$min\left(\frac{\sigma_U(x)}{\sigma_{VM}(x)}\right) \geq n_d \tag{1}$$

Where m is the total mass; ρ is the density; E is the elasticity modulus; x is a location in the space domain Ω; ρ_1 and ρ_2 are respectively the density of materials 1 and 2; σ_U is the material ultimate strength; σ_{VM} is the Von Mises stress; and n_d is the minimum acceptable design factor (or safety factor). The main role here is played by the restriction, which sets a minimum allowable value for the design factor.

To achieve a reliable solution using an Evolutionary Algorithm, not only the final result is important, but also the path taken to achieve it. In an ideal scenario, during the gradual addition of a weaker material, the maximum stress of the structure would be located at the primary and stronger material and would be kept at the lowest level. With the process going on, the stress in the weaker material being added would gradually increase, with its design factor increasing towards the design factor of the strong material. However, as seen in literature, such a sensibility field that could perfectly guide this evolution according to the maximum stress is not yet mathematically performed. Alternative methods that approximate this ideal scenario were then implemented.

2.3 Numerical Implementation

For the numerical implementation, the algorithm presented in the work of Sigmund (2001a) was taken as base, in the environment of the software Matlab (2016). The method uses Von Mises stress as guidance to the evolution. The advantage of using Von Mises as sensibility is that it has a direct physical meaning to our restriction. Based on trials and observations, the algorithm shown in Fig. 3 was created in order to dictate how the evolution would occur according to which material is being added in a specific iteration, and on which material the lowest design factor is located.

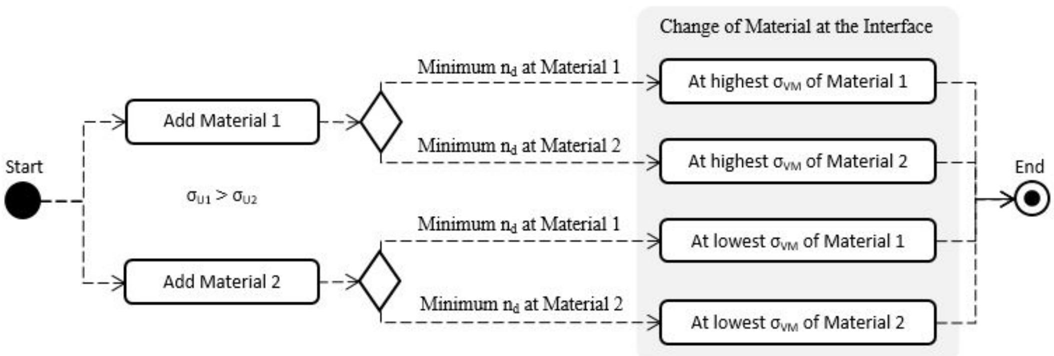

Figure 3. Decision making algorithm to set where the exchange of material will be made.

So, for a given moment in evolution, there are two possible paths: adding the stronger material or the weaker. The question here is where the material change should take place. For that, we find which material is more critical in the system and it is closer to failure (with the minimum design factor). Based on this, we use only the Von Mises stress of this material as the evolution criteria, since this material becomes more relevant. Then, depending on the material being added in the iteration, whenever the weaker or the stronger, we add it at the lowest or the highest (respectively) stress region of the interface between the materials.

Although this is an heuristic method on dealing with the maximum stress criteria, this method has a important impact on the stress at the interface of the two materials, which is also a point of concern for Tailored Forming. The stress at the interface needs to be as homogeneous as possible, since a stress concentration could damage this bond between the two metals. So, to guarantee this homogenization during the entire evolution, it was introduced steps where the mass is kept constant and a shape adjustment is made, as illustrated in Fig. 4. These steps are implemented using the same algorithm showed in Fig. 3, where the addition of each material is intercalated, in order to keep the mass around the same value. This provides to the method a desirable bi-direction ability.

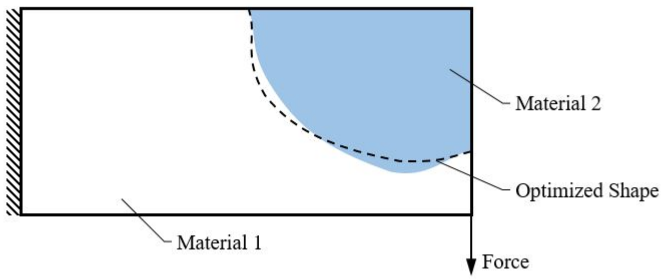

Figure 4. Shape adjustment of the interface geometry in order to homogenize its stress.

This approach, called here shape adjustment step, approximates the concept of Shape Optimization methods, as the Net-based (Harzheim, 2008). For this implementation, a new parameter must be introduced, where it defines how frequently these steps of shape adjustment occur.

As mentioned earlier, too generalized concepts faced unnecessary difficulties and we intend to focus on solving our particular objective, which is Tailored Forming. With the concept proposed and the restrictions imposed, it was possible to make a big amount of different implementation trials. After every try, the evolution and final result was observed and analyzed. According to this interpretation, these implementations were evaluated about its impact and then it was kept in or excluded from the algorithm. Figure 5 gives a basic description on how the numerical implementation works, where m_S assumes the step values where the shape adjustment is made.

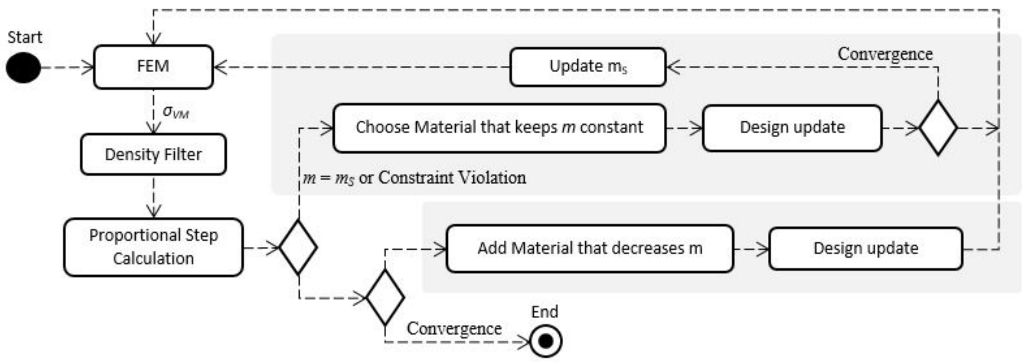

Figure 5. Simplified description of the algorithm implemented.

As seen, a density filter was implemented, in order to control mesh dependency and check-board problems (Bourdin, 2001). A result expected from the filter is a smooth result, and it was observed that the density filter provided a better result than the sensibility filter. Another implementation made was a proportionality of the steps in relation to the constraint. As the the result gets closer to the constraint, the steps become smaller, as contribution for the convergence.

Finally, it can be seen that there are two situations where the minimization of mass stops and the algorithm enters in a loop where the design update happens in order to homogenize the stress. One happens in chosen points where the mass reaches a predetermined mass (m_S), and then after this internal loop is converged, the value of m_S is decreased. The other is when the constraint is violated, then the system gives a step back and tries to improve the stress at the surface, in order to try to keep the reduction of mass. If after this improvement the mass can not be reduced without violating the constraint, the simulation ends.

3. RESULTS

The results of the implementations were evaluated through simulations with classical cases of topology optimization, which are the MBB-Beam and L-shape beam. The simulations were all made with the Steel being the primary material ($E = 205GPa$ and $\sigma_U = 1GPa$), and Aluminum being the second material ($E = 71GPa$ and $\sigma_U = 310MPa$).

3.1 MBB-Beam

The evolution and final result for a MBB-Beam can be seen in Fig. 6, where i gives the number of iterations of the presented design. The initial point was chosen to be the one with minimal stress.

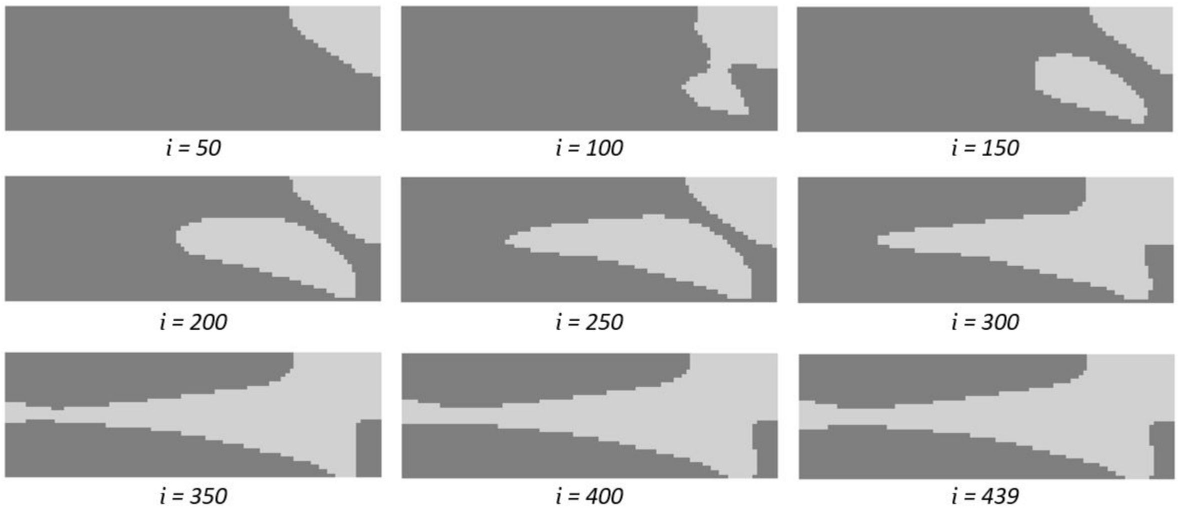

Figure 6. MBB-Beam simulation; Mesh 90x30; $r_{filter} = 4$; initial step: 10 elements; shape adjustments intervals: 1%v/v; safety factor constraint: 98.9% of initial. Final mass: 72%; final volume of Aluminum: 43%v/v.

In Figure 7 it can be seen for the resultant design, the stress ratio distribution $\left(\frac{\sigma_{VM}}{\sigma_{adm}}\right)$, where σ_{adm} is the maximum admissible stress in each material according to the safety factor constraint.

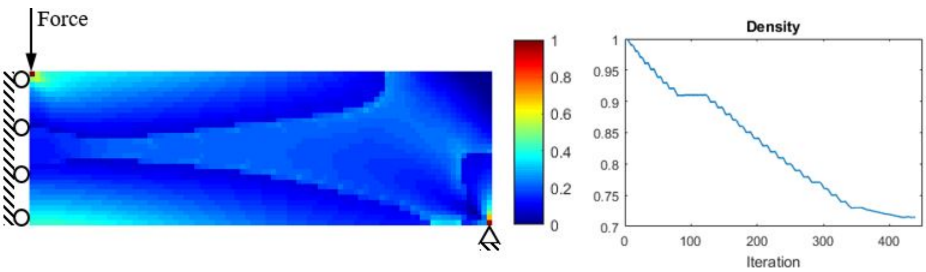

Figure 7. Stress ratio distribution of the result for the MBB-Beam and density evolution history.

The evolution of relative density is also presented in Fig. 7, showing clearly the steps of shape adjustment. It is noticed, for example, that a long step of adjustment is present around $i = 100$, which is the moment that an abrupt change in the topology of the structure happens. Another point of observation is the good distribution of stress in the result, with the joining zone having mostly homogeneous stress.

3.2 L-shape Beam

With the same procedure, the simulations for the L-shape beam were executed and the results are presented in Fig. 8. In this case, the weight reduction was higher, probably because of the high stress concentration seen in the point at the corner of the shape. Another observation here is that a bigger variation of topology is seen during the evolution, which also happens during longer periods of shape adjustment.

This simulation for the L-shape beam was also repeated with a higher value of shape adjustments intervals (10%). It was observed however, that the same final design was achieved, but with 55% less iterations and a different evolution path. This might, however, cause impact in the result, requiring consciousness when calibration this parameter.

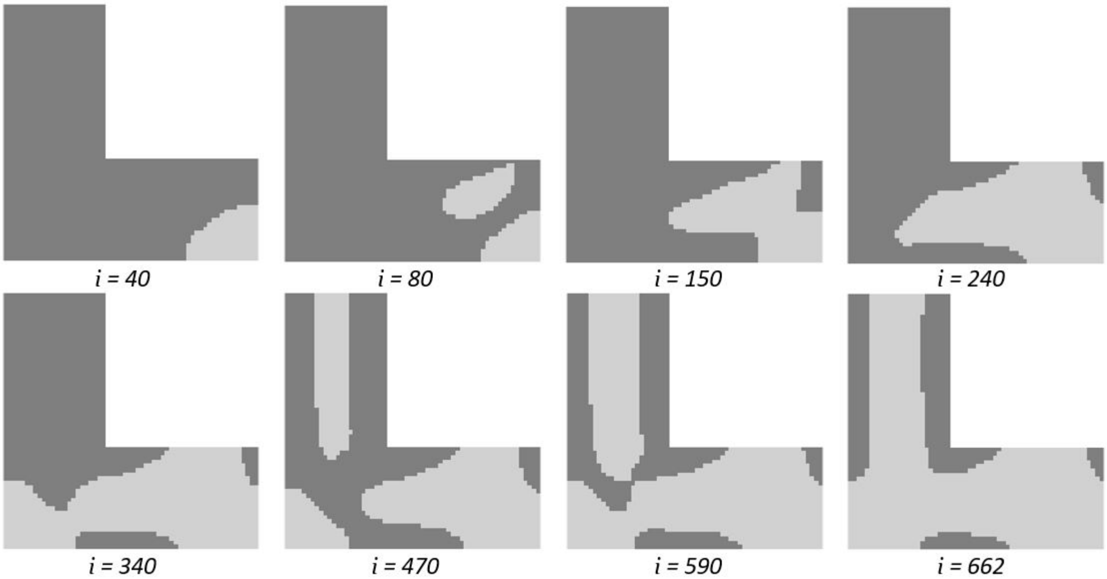

Figure 8. L-shape Beam simulation; Mesh 60x60; $r_{filter} = 4$; initial step: 10 elements; shape adjustments intervals: 1%v/v; safety factor constraint: 99.6% of initial. Final mass: 52.6%; final volume of Aluminum: 73.1%v/v.

4. DISCUSSION AND CONCLUSIONS

The initial objective of this research was the study of topology optimization tools and the development of one that would serve as first guideline for design engineers to deal with the multi-material challenge found in Tailored Forming. Before detailed design, the first difficulty is how to distribute the materials, which is the question that the method presented tried to answer. Although there is still a long path of research to be made, the results presented here were satisfactory.

A comparison with traditional SIMP and BESO, using algorithms from the work of Sigmund (2001a) and Huang and Xie (2010), was made for the MBB-Beam using our final volume achieved as input data. The design of each method can be seen in Fig. 9. The present method result was very similar to SIMP, but with the advantage of having no intermediate material zone. Having all three designs the same final weight, the difference in maximum stress or compliance observed was not significant, considering the numerical error present.

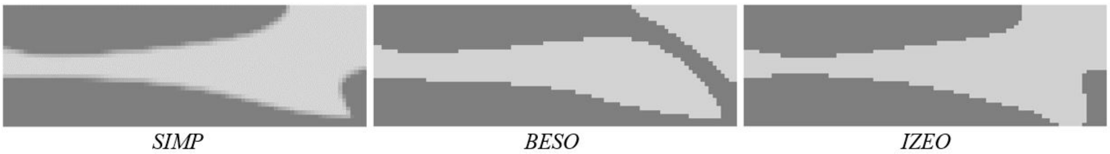

Figure 9. Comparison between design results for the MBB beam.

The biggest difference of IZEO in comparison to other methods is the number of iterations needed, which is much higher. This problem is intensified when small steps of shape adjustment are used, and could become even worse if implemented in bigger models. However, although computational time has always been a concern in TO techniques, this issue tends to become less important, with the fast advance of computer sciences.

The stress homogenization at the interface is an important feature of the method, with a positive impact in the component's performance. As mentioned, one of the objective of Tailored Forming research is the development of lighter materials, which brings great benefits in dynamic components. So, a balance between strength and stiffness become crucial in such designs. For this reason, the proposed method showed a promising approach, since it deals with stress constraints, its homogenization and the reduction of compliance.

The immediate future step of development is the implementation of manufacturing constraints. As seen, the method itself did not work as a restriction, only the filter implemented. The initial idea, however, is that in following phases this approach will facilitate the implementation of manufacturing constraints. This is a topic that cannot be neglected, since its pointless to create designs that cannot be manufactured. Such implementations will bring a lot of new challenges, mainly because of Tailored Forming specific restrictions, such as forging direction.

Other important points still need to be studied, like the use of this tool with other components and the use of a specific model to describe the characteristic of the joining zone, since it has properties different from both materials. Besides the great advances of manufacturing process and computer engineering, here it was show the relevance in keeping the same pace of development in design.

5. ACKNOWLEDGMENTS

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