Lightweight design of an automotive lower control arm using topology optimization for forming process

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Abstract. The global environmental regulations have become very strict nowadays, thus most car manufacturers aim to fulfil such restrictions by different strategies including lightweight technologies that contain design, advanced materials and manufacturing. Hereby, optimally designed geometries of structural components needs to be conformed to their functional requirements and manufacturing process. In this work, a topology optimization (TO) was performed for weight reduction and performance improvement of a lower control arm (LCA) of vehicle suspension. First, FE simulations of the recently used LCA were performed under different load cases according to the actual application. The resulted stress distribution and overall stiffness were gathered as the baseline reference. Then, TO procedure was carried out and critical regions for load carrying were classified. In addition, the member-size constraint was applied to enable a LCA layout, which can be likely produced by metal forming process. The introduced optimization method serves as a guidance in practice for the lightweight design of other automotive stamping parts.

1. Introduction

It is widely known that light-weighting is a great method for car manufacturers to fulfill the reduction of greenhouse gas emissions and fuel consumption, which finally affects the design and manufacturing cost. Within an industry 4.0 approach, the finite element analysis (FEA) and other numerical methods like topology optimization (TO) are hereby crucial tools, especially in the aerospace and automotive industries. In general, such techniques have been increasingly applied to achieve structural requirements such as stiffness, stresses and dynamic behavior so that failure of concerned parts is prevented [1-3]. In [1], the comparisons between experimental investigation and FE modal analysis of an automotive rear sub-frame were shown. The numerical results agreed well with the experimental data under various dynamic parameters like natural frequencies, mode shapes, and frequency response functions of the structure. Both typical and uncommon failure modes in connecting rods of internal combustion engines were investigated by using FE predictions in [2]. The locations of the most critical sections were reported.

In many cases, TO was used to provide useful guidelines for the design of structural components for load carrying applications [4-8]. The TO was employed to save weight of milled parts of helicopter crashworthy pilot seat in [4]. Xu et al. [5] proposed a TO method based on solid isotropic
Microstructure with penalty (SIMP) to reduce the weight of key components and keep required overall stiffness of stamping die for high-strength sheet metal. A failed clutch fork was completely re-designed by means of topology and shape optimization approach [6]. The mass reduction of 24% was obtained with a maximum stress reduction of 9% and the rigidity improvement up to 37% in comparison to the previous clutch fork. The TO techniques were applied to design steel I-section perforated beams by Tsavdaridis et al. [7]. It was reported that the stiffness and yield load of the optimized design were increased, while there were also various restrictions including the complexity of obtained web geometry and analysis difficulties. In [8], an automotive component was designed by using TO, in which compliance minimization and eigenvalue maximization were considered. It is found that the new design was superior to the current part with regard to both static and dynamic performance. Nevertheless, the results obtained from the TO needed to be appropriately interpreted. Also, they often were not well complied with any conventional manufacturing process except for the additive manufacturing [9-10]. Zuo et al. [9] stated that TO has currently become a powerful method in the design of new engineering products, but a wide range of problems including porosity, a design with checkerboards, mesh dependency, local minimum results, etc. often led to non-manufacturable or non-machineable results that could not be accomplished later in the manufacturing process. Therefore, a hybrid TO algorithm combining the method of moving asymptotes and wavelets as manufacturing and machining constraints was introduced to overcome this problem. Costi et al. [10] presented a methodology consisting of different TOs for reducing the weight of an automotive hood substructure. After the optimized model with the smallest mass was obtained, frame and braces were redesigned according to the criteria of manufacturability. The fundamental concept of TO procedures could be referred to the work of Bendsøe and Sigmund [11]. Cavazzuti et al. and Mantovani et al. [12-13] employed different optimization methods and comprehensively studied their results for lightweighting a complete car chassis and dashboard. Basically, manufacturing requirements were not automatically taken into account and thus most of the interpreted results could not be produced. Due to this point of view, a manufacturing constraint is necessary by performing the TO so that the given design becomes closer to a manufacturable one and the subsequent interpretation is also facilitated. Several procedures of TO with different constraints such as single and split draw constraints were conducted for enabling a design solution for casting and extrusion process, then each solution was compared in [13]. Otherwise, the member-size constraint is a known requisite in TO for controlling the minimum length scale of examined structure that has been applied in many works [14-16].

In this work, a TO based design methodology for an automotive control arm was presented. It was aimed that the resulting part is possibly able to be produced by metal forming process so that the currently employed manufacturing is not affected. Both structural performance targets and member-size constraint were considered. Hereby, the manufacturability of achieved design were enabled. The optimized part was then evaluated with respect to the resulting stiffness and stress distributions in comparison with the baseline model and that without using the manufacturing constraint. This work attempted to provide a practical way for applying the TO method. The limitations of used member-size constraint are also shown.

2. Concept of used topology optimization method
A topology optimization is generally used to determine the best material utilization or distribution in a design space under a given load. Hereby, the structural optimization aims to achieve a local minimum as expressed in equation (1).

\[
\min_{x \in D} f(x) \\
\text{subject to } c(x) \geq 0
\]  

(1)

Where the vector \( x \) represents a parameterization of the problem, \( D \) is the design domain or volume space, \( f(x) \) is the objective function, and \( c(x) \) are the constraints of the optimization. The objective function and the constraints are such structural responses obtained from a FE analysis.
The density $\rho$ of each $i$-th element in the calculated FE model is given by equation (2).

$$\rho_i(x_i) = x_i \rho^*$$  \hspace{1cm} (2)

Where $\rho^*$ represents the full density of concerned material. Therefore, the material density and the material stiffness can be correlated according to this equation. The solid isotropic material with penalization (SIMP) method was applied in this work, which assumed that the stiffness $E$ of the $i$-th element of model is given as following.

$$E = \rho^p E^0, \quad \rho \in [p_{\text{min}}, 1], \quad p > 1$$  \hspace{1cm} (3)

Where $p$ is the penalizing factor that penalizes elements with intermediate densities to approach 0 or 1, $p_{\text{min}}$ is the lower density value limit to avoid singularities. Thus, the penalization is achieved without introducing any explicit penalization scheme. For materials with Poisson ratio $\nu = 0.3$ like steel as used here, it was recommended in [17] to use $p \geq 3$.

3. Topology optimization of an automotive control arm

In this work, the homogenization method, which was introduced by Bendsøe in [18], has been employed to solve the TO problem. The method is known as the solid isotropic material with penalization (SIMP) method giving rise to the large class of density-based methods, in which the calculated values of material densities could attain any values between zero and one. This algorithm could deal with large amounts of continuous variables and multiple constraints were also available. However, material properties needed to be modelled in a continuous manner, which was only allowed through an interpolation process. The interpolation was essentially based on a power law. Hereby, the Young's modulus of the material was assumed as the scalar selection field. The value of the penalization parameter of 3 was defined. In the SIMP method, a lower bound of the Young's modulus was included in order to ensure that the derivatives of given objective function were non-zero when the material density became zero.

The design object was the automotive control arm, which was a main part in the suspension system of vehicle. Figure 1(a) depicts the overview of a suspension system [19] and Figure 1(b) illustrates the lower control arm examined in this work. The control arms governs the motion of wheels of moving vehicle. It forms a body of suspension connecting the chassis and suspension hub that carries the wheel. This hub is assembled with both upper and lower control arm. The end of the control arm is attached to a single pivot that is usually a rubber bushing. This part can thus control the position of the outboard end by only a single degree of freedom and maintain the radial distance from the inboard mount.

Figure 1. (a) A suspension system and (b) examined lower control arm [19].
According to the described motion of control arm, load cases for FE simulations were defined as applied load on the front-end area, which was the area connecting to the suspension hub and therefore responsible for any load transfer from wheel to suspension components. The back-end areas served to maintain the position of control arm on the chassis structure and could only move in the tangential direction. Hence, these both areas of the FE model should be fixed for all translations and rotations. Figure 2 presents all load cases applied to the control arm in FE simulation, which consisted of longitudinal force and lateral forces at front-end and fixed supports at back-end areas. The used loading conditions took into account all critical standard driving condition including pothole breaking, reverse breaking and cornering through inner and outer wheel. These load cases were given during the optimization process as a multiple weighted objective function. Firstly, the TO process was performed without consideration of any manufacturing constraint in order to determine the most critical loading path and resulting optimized geometry. Then, the member-size constraint was incorporated, for which different configurations were also studied. The result of TO combined with the member-size constraint could be well interpreted as a sheet metal-alike layout. Note that only the outline of members given by the TO was utilized to generate the final model and the inner geometries of the members were neglected.

![Figure 2](image-url)

**Figure 2.** Used load cases applied on the front-end area of based-line model.

In this work, the TO of the control arm was carried out in ABAQUS with embedded TO module. The material used for the control arm was the high strength steel grade 590. The linear elastic property was assumed, in which the Young’s modulus of 210,000 MPa and Poisson’s ratio of 0.3 were provided. The material density was equal to 7.83 kg/dm³. The weight of this control arm represented approximately 3 percent of the overall weight of suspension system and equal to 8.0 kg.

3.1. **TO with weighted compliance without manufacturing constraint**

For such control arm, an adequate compliance was used as the required design response. The compliance was basically defined as a magnitude inversely proportional to the structural stiffness. Therefore, the objective function was defined to minimize weighted compliance of part subjected to all load cases shown in Figure 2. To minimize the compliance was equivalent to maximizing part stiffness. In this case, the manufacturing constraint or member-size constraint was still not given during the TO.

To perform the TO, an initial design domain needed to be first generated on the basis of the base-line model. The initial domain of control arm was simply a rectangular shape, as depicted in Figure 3, which was then used as the reference boundary of the TO process. The regions for giving the boundary and loading conditions according to the front- and back-end areas of the base-line model were defined as the non-design spaces. The loads in the longitudinal direction, which represented the inner and outer wheel cornering, were applied to the reference point of a coupling constraint attached to those front-end area of the model. In order to attain a desired stiffness equally in all directions, the weighting
value of each loading condition was provided proportionally to the corresponding force magnitudes in the objective function. These pre-defined conditions were also used for the cases of lateral load. In the simulation, coupling constraint at both back-end regions was fixed in all translations and rotations. By this manner, obtained optimization result could be a free-topology control arm which showed the greatest resistance to deform with regard to the defined load cases and design space. The optimal structural material layout was corresponding to the most effective load-carrying path in the design domain.

![Design domain](image)

**Figure 3.** Initial design domain.

The optimized topology result of the investigated control arm was illustrated in Figure 4(a). It is noted that the TO procedure was conducted without any restriction of desired volume or mass. The volume of the resulted optimized-topology accounted for around 15 percent of that of the initial design model with respect to the defined design space in Figure 3. It is seen that this optimized geometry still showed organic-like shape that required a further interpretation process. Therefore, the optimized topology shape was precisely re-modelled and the interpreted geometry is depicted in Figure 4(b). It was found that the mass of optimized-topology and interpreted geometries were about 48 and 59 percent of the mass of base-line model, respectively. From the interpretation, the mass of re-generated model was slightly increased and some detailed shapes were altered when comparing to the optimized-topology one.

![Interpretation](image)

**Figure 4.** (a) Optimized-topology result and (b) interpreted model of examined control arm.

### 3.2. TO considering member-size constraint

In this work, it was also aimed to achieve a TO result which could be likely produced by a conventional metal forming. The TO process with consideration of the member-size constraint was thus performed. Hereby, the same objective function was kept, in which the minimization of compliance for all load cases without weight restriction. The effect of given member-size on the optimized topology was initially studied and the results are shown in Figure 5. Hereby, the pre-defined
member-size was varied between 6 mm and 18 mm. It is seen that the obtained topologies were significantly changed in dependence on the applied member-size. These resulted topologies could be classified into 5 groups, designated by a number in the circle. When such rather large member-sizes were defined, the results were converged to a typical optimized topology without constraint, in which the most significant load carrying path of the control arm could be taken into account. The large member-size condition provided more freedom to generate the most optimum topology without size restriction. By giving smaller member-sizes, the size and thickness of continuous bulk regions in the topologies became smaller. In this case, the typical optimized layout could no longer be generated, while it was still attempted to maintain slightly inferior areas for the load carrying path. Finally, the results were considered as failed if the defined member-size was smaller than the used mesh size. Hereby, the resulted topologies showed many unconnected members and regions and thus could not be utilized. For this work, the results of the third group in Figure 5 were used, since the generated regions were mostly connected corresponding to the calculated loading path and exhibited appropriate thickness that could be further interpreted as a sheet metal component. It is noticed that there were a few number of small unconnected areas which were then neglected. For the interpretation step, the outline of optimized topology model from the third group was applied to generate a sheet metal-alike model, in which all discontinuous surface areas were combined. The member-size between 11 mm and 13 mm was eligible for the member-size constraint of the TO in order to obtain an optimized design of the examined control arm for sheet metal forming.

![Figure 5. Results of optimized topology using various member-sizes.](image)

Figure 6(b) depicts the resulted control arm which was interpreted as a sheet metal-alike shape with the thickness of 3 mm in comparison with the optimized-topology result by using the member size of 12 mm shown in Figure 6(a). The final weight of the interpreted control arm with consideration of the member-size constraint of 12 mm reached about 68 percent of that of the base-line model. It was observed that the generated areas in the optimized model using the member-size constraint were restricted to many small members due to the given minimum size. Such thin sheet regions in the middle of the optimized model were considered during the interpretation, because they represented the intermediate densities close to 1 that were significant for the load bearing capacity. In addition, such member-size constraint could lead to a design with an increased weight. For example, the optimized model in Figure 6(a) exhibited around 20 percent mass increase from the base-line model. Nevertheless, the gained weight could be reduced during the interpretation, in which the thickness of sheet was appropriately defined.
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Figure 6. (a) Result of optimized-topology using 12 mm member size and (b) sheet metal-alike interpreted model of examined control arm.

4. FE analyses for evaluating the performance of results

In order to assess the performance of the sheet metal-alike model, optimized model without using the member-size constraint and base-line model, maximum deformation and distribution of equivalent stress of the respective control arms under different load cases from the FE simulations were compared. Figure 7(a), 7(b) and 7(c) illustrate the equivalent stress distributions predicted by the FE analyses of the control arms based on the sheet metal-alike model, optimized model without manufacturing constraint and base-line model, accordingly. It was obvious that the base-line model exhibited the highest stress concentration, while the sheet metal-alike model achieved the lowest stress peaks for all loading conditions. The optimized design without using the member-size constraint showed the intermediate stress peaks between other both models. The critical sites on all three control arms under each load case were not the same that was directly affected by their geometries.

![Figure 7](image)

Figure 7. Equivalent stress distributions of (a) the sheet metal-alike model, (b) optimized model without consideration of the member-size constraint and (c) base-line model calculated by FE simulations.
The performances of the control arm designs subjected to the varying load conditions were compared in term of the calculated maximum deformation and stiffness, as shown in Figure 8(a) and 8(b), respectively. It can be seen that the TO results using the member-size constraint or the sheet metal-alike model exhibited significantly lower maximum displacements as well as higher overall stiffness values than the other models. However, the weight of this model was somewhat larger than that of the optimized model without using the constraint. The optimized model without the manufacturing consideration exhibited the lowest mass. However, its maximum displacement was lower than that of the base-line model in the case of the load case 3 and 4 that implied a higher overall stiffness. It seemed that the base-line model was still an acceptable design when both mass and performance regarding the minimum compliance were taken into account. The member-size constraint could be applied during the TO process in order to obtain a sheet metal-alike result. It must be also noted that the balance of achieved weight and stiffness depended strongly on the interpretation procedure that might be manually adjusted by the designer.

Figure 8. (a) Maximum deformation and (b) overall stiffness values of the examined control arms based on different designs predicted by FE analyses.

5. Conclusion and remarks
- By using the weighted objective function regarding different load conditions, the TO results without manufacturing constraint could achieve the control arm with a significant weight reduction.
- The member-size constraint provided the TO result, which could be more simply interpreted as a sheet metal-alike model. Its overall compliance was also greatly enhanced. Nevertheless, the final weight was still higher than that of the optimized model without the constraint. In addition, the given member-size strongly affected the obtained TO results and should be precisely investigated.
- The introduced approach can serve as a practical guidance for attaining a TO design for further manufacturing by conventional metal forming.

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