Shape optimization of a control arm produced by additive manufacturing with fiber reinforcement

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Abstract. Additive manufacturing makes possible to overcome the limitations of subtractive manufacturing and supposes a transformation with respect to the traditional processes, allowing to manufacture complex geometries by controlled deposition of material. In the automotive industry, the application of continuous fiber reinforcement, in combination with shape optimization for additive manufacturing, can produce parts with higher mechanical performance. This paper reports the shape optimization problem of a suspension control arm to be produced by additive manufacturing with fiber reinforcement, using finite element analysis. First, the current material, loading conditions and constraints to which the control arm is subjected were determined, considering its traditional design. Then, a numerical model of the part was developed considering its current material and shape to obtain the total deformation and von Mises stress distributions. Afterwards, the new material model was defined, and the shape optimization was performed with the goal of maximizing stiffness. Finally, the results from the optimization process were validated by manufacturing and testing the part.

1. Introduction
In industry, casting, plastic deformation and material removal operations are commonly used for manufacturing, these are the most traditional processes. However, many component designs of different products that are currently commercialized are limited by traditional manufacturing. It does not allow design flexibility since it cannot achieve complex shapes. Some complications presented in subtractive manufacturing are the need for fixtures, diverse tooling, the possibility of collisions, and difficulty of the cutter in reaching deeper and invisible zones [1]. Other traditional processes, including forming techniques, impose additional design constraints to those inherited by the subtractive techniques used to fabricate the required tools and patterns [2]. This means that custom designs could be expensive and difficult to manufacture.

However, the development of additive manufacturing (AM) makes possible to overcome limitations and supposes a transformation with respect to the traditional processes, adding material exclusively where it is necessary. This technology is changing the way products are designed and manufactured. It favours the creation of innovative products and makes possible the fabrication of new shapes and complex geometries with customizable material properties [3], such as those resulting from shape or topology optimization [4].
Shape optimization techniques seek to obtain the lowest possible weight, often performing a finite element analysis (FEA) to search in the solution space the optimal configuration. The FEA together with optimization procedures generates superior part designs [5,6]. Therefore, AM opens the possibility of rethinking the designs of products, in order to decrease their weight and save material. This manufacturing process is attractive to weight sensitive applications at industries such as aerospace, automotive, sports, among others.

In the process of redesigning structural or machinery components, it is essential to consider the importance of material strength, so that the parts can fulfil their function. Composites materials allow to combine the properties of various materials by synthesizing a new material with better properties [7], these materials potentially expand the use of AM. In the case of materials with fiber reinforcement, it is important to take into consideration the proper fiber placement, fiber size, and the correct selection of materials, aspects that significantly influence at the time of manufacturing and testing [8].

The use of composite materials with continuous fiber reinforcement can produce more satisfactory results than short fiber [9], generating parts with a higher-grade design and improved functionality. An AM technology developed by Markforged [10] allows using continuous fiber reinforcement in fused deposition modelling (FDM). The mechanical properties of 3D printed parts made with this technology have been evaluated, and simple models have been proposed to predict them [11]. Other researchers studied failure modes and damage [12], as well as other properties like interlaminar shear strength [13], and effects of part orientation, number of fiber layers, and fiber layer proximity [14].

This paper aims to perform the shape optimization of a suspension control arm using FEA, in order to be produced by AM with fiber reinforcement. Early adoption of technical innovation represents a competitive advantage for developing countries. In this context, AM poses a shift in machine design that could impact many industrial sectors. Initially, the current material, loading conditions and constraints to which the control arm is subjected were determined, taking into account its traditional design. Secondly, the analysis of the part was developed considering its current material and shape to obtain the total displacement and von Mises stress distributions and their maximum values. Then, the new material model was defined, and the shape optimization was performed with the goal of maximizing stiffness. Next, the results from the optimization process were validated by manufacturing and testing the printed part. Finally, conclusions were formulated.

2. Materials and methods

2.1. Current control arm model

The suspension system of a buggy car, Figure 1(a), was taken as a reference for the study. This system was analysed to obtain the forces on the lower control arm, for the calculation of stress and displacement fields with its current design using Ansys v18.1. The geometry used to study the current model can be seen in Figure 1(b). The material of the control arm was steel, one of the most used to build this mechanical part in commercial automobiles.

FEA requires the appropriate definition of boundary conditions and mesh for optimal solution [15]. The Neumann and Dirichlet boundary conditions corresponded to the loads applied to the control arm and its supports, respectively. To obtain the reactions forces in the component that was analysed, a kinetic analysis was performed using SolidWorks Motion complement. In this process, the following parts of the system were modelled: the upper control arm, the lower control arm, the spring shock absorber, and the ball joints.

A quarter-vehicle model was taken into account to perform the study since it is a simple model but widely used in suspension design [16]. The assembly shown in Figure 1(b) was used to calculate the reactions in the lower control arm. In this case, the spring shock absorber is not connected to the lower arm as usual, but to the upper one. An upward vertical force of 1125 N was applied in the middle of the steering knuckle, this magnitude corresponds to a quarter of the weight of the vehicle (including passengers). For the simulation, the spring stiffness used was 30 N/mm and the damping coefficient of
the shock absorber was 0.22 Ns/mm. The forces calculated were the reactions on the lower control arm due to the contact with the ball joint.

![Figure 1. Real (a) and modelled (b) suspension systems.](image)

Through the kinetic analysis, graphs that show the variation of the components of the force with respect to time were found. Since the force was not constant, two analyses were carried out. The first one for the initial time and the second one for the steady state. For the FEA, the supports taken into account for both analyses were cylindrical supports. These supports avoid rigid body motion in the static structural analysis that was performed.

2.2. Topology optimization of the control arm
To find an optimal shape for the suspension control arm, an oversized model was designed, and its stress distribution was calculated. This geometry was used to carry out the topology optimization, eliminating areas with low stress. Then, the optimized model was analyzed.

Initially, the material and geometry of the control arm were defined. The material selected was nylon and the mechanical properties are presented in Table 1. As this part is to be built by AM, with a triangular filling pattern and 37% filling density, these properties do not correspond to the nylon filament. For the calculation of the properties, tensile values obtained in previous studies were taken as reference [17]. In this way, interpolations were made between the values of 20% and 50% for a triangular pattern, and the properties for 37% filling density were obtained.

| Property               | Value         |
|------------------------|---------------|
| Tensile ultimate strength | 18.50 MPa     |
| Young’s modulus         | 248.50 MPa    |
| Poisson’s ratio         | 0.47          |
| Bulk modulus            | 1294 MPa      |
| Shear modulus           | 84.60 MPa     |

The boundary conditions for the optimization process had to be selected either from the first analysis or from the second one. Then, the most critical condition was chosen. Additionally, an optimization region, objectives and constraints were defined. The optimization region was the complete body excluding the areas where the boundary conditions were applied. The objective was to minimize compliance and the constraint was a mass reduction to reach 30% of this.

After carrying out the optimization, a faceted body is generated. For the analysis of the optimized model, a reconstruction process of the faceted geometry was carried out to generate a simpler solid body and facilitate the obtaining the stress and displacement distributions. This reconstruction was carried out from the profiles of the cross sections of the faceted body that resulted from the optimization.
2.3. Manufacturing and validation
The optimized control arm was printed with continuous fiber reinforcement using the Mark Two © Markforged printer. The material selected for the matrix was nylon and fiberglass for the reinforcement. Fiberglass helps to increase the strength and the stiffness of the part. Besides, it is the most effective material considering its cost, compared to carbon or Kevlar reinforcement.

Four fiberglass layers were added in the control arm. The printing parameters used are presented in Table 2. The control arm was divided into two parts since the build volume of the printer was not large enough. Then, they were joined with the Loctite® 401 instant adhesive. The orientation of the fibre is illustrated in Figure 2. Two of these layers of fiber were located on the top of the arm and the other two on the bottom, next to the roof and floor layers. These areas were chosen because they were the most loaded, where a large amount of material was required, according to the topology optimization. Metal inserts were used to reduce wear due to friction with the other parts of the vehicle.

After printing the two parts of the control arm, joining them and introducing the inserts, the validation of the design was carried out. For this, the printed control arm was tested in the buggy car by assembling it on the suspension system.

| Parameters          | Setting          |
|---------------------|------------------|
| Filling pattern     | Triangular       |
| Filling density     | 37%              |
| Roof and floor layers | 4               |
| Wall layers         | 2                |
| Total fiber layers  | 4                |
| Fiber fill type     | Isotropic fiber  |
| Concentric fiber rings | 3               |

Figure 2. Fiber orientation for the (a) left and (b) right parts.

3. Results

3.1. Current control arm model
The results of reaction forces in the lower control arm are shown in Figure 3. As expected, the forces in the z-component were the most significant, and the x-components were almost nil, although, all of them were low. The resultant forces used for the first and the second analyses were 68.9 N and 82.6 N, respectively.

From the two analyses, the first was the most critical since it had higher stress and displacement values, see Figure 4(a) and Figure 4(b). The equivalent von Mises stress distribution resulted from the first analysis had a maximum value of approximately 22 MPa, and the maximum total displacement was approximately 5E-5 m.

3.2. Topology optimization of the control arm
As previously mentioned, in order to carry out the process of shape optimization, an oversized control arm was designed to later remove the zones that presented low stresses. Figure 5 shows the equivalent von Mises stress of this oversized part, the maximum value was near 3 MPa. To achieve the optimal shape, it was necessary to perform 29 iterations. The result obtained from the optimization process is shown in Figure 6.
Figure 3. x, y and z-component of the force due to the contact with the ball joint.

Figure 4. Stress (a) and total displacement (b) distributions of the first analysis of the current model.

Figure 5. Stress distribution of the oversized model.

Figure 6. Optimization result.

The geometry resulting from the topology optimization was post-processed to obtain a non-faceted reconstructed geometry, which facilitates the design and manufacture of the final prototype. When analyzing the optimized reconstructed geometry, both the stress and the total displacement fields were calculated. The equivalent von Mises stress distribution is shown in Figure 7(a) and total displacement in Figure 7(b). The maximum stress was 2.7 MPa and the maximum displacement was 9.3 mm. Therefore, with respect to the current control arm model, the difference between the maximum stress values is not significant, but greater differences are observed in terms of total displacement.

Figure 7. Stress (a) and total displacement (b) distributions of the optimized model.
3.3. Manufacturing and validation

The optimized geometry was manufactured by AM in nylon reinforced with fiberglass, using the parameters in Table 2. The printed parts in which the control arm was divided are shown in Figure 8. The printings were satisfactory although the dimensions were not accurate, especially those of the holes. It was also observed that in the areas where support material had to be removed, the quality of the surface was rough. Table 3 presents the details of each of these parts.

![Figure 8. Parts of the printed control arm.](image)

| Table 3. Printed parts details. |
|----------------------------------|
| Part detail | Part 1 | Part 2 |
| Print time  | 19h 59m | 19h 35m |
| Material cost | 24.49 USD | 23.77 USD |
| Mass of part | 84.41g | 82.12g |
| Plastic volume | 100.07 cm³ | 97.44 cm³ |
| Fiber volume | 2.23 cm³ | 2.12 cm³ |

The final printed control arm (after joining the two parts and introduce the brass inserts) is presented in Figure 9(a). The weight of this final part was 216 g, which is significantly lower compared to the 835 g of the steel control arm. The assembled suspension of the buggy car with the printed part can be seen in Figure 9(b). The control arm was mounted easily in the suspension, its dimensions were adequate for normal operation and to keep the wheel in vertical position. No failure was observed in the part. Figure 9(c) shows the control arm after the test.

![Figure 9. Printed control arm (a) before, (b) during and (c) after the test.](image)

4. Conclusions

In the present work, the topology optimization of a lower control arm of a buggy car produced by AM was performed. First, an FEA of the lower control arm of the suspension system was done to obtain the stress and displacement fields. For this purpose, the forces on the lower arm were calculated using a kinematic model. The resulting loading conditions were low, the maximum force was near 83 N and, therefore, there were also low stresses, close to 20 MPa. These results showed that it was feasible to optimise the shape of the arm to save material and lighten the part. Additionally, regarding the material, a change from steel to a reinforced composite printed by AM was proposed.

The optimization process was carried out for the control arm using topology optimization. The stress values were decreased from 20 MPa to almost 3 MPa, and a reduction of almost 75% of its weight was achieved, compared with the initial steel configuration. In terms of automotive parts, this means lower consumption of energy by the vehicle, requiring less fuel. Therefore, this manufacturing process together
with the topology optimization approach can yield significant weight reductions and also high values of strength when incorporating fiber.

On the other hand, it would be appropriate to deepen more in the study of the loads to which the part is subjected, since in this study only the weight of the vehicle and passengers was taken into account, but there are other conditions that may also affect the part.

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