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Finite element analysis study: Topology optimization for the front lower arm with innovative double and complex phase materials

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Abstract

Suspension systems used in vehicles are an important factor affecting comfort, safety, and vehicle performance. These systems are effective in the vehicle's total weight and fuel consumption. However, while lightening the weight, it should also be ensured that the strength is within safe limits. For this purpose, dual-phase (DP) and complex-phase (CP) steel materials were used. In the study, the topology optimization of the front lower suspension arm, designed for a light commercial vehicle, was carried out with the finite element method. As a result of the topology optimization, the weight was reduced by 7.5% compared to the current design, while maintaining the safe strength values. This result will significantly contribute to reducing material costs by using dual-phase (DP) and complex-phase (CP) steel materials, reducing exhaust emissions by lightening vehicle weight, and developing more sustainable designs.

Keywords: Finite element method, Automotive, Topology optimization, Lower control arm, Suspension system

1. Introduction

Depending on the developments in computer systems, there are many studies on topology optimization with the finite element method and saving in terms of material, time, and weight [1–3]. This method is preferred in almost every field, especially in the manufacturing industry, space and aviation, medical and defense industries. In topology optimization studies, besides creating innovative designs, it is aimed to develop light, aesthetic, and easy-to-manufacture products [1], [4].

To make an effective topology optimization, first of all, it is necessary to know the place of use and material class of the steels in the vehicle [5]. Steels used in the vehicle are hardenable, high strength and low alloying (HSLA) steels, and Advanced High Strength Steels (AHSS) [6]. In Figure 1, conventional and dual-phase high-strength steels used in the automotive industry and the corresponding elongation-tensile strength graph are shown.

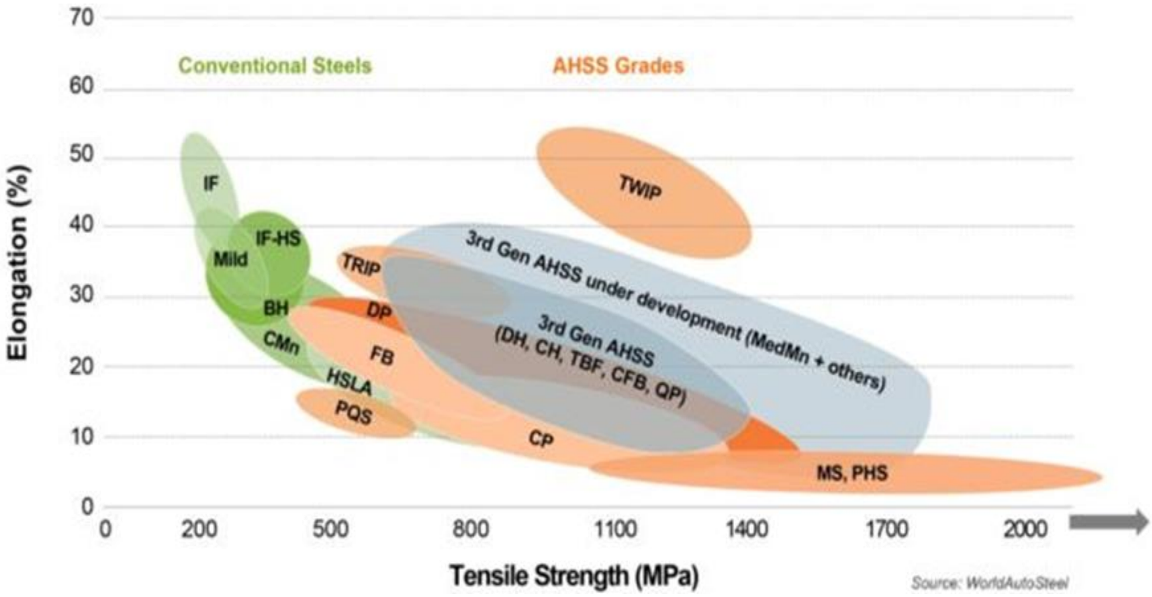


Figure 1. Conventional and dual-phase high-strength steels used in the automotive industry and the corresponding elongation-tensile strength graph [6]

The lower suspension arm is an important element that is used in suspension systems and transfers the maximum load that occurs under working conditions to the lower arm [3]. Therefore, analyzing and interpreting the stress distribution in the lower suspension arm will affect the success of the study.

In studies on topology optimization, it has been stated that after applying the optimization, parameters such as total deformation, von Mises stress, maximum shear stress, and weight will be reduced compared to the previous study [7], [8]. In the studies conducted to investigate the effect of different materials during the topology optimization, the finite element method was used and as a result, it was emphasized that it provided cost savings and improved material quality [3],[9]–[11].

In the article study, the lower suspension arm model was designed for 4 different materials using Ansys software and it was aimed to optimize the topology with the finite element method. As a result of the study, it is aimed to obtain a lighter, more durable, and cheaper product compared to the existing system. Figure 2 shows the suspension arm and connection types used in a light commercial vehicle designed to be examined in this study.

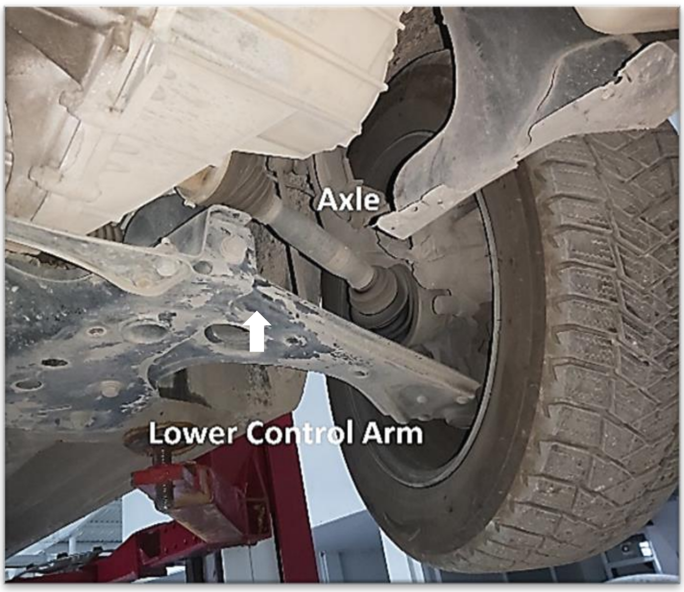


Figure 2. Lower suspension arm, axle, spring, and front wheel connection

In the suspension system, topology optimization is generally applied under static load conditions [4]. In this study, a numerical analysis was carried out in order to reduce the weight of the lower suspension arm of a light commercial vehicle using the topology optimization method. Topology optimization was made with the finite element (SE) method and applied to the front lower suspension arm design. In the research, topology optimization was made using EN24, CP700/800, CP800/1000, and DP980 steel materials, and the weight was reduced without reducing the current strength.

2. Materials and method

In this study, computer-aided design (CAD) and computer-aided analysis (CAE) methods including finite element method were used. In Ansys software, design changes were made using the CAD file obtained after topology optimization. Meanwhile, in order to create a continuous and homogeneous structure, the geometries obtained as a result of the optimization were converted into smooth geometries, and the analyses were repeated. As a result of the analysis, optimum geometry, and structures were obtained after the topology optimization.

While performing topology optimization, different road conditions are taken into account, and analyses are performed for these conditions. In general, 13 different road conditions are defined that affect the movement of the vehicle [12]. Generally, the first and second road conditions of these road conditions are taken into account. It is defined as the static weight of the vehicle and its condition in stationary conditions (first road condition) and the maximum load condition when the vehicle passes through the ditch (second road condition). In the case of the first road condition, the total load is determined by considering the weight of the vehicle and the contact points of the wheels with the ground [13]. The boundary conditions used in the analysis for the first path condition are shown in Figure 3.

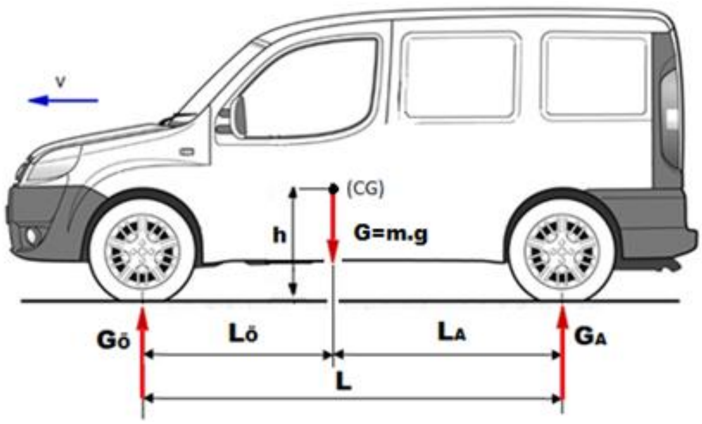


Figure 3. Boundary conditions used in the analysis for the first path condition

In the case of the second road condition, the condition of the vehicle passing through the ditch was taken into account, and analyses were performed for acceleration of 3g. This road condition, which is called the second road condition, has been preferred because it includes the most severe conditions among a total of 13 road conditions. Ga and Go represent the reaction forces acting on the wheels from the ground. An example calculation for these two parameters is given below formulas as an Equations 1 and 2.

$$G = m \times g \tag{1}$$

$$G_A = (m \times 3g \times L\ddot{o}) / L \tag{2}$$

The model shown in Figure 3 was used while calculating the force acting on the lower suspension arm.

The types of materials used in the article and their properties are shown in Table 1. These materials are AHSS group materials and are called first generation materials.

Table 1. The material properties of the lower suspension arm used for the SE analysis in the article study are given [6], [10], [14]

Material Properties	Material types (AHSS group 1st generation materials)			
	EN 24	DP 980	CP 700/800	CP 800/1000
Modulus of elasticity (GPa)	2,1 x 10^5	2,1 x 10^5	2,1 x 10^5	2,29 x 10^5
Poisson's ratio	0,3	0,3	0,3	0,3
Yield strength (MPa)	680	720	720	845
Compressive strength (MPa)	680	720	720	845
Max. tensile strength (MPa)	850	1030	845	1005
Density (kg/m3)	7840	7860	7850	7850

2.1. Computer-aided design (CAD)

To create the CAD designs, a sample lower suspension arm used in the market was taken and modeled in Solidworks software. For this model, the current strength and weight values that should be in the light commercial vehicle have been determined.

2.2. Finite element method and computer-aided analysis (FEM, CAE)

Static analysis of a complex structure can be performed using the SE method. Formulations developed for analysis are partially found in the literature [11]. In the article study, the loads on the lower suspension arm were calculated for the size and loading condition given in Figure 4.

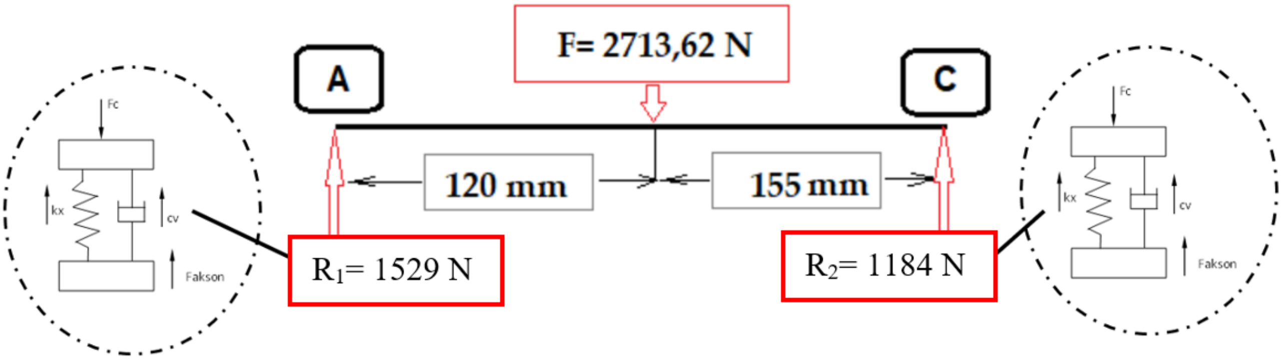


Figure 4. Schematic representation of force distribution (free body diagram)

$$F_{max} = \sqrt{(kx)^2 + (cwx)^2}\ , \ F_{max} = x\sqrt{(k)^2 + c^2w^2} \quad (3)$$

$$\text{Permeability} = \frac{k^2+c^2\omega^2}{\sqrt{(k-m\omega^2)+(r\omega^2)}} \quad (4)$$

ω = Frequency of driving force, k=Spring coefficient, c=Damping constant, Faxon= Reaction forces of R1 and R2

ω_n = Natural frequency

$$\omega_n = \omega_n = \sqrt{\frac{k}{m}} = 2\pi f_n \quad (5)$$

$$\omega = \frac{\pi n}{30} = engine\ speed \quad (6)$$

Permeability indicates how much of the total weight force is transferred to the suspension arm. Formulas used to calculate the load on the suspension arm are given in Equations 3, 4, 5 and 6.

Depending on the road conditions, the loads on the suspension arm vary according to the stationary vehicle and passing through the obstacle. Table 2 shows the variation of load conditions depending on the road condition.

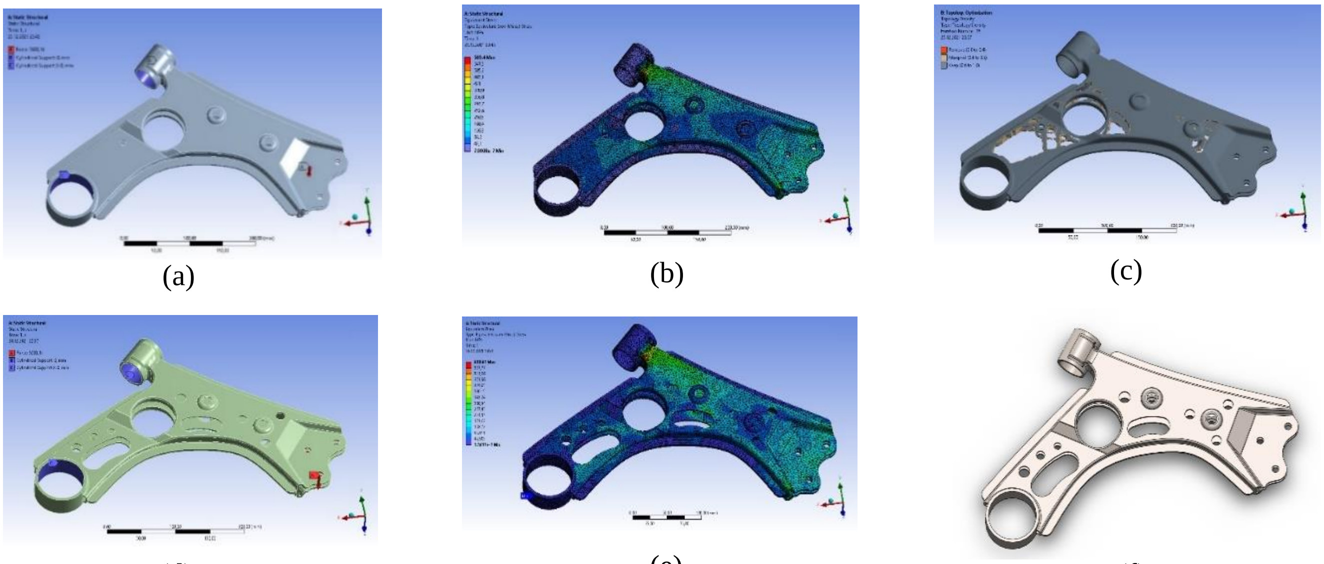
Table 2. Some standard load types used by vehicle manufacturers [12]

Standard Load Cases		Acceleration (g)		
		x	y	z
1. Road condition	Stationary vehicle	0,00	0,00	1,00
2. Road condition	Crossing obstacle (vertical direction 3,00 g)	0,00	0,00	3,00

2.3. Topology optimization

Today, topology optimization has become a necessary method in order to reduce weight, exhaust emissions and save fuel.

The data obtained as a result of the topology optimization was rearranged and the lower suspension arm was modified. Structural analyzes were repeated on this new model and the suspension arm model was given its final shape. Figure 5 shows the topology optimization steps for the lower suspension arm.



(a) (b) (c)

(d) (e) (f)

Figure 5. Topology Optimization Stages for the Lower Suspension Model
a) Boundary conditions, b) Static analysis c) Ansys topology optimization, d) Improved model e) Application of static analysis on the new model f) Final model

In Figure 6, the initial state of the CAD model and the model obtained after optimization are shown.

(a) (b)

Figure 6. Lower suspension arm models a) first model b) final model obtained after topology optimization

3. Results and discussion

3.1. Effect of material type on topology optimization

The most important parameter for part design and topology optimization studies is the strength of the steel. Although many different types of steel are used in the automotive industry, it is seen that HSLA and AHSS steels are used more widely [15]. There are some fundamental differences between HSLA and AHSS steels used in the automotive industry, one of which is their microstructures [16]. AHSS steels contain multiphase microstructures as well as ferrite, pearlite or cementite phases. It is seen that multiphase microstructures have different mechanical properties [17], [18]. AHSS steel types have mechanical and physical properties superior to conventional steel. In addition, there are varieties with very high yield and tensile strengths and oven-hardening behavior [6].

Based on the literature information used in the study, static analyses were made on the complex-phase (CP) and dual-phase (DP) steel types in the 1st generation AHSS steels, and topology optimization was applied. In the study, the steel types and topology parameters used in the suspension arm were changed, the appropriate places were emptied and weight reduction was achieved. The high strength values of complex-phase and dual-phase steels, as well as the advantages of lightness, are of particular importance for developing automotive technology [16].

3.2. Cost comparison

As the lower suspension arm material, some series of complex-phase steel and dual-phase steel were preferred in the analysis depending on the road condition. DP600, DP800, and DP1000 steels are widely used in today's automotive industry [19].

Complex-phase steels have higher formability than dual-phase steels and contain some bainite as well as martensite and ferrite phases. The strength values of complex phase steels are between 800 MPa and 1180 MPa. In terms of cost, DP980 dual-phase, CP700/800, and CP 800/1000 complex-phase steels were preferred for suspension arm topology optimization due to reasons such as material type, weight reduction, and unit price effect. As indicated in Table 3, it is seen that it is cost-effective to use high-strength steel instead of cast iron, mild steel, or aluminum.

Table 3. Weight reduction and unit price comparison of light automotive materials [20]

New material	Available material	Weight reduction (%)	Unit price (Per piece)
High Strength Steel	Mild Steel	10-25	1
Aluminum	Steel, Cast Iron	40-60	1,3-2
Magnesium	Steel or Cast Iron	60-75	1,5-2,5
Magnesium	Aluminum	25-35	1-1,5
Glass, FRP, Composite	Steel	25-35	1-1,5
Carbon, FRP, Composite	Steel	50-60	2-10+
Al matrix, Composite	Steel or Cast Iron	50-65	1,5-3+
Titanium	Alloy Steel	40-55	1,5-10+
Stainless Steel	Carbon Steel	20-45	1,2-1,7

3.3. Coefficient of safety and comparison of stress values

First of all, a large material list was created for the lower suspension arm material. Depending on the first road condition of the vehicle, approximately 10 material types were used at 1200 N. These materials are AISI 1040, CP 350/500, CP700/800, CP800/1000, DP600, DP780, DP 980, EN24, Fe590, HSLA550 and FB600. Many static analyses have been applied for the first and second path conditions in the determined materials and it has been seen that the materials are suitable in terms of topology optimization. Ansys program topology optimization module is used for the second path condition. When the analysis results are examined, it is seen that the yield values of these materials are slightly above the reference values. At full load, in case of vertical acceleration of 3g and a force of 3600N, it has been deemed appropriate to use EN 24, DP 980, CP 700/800, and CP 800/1000 materials.

As a result, DP980 and CP 700/800 materials have taken acceptable values considering their safe stress values. Since the yield strength of the CP 800/1000 material is around 845 MPa, the safety factor was found to be the highest. According to the analysis results, although the safety values of EN 24 material are low, it meets the desired safety values in terms of the safety coefficient in case of maximum load with a vertical acceleration of 3g.

The von Mises stress values before and after the topology optimization according to the material type used in the lower suspension arm model are given in the graph in Figure 7. Looking at the graph, it is seen that there is no significant increase in stress after optimization and the factor of safety remains at the same levels. This shows that the topology optimization is achieved by unloading from the most suitable regions, depending on the geometry of the model. In both cases before and after topology optimization, the same type of steels with high yield strength were used.

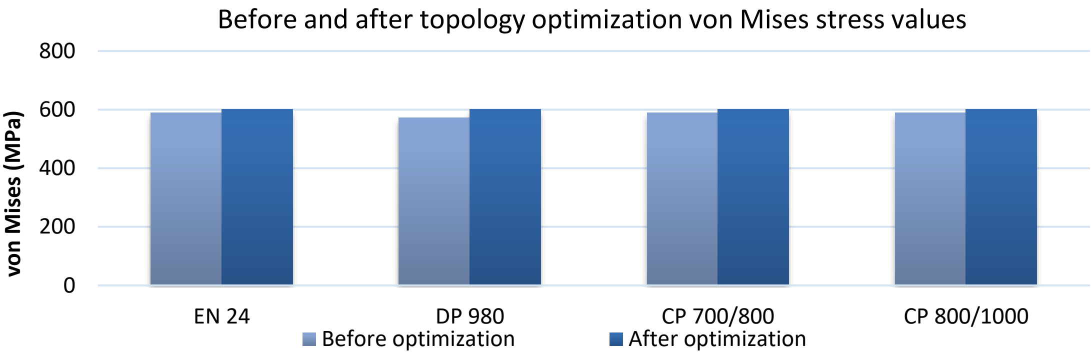


Figure 7. Von Mises stress values before and after topology optimization

4. Results

When the analysis and topology studies were examined, it was observed that the bushings placed during assembly were not used, and only the topology optimization of the body part was made [2]. It was observed that the suspension arms used mostly in passenger cars were taken as a reference in topology optimization studies. Complex-phase (CP) and dual-phase (DP) steel material types used for analysis and topology optimization are steel materials that are being used abroad but have just begun to be used in our country. The proposed CP700/800 and DP980 dual-phase steel material is cheaper and has higher strength than existing materials [16], [19]. Therefore, the use of innovative materials provides multiple benefits by increasing product durability while reducing cost and weight. In Figure 8, the geometry of the lower suspension arm is given before and after the topology optimization.

a)

b)

Figure 8. Lower suspension arm design, a) Before optimization, b) After topology optimization

As a result, the advantages of lightness besides the high strength values of complex-phase (CP) and dual-phase (DP) steels are of particular importance for developing automotive technology. The 7.5% weight reduction obtained after optimization shows that these material types will be preferred more in the automotive industry in terms of fuel savings and reduction of emission values. This allows car manufacturers to reduce vehicle weight while maintaining safety standards. In addition, it is known that it allows for to reduction of fuel consumption and exhaust emissions.

By using the data obtained from the analysis results (border conditions, material types, static load conditions, mesh modeling, topology optimization, etc.), this information is given in detail in the study as a reference to the companies that produce the lower suspension arm. Parameters such as cost, machinability, and weight reduction were evaluated as a separate procedure to determine the economic gains. The proposed CP700/800 and DP980 dual-phase steel material is 76.8% cheaper and has 4.8% higher strength in terms of strength compared to the currently used materials. The use of dual-phase materials provides many benefits by increasing product strength while reducing cost and weight. These values are shown numerically in Table 4.

Table 4. Comparison of cost, strength, and weight for CP700/800 and DP980 dual-phase steel material

Parameters	Before Optimization	After Optimization	Difference (%)
Cost decrease (unit)	500	116	76,8
Strength increase (MPa)	571,75	600,67	4,8
Weight reduction (g)	2985	2760	7,5

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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