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Lightweight Frame Topology Optimization Method Based on Multi-objective

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Abstract: The application of new materials is an important direction for automotive lightweighting. On the basis of ensuring the comprehensive performance of components, the optimization of new material structures through topology optimization methods can further improve the level of lightweight components. This paper takes the automobile frame as the research object, based on the magnesium alloy, studies the frame topology with the objective function of mass and strength under multiple working conditions, and realizes the lightweight of the automobile frame structure through the multi-objective topology optimization method. According to the topological optimization method of penalty function for solid isotropic materials, the objective function of the quality topology optimization and the objective function of intensity topology optimization under multi-operating conditions are defined by the compromised programming approach. This method avoids the disadvantage that single-target topology optimization cannot consider other factors and is suitable for multi-objective topology optimization of continuum structures.

Key words: Frame, multi-objective topology optimization, magnesium alloy, lightweight.

1. Introduction

In recent years, the crisis of energy and the environment has accelerated the strict control of national governments' energy consumption and emissions from the automotive industry with the continuous development of modern industry. By 2020, the fuel consumption of passenger vehicles in countries and regions other than the United States will be strictly limited to 5 L/100km and the carbon emissions will be more stringent (domestic at 2020). The use of national VI emission standards will force the lightweight design of automobiles to become one of the necessary ways to improve energy consumption. The future direction of automotive lightweighting includes the systematic design and integration of optimized design methods for automotive structural parts, multi-material integration, and lightweighting technologies. Therefore, the use of modern optimization methods to improve the design of automotive lightweight structural parts can achieve multiple goals of reducing vehicle energy consumption, reducing emissions and improving the overall performance of the vehicle [1-3].

In the early conceptual design process of mechanical structures, given the design goals and constraints, finding the best and most likely product topology or material layout is very important for the development of new products. The topology optimization of the continuum structure can provide designers with a conceptual design scheme at the initial stage of the engineering structure design, so that the structure can be optimized in terms of layout, thereby changing the previous design, verification, and revision of an ever-repeated development process. Compared with structural optimization and shape optimization, topology optimization of continuum structures can achieve greater economic benefits. It is considered to be a more challenging field and has become a popular topic in structural design research today.

This article focuses on the lightweight of the

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automobile frame, applies the topology optimization theory, and studies the lightweight structure of the automobile. Through the rational and accurate design of the structure, the main bearing components of the automobile frame are optimized and strengthened, and the strength is satisfied. At the same time, the size of the cross-section is reduced, material thickness is improved to achieve lightweight design.

2. Multi-objective Topology Optimization Theory Setup

The most common topology optimization is the variable density material interpolation method, which includes SIMP and RAMP. The theory of variable density is to convert the discrete optimization problem into a continuous optimization problem by introducing an intermediate density unit. In reality, the intermediate density unit does not exist and cannot be manufactured. Therefore, the intermediate density unit should be reduced as much as possible, the number of which needs to be penalized only for the intermediate density that appears in the design variables [4].

The most commonly used material interpolation model method, SIMP formula, is expressed as:

$$E(x_i) = E_{min} + (x_i)^p(E_0 - E_{min}) \tag{1}$$

where E_0 is the initial elastic modulus; p is the penalty factor, $p > 1$; x_i is the density value of the material at i.

2.1 Topology Optimization Function with Quality as Its Goal

Under multiple operating conditions, the topological optimization model of the frame was established with the strain energy as the constrained mass as the optimization goal. At each load condition, a structural strain energy is used to replace all stress constraints on all elements, and the method is used to obtain the strain energy required for the structure. According to the ICM optimization method proposed by YunkangYan [9], for the continuum structure, the Mass is taken as the objective function, and the structure of the individual working conditions needs to be used as the constraint, and the structural topology optimization formula model is shown below:

$$\begin{cases} find\ t \in E^N \\ \min W = \sum_{i=1}^{N} w_i \\ \mathrm{s.t.}\, e_i \le \overline{e_l} \end{cases} \tag{2}$$

$$0 \le \underline{t_i} \le t_i \le 1\ (i = 1, \cdots, N; l = 1, \cdots, N)$$

where t is the element topology design variable vector; E is the elastic modulus; N is the number of unit topology design variables; W is the structural weight; e_i is the strain energy of the i-th cell.

In this paper, under the two working conditions of bending and torsion, and the constraints of each working condition are different, different topology structures are obtained through topology optimization. Therefore, multi-quality topology optimization is a multi-objective topology optimization problem. The traditional multi-objective optimization problem uses linear weighting and the multi-objective problem of the paradigm is transformed into a single-objective problem. However, for the non-convex optimization problem, this method cannot ensure that all pareto optimal solutions are obtained [5]. This question uses the compromise planning method to study multi-objective topology optimization problems. Therefore, the objective function of mass topology optimization under multiple operating conditions is obtained.

$$\min_M C(M) = \left\{\sum_{k=1}^{m} w_k^q \left[\frac{C_k(M) - C_k^{min}}{C_k^{max} - C_k^{min}}\right]^q\right\}^{\frac{1}{q}} \tag{3}$$

where m is the total load conditions; n is the total number of units; w_k is the weight of the k-th working condition; q is the penalty factor, $q \ge 2$; $C_k(M)$ is the quality objective function of the k-th working condition; C_k^{max} and C_k^{min} are the maximum and minimum values of the quality objective function of the k-th working condition, respectively.

2.2 Topology Optimization Function with Intensity as Its Goal

In isotropic materials, Von Mises stress is the most commonly used criterion. For planar problems, Von Mises stress is defined as:

$$\sigma^{\mathrm{VM}} = \left(\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2\right)^{1/2} \quad (4)$$

In the formula, σ_x and σ_y are normal stresses in the x and y directions, and τ_{xy} is the shear stress.

The stress value σ_e^{VM} of each cell will be compared with the maximum value σ_{max}^{VM} of all the stress, and all cells that satisfy the following formula will be retained.

$$\frac{\sigma_e^{VM}}{\sigma_{\max}^{VM}} \geq PP_i \quad (5)$$

where PP_i in the formula is the current deletion rate, which is a gradually changing quantity, and the structure is optimal after multiple iterations. When steady state is reached under the effect of the erasure rate PP_i, an evolution rate EP is introduced to increase the original erasure rate. As shown in Eq. (6), the structure is optimized under the new erasure rate [6]. When the desired optimization goal is reached, stop iterative optimization.

$$PP_{i+1} = PP_i + EP \quad (6)$$

2.3 Multi-objective Topology Optimization Function with Quality and Strength Indicators

In the multi-objective topology optimization of the structure, the stiffness is taken as the constraint, the topological optimization of the quality and strength targets in static multi-operating conditions is also performed. The objective function of multi-objective topology optimization is obtained by combining the third-intensity theory with the compromise planning method:

$$\begin{cases} min\,F(M) = \left\{ r^2 \left[\sum_{k=1}^{m} w_k^q \dfrac{C_k(M) - C_k^{\min}}{C_k^{\max} - C_k^{\min}} \right]^2 + (1-r)^2 \left[\dfrac{I_{max} - I_{(\sigma)}}{I_{max} - I_{min}} \right]^2 \right\}^{\frac{1}{2}} \\ \dfrac{\sigma_e^{VM}}{\sigma_{\max}^{VM}} \geq PP_i \end{cases} \quad (7)$$

where I_{max} and I_{min} are the maximum and minimum stress value of the frame.

3. Multi-objective Topological Optimization Model of Lightweight Frame Structure

3.1 The Establishment of Topology Optimization Model

This research model refers to the subaru-sanba frame model currently on the market for research purposes. This frame is an un-load body. In the original car, components such as engine, steering gear and transmission are mounted on this frame. All parts are connected to the frame through brackets, and the weight of the entire body is loaded on various parts of the frame. This article is to modify the frame on the basis of the original car to meet the strength requirements of new energy electric vehicles. The CAE model of the new energy electric vehicle frame is shown in Fig. 1. This model was divided into 0.5 mm-sized tetrahedral meshes using hypermesh, a total of 32,826 units; it is loaded with 35 kg motor, acting on both sides of the main beam at the rear of the frame; passengers and goods are 350 kg, on the middle of the frame; the body is 150 kg, as indicated by the green arrow in Fig. 2; the support points are the 8 hinges of the triangle in Fig. 2. Detailed loading conditions are shown in Fig. 2.

Magnesium alloy material was selected as the lightweight material of the frame, and referenced to other conventional materials, a multi-objective magnesium alloy frame topology optimization design was carried out to achieve the goal of lightweight frame.

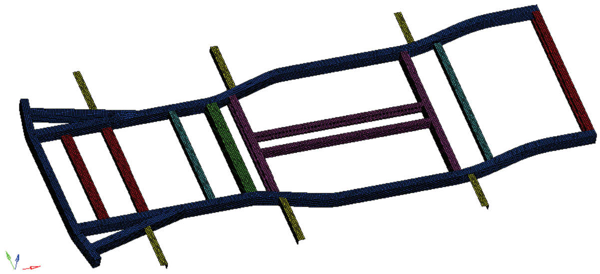


Fig. 1 Frame finite element model.

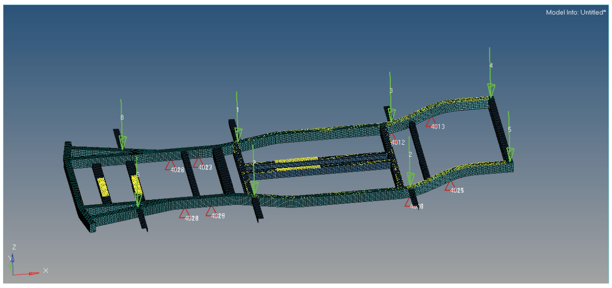


Fig. 2 Load and constraint boundary conditions.

The frame material is the three materials in Table 1. The ultimate goal of this paper is to perform topological optimization analysis of the frame structure under the magnesium alloy AZ91 material, and the results obtained are compared with the strength results and quality results of the current SPFH540 steel and T6061 aluminum alloy materials to achieve the goal of light weighting.

3.2 Frame Topology Optimization Analysis

Taking into account the actual operation of the car, the frame operating modes mainly include bending conditions and twisting modes, showed in Table 2, so in the frame topology optimization design process, we should take into account the impact of the actual operating modes.

4. Lightweight Frame Design Based on Multi-objective Topology Optimization

Based on the multi-objective topology optimization theory and the lightweight frame finite element model, a custom function provided in optistruct is used to define the compromise planning formula and strength theory formula in this paper. The multi-objective topology is proposed by using the custom function in optistruct which is used as an objective function to perform topology optimization. Because the load of un-load body mostly acts on the two main beams of the frame, this paper mainly analyzes and optimizes the section of the main beam of the frame [8].

Table 1 The mechanical properties of Aluminum ,Steel and Magnesium.

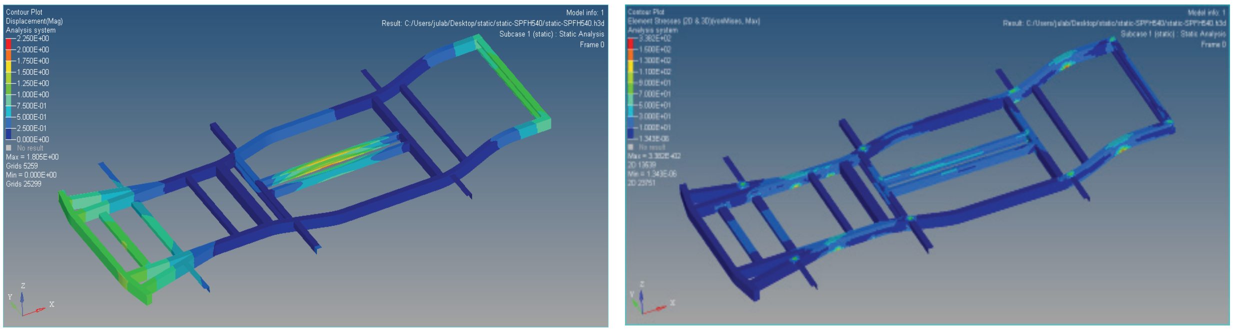
	SPFH540	Aluminum 6061-T6	Magnesium AZ91
Density (kg/m³)	7,850	2,700	1,830
Coefficient of elasticity (GPa)	210	69	45
Poisson ratio	0.3	0.33	0.35
Yield strength (MPa)	355	276	160
Tensile strength (MPa)	540	310	340

Table 2 Constrained position for each working condition[7].

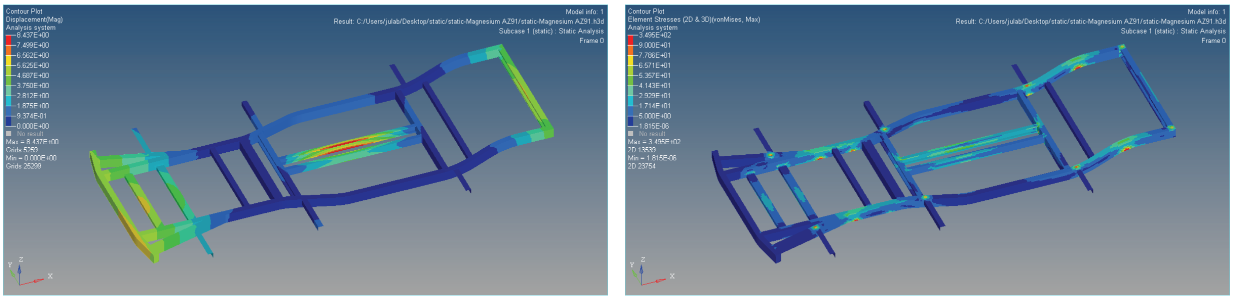
Suspension position	Bending	Torsion
Left front suspension	x, y, z	x, y, z
Right front suspension	x, z	x, z
Left rear suspension	y, z	y, z
Right rear suspension	z	

Table 3 Three kinds of materials analysis results.

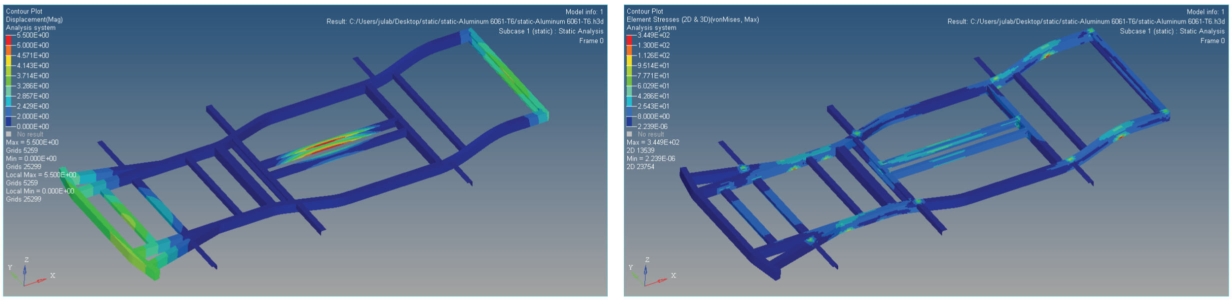
	Spfh540	Aluminum 6061-T6	Magnesium AZ91
Mass (kg)	180	61	42
Displacement (mm)	1.80	5.5	8.43
Stress (MPa)	338.2	344.9	349.5



(a) Displacement and stress of steel



(b) Displacement and stress of aluminum alloy



(c) Displacement and stress of magnesium alloy

Fig. 3 Three kinds of materials analysis results.

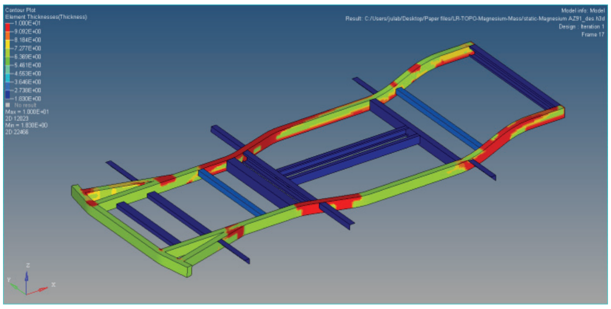
The strength analysis of the above three different materials was carried out and based on the calculation results of Spfh540 steel and T6061 aluminum alloy strength, the design goals of the magnesium alloy frame were determined. Fig. 3 shows the stress and deformation of the three materials. Before optimization, according to the properties of the material, only the Sphf540 steel material meets the requirements in terms of displacement and stress and meets the actual requirements.

Table 3 compares the deformation and stress of the three materials and determines the target values of displacement and stress under magnesium alloy materials.

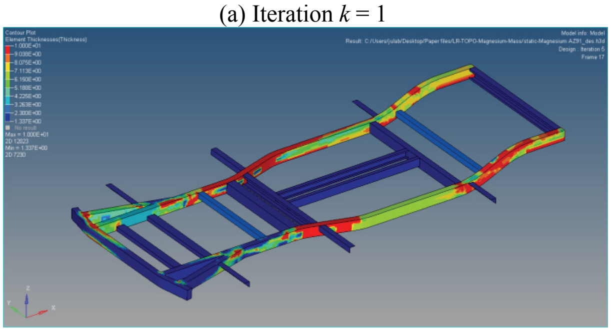
In this study, due to reference to the frame of the existing vehicle model, the optimized optimization function of the optistruct is applied under the cross-sectional conditions of the main beam, and the section of the main frame beam is mainly optimized to achieve the best section size. In the static topology optimization of the frame, two kinds of working conditions are considered, namely bending conditions and torsional conditions. The two working conditions are equally important, and the weights of all working conditions are 0.5. Similarly, in the multi-objective topology optimization synthesis function, the weight of the intensity is 0.4 and the weight of the quality goal is 0.6 [9, 10].

Fig. 4 shows the iterative process of the multi-objective function under two operating conditions. It is shown in the iteration processing the figures, the section thickness of the main beam increases or decreases in different degrees, among which Fig. 4d is the optimal topology.

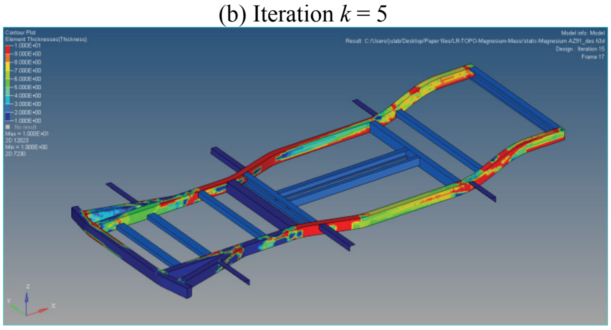
Fig. 5 shows the iterative curve of the maximum stress value of the frame under both bending and torsion conditions. With the increase in the number of iterations, the stress is always maintained below the magnesium alloy material yield strength (160 MPa), which is 33.4 MPa and 104 MPa, satisfying the structural strength requirements.



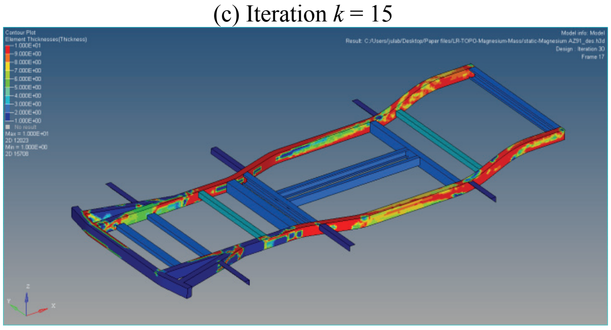
(a) Iteration $k = 1$



(b) Iteration $k = 5$



(c) Iteration $k = 15$



(d) Iteration $k = 30$

Fig. 4 Car frame iteration diagram.

Fig. 6 shows the quality optimization curve for the beam in the design area. With the increase in the number of iterations, the mass Mass decreases gently. After the 18th iteration, the mass Mass stabilizes and eventually reaches 27 kg. Since the weight of the un-designed area beam is 6 kg, the total mass of the optimized frame is 33 kg. As shown in Table 4, before the optimization of the frame, the density of the magnesium alloy is the smallest, so the unoptimized magnesium alloy frame has a weight reduction of 76.7% and 31.1%, respectively, compared with the steel and aluminum alloy materials, initially achieved the purpose of lightweight frame. After multi-objective topology optimization in this paper, while satisfying the stress intensity, the mass ratio is reduced by 21.4% before optimization, which means that the goal of lightening the frame is achieved.

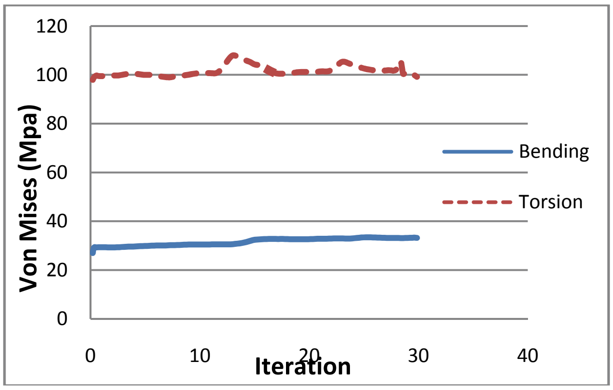


Fig. 5 Multi-condition stress iteration graph.

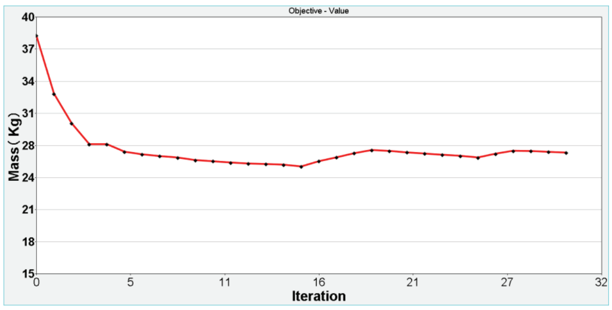


Fig. 6 Mass iterative graph.

Table 4 Quality comparison.

Materials	Steel	Al-Alloy	Mg AZ91 (Before)	MgAZ91 (After)
Frame mass (kg)	180	61	42	33
Mg optimize weight loss (%)	76.7%	31.1%	—	21.4%

4. Conclusion

(1) A multi-objective optimization theoretical model was established that satisfies the strength and light weight of the automobile frame.

(2) The optimization study of the magnesium alloy frame was carried out based on the strength targets of different materials, and the strength analysis results of three different materials were compared, and the multiple goals of strength and mass of the magnesium alloy frame were determined; For the purpose of designing variables, satisfying strength and light weight, a topological optimization analysis was performed on the frame.

(3) Taking into account the actual operating conditions of the car, the topology optimization analysis of the vehicle frame takes into account the bending and torsion conditions of the vehicle and realizes the optimization of the vehicle frame performance with multiple operating conditions and multiple objectives. According to the analysis results, after using the magnesium alloy material for replacement and analyzing the topology of the automobile frame structure, the goal of reducing the weight of the automobile frame can be achieved while satisfying the frame strength requirements. The optimized magnesium alloy frame is 81% lighter than the original steel frame.

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