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ENHANCING ENGINE MOUNT DESIGN THROUGH TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTURING (Sim-AM 2025)

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Abstract. The recent advancements in additive manufacturing technologies, coupled with the implementation of topology optimization techniques, are decisively redefining the framework for the design and fabrication of mechanical components. In the present study, a commercial automotive engine mount was investigated through the application of the SIMP (Solid Isotropic Material with Penalization) topology optimization algorithm, as implemented in commercial software nTop. The resulting optimized geometries exhibit a high degree of structural complexity, which can be feasibly manufactured only through additive manufacturing processes. The component was initially digitized using a structured light 3D scanner, and its structural integrity was evaluated via finite element analysis. Following this, a topology optimization study was performed, and the structural response of the optimized design was reassessed. The topology optimization process resulted in a mass reduction of approximately 30% for the engine mount bracket. Although the von Mises stresses increased by nearly 60%, the maximum displacement remained almost unchanged. To further explore lightweight design strategies, two alternative infill configurations gyroid lattice and auxetic re-entrant structures were applied to the original geometry. The gyroid structure achieved a 13% reduction in mass and a 3% decrease in internal stress but caused a 74% increase in total displacement compared with the topology-optimized model. Conversely, the auxetic reentrant design led to a 13% increase in mass, a 6.8% reduction in internal stress, and a 66% increase in total displacement. Overall, the findings clearly demonstrate the distinct mechanical behavior of the topology optimized model compared to the lattice based gyroid and auxetic configurations.

1 INTRODUCTION

All The primary objective of engineers, throughout history, has been the development of structures that combine low weight with high strength. Although numerous ideas and methodologies have been proposed toward achieving this goal, significant challenges have persisted [1,2]. Some of these difficulties occurred from the limitations of available manufacturing technologies, while others arose from the inability to solve complex computational problems that demanded substantial computational resources. In recent years, considerable progress has been made in overcoming both computational and manufacturing constraints [3, 4]. The application of computational engineering now enables the resolution of highly complex problems, while major advancements in manufacturing technologies, particularly the rapid development of additive manufacturing, have created the conditions necessary for the fabrication of structures characterized by high complexity geometries [5, 6].

1.1 Topology optimization and additive manufacturing

The definition of the optimization problem constitutes a combination of multiple parameters related to the structural design study of a construction or an object. The objective is to determine the optimal structural design solution within a predefined design domain [7, 8]. To solve this problem, input data include the model's volume, loading conditions, and the boundary or support constraints applied to the structure [9]. Additionally, further constraints may be imposed, such as the size and position of holes, as well as the presence or absence of material in specific regions [10–12]. Topology optimization is well known methodology and is defined as a mathematical process that optimizes the distribution of material within a predefined design domain to satisfy boundary conditions and design constraints [13]. Often, the structure resulting from topology optimization is extremely difficult, or economically impractical, to manufacture using traditional production methods, such as subtractive techniques [14–16]. In such cases the use of additive manufacturing proves both useful and effective, as these techniques enable the creation of virtually any structure regardless of its degree of geometric complexity. Moreover, economic analyses clearly demonstrate the cost advantages associated with the implementation of additive manufacturing techniques [17].

1.2 Direct applications of topologically optimized mechanical components

The use of topology optimization in the design of new mechanical components, as well as in the redesign of existing ones, is becoming increasingly popular [18]. Ready-to-use products for the automotive, aerospace, and aviation industries are now being produced using additive manufacturing techniques[19]. In automotive industry there are some examples of optimized components. In a paper a finite element model of an automotive engine bracket and uses topology optimization under static loading conditions to determine the optimal material distribution was studied. The optimized design satisfies displacement and stress constraints, while achieving about 40% mass reduction compared to the original bracket [20]. Another research focuses on the weight reduction of a brake pedal utilizing lattice structures though topology optimization. The results show that displacement and stress for the solid and optimized parts are comparable with a 21.2% reduction in mass [21]. Other study explores the use of optimized lattice structure on a spur gear considering weight reduction within defined displacements and stresses. A finite element model of spur gear is considered for analysis, the results show that stresses on optimized spur gear remains same as that of fully solid spur gear even after 19% volume reduction [22]. The literature review indicates a lack of sufficient research papers in this specific area. The present study aims to investigate the optimized design of a car engine mount bracket through topology optimization and to explore alternative design solutions incorporating gyroid and auxetic lattice structures.

2 MATERIALS AND METHODS

As shown in Figure 1, the current study follows a workflow methodology that begins with the creation of a high-accuracy 3D model. The analytical 3D model was developed from a real engine mount part using a standard structured-light 3D scanner. Subsequently, a fully editable mesh model was generated to enable the redesign of critical surfaces and the addition of necessary geometric features. The mechanical behavior of the actual component was evaluated numerically. Under the same boundary conditions, topology optimization was performed using the SIMP algorithm implemented in the nTop software. The optimized model was then analyzed numerically to assess its mechanical performance. To further evaluate the topologically optimized solution, two additional lightweight engine mount models were created: the first incorporating a gyroid lattice structure and the second an auxetic lattice structure. The mechanical responses of these designs were compared with that of the topologically optimized model.

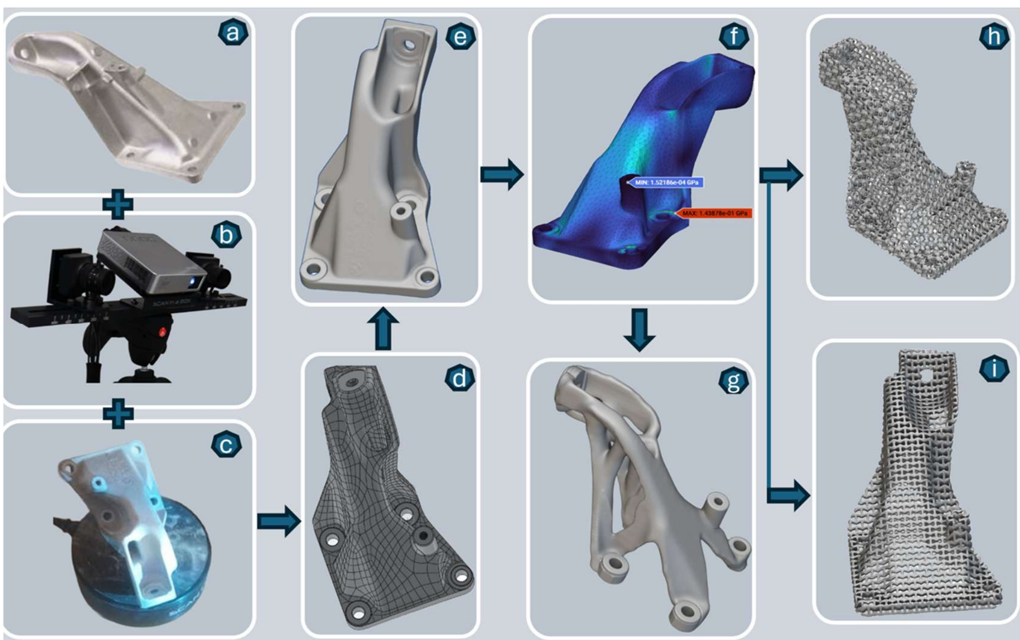

Figure 1: Workflow followed: a) real engine mount bracket, b–c) 3D scanning process, d) initial triangulated model, e) final 3D model, f) numerical evaluation of the real bracket, g) topologically optimized bracket design, h) model incorporating a gyroid lattice, and i) model incorporating an auxetic lattice

2.1 Preprocessing and Model Setup for Numerical Simulation

After the scanning process, a high-accuracy 3D model was created (Figure 2). The engine mount bracket supports the BMW N42B18 engine model. The total engine weight, including lubricant and fluids was 178 kg. The allowable force is calculated as:

$$Fallowable = m \cdot SF \cdot k \cdot g \tag{1}$$

Where:

$m = 178$ kg, total engine mass (including lubricant and coolant)

$SF = 1.4$, safety factor

$k = 2$, failure factor
$g = 9.81$ m/s^2

The resulting allowable force was $F_{\text{allowable}} = 4889$ N, and a nominal design load of $F_{\text{nominal}} = 4900$ Nwas adopted for subsequent numerical analyses.

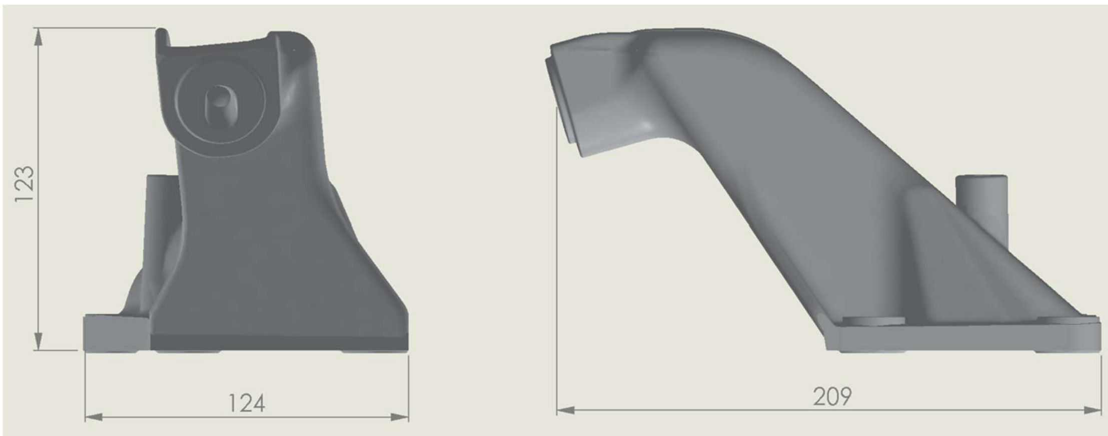

Figure 2: Mount bracket layout

For the material study, an aluminum alloy (Al2139 AM) developed by EOS which is fully suitable for additive manufacturing was selected. The material properties are presented in Table 1. A total force of 4900 N was applied to the upper surface (Figure 3a). The bracket is mounted at four points where it is securely fastened. At these locations, a fixed constraint is implemented (Figure 3b). Under the defined boundary conditions, a finite element (FE) volume mesh model consisting of 231,882 triangular elements was created (Figure 3c,3d).

Table 1: Material properties

Poisson's Ratio (ν)	Tensile Strength (MPa)	Young's Modulus (GPa)	Yield Strength (MPa)	Density (g/cm^3)
0.33	520	73	460	2.84

Based on the defined boundary conditions, a finite element analysis (FEA) will be performed to evaluate the mechanical behavior of the initial real model. The results indicate that the maximum displacement is approximately 0.28 mm, while the von Mises stress reaches 0.143 GPa (Figure 4). Subsequently, under the same boundary conditions, a topology optimization study will be conducted, followed by the evaluation of the mechanical behavior of the remaining models featuring gyroid lattice and auxetic structure infill.

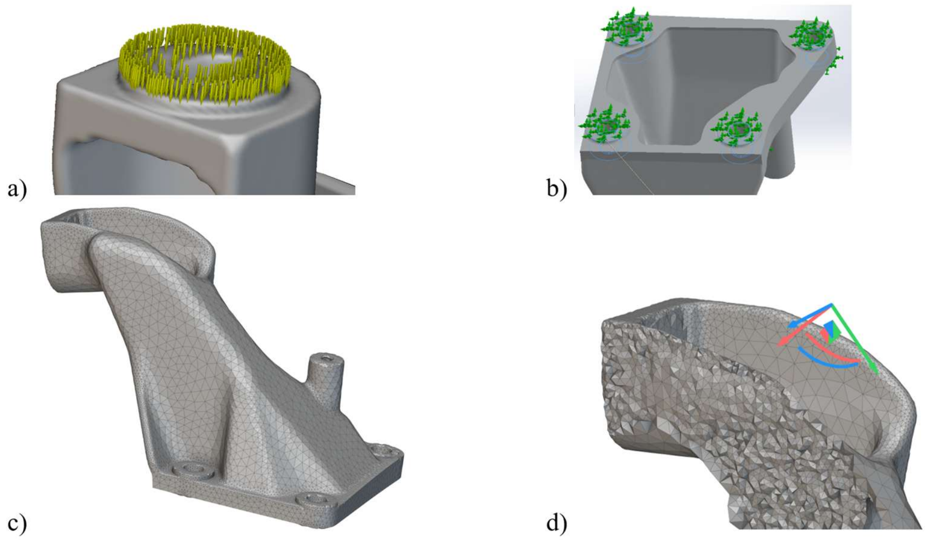

Figure 3: Finite Element solid model preparation, a) applied force, b) fixed constraints, c) meshing model, and d) volume mesh model

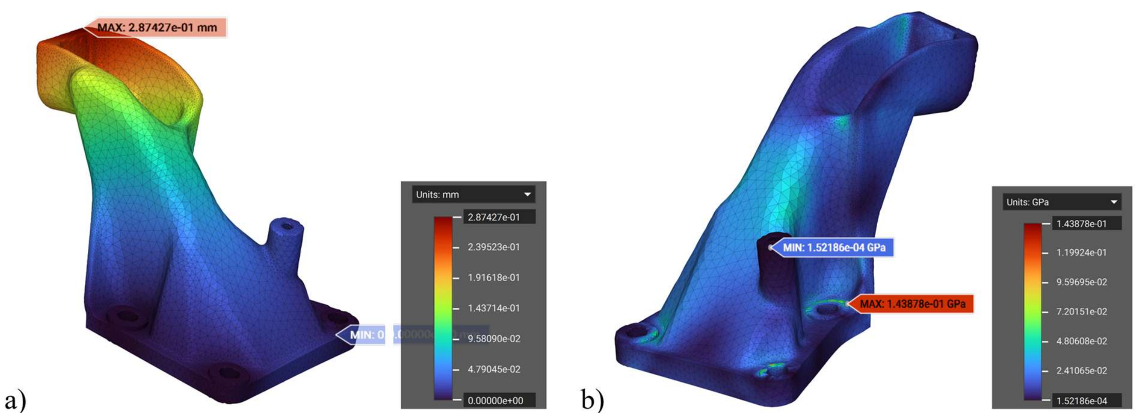

Figure 4: Mechanical behavior of the initial model, a) maximin displacement, and b) Von Misses stress

3 RESULTS

3.1 Topology optimization study

The objective of the present study is to evaluate the mechanical behavior of a topologically optimized model of an automotive engine mount bracket. The topology optimization study was performed using nTop software (nTopology, USA) employing a penalization-based algorithm. The optimization analysis was conducted under the boundary conditions described above. The main design constraint for satisfying the objective function was the volume fraction, which was set to a value below 0.5. Additional design constraints included setting the boundary penalty to 0.2 and the maximum number of iterations to 100. After 43 iterations the algorithm terminated, and the objective goal was satisfied (Figure 5a). The weight reduced by 29.6% (from 939 to 661 grams) compared with the initial model. After defining the regions of the model that must remain unchanged for fastening purposes or for assembly onto the engine base, the final geometry of the optimized model was created (Figure 5b). From the evaluation of the TO model, it was observed that the total displacement decreased by 2.4% (Figure 5c), while the von Mises stress increased significantly by 63% (Figure 5d).

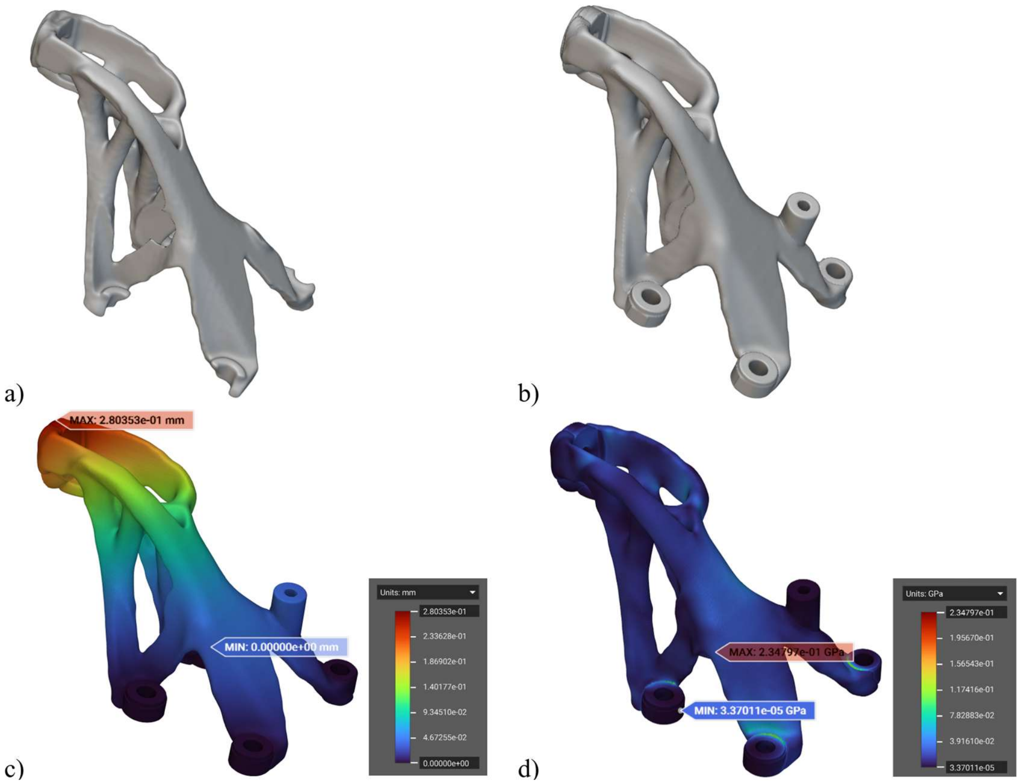

Figure 5: Topology optimization, a) initial results from TO study, b) after the design post processing the final TopOpt model, c) the maximum displacement is 0.28mm, and d) the maximum Von Misses stress is 0.234 GPa

3.2 Utilizing gyroid lattice in bracket design

To further evaluate the performance of the topology-optimized model, a new design incorporating a gyroid lattice structure was created using a 10×10×10 mm unit cell with a 2 mm wall thickness (Figure 6a, 6b). This model was subsequently compared with the TO model. The gyroid lattice–infilled bracket exhibited a 13.7% reduction in mass relative to the topology-optimized model. However, the total displacement was increased about 74% (Figure 6c), while the von Mises stresses decreased slightly by 2.9% (Figure 6d). It is noteworthy that, as in the previous analysis, the maximum stress values were observed in the regions where the bracket is bolted, and the fixed constraints are applied. Nevertheless, in practice, the fixation of the model is not perfectly rigid, as the bolts allow for a small degree of displacement that contributes to stress relief.

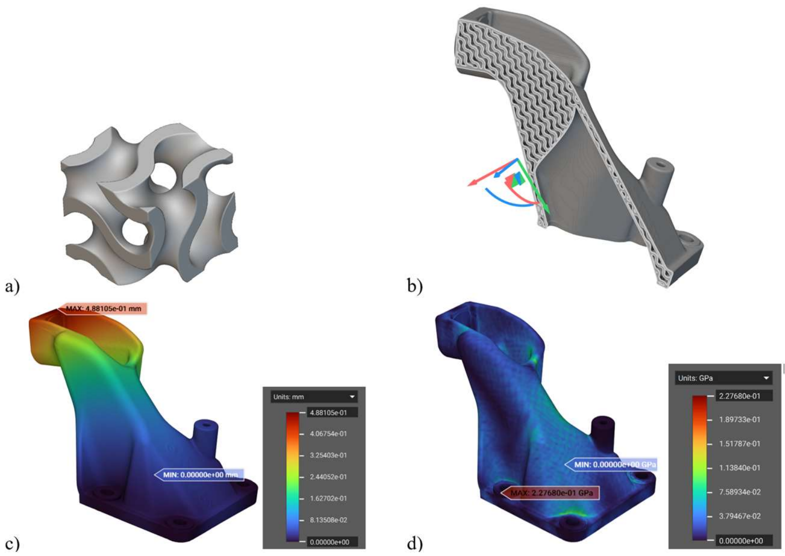

Figure 6: The bracket model consisted of gyroid lattice, a) the gyroid core element 10x10x10, b) the bracket model infilled by gyroid lattice, c) the maximum displacement, and d) the maximum Von Misses stress

3.3 Integrating auxetic reentrant structure in bracket design

The above results are considered reasonable, as the increased elasticity of the gyroid based model may lead to greater displacement while simultaneously reducing the developed stresses due to the lattice structure. It is therefore helpful to also examine the behavior of the initial model using an auxetic re-entrant structure, taking advantage of the significant benefits this type of structure offers in terms of uniform stress distribution and overall mechanical performance.

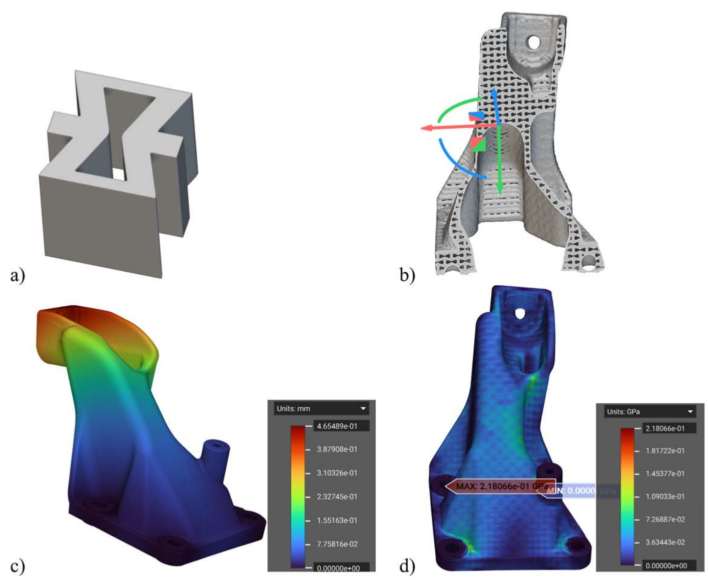

Figure 6: The backet model with auxetic reentrant, a) the core gyroid element 10x10x10, b) the bracket model infilled by auxetic material, c) the maximum displacement, and d) the maximum Von Misses stress

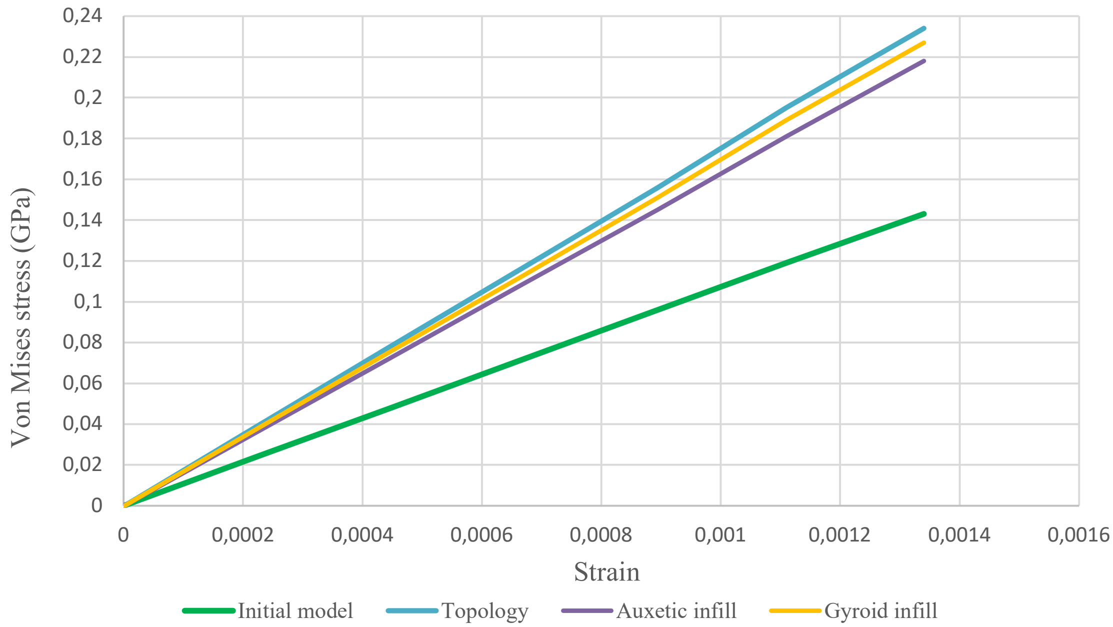

Figure 7: Stress-Strain curves

Figure 7 shows the stress–strain curves of all the evaluated models. It is evident that the original model demonstrates the best mechanical performance. The other three bracket models exhibit higher stress levels. However, the corresponding strain does not increase proportionally.

4 DISCUSSION

The objective of this study is to apply topology optimization using SIMP method to redesign the engine mount bracket of a passenger vehicle (BMW E46) in a manner suitable for manufacturing through metal additive manufacturing. The results of the topology optimization yielded a new design concept, in which the weight of the optimized bracket reduced approximately 30% compared with the original component. Mechanical evaluation of the topology optimized part revealed that, although the total displacement remained nearly unchanged, the applied stresses increased significantly by approximately 60%. While this initial result may raise concerns, it does not indicate a risk of component failure, as the yield strength of the selected printing material (Aluminum Al2139 AM) is 460 MPa, whereas the maximum stresses developed in the optimized model reach 234 MPa. Moreover, as also shown in the stress–strain curve, the TO model exhibits increased stress levels without a corresponding increase in deformation, which confirms its mechanical stability. It is also noteworthy that the highest stress concentrations occur in the regions where the component is bolted, as fixed boundary constraints were applied during the analysis. A potential redesign focusing on reinforcing these localized areas could further reduce stress magnitudes while maintaining weight reduction benefits.

Subsequently, the initial bracket geometry was further evaluated by maintaining the same external shape while replacing the internal solid volume with two different lattice configurations: a gyroid structure and an auxetic re-entrant structure. The purpose of employing these lattice structures was to evaluate the mechanical performance of the topology optimized model using alternative lightweight designs that are also compatible with metal additive manufacturing. The results indicate that, in the topology-optimized model, the reduction in weight is lower compared to the designs incorporating gyroid and auxetic lattice structures, while the resulting von Mises stresses are only slightly higher. A particularly important observation concerns maximum displacement, where the topology optimized model exhibits significantly lower values than both the gyroid and auxetic structures.

5 CONCLUSSION

This study demonstrated the use of topology optimization for redesigning an automotive engine mount bracket compatible with metal additive manufacturing. The optimized design achieved a substantial mass reduction of approximately 30%, while maintaining comparable total displacement to the original model. Although a 60% increase in von Mises stress was observed, the maximum stress values remained well below the yield strength of the selected material (Al2139-AM), confirming the structural integrity of the optimized component. To further investigate lightweight design alternatives, gyroid and auxetic re-entrant lattice structures were incorporated into the original geometry. The gyroid lattice resulted in an additional 13% weight reduction but caused a considerable increase in total displacement (74%). In contrast, the auxetic lattice led to a 13% increase in mass, a 6.8% reduction in von Mises stress, and a 66% increase in total displacement. These findings emphasize the inherent tradeoffs between stiffness, stress distribution, and mass efficiency in lattice based designs. Overall, the results indicate that topology optimization offers a structurally efficient and manufacturable solution for engine mount brackets. Lattice-based modifications provide further potential for weight reduction. However, they require careful design to manage stiffness and displacement. Future research should focus on hybrid approaches combining topology optimization with locally reinforced lattice structures, experimental validation and manufacturability assessment using metal additive manufacturing techniques.

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