Simulation and Topology Optimization of a Vehicle Door Hinge for Additive Manufacturing

G. H. Okoth, R. Ndeda, P. Raghupatruni, E. O. Olakanmi

Abstract**—**Additive manufacturing technologies offer unique capabilities that result in the creation of innovative, high-performance complex design geometries at reduced material cost. These novel design approaches can be fully realized through topology optimization which allows for greater material distribution usually optimized against a specific design objective. A vehicle door hinge design was analyzed using a finite element analysis which was then optimized to be additively manufactured with AlSi10Mg alloy. Based on the results of the structural analysis, topology optimization was performed to remove material from areas that did not significantly contribute to carrying the required loads. From the topology optimization results, the part was then remodeled in CAD software for additive manufacture using the AlSi10Mg alloy. Additional finite element analyses were carried out on the new CAD model to determine the load-carrying capacity of the design. The final design was then prepared for the final additive manufacturing.

Keywords**—**additive manufacturing, aluminum alloy, compliance, finite element analysis, topology optimization.

I. INTRODUCTION

DESIGNERS and manufacturers in the vehicle industry are increasingly pursuing sustainable manufacturing methods necessitated by diminishing energy resources, increasing global warming, and the need to meet new legal, safety, and environmental obligations [1]. To achieve this, there has been accelerated research into the use of low-density materials in the fabrication of vehicle components aimed at lowering the use of energy and mitigating climate change through reducing carbon dioxide (CO^2) emissions. According to Helms and Kobayashi [2], nearly 75% of commercial vehicle fuel consumption is related to its weight. This means that the reduction of the vehicle weight means burning less fuel per distance covered. Consequently, less fuel burned ensures lower (CO^2) emissions. Yilmaz et al. [3] studied the fabrication of lightweight commercial vehicle door hinges using three aluminum alloys (Al6082, Al6262, and Al7075) instead of steel. The door hinges were fabricated on a 1500-ton capacity screw press forging machine using a 400°C close-die hot forging process. The study reported an approximately 65% reduction of door hinge weight using AA7075-T73 alloy. This study investigates the possibility of further weight reduction on a vehicle door hinge using AM, in combination with topology optimization.

The vehicle door hinge is composed of four parts; a fixed part, a mobile part, a hinge pin that fastens fixed and mobile parts, and bushes [3] as shown in Fig. 1.

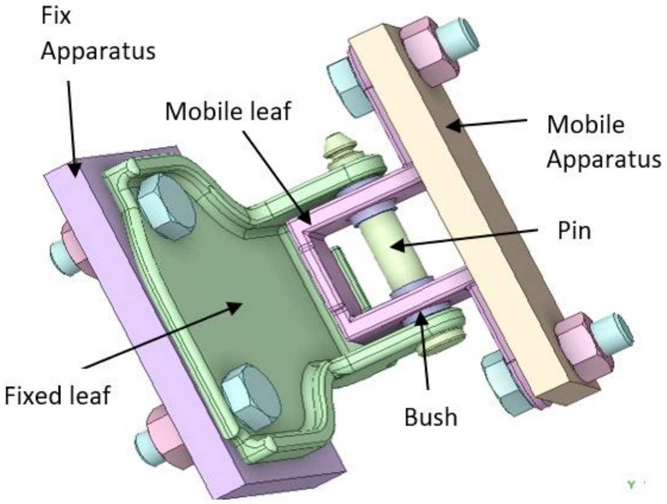

Fig. 1 3D model of the vehicle door hinge

Historically, one of the widely used vehicle component manufacturing techniques is cold forming, where suitable stresses cause plastic deformation of materials in the production of the desired shapes at room temperature [4]. During the cold forming process, the material is basically displaced and/or deformed but not removed. Cold forming is preferred for installation systems with relatively light dimensional tolerances [5]. However, the conventional forming of aluminum alloys encounters major issues such as the low formability and stiffness at room temperature that causes high spring back

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consequently limiting their application to the forming of complex shaped components [6]. In addition, the increasing demand for complex designs and the use of low-density materials is posing a challenge in the continued use of cold forming techniques in vehicle parts manufacture [7], [8]. Hot stamping is another method used in vehicle parts manufacture. Similarly, hot stamping processes are also relatively complex since post-fabrication processes such as quenching are important in controlling the cooling rate and the subsequent post-form strength [9].

The possibilities of weight reduction in the manufacture of lightweight vehicle components have been further enhanced by design topology optimization. The method entails finding the optimal structure with respect to its boundary constraints and design in order to reduce its weight. As earlier mentioned, it is difficult to fabricate optimized designs using conventional fabrication techniques due to the resulting complex geometries obtained. Additive manufacturing (AM) is one method of overcoming this challenge.

Additive Manufacturing has the ability to deliver very intricate and complex geometry parts with a minimum need for post-processing built from novel materials with minimum material waste [10]. It is also useful in reducing weight since lighter structures can be manufactured using high-strength aluminum alloys with excellent machinability and high strength-to-weight and stiffness-to-weight ratios [7]. AM processes are distinct in the way layers are deposited during the creation of parts, materials, and operating principles used.

There has been increased research on employing AM technologies to fabricate design-optimized components using low-density materials [11]. This study investigates the use of AlSi10Mg alloy in the fabrication of a topology-optimized door hinge via AM. AlSi10Mg is an aluminum alloy with dynamic toughness, strength, and good hardness. The magnesium in its chemical composition improves the alloy's ductility and modulus of elasticity properties [12]. The alloy is mostly used as a casting alloy. Powder made from AlSi10Mg is conventionally used in AM applications due to the high mechanical strength, low density, and corrosion resistance of the fabricated components [8]. In addition, AMed components fabricated with AlSi10Mg require relatively less thermal post-processing compared to cast components [13]. Industrial applications of the alloy are found in the automotive, aerospace, and molding industries in the fabrication of components like brackets, brake calipers, heat sinks, etc. Ch et al. [4] reported that the near-eutectic composition of Al and Si in AlSi10Mg results in a small solidification range, making the AM process relatively easy compared to the use of high-strength aluminum alloys such as the 7000 series used by Yilmaz et al. [3] in their design study.

Table I and Table II show the chemical composition and mechanical properties of AlSi10Mg powder respectively.

TABLE I
CHEMICAL COMPOSITION OF AlSi10Mg

Element	Concentration (Wt. %)
Si	9.0 – 11.0
Mg	0.2 – 0.45
Fe	< 0.55
Cu	< 0.05
Mn	< 0.45
Zn	< 0.1
Ti	< 0.15
Ni	< 0.05
Pb	< 0.05
Sn	< 0.05
Al	balance

TABLE II
MECHANICAL PROPERTIES OF AlSi10Mg

Properties	Value
Density(g/cm^3)	2.67
Tensile Strength UTS (MPa)	> 370
Yield Strength (MPa)	> 200
Young's Modulus (GPa)	> 65
Elongation at Break (%)	< 7

II. METHODOLOGY

Comparative simulations of the vehicle door hinge design were done using structural steel and AlSi10Mg materials. A finite element analysis (FEA) of the hinge design was solved using Ansys software. The results of the structural analysis were then used to carry out a topology optimization (TO).

A. Finite Element Analysis (Static Structural Analysis)

In this study, static structural analysis is basically a finite element analysis used to determine the stiffness response of the hinge based on some boundary conditions of static loading and specified fixed support. Both the structural steel and AlSi10Mg materials were assumed to have a service temperature of 25ºC. The force exerted on the mobile apparatus (in accordance with UNECE R11) [14] was defined by component forces, with X and Y components both set at 0 N while a force of 4500 N was applied to the Z component. Bolt pretensions on the four screws were 21 N. Fixed support was added to the fixed leaf.

The FEA discretization of the hinge geometry obtained the following mesh properties; mesh size was 1.0 mm for all the parts with tetrahedron (four nodes of first order) elements for the hinge, axis pin, and bushes and hex-dominant elements for the fixed apparatus. The number of mesh parameters was 576,807 nodes and 393,772 elements for a model size of 90 mm x 90 mm x 6 mm.

The mesh convergence graph shown in Fig. 2 below guided the choice of the mesh size while Fig. 3 depicts the mesh used in the FEA study.

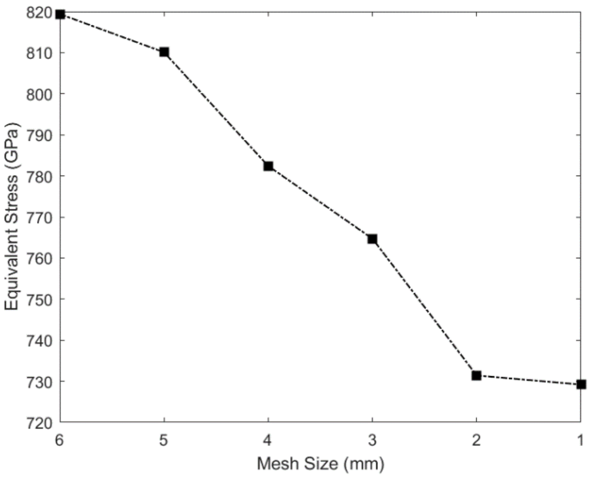

Fig. 2 Mesh convergence graph

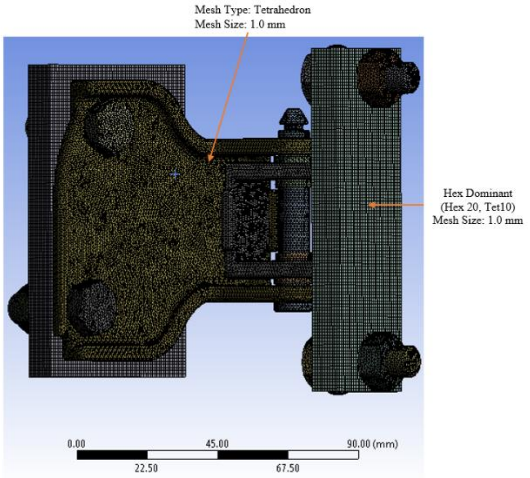

Fig. 3 Mesh geometry properties

B. *Topology Optimization*

Topology optimization (TO) is a mathematical method that spatially optimizes the redistribution of material, by fulfilling certain constraints and minimizing a predefined cost function within a given domain i.e., minimization of structural compliance [15]. For this study, the predefined cost function, which is the material cost, is mass; because the cost of fabrication increases with an increase in the material used. Design flexibility is offered by TO as it allows for material redistribution hence offering the potential to reduce material cost. Topology optimization generates a free-form geometry that is usually optimized against a specific objective as shown in the mathematical representation in Equation 1.

$$Min\ W(x) = \rho_i l_i A_i \qquad (1)$$

subject to stress, strain, mass, or displacement constraints where W(x) represents the weight of the structure. The weight is the product of its density, length, and cross-sectional area. The objective function {W(x)} is subjected to the design and state variable constraints to steer the optimization to a sought solution in a given number of iterations. The difference between TO and shape/sizing optimizations is that the design in the latter can attain any shape within the design space which is undesirable for this study. The objective is to obtain a lighter structure without altering the shape or size of the hinge hence the choice of TO, which is constrained to deal with predefined configurations. The optimization process in the FEA process solves the optimization task by minimizing compliance under a mass constraint [16].

The results of the static structural analysis were then used to perform the TO. The material was removed from parts that were not significantly contributing to carrying the subjected loads. The simulations were done with the vehicle door in a fully open position; when the hinge system experiences maximum loading. The topology of the fix leaf was selected for a density-based optimization process while all the other parts of the hinge system were marked as exclusion regions. Some surfaces of the fix leaf (edges and fastening holes) were also excluded during the optimization process. The maximum number of iterations was 500 with a convergence accuracy of 0.1%. The set objective was to minimize weight; hence the response constraint was mass.

The resulting geometry was expected to be highly complex and rough hence topology simplification and smoothening were required. The simplification was done using Ansys Space Claim software. The smoothened design was also re-analyzed to check if the load-carrying capacity of the part remained unaffected.

III. RESULTS AND DISCUSSION

A. *Finite Element Analysis*

Fig. 4 shows the von Mises stress distribution on the hinge after a finite element analysis. von Mises stress is used to predict the yielding of materials subjected to complex loading. The load applied was 4500 N in the Z direction of the mobile apparatus simulating the door of the vehicle. A maximum von Mises stress of 125 MPa was observed on the flanges of the fix leaf. Other parts of the hinge that experienced relatively higher stresses were the lower parts of the pin and lower bush (41 MPa – 69 MPa). In comparison, the maximum stress of the analyzed hinge with AlSi10Mg was lower than the maximum yield stress value (200 MPa) which translates to no plastic deformation experienced on the hinge assembly.

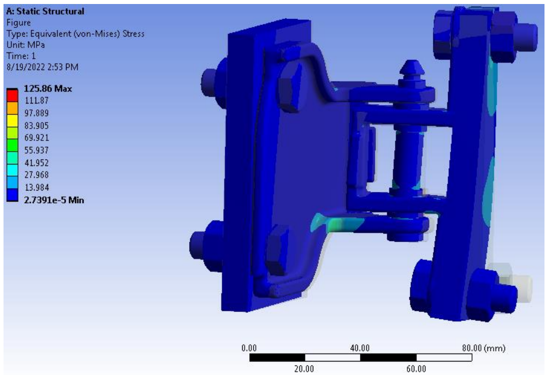

Fig. 4 Equivalent von Mises Stress distribution on the hinge

Fig. 5 shows the equivalent elastic strain on the hinge. The obtained results depicted a maximum strain value of 0.0062991 mm/mm. For the displacement values, the maximum total deformation was 0.034617 mm shown in Fig. 6. The maximum deformation was experienced on the lower fastening holes of the mobile hinge.

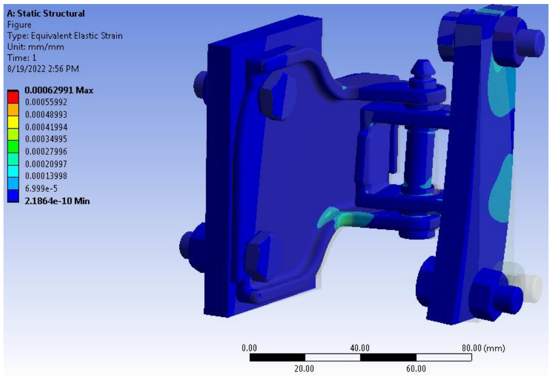

Fig. 5 Equivalent Elastic Strain on the hinge

The results also show that the displacement values were higher in the aluminum alloy sample compared to that of the steel sample. This is due to the difference in the elasticity modulus which is higher in AlSi10Mg compared to that of steel. However, the resulting maximum displacement values showed compliance with the United Nations Economic Commission for Europe Regulation No. 11 (UNECE R11) acceptance criteria [14].

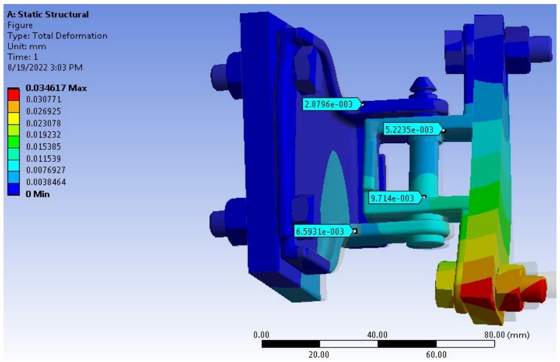

Fig. 6 Total Deformation on the hinge

B. *Topology Optimization*

The TO performed caused a significant movement of the finite elements. The total time spent to obtain the solution of 50% mass removal on the optimization region was 43 minutes and 50 seconds. The re-analyzed hinge geometry (10% mass removal) returned a maximum Young's modulus of 64002 MPa which slightly varies with the un-optimized geometry (61261 MPa). This shows that the load-carrying capacity of the optimized part remained unaffected at 10% mass removal. Fig. 7, Fig. 8, and Fig. 9 show the respective resulting geometries of the optimizations with different retained mass thresholds. To retain the load-carrying capacity (mechanical integrity) and functionality of the hinge, a 12% mass removal on the fix leaf was determined to be the optimal mass that can be reduced in the optimization region. This was done through an FEA reanalysis of the hinge whereby breakage of the hinge was observed beyond 12% mass removal. This was determined by calculating the respective Young's moduli (from max stress/strain) of the subsequent mass removals. For 12% mass removal, Young's modulus was 64997 MPa while 13% mass removal was 65012 MPa as shown in Table III. There was a visible fracture around the upper fastening screw of the fix hinge. AlSi10Mg has a maximum Young's modulus of 65000 MPa at room temperature.

TABLE III
MASS REMOVAL Vs YOUNG'S MODULI

% of Mass Removal	Young's Modulus (Max MPa)
0 %	61261
10 %	64002
12 %	64997
13 %	65012
30 %	132461
50 %	199806

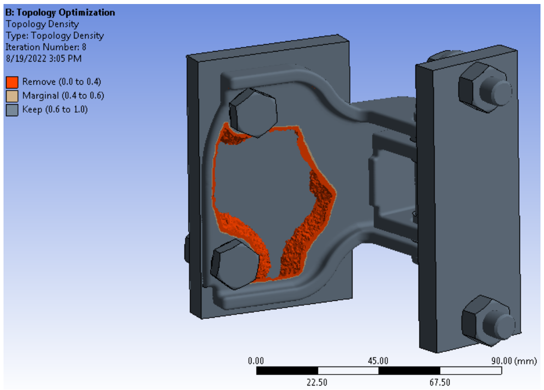

Fig. 7 10% Mass removal

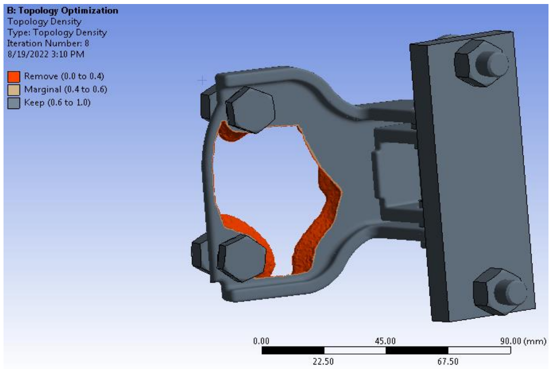

Fig. 8 30% Mass removal

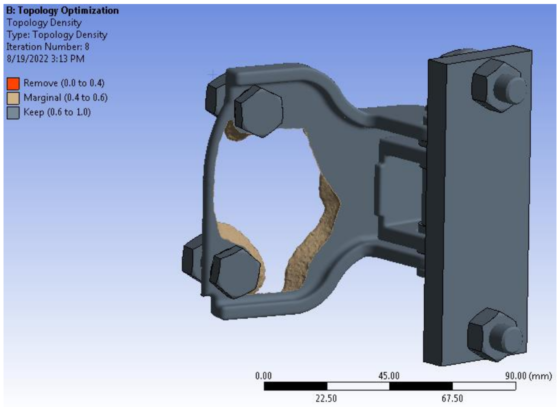

Fig. 9 50% Mass removal

IV. CONCLUSIONS

In this study, simulation and topology optimization of a lightweight vehicle door hinge for additive manufacturing were successfully carried out. The FEA results were used to remove material from parts that did not significantly contribute to carrying the required loads through TO in Ansys MAPDL software. The simulation results will be validated through experimental data to be obtained from the AM fabrication of the optimized design. The fabricated lightweight structure must meet both the UNECE R11 and Federal Motor Vehicle Safety Standard (FMVSS0206) set standards [17] for it to be deemed safe. Vehicle light-weighting is aimed at achieving economic and environmental sustainability through the reduction of the weight of its various components. The long-term effect of the foregoing is the attainment of the Sustainable Development Goals (SDGs) on the environment which emphasize the importance of carbon emissions reduction, improvement of energy consumption, environmental degradation prevention, and preservation of the ecosystem with an aim of supporting inclusive economic and human development.

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