ADDITIVE MANUFACTURED LIGHTWEIGHT VEHICLE DOOR HINGE WITH HYBRID LATTICE STRUCTURE

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Abstract

Replacing the body components to high strength low density cellular structures with additive manufacturing are promising candidate for design lightweight and complex parts especially for automotive industry. However, automotive manufacturers must take into consideration the global technical regulations. The goal of this research is to evaluate the limitations of additive manufacturing technology to produced vehicle door hinge with hybrid lattice structures to fulfill the safety criteria. Mechanical properties and anisotropy level of different build directional (0°, 45°, and 90°) tensile specimens, fabricated from maraging steel (MS1) using Direct Metal Laser Sintering (DMLS), have been investigated. Specimens are analyzed by mechanical tensile test and Vickers hardness test. To make good use of additive manufacturing technology, a topology optimization software (i.e. Inspire®) optimized vehicle door hinge with lattice structure. In this context, complex geometry hinge component designs are manufactured using EOS M290 additive manufacturing system with maraging steel. However, predict the mechanical behavior of door hinge system remains a challenge, especially against the global technical regulation (ECE-R11). This paper presents an approach to finite element analysis of regulation to simulate mechanical behavior of door hinge with hybrid lattice structures. Moreover, criteria of regulation acceptance for printed hinge designs are examined. Referring on the results obtained, an interpretation was made to increase the use of potential of additive manufacturing technology in the automotive industry.

Keywords: Additive Manufacturing, Finite element analysis, Lattice structures, Maraging Steel, Mechanical properties, Vehicle door hinge

Introduction

The additive manufacturing technology lighted the way of producing parts regardless of geometric complexity which is challenging to produce with traditional subtractive manufacturing methods. Lightweight design which is required for aviation, automotive industry, etc., is the lie behind of this geometric complexity. To achieve this kind of dealing, mechanical designers need to know technical limitations of additive manufacturing. Nonetheless, design freedom is considered as strong side of additive manufacturing. This process can be used either to lighten the components with extraordinary manufacturing speed or can be used for produced components with decent cost compared to conventional procedures [1, 2].

High-strength low density cellular structures is one of the key approaches of lightened the components. However, predictions of the mechanical behaviour of cellular structures are established on base analytical method or numerical method such as finite elements. In analytical method, single cell unit are examined to predict the mechanical properties of cellular structures [3]. In numerical modeling, simulate the mechanical properties of cellular structures remains a challenge due to high number of struts [4]. Use of lattice cells is one of the approaches of high strength structures with low mass such as metal foams, sandwich structures, etc. [3]. Cubic, Crossing rod, Tetrahedral or Kelvin Cell, etc. are the repeating pattern for different type of lattice structures [5, 6]. Increasing the struts in entire lattice pattern make more complicated model for numerical analysis [7]. The lattice structures studied in this work constituted with Inspire® optimize software in arbitrarily order.

Maraging steel (MS1), developed by EOS for their Direct Metal Laser Sintering (DMLS) systems is one of the promising materials for use of additive manufacturing. MS1, that is Fe-Ni based powder alloy, show high strength combined with excellent dimensional stability and convenience to age heat treatment [8]. Determination of mechanical properties of MS1 depends on production ability of DMLS. As use of additive manufacturing technology increase, production stability and repeatable mechanical properties will be demanded. However, there is a need for understanding of isotropy level of mechanical properties. Indeed, there is discrepancy of the mechanical properties depending on the build orientation [9, 10]. In this paper, we examined anisotropy variation of tensile specimens which have been fabricated on EOS M290 additive manufacturing system with different build orientation. Nonetheless, material hardness and microstructures were studied to determine mechanical properties of the MS1. The results obtained were used on numerical analysis to optimize high-quality parts with new knowledge towards of MS1.

Moreover, in this work vehicle door hinge which fabricated with hybrid lattice structured MS1, investigated under condition of global technical regulation (ECE-R11) [11]. Optimized hybrid lattice structured vehicle door hinge system is numerical and experimental analysed. During this process, a new perspective was tried to bring for automotive industry parts which has functionally tough regulation.

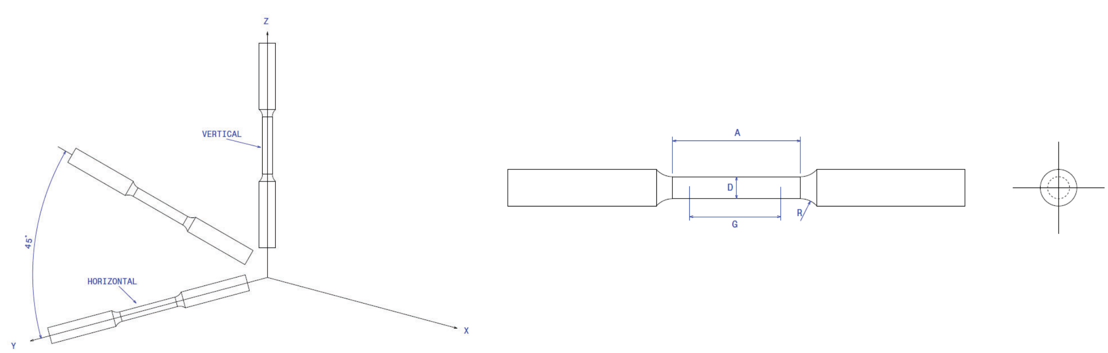
Material and Methods

1. Fabrication on Specimens

Tensile specimens were fabricated from Maraging Steel (MS1) powder on EOS M290 additive manufacturing system. Table 1 presents an overview of the chemical composition of MS1 (X3NiCoMoTi) material. The testing procedure was based on ASTM E8 standard. For this purpose, circular cross-section shape test specimens that meet the standards was fabricated. Four sets of test specimens were built with vertical, horizontal and 45° angle inclined orientation in the 250 × 250 × 325mm processing working area (Fig 1a). The fabricated specimens were machined and surface-grinded to standard geometry which is shown in Fig. 1b. The finished specimen dimensions and tolerances are shown in Table 2. Heat treatment was not implemented to the test specimens.

Table 1. Chemical composition (wt%) of MS1 powder used in the experiment

Alloying Element	Ti	Al	C	Fe	Mn	Ni	Si	Cr	Cu	S	P	Co
wt (%)	0.6-0.8	0.05-0.15	≤0.03	Balance	≤0.1	≤17-19	≤0.1	≤0.5	≤0.5	≤0.01	≤0.01	8.5-9.5



(a) (b)

Figure 1: Specimens manufacturing conditions (a) built orientation of test specimens (b) geometry and dimension of test specimens according to standard ASTM E8

Table 2: Finish-machined specimen dimensions and tolerances

	Dimensions (mm)
G—Gauge length	24.0 ± 0.1
D—Diameter	6.0 ± 0.1
R—Radius of fillet, min	6
A—Length of reduced section, min	30

2. Characterization

Tensile measurements were performed on the specimens using tensile tester applying standard ASTM E8. Three samples of each different orientation were tested. Hardness testing of MS1 material fabricated by DMLS was measured according to ASTM E92. The hardness specimens were prepared at 6mm × Ø12mm dimensions. Measurement was conducted under room temperature (20 ± 5°C). The test was done by Metkon Micro/Macro Vickers Hardness tester. Measurements were carried out on two faces at least four times, afterwards average of these results was taken into consideration. To determine actual hardness value, three standard deviations of hardness data were considered as valid results.

Furthermore, printed hinge with hybrid lattice structure were investigated for United Nations Agreement of Uniform Provisions Concerning the Approval of Vehicles with Regard to Door Latches and Door Retention Components (ECE-R11). Regulation applies to vehicle door retention components such as hinges and other supporting parts. According to regulation each door hinge system shall not separate when a longitudinal load of 11 kN is applied, and a transverse load of 9 kN is applied. Fig 2 shows transverse load test procedure. Hinge position must simulate vehicle position (door fully closed) relative to the hinge centerline [11].

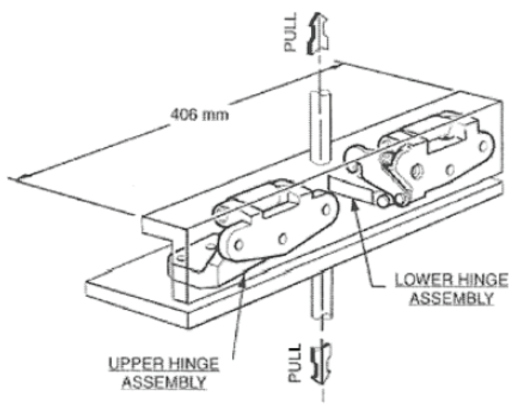


Figure 2: Test procedure of door hinge system

3. Lattice Optimization

Lattice structures emerged a new structural layout which consists rod elements connected each other just like steel roof structure of any factory building. The inspiring structural model is combination of a smaller sub-pattern we call lattice cell which repeats itself throughout the whole structures of rods call lattice structures. The objective of lattice optimization technique is to change the intermediate density elements with cells that is created during classical topology optimization. Each of the elements of the structural models takes a value with respect to their density, and these values are evaluated with lower and upper limits. The lower limit value stands for fully density elements that should stay where they are. Lattice optimization has been carried out in only one step from solid geometry using Inspire® 2019 [12].

In our case, the objective considered for our optimization study is minimized the mass target while meeting the stiffness requirement as the same time. Target length, minimum diameter, and maximum diameter values, which are specified considering Additive Manufacturing process, have been inputted as run parameter.

Based on the prior experiences, an existing vehicle front door hinge mechanism was considered as design space. This mechanism required some geometric constraints. Non-design space of hinge system included flat surfaces of 1 mm thickness on the both hinges bottom faces, pin holes with 3 mm diameter and flat surface of axis pin holes either side of the hinges. Besides, for the functionality of hinge system, pins on the rotation axis of the hinges considered as non-design space. Inspire® software was used for lattice optimization with material of linear isotropic maraging steel. For determining on boundary conditions for lattice optimization, external load terms and fixed components on the hinge system were chosen based on ECE-R11 regulation procedure (Fig. 3).

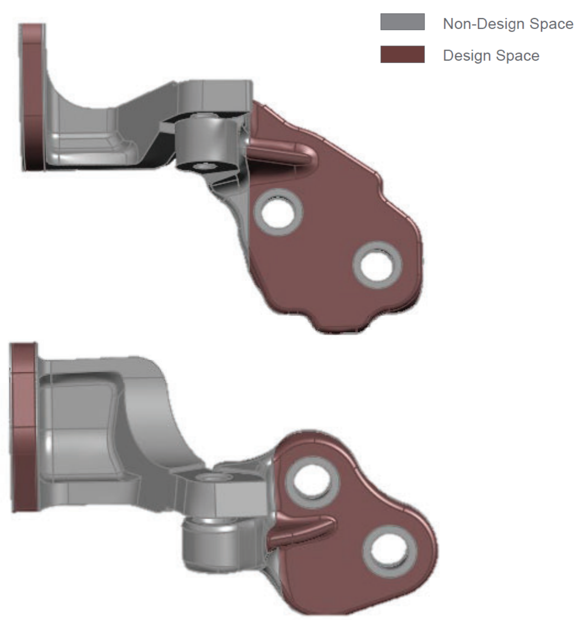


Figure 3: Loading directions for baseline design made with MS1 alloy.

4. Finite Element Analysis

The analysis of hinge strength under regulatory condition was performed with Altair's Radioss structural analysis software which is used for evaluation of complex nonlinear problems. Finite element model was created using Hypermesh. The critical loads and boundary conditions were considered identical as optimization procedure. However, knowledge of additive manufacturing process is still comparatively data deficient, experimental results of mechanical properties of MS1 which is assumed nonlinear plastic material, were employed in structural analysis. That means, elastoplastic material was defined by stress-strain curves from tensile experiment data. Additionally, upper and lower hinge system positioned the exact spot on the car body. Central pin which connected the mobile and fix part together were chosen and modeled with prior experiences. Besides maximum stress, stiffness and deformation values were considered as test variables.

On the other hand, to simulate mechanical behavior of the complex lattice structures, beam model was integrated to the analysed. In hybrid structure, solid elements are directly attached to lots of beam elements using contact algorithms. Because of it is hard to integrate and assign their properties and materials of a great number of beams with different dimensions within Hypermesh, a macro has been written to organize this process. For this analyses, 20,111 beam elements and 38,452 tetra solid elements are used to represent the hybrid hinge numerical model.

Result and Discussion

1. Mechanical Properties

Tensile stress (σ) - strain (ε) curves and measured values of material MS1 produced by DMLS with different build directions is shown in Fig. 4 and Table 3. Curves of tensile diagrams show that significant anisotropy has been confirmed. As a result, the highest strength can be seen as horizontal specimens' curves. Besides, yield strength and elongation at break values are in good agreement with referenced reports for horizontal specimens. Other oriented specimens' measured values are identical and yield strength is almost 200 MPa lower and tensile strength is approximately 50 MPa lower. For inclined and vertical specimens, elongation at break values are significantly decreased. This may be associated with microstructural build up the process of layers, since higher tensile strength and elongation at break is achieved in horizontal orientation.

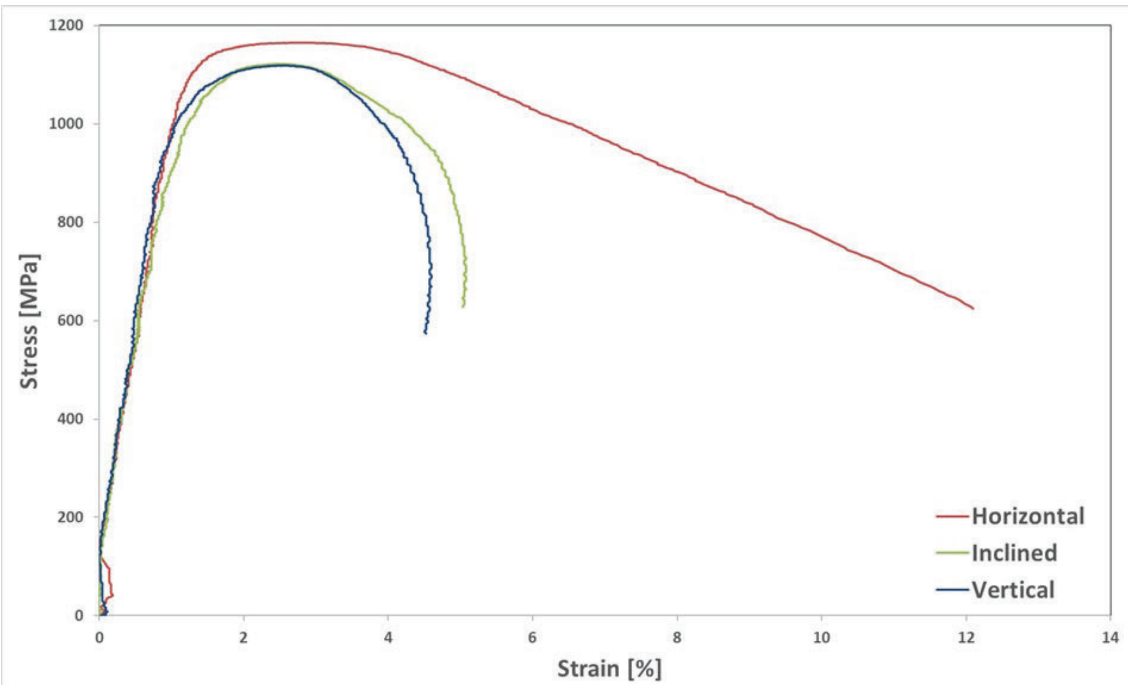


Figure 4: Stress (σ)-strain (ε) curves of MS1 test specimens

Table 3: Mechanical properties data retrieved from MS1 produced by DMLS

Orientation	E [GPa]	$R_{p0.2}$ [MPa]	R_{UTS} [MPa]	A_t [%]
EOS Horizontal	150±25	1100±100	1200±100	12±4
EOS Vertical	140±25	930±150	1100±150	-
Horizontal	115	1089	1173	12
45° Angle Inclined	111	887	1122	5
Vertical	129	901	1119	4.5

The experimental hardness measurements of MS1 material made by DMLS are shown in Fig. 5. The graph comparing Vickers Hardness value of the supported surface and non-supported surface shows notable discrepancy between variables. Supported surface measured high hardness level and maximum hardness value (417.4 HV). In addition to this, non-supported surface shows much lover hardness values.

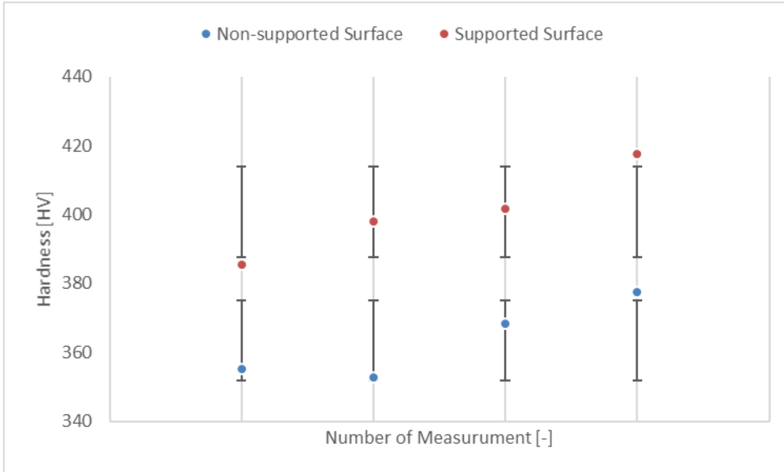


Figure 5: Ratio of hardness (HV)

2. Optimization Results

The lattice optimization was implemented to hinges system included mobile and fix parts. Although it is producible as is, surface smoothing was performed to reduce stress concentration. Lattice optimization was performed on the baseline geometry at regulations norms. Under the optimization phase, vertical oriented MS1 data was used to modelling of material behavior of baseline geometry and Fig. 6 shows the structures that were obtained. For optimized components, %16 weight was significantly alleviated from baseline geometry. Due to the fact that Inspire optimization software may able to support only linear material definition, the stress results have been occurred far more than yield stress of MS1. Lattice optimization parameters were selected as, target lattice length (5 mm), minimum diameter (1 mm), maximum diameter (2 mm) and maximum stiffness for the objective.

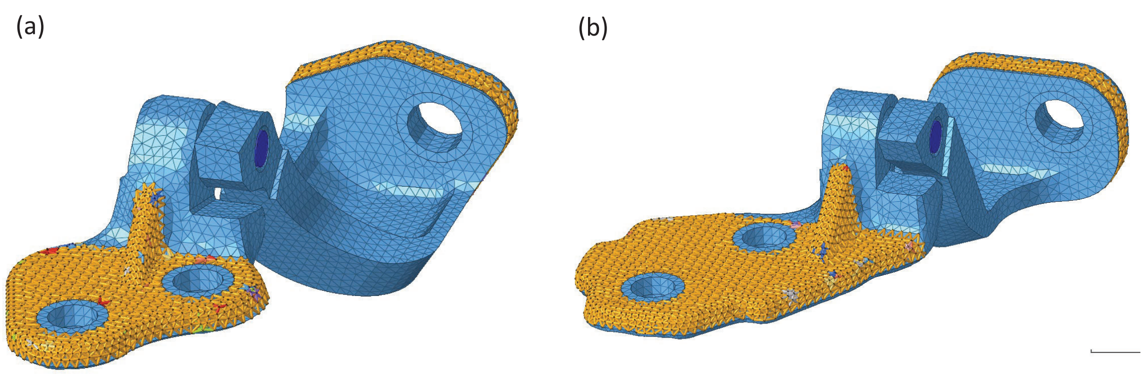


Figure 6: Components with lattice optimized (a) upper hinge, (b) lower hinge

3. Finite Element Analysis

According to the regulation requirement door hinge system must not separate when loads are applied. That means plastic deformation will be considered as acceptable unless it is not exceeding the plastic deformation limits of all materials. Mechanical behaviors of hinge system were analyzed and illustrated in Fig. 7 with Von Mises stress and maximum displacement for all directions individually.

Under longitudinal load, maximum Von Mises stress that is 934 MPa was observed on upper mobile hinge part (Fig. 7a, b). Plastic deformation on lattice structures concentrated near the pin hole. Although maximum Von Mises stress is higher that the yield stress, plastic strain value is reasonable for mentioned boundary condition. It is important to be aware that, collection of plastic deformation on the beams proves accuracy of modeling of beam and mesh model. For transverse load case, maximum Von Mises stress (691 MPa) was observed on the surface of pin connection between mobile hinge and axis pin. It is lower than the yield stress value, which means no plastic deformation on the hinge system for this case (Fig 7c).

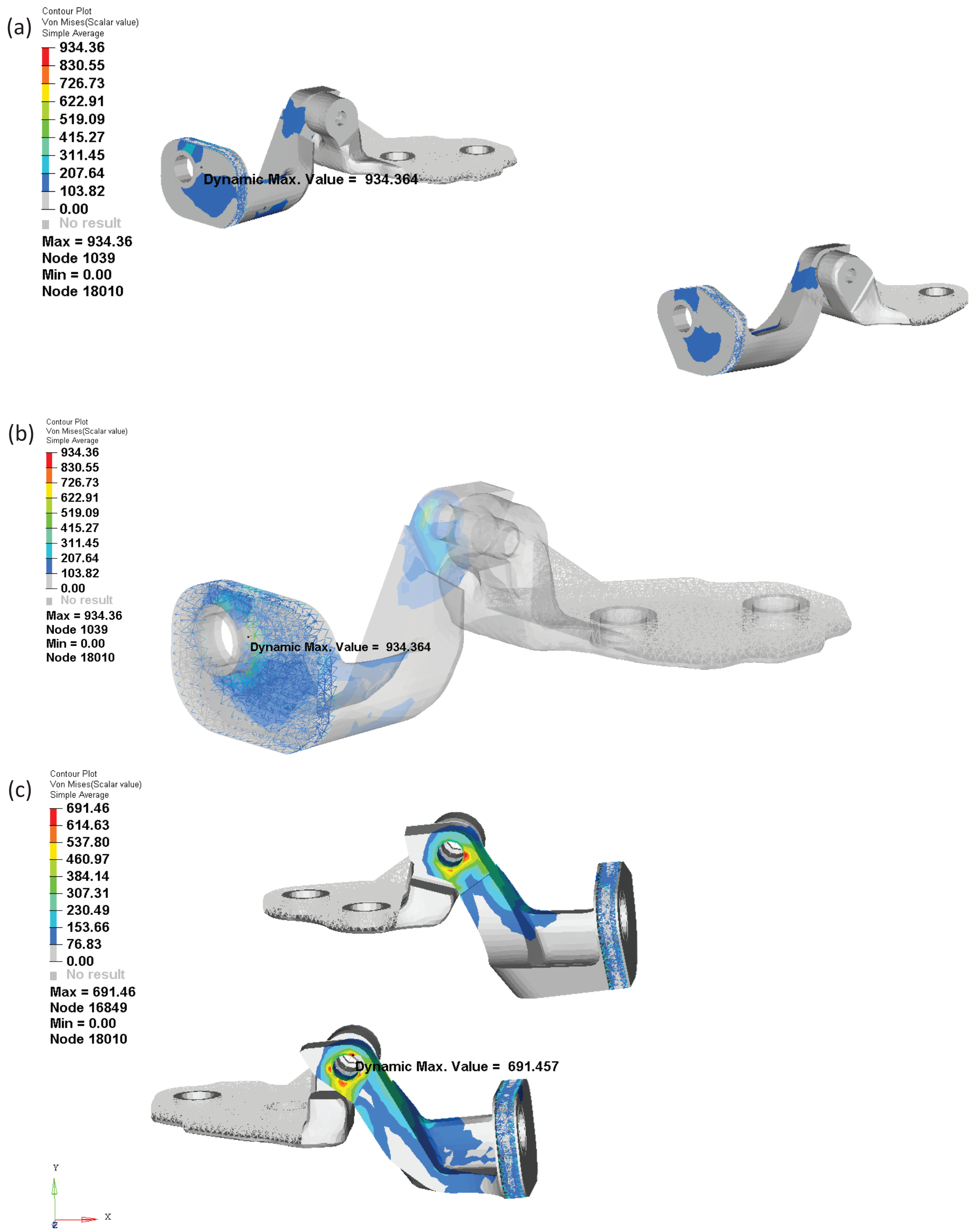


Figure 7: Optimized structure solutions resulting from the model (a), (b) maximum Von Mises stress for longitudinal load, (c) maximum Von Mises stress for transverse load

It is worth mentioning that it is possible to optimize and build hinge system without lattice structures but cost of manufacturing and built time will be higher the base design. Manufacturing cost of lighter part (%16) without support will be lower than using optimized parts. Nevertheless, for the low quantity products fabricating complex part decent cost will be a good alternative to conventional technologies.

Conclusion

In automotive industry, it is important to fulfill the safety regulation while insuring mechanical resistance of the parts. For adaptation of additive manufacturing into the automotive industry, a case study has been demonstrated to be successful under safety regulations. Combining lattice optimization method with DMLS process could open the way of weight reduction beyond the countless possibilities. The results of the present study confirm the validity of complex geometry of vehicle hinge parts produced by AM with finite element analysis. The following conclusions can be made based on the above research.

(1) In the case analysed here, the aim was to demonstrate value of cellular structures combine with the simulation of AM materials parts. It was found that significant weight reduction is feasibly due to simulation approach and mechanical properties AM material.
(2) While optimized parts fulfilled the safety criteria, also weight was reduced. Potential of using AM technology in automotive industry is inevitable, we foresee rapid progress in the near future.
(3) Anisotropy level of additive manufacturing materials depends on part orientation and builds direction. Horizontal build specimens show higher degree of strength and elongation. Although the other build directions specimens show slightly lower strength, very large-scale of decrease were observed at elongation at break values.
(4) For the future work, fatigue behaviour of AM materials could be considered as active factor on the functional parts.

Acknowledgements

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References

[1] S. Hallgren, L. Pejryd and J. Ekengren, "(Re)Design for Additive Manufacturing," in *CIRP Design Conference*, Stockholm, 2016.

[2] S. Crump, "Apparatus and Method for CreatingThree-Dimensional Objects". United States of America Patent US5121329A, 09 June 1992.

[3] L. Gibson and M. Ashby, "Cellular Solids: Structure And Properties", Cambridge University Press, 1997.

[4] T. Bhardwaj, S. Singh and M. Shukla, "Finite Element Modeling and Analysis of Implant Scaffolds," in *International Conference on Advances in Mechanical, Industrial, Automation and Management Systems*, Allahabad, 2017.

[5] J. Hawreliak, J. Lind, B. Maddox, M. Barham, M. Messner, N. Barton, B. J. Jensen and M. Kumar, "Dynamic Behavior of Engineered Lattice Materials," *Scientific Reports 6.,* 2016.

[6] A. Panesar, M. Abdia, D. Hickman and I. Ashcroft, "Strategies for Functionally Graded Lattice Structures Derived Using Topology Optimisation For Additive Manufacturing," *Additive Manufacturing,* vol. 19, pp. 81-94, 2018.

[7] P. Terriault and V. Brailovski, "Modeling and Simulation of Large, Conformal, Porosity-graded and Lightweight Lattice Structures Made by Additive Manufacturing," *Finite Elements in Analysis and Design,* vol. 138, pp. 1-11, 2018.

[8] J. Mutua, S. Nakata, T. Onda and Z. C. Chen, "Optimization of Selective Laser Melting Parameters and Influence of Post Heat Treatment on Microstructure and Mechanical Properties of Maraging Steel," *Materials and Design,* vol. 139, pp. 486-497, 2018.

[9] D. Croccolo, M. Agostinis , S. Fini, G. Olmi, F. Robusto, S. Kostić, A. Vranić and N. Bogojević, "Fatigue Response of As-Built DMLS Maraging Steel and Effects of Aging, Machining, and Peening Treatments," *Metals,* vol. 8(7), 2018.

[10] B. Mooney, K. I. Kourousis, R. Raghavendra and D. Agius, "Process Phenomena Influencing the Tensile and Anisotropic Characteristics of Additively Manufactured Maraging Steel," *Materials Science & Engineering A,* vol. 745, pp. 115-125, 2019.

[11] *Vehicles with Regard to Door Latches and Door Retention Components.* [Art]. Status of United Nations Regulation, 2010.

[12] "Simulation Driven Design with Inspire," Altair University, 2018.