# DESIGN OPTIMIZATION OF ALUMINUM HINGE PARTS FOR LIGHTWEIGHT VEHICLES: PERFORMANCE, DURABILITY AND MANUFACTURABILITY

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**Abstract —** Today, global energy demand and the importance of sustainable environment are growing rapidly. Thus, producing fuel-saving and energy-efficient vehicles in the automotive industry has become a priority target. While becoming conscious of consume fuel, reducing the weight of the vehicle for fuel saving have been studied and shown to be necessary. Much effort is currently being aimed at reducing the weight of vehicles in order to improve fuel efficiency and to reduce greenhouse gas emissions. The automotive industries visualize that a multi-material vehicle parts are one of critical factors to succeed this aim. It can be achieved by replacing materials with high strength steel and aluminum alloys in the vehicle. It must be done without compromising the performance or the safety of the vehicle by using an appropriate material at the right position.

The future opportunities for new lightweight vehicle parts have been investigated by using topology optimization methods. And also finite element analyses (FEA) is an important tool for achieving it since it decreases prototyping costs and time. Vehicles have different door systems and one of the important parts of them is hinge. Door hinges are a key product in the automotive industry. The function of automotive door hinge is not only to close, open, and keep the open angle of the door but also to reduce traumas for passengers in the car when a vital accident occurs. An automotive door hinge is mainly composed of four elements, mobile part, fixed part, hinge body and link. In this study, an approach for FEA and re-design process for automotive door hinge link is presented. Hinge link is made of mild steel, currently. Structural analyses are applied on hinge link by using Hyperworks. The boundary conditions, which are used in the analysis, are determined according to the data from test bench. After evaluation of the FEA results, this part was manufactured by aluminum alloy with the same design for lightweighting. The new prototype hinge link was performed fatigue test and failed. Besides, FEA results showed that higher stress occurred on it. Therefore, the hinge link was completely re-designed by using topology optimization methods. Topology optimization was performed in solidThinking Inspire. By applying topology optimization three different models were created. The most strength design was selected accordingly the FEA results. To verify the analyses results prototype hinge link was conducted fatigue tests. The results indicated that, the new design of the hinge link which made of aluminum provided the desired safety condition and nearly 60% weight reduction was achieved.

## I. INTRODUCTION

There have been growing concerns over fuel consumption and pollution caused by the increasing number of vehicles, and the automotive industry is under great pressure to reduce fuel consumption and emissions. There are a number of approaches for improving vehicle energy efficiency and lowering emission rates [1,2]. Vehicle weight reduction has been considered as one of the most important solutions to improve fuel economy and reduce harmful emissions. This is an integrative technique that utilizes all fields of optimized design, manufacturing and suitable material selection. So that is possible to reduce the mass of an entire structure and its single elements while increasing the functional quality. Innovative and optimum design is one of the key approaches for lightweighting. Material substitution is another method for this purpose, where existing materials such as mild steel and iron are replaced with high strength steel and aluminum alloys [3].

A successful material selection process is only possible through an optimized and balanced solution between cost reduction and improved safety. It is believed that the lightweighting can be obtained by the use of multiple materials without cost increase [4]. Various weight reductions of vehicle parts have been observed using high strength steel, aluminum and composite materials. However, cost is the main barriers to replacing conventional steel with these materials. Therefore, the design of optimized multi-material automotive parts requires effectively evaluating the advantages and disadvantages of using multiple materials for components [5]. It is very important to select right material types for right locations of the parts to get desired functions and weight reduction. There are various studies about multi-material solutions of the vehicle lightweighting in the literature [6,7].

In terms of material substitution, aluminum is increasingly the material of choice for automotive industry as they address growing concerns about sustainable environment. One of the main advantages of aluminium is availability in a large variety of semi-finished forms (casting, sheet and extrusion etc.). All forms are suitable for mass production and innovative solutions in automotive industry. Compact and highly integrated parts meet the high demands for high performance, quality and cost efficient manufacturability [8,9]. Due to superior properties and lightweighting potential, aluminum alloys are investigated and utilized in automotive sector. During the last decade the average amount of aluminium used in vehicles has doubled, and based on the new design concepts progress will keep on following this trend in the coming years [10,11].

As well as superior properties of aluminum, it is highly recycled due to the high value of aluminum scrap, and the use of recycled aluminum in automobile industry provides additional environmental benefits [12]. Today, nearly two-thirds of the aluminum used in automotive applications is recycled metal [13]. Despite its high costs, in the manufacturing phase also it has some benefits. Aluminium is extensively adaptable to tooling and machining processes. Mostly tooling costs are lower than steel and the high speed at which certain processes can be completed, offer greater cost savings. According to a sustainability study on automotive materials, aluminum achieved the best lifetime performance for overall energy use and greenhouse gas emissions. The life-cycle assessment study on the impact of aluminum and steel parts showed that aluminum 20% more energy savings to steel [14].

Optimum design solution from a weight and cost perspective is an important task for lightweighting especially for aluminium alloys. In part manufacturing, material substitution is generally connected to an extensive re-design procedure. Competitive use of aluminium in structures requires an aluminium-oriented design approach and suitable manufacturing process selection. Only a material substitution does not result in an optimum solution for cost and lightweighting. Too much material causes higher cost and heavier products without benefits. As well as there is also pay an attention to choose extreme weight reduction with materials which cost is too high. Therefore, it is essential to evaluate the cost-efficiency and weight reduction together [15].

Optimization is valuable tool for lightweighting and cost reduction of automobile parts. Finite element based topology, shape and size optimization approaches are available for product design. Size and shape optimization methods solutions are keep the same topology of the beginning design so these solutions are not optimal [16]. Shape optimization is more flexible than size optimization due to changeable geometric boundaries. Topology optimization allows the maximum freedom in the design space by a possible change even in the structure [17]. Finite element based topology optimization method is typically used as part of a multi-phase product-design process. Firstly topology optimization is performed in an enveloping design space to get an idea about the product. And then suggested design from topology optimization is interpreted to form an engineering design which is then optimized using detailed size and shape optimization methods.

Since material substitution and topology optimization procedures have considerable interest in automotive parts lightweighting, there are several studies in the literature. Kim et al. (2014) designed suspension lower arm in combination with FEA and design optimization. They stated that, new lower arm more stiffness and compared to the conventional steel lower arm while having 50% less weight [18]. Polavarapu et al. (2009) used topology optimization combined with free-size optimization for lightweight design of a die cast automotive seat frame [16]. Hirsch (2011) showed the lightweighting potentials and targets of the sector. He stated that it is possible to achieve 50% weight savings of parts with the help of aluminum while maintaining safety and performance [19].

The objective of this study is to design and prototype lightweight aluminum hinge link part for vehicle doors according to safety regulations. An approach of FEA and re-design process of automotive door hinge link was conducted. Different link designs were revealed and verificated by the FEA. New aluminum hinge link part was manufactured and bench tests were conducted. The mass reduction obtained was nearly 60%.

## II. AUTOMOTIVE DOOR HINGES

Door hinges are an automotive part that contacts door to the vehicle body. Hinges are one of the key products in the passenger and freight safety. Their prior function is to assemble the door to the vehicle body. In addition, lock and unlock to the door and in this way ensure occupant and freight safety. Door hinges may keep the open angle of the door but also reduce traumas of the occupant while a crash occurred.

A hinge consist four main parts. These components are mobile part, fixed part, hinge body and link. Mobile part is assembling the hinge to the door and fixed part is connecting the hinge to the vehicle body. Bush is a part that pin is rotating in. In the scope of the work the hinge comprised double rotational axis. So it has mobile hinge body, short pins and bushes and link part that is guiding to mobile parts (Figure 1).

A hinge link is essential part of the mechanism (Figure 1). It is guiding part which allows working together mobile and fixed parts. It has two holes for connecting the fixed part to the mobile parts with the help of the pins and bushes. Dimension of the link parts up to hinge model and vehicle pillar design. Because when the door is closed link part must be cover the fixed part gaps for aesthetic aspect. In verification test, especially hinge durability test, it exposed moment force. Holes are the most critical

parts of the link part and usually damage is occurred these areas in bench tests.
Conventional hinge material is high strength low alloy steel and manufactured by forging as first operation and second operation is machining for creating holes and reach surface roughness.

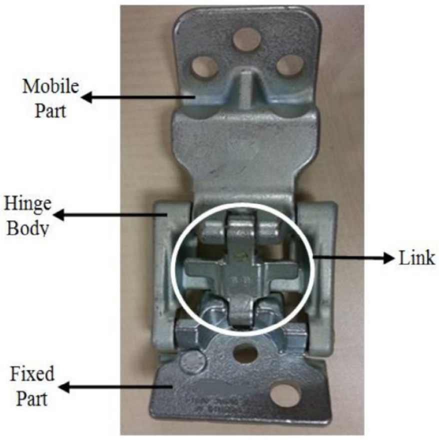
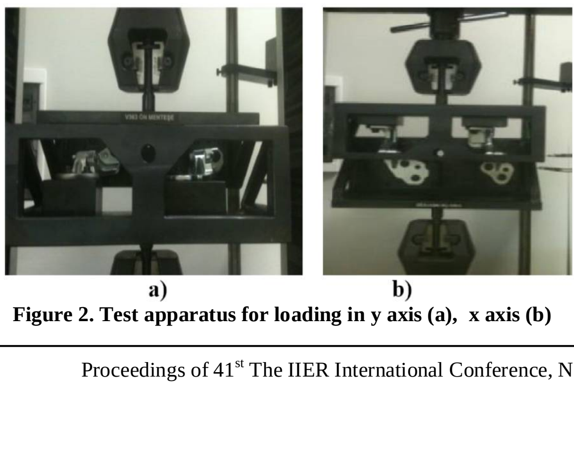



**Figure 1. Conventional vehicle door hinge**

## III. SAFETY REQUIREMENTS AND TEST STANDARDS OF AUTOMOTIVE DOOR HINGES

Due to the hinge mechanism is one of the essential parts of passenger and freight safety, it should meet various safety tests. These tests largely depend on the customers' demands and door specifications (rear cargo door, front side door etc.) One of the main requirements of the hinge mechanism is hinge strength test. It specifies requirements for side and rear door locks and door retention components (latches, hinges etc.), to minimize the likelihood of passengers being thrown from the vehicle as a result of crash. In this test, according to x and y axis direction of the vehicle, the door is subjected specified forces when it closed. After the test should be no fracture on the structural elements. Figure 2 shows the test bench of the hinge strength test according to the x and y axis of the force.
The other important test is door sag test. In this test door has to be fully opened and hinges is subjected to required force (z axis) from the locking point of door. After the force, maximum displacement in the elastic and plastic region checked from the bottom point of the door.



**a) b)**
**Figure 2. Test apparatus for loading in y axis (a), x axis (b)**

Drop off position displacement of the door is other requirements of the hinge mechanisms. When the door is in closed position and only force is mass of door, maximum displacement of door should not be more than a specific value (depends on customers' demands). This is measured from latch point of door.
Hinge durability test is the most damage occurred and most critical bench test of the verification process (Figure 3). The purpose of this test is to investigate the durability of the hinges under the high cyclic loads. Door is opened and closed within the scope of the test nearly 100,000 times (depends on customers' demands). After the test it should not occurred any damage on the hinge parts.

**Figure 3. Hinge durability test bench**

## IV. METHOD

Computer-aided design (CAD) and finite element analysis (FEA) are accepted across a wide range of industries as a crucial tool for product design. These tools are essential to accurately predict the performance of automotive parts accordingly international standards. When designing an automotive hinge most of the variables to be considered relate to either geometry or materials. A valuable tool for facilitating and shortening this complex design process are numerical simulation using FEA. FEA can predict the response of a particular design under specific conditions and provide data that can be used in the design phase [2].
Designers should know the functional requirements of the product during the design phase. As well as they should know the material specific properties due to each material possesses its own mechanical properties. The properties of a material will determine the performance of the product; therefore material selection phase is a critical stage in product design. Methods to be followed in hinge manufacturing as can be seen Figure 5.
First stage of the study is solid model creation of the link part. Customer's specific demands, safety standards and dimensions of the hinge are taken in to consideration. The link design should be maintenance

the hinge durability test without any damage. And other important design criteria for the link are visual appearance. Due to hinge mechanism can be easily seen on the vehicle rear pillar, it must be designed visual aspect. When the door is closed it covers the gap between the hinge body parts. Therefore dimensions of the hinge link have some constraints.

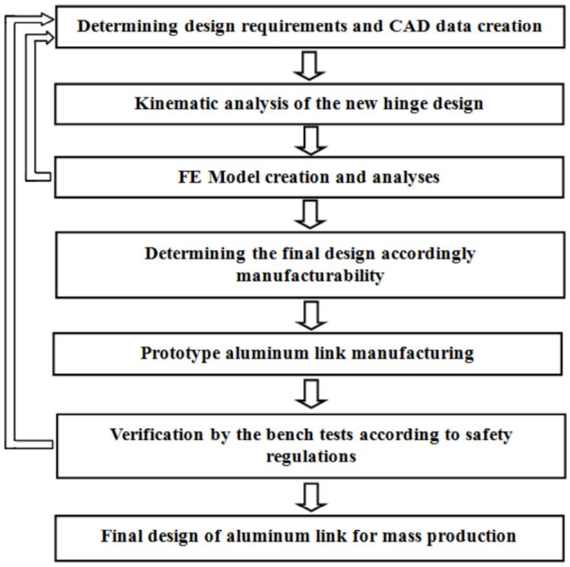



**Figure 4. Flowchart of the automotive hinge production**

This study has started with conventional hinge designs which appeared accordingly by the vehicle door systems. New design kinematic analysis is important due to the relative motion between the fixed and mobile parts. After the design phase, kinematic analyses are conducted to verify motions between the hinge parts.

After the solid model and kinematic analyses, FE model is created. The solid model of the hinge link part exported from CATIA for creation of the finite element model to HyperMesh. Finite element model has been prepared on HyperMesh V13.0. The parts are meshed with tetra parabolic elements. Pins and bushes are modeled and contacts are defined between these parts (Figure 5). The FE model is consisted 120,000 nodes and 520,000 elements. Contacts types are type 7 and frictional. Friction factor is taken 0.2.

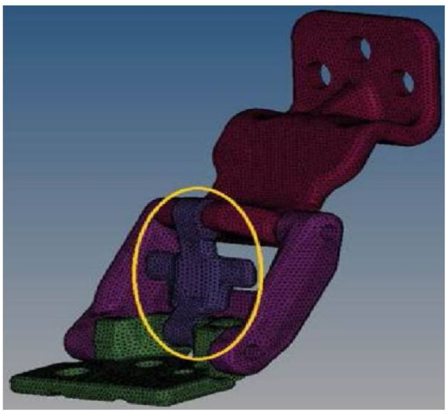


**Figure 5. FE model of the hinge**

Material properties are important for FE analysis. In this study conventional high strength low alloy steel and AA6082 aluminum alloy are used. Their mechanical properties can be seen Table 1. The AA6082 aluminium has found many applications in automotive lightweighting due to formability, corrosion resistance and surface properties.

**Table 1. Material Properties of steel and aluminum alloy**

| Material Properties | Steel | Aluminum 6082 |
|---|---|---|
| Elasticity Modulus (MPa) | 210000 | 69000 |
| Yield Stress (MPa) | 355 | 289 |
| Tensile Stress (MPa) | 554 | 324 |

Loads and boundary conditions which are applied on the link are defined in HyperMesh. Loads from latch point, are applied to mobile part for opening the door. The torque applied during analysis is depending on the door weight. In this study 30 Nm torque is applied. Fixed parts are fixed from holes (Figure 6). Then stresses of the hinge link is observed while opening and closing operations of the door. The FEA type is nonlinear implicit, and after the finite element modeling part, analyses are simulated via RADIOSS. With the help of the HyperWiew, stress values are examined.

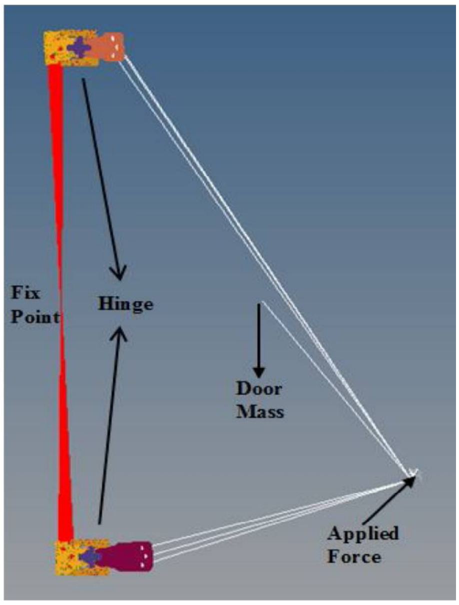



**Figure 6. Boundary conditions of the FE analysis**

After examination of the analyses results topology optimization procedure is conducted. The hinge link, which designed aluminum alloy, is re-designed by using topology optimization methods. Topology optimization was performed in solidThinking Inspire.

At the end of the study, the final design of the hinge link is determined and manufactured as a prototype. In this stage manufacturability, tooling costs and weight reduction targets are considered. Consequently, new aluminum hinge link is manufactured and it is subjected bench test for validation. Correlations between test and analysis result are investigated.

## V. RESULTS AND DISCUSSION

At the beginning of the study, topology optimization method is conducted. The boundary conditions of the link part are applied on the design space. Design spaced is determined based on the conventional link part. Optimization target is defined to make stiffness maximization and volume reduction of the link part defined 45%, 40% and 35% respectively. The result of the topology optimization for 35% volume reduction is given Figure 7.

After the topology optimization process new hinge link is designed. At this point manufacturability is very important aspect. Due to this part is manufactured by forging operation, unloading is not appropriate. In addition, hinge links one of the important aims is covering the gaps inside the hinge body. For these reasons, with the help of the approximate shape from the result of the topology optimization and design knowledge, the new hinge link is developed (Figure 8).

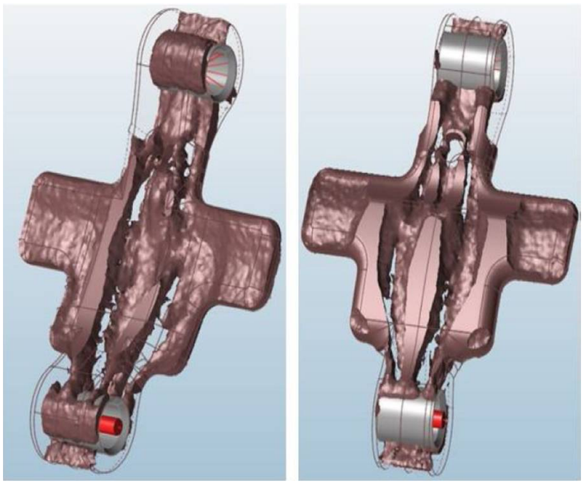


**Figure 7. Topology optimization result**

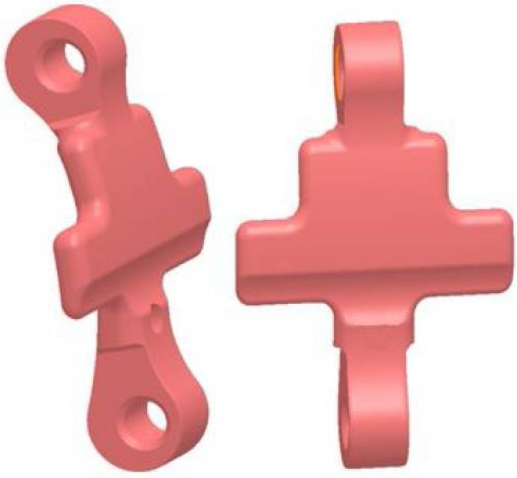


**Figure 8. CAD model of the hinge link part**

Verification procedure is important for hinge elements. After the CAD data creation, conventional steel hinge link was conducted FE analysis. The analysis results showed that, link part is provided desired safety regulations and maximum Von Mises strength was acceptable range (Figure 9).

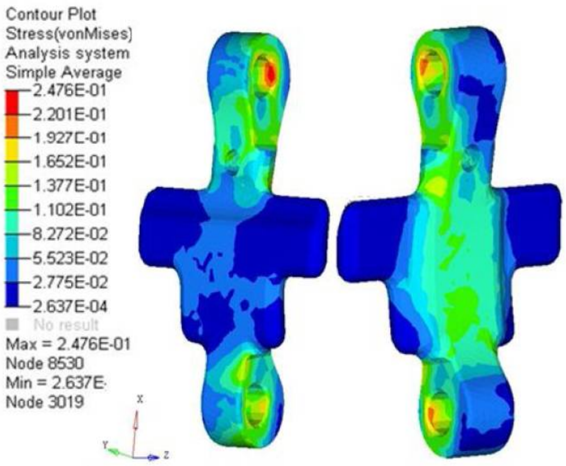



**Figure 9. Von Misses stress results of conventional design with steel**

Due to weight reduction is the most important objective of this study; firstly proper material selection phase is conducted. Aluminum alloys are promising materials for this purpose. 6082-T6 aluminum alloy is selected in this study. Since competitive use of aluminium in hinge parts requires an aluminium-oriented design approach, the design effect was examined in this study. Without any design changes, only material substitution, aluminum hinge link part was conducted FE analysis. As expected, hinge link part is failed in the FE analysis. Accordingly the analysis results, maximum Von Mises strength is 290 MPa and it occurred at around the hole in the upper portion of the link part (Figure 10).

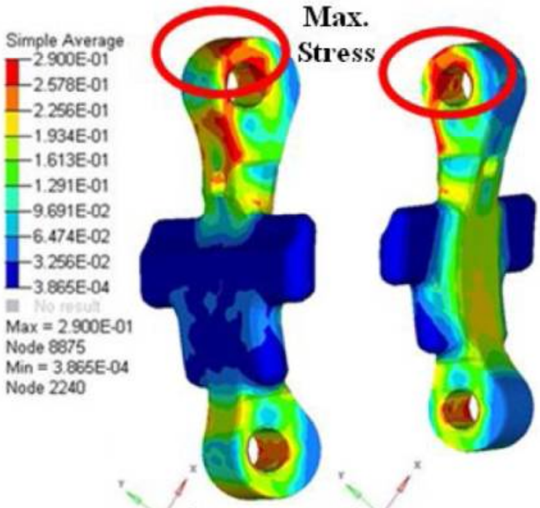



**Figure 10. Von Misses Stress results of conventional design with aluminum (t=2.8 mm)**

Aluminum hinge link, which is the same design with steel link, also damaged in hinge durability tests. Accordingly the FEA result, in the bench test also damage is occurred top hole of the link (Figure 11).

**Figure 11. Failed aluminum link after durability test**

After the examination the bench test and FEA results, decided to reinforce the aluminum hinge link design. For this purpose, to obtain the optimum solution (design constraints and sufficient strength), different surrounding the holes thicknesses (t) is used in FEA (Figure 12). Four different thicknesses (3.5, 4.5, 4.7 and 4.8 mm) are examined. The maximum thickness is determined the hinge kinematic and dimensional boundary conditions.

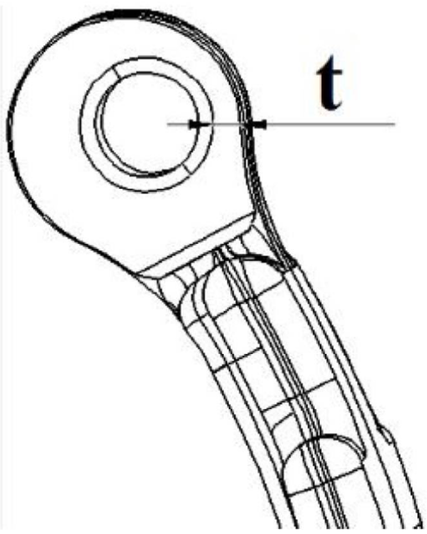



**Figure 12. Thickness of the hole surrounding area (t)**

In first case (Design-1) FE analyses, surrounding the holes thicknesses (t) were chosen 3.5 mm and analyses conducted. Maximum Von Misses stress value is nearly 287 MPa and occurred on the same region as steel design. When the results are analyzed, for getting the high resistance, is found that the thickness should be around 4.5 mm. Then new designs are conducted according to this analysis.

In the Design-2, t was chosen 4.5 mm. As seen in Figure 13 maximum stress occurred on the same region and nearly 283 MPa.

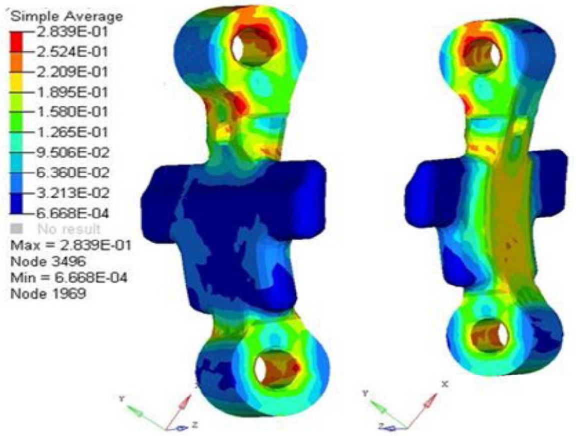



**Figure 13. Von Misses stress results of t=4.5 mm**

In the third case (Design 3), thickness (t) was increased 4.7 mm. Boundary conditions were taken same as which was applied in the first case. In this case, it was observed that maximum stress decreased and value was nearly 279 MPa (Figure 14).

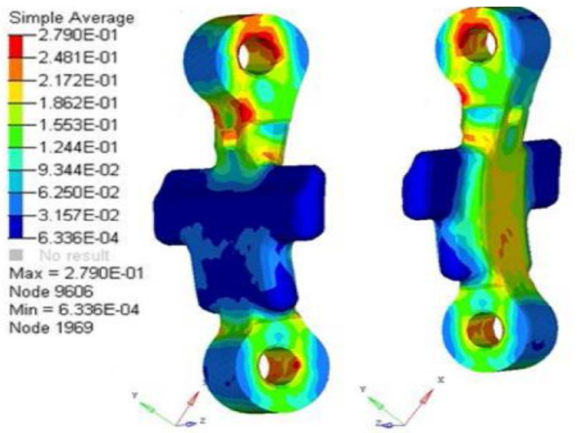



**Figure 14. Von Misses stress results of t=4.7 mm**

In the last case, thickness was increased from 4.7 mm to 4.8 mm (Design-4). It is the maximum thickness permitted by the hinge design and vehicle body design. As seen in Figure 15 maximum stress occurred on the same region and nearly 272 MPa. The FEA results of the different thicknesses aluminum hinge models and weight reductions are given Table 2.

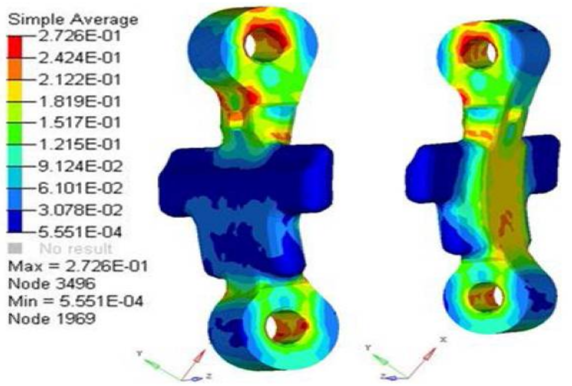



**Figure 15. Von Misses stress results of t=4.8 mm**

**Table 2. FEA and weight reduction results of the different thicknesses**

| | Material Type | Thickness (mm) | Von Misses Stress (MPa) | Weight Red. (%) | Durability Test Results |
|---|---|---|---|---|---|
| Initial Design | Steel | 2.8 | 247 | - | Ok. |
| Initial Design | AA6082 | 2.8 | 290 | 64 | Failed |
| Design-1 | AA6082 | 3.5 | 287 | 62.5 | Failed |
| Design-2 | AA6082 | 4.5 | 283 | 61.6 | Failed |
| Design-3 | AA6082 | 4.7 | 279 | 60.8 | Failed |
| Design-4 | AA6082 | 4.8 | 272 | 60 | Ok. |

As results of the analyses, aluminum-orientated design was obtained (Figure 16). New design has a design strengthening procedure. The thickness of the hole surrounding area was increased and stress value was decreased. Although increasing the thickness, with using aluminum alloy, link part has nearly 60% weight reduction than steel link.


**Figure 16. Final design of the link part**

In order to verify the results of analysis, prototype hinges which consists aluminum link with new design is manufactured (Figure 17) and subjected hinge durability bench tests. In this test results, strengthening design of aluminum link is pass the durability tests, unlike the initial design.

**Figure 17. Prototype of the new aluminum hinge link part**

## CONCLUSION AND FUTURE WORK

In this study, an automotive door hinge link part is re-designed as aluminum-oriented design. Link part is modelled for three different thickness of the hole surrounding area analyses are carried out. Analyses results correlated by the experimental hinge durability tests. Maximum stress values are decreased nearly 7% for strengthening design. With the engineering design process and material substitution, an overall reduction in weight of 60% was achieved over a reference steel hinge link part. Also, new aluminum hinge link is achieved safety tests.

This study is the first step of the ongoing project which aim design and manufacture aluminum hinge for automotive doors. At the end of the project aluminum hinge developed to be appropriate in terms of cost and manufacturability. And also service life is guaranteed as high as 100,000 cycles. New aluminum hinges are manufactured to be appropriate to the target of 30% weight reduction. As a result of the project, aluminum hinges can be manufactured using less raw material and machining processing costs and time will be reduced compared to steel hinges. The hinge is developed in this project is component with a high production volume. It produced about 900,000 units per year. Therefore, material consumption reduction, cost reduction and lightweighting potential are quite high for this component. Following stages of this study, other hinge parts are re-design with the help of the optimization techniques and then aluminum-oriented designed.

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