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# Lightweight Design and Structural Analysis of a Wheel Rim Using Finite Element Method and Its Effect on Fuel Economy and Carbon Dioxide Emission

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**Abstract**

Wheel rims made of metal alloy considerably impact the vehicle's overall weight. Consequently, employing alloys in the design of wheels results in higher fuel efficiency and lower carbon dioxide emissions. Weight reduction of vehicles also leads to better acceleration. Lightweight automotive design has been increasingly popular in recent years as a means of conserving energy and protecting the environment. The rim is an essential feature of the vehicle since it bears a substantial portion of its overall weight. A vehicle's weight can be greatly reduced by using a lightweight rim. However, the impact of a lightweight rim on improved fuel economy and reduced carbon dioxide emissions has not been widely explored. In this study, a wheel rim has been designed, and a finite element model has been developed considering radial load, where tire pressure has also been considered. A practical experiment with identical parameters had also been carried out. The values of equivalent stress, strain, and deformation for a metal and an alloy which is steel and cast aluminum alloy (A356.0), respectively, have been compared. In terms of structural stability, steel and cast aluminum alloy have shown fairly similar results based on equivalent stress and deformation. However, the use of cast aluminum alloy has greatly decreased the rim's weight as a result of its low density and high specific strength. Additionally, the aluminum alloy rim has shown superior fuel efficiency and lower carbon dioxide emissions. According to the findings, cast aluminum alloy rims are more feasible when building a vehicle wheel rim since they minimize the wheel's and vehicle's weight while maintaining structural strength. It leads to less fuel consumption, which can save fuel costs and is important for energy conservation.

**Keywords**

*Materials; Modeling; Simulation; Mechanics; Wheel rim; Inflation pressure; Radial load; Structural analysis*

## 1 Introduction

In recent years, more and more attention has been paid to the lightweight design of automobiles since the automotive industry demands higher energy efficiency and environmental protection. Wheels must be strong and light enough to support the vehicle and all the forces that act on the wheel [1]. The growing need to enhance fuel economy, prompted by worries about global warming and energy consumption, considerably impacts material selection. Automobile manufacturers, for example, are required by US federal regulations to reduce vehicle exhaust pollutants, increase occupant safety, and improve fuel efficiency [2]. Using 1 kg of aluminum in a vehicle may lower the car's weight by 2 kg. In general, for every 10% reduction in car weight, fuel consumption can be reduced by 6% to 8%. $CO_2$ emissions may be reduced by roughly 5 g/km by lowering vehicle weight by 100 kg. $CO_2$ Emission Standards set by the EU are now about 230 g/km. The weight of a typical aluminum item can be lowered by 30% to 40% of the vehicle's total weight. It also affects the acceleration and noise of a vehicle.

Yaman and Yegin presented that because of the rotating moment of inertia impact during motion, weight reduction of the wheel is more efficient than lessening weight elsewhere in the vehicle. As a result, the wheel design should consider the basic characteristics of a light commercial vehicle, such as NVH and weight. Also, several engineering goals, including specific essential performance and durability standards, must be met.

X Jiang et al. stated that it is critical in the current design to increase development efficiency and lower the number of tests. Computer-aided engineering (CAE) is a valuable technique for improving and developing automobile wheels in order to attain these aims. FEA may tell us if we have succeeded or failed, but they will not assist us in improving the design anymore. Experimental stress analysis is becoming increasingly important to validate each new wheel design. With the use of ESA, one can determine the exact stresses operating at a specific spot on the wheel during operation, which is extremely useful for design improvement. Also, it gives an idea about the behavior wheel in real life. On the other hand, the necessity of a

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prototype renders the validation process time-consuming, expensive, and inefficient [3]. Two working conditions of the wheel are bending load when driving and static load while the vehicle is stopped; these two working situations should be considered while constructing the wheel [4]. The weight of an automobile is balanced by the vertical reaction forces imposed by the road surface on four tires. Each force is transmitted via the tire, compressing the wheel in a radial direction. With a continuous revolution of the wheel, the radial load becomes cyclic when the automobile is in motion. For the sake of structural integrity, a rigorous examination of a wheel's radial load is necessary. The radial load is defined as the force applied on the bead seats as a result of the weight of the car reacting vertically on the road surface. The radial load is equivalent to a static load applied to both the rim and the tire in a direction normal to the road surface. For a radial load, the rim's tensile strength significantly impacts the spinning wheel's durability or fatigue life. It allows for an accurate assessment of the stresses that must be focused on the rim [5]. The influence of tire air pressure is an important parameter to consider while designing a wheel. Unfortunately, most of the time, it is neglected, which can affect the result. Pressure in the tire is considered to remain constant, with no effect on wheel rotation. However, it tends to alter the strains imposed on the rim. The tire air pressure is applied to the rim's outer surface as well as the rim flange indirectly. The air pressure pressing on the tire's sidewall creates an axial load. This load changes depending on the following factors: (a) tire type, (b) aspect ratio of the tire's cross-section, and (c) tire reinforcement structure.

The rim and spokes make up the majority of the wheel [6]. Most radial load operates on a few critical locations on the rim – inboard and outboard bead seats where the tire rests. The tire pressure acts on the rim flanges. The rim flanges are affected by tire pressure (j starns). To check the validity of the materials in terms of structural stability, we analyzed the loads on the key points of a wheel and compared the values for equivalent stress and deformation [7].

In this paper, the von Mises (equivalent) stress and deformation in the wheel's key points are investigated numerically and experimentally. FEA and ESA were considered to evaluate which materials are more structurally stable and lightweight between steel and aluminum alloy. Unfortunately, there is no noteworthy research where FEA and ESA have been considered simultaneously to reach a conclusion. In this paper, results from both methods were compared for the first time to reach a more accurate conclusion. Moreover, the effect of tire inflation pressure combined with other loads has also been introduced. The values of fuel consumption and carbon dioxide emission have also been compared for both materials to conclude which is superior in energy conservation and is more environmentally friendly.

## 2 Methodology

### 2.1 Materials

Material selection plays a significant part in determining the performance and weight of the wheel. Steel and cast aluminum alloy (A356.0) were the two materials used for simulating the structural behavior of the rim. The density of materials was uniform all over the body. Steel and aluminum are considered to show isotropic behavior.

Steel has proven its worth as a conventional automotive material. New high-strength steels are increasingly being employed for high-strength stress elements. High-strength steel sheets can be used in auto bodies to improve components' impact energy absorption capacity and resistance to plastic deformation [8]. However, aluminum has a density that is 1/3 that of steel. Aluminum, on the other hand, has a lesser stiffness than steel. When aluminum is subjected to the same force as steel, the result is that aluminum has a little larger elastic distortion. Cast Aluminum Alloy rims are considered because they weigh much less than steel rims while almost holding their structural integrity.

**Table 1** Material properties of steel and cast aluminum alloy

| Characteristics Name | Steel | Cast Aluminum Alloy (A356.0) |
|---|---|---|
| Young's Modulus | 200000 MPa | 70000 MPa |
| Poisson's Ratio | 0.3 | 0.34 |
| Bulk Modulus | 166670 MPa | 62000 MPa |
| Shear Modulus | 76923 MPa | 24132 MPa |
| Compressive/Tensile Yield Strength | 250 MPa | 250 MPa |
| Density | 7850 kg/m$^3$ | 2670 m$^3$ |

### 2.2 Design

The 3D modeling of the rim was done by SOLIDWORKS 2021 software. The front view of the wheel rim can be seen in Figure 1, while the side view can be seen in Figure 2. The diameter of the rim was 400 mm, and the width was 200 mm. The outboard bead seat was 51 mm wide, the inboard bead seat was 17.67 mm wide, and the thickness was 6 mm for both bead seats. There were four holes, and each had a diameter of 15 mm. The outboard flange was 10 mm in width and 9 mm in thickness. The inboard flange was 6 mm wide and 4 mm thick.

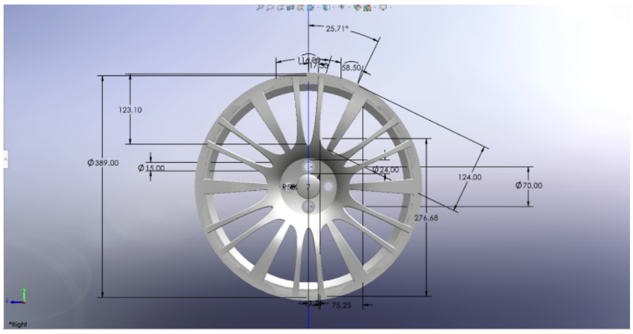

**Figure 1** Front view of wheel rim

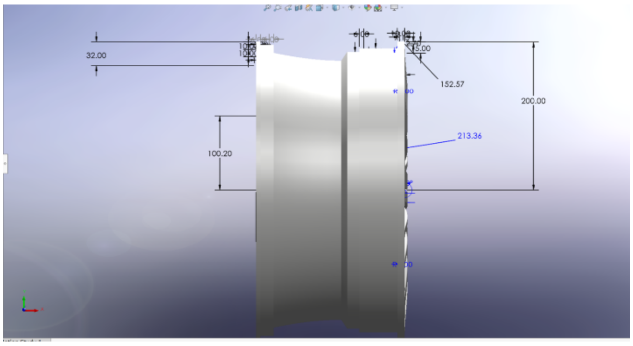

**Figure 2** Side view of wheel rim

## 2.3 Load Calculation

### 2.3.1 Radial Load

The mass of the car is 2000 kg without the rims, and the mass of 5 passengers is 400 kg. So, the total mass of a car without wheels = 2400 kg. The average maximum load on the tire, $Fr = ((2400/4)*9.8) = 5885$ N.

The radial load is expressed by the equation,

$$Q = Sr \times Fr \tag{1}$$

Where $Sr = 2.2$ acceleration test factor in conformance with SAE J328 specification.

In an actual wheel, the radial load is applied to the wheel at the bead seats with the tire. As a result, distributed pressure is loaded directly onto the bead seat of the model used in this analysis. Along the circumferential direction, pressure is assumed to follow a cosine function distribution. Accordingly, the distributed pressure, $Wr$, is given by the expression,

$$Wr = W_0 cos_0 \left\{ \left(\frac{\pi}{2}\right) \left(\frac{\theta}{\theta_0}\right) \right\} \tag{2}$$

Here, $\theta$ = angle of loading and $\theta_0$ = central angle of pressure distribution

$W_0$ is the maximum pressure on a bead seat. It is expressed by,

$$W_0 = \frac{(Fr \times 3.1416)}{(8 \times b_{beadseat} \times r_b \times \theta_0)} \tag{3}$$

Where, $r_b$ = radius of rim, $b$ = width of bead seat

Width of outboard bead seat, boutboard = 51 mm and width of inboard bead seat, binboard = 17.67 mm

Therefore, $W_0$ (outboard) = 0.952 MPa and $W_0$ (inboard) = 2.75 MPa

For, $\theta = 0^{o}$ and $\theta_0 = 30^{o}$

$Wr$ (outboard) = 0.952 MPa and $Wr$ (inboard) = 2.75/2 MPa, as half of the pressure acts on the inboard bead seat and the other half acts on the inboard [5].

### 2.3.2 Tire Inflation Pressure

Aspect ratio of tire = 45% (of width) = 90 mm

Tire inflation pressure, $P_0$ = 35 psi = 0.241 MPa, $rf$ = 200 mm.

The load on a unit length of the circumference of the rim flange of the rotating wheel is calculated using the expression $Tf = Fp/4\pi rf = (a_2\text{-}rf_2)(P_0/4rf) = 0.013$ MPa.

Half of $Tf$ acts on each inboard and outboard flange [7].

# 3 Finite Element Analysis

It is critical in the current design to increase development efficiency and reduce the number of tests. Because real-life tests can cost a lot, vary with the research, and also takes much effort, computer-assisted engineering (CAE) is a useful technique for improving and developing automotive wheels in order to attain these aims. In our analysis, Ansys 2020 R1 software was used to simulate the structural analysis.

## 3.1 Structural Analysis Condition

The mesh subdivision was used to perform a thorough three-dimensional stress analysis. The finite element model was built so that the model's geometry was identical to the rims. There are 422941 nodes and 255093 elements in the finite element model. The relevance center of the mesh was fine, and the smoothing was high. The model was tested with different element sizes to test the model's convergence. The rim was made of cast aluminum alloy and steel. The analysis was done using the following steps:

- The bolt circle's boundary constraints were set (Figure 3). The holes were also constrained (Figure 4) [9].
- The forces calculated in advance were applied to the positions described in the previous subsections.
- A compressive load of 0.925 MPa was applied on the outboard bead seat, as shown in Figure 5, and

1.325 MPa was applied on the inboard bead seat, as seen in Figure 6.

- 0.241 MPa tire air pressure was applied to the well (Figure 7), and 0.0065 MPa tire pressure was applied on both flanges as a tensile load illustrated in Figures 8 and 9 [10].

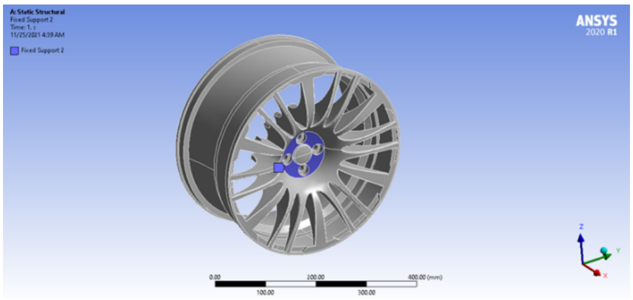


**Figure 3** Boundary condition (fixed support on disk)

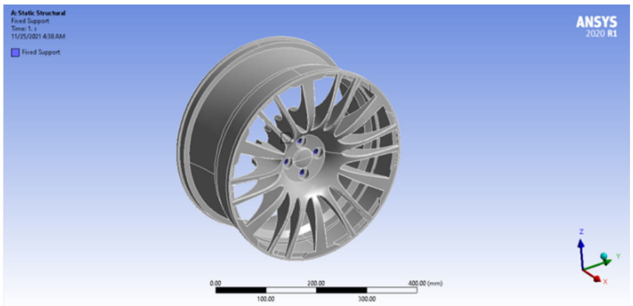


**Figure 4** Boundary condition (fixed support on lug holes)

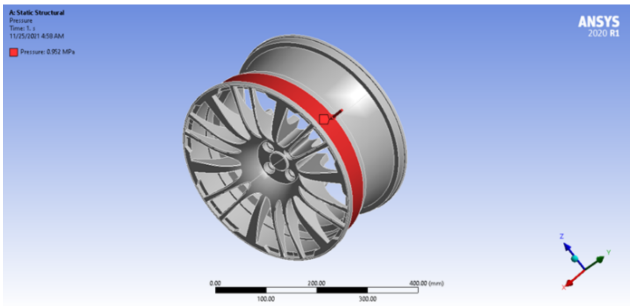


**Figure 5** Pressure applied on outboard beadseat of wheel

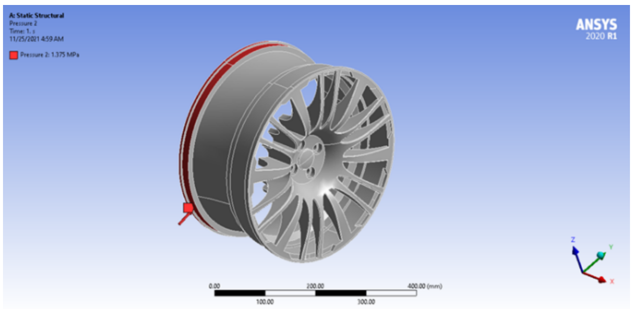


**Figure 6** Pressure applied on inboard bead seat of wheel

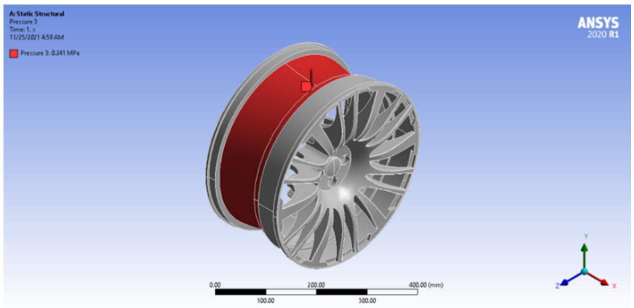


**Figure 7** Pressure applied on well of wheel

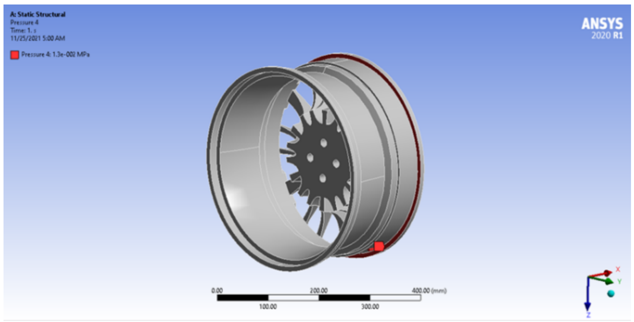


**Figure 8** Pressure applied on outboard flange of wheel

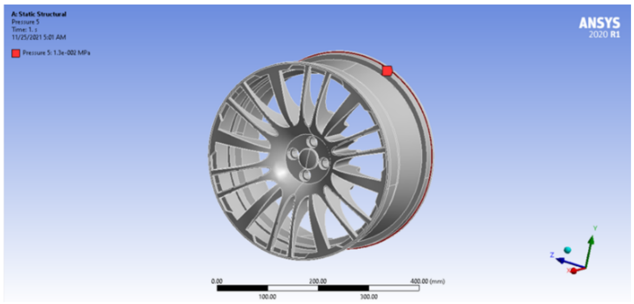


**Figure 9** Pressure applied on inboard flange of wheel

The distribution of Von Mises stress for compressive loads on the bead seats and tire pressure on well and flanges, deformation and strain values were found out. As real-life load values were used, the deformation and strain were in elastic limit. Our Von Mises stress results can be analyzed and compared in the basic strength theory according to the Von Mises yield condition (mainly Mohr strength theory). On this foundation, we can ensure the wheel's safety in the elastic range.

## 4 Experimental Analysis

Compression tests are performed to determine the behavior of a material under load. It is established how much stress a material can withstand over time under a load (constant or progressive). Experimental analysis was performed for validation.

### 4.1 Experimental Model

The same wheel model was taken as the design, and the calculated loads were applied to the key areas. The rim was made of aluminum alloy (A356.0). The dimensions were also the same as the model. Experimental analysis was done mainly on the outboard and inboard bead seat areas.

### 4.2 Testing Procedure

This experiment was performed in Universal Testing Machine (UTM). The compression tests were carried out by interposing the test specimen between two cross heads as before and applying a force to it by bringing the cross heads together, as shown in Figure 10. The specimen was compressed during the test, and the deformation and strain for the applied load were recorded.

In our case, we held the rim between the crossheads and subjected it to a real-life compressive load that usually acts on a vehicle rim similar to a static load. It is also known as the radial load. As the geometry of the rim was not uniform, different loads were applied on the outboard bead seat, inboard bead seat, and rim surface according to their construction and calculation. In this experiment, we applied loads that act on a rim in practical life, which is less than the amount needed for failing. The main aim was to compare the value of obtained deformation and strain for different materials, which in this case were steel and cast aluminum alloy.

Figure 10. Compression test of the rim using UTM

## 5 Result

The simulation results for total deformation and equivalent stress in key points of the rim are shown in the following figures. Total deformation and equivalent stress in the inboard and outboard bead seat for aluminum alloy and steel are shown in Figures 11-18. The same results for both materials in the inboard and outboard flange are illustrated in Figures 19-26. In addition, Figures 27-30 demonstrate the results for the good area. The comparison of numerical values for total deformation and equivalent stress in the five key points between the two metals is shown in Figures 31-35. Figures 36 and 37 demonstrate the comparison between numerical and experimental results for aluminum alloy in both inboard and outboard bead seats.

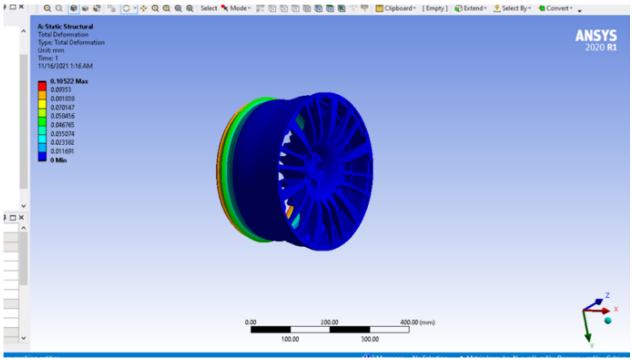


**Figure 11** Total deformation of Al alloy inboard bead seat

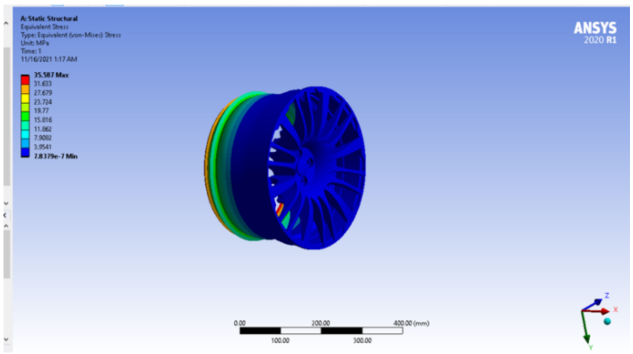


**Figure 12** Equivalent stress of Al alloy inboard bead seat

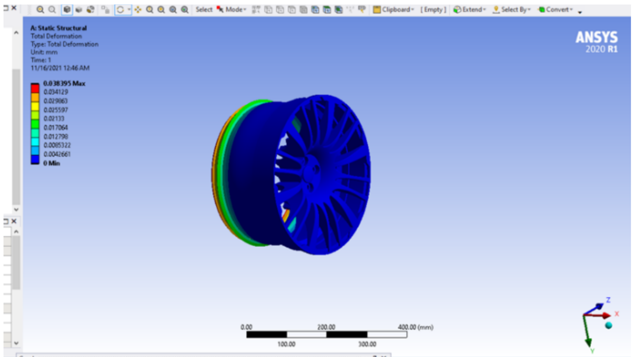


**Figure 13** Total deformation of Steel inboard bead seat

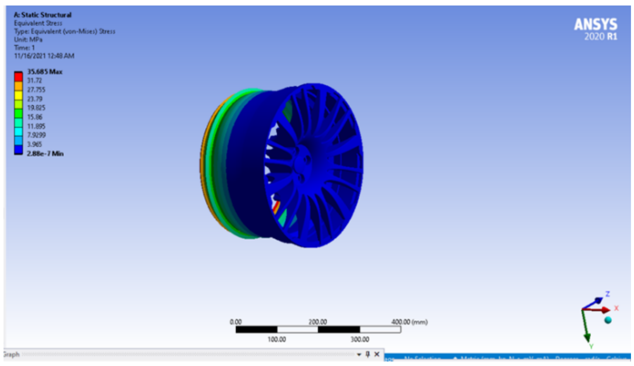


**Figure 14** Equivalent stress of Steel inboard bead seat

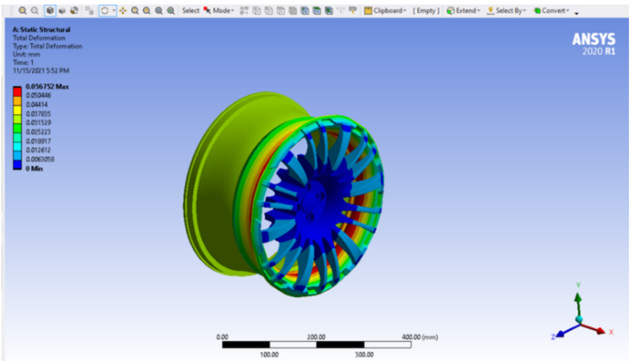


**Figure 15** Total deformation of Al alloy outboard bead seat

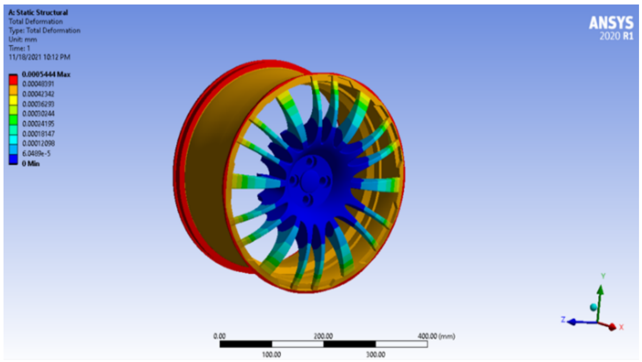


**Figure 19** Total deformation of Al alloy inboard flange

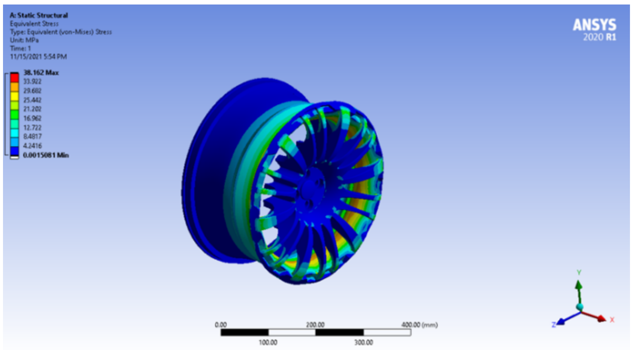


**Figure 16** Equivalent stress of Al alloy outboard bead seat

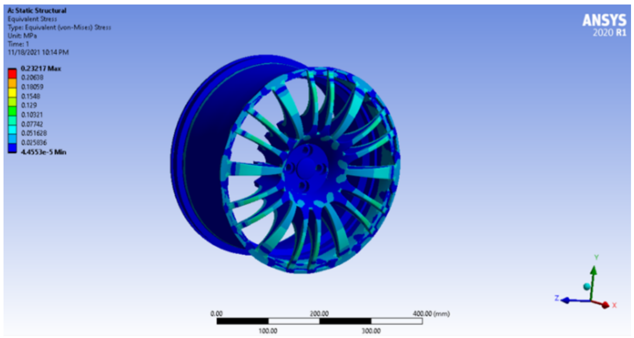


**Figure 20** Equivalent stress of Al alloy inboard flange

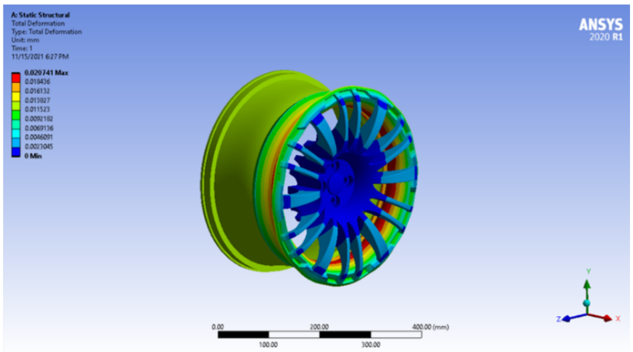


**Figure 17** Total deformation of Steel outboard bead seat

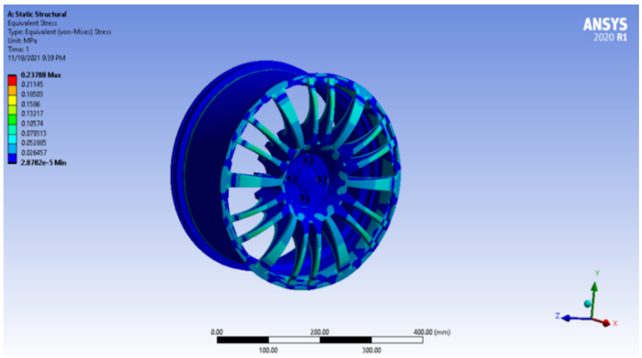


**Figure 21** Equivalent stress of Steel inboard flange

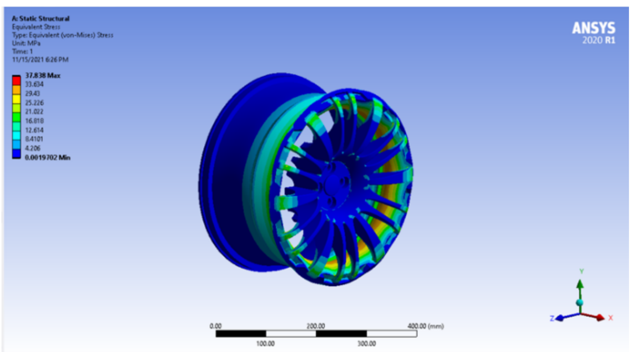


**Figure 18** Equivalent stress of Steel outboard bead seat

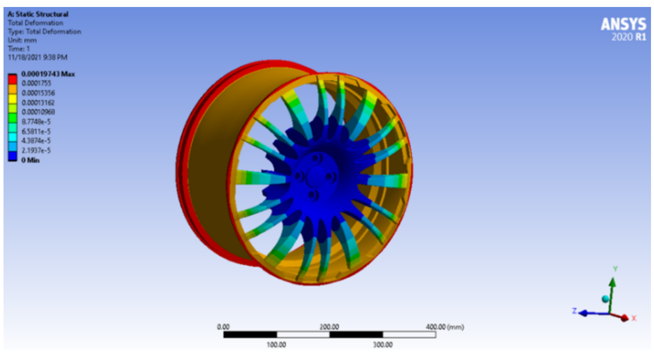


**Figure 22** Total deformation of Steel inboard flange

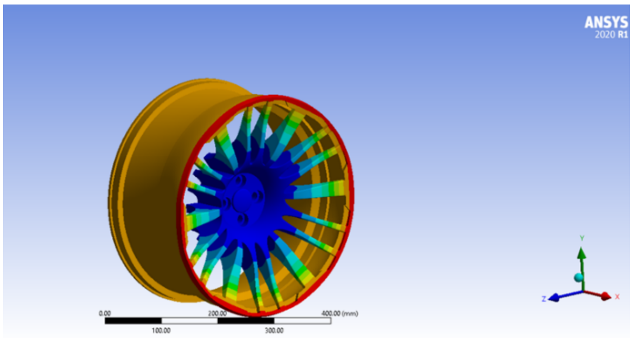


**Figure 23** Total deformation of Al alloy outboard flange

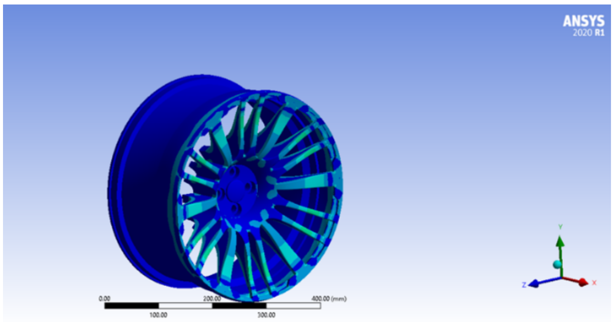


**Figure 24** Equivalent stress of Al alloy Outboard flange

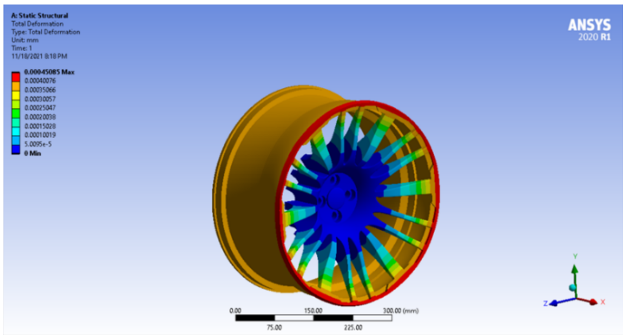


**Figure 25** Total deformation of Steel outboard flange

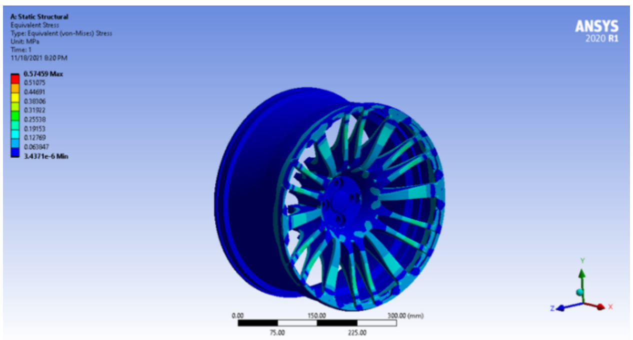


**Figure 26** Equivalent stress of Steel outboard flange

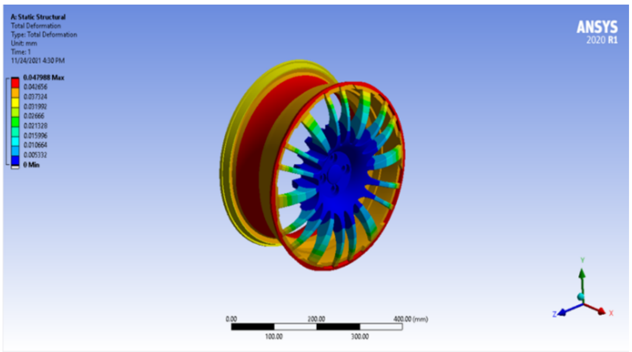


**Figure 27** Total deformation of Al alloy (well)

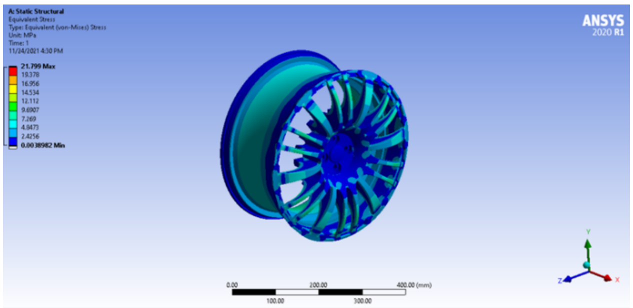


**Figure 28** Equivalent stress of Al alloy (well)

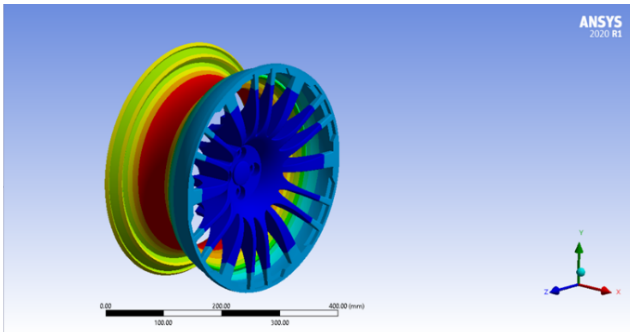


**Figure 29** Total deformation of Steel (well)

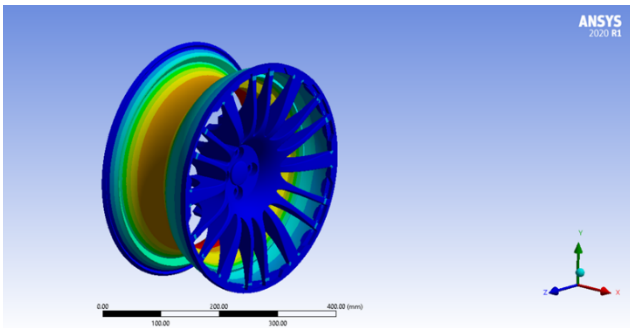


**Figure 30** Equivalent stress of Steel well

## 5.1 Comparison of Cast Aluminum Alloy and Steel based on Numerical Result

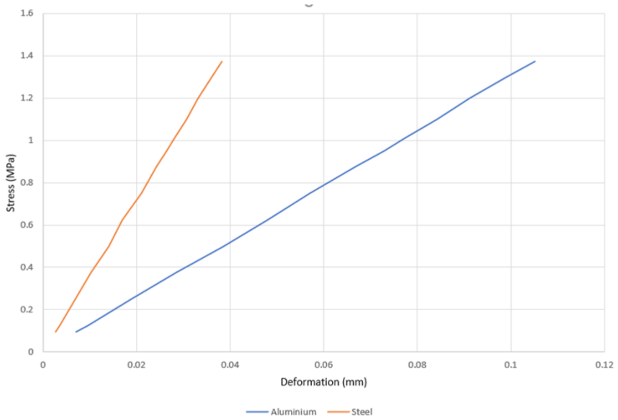


**Figure 31** Computational stress vs deformation curve for inboard bead seat

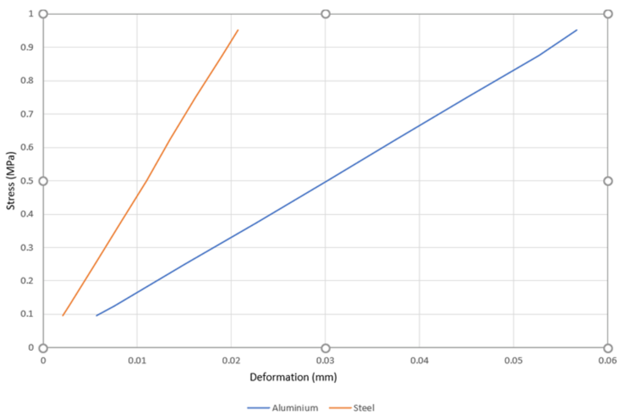


**Figure 32** Computational stress vs deformation curve for outboard bead seat

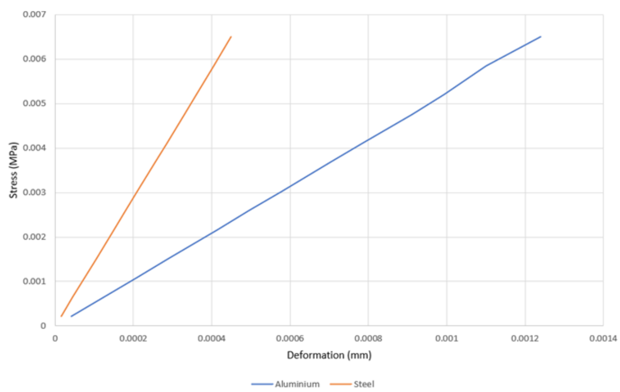


**Figure 33** Computational stress vs deformation curve for outboard flange

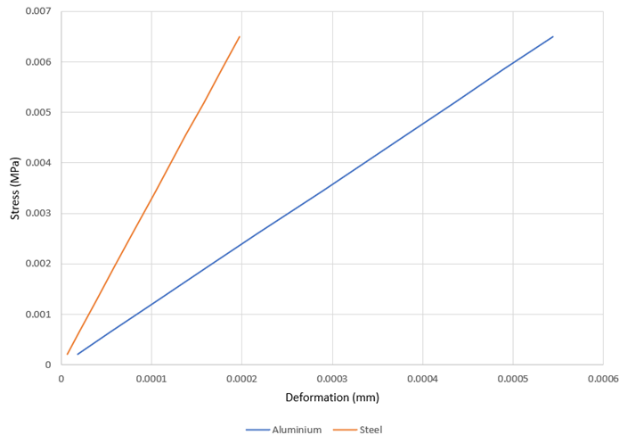


**Figure 34** Computational stress vs deformation curve for inboard flange

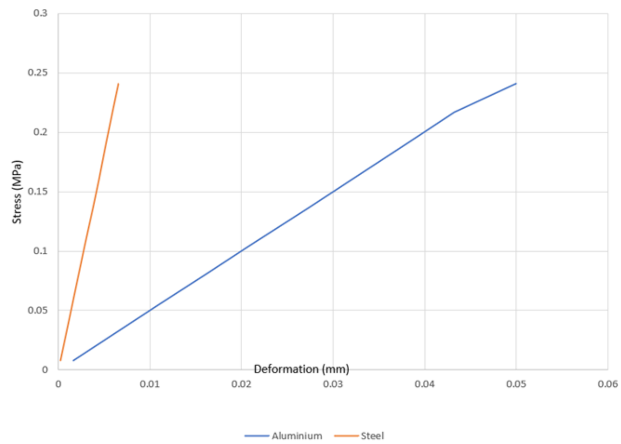


**Figure 35** Computational stress vs deformation curve for well

## 5.2 Comparison of Numerical Result and Experimental Result for Cast Aluminum Alloy

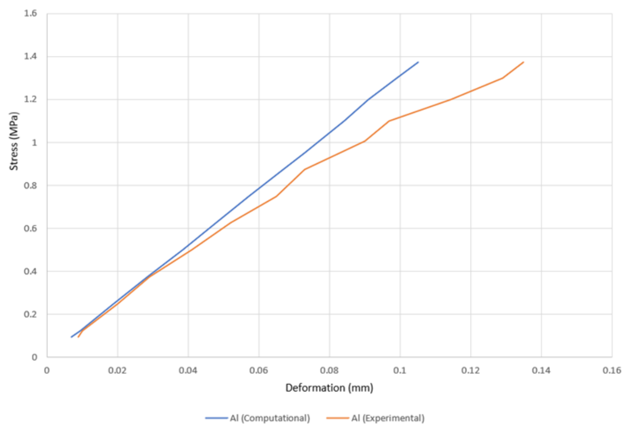


**Figure 36** Computational vs experimental stress-deformation curve for inboard bead seat

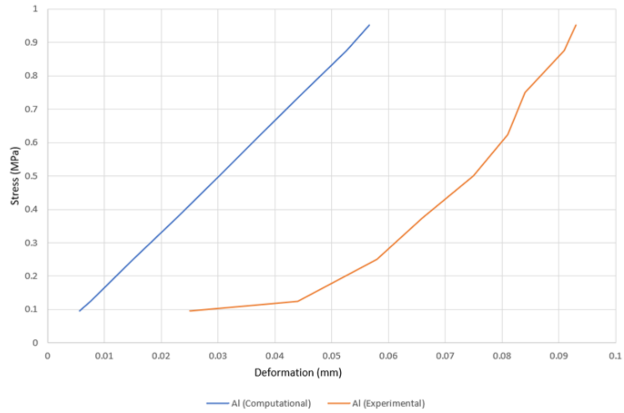


**Figure 37** Computational vs experimental stress-deformation curve for outboard bead seat

### 5.3 Weight Reduction, Fuel Consumption and $CO_2$ Emission Calculation

The volume of the rim = 3323073 mm$^3$. If we use steel rims, the mass of four wheels is (26*4) kg = 104 kg. If we use cast aluminum alloy rims, the mass of four wheels is (9*4) kg = 36 kg.

The model we considered is an Audi A8 with a steel body, and the mass of this car is 2400 kg (with passengers). The average fuel consumption is 9.9L/100km, and emissions are 199 g/km.

So, if we use steel rims, the mass is $M_{st}$ = (2400+104) kg = 2504 kg. We can calculate the energy consumption and $CO_2$ emissions from the following formulae [11].

$$E_{al} = \left\{1 - \left(\frac{M_{st} \times xy}{100}\right) \times i\right\} \times E_{st} \quad (4)$$

$$V_{al} = 5 \times \left\{V_{st} - \left(\frac{M_{st} \times xy}{100}\right)\right\} \quad (5)$$

Where $M_{st}$ is the mass of a car with all steel body; $E_{al}$ is the average energy consumption of all aluminum body cars; $E_{st}$ is the average energy consumption of all steel body cars; $V_{al}$ is $CO_2$ emissions of all aluminum body car; $V_{st}$ is $CO_2$ emissions of all steel body car; $x$ is the percent of aluminum in total vehicle; $y$ is the percent of aluminum in body structure; $z$ is the percent of steel.

Rims are around 4% of the body mass of the whole car. So, we considered $x$ = 4%, $y$ = 4% and $z$ = 70%.

Therefore, energy consumption for steel, $E_{st}$ = 12.83L/100 km, and $CO_2$ emissions for steel, $V_{st}$ = 540 g/km.

If we use cast aluminum alloy rims, the total mass of the car is $M_{al}$ = (2400+36) kg = 2436 kg.

So, if four steel rims have a mass of 104 kg and four cast aluminum alloy rims have a mass of 36 kg, the weight reduction of rims is ((104-36)/104)*100 = 65% (approx.)

**Table 2** Comparison of steel and cast aluminum alloy based on average energy consumption and $CO_2$ emissions

| | **Steel** | **Aluminum** |
|---|---|---|
| Mass | 104 kg | 36 kg |
| Fuel consumption | 12.83L/100 km | 9.9L/100km |
| $CO_2$ emission | 540 g/km | 199 g/km |

## 6 Result

Figures 11-30 demonstrate the total deformation and equivalent stress values for steel and cast aluminum alloy. The maximum values of total deformation and equivalent stress in the five key points of the rim are shown here. The figures can also show the areas where the maximum deformation and stress are formed.

Steel has a compressive yield strength of 250 MPa, which is more than cast aluminum alloy (195 MPa). It means steel can withstand more load before permanent plastic deformation. Even if we consider ultimate strength, steel has a higher value of 460 MPa, whereas for cast aluminum alloy, it is 247 MPa. So, the cast aluminum alloy will fail way before steel.

Figures 31-35 show that the deformation values are similar for both materials when low stress. With increasing stress, steel shows lower deformation values in all the key areas. However, the maximum stress and deformation values are close to each other for steel and cast aluminum alloy. For validation, the FEA values and ESA values were compared, as shown in Figures 36-37. The values of equivalent stress and deformation in both bead seat areas are considered for cast aluminum alloy, and it is seen that for inboard bead seats, the results are similar. However, for the outboard bead seat, the results vary a little. The reason is that the practical experiment was not hundred percent accurate. Therefore, the experimental values varied from the computational values. So, we can conclude that steel is better for manufacturing rims than cast aluminum alloy for structural purposes. However, we have considered practical loads instead of one stress value that is way below the yield strength of conditions, and the stress values are way below the yield strength of both cast aluminum alloy (A356.0) and steel. So, none of them are going to fail. So, under these conditions, cast aluminum alloy (A356.0) works fine.

Moreover, steel has a much higher density than cast aluminum alloy. This property affects fuel economy, acceleration, carbon dioxide emission, etc. It is clear from the calculations above. It may not seem very noticeable, but it has a huge impact when we consider 100,000 km. We have considered practical loads instead of loads needed for the material to fail.

So, even though steel is slightly better than cast aluminum alloy in terms of construction, values of deformation and stress for cast aluminum alloy are within the elastic limit. For practical loading conditions, it can withstand more load than necessary.

## 7 Conclusion

The results of the completed mechanical experiments (tensile strength test, bending strength test) confirmed that the used in this study shows that even though steel can withstand more load before plastic deformation and also before failure, cast aluminum alloy has values of deformation and stress that are in the acceptable range. Cast aluminum alloy also reduces the mass of the rims significantly. So, we get better fuel economy and $CO_2$ emissions. We also get great handling improvement and acceleration not discussed in the experiment. Although cast aluminum alloy rims have a complicated manufacturing process and cost more than steel rims, we get more mileage with less fuel in the long run, and the environment is harmed less. It would be ideal if all the forces could be applied simultaneously in experimental analysis. However, it was avoided due to a lack of resources and equipment. For the same reason, only the bead seats were subjected to load in physical experiments instead of all five key areas.

Aluminum alloy rims are a better choice but certainly not the best. Mg alloy rims are much lighter but less durable, and in today's world, composite wheels are getting more priority, for example, carbon fiber wheels. However, they are much expensive and not for everyone. Future efforts should be made to make the rim more durable but also lightweight at the same time, and it should not be limited to metals and alloys. Composite materials for structural purposes should be given more priority.

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