Materials Effect on Mechanical Properties and Weight Loss for Vehicle ABS Ring: A Simulation-Based Study

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Abstract

The ABS ring, as a critical component of a vehicle's antilock braking system, is subjected to transient impact pressure during dynamic driving conditions. This study investigates the mechanical behavior of the ring's teeth under such pressures through numerical simulation conducted in Abaqus. A detailed three-dimensional model of the ring was developed, and its nonlinear, strain-rate-dependent properties were characterized for the selected material. High-speed dynamic contact loading was applied to simulate impact conditions, and structural responses, including surface pressure distribution, stress concentration, and deformation, were extracted. The results demonstrate that optimizing the tooth geometry and selecting materials capable of effectively absorbing pressure can significantly reduce the risk of localized failure. These findings contribute to enhancing the durability of ABS components and improving braking performance under critical conditions. Finally, the results showed that the use of titanium alloy while maintaining mechanical properties can reduce the weight of this piece by up to 150 grams, which reduces fuel consumption and has an effective role in the development and protection of the environment.

Keywords: ABS Rim, Ti-6Al-4V, Aluminum, Abaqus, Mechanical Properties, Simulation.

1. Introduction

The automotive anti-lock braking system (ABS) is an active safety device that can prevent wheels from locking during braking, helping to avoid rear wheel sideslip, wheel spin, and loss of front-wheel steering ability. It enhances the vehicle's ground adhesion, thereby improving braking stability, maneuverability, and reducing braking distance. In this paper, the automobile ABS [1-3]. When designing ABS sensor rings, selecting the right material is crucial for ensuring long-lasting mechanical performance, environmental resilience, and accurate signal detection. Stainless steel remains a top choice due to its high corrosion resistance, excellent tensile strength, and ability to withstand vibration and impact, making it suitable for vehicles operating under tough climatic and road conditions. Steel alloys made through powder metallurgy, involving controlled alloy composition and high-temperature sintering, provide exceptional magnetic permeability, structural consistency, and wear resistance- enabling reliable and uniform signal generation even in challenging environments. Magnetic composite materials, which are polymers embedded with fine metallic particles, present a promising balance of reduced weight, acceptable magnetic sensitivity, and stable signal output, though their widespread adoption in automotive applications remains under development pending further durability testing [4, 5].

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Lightweight ABS plastics with metallic coatings—applied via processes like electroless plating or physical vapor deposition—reduce rotational mass, boost corrosion protection, and offer sufficient magnetic response, contributing to better fuel efficiency while maintaining signal stability. Despite this variety, powder metallurgy steel alloys and steel-based materials generally continue to dominate the industry, favored for their optimal combination of manufacturing cost, magnetic performance, mechanical strength, and compatibility with large-scale automotive production processes. Ti- 6 Al- 4 V, also known as Grade 5 Titanium, is among the most widely used titanium alloys in advanced engineering applications. It contains roughly 90% titanium, 6% aluminum (which stabilizes the alpha phase), and 4% vanadium (which stabilizes the beta phase). As an α + β alloy, Ti- 6 Al- 4 V features a dual-phase microstructure that allows its mechanical properties to be precisely tuned through thermal treatments [6, 7]. This alloy offers high tensile strength (~950 MPa), a low density of 4.43 g/cm³, and excellent corrosion resistance, making it especially valuable in environments that require lightweight yet durable components. Its outstanding strength-to-weight ratio, biocompatibility, and thermal stability make it a preferred material in aerospace, biomedical engineering (such as implants), high-performance automotive manufacturing, and marine industries. Additionally, Ti- 6 Al- 4 V is compatible with traditional machining, welding, and additive manufacturing processes, enhancing its versatility across different fabrication methods [8-10].

The Ti-6Al-4V alloy was selected for this application due to its outstanding properties, including lightweight structure, excellent corrosion resistance, and oxidation stability. With its dual-phase (α + β) microstructure and low density (approximately 4.43 g/cm³), it is an ideal choice for designing durable and lightweight components. A stable TiO_2 oxide layer naturally forms on the surface, acting as an effective barrier against corrosion and surface degradation. This eliminates the need for additional anti-corrosion treatments, which are typically required for conventional metallic components [11,12]. Furthermore, Ti-6Al-4V exhibits high thermal resistance, maintaining its structural integrity up to ~400°C. This makes it suitable for applications exposed to fluctuating or elevated temperatures. Overall, Ti-6Al-4V provides an optimal combination of mechanical strength, weight reduction, and environmental durability, making it a strategic material for advanced engineering designs [13].

In recent decades, the use of simulation software in engineering has emerged as a vital tool for the analysis, design, and optimization of complex systems. These tools enable the evaluation of component behavior under realistic conditions without the need for physical prototyping, which leads to reduced costs, enhanced design accuracy, and accelerated product development. In this study, ANSYS Workbench was employed for stress and deformation analysis, SolidWorks for geometric design of the component, and MATLAB Simulink for dynamic modeling and control. The integration of these platforms allows for a multidimensional assessment of component performance within a virtual and controllable environment [14-16]

In addition to the aforementioned platforms, Abaqus was utilized for high-fidelity finite element analysis (FEA), particularly in evaluating localized stress concentrations and nonlinear material behavior under impact and pressure conditions. Its robust solver capabilities and support for complex contact interactions enabled precise simulation of component performance under realistic loading scenarios. The integration of Abaqus into the workflow provided enhanced accuracy in predicting deformation, failure modes, and stress distribution, especially for components with intricate geometries and heterogeneous material properties [17].

This research aims to enhance the technical performance and reduce the overall weight of the vehicle's braking system by replacing the conventional ABS sensor ring material (typically steel) with the Ti-6Al-4V alloy. Ti-6Al-4V offers a high strength-to-weight ratio, exceptional resistance to corrosion and oxidation, and stable mechanical behavior under elevated temperatures, making it an ideal candidate for automotive applications. By implementing this alloy, the design is expected to achieve greater durability and reduced component mass, contributing to improved fuel efficiency and dynamic vehicle performance.

2. Materials and Methods

2.1. Materials

To evaluate structural performance and assess engineering applicability, four materials with distinct metallurgical characteristics were examined. These include low-carbon steel (SMF1015), advanced titanium alloy (Ti–6Al–4V), lightweight magnesium alloy (AM60B), and corrosion-resistant stainless steel (316L). The selection of these materials was based on a range of parameters such as density, tensile strength, hardness, Young's modulus, and yield strength. The following table presents the chemical composition of each material [18, 19].

In this study, four engineering materials—SMF1015, Ti–6Al–4V, AM60B alloy, and stainless steel 316L—were investigated based on their distinct physical and mechanical properties (Table 1). Selection criteria included density, Young's modulus, tensile strength, corrosion resistance, and manufacturability, aiming to assess their functional behavior under various loading and environmental conditions.

SMF1015, a low-carbon steel with a ferritic structure and simple chemical composition, is widely used in cast and welded components due to its high formability and cost-effectiveness. It exhibits a Young's modulus of approximately 200 GPa and a tensile strength ranging from 420 to 500 MPa. Its hardness and strength characteristics can be enhanced through heat treatment, offering flexibility in mechanical optimization.

Ti–6Al–4V, an advanced α+β titanium alloy with a density of about 4.43 g/cm³, provides an exceptional combination of low weight, high strength, and excellent corrosion resistance. It maintains mechanical performance up to temperatures near 400°C, making it ideal for components exposed to harsh environments and thermal stresses. The material demonstrates tensile strengths between 900 and 1100 MPa and Young's modulus within the range of 110 to 120 GPa.

AM60B, a magnesium-based alloy with an ultralow density (approximately 1.8 g/cm³), is extensively applied in the manufacturing of lightweight automotive parts. Its composition includes 6% aluminum and trace amounts of manganese, enhancing casting characteristics and surface corrosion resistance. With a tensile strength in the range of 220 to 260 MPa and a Young's modulus of approximately 45 GPa, its moderate hardness is offset by excellent impact absorption and workability—key features for structural weight reduction. Stainless steel 316L, composed of chromium, nickel, and molybdenum, exhibits outstanding corrosion resistance, particularly in chloride-rich and acidic environments.

Table. 1. Chemical Composition (%wt.) of Selected Engineering Materials.

Name	Mg	Si	Mn	Ni	Fe	Al	Ti	V	Zn	C	Cr	Mo	P - S	N
SMF1015	0	0.750	0.500	0	Base	0	0	0	0	0	0	0	0.025	0
Ti-6Al-4V	0	0	0	0	0	6.00	Base	4	0	0	0	0	0.028	0
AM60B	Base	0.100	0.500	0.002	0.005	6.00	0	0	0.200	0	0	0	0.025	0
Stainless Steel 316L	0	0.75	2	12	Base	0	0	0	0	0.030	17.0	2.50	0.045	0.100

It possesses a density of 7.9 g/cm³, tensile strength between 500 and 620 MPa, and a Young's modulus of around 193 GPa. Its durability and consistent performance under severe environmental conditions make it a reliable choice for pharmaceutical, food, medical, and marine industries.
This comparative analysis provides a solid basis for optimized material selection in industrial component design, especially in applications where weight minimization, thermal stability, and environmental resilience are critical.

2.2. Methods and Simulation

Fig. 1. shows the final 3D model of the sample. In this study, the ABS ring was designed and modeled in 3D in a CAD software environment, and an attempt was made to make the part more similar to the parts used in reality. For dynamic finite element analysis, ABAQUS software was used to investigate the torque applied to the ring and the impact pressure on the ABS ring teeth.

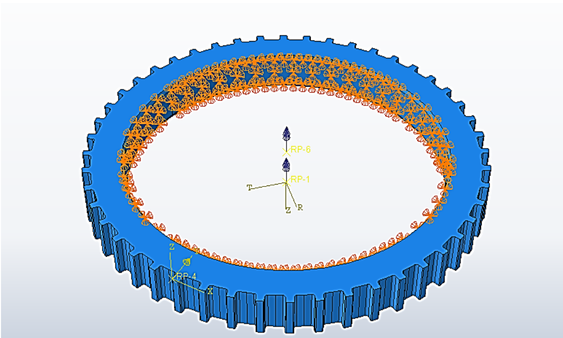

Fig. 1. Design in CAE software.

It should be noted that the ABS ring plays an important role in the performance of the ABS. Its precision-machined teeth are exposed to impact loads caused by sudden braking, uneven road surfaces, and wheel imbalance. This paper compares experimental studies and numerical simulations and introduces solutions for selecting engineering materials to increase the durability and reliability of the structure. At the same time, the goal was to reduce the weight of the part.
In the software, the Dynamic Explicit solver was used in 0.001 seconds for 4 materials, one of which is the material currently used in cars, to record the nonlinear force behavior.
In this analysis, a torque of 200 N.m and a momentary pressure of 10,000 N.m are applied to one of the teeth, and a support is placed inside the rim that prevents the rim from moving in three directions.
This force value is estimated from an article that shows a rigid object weighing approximately 500 g perpendicular to the tire with the SAE J175 standard [20-22]. Of course, in another study, Ti-6Al-4V alloy with a thickness of 2 mm is used. Mechanical properties are obtained from ASTM B265, which is also considered for the selection of one of the new materials [23-26]. Considering the design that also includes fine teeth, a mesh with a length of 1.5 mm and hexagonal C3D8R is considered. The reason for using fine meshes is to obtain values close to reality for stress and displacement (Fig. 2).

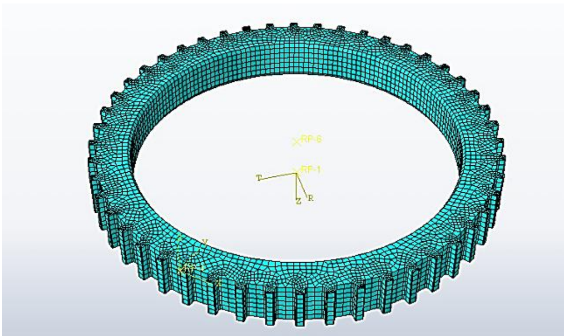

Fig. 2. Mesh design.

The evaluation criteria included effective stress, total deformation, and optimization of the weight of the structure. Finally, based on the simulation results, a real part sample was fabricated, and the dimensional specifications were measured. Given that new materials were introduced in this study, it was necessary to consider the feasibility of fabricating the real part, and therefore, the part was fabricated with the alloy that showed the best properties in the simulation.

3. Results and Discussion
3.1. Simulation Results

Fig. 3. shows the changes in von Mises stress observed for steel, titanium, and magnesium alloy samples.

The results show that the 1015 steel alloy has shown the best conditions, although the difference with titanium is very small. This small difference somewhat indicates the important point that the use of titanium alloy in the manufacture of the part is possible. It is noteworthy that the magnesium alloy has shown poor strength, which limits its use.
Fig. 4. and Fig. 5. also show the minimum and maximum stress values. As is clear, the magnesium alloy used is relatively weak, and the steel alloys are superior. However, given that the density of titanium is approximately half that of steel, the slight difference in stress values can be ignored, and the titanium alloy can be used in the production of this part. It is noteworthy that since the Ti-6Al-4V alloy is a two-phase alloy and its structure is alpha + beta, it has high strength and can be used in automotive applications. It is noteworthy that the strength of the teeth was considered in this research, and the production method can also be effective. Researchers are suggested to use different production methods, such as machining and powder metallurgy.

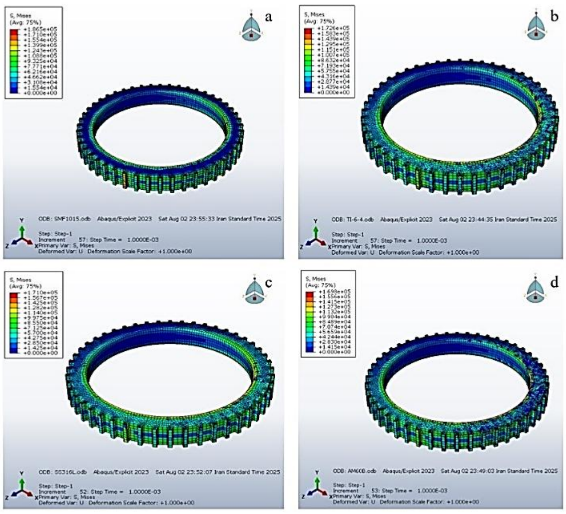

Fig. 3. Results of von Mises stress in simulation with materials: a) SMF1015, c) Ti-6Al-4V, b) Stainless Steel 316L, d) AM60B.

Fig. 6. displays the shear stress applied to the part made from different alloys. As shown, there is no significant difference in shear stress among the alloys, which is a strength of the titanium alloy. Of course, magnesium, despite being lightweight, remains weaker than the other alloys. The shear strength of titanium may be attributed to its microscopic structure, which resists shear forces. Fig. 7. also illustrates the displacement changes for different alloys. It is evident that steel offers optimal conditions, and its higher mechanical strength contributes to this. However, when considering the strength-to-weight ratio, titanium alloy could be more advantageous, especially in advanced vehicles, due to its lower weight, making it a logical choice for manufacturing this part.

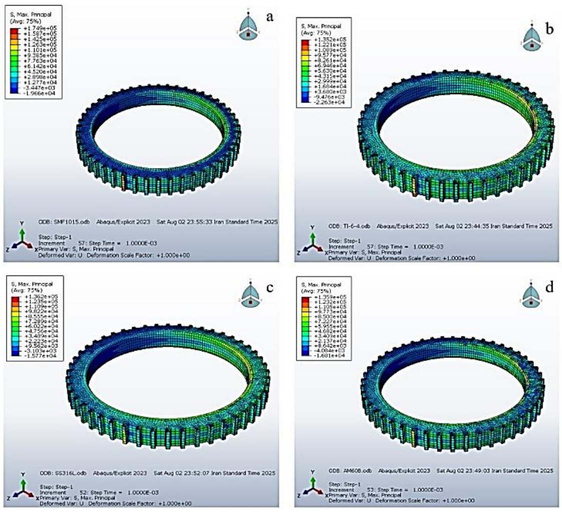

Fig 4. Results of maximum stress in simulation with materials: a) SMF1015, c) Ti-6Al-4V, b) Stainless Steel 316L, d) AM60B.

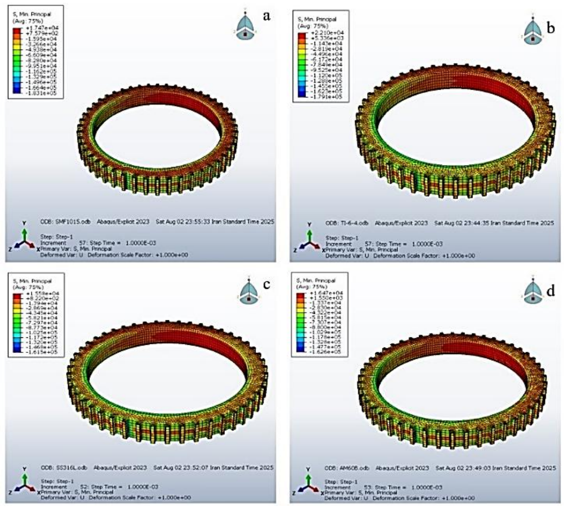

Fig. 5. Results of minimum stress in simulation with materials: a) SMF1015, c) Ti-6Al-4V, b) Stainless Steel 316L, d) AM60B.

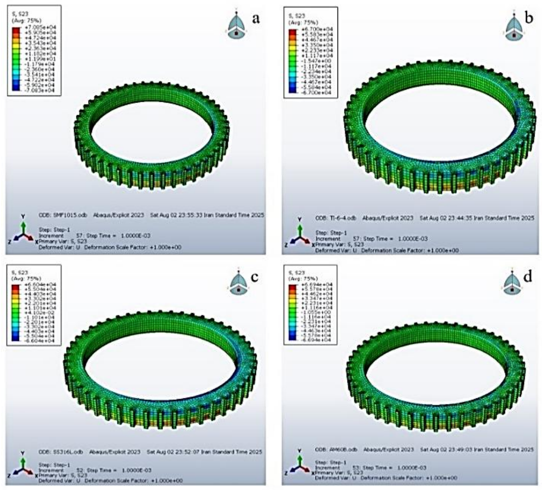

Fig. 6. Results of shear stress (S23) simulation with materials: a) SMF1015, c) Ti-6Al-4V, b) Stainless Steel 316L, d) AM60B.

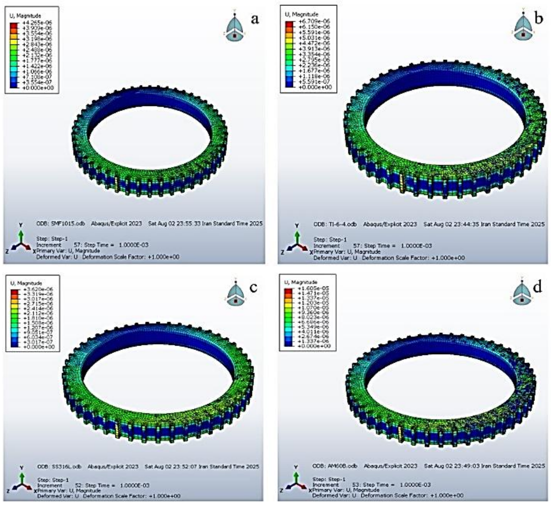

Fig. 7. Results of Magnitude Displacement in simulation with materials: a) SMF1015, c) Ti-6Al-4V, b) Stainless Steel 316L, d) AM60B.

3.2. Part Manufacturing

Fig. 8. shows the final part made of titanium alloy. Powder metallurgy was used to manufacture this part, and the final structure of the part was created. The results show that it is possible to manufacture the part with titanium alloy, and the part is free of surface damage or damage to the teeth.
Also, for comparison, the hardness of two alloys of Ti-6Al-4V and 1015 steel was compared after manufacturing. Fig. 9. shows the hardness test results of the samples.

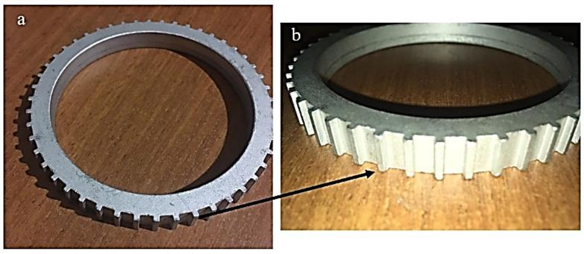

Fig. 8. Final sample manufactured with powder metallurgy, a)

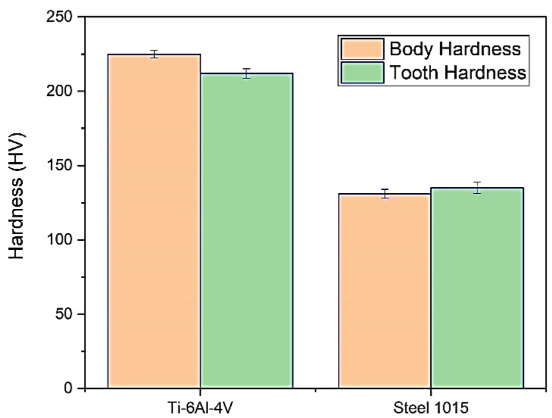

Fig. 9. Hardness of different samples after manufacturing, without any additional heat treatment.

As it is clear, titanium has favorable conditions and the hardness of the alloy in the tooth is higher than that of steel, which can help the performance and life of the part. According to the results, the development of this titanium part can lead to halving the weight and maintaining mechanical properties.

4. Conclusion

In general, reducing the weight of automotive parts is one of the important issues that is considered in the automotive industry. In this research, the ABS ring, which is one of the automotive parts, was studied and simulated. The results showed that the use of titanium and magnesium alloys is possible, but magnesium does not have desirable mechanical properties compared to steel. In contrast, two-phase titanium can create desirable mechanical properties that can be used in the manufacture of this part. The manufacturing results also showed that it is possible to manufacture the part with titanium alloy without any problems and that it is possible to develop this part with this alloy. It is also worth mentioning that if a steel alloy is used, the weight of the part is about 310 grams, which if titanium is used, the weight is reduced to about 150 grams, and considering the consumption factor of this part (2 pieces per vehicle), the weight reduction created is also effective in the fuel consumption of the vehicle.

Declarations statements

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflicts of interest

The authors declare that there is no conflict of interest.

Authors Contributions

M.Mehrjoo: Design the 3D model, First draft, Final approval. T. Ghanbari: Design the 3D model, First draft, Final approval, Y. Ghasemi: Project manager, Perform simulation, First draft, Final writing, Final approve. O. Ashkani: Sample Manufacturing, Supervision, Hardness test, Final approve. S. Mahboubizadeh: Design the 3D model, First draft, Final approval.

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