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Article

Design and mechanical analysis of bushings made from TPU using additive manufacturing and the finite element method

Diseño y análisis mecánico de bujes fabricados en TPU aplicando manufactura aditiva y empleando el método por elemento finito

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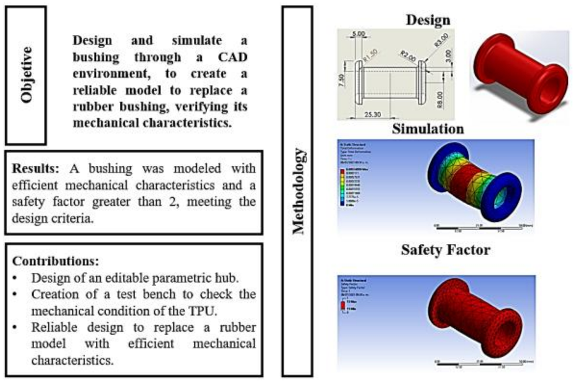
Abstract

The study focused on analyzing the mechanical behavior of a front suspension fork bushing for an all-terrain vehicle (ATV), manufactured using Thermoplastic Polyurethane (TPU) through additive manufacturing, specifically 3D printing. This technology enables the creation of customized designs, reduces production time, and minimizes material waste. TPU, an elastomer with remarkable physical and mechanical properties, was evaluated as a potential substitute for natural rubber, which is the primary material traditionally used for bushings in the automotive industry, especially in the production of tires, hoses, and seals. The analysis was conducted through CAD modeling and finite element simulations, subjecting the bushing to torsional and shear stresses typical of vehicular suspension systems. The results indicated that TPU could serve as a replacement material for the established requirements. Given that replacement parts are not always acquired in a timely manner, the study focuses on providing a viable alternative for the automotive industry.



Design and simulate a bushing through a CAD environment, to create a reliable model to replace a rubber bushing, verifying its mechanical characteristics.

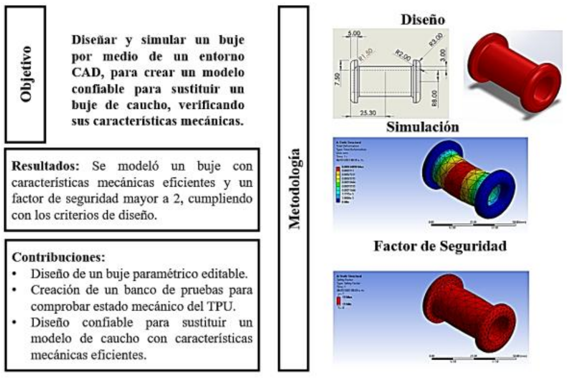
Results: A bushing was modeled with efficient mechanical characteristics and a safety factor greater than 2, meeting the design criteria.

Contributions:
- Design of an editable parametric hub.
- Creation of a test bench to check the mechanical condition of the TPU.
- Reliable design to replace a rubber model with efficient mechanical characteristics.

TPU, Additive manufacturing, FEM

Resumen

El estudio se centró en analizar el comportamiento mecánico de un buje de horquilla de la suspensión delantera de una cuatrimoto, fabricado en Poliuretano Termoplástico (TPU) utilizando manufactura aditiva, específicamente impresión 3D. Esta tecnología permite generar diseños personalizados, ahorrar tiempo de producción y reducir el desperdicio de material. El TPU, un elastómero con propiedades físicas y mecánicas destacadas, se evaluó como posible sustituto del caucho natural, el cual es el material que se usa principalmente en la fabricación de los bujes, tradicionalmente utilizado en la industria automotriz, particularmente en neumáticos, mangueras y sellos. El análisis se realizó mediante modelado CAD y simulaciones de elementos finitos, sometiendo el buje a esfuerzos torsionales y cortantes, típicos en sistemas de suspensión vehicular. Los resultados indicaron que el TPU podría ser un material sustituto para los requerimientos establecidos, ya que en ocasiones las refacciones no son adquiridas en tiempo, el estudio se centra en una opción viable en la industria automotriz.



Diseñar y simular un buje por medio de un entorno CAD, para crear un modelo confiable para sustituir un buje de caucho, verificando sus características mecánicas.

Resultados: Se modeló un buje con características mecánicas eficientes y un factor de seguridad mayor a 2, cumpliendo con los criterios de diseño.

Contribuciones:
- Diseño de un buje paramétrico editable.
- Creación de un banco de pruebas para comprobar estado mecánico del TPU.
- Diseño confiable para sustituir un modelo de caucho con características mecánicas eficientes.

TPU, Manufactura aditiva, FEM

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Introduction

The relationship between man and machine has driven the development of technologies that have transformed society, with the automobile as a clear example of this evolution. Since the Industrial Revolution, advances in science and technology have enabled the creation of internal combustion engines (ICEs), an essential system in the history of the automobile, fuelled by the knowledge of oil as an energy source. Today, cars continue to evolve, integrating electric motors and continuously improving their systems to optimise performance, safety and efficiency.

One of the most relevant systems is the suspension system. This system absorbs road irregularities, controls inertias and is key to vehicle stability and comfort (Cortés et al., 2017). The bushings, vital elements within this system, allow flexibility in the joints, prevent component breakage and prevent impacts from directly affecting the chassis, thus guaranteeing the vehicle's safety and manoeuvrability.

In addition to advances in automotive engineering, manufacturing has also evolved. According to Cortés et al. (2017), companies are forced to reconfigure their processes due to global competition and technological development. Horst et al. (2018) point out that additive manufacturing, or 3D printing, has transformed production lines, allowing for reduced costs and development times. This technique offers greater flexibility, efficiency and the ability to produce complex and customised geometries, making it a key solution to current industry problems, such as the shortage of spare parts that can affect critical systems such as suspension, compromising driver safety.

In this way, additive manufacturing offers significant added value compared to traditional techniques, as it optimises processes and responds quickly to market demands, providing innovative solutions in sectors such as automotive. A new alternative to traditional manufacturing processes is presented, highlighting its development and associated issues.

The materials commonly used in the automotive industry and the type of tests carried out on the bushings are described, as well as the tools used to carry out these studies, for which the finite element method will be the fundamental task to calculate the stresses of the model. All this in order to develop a bushing for use on a quad bike capable of resisting the loads applied to it and with a safety factor greater than 2.

Background

The automotive industry has evolved significantly with the advent of Industry 4.0, with additive manufacturing (AM) standing out as one of the most important emerging technologies. Traditionally, the production of automotive components was carried out through subtractive processes, generating material waste. AM, on the other hand, makes it possible to generate objects in a precise and customised way, optimising resources and reducing manufacturing times (Dilberoglu et al., 2017; Haleem & Javaid, 2019). Despite its benefits, AM still faces challenges in terms of cost, material limitations and product strength. Nevertheless, its implementation offers significant advantages, particularly in the use of metals and, potentially, other innovative materials.

In relation to elastomeric polymers, these have gained ground in the automotive industry for their properties such as friction resistance and the ability to absorb impacts (Ramos, 2018). These materials, such as nitrile rubber and polyurethane, are mainly used for fuel seals and in suspension systems (Lewitzke & Lee, 2001). Despite their current applications, there is a field of opportunity in exploring novel elastomers in conjunction with MA to develop more advanced and functional components.

Recent studies have investigated the properties of elastomeric bushings through mechanical testing. Non-linear behaviours have been identified in these components due to material characteristics, which affect their response to torsional and deflectional stresses (Kadlowec et al., 2009). Simulations based on the finite element method (FEM) have allowed more accurate prediction of the behaviour of these components, although the computational results do not always completely match the experimental results (Elango et al., 2022).

The use of FEM in combination with MA is positioned as a key tool to optimise the design and improve the durability of these components. The recent problem of automotive parts shortages has significantly affected the sector, with waiting times for spare parts increasing dramatically since 2020, reaching up to four months in some cases (Torres, 2022; Navarrete, 2022). In this situation, AM presents itself as a viable solution to mitigate this crisis, enabling the rapid and efficient manufacture of components, including those that are no longer in production. In summary, the combination of additive manufacturing and finite element simulation not only offers innovative solutions to address the shortage of automotive parts, but also allows optimising the design of components such as elastomeric bushings, improving their performance and reducing costs and production times.

Suspension system and bushings

The automotive suspension system, responsible for reducing road impacts, is composed of elements such as springs, shock absorbers and bushings (Arellano et al., 2016). Bushings, parts located at the junctions of the suspension system and the chassis, absorb much of the energy generated by road shocks and allow a slight movement of the suspension without compromising the rigidity of the system, avoiding the breakage of components and reducing noise and vibrations (Ortega, 2022). Bushings, generally made of rubber or synthetic materials, help prevent friction and improve the durability of the system (see Figure 1).

Box 1

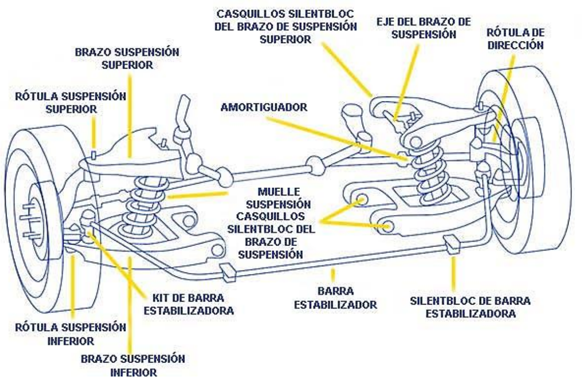

Figure 1

Main components of the suspension and steering system.

Source: MOOG®, 2023

Additive manufacturing

Additive manufacturing (AM), also known as 3D printing, is defined according to ISO/ASTM 52900-2015 as the set of technologies that create physical objects by successive addition of material (Costa, 2019). The material extrusion technique, also known as FFF (Fused Filament Fabrication) or FDM (Fused Deposition Modelling), consists of selectively depositing molten material through a nozzle. It is the most common method in 3D printing, as it is widely adopted in desktop printers. The process requires three axes of motion and a material capable of flowing through a nozzle, allowing layer-by-layer construction of a three-dimensional object. Layer height and control of material flow are key factors in print quality. In this case, the Dremel® DigiLab 3D45 printer was used (see Figure 2), which employs this material extrusion technology. It is a printer with advanced features such as an extruder that reaches temperatures of up to 280 °C, compatibility with materials such as PLA, nylon and eco-friendly ABS, and a layer resolution of between 50 and 100 microns. Its maximum printing volume is 25.5 x 15.5 x 17 cm, and it is operated via a 4.5" touch screen.

Polymaker is a brand of high quality filaments with high mechanical properties. To maintain this level of quality, Polymaker thoroughly controls every stage of production of its wide range of 3D printing materials. The filament that will be used to manufacture the bushings is PolyFlexTM TPU95 (see Figure 2).

Box 2

Figure 2

Dremel DigiLab 3D45 and PolyFlexTM TPU95.
Source: Dremel®, 2023.

Thermoplastic polyurethane (TPU)

According to Xu et al. (2020) thermoplastic polyurethane (TPU) is a polymeric material that has high ductility, good biocompatibility and excellent abrasion resistance. It can be used in structures that require high ductility, such as energy absorbing structures and portable devices. These properties pave the way for the manufacture of functional TPU parts for applications in various fields, such as aerospace engineering, medical devices and sports equipment.

All test samples were printed under the following conditions:

- Nozzle temperature = 225 °C
- Print speed = 30 mm/s
- Nozzle diameter = 0.4 mm
- build plate temperature = 80 °C
- Filling = 100%
- Layer size = 0.1 mm

Bushing stresses

Typical stresses to which bushings are subjected are as follows:

Shear stress: According to Beer et al. (2017), it is generated when opposing transverse forces are applied on a body, producing a displacement parallel to the cross-section of the material. The average shear stress can be calculated by dividing the shear force by the cross-sectional area, as shown in Equation (1):

$$\tau_{prom} = \frac{P}{A} \qquad [1]$$

EsfTorsional bending: Occurs when an object experiences a torsional moment that tends to rotate the object around its longitudinal axis. The maximum torsional shear stress is calculated by Eq. (2):

$$\tau_{max} = \frac{Tc}{J} \qquad [2]$$

Where T is the torsional moment, c is the cross-sectional radius, and J is the polar moment of inertia. In the case of hollow shafts, the maximum shear stress is obtained from Eq. (3):

$$\tau_{max} = \frac{16TD}{\pi(D^4 - d^4)} \qquad [3]$$

To ensure the structural integrity of the design, the factor of safety (FS), which relates the yield stress to the yield stress, is used.σ_y con the design effort $\sigma_{diseño}$ (Macías, 2019; Kumar, 2018). The formula is given by Equation (4):

$$F.S. = \frac{\sigma_y}{\sigma_{diseño}} \qquad [4]$$

A **factor of safety** greater than 1 indicates that the component will resist the applied loads, while a value less than 1 suggests the need to redesign or change the material. In summary, shear and torsional stresses are fundamental to assessing the strength of components subjected to transverse forces or torsional moments. Through the corresponding equations, together with the calculation of the factor of safety, it is ensured that the designed components perform within the elastic limits of the material and do not fail under operational conditions.

Finite element method

The finite element method (FEM) is a key numerical technique in engineering for solving complex problems in structures, fluids and multi-physics phenomena. According to Bathe (2007), it allows modelling and predicting the behaviour of designs, improving their safety and efficiency. Dhatt et al. (2012) explain that FEM transforms partial differential equations into systems of algebraic equations, relying on engineering science, numerical methods and computational tools.

The FEM process consists of three stages:

1. **Pre-processing**: Geometry definition and meshing, assigning material properties and initial conditions.

2. **Solver**: Selection of the appropriate physical model and solving the equations until convergence is achieved.

3. **Post-processing**: Visualisation of results in 2D or 3D graphics to analyse stresses and deformations.

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This approach is essential for the implementation of a TPU bushing, where the FEM will be applied to develop a viable model to ensure its performance under various conditions, optimising its design to achieve a balance between flexibility and strength in automotive applications.

Methodology

The criteria and processes followed for the development of the TPU bushing model and the tools used to calculate the stresses in the model are presented below, in order to calculate the integrity of the design and to have a viable alternative linked to the stress concentration and the safety factor. We start by defining the geometric characteristics and material properties of the suspension system fork bushing. Subsequently, the model is designed using CAD software, in this case SolidWorks®. Subsequently, a structural analysis is performed using the finite element method (FEM) to evaluate the behaviour of the bushing under torsional and shear forces. Based on the FEM results, the design will be adjusted if necessary to later print the model and have a design which can be used in the fork of the ATV.

Bushing Modelling

The development of the TPU bushing for the suspension system of a quad bike donated to UAQ started with a literature review of elastomeric polymers in the automotive industry (see Figure 3).

Box 3

Figure 3
ATV fork with bushings of interest.

The geometric properties of the bushing were defined, using as a reference the front suspension bushing, which was decoupled using a hydraulic press, revealing deformations in the rubber parts. It was decided to redesign the bushing in a single piece of TPU to improve its flexibility and elasticity, providing greater security to the steel axle. Rounded edges with a radius of 3 mm were implemented to increase the contact surface and reduce the concentration of stresses in the areas of diameter change. The modelling was carried out in SolidWorks® (see Figure 4), creating a sketch with the dimensions of the reference bushing and its modifications.

Box 4

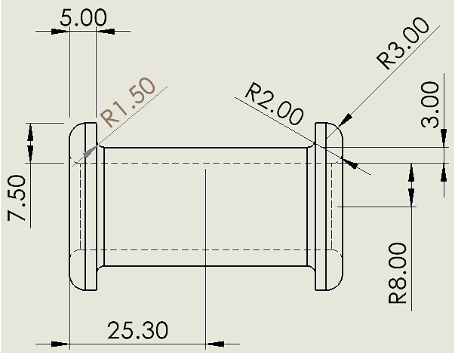

Figure 4
Dimensions corresponding to the hub

TPU material properties

As mentioned, in the pre-processing stage, once the geometry model is available, the material properties will be assigned, the ANSYS® software student version does not have the TPU material, in order to characterise the properties of the TPU filament that will be used, in this case, PolyFlexTM TPU95 (see Figure 5), as well as the reference of other filaments such as TPU 95A of the Ultimaker brand (see Figure 5), will be taken as the properties of the TPU filament that will be used, in this case, PolyFlexTM TPU95 (see Figure 5), as well as the reference of other filaments such as the case of TPU 95A of the Ultimaker brand.

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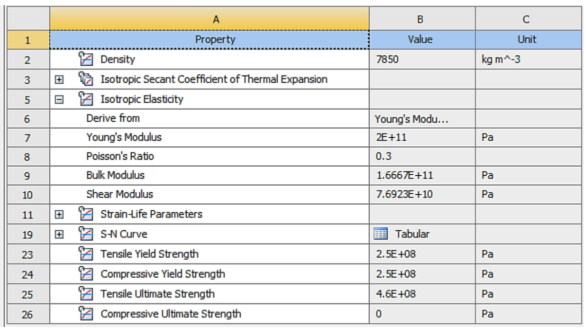
Box 5



	A	B	C
1	Property	Value	Unit
2	Density	7850	kg m^-3
3	⊞ Isotropic Secant Coefficient of Thermal Expansion		
5	⊟ Isotropic Elasticity		
6	Derive from	Young's Modu...	
7	Young's Modulus	2E+11	Pa
8	Poisson's Ratio	0.3	
9	Bulk Modulus	1.6667E+11	Pa
10	Shear Modulus	7.6923E+10	Pa
11	⊞ Strain-Life Parameters		
19	⊞ S-N Curve	Tabular	
23	Tensile Yield Strength	2.5E+08	Pa
24	Compressive Yield Strength	2.5E+08	Pa
25	Tensile Ultimate Strength	4.6E+08	Pa
26	Compressive Ultimate Strength	0	Pa

Figure 5

Characterisation of the TPU in ANSYS ®.

The meshing will be performed automatically with the tetrahedral elements that the software offers by default, in this case different numbers of elements and nodes were calculated, generating automatically 2422 elements and 4605 interaction nodes. The bushing will be subjected to torsional and shear forces, so it is necessary to perform a static analysis that recreates these forces, which is why the beam element was selected for the approximation (BEAM188).

Initial loading conditions

According to a variety of models of Italika ATVs such as the ATV200 or ATV150 the maximum load capacity is 150 kg. Ideally, the weight carried by a vehicle is distributed over the number of wheels. In the case of an ATV, a value of approximately 40 kg load will be assigned to each wheel under maximum load conditions, taking into account the occupant and the weight of the chassis.

Calculation of the stress and torsional moment

The first type of stress to be analysed will be torsional stresses, therefore, it will be necessary to calculate the torsional moment applied on the hub:

$$F_{carga} = 40\ kg * 9.81 \frac{m}{s^2} = 392.4\ N \qquad [5]$$

The torsional moment is therefore:

$$M = 392.4\ N * 0.07343\ m = \mathbf{28.8139\ Nm} \qquad [6]$$

Two fixed supports will be assigned to the ends, where ideally the bolt and nut assembly will be fixed to the fork, likewise in the central part of the bushing the calculated torsional moment is set, see Figure 6:

Box 6

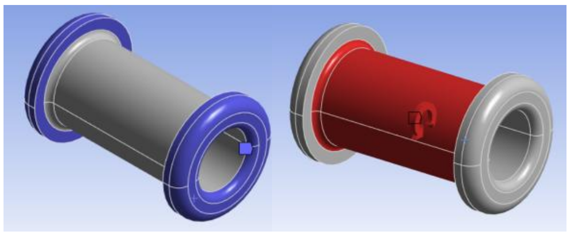


Figure 6

Bushing end supports and moment configuration

Shear stress

A longitudinal load shall be applied to simulate a shear force. The force value to be applied will be 394.4 N, calculated force and fixed support previously selected, the selected area of interest will be the same in red as in the moment configuration shown in figure 6.

Results

The results obtained by the simulation will be shown in which the stresses to which the bushing is subjected in the two stress representations are represented and at the end the factor of safety of the bushing will be denoted to validate the use of the model as a viable design.

Torsional stress in $^{ANSYS®}$.

In the following, the results obtained for the behaviour of the bushing under torsional stress are presented, the selected diagrams of interest are: Equivalent Stress (Von-Mises), the Total Deformation and the corresponding safety factor. Figure 7 shows the Von-Mises equivalent stress with a maximum value of only 0.018998 MP and it is just in the stress concentration zone due to the variation of the bushing diameter.

Box 7

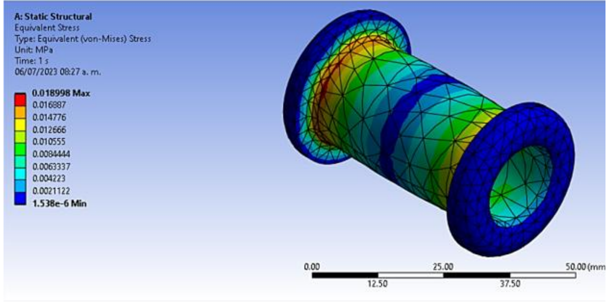


Figure 7

Von-Mises equivalent stress under torsional stress.

On the other hand, Figure 8 shows the total deformation obtained and it is approximately$1.3484x10^{-6}\,mm$, ua fairly small value which does not generally deform the TPU bushing.

Box 8

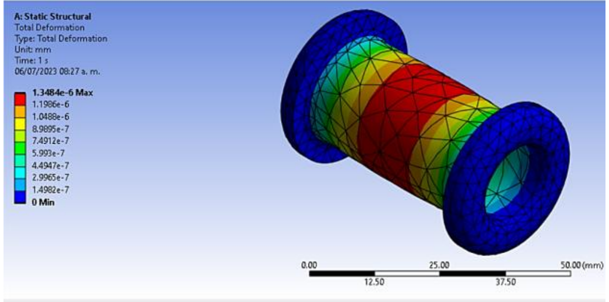


Figure 8

Total deformation under torsional stress

Finally, the safety factor value shown in Figure 9 indicates that it is 15, both the minimum and the maximum, since the ANSYS® software works with this maximum safety factor value. It can be said that the material is sufficiently safe for this type of stress.

Box 9

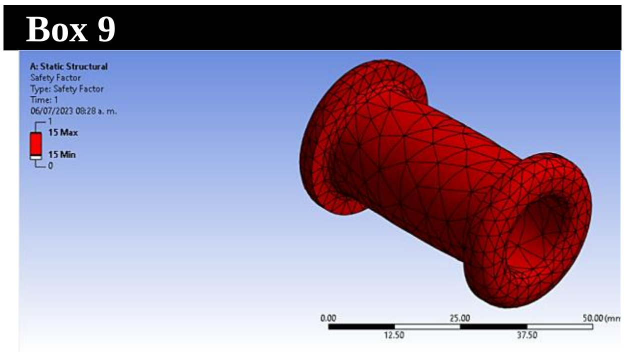


Figure 9

Corresponding factor of safety against torsional stress

Shear stress in ANSYS ®

Equally favourable shear behaviour was obtained, where the maximum equivalent stress is 3.6991 MPa present at the highest stress concentration (see Figure 10).).

Box 10

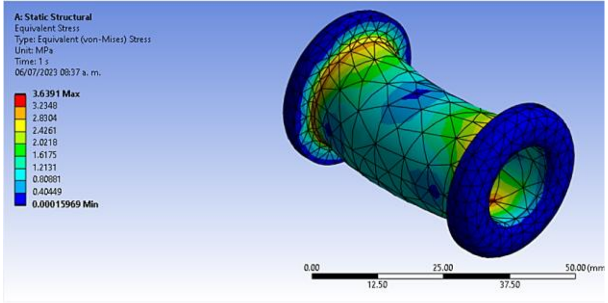


Figure 10

Von-Mises equivalent Von-Mises shear stress

The deformation obtained is barely is of$3.499x10^{-4}mm$, pr The steel is practically not deformed under this stress, with the greatest deformation occurring in the middle of the bushing (see Figure 11).

Box 11

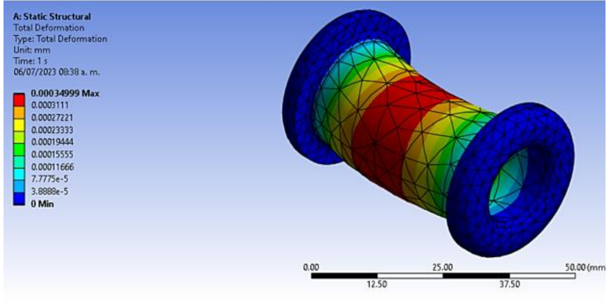


Figure 11

Total shear deformation

Similarly, the factor of safety obtained indicates that the material will be safe enough to be used for this type of stress as it is greater than 2 as shown in Figure 12.

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Box 12

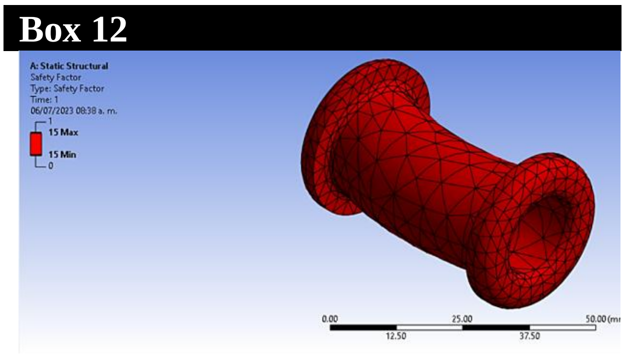

Figure 12
Corresponding factor of safety for shear stress.

Conclusions

Based on the above tests, it was concluded that a better print quality is obtained when the printing speed percentage is decreased, on the other hand, the component was too soft and flexible due to the 20% filler, so it was found to be too soft and flexible, for the last test with the printing speed parameters of 20% and a filling of 100%, a bushing was obtained that was rigid enough to be able to fulfil the corresponding function of cushioning and providing flexibility, similar to having a real bushing with the manufacturing process by means of injection moulds, as this way the quality of the filling is not lost nor does it present faults due to having hollow spaces in its interior (see Figure 13).

Box 13

Figure 13
Printed bushings for experimentation.

The present analysis of the Thermoplastic Polyurethane (TPU) bushing has demonstrated its potential as a viable solution to address the shortage of spare parts in the automotive industry, especially for parts that are difficult to obtain or discontinued in Mexico.

Throughout the development of the project, the mechanical behaviour of TPU has been evaluated in comparison to conventional rubber, suggesting the possibility of replacing rubber in its entirety, although a simultaneous analysis of both materials is needed to confirm this hypothesis.

It is essential to note that this study is based on mechanical testing only, and the thermal behaviour of TPU represents a valuable area of future research, given that the suspension system experiences temperature variations during operation. With the results obtained according to the deformations and stresses it can be observed that the desirable factor of safety is greater than 2 obtaining a feasible model within the desired design characteristics.

Experimental validation, which is still under development, will benefit from the stress calculations obtained in this analysis, which will allow more accurate testing under real conditions. Moving forward, it is suggested that the hub be mounted on a functional quad bike, as the current quad bike, which is disassembled, limits the scope of practical testing. All in all, the results obtained so far indicate that the TPU could be a promising alternative to solve the current problem of spare parts availability.

Disclosures

Conflict of interest

The authors declare that they have no conflict of interest. They have no known competing financial interests or personal relationships that might have appeared to influence the article reported in this paper.

Contribution of authors

The contribution of each researcher to each of the points developed in this research was defined on the basis of the following:

Contreras-Chávez Axel Aldahir: Contributed in the conceptualisation, methodology, software, writing and preparation of the main draft.

Villagómez-Moreno José: Contributed to the conceptualisation, writing, revision and editing, supervision and administration of the project.

Manríquez-Padilla Carlos Gustavo: Contributed to the conceptualisation, writing, review and editing, supervision and administration of the project.

Pérez-Cruz Ángel: Contributed to the conceptualisation, drafting, review and editing, supervision and administration of the project.

Availability of information and materials

For any information related to the project please contact the reference author.

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Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ATV	All-Terrain Vehicle
CAD	Computer-Aided Design
FDM	Fused Deposition Modeling
FEM	Finite Element Method
FFF	Fused Filament Fabrication
FS	Factor of Safety
MA	Additive Manufacturing
MCI	Internal Combustion Engines
MEF	Finite Element Method
PLA	Polylactic Acid
TPU	Thermoplastic Polyurethane
UAQ	Autonomous University of Querétaro

References

Background

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