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A NUMERICAL ANALYSIS ABOUT REPLACEMENT OF STEEL WITH POLYAMIDE COMPOSITE IN THE DEVICE FOR DIMENSIONAL CONTROL

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Abstract. Generally, the devices for dimensional control used in segments such as mechanical metal and mining are manufactured of steel or aluminum, materials that offer great resistance to fatigue and wear. The objective of this study is to replace a dimensional control device made of welded ASTM A36 steel sheets and steel tubes for one made of polyamide composite with glass fiber (PA 6 GF30 and PA 6.6 GF50) using the Material Extrusion process with the Additive Manufacturing (AM) technology. This is needed to achieve ergonomic requirements according to the NIOSH equation, eliminating possible failures in conventional operations and decrease the mass. The comparison between the steel dimensional control device and the PA 6 GF30 / PA 6.6 GF50 device was performed using the Finite Element Method (FEM) applied to deflection and wear resistance. An acceptable displacement was obtained for both composites, and also a reduction in the mass of the device of 67.5% for PA 6 GF 30 and 56.3% for PA 6.6 GF50. In conclusion, both composites have the capacity to withstand the same efforts as steel.

Keywords: Polyamide, Fiberglass, Control Device, Finite elements, Additive Manufacturing.

1. INTRODUCTION

Large-scale productivity is required in several segments, for example mining, which is one of the major sectors responsible for the development and improvement of quality of life (COURA, 2014). To meet the high productivity that the market demands, the process of dimensional control of your products must be done quickly and accurately, being this the reason why many manufacturers choose to use measuring devices instead of perform this process with traditional instruments.

Normally, the devices for dimensional control are manufactured of steel or aluminum to offer optimum properties to the project, however, in addition to the possibility of failures in conventional operations, in many cases the manufacture with these materials results in a device with a very high weight. Therefore, due to these needs, it was studied the replacement of steel for the polyamide composite in one of these devices using the Material Extrusion process, which is an Additive Manufacturing (AM) technology.

The polymers have some disadvantages when compared to metallic and ceramic materials, for example the tensile strength and the modulus of elasticity. To improve some of its properties, reinforcement materials (fibers, spheres or particles) are added in polymer composition, giving rise to polymeric composites.

The PA 6.6 polyamide with fiberglass reinforcement in its composition stands out among the polyamides. This material offers, among its main characteristics, great mechanical resistance, good resistance to the weather, low friction coefficient and good resistance to fatigue (WIEBECK, 2005).

The objective of this research is to replace the material of the dimensional control device, from steel to polyamide composite with fiberglass commercially obtained. Using the Finite Element Method (FEM), the mechanical properties of both composites will be compared under the same operating conditions to which the device made of steel is subjected.

2. LITERATURE REVIEW

There are many different types of devices in several segments in the industry some of them being measuring instruments, and some of them are used to control and inspect finished products. They are designed according to the conditions of each project, they may be manufactured in different types of materials, such as steel or aluminum.

Dimensional control devices can provide high precision control to the product, for linear and angular tolerances as well as geometric tolerances, ensuring reliability and safety for the process it was designed for. These instruments are also very efficient for production in series where there is the need of inspecting all or almost all parts, since measuring many of the same object using traditional instruments would be time consuming. Therefore, many companies use

dimensional control devices due to the need of productivity, so the process of checking products must be done quickly and safely.

Polyamide (PA) is a polymer that has been increasingly replacing metal in several segments due to its excellent characteristics. Polyamides are light, have excellent mechanical properties, weather resistant, low friction coefficient, high melting temperature, good impact resistance and high fatigue resistance.

Among the existing polyamides, there are PA 6 and PA 6.6, which are considered the main engineering thermoplastics. PA 6 contains 6 carbon atoms because it is obtained from Caprolactam, an organic compound that has 6 carbon atoms in its composition and PA 6.6 that has 12 carbon atoms because it is obtained from adipic acid (which has 6 carbon atoms) and hexamethylenediamine (which also has 6 carbon atoms) (WIEBECK, 2005).

Due to the fact that PA 6 and PA 6.6 are composed of amide functional group (CONH) they are shorter and allow more hydrogen bonds to be formed, this increases water absorption values when compared to other polyamides, which can decrease its degree of crystallinity and consequently reduce some properties, such as stiffness and traction, however, it increases its impact resistance and toughness (WIEBECK, 2005).

To improve some of the properties of polymers, reinforcement materials are added to their composition, giving rise to polymeric composites. Composites are formed by two phases, the continuous polymeric phase called matrix and the discontinuous phase, which is the fiber reinforcement normally formed by fiberglass, aramid or carbon. Glass fiber reinforcements are widely used because they are purchased at a low cost when compared to other reinforcements, they also offer great characteristics to the material, such as low thermal expansion coefficient, high tensile strength and good impact resistance (WIEBECK, 2005).

2.1 Recommended weight limit according to the NIOSH equation

In 1981, the American government agency National Institute on Occupational and Safety Health (NIOSH) developed an equation to calculate the weight limit for handling loads taking into account some factors. The objective of NIOSH was to create a technique capable of identifying the risks of backache linked to physical load, in order to recommend a weight limit. The last review performed on the equation was in 1994, determining the Recommended Weight Limit (RWL) based on seven factors according to Eq. (1).

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM, \tag{1}$$

Considering:

LC = Load Constant.
HM = Horizontal Multiplier.
VM = Vertical Multiplier.
DM = Distance Multiplier.
AM = Asymmetric Multiplier.
FM = Frequency Multiplier.
CM = Coupling Multiplier.

As we can see in Equation (2), the lifting index of the NIOSH equation is the quotient between the weight of the lifted load and the weight of the recommended load. Since the risk function is not defined, it is impossible to reach a precise degree of risk, however, we can consider three risk zones:

1) Limited risk: lifting index < 1. Most workers should not have any problems with this task.
2) Moderate risk increase: 1 < lifting index < 3. With the accomplishment of this task, some workers may suffer injuries or become ill. Therefore, this task must be redesigned or directed at selected workers.
3) High risk increase: lifting index > 3. Ergonomically unacceptable task and must be modified.

$$\text{Lifting index} = \frac{\text{weight of the lifted load}}{\text{weight of the recommended load}}, \tag{2}$$

2.2 Additive manufacturing

The basic principle of Additive Manufacturing (AM) is to manufacture a product without having to carry out a planning process. While other processes need a technical analysis in relation to the part, geometry to determine for example the operations to be done and the tools to be used, AM only needs some data and a little understanding of how the machine works and how the materials are used (GIBSON et al, 2010).

Using Additive Manufacturing technology, the parts are manufactured in layers, and each layer is a cross section obtained from the 3D CAD file. The thickness of the layers directly influences the final result because the thinner the

layers are, the better the end product. The construction material of this technology can be processed as powder, molten material, solid sheet or liquid photopolymer (GIBSON et al, 2010).

Extrusion-based systems consist of forcing the material to pass through a nozzle using pressure, which when constant together with the speed of application on the deposit surface, results in an extrusion with a constant transverse diameter. Upon exiting the nozzle, the material must be in a semi-solid state to fuse with the material already extruded previously, and thus forming a solid structure.

Among the existing extrusion additive manufacturing technologies, the Fused Deposition Modeling (FDM) developed by Stratasys is the most used due to the variety of materials and the excellent mechanical properties presented in its parts (GIBSON et al, 2010).

The system of this technology consists of liquefying the polymer through a heating chamber fed by a filament that is pushed by a mechanism to generate the extrusion pressure. The speed of construction is the main disadvantage of this technology when compared to other systems.

2.3   Finite element method

The Finite Element Method (FEM) is a structural analysis tool capable of studying many systems of different geometries, simple or complex, and for this reason it is widely used by engineers, mathematicians, scientists and other professionals. In addition, FEM has a wide field of use, which can be applied in linear studies, non-linear studies, static studies, dynamic studies, fluid mechanics, among others. For the correct use of this method, it is often necessary to divide a complex system into several simpler systems, and thus, obtain the solution of the problem in question by combining the partial data obtained.

The process of discretizing the domain of the equation in sub-regions of simple geometry is, in general, the main idea of the FEM. The sub-regions can be triangular, tetrahedral, quadrilateral, among others, which due to having finite dimensions, are known as "finite elements". These finite elements are connected to each other by points called "nodes", rise to a finite element mesh. Therefore, the mesh represents the union of finite elements, which often depends on good refinement to achieve acceptable efficiency. Some mesh factors are directly related to the accuracy of the results, such as the number of nodes, number of elements, size of elements and type of elements (CHEN e LIU, 2015).

With an acceptable level of knowledge in relation to the parameters involved, it is possible to predict different situations with structural analysis, and thus, improve processes and reduce manufacturing costs. Using interpolation functions, FEM reduces the behavior of an infinite field of points into a finite number of points, so it is unthinkable to perform an analysis of complex structures and other systems in a matrix formulation without using this method (TENEK e ARGYRIS, 1998).

3. METHODOLOGY

The product studied in this research is a dimensional control device called by the company "X" as "template". This template is used in the mining industry to perform dimensional control of lining, which are used to protect the interior and also to reduce the slip between the grinding load and the inner wall of many mills, such as the ball mill.

Figure 1 is a 3D representation of the lining that will be controlled by the studied template. The approximate dimension of the lining is 425 mm x 1600 mm x 1750 mm, while the profile to be controlled is the contact face with the mill (radius area shown below), the holes and the external profile.
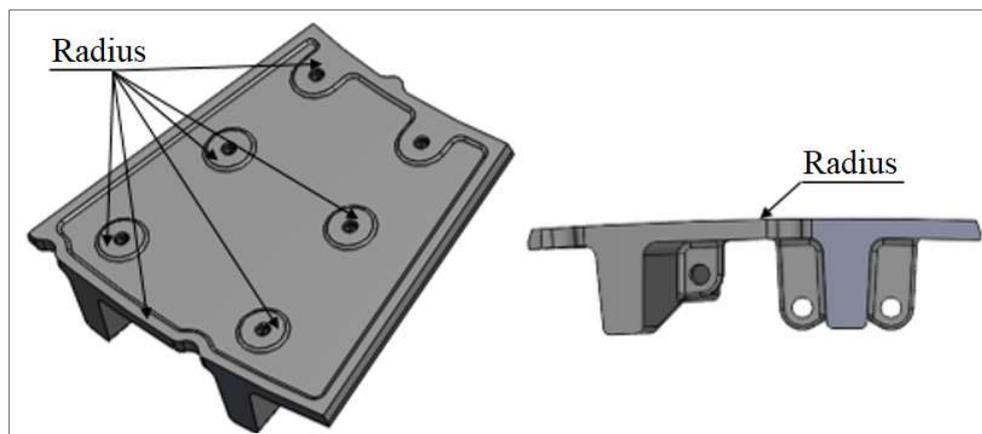

Figure 1. Lining.

This template was manufactured by the outsourced company "2X" out of ASTM A36 steel and steel tubes joined by welding. We can see that it contains the same profile and the same radius as the lining (Fig. 2).
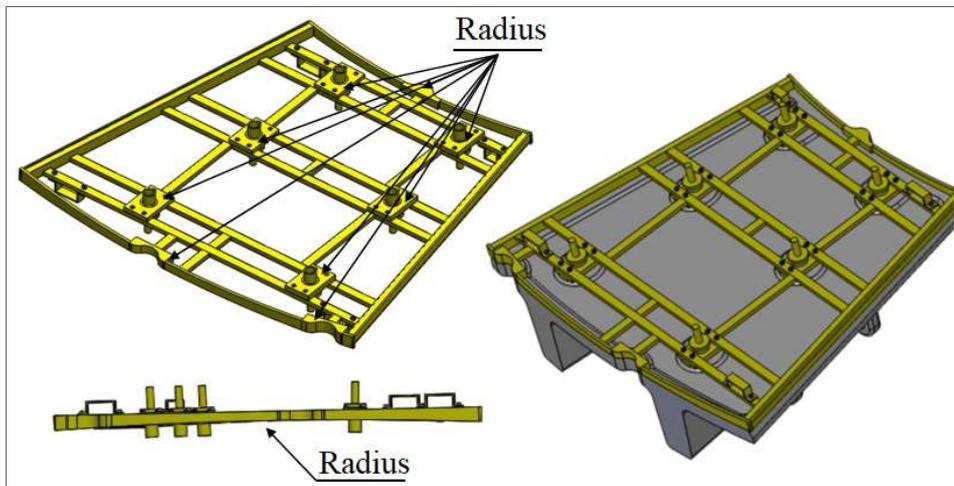

Figure 2. Template made of steel and assembly on the lining.

Because the existing template is made of welded steel plates and tubes, two possible problems have arisen. The first one is related to welding, to guarantee the final dimensioning of the template fits the project requirements of company "X", it is necessary to perform machining on all contact surfaces after welding, that is, the welding must be made with excess material. The second is the final weight of the template.

3.1   Calculation of the recommended weight limit according to the NIOSH equation

The weight of the current template is 71 kg and due to it being positioned on the lining manually by two people, the Recommended Weight Limit was calculated according to the NIOSH equation.

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM, \tag{2}$$

$$RWL = 23 \times 0.77 \times 1 \times 0.93 \times 1 \times 1 \times 1 = 16.47 \text{ kg,}$$

Two people carry out the process, then:

$$16.47 \times 2 = 32.94 \text{ kg (RWL final)}$$

Therefore, the maximum weight that the template can have is 32.94 kg.

$$\text{Lifting index} = \frac{\text{weight of the lifted load}}{\text{weight of the recommended load}} = \frac{71}{32,94} = 2.15, \tag{2}$$

The lifting index presented a moderate risk, that is, some workers may suffer injuries or become ill, therefore, this task must be redesigned or directed at selected workers (SIT, 2002).

3.2   Mechanical structural analysis using the Finite Element Method

To verify that the template was correct after its final machining, it was positioned on an already approved lining. To meet the design dimensioning specifications, it must be able to withstand the gravity load without suffering displacements greater than 0.5 mm in the contact areas.

With the use of a digital caliper with a measuring range of 0-150mm and a resolution of 0.01mm, it was possible to observe that the template had large clearances (Fig. 3), and due to this, a mechanical structural analysis was performed using the Finite Element Method (FEM) in SolidWorks software to solve the cause of the problem.

Figure 3. Initial device showing clearances.

The input data needed to perform the analysis of this study were defined based on information acquired from company "X". The device's carrying straps were considered as fixed points and the load used was gravity. The material used was ASTM A36 steel, an isotropic material from the SolidWorks material library. The amount of elements and the amount of nodes present in a mesh are factors that affect the precision of the result. With the use of the high quality standard SolidWorks mesh to perform a linear analysis on the device studied here, we believed to achieve a result close to reality, because with the use of this feature, the device had 27429 nodes and 14536 elements, numbers considered good for the complexity of the analyzed model.

In the analysis of von Mises stress, all points of the template presented a stress below the yield limit, ensuring that the material will not undergo permanent deformation. In the analysis of the resulting displacement, the template showed a maximum displacement of 0.24 mm, which for this application is an acceptable displacement. Deformations were minimal and the minimum safety factor found was 18.6. In Figure 4, we can see the representation of the resulting displacement in the initial device.
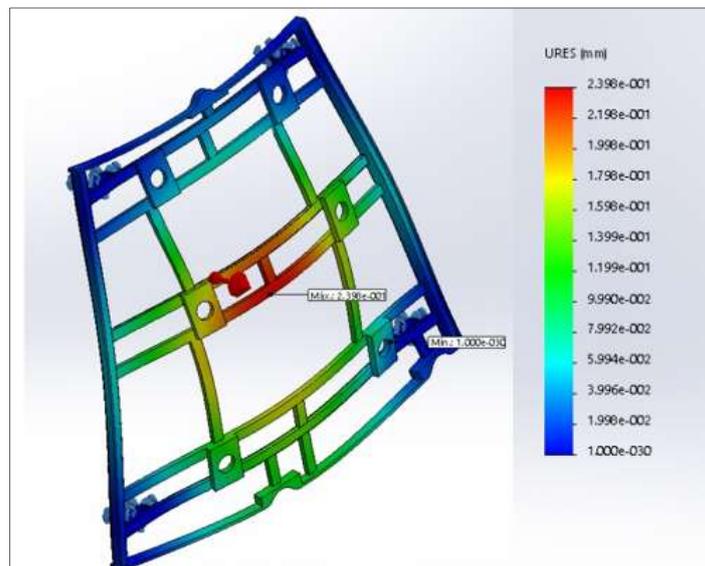

Figure 4. Analysis of the resulting displacement in the initial device.

After analyzing the results obtained with the mechanical structural analysis by FEM, it was concluded that it was for the template to meet the design dimensioning specifications, because the maximum displacement found was 0.24 mm and the maximum allowed displacement is 0.5 mm. So, why did the template show absurd clearances in the physical test? The template was machined in a CNC boring machine HBM 130T ROMI in the vertical position (standing) supporting the template in a steel corner as shown in Figure 5.
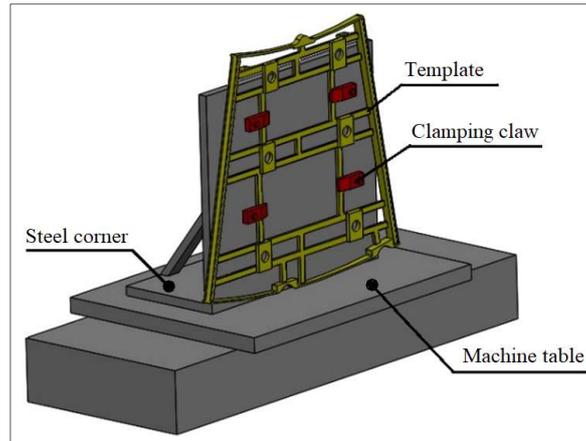
Figure 5. Fixing the template for machining.

The template was fixed to a steel corner using clamping claw tightened by screws, which when tightened moves the template to the steel corner, that is, the back of the template is forced to touch the corner of steel. This done, the operator performed the final machining of the contact areas of the template, and then loosened the clamping claw and removed the template from the machine.

If during the welding process any torsion or displacement occurrs that would compromise the alignment of all the parts located at the rear of the template, when loosening the clamping claw, these parts return to the previous position, causing a non-compliant profile due to torsion and / or displacement. Therefore, it was concluded that the error was not in the design, but in the machining process that was carried out inappropriately.

3.3   Proposed situation

With the aid of SolidWorks software to perform computational simulations and analysis, the objective of this research is to replace the existing template, which as previously mentioned, is made of steel and has a weight above recommended by the NIOSH equation due to its high density. The high weight, which is one of the problems found in the template, can be easily solved by manufacturing it in aluminum for example, however, we will still have the problem with welding and machining.

Taking into account all the project data, the purpose of this study is to replace a dimensional control device made of steel (ASTM A36 and steel tubes) for one made of polyamide composite with glass fiber using the Material Extrusion AM process, thus eliminating welding and machining operations.

The composite PA 6.6 GF50 stands out when compared to similar composites for presenting less deflection and, consequently, less displacement in operation (SILVA, 2014). However, due to the inexistence of PA 6.6 GF50 in filament, the study will also be carried out in PA 6 GF30, which is a material available in the filament market.

The research will be carried out with theoretical and practical studies to validate a proposal for exchange of material in a dimensional control device, in a way that meets dimensional and ergonomic requirements. Based on NIOSH equation the maximum weight that the template can have is 32.94 kg.

The polyamide composites used in the research were PA 6 (belonging to the Xstrand commercial family) and PA 6.6 (belonging to the Technyl commercial family). Table 1 shows the main mechanical and thermal characteristics of the studied materials.

Table 1. Main mechanical and thermal physical characteristics of the studied composites.

MAIN MECHANICAL AND THERMAL PHYSICAL CHARACTERISTICS			
	Properties	**PA 6.6 GF 50 (injection)**	**PA 6 GF 30 (filament)**
Tensile	Tensile Modulus (MPa)	13000	7400
	Tensile Strength (break) (MPa)	220	102
	Elongation (break) (%)	1.8	2.1
Flexion	Flexural Modulus (MPa)	16780	6100
	Flexural Strength (MPa)	355	170
Impact resistance	Izod Impact, Notched (kJ/m²)	14	-
	Density (kg/m³)	1570	1170
	Water Absorption (%) - 24h a 23°C	0.6	0.58
	Melting Temperature (°C)	260	206
	Deflection temperature - load 1.8 MPa (°C)	>=240	124

Structural analysis through Finite Element Method were performed in SolidWorks software and, with the exception of the yield limit, all data necessary to perform the characterization of the studied materials were acquired in the datasheets from Xstrand (PA 6 GF30) and Technyl (PA 6.6 GF50). After performing several comparisons with the Xstrand filament PA 6 GF30 tensile and flexion modules and the Technyl PA 6.6 GF 30 for injection, it was concluded that the value of the PA 6 GF 30 filament (Xstrand) is about 77 % of the value of PA 6.6 GF 30 for injection.

According to SILVA (2014), the yield limit value is 97.3 MPa for PA 6.6 GF50 (injection) and 69.3 MPa for PA 6.6 GF30 (injection). Then, the value used for the yield limit of PA 6 GF30 in filament (Xstrand) was 53.36 MPa (77% of 69.3 MPa). Table 2 contains the data used to characterize the studied materials.

Table 2. Data for characterization of composites in SolidWorks.

CHARACTERIZATION IN SOLIDWORKS		
Properties	PA 6.6 GF 50 (injection)	PA 6 GF 30 (filament)
Elastic modulus (MPa)	13000	7400
Especific mass (kg/m³)	1570	1170
Tensile Strength (MPa)	220	102
Yield limit (MPa)	97.3	53.36

4. RESULTS AND DISCUSSION

The structural analysis carried out previously proved that the initial geometry of the device already met the needs for the project in relation to the maximum allowed displacement but with a very high weight due to the fact that the template is made of steel. So, another structural analysis was carried out changing only the template material to polyamide PA 6 GF30 to obtain a starting point. As we can see in Figure 6, the result obtained was as expected, that is, the device presented a displacement above the allowed (0.65 mm).
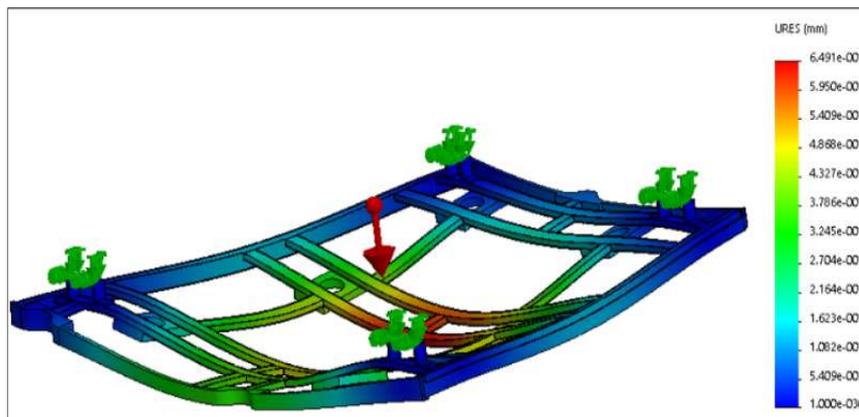

Figure 6. Starting device designed in PA 6 GF30.

The new device will be manufactured in polyamide composite reinforced with glass fiber (PA 6 GF30 and PA 6.6 GF50), and for this reason, it was necessary to change its geometry according to the characteristics of the new material and the new manufacturing process. Therefore, even if the initial device designed in the PA 6 GF 30 had an acceptable displacement, it would be necessary to perform some changes to its profile to meet not only the characteristics of the manufacturing process, but also some specific requirements of the day to day in the industry. For example, a more robust structure due to the device being used for the control of metal parts in a work environment that presents a high risk of collisions, since its placement on the lining is carried out manually by two people.

The new device for dimensional control (Fig. 7) was designed to meet the robustness factor, which is a very important factor for this application, because the device cannot suffer any damage on its contact area. Also, the load-displacement, which in this case is gravity, in the virtual model, is expected to be below 0.5 mm, which is the maximum displacement allowed for the project by company X.
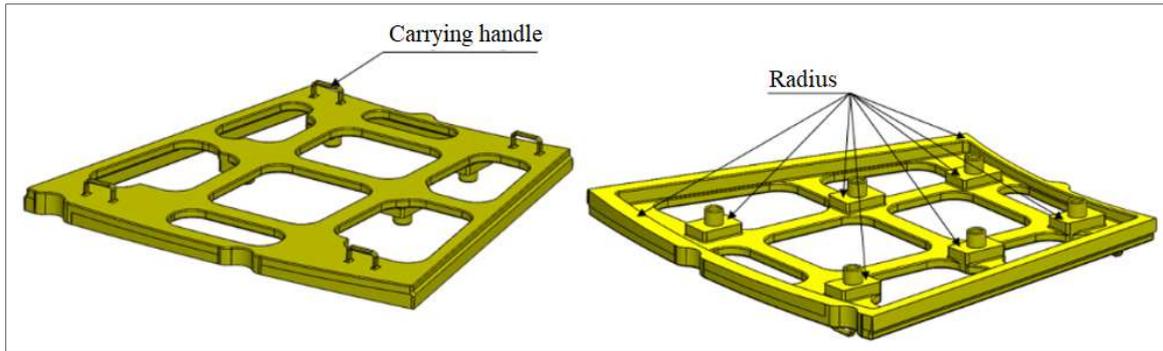
Figure 7. Device with final geometry in polyamide composite.

With the geometry defined and the materials characterized, the mass of the device was verified with both materials, thus obtaining a mass of 31 kg with the composite PA 6.6 GF50 for injection and 23.1 kg with the composite PA 6 GF 30 in filament.

4.1   Mechanical structural analysis using the Finite Element Method in final geometry

The first analysis performed on the device with final geometry was with the PA 6.6 GF50 composite for injection. In the analysis of von Mises stress, the device presented stresses below the yield limit in its entire profile, an expected result. The resulting displacement also obtained a positive value, presenting a maximum displacement of 0.17 mm. The deformations suffered were minimal and the minimum safety factor found with this composite was 28.07. The device with final geometry in composite PA 6.6 GF50 for injection met all the requirements of the project, however as previously mentioned, due to the inexistence of this material in filament, the analysis was also carried out with the composite PA 6 GF30, which is a material available in the filament market.

The result of the analysis of von Mises stress with the composite PA 6 GF30 in filament also showed stresses below the yield limit in the entire profile of the device. Even with a significantly lower percentage than fiberglass, the value obtained in the resulting displacement was 0.22 mm, a positively unexpected result. The deformations suffered were also minimal and the minimum safety factor found was 20.5. We can see in Figure 8 the representation of the resulting displacement in the final geometry for both composites.
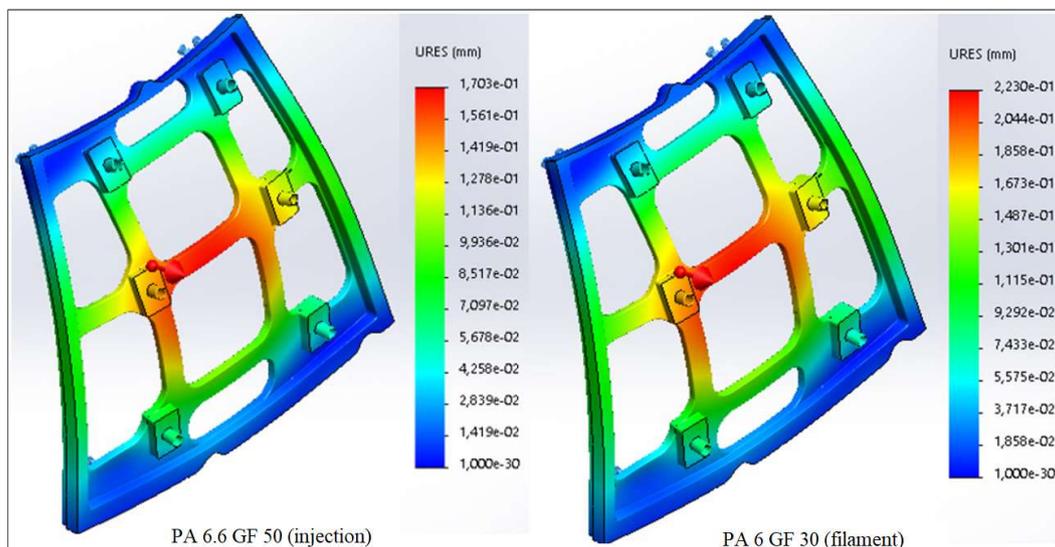

Figure 8. Analysis of the resulting displacement in the final geometry for both composites.

The device with final geometry in composite PA 6 GF30 in filament, besides meeting all the requirements for the project, this material also makes it possible to perform the Material Extrusion AM process due to its existence in the filament market.

The results obtained for the mechanical analysis showed that the glass fibers have a great influence on the performance of the device in question. Strictly respecting the same geometry, both composites met the design requirements with some particularity.

The device with final geometry made of composite PA 6 GF 30 in filament showed a difference of 0.02 mm in relation to the maximum displacement found in the initial device made of steel, while the device with final geometry in composite PA 6.6 GF50 for injection had a difference of 0.07 mm.

Among the requirements desired in this research, mass was the factor that showed the greatest difference between the analysis. The device with final geometry in composite PA 6 GF 30 in filament obtained a reduction of 67.5% in relation to the mass of the initial device made of steel, while the device with final geometry in composite PA 6.6 GF50 for injection obtained 56.3% reduction. Highlighting the composite PA 6 GF 30 in filament.

For the final developed geometry, the results showed that the composite PA 6 GF 30 in filament had greater deflection and less mass compared to the composite PA 6.6 GF50 for injection. Table 3 shows the main results obtained from the analysis.

Table 3. Main results obtained with mechanical structural analysis.

MAIN RESULTS OBTAINED WITH MECHANICAL STRUCTURAL ANALYSIS				
	Device with initial geometry made of steel	Device with initial geometry in PA 6 GF30 (filament)	Device with final geometry in PA 6.6 GF50 (injection)	Device with final geometry in PA 6 GF30 (filament)
Maximum displacement found (mm)	0.24	0.65	0.17	0.22
Weight (kg)	71	10.6	31	23.1
Status	Failed: even though approved in the structural analysis, the device presented a high weight and a displacement above the allowed due to the error in the machining process.	Failed: the device presented a displacement above the allowed and also an inappropriate geometry for the application.	Failed: the device met all the requirements of the project, however, its non-existence in the filament market makes the Material Extrusion AM process impossible.	Approved: the device met all the requirements of the project, including the its availability in the filament market, which makes it possible to carry out the Material Extrusion AM process.

5. FINAL CONSIDERATIONS

To achieve an accurate result using the finite element method, the correct would be to perform physical mechanical tests using specimens of exactly the same materials as the research, and thus perform the characterization of these materials in the software. The characterization of the composites in this research was carried out according to data obtained from their respective datasheets, however, the yield limit of both materials was not provided and unfortunately, it was not possible to acquire them to perform the necessary physical mechanical tests. So, to obtain the yield limit of the PA 6.6 GF50 composite for injection (Technyl) a master's dissertation was used as a reference and for the PA 6 GF30 composite in filament (Xstrand) several comparisons were made with the tensile and flexion modules of similar composites.

Based on the results of the analysis carried out, the PA 6.6 GF50 composite for injection stands out for presenting less displacement, resulting from the gravity force, when compared to the PA 6 GF 30 composite in filament.

Using a different geometry, both devices designed in polyamide composite endured the same efforts as the device made of steel, but with a much lower weight. The device designed in PA 6 GF 30 (filament) obtained a reduction of 67.5% and the device in PA 6.6 GF50 (injection) obtained a reduction of 56.3%, highlighting the composite PA 6 GF 30 (filament) for presenting greater weight reduction.

The two composites studied met the requirements of the project, thus proving the importance of reinforcements in their composition. In many analysis like this, which are aimed at replacing steel with polymer, the absence of reinforcements in the polymer composition would make it difficult or even impossible to perform the substitution.

With the final geometry sizing approved and without considering the durability of the device in terms of moisture for example, the use of the device with final geometry in polyamide composite will contribute to the company "X" achieving a high productivity with the measurement carried out, quickly and accurately, of its lining respecting the ergonomic concepts.

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