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Aplicación de Tecnologías de Fabricación Aditiva al Diseño de Insertos Plásticos en Aplicaciones de Moldeo por Inyección

Application of Plastic Materials in the Manufacturing of Injection Molding Inserts Using Additive Manufacturing Processes

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Resumen – La creciente demanda de componentes plásticos complejos en series cortas ha impulsado la evolución de los procesos de fabricación. La fabricación aditiva permite la producción de piezas personalizadas con geometrías complejas y ciclos de vida reducidos, aunque su anisotropía limita la funcionalidad de los componentes plásticos. En este contexto, los nuevos materiales plástico y las revolucionarias tecnologías de prototipado rápido ofrecen una alternativa eficiente, permitiendo la fabricación rápida de moldes para inyección con propiedades comparables a los producidos en serie. Este estudio presenta una evaluación del comportamiento mecánico de moldes fabricados con material plástico PA reforzado con fibra de vidrio, mediante simulaciones numéricas bajo condiciones operativas reales. Los resultados indican una distribución uniforme de tensiones en la cavidad del molde, con valores de 25 MPa y 18 MPa, sin superar el límite elástico del material. Los desplazamientos máximos registrados fueron de 0.095 mm y 0.041 mm, garantizando la integridad estructural de los insertos durante su uso. Estos hallazgos destacan el potencial de los materiales plásticos en la fabricación de moldes para series cortas, proporcionando una solución rentable y eficaz para la producción de componentes poliméricos personalizados y de alta complejidad.

Palabras clave – CAD, diseño industrial, impresión 3D, moldeo por inyección, fabricación aditiva.

Abstract – The growing demand for complex plastic components in short series has driven the evolution of manufacturing processes. Additive manufacturing enables the production of customized parts with complex geometries and reduced life cycles, although its anisotropy limits the functionality of plastic components. In this context, the new plastic material and the revolutionary rapid tooling technologies offer an efficient alternative, enabling the rapid manufacture of injection molds with properties comparable to those produced in series. This study presents an evaluation of the mechanical behavior of molds made with glass fibre-reinforced PA plastic material, using numerical simulations under real-life operating conditions. The results indicate a uniform stress distribution in the mold cavity, with values of 25 MPa and 18 MPa, without exceeding the material's yield strength. The maximum displacements recorded were 0.095 mm and 0.041 mm, ensuring the structural integrity of the inserts during use. These findings highlight the potential of plastic materials in short-run mold manufacturing, providing a cost-effective and efficient solution for the production of highly complex, customized polymer components.

Keywords – CAD, Industrial design, Injection molding, Additive manufacturing.

1. INTRODUCTION

Injection molding is a key process in the manufacturing of plastic products due to its ability to produce parts with high precision, complex geometries and tolerances in an efficient and repeatable manner [1-3]. The molding process is based on the injection of a molten thermoplastic polymer into a closed mold at high pressure, where the material is cooled and solidified taking the desired shape of the final product [4-6]. Thanks to its high degree of automation and repeatability, this manufacturing process has become the most widespread technology for producing plastic components in various industries such as automotive, electronics, medical devices, packaging and consumer goods [7-9]. Molds are mainly used in high-volume series production, where the amortization of the mold over millions of production cycles justifies the initial investment [10-11]. Despite its advantages, injection mold manufacturing is a technical and economic challenge, since conventional molds are made from hardened steels, which involves high-precision and high-cost machining processes [12-14]. Its production requires traditional CNC techniques such as milling, drilling, wire EDM and grinding, which require long manufacturing times [15-17].

However, the evolution of the industry in recent years has introduced new trends in flexible and on-demand production [18], which has led to a change in the way injection molds are designed and manufactured [19]. Factors such as mass customization, reduced product development times and the need for iterative testing before series production have driven the search for more agile and cost-effective solutions for tooling manufacturing [20-23]. In this context, additive manufacturing (AM) [24] has emerged as a promising alternative for the production of injection molds and tooling [25], especially in low-volume and rapid prototyping applications [26]. Unlike traditional machining, which removes material to obtain the desired geometry, additive manufacturing builds objects layer by layer from polymeric, metallic or composite materials, allowing molds to be manufactured more quickly and with less material waste [27-28].

The use of advanced polymers and reinforced composites in the 3D printing of injection molds has opened new opportunities in the industry [29]. Materials such as polyetheretherketone (PEEK), polyamide 6 (PA6) and polycarbonate (PC), reinforced with carbon or glass fibre, have demonstrated adequate mechanical and thermal properties to withstand the working conditions in injection molding. Despite these advantages, the thermal and mechanical strength of polymeric molds remains a limiting factor compared to metal molds. In recent years, numerous studies have been developed to evaluate the viability of additively manufactured molds in real industrial environments. Krizsma *et al.* [30] investigated the production of ABS mold inserts using MEX (Material Extrusion) technology, analyzing how the percentage of filling influences the strength of the molds. The results showed that 80% of filled inserts were suitable for low-volume injection, while lower-density inserts showed earlier structural failures. On the other hand, Storti *et al.* [31] performed numerical simulations and experimental tests to evaluate the thermal efficiency of molds printed with conformal cooling channels. Their findings indicated that these designs can reduce the thermal gradient by more than 6°C, improving the temperature uniformity on the mold surface by 42%, which translates into a lower level of residual stresses and defects in the injected parts. In the area of durability, Davoudinejad *et al.* [32] subjected additively manufactured mould inserts to accelerated thermal ageing tests, simulating continuous production conditions. These tests allowed us to evaluate the thermal and mechanical fatigue resistance of the molds over multiple injection cycles, providing key information on the degradation of materials under industrial conditions. From an economic point of view, Bagalkot *et al.* [33] analysed the profitability of 3D printed moulds (3DIM) for low-volume injection, demystifying the belief that their structural failures are due only to injection pressures. Their studies revealed that other factors, such as printing orientation, infill type and material anisotropy, play a crucial role in the service life of these molds.

In this line, the research presented in the paper focuses on the evaluation of injection molds made of glass fibre-reinforced Polyamide (PA66), a material with superior mechanical properties to conventional polyamides. The analysis is carried out in a real industrial case, where the molds are subjected to representative working conditions, evaluating their structural behavior through numerical simulation and experimental tests. The results obtained highlight the potential of 3D-printed injection molds for the manufacture of short runs, significantly reducing costs and production times compared to metal molds. The combination of reinforced materials and optimized design strategies allows for improving the thermal and mechanical resistance of the molds, opening new possibilities for their application in the manufacture of customized plastic products and industrial prototyping. The development of new materials, printing techniques and validation methodologies will be key to consolidating additive manufacturing as a viable alternative in the injection molding industry.

2. METHODOLOGY

This section details the geometric, functional and manufacturing characteristics of the injection mold used in the case study. The mold design is analysed in depth, addressing aspects such as its structural configuration, the arrangement of the cavity and core, as well as the auxiliary mechanisms necessary to guarantee an efficient injection process with high-quality standards. Likewise, detailed technical information is provided on the selection of the plastic material used in the injection moulding process, considering its mechanical, thermal and rheological properties, as well as its compatibility with the requirements of the transformation process. The choice of polymer is justified based on criteria of mechanical strength, dimensional stability, ensuring that the selected material is optimal for the geometry of the part and the performance of the mold. Finally, the specific operating conditions of the manufacturing process are described, including key parameters such as polymer melting temperature, injection pressure, etc.

2.1 Geometric and functional characteristics

Figures 1, 2 and 3 illustrate in detail the geometric characteristics of the plastic part under study, as well as the geometry of the cavity and core plates involved in its manufacture by injection molding. The designed part (see Fig. 1) is intended to be integrated into a drone, where it plays a fundamental role in both structural and functional terms. Its main purpose is to act as a trim, improving the aesthetics of the device without compromising its performance. However, in addition to its aesthetic function, the part also contributes to increasing the structural rigidity of the assembly, which translates into greater stability and resistance to mechanical stress during the operation of the drone. It also performs a protective function by protecting the internal electronic components and batteries of the device from impacts, dust and other environmental factors that could compromise its operation. From a dimensional point of view, the part has an optimized geometry for injection molding, with dimensions of 201 mm long, 201 mm wide, 32 mm high and a nominal thickness of 3 mm (see Fig. 1).

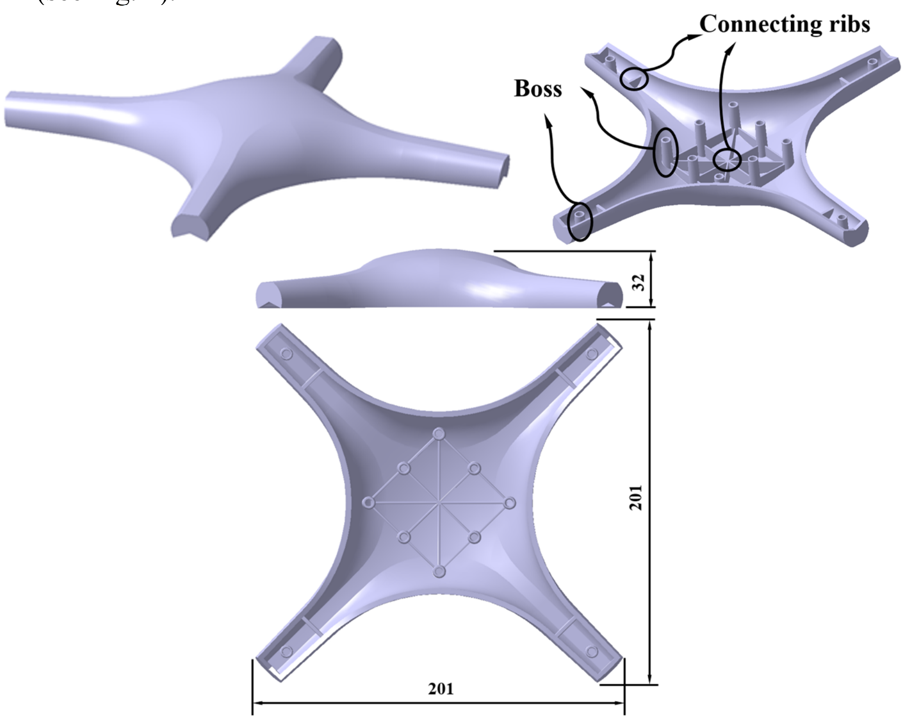

Fig. 1. Geometry of the plastic piece under study.

A detailed analysis of the design has been carried out to ensure the viability of the molding process, minimizing common defects such as sink marks, sink marks or differential shrinkage. To do so, thickness optimization criteria have been applied, ensuring a uniform distribution of the material and avoiding unnecessary accumulations that could generate residual stresses or difficulties in the cooling phase. Special attention has been paid to critical elements in the geometry of the part, such as roundings, bosses and structural reinforcements, which are usually areas where mechanical and thermal stresses tend to concentrate. These details have been designed considering validation studies to foresee possible areas of stress concentration and improve the durability of the part.

The mold design has been optimised to ensure accurate reproduction of the part geometry and ensure high repeatability in manufacturing. A cross-rib grid has been incorporated into the internal part of the part, to increase rigidity without adding excessive weight or significantly increasing material consumption. This reinforcement system better distributes stresses during the injection process and in the operation of the drone, providing greater structural stability.

In addition, the mold has strategically located bosses, designed to allow a removable attachment of the part to the lower casing of the drone. These bosses have been precisely sized to ensure correct alignment and assembly without generating excessive stress points in the injected part.

The dimensions of the cavity and core plates have been established based on the characteristics of the part and the specifications of the injection machine used in the study. In this case, the plates have dimensions of 546 mm on the X axis, 546 mm on the Y axis, and a depth of 176 mm on the Z axis. The complete design of the part and the mold has been developed using the commercial software Dassault Systèmes CATIA V5, a tool widely used in the industry for 3D modelling. This software has allowed to perform preliminary assembly studies, interference analysis and thickness optimization, ensuring that both the part and the mold meet the expected functional and manufacturing requirements.

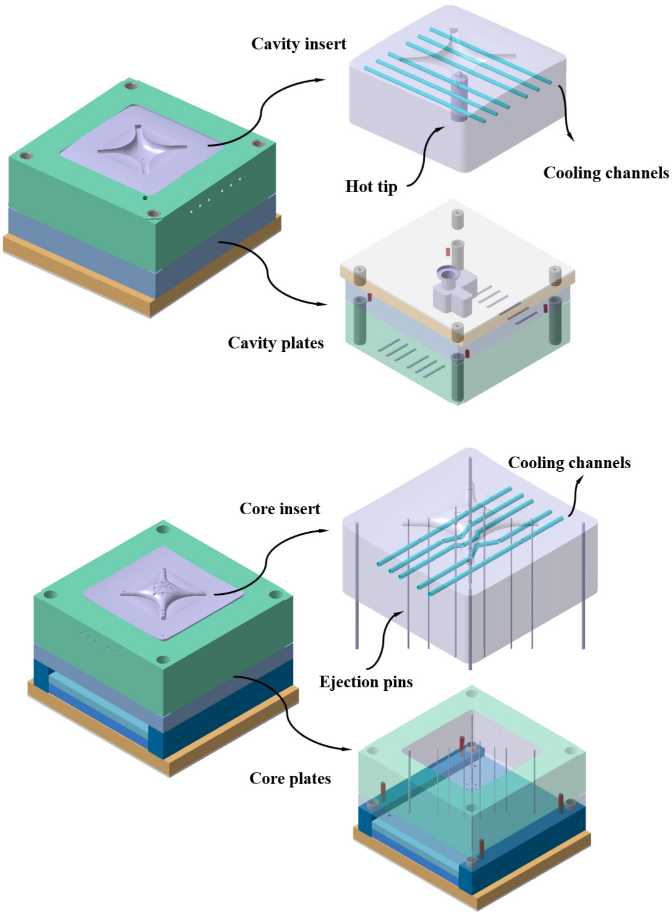

Fig. 2. Design of the main injection mold plates.

For the ejection of the part, 15 cylindrical ejectors have been arranged. The ejectors guarantee a uniform and controlled extraction, minimizing possible defects and ensuring the dimensional quality of the final product.

The mold design incorporates an efficient cooling system, based on straight channels strategically located in the cavity and core areas. These channels have a diameter of 9 mm and are distributed homogeneusly.

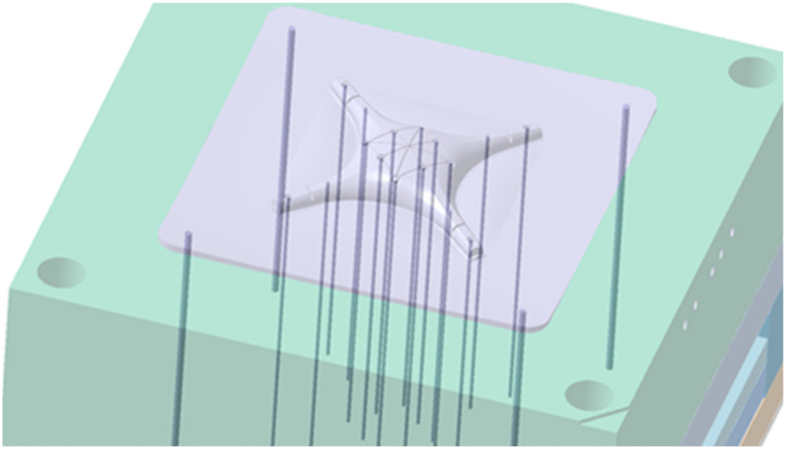

Fig. 3. Location of the ejectors.

2.2 Numerical modeling by FEM

In order to verify the structural behavior of the design of the main injection mold inserts in the present case study (see Fig. 2), numerical simulations have been carried out using the commercial software Ansys Mechanical. These simulations correspond to mechanical-static analyses, with the objective of evaluating the resistance of the inserts to the load conditions generated during the injection process of the plastic part.

The study has been designed considering the most restrictive load scenario to which the analyzed geometries are subjected, ensuring that the model accurately represents the real operating conditions. As shown in Fig. 4, during the injection phase of the molten polymer into the mold cavity, the maximum pressure of the process is reached. At this critical moment, the mold inserts must withstand the stresses generated by the internal pressure without compromising their structural integrity or presenting deformations that may affect the dimensional quality of the molded part.

To ensure that the design meets industrial requirements, two fundamental evaluation criteria have been defined:

• Structural strength: The inserts must not exceed the elastic limit of the material from which they have been manufactured, avoiding permanent plastic deformations or possible structural failures that compromise the functionality of the mold throughout its useful life.

• Maximum allowed deformation: A maximum threshold of 0.1 mm of displacement has been established, since higher values could generate inaccuracies in the geometry of the injected part, affecting its fit and compatibility with other components of the drone. This technological requirement is a commonly accepted standard in the injection molding industry, where dimensional accuracy is critical to ensure proper assembly and high quality in series manufacturing.

To evaluate the magnitude of the pressures experienced by the inserts during the injection phase, a rheological simulation of the mold cavity filling process has been carried out. This simulation has been performed using the commercial software Autodesk Moldflow Adviser 2024, a tool specialized in the simulation of injection molding, which allows predicting with great precision the behaviour of the molten polymer inside the mold, optimizing parameters such as the filling speed, pressure distribution and the thermal gradient in the cavity.

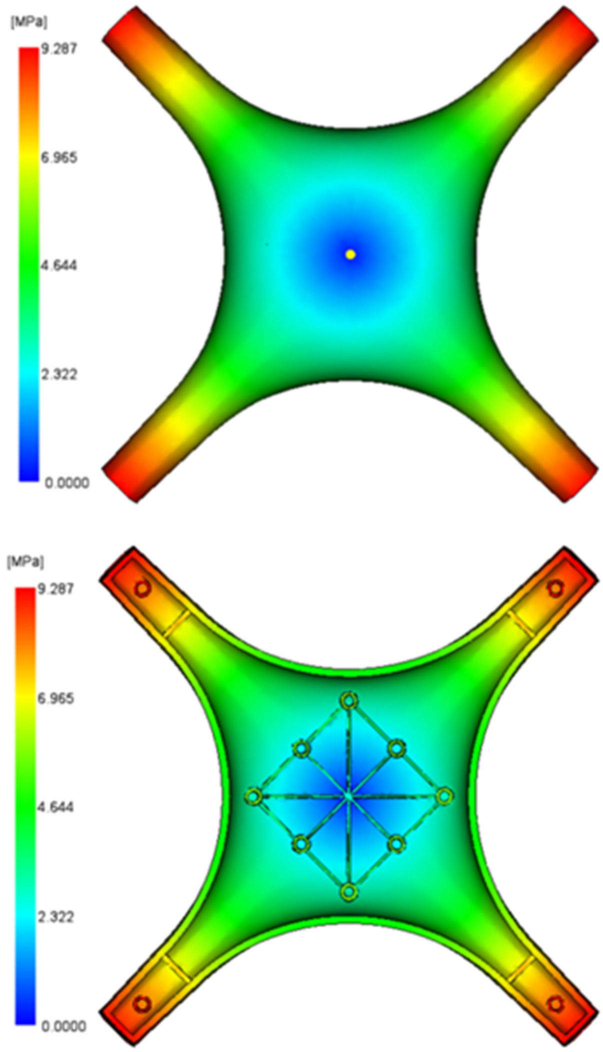

Fig. 4. Prediction of the injection pressure map of the plastic part obtained by FEM simulation with Moldflow to define the maximum pressure supported by the mold.

Rheological analysis has made it possible to accurately define the configuration and magnitude of the operating parameters involved in the injection molding process.

2.2.1 Materials

Table 1 presents the values established in the simulation for the case study, considering the use of PP (polypropylene) plastic material, which was selected due to its combination of low density, good mechanical strength, and ease of processing in industrial injection molding applications. The defined thermal and rheological properties have been established by the manufacturer and supplier of this plastic material.

Table 1. Rheological simulation configuration for the analysis of the plastic part filling phase, using PP as plastic material.

Parameter	Unit	Magnitude
Injection Temperature	ºC	180
Mold Temperature	ºC	20
Injection Machine Maximum Pressure	MPa	180
Injection time of the machine	S	0.765

The plastic material assigned to manufacture the injection mold inserts is Therma-TechTM TT6600-5008 X1 EC Anthracite. This plastic material is distributed by the company Avient and is a derivative of PA (Polyamide), with the trade name Polyamide 66 (Nylon 66). The mechanical and thermal properties of this plastic material are shown in Table 2 and have been established by the manufacturer and supplier of this plastic material. Numerical modeling of plastic materials, in numerical modeling software using FEM, has been defined as elastic and linear. This definition is based on the assumption that the plastic material itself, used in the manufacture of mold inserts, does not exceed the material's yield strength, and therefore its mechanical and structural behavior is purely elastic and linear.

Table 2. Mechanical and thermal properties for the plastic material Therma-TechTM TT6600-5008 X1 EC Anthracite of the injection mold inserts.

Parameter	Unity	Magnitude
Density	g/cm^3	1.58
Elastic Modulus	MPa	12,500
Poisson's Ratio	–	0.3
Yield Strength	MPa	65
Coefficient of thermal expansion	1/ºC	$7 \cdot 10^{-5}$
Mold Temperature	ºC	20

2.2.2 Load scenario and Boundary conditions

To simplify the mechanical simulation modelling process while defining a realistic loading scenario that ensures the structural integrity of the injection mold inserts, an approach was chosen that efficiently represents the loading conditions. As illustrated in Figure 5, a uniform pressure was applied along the internal surfaces of the insert cavity. This pressure was defined with a magnitude equal to the maximum pressure obtained during the injection phase, ensuring that the analysis faithfully reflects the stress state to which the mold components are subjected under operating conditions. By establishing a uniform and homogeneous load, the study focuses exclusively on the mechanical response of the inserts, evaluating their ability to withstand internal pressure without exceeding the admissible stress and strain limits. It should be noted that the mechanical numerical simulations, carried out using FEM software, developed in this research work are defined as static and linear.

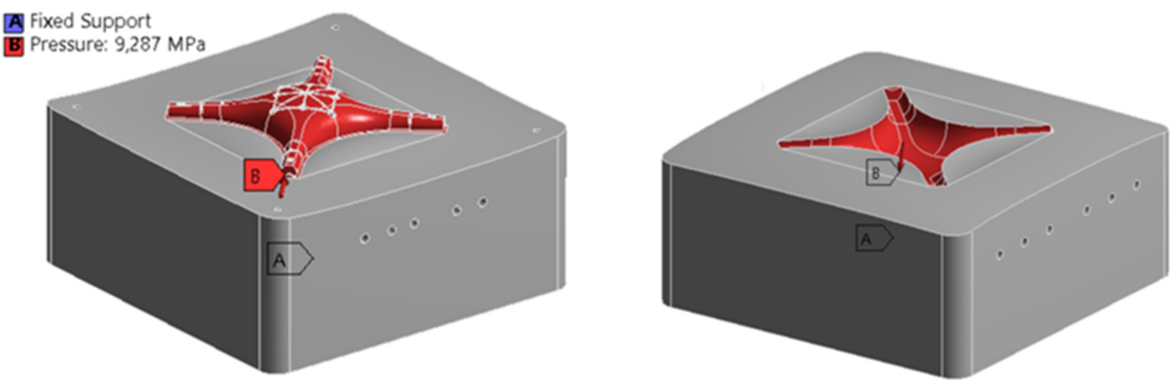

Fig. 5. Definition of the load scenario and boundary conditions for the numerical simulations in the software Ansys Mechanical 16.

The choice of uniform pressure as a boundary condition in structural simulation is justified because, although in the actual injection process, the pressure distribution within the cavity varies depending on the part geometry, the location of the injection channels, and the viscosity of the molten material, in practice, the maximum pressure value is the critical factor that the structure must withstand. Applying this value throughout the cavity constitutes a conservative design criterion, ensuring that the inserts are capable of withstanding the most demanding loads that may arise in series production.

Likewise, in order to complete the boundary conditions of the structural analysis, appropriate constraints have been applied to accurately represent the interaction of the inserts with the main injection mold plates. In this regard, fixed support or bearing has been defined on all surfaces of the inserts that are in contact with the mold plates. This restriction prevents any type of displacement or rotation in these areas, ensuring that the inserts are fully secured, as occurs under real-life operating conditions.

Furthermore, to more accurately reflect the thermal behavior of the system, a thermal reference condition was imposed. The geometry of the inserts was considered to be at the service temperature of the injection mold, which was set at 20°C, thus ensuring the consistency of the thermal-structural analysis. This condition is especially relevant given that the materials used to manufacture the inserts can experience variations in their mechanical properties depending on the temperature. Fig. 5 and Table 1 summarize the values and configurations used to define these boundary conditions

2.2.3 Mesh

To discretize the geometry of the inserts and generate the mesh used in the numerical simulation, a strategy was chosen that guarantees a balance between precision and computational efficiency. A mesh consisting of second-order tetrahedral elements, specifically of the Solid92 type, was used, with 10 nodes per element. This type of element was selected due to its ability to provide precise solutions to structural analysis problems involving complex geometries and significant stress gradients.

Regarding the element size, it has been determined that a characteristic dimension of 4 mm is adequate to capture the mechanical response of the inserts in sufficient detail without incurring excessive computational costs. In particular, it has been verified that the element size used allows an adequate representation of critical areas, such as corners, curvature radii, and stress concentrations around contact surfaces. The element size used in the numerical simulations performed is determined by a mesh convergence analysis. This operation ensures that the defined mesh exhibits an accuracy appropriate to the type of structural analysis performed, while also maintaining adequate computational efficiency. The numerical simulation has been carried out using the commercial software Ansys 16, used in industry and research for the structural analysis of components subjected to complex loading conditions. Figures 6 and 7 show the details of the mesh used, including the distribution of the elements and the local refinement applied in the areas of greatest interest. This simulation configuration allows obtaining accurate results regarding the distribution of stresses and displacements in the mold inserts, ensuring that the design meets the established structural requirements and providing key information for possible optimizations in future design iterations.

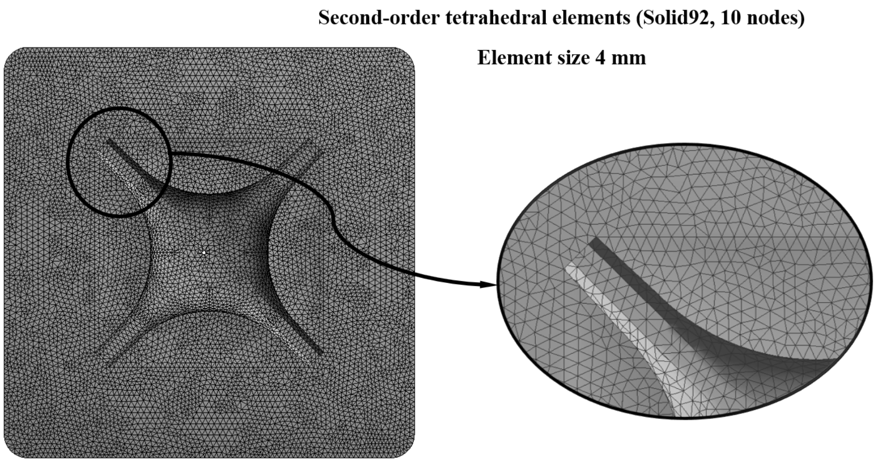

Fig. 6. Mesh definition for the injection mold cavity insert.

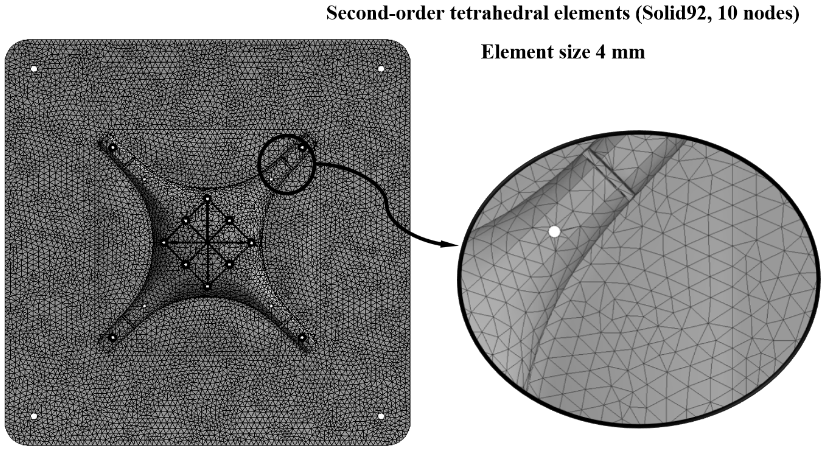

Fig. 7. Mesh definition for the injection mold core insert.

3 RESULTS

Fig. 8 and Table 3 show the magnitude of the Von-Mises stress map along the surface of the plastic part. As can be seen, despite having equal maximum stress values of 18.549 MPa and 53.428 MPa, respectively, the stress map is distributed uniformly along the surface of the mold cavity with a magnitude equal to 4.18 MPa and 15.93 MPa. Furthermore, considering the mechanical properties of the plastic material described in Table 2, it is verified that, during the injection process, the plastic material of the inserts does not exceed its elastic limit and, therefore, its structural safety is maintained during its service condition.

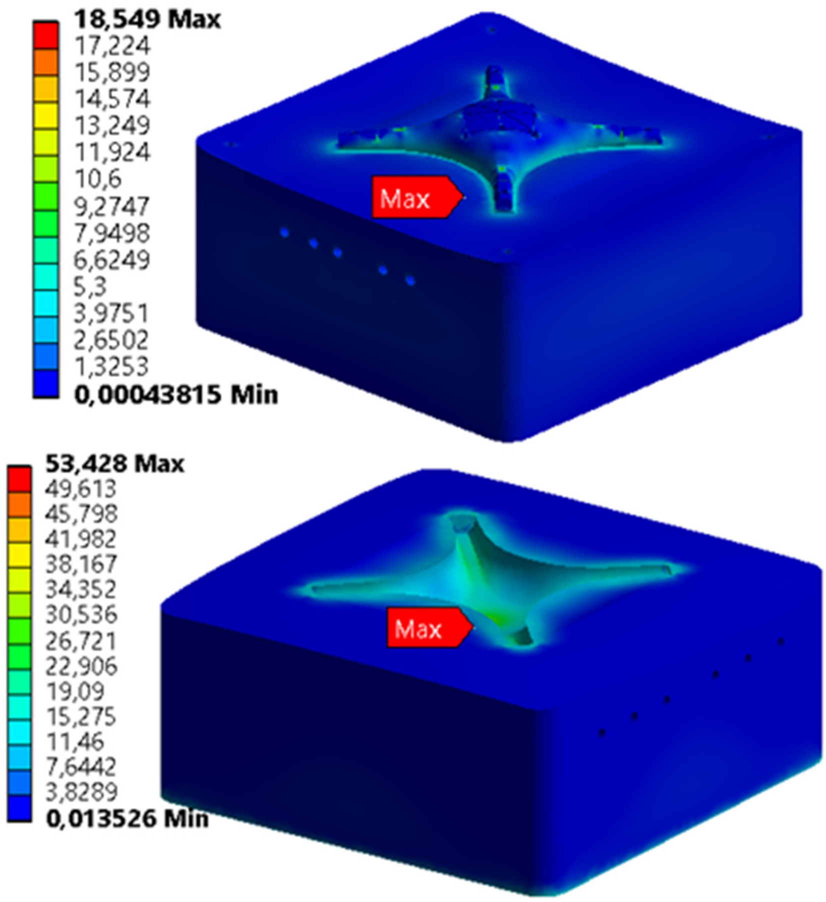

Fig. 8. Von-Mises stress map [MPa] along the surface of the injection mold inserts.

On the other hand, Fig. 9 and Table 3 show the displacement map along the surface of the plastic part. The results indicate that the displacement field on the insert surface is dominated by the effects of the thermal expansion of the material. This thermal behavior of the material has a greater influence on the displacement field than the deformation generated by the injection pressure. That is, the thermal effects of the material expansion take priority over the effects of the injection pressure in the mold cavity. Furthermore, the maximum displacements obtained are equal to 0.056 mm and 0.067 mm, in the positive direction along the insert transverse axis, never exceeding 0.1 mm.

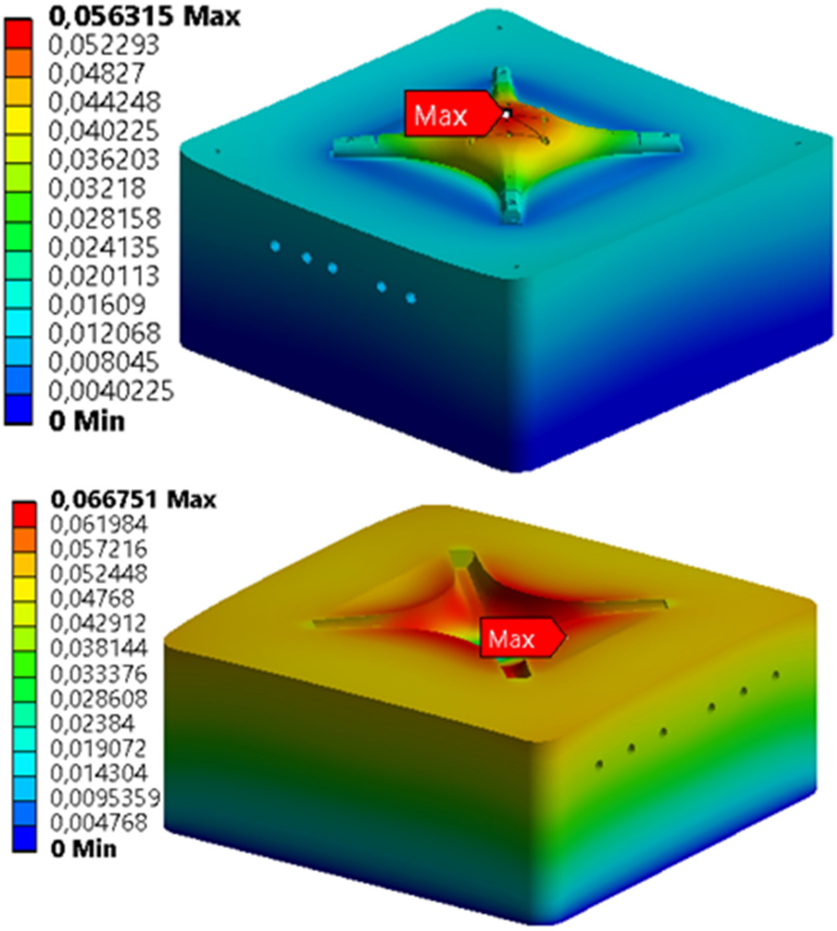

Fig. 9. Map of displacements [mm] along the surface of the injection mold inserts.

Table 3. Results obtained from the numerical simulations performed.

Maximum Values		PA reinforced	Steel P20
Von–Mises Stress [MPa]	Cavity	53.428	65.899
	Core	18.549	17.828
Displacements [mm]	Cavity	0.067	0.006
	Core	0.056	0.003

Table 3 also compares the maximum results obtained in the numerical simulations performed for the plastic material of the injection mold inserts with the results obtained with a metallic material, P-20 steel, under the same boundary conditions and loading scenario. The thermal and mechanical properties of the metallic material P20 steel are determined from the database of the numerical simulation software Ansys Mechanical. As can be seen, the maximum stress values are analogous for both materials, since the geometry, load scenario, and boundary conditions remain constant for the simulations performed. The small difference is derived from the stresses generated by the thermal condition imposed on the geometry under study, so that the inserts are under the service conditions and temperature of the injection mold. Since the thermal expansion coefficient of both materials is different, the secondary stresses produced by the effect of temperature are also different. Although this effect does not represent a principal component in the stress map, it justifies the differences obtained in the numerical results for both materials. On the other hand, the maximum displacement values obtained for both materials differ significantly. This result is mainly due to the difference in the elastic modulus and coefficient of thermal expansion between the two materials. However, it is worth noting that the results obtained for both materials, despite differing in their elastic and mechanical properties, meet the mechanical and structural design requirements.

Finally, from the numerical modeling of the mechanical simulations carried out, it can be verified that the structural behavior of the plastic material, reinforced PA, for the injection mold inserts is valid and meets the requirements established in the industrial sector of injection molds, since the stress field does not exceed the elastic limit of the material and, as shown in Table 3, the maximum displacements obtained are, for both geometries of the mold inserts, less than 0.1 mm.

4 CONCLUSIONS

The purpose of this research is to thoroughly evaluate the mechanical performance of injection molds made from reinforced PA plastic. To this end, a series of numerical simulations were developed that accurately reproduce the real-life operating conditions to which these molds would be subjected during the polymer injection process. This approach has enabled a comprehensive and detailed analysis of the molds' mechanical behavior, identifying the main parameters that affect their structural strength and durability in service.

The research results demonstrate that plastic molds can meet the demanding structural requirements required for short-run part production, representing a viable alternative to conventional metal molds in certain industrial scenarios. In particular, it has been shown that, under the load and temperature conditions typical of injection molding, reinforced PA molds can maintain their structural integrity without exhibiting critical deformations or premature failure, making them a potentially attractive solution for applications where rapid manufacturing and cost reduction are key factors.

These findings not only underscore the technical viability of plastic molds in the injection molding industry but also open up new perspectives for future research and applications. The possibility of using plastic molds in industrial processes with specific customization requirements and accelerated development cycles is especially relevant in a context where the manufacturing of complex and customized polymer components is increasingly in demand. Thanks to their optimized mechanical properties, these molds could significantly contribute to the evolution of the advanced manufacturing industry, providing flexible and adaptable solutions for different production sectors.

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RESEARCH DATA DISCLOSURE

The results and data from this research are available upon request from the authors.

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