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COMPARATIVE STUDY OF MECHANICAL PROPERTIES OF POLYAMIDE 12 MANUFACTURED BY ADDITIVE MANUFACTURING AND CONVENTIONAL PROCESSES

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Abstract. *The benefits of additive manufacturing (AM), such as design customization, weight reduction and reduced lead time, drew a lot of attention from the industry, being used by various segments such as aerospace, automotive and in applications in the health sector. Among the existing AM technologies, those based on Powder Bed Fusion (PBF) principles, can process different classes of materials including thermoplastic polyurethane (TPU), polypropylene (PP) and polyamide 12 (PA12), being the latter the most used polymer in PBF technologies. This is mainly because the wide range between its initial melting and their crystallization temperature. The literature reveals many research comparing different AM technologies used to print PA12 and only few studies to evaluate AM with conventional processes. This work aims to evaluate the mechanical properties of PA12 parts produced by AM HP Multi Jet Fusion (HP-MJF), which is a PBF based technology, and to compare the results with the literature data from conventional processed parts. The specimens for tensile and impact properties were printed on the diagonals of the vat polymerization with an inclination angle of 20° and a distance of 7 mm between each other, as per recommendations of the technology developer and according to data from studies of the same nature. The results reveal that AM parts yields properties equivalent to those obtained upon conventional processing which brings AM as an alternative to the application of conventional processes.*

Keywords: *powder bed fusion; conventional processes; polyamide 12; mechanical properties.*

1. INTRODUCTION

Additive manufacturing (AM) enables the manufacture of complex parts from a 3D model quickly and with design freedom, which has sparked increasing interest across industries such as medical, aerospace, automotive, and energy. This is because it allows complex and faithful-to-design parts to reduce the need for many steps, as in conventional processes, when there is a need for straight cuts or round holes, for example (Debroy et al., 2018).

Powder Bed Fusion (PBF) is one of the seven AM processes, as outlined in the ISO/ASTM 52900:2018 standard, based on printing parts from material in powder form. In PBF, thin layers of powder are deposited, and then sintered or melted by an energy source in the areas preselected by the software. The unsolidified powder layers serve as support for the forming layers that are creating the final part (Avrampos; Vosniakos, 2022).

Furthermore, the development of new AM technologies has enabled an increase in the production rate of parts with complex geometries without losing mechanical performance. Within PBF, technologies based on the use of laser or inkjet are the ones that receive the most attention, because they can provide properties comparable to those offered by conventional processes, such as injection molding (Podsiadły et al., 2021).

Agarwal et al. (2018) investigated the tensile and fatigue properties of epoxy-fiberglass LPR (conventional process, done by wet lay-up and vacuum bagging) and nylon-fiberglass composites made by Composite Filament Fabrication (CFF), recent AM technology and that uses material extrusion. The authors observed that the manufacturing process of composite filaments presented a lot of versatility and the possibility of application in several components, in addition to having better tensile and fatigue properties when compared to conventional processes for fiber-reinforced polymers.

Toro et al. (2020) analyzed and compared the mechanical response of standard specimens manufactured by two different processes using carbon fiber-reinforced PA 6, injection molding and Fused Deposition Modeling (FDM), an AM technology that uses material extrusion. At the end of the study, it was identified that the tensile properties were 21% lower than those obtained by injection molding, but the compression tests revealed similar behavior between the MA and injection parts, thus directing possible applications.

Already Do et al. (2023) compared the thermal conductivity and mechanical properties of standard samples made Polymer Composites with Hexagonal Boron Nitride when manufactured by injection molding, laser based PBF and also by casting. They concluded from this that there is a need for greater compatibilization of the printed composite to obtain better properties. Thus, showing varied works analyzing AM and conventional processes, but most focused on technologies that are based on extrusion material.

PBF technologies have a certain variety of materials for printing and among these possibilities, polyamide 12 (PA 12) is considered the main material used by powder-based AM processes, like Multi Jet Fusion (MJF). When heated to its glass transition temperature, PA 12 does not soften due to its semicrystalline nature. The crystalline portion of the polymer restricts the movement of the amorphous part, resulting in high sintering and the production of more compact parts during the printing process (Xu et al., 2019). Polyamides are widely used in manufacturing processes due to the advantages they offer, and PA 12 is commonly utilized in both conventional and MJF technology.

In the quest to accelerate its development, new technologies have emerged that contribute to increased processing speed. Technologies such as Multi Jet Fusion (MJF), that use the face-slice relationship as a process, unlike previous technologies that were based on the point-line-face-body relationship, being a more complicated procedure and generating processing speed limitation (Xu et al., 2019). MJF uses a set of infrared lamps as an energy source to melt selected areas that have been blasted with a fusing agent, and a detailing agent is also used to prevent melting close to the contours of the part and improve its resolution, as stated by Cai et al. (2021) and is exposed in Figure 1.

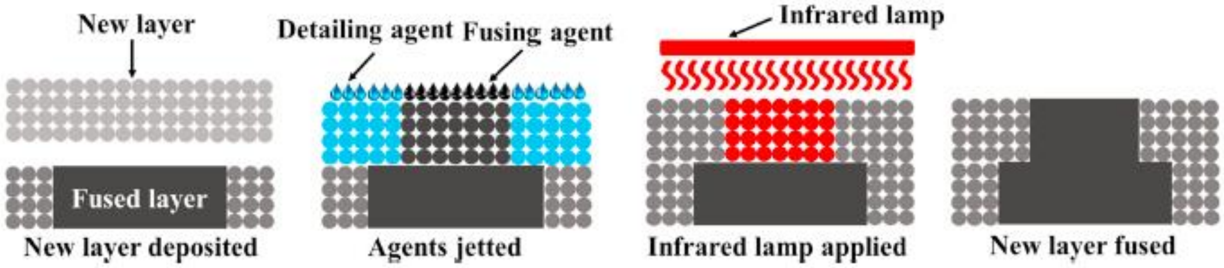

Figure 1: Schematic illustration of the MJF technology. Adapted from Cai et al. (2021).

However, studies comparing the mechanical performance of this material when manufactured in a conventional way, such as extrusion or injection, with data from when it is manufactured using the PBF process are not abundant. Based on this, the focus of this study is to analyze and compare the mechanical properties of PA 12 when manufactured by PBF with data from conventional processes in the literature, such as research studies and datasheets from manufacturers.

2. METHODOLOGY

2.1 Machines and materials

The specimens were produced using a HP printer model 5210, which uses MJF technology and has an effective build volume of 380 x 284 x 380 mm. The printing setup was according to the manufacture recommendation and used slow cooling and reused powder in a missing ratio of 80% reused powder and 20% virgin powder. According to the datasheet specifications, the used PA12 powder has a melting point of 187° C, particle size of 60 µm and a bulk density of 0.425 g/cm3.

2.2 Sample preparation by MJF

In total 18 specimens were printed, of which 6 were used for tensile tests and 12 specimens for Izod impact tests. The printing was carried out with the positioning of the samples on the diagonals of the vat, inclination of 20º and spaced of 7 mm between each sample. This arrangement follows the recommended guidelines provided by the technology manufacturer and based on previous studies conducted on the same technology, with the samples oriented in the Z direction.

The samples for the tensile test had a tie-shaped dimension and follows the ASTM D638 standard. The main dimensions were 165 mm in length, 19 mm in width and 3.2 mm in thickness, with a usable area measuring 115 mm in length by 13 mm in width. For Izod impact test, 12 specimens were printed in rectangles of 80 mm in length, 10 mm in width, 4 mm in thickness already containing the notch indicated in the ISO 180 standard. The printed samples are shown in Figure 2.

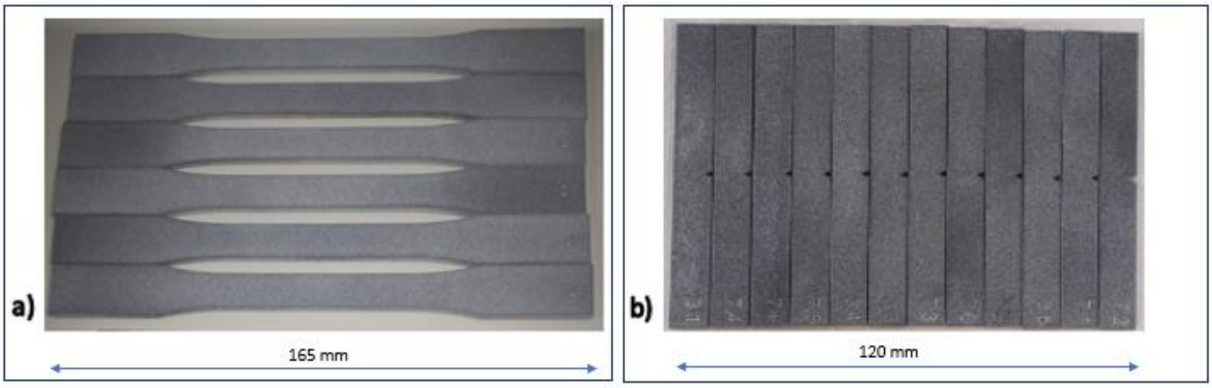

Figure 2: Specimens printed samples in PA12 for this work: a) tensile tests and b) Izod impact tests.

2.3 Mechanicals tests and comparison

The mechanical properties were evaluated in accordance with their respective standards. For the tensile tests the established in the ASTM D638 standard was used, being carried out with a test speed of 5 mm/min and in universal equipment manufactured by EMiC model DL2000.

For the Izod impact tests, the established in the ISO 180 norm was followed, carried out in equipment manufactured by EMiC. The air resistance was measured at 0.1 J, this measurement is necessary for calculations as the test equipment is manually operated. The mechanical properties obtained by the specimens of PA12 produced by HP MJF were then compared with properties for PA12 manufactured by conventional processes such as injection molding and extrusion. Published studies and manufacturer datasheets were considered for this search.

3. RESULTS AND DISCUSSION

Before carrying out the tests to analyze the mechanical properties, the dimensions of the samples manufactured using PBF technology were verified and their weight were measured. During this evaluation, the formation of a concave relief was observed on one of the flat faces of the printed samples. According to Mele, Campana and Monti (2019) this concavity phenomenon is due to the capillarity effect, which is caused by the presence of surfactant changing on the contour between the two chemical agents used in the process, the detailing agent and the fusing agent. This may cause distortions of the liquid surface curves. This is followed by a contraction that occurs during the solidification and cooling of the material, altering the volume of the printed piece.

The results from the tensile tests show a tensile strength of 42.41 MPa, tensile modulus of 1623 MPa and elongation at break of 8.85%. Table 1 presents the data obtained from the literature and datasheets from companies in the industry. It can be noticed that the tensile properties of PA12 produced by HP-MJF are relatively close, except for elongation at break, when compared to injection molding and extrusion. The values of the tensile modulus are the closest to those presented by conventional processes, indicating that the rigidity of the material when printed by PBF is within the range of those obtained by injection molding and extrusion process. This is evident when analyzing the results of Salazar, Cano and Rodríguez (2022), who found results through the injection molding process very close to those found in the work presented here, highlighting the superior tensile modulus when using MJF technology.

According to Xu et al. (2019), as it is emerging, the MJF technology employed is still under development in terms of its process and processing parameters for different materials, and it is also important to research a specific powder material for this technology to unlock its full potential. This could make PBF technology even more competitive in terms of mechanical performance. As already explained, the data that differs from those found for the conventional processes is the elongation at break, and it is possible to observe that by the injection molding process this data can reach more than 50%, indicating a significant increase in the initial length of the analyzed specimen.

Table 1. Tensile Properties for PA 12 AM-PBF and conventional processes.

Tensile strength (MPa)	**Tensile modulus (MPa)**	**Elongation at break (%)**	**Processes**	**References**
53	1700	> 50	Injection molding	VESTAMID (2019)
46	1600	> 50	Extruded	VESTAMID (2019)
50	1800	200	Extruded	SMITHS (2022)
50	1800	200	Injection molding	PLASTIM (2015)
56 - 65	1600	300	Extruded	HERNANDÉZ (2016)
47	1290	64	Injection molding	Salazar, Cano e Rodríguez (2022)
64	2964.3	200	Hot – pressed	Bahrami, Abenojar e Martínez (2021)
42.41	1623	8.85	AM - PBF	The present study

For the extrusion process, the elongation at break reached 300%, indicating a threefold increase in its initial length, enabling a wide range of potential applications. Meanwhile, the elongation at break found when considering the PBF technology was 8.85%, something close to that indicated by the technology manufacturer and reported in the literature for MJF, but it is a value much lower than those found for conventional processes.

These contradictory results regarding tensile strength, tensile modulus and elongation at break may be associated with the fact that samples produced by injection molding, for example, are almost completely dense and with a higher degree of crystallinity than samples produced through the MJF technology, as indicated by Salazar, Cano and Rodríguez (2022). Additionally, there is a different thermal history during manufacturing processes, which impacts the mechanical performance of the manufactured components.

Unlike the results found for the tensile properties, the impact strength by the PBF process is within the range of the results found for injection molding, but much lower than two of the results available for the extrusion process, which are shown in Table 2. With an impact strength of 4.54 KJ/m2, the AM–PBF has a fracture toughness like that of samples manufactured by injection molding. However, when analyzing the results of the samples manufactured by extrusion, the AM presents a value that is 3 times lower.

Despite presenting lower results compared to extrusion, the samples of AM–PBF when in a triaxial stress conditions present exhibit toughness like those observed for injection molding. In addition to presenting desirable properties over conventional processes, AM-PBF demonstrates superiority when compared to certain technologies used in additive manufacturing. Zhu et al. (2017) investigated the properties of PA12 and its composite produced by Fused Deposition Modeling (FDM). They found that for the base polymer, the tensile strength, modulus of elasticity, and elongation at break were 43.8 MPa, 1495.2 MPa, and 68.1%, respectively.

Another interesting point is the fact that AM has been shown to be more environmentally friendly than some conventional processes, as indicated by Výtisk et al. (2022) in their investigation of the environmental impacts generated by the manufacturing of an air ejector and an orifice plate, both produced through AM and conventional metal processes, using a Life Cycle Assessment (LCA). The authors identified that the conventional process generated more impacts than AM in terms of terrestrial acidification, stratospheric ozone depletion, photochemical ozone formation, and fine particle formation.

Table 2: Impact strength for PA 12 AM–PBF and conventional processes.

Impact strength – Notched (KJ/m^2)	Processes	References
3.5	Injection molding	VESTAMID (2019) – Charpy
5	Extruded	VESTAMID (2019) – Charpy
20	Extruded	SMITHS (2022)
10 - 20	Extruded	HERNANDÉZ (2016) – Charpy
4.54	AM - PBF	The present study – Izod

4. CONCLUSIONS

Several studies have been conducted to compare the mechanical properties of parts manufactured by conventional and AM processes. These researches have investigated characteristics such as tensile strength, fatigue strength, optical properties, mechanical response and thermal conductivity. However, the scarcity of works that compare the mechanical performance of PA 12 when manufactured by conventional processes, such as extrusion or injection, with data obtained through the PBF process is notable.

From this study, it is possible to identify that properties such as tensile strength and elongation at break presented an average value of 15% and 93% respectively, lower than the same properties identified for the injection molding process. However, the tensile modulus was 1 .62% higher, as well as impact strength, with a superiority of 29.7%. In contrast, while compared with the extrusion process the tensile strength and elongation at break are 18.1% and 96.6% lower, respectively. In this case, the modulus of elasticity was 2.58% lower compared to the extrusion process, and the impact strength was 65.9% lower.

Lower results were also found when compared to hot pressing, with these being the furthest when analyzing the values for the other conventional processes. Therefore, the objective of this study was to gather data by analyzing and comparing the mechanical properties of PA 12 when manufactured by PBF with data available in the literature for conventional processes. By providing this comparison, the proposed study seeks to contribute to the scientific knowledge about the mechanical properties of PA 12 manufactured by PBF compared to well-established processes. It also aims to assist in the process selection process for applications of interest by showing that the properties of AM can compete with those of conventional processes depending on the desired purpose.

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