Development of a methodology for hybrid products during the Additive Manufacturing process

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Abstract: The development of new products, by Additive Manufacturing technologies, is an alternative in the present industry, since AM offers the possibility to fabricate products in just one process. In the AM technology, the parts are created, layer by layer, from a 3D CAD data, however, the products can have important requirements that imply an external part, for example, a metallic element, an optical fibre or thin sensors, that cannot be produced in the same technology or by an AM process and for that it needs to be embedded in the product.

This paper presents the ongoing studies around the placement of inserts during the building process on AM technology, with the focus on the methodology and the parameters for production. In this paper, a set of parts were designed, produced and tested (the insert proposal). The preliminary studies include different tolerances experiments, with the focus of identifying the geometric requirement for an insert and the investigation to understand the method to fabricate products with multiple inserts, by embedding products that already have an insert.

The information resulting from the preliminary studies was applied in the development and production of a final product, demonstrating that it is possible to develop new products (hybrid products), made by AM, with functional inserts in one fabrication process.

Keywords: Additive Manufacturing, Hybrid Products, Insert, Product Development

Introduction

Additive Manufacturing (AM) is a production technology, in constant development, as an alternative to conventional technologies. According to the ASTM F2792 standard (2013), AM technology is defined as the process of adding materials to produce objects from 3D model data, layer by layer (ASTM International, 2013).

The use of AM technologies, in the product development process, allows the production of prototypes for preliminary studies, ergonomic and mechanical tests. Due to technological development in recent years, AM technologies started to be employed as production technologies for final products (Klahn *et al.*, 2014; Hällgren, Pejryd, & Ekengren, 2016). These technologies allow alternative features design with geometric freedom, process speed, multi-material products in a single step process, embedding parts during the building process, and also, lower costs than conventional technologies (Espalin *et al.*, 2014; Ota *et al.*, 2016; Thompson *et al.*, 2016). Due to the vast possibilities that AM technologies allow, it finds applications in various fields including consumer products, medical field and space industry (Gibson, Rosen & Stucker, 2010; Gebhardt, 2011; Klahn *et al.*, 2014).

This study focuses in the development of a methodology for hybrid products (i.e., products composed by two or more materials produced in a single process or by embedding inserts), by means of AM. Figure 1 illustrates the definition for hybrid products.

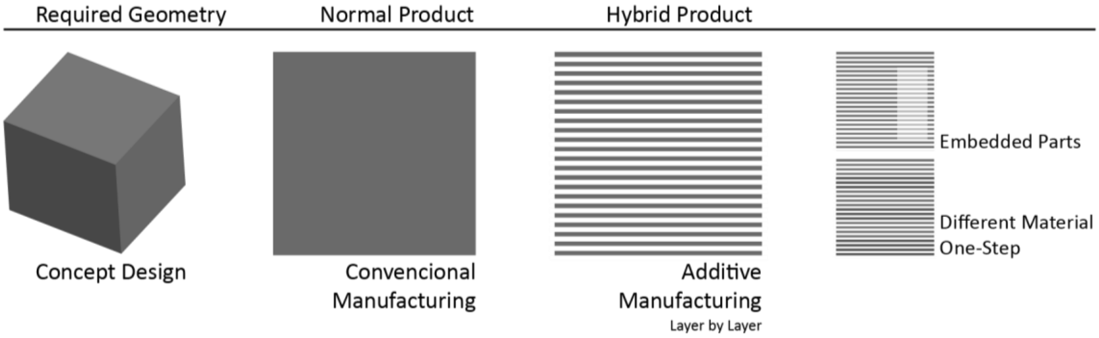

Figure 1: Hybrid Products illustrative definition.

Fused Deposition Modeling (FDM) and Polyjet (PJ-3DP) processes were the selected AM technologies for the development of an embedding methodology for inserts (parts that add functionality) during the building process and, to identify limits and capabilities of both processes.

The embedding process involves a series of considerations for all steps. Some authors (Kataria *et al.*, 2001; Mavroidis *et al.*, 2004), that investigate the process of embedding parts during the AM process, have identified some crucial phases for the embedding parts process. In the research of Meisel *et al.*, (2014), the thematic of the author was the process for embedding actuating components in the PolyJet printed parts, with the following steps: (i) Designing a cavity for the component; (ii) Pausing the build at the top layer of the cavity; (iii) Inserting the component and, (iv) Resuming the build. The steps identified by the author, involve considerations that are related to the technology process.

The FDM process consists of melting prefabricated thermoplastics filaments, through a two-nozzle heated head extrusion (one for the building material, another for the support material) and deposition of materials, layer by layer, following a predefined toolpath from a 3D CAD model. The range of the materials includes regular and high-performance thermoplastics.

The polyjet process is categorized as a jet technology. The process consists in a multinozzle print head, to print liquid directly in droplets of build material selectively deposited on the component from a 3D CAD model, and then cured by high- intensity UV lamps. The materials range include: model material (e.g., rigid, opaque, transparent, flexible) and support material (Gebhardt, 2011; ASTM International, 2013). Figure 2 depicts the printing section of both processing technologies. The process of embedding inserts for FDM and Polyjet processes demands particular attention to mechanical tolerances, and to the support material required for critical locations of the parts. These considerations were based on the Stratasys guidelines for FDM and in literature review for Polyjet (Stratasys, 2017).

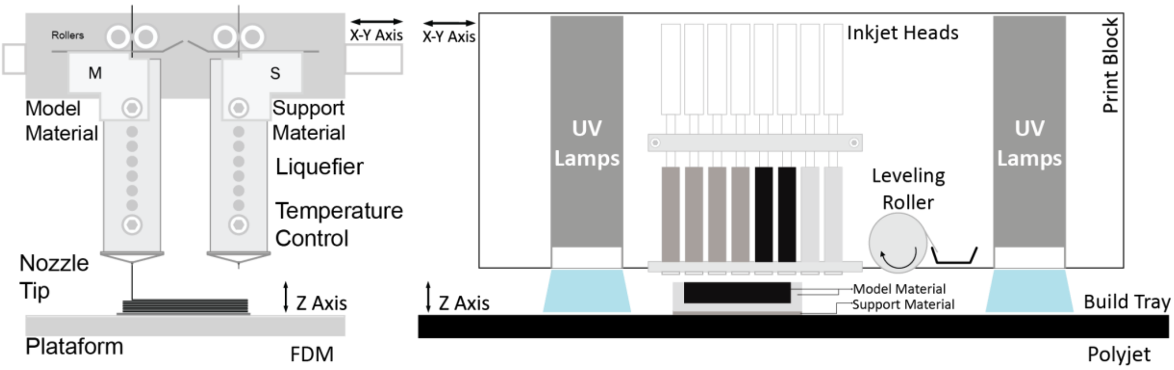

Figure 2: Process scheme for the FDM and Polyjet printing components.

The following sections of this paper present the developed embedding methodology and validation by means of an experimental procedure, for both FDM and Polyjet AM technologies. A hybrid product manufactured based on the proposed methodology is introduced followed by the conclusions.

Methodology for the insert process

The methodology approach considered for the embedding process for FDM and Polyjet processes is presented in Figure 3. It considers a series of stages that include planning, developing, and manufacturing, all interconnected by specific activities and tasks. The following sections report the experimental procedure and main considerations regarding the defined tasks.

Figure 3: Schematic representation of the methodology approach.

Requirements Definition

The definition of the main requirements is a mandatory activity that influences the subsequent stages of the embedding process methodology. In this activity, two tasks were considered: the definition of the insert typology and the adequate selection of the manufacturing technology.

The definition of the insert typology aims the identification and evaluation of specific features of the insert that may influence the embedding process in order to, in a preliminary stage, understand the constraints and simplify the process. The required features to consider, at this stage, include: (i) geometry complexity (insert complexity implies embedding difficulty, which may require shape conversion to a basic geometry); (ii) insert dimensions (influences the process accuracy for a correct placement of the insert during the embedding process); (iii) insert functionality (the function of the insert is dependent of processing constraints); and (iv) insert material (the adhesion and bonding between the insert and the construction material influences the processing quality and reliability).

The identification of the manufacturing technology for the embedding process should occur at an early stage, in order to consider the process specifications, which are dependent on the building material. For example, in processing technologies that uses a heated building chamber, the temperature at which the insert is placed into the building part must be considered, as the insert may not withstand such values.

CAD Preparation

The CAD preparation is an activity that is related to the planning and development stages. It consists in the 3D model CAD optimization considering the previous definitions for the requirements regarding the selected insert and manufacturing technology identified. The most critical feature of the model is the cavity, in which the insert is placed, during the building process. The cavity design is a negative of the insert shape and, depending on the insert geometric complexity, it may be necessary to develop an embedding strategy for the cavity design that resorts to shape converters techniques. In general, the 3D model CAD is converted into a .stl file that is then used for the production of a 3D model CAD in the AM technology software. Figure 4 depicts the steps of a technique approach for the conversion of complex geometries into basic shapes.

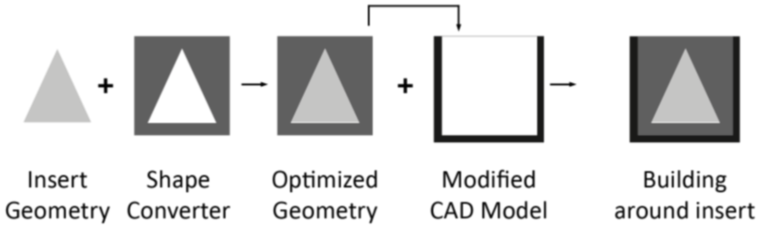

Figure 4: Schematic representation of the sequential steps for an embedding strategy.

Data preparation

Data preparation is an activity that connects the development and manufacturing stages. In this activity, the setup of the files is defined considering a series of factors that include the selected manufacturing technology, the orientation of the part for production (which may limit the placement of the insert, as it is required to be parallel to the building tray), and the layer at which the building process should be paused for the placement of the insert into the cavity for embedding.

Regarding the FDM process, the data preparation is of great importance as it is in this activity of the methodology, that all the setup files that are required for the correct production of an embedded insert are defined. The setup files definition includes: (i) the division of the model by layers (slicing), (ii) the generation of a support structure to aid the building of the intended part, (iii) the definition of the tool path during the material deposition, and (iv) the building. Typically, the generation of a support structure in critical locations, such as cavities or holes, is automatic, and therefore, special attention to support structures building inside cavity features, that are intended for inserts embedding is required. In the FDM process it is possible to visualize the support structure defined by the software and, if necessary, rearrange its structure by a manual input while assuring no automatic rearrangement by the software. For the insert placement, the command *"Insert Pause"* should be selected to assure the production interruption until opposite order. The layer to pause is correspondent to the last layer of the cavity.

For the Polyjet technology, the same steps are performed with exception of the support structure definition which is not possible to alter. The software allows the previous identification of the layer at which the production should pause for the insert placement.

Production

The production is an activity inherent to the manufacturing stage, and it implies a series of tasks for embedding an insert. For instance, in some occasions, the inserts may require a pre-treatment to improve adhesion to the polymer filament material. The pre-treatment consists in an initial cleaning step for impurities removal followed by a polymeric spray coating, homogeneously distributed, over the insert surface after which, it is necessary a dry time that varies according to the coating thickness. (Stratasys, 2009)

Considering that both manufacturing technologies in analysis have a building chamber that creates a specific environment for the production of a part and that, for the placement of an insert into the cavity of a building part it is necessary to open the chamber, an alteration of this environment is expected. The level of this alteration and its implications to the building product is unpredictable however, it is expected that a fast insert placement may avoid abrupt oscillations of the conditions of the build chamber. During the insert placement, it is important to align the upper surface of the insert with the top layer of the cavity. If the insert is placed bellow the top layer, a relaxation of the deposited material occurs which will appear as gaps or depression defects in the final product while if the insert is placed above the top layer, the movements of the deposition head are blocked by collision with the insert (Figure 5).

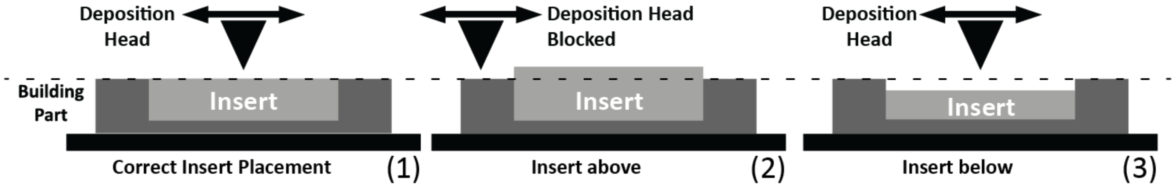

Figure 5: Insert Placement process.

The resume of the building varies according to the technology. For the FDM process, as the building chamber is heated, after the placement of the insert, a wait time should be considered to assure the stabilization of the build chamber temperature previous to the continuation of the building process.

For the Polyjet technology, the building pause must be performed manually and carefully to avoid unwanted damaging of the building part.

Experimental Procedure

The experimental procedure involves a series of interconnected and complementary tasks, that aim the validation of the identified stages and activities of the embedding methodology. The experimental procedure, in the FDM process, was performed by using a Fortus 900mc^{TM} equipment with a selected layer thickness of 0.254 mm and ASA^{TM} (Acrylonitrile Styrene Acrylate) as building material. For the Polyjet process, an Object500 Connex 3^{TM} was used with the Digital Material printing mode (30-micron resolution), a selected layer thickness of 0.030 mm, and a rigid opaque resin (VeroBlack^{TM}) as model material. In the Planning stage, the typology of the inserts was defined. For this evaluation, standard metallic objects with circular and hexagonal shapes were selected as inserts (a standard nut M6 and a standard plain washer M12). The variable shapes for an insert allow to analyse and understand the influence of the geometry over the sequence of steps of the methodology. The placement of the inserts will consider vertical and horizontal positioning, relative to the building tray, which is intended to be static requiring a proper embedding of the insert in order to avoid undesired motion.

According to the insert typology, a series of considerations are necessary for the correct designing of the cavities. The insert was defined as static, meaning that the selected dimensional tolerance between the insert and the cavity, should be the minimum possible. For the correct identification of the most suitable dimensional tolerance, a ruler (Figure 6) presenting a series of rectangular shaped cavities with dimensional tolerances ranging between 0 – 0.5 mm with 0.05 mm intervals was designed and manufactured for a specific cubic shape insert (20 x 20 mm) by both selected production technologies. Once fabricated, the definition of the dimensional tolerance counted with the evaluation of two main aspects: (i) easy placement (assuring the complete entrance of the insert in the cavity); and (ii) a tight gap between the insert and the cavity that does not interfere with the correct placement of the insert.

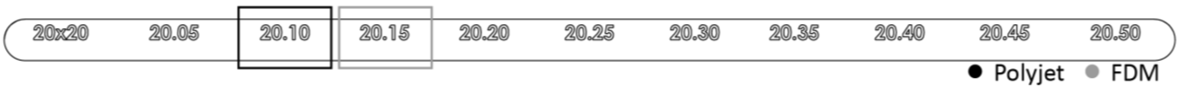

Figure 6: Representation of the ruler and the most suitable result for each technology.

Once identified the most suitable dimensional tolerance for each AM technology (0.15 mm for FDM and 0.10 for Polyjet), the test was repeated for only the cavity presenting the intended dimensional tolerance in five distinct locations over the building tray. This process was repeated three times for both processing technologies and the average value for each position allowed to understand the dimensional variation according to the positioning across building tray.

Figure 7 shows the average values for each position over the building tray. The expected line is the value of the dimensional tolerance defined as the most suitable for the cavity.

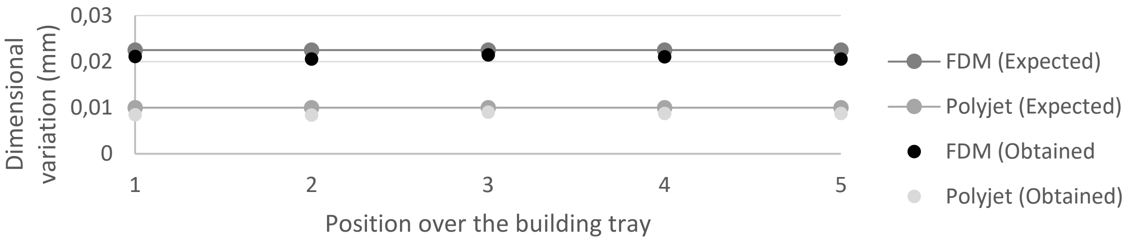

Figure 7: Dimensional variation versus position over the building tray for FDM and Polyjet.

According to the results, FDM is very reliable (small dimensional variation) especially considering that a thicker layer is being employed. The dimensional variation is similar to the one obtained by the Polyjet process with a thinner layer.

The design of the cavities for the selected inserts (standard nut M6 and a standard plain washer M12) was developed considering the defined and validated dimensional tolerance required for each process. For both processes, 3D model CAD files were developed to test the embedded process.

Figure 8 depicts the 3D model CAD developed for both processes.

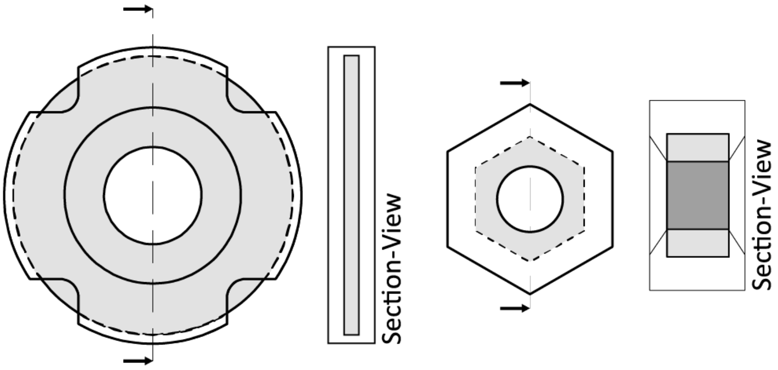

Figure 8: 3D model CAD developed for: standard plain washer M12 (left), and standard nut M6 (right), with section-view.

In some cases, depending on the shape of the insert, geometry conversion can be necessary to facilitate the embedding process. For this proceeding, it was defined that the production will be performed in two tasks that include: (1) production for geometry conversion (embedding insert in an easier configuration); and (2) embedding the processed new geometry (new embedding of the embedded insert). This processing approach was performed for both processes in analysis.

For the FDM production of developed CAD models, .stl files were exported for the production setup. Regarding Data Preparation, Insight^{TM} software was used for the management of the support structure generation and its formatting according to the needs. With this software, it is also possible to pause at the top layer for the placement of the insert. In this case study, the support material structure was deleted in the cavity regions for the insert placement previous to start building.

In the case of the Polyjet process, the support material configuration is not accessible for alteration as intended previous to the building.

The selected inserts are metallic and therefore, require a two-step pre-treatment to improve adhesion with the building material. The first step is related to the insert cleaning which was performed with a chemical product and the second step resourced to an acrylic spray coating.

The Manufacturing stage is different for both building processes. For instance, in the FDM process, the parts are built without support material inside the cavities, and the pausing occurs automatically as configured. Regarding the Polyjet process, the process is manually stopped and the support material structure must be manually removed. This is a task that requires particular attention to avoid eventual damaging. Once the support structure is removed, the insert is placed inside the cavity and the building is resumed. Figure 9 shows the resulting prototypes for FDM and Polyjet processes.

Figure 9: Resulting prototypes for: (a) FDM process; and (b) Polyjet process.

Standard nuts M6 inserts were first embedded in a horizontal position for shape conversion, and second, embedded vertically on the part being built. This proceeding facilitates and improves the embedding of inserts with complex geometries. Products with surface quality, improved adhesion and static inserts as intended is shown in Figure 10.

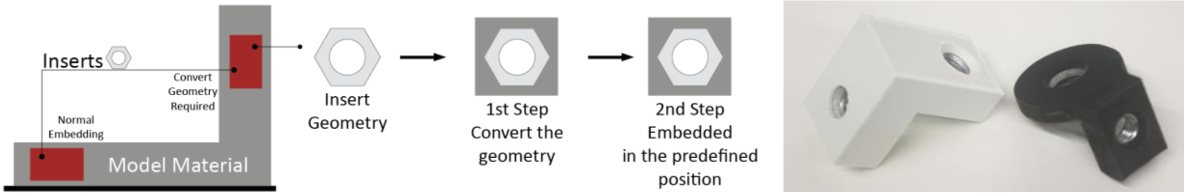

Figure 10: CAD schematic representation of the embedding process for geometry conversion (left); and resulting prototypes for FDM and Polyjet (right).

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Conclusion

Additive manufacturing technologies allow the fabrication of products with complex features and particular aspects. Embedded inserts are being widely researched, especially during the building process. Although reported in literature for a wide diversity of applications, the embedding procedure still requires a deeper understanding and validation regarding the embedding strategy definition for inserts with complex geometries.

An embedding methodology for FDM and Polyjet processes was defined considering three main stages, and a series of interconnected activities for the creation of hybrid products, by using external elements to add functionality. The embedding methodology was evaluated and validated for both technologies considering the pre-defined requirements. The reliable results obtained indicate the potential applicability of this methodology for hybrid products by both, avoiding additional post-production steps while also by allowing an easy integration of variable shapes and materials into a building part to add functionality to the final product. When comparing the pros and cons, of both technologies, it is noticeable that FDM technology presents advantages regarding the automatic control of the support material geometry and location in the building part, and also, automatic pause to integrate the insert, while for Polyjet technology, the support material generation is unchangeable therefore requiring manual removal previous to insert placement.

The developed methodology was proved successful for the selected building processes however, for its application to other AM technologies a refinement and adaptation of the activities is necessary.

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