FABRICATION OF AN ADDITIVE MANUFACTURED MOULD FOR THE PRODUCTION OF A DRONE ENGINE COVER USING THE INFUSION COMPOSITES PROCESS

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ABSTRACT:

Metal moulds have historically been employed in the fabrication of composite components. The primary drawbacks associated with this method of mould fabrication include the substantial time investment required and the significant expense, which necessitates amortisation only when manufacturing large quantities of a component. As an alternative, we propose the utilisation of moulds fabricated by fused deposition modelling (FDM) technique. The primary benefit of this technology is their accessibility, which facilitates their localised manufacturing in a significantly reduced timeframe. This renders them well-suited for the fabrication of moulds for composite components in limited production runs. Moreover, the utilisation of biodegradable materials derived from renewable sources during manufacturing processes enables the creation of moulds in a more sustainable manner. In this case study, the computer-aided design (CAD) process and manufacture of a mould using FDM for the production of a cover for a drone engine is presented. The design phases and requirements are out-lined, and the challenges encountered during the process are discussed. The infusion process is conducted using sustainable materials such as flax and bioepoxy resin. The final result of this process is the engine casing, which is composed of the aforementioned materials as part of the Sustainable Industrial Design of Textile Structures for Composites European project (SustDesignTex). In conclusion, the utilisation of FDM technology facilitates the manufacture of polylactic acid (PLA) moulds for small series of parts in a more accessible and economical way compared to costly conventional methodologies. The most no-table result of the study was that the curing of the resin should not exceed 40°C, as exceeding this temperature results in mould deformations, shortening its lifespan.

Keywords: *3D printing, composites materials, fused filament fabrication (FFF), infusion composites, infusion moulds.*

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1. - INTRODUCTION

Additive manufacturing (AM) is a group of process whereby parts are created by the addition of layers of material. In comparison with conventional machining and deformation processing methods, AM's layer-by-layer processing technology exhibits numerous significant advantages. These include the direct manufacturing process without the use of moulds, the absence of restrictions on the degree of structural complexity, greater freedom for innovative design, enhanced material utilisation and greater accessibility of use without the necessity to outsource production to other countries [1].

AM is a broad term encompassing a wide range of techniques. One of the most well-known of these is FDM, which is a straightforward and economical manufacturing process in comparison to alternative AM techniques [2]. The FDM process is

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characterised by the utilisation of a continuous filament of thermoplastic material, which is fed into the print nozzle. This filament can be either a pure thermoplastic or a thermoplastic composite [3].

This technology is primarily employed for the purpose of prototyping, a practice largely dictated by the inherent characteristics of the components it produces. A notable attribute of FDM-produced components is their comparatively lower mechanical strength when compared to those fabricated through conventional injection moulding methodologies. The rationale underlying this phenomenon pertains to the fact that the mechanical properties of FDM components are contingent upon the structural characteristics of the polymeric materials employed, in conjunction with the printer settings such as the temperature of the nozzle and the build plate, the layer height, the infill ratio and the velocity. These parameters, therefore, define the mechanical properties, and the layers' orientation exerts a significant influence on the strength and quality of the parts [4].

Nevertheless, owing to its accessibility and reduced costs, there has been a growing interest in exploring new applications of FDM technology, particularly in scenarios where batch sizes are minimal or where the production of prototypes is the primary objective. This is evident in the contemporary industrial landscape, where the demand for components that are characterised by reduced weight and improved performance has resulted in an increased adoption of polymer matrix composites in various sectors, including the automotive and aerospace industries. The moulding processes employed for the production of these components are contingent upon the number of units intended for manufacture. Typically, these moulds are composed of fibreglass, with the addition of a thin layer of gelcoat, which serves the purpose of reducing surface roughness and achieving a refined final surface on the component. Conversely, metal moulds offer enhanced durability, yet their manufacturing complexity, particularly in the case of carbon fibre prototypes, renders them significantly more expensive and time consuming. The utilisation of FDM technology for mould construction can be a cost-effective approach; however, the layer deposition process tends to result in a comparatively high level of surface roughness. Thus, it is challenging to achieve the same level of surface finish as with metal or gelcoat moulds without re-sorting to the use of fillers, despite the potential for surface refinement through reduced layer height. This underscores the efficacy of FDM moulds as a viable alternative for small production, contingent upon the implementation of a post-processing procedure on the surface that will be in contact with the part to be manufactured, owing to the inherently rough finish characteristic of 3D printing [5, 6].

One such application involves the utilisation of 3D printed moulds for the manufacturing of different products such as polyurethane foam components for the automotive industry. An example of this phenomenon is evidenced in the research con-ducted by Romero et al. [7], who emphasised the pivotal role of ensuring optimal surface preparation prior to the moulding process. Specifically, they highlighted the necessity of meticulous polishing of the surface in contact with the polyurethane foam to ensure effective demoulding outcomes. The investigation focuses on the behaviour of two moulds of identical geometry, one fabricated from acrylonitrile butadiene styrene (ABS) (acetone solvent, 45 minutes setting time) and the other from high-impact polystyrene (HIPS) (limonene solvent, 1 minute setting time). Both materials underwent chemical treatment to enhance their surface finish. The moulds are subjected to multiple cycles to assess their behaviour over time, with only a release agent utilised in the initial cycle. Subsequent analysis of the roughness of each mould indicates that the HIPS mould is more suitable for this application, as well as demonstrating the advantage that it requires less time of exposure to the solvent to improve its surface finish.

Also, Ferretti et al. [8] created a mould using the technique material polyvinyl butyral (PVB) and PLA to make a carbon fibre fuel cover for a racing motorbike. The mould was constructed such that its skeleton was composed of PLA, whilst its interior was composed of PVB, with the objective of achieving an optimal surface after printing. The solvent employed was isopropyl alcohol (IPA), a substance that exerts its effects exclusively on the material selected for the interior of the mould. This approach enabled the attainment of a polished surface, deemed suitable for the fabrication of the requisite component by means of vacuum infusion utilising carbon fibre. The study identified two primary limitations: the dimension constraints on the printing plate and smoothing chamber, and the printing orientation. Additionally, achieving higher tolerances than those reported was challenging, particularly for large parts due to the materials utilised.

Moreno-Nieto et al. [9] conducted two experiments to optimise the process parameters for mold production using a combined Fused Granular Fabrication and milling method. The optimal extrusion temperature (260°C) and extrusion multiplier (0.172%) were identified as the key factors in reducing macro- and micro-defects in ASA with 20 wt.% carbon fibre. The study also established a correlation between milling speed, strategy, and surface roughness, concluding that a specific milling speed range is necessary depending on the strategy used. It was determined through rigorous testing that a distance of 4 mm to the perimeter was the optimal solution under the prevailing conditions.

Wang et al. [6] conducted a study on the durability and dimensional stability of a 3D-printed composite mould for carbon fibre versions of the aircraft reciprocating engine valve cover. The mould was printed using polyphenylene sulfide (PPS) and 50% carbon fibre by weight through a 4.0 mm nozzle in 6.15 mm wide, 1.5 mm thick beads. The carbon fibre valve covers obtained from this mould were then evaluated for dimensional accuracy and quality. The additive manufactured composite mould functioned in

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accordance with the established protocol and was utilised to successfully manufacture all the six carbon fibre valve covers. However, it was observed that this printed composite mould exhibited an increase in defect levels following each demoulding process. These defects observed in the infused covers were primarily attributable to this damage. The majority of these defects were of a cosmetic nature and could be readily rectified by means of minimal post-treatment, such as sanding and the application of clear coats of varnish.

A further consideration is the environmental impact of FDM technology. The prevalence of AM in the industry is increasing, due to its capacity to produce smaller runs more economically. It has also been identified as a more sustainable method than conventional manufacturing methods as shown the study realized by Andreozzi et al. [10]. They conducted a study of 3D-printed composite molds for the purpose of producing components for the automotive sector in carbon fiber-reinforced polymers (CFRP). Life cycle assessment analysis demonstrated that 3D-printed molds reduce environmental impact by 18% compared to aluminum ones. This suggests that the use of 3D-printed molds is ideal for prototyping, small-batch production, and customised components and leads to greater sustainability benefits for low-volume production.

Furthermore, the study performed by Kafara et al. [11] compares the environmental impacts of conventional and AM of mould cores used in CFRP production. The findings indicate that the environmental impact of AM processes is less significant than that of conventional manufacturing processes. This is particularly evident in the reduction of damage caused by resources, which is significant in terms of environ-mental impact.

To summarise, the advantages of moulds fabricated by additive manufacturing, as outlined in the literature, include increased accessibility [2], reduced economic costs [2], decreased manufacturing time [5, 6], on-site production [5, 6] and a lower environmental impact [11]. The limitations of the process are as follows: it is only suitable for short runs [5, 6], the lower surface quality necessitates post-processing [7], it is only durable to a limited extent [6], it is only suitable for curing at low temperatures [10], and it is limited in size [8].

In this instance, the decision has been taken to utilise this technology to manufacture a mould for the production of an engine cover for a drone, which will be created using the infusion process with flax and bio-epoxy resin [12, 13], forming a composite material [14]. This process is outlined in more detail in the following section.

The present study focuses on the design and fabrication of a mould utilising sustainable materials through the implementation of FDM technology. Throughout the process, an analysis will be conducted of the strengths and weaknesses to be taken into account in the design of moulds manufactured using this technology for sustain-able part infusion fabrication.

2. - MATERIAL & METHODS

This section delineates the process of design and development of the mould for the fabrication of a casing for a drone engine. This study has resulted in the production of three prototype motor casings as illustrate figure 1 (A).

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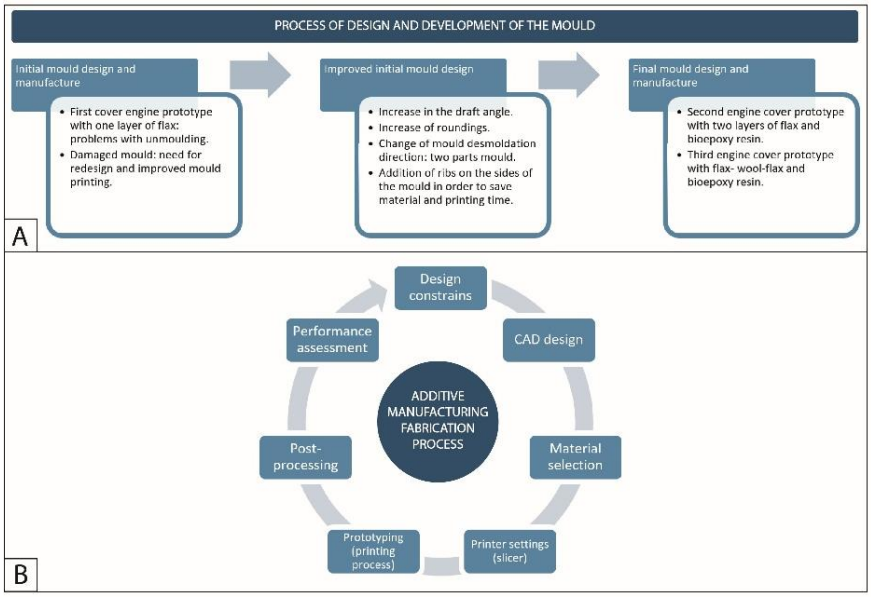


Fig 1. Concise overview of the process that was carried out (A). Additive manufacturing fabrication process (B).

The methodology employed for the design and fabrication of the moulds was that of the additive manufacturing process as shown in figure 1(B). The process is explained in detail section below.

2.1.- MOULD DESIGN AND FABRICATION

The desired cover that will be obtained from the mold is illustrated in figure 2 (A).

Given the configuration of the drone's engine cover, the initial design constraints for the mould are that the removal angle must be greater than five degrees, the corners must be rounded and the wall thickness must be greater than 25 millimeters.

Initially, the design of the mould was executed utilising the CAD Solidworks 2023 software. Following the creation of the virtual mould geometry, the SolidWorks file was converted to STL format, which is compatible with the 3D printer software, enabling the production of the mould. Thereafter, the STL file was transferred to the software computer that controls the 3D printer. The software, named OrcaSlicer, was utilised to prepare the G-code instructions for the FDM printer creality-K1 with the selected printer settings (table 1). The initial mould that was printed is illustrated in figure 2 (B). The material selected for the printing process was PLA which is a bio-based and bio-degradable thermoplastic polymer which is derived from cornstarch. It exhibits favorable mechanical and processing properties, thus making it a viable replacement for petroleum-derived polymers. However, it is a hydrophobic substance that is not particularly tough, and it undergoes a relatively slow rate of degradation. In addition, it is not very thermally stable [15]. Consequently, the enhanced version comprising various additives, designated as PLA+, which exhibits superior printability and mechanical strength, has been selected for the additive manufactured of the mould. The selection of this material is predicated on two factors: firstly, its status as one of the most sustainable and easy-access materials in this manufacturing process, and secondly, its inherent properties that render it a suitable candidate for the intend-ed application.

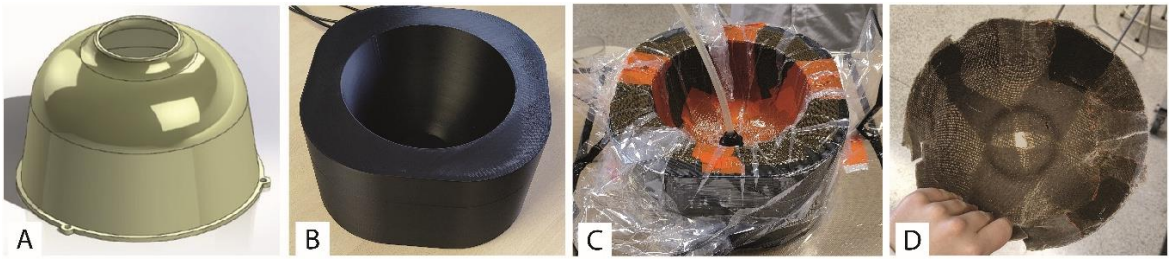


Fig. 2. Engine cover for a drone (A). First mould printed (B). Infusion process (C). First prototype obtained from the infusion process (D).

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Printing parameters for the initial and the final moulds are presented in Table 1.

Mould design	Nozzle temperature (ºC)	Bed temperature (ºC)	Infill (%)	Infill type	Nozzle Diameter (mm)	Perimeters	Layer Height, (mm)	Top and bottom layers
Initial	210	60	22	Gyroid	0.4	4	0.24	4
Final	230	60	25	Gyroid	0.4	4	0.20	5

Table 1. Printer settings of the initial and the final moulds.

Subsequent to the printing process, it is imperative to undertake the post-processing of the mould, which involves the meticulous polishing of the surface using the water sanding process. This procedure is undertaken to rectify the undesirable roughness that is often associated with the conventional finish of FDM-type printing.

Subsequent to the meticulous polishing of the surface, the mould is impregnated with a release agent, most commonly wax, with the objective of ensuring the subsequent release of the moulded part.

Then, the vacuum infusion process is initiated. The first cover engine prototype was obtained from the infusion vacuum process, which was made with 560gr/m2 flax patterns by Libeco TM superposed, and the bioresin SR GreenPoxy 33/ SD 4773 by Sicomin company. Subsequent cutting operations have been carried out with the aim of creating space for the engine's axis. Figure 2 (C) illustrates the aforementioned process and the figure 2 (D) illustrates the result obtained from the infusion process, in which defective coverage is evident.

Following, a preliminary evaluation of the infusion process is conducted, which serves to ascertain the efficacy of the mould.

Subsequent to the initial trial, it was determined that the demoulding of the infused component was not optimal, necessitating the implementation of enhancements in the design. These enhancements comprised the widening of the demoulding angle and the direction of demoulding. This was accomplished by utilising a two-part mould configuration (figure 3 (A and B)), contrasting with the original single-part design. Consequently, demoulding is facilitated in a manner that is not detrimental to the component. In addition, the quality of the mould printing was to be enhanced. This was to be achieved by lowering the higher layer in the printing settings parameters, thus resulting in a surface of superior quality and reduced distance between layers.

It was also determined that the material utilised in the mould should be reduced through the incorporation of ribs on the exterior. Furthermore, the mould will be equipped with tabs in the lower region to facilitate the centring of the two moulds during closure, in addition to the perforations designated for the insertion of screws to ensure optimal closure. The printing settings utiliced for final mould appeared in the table 1.

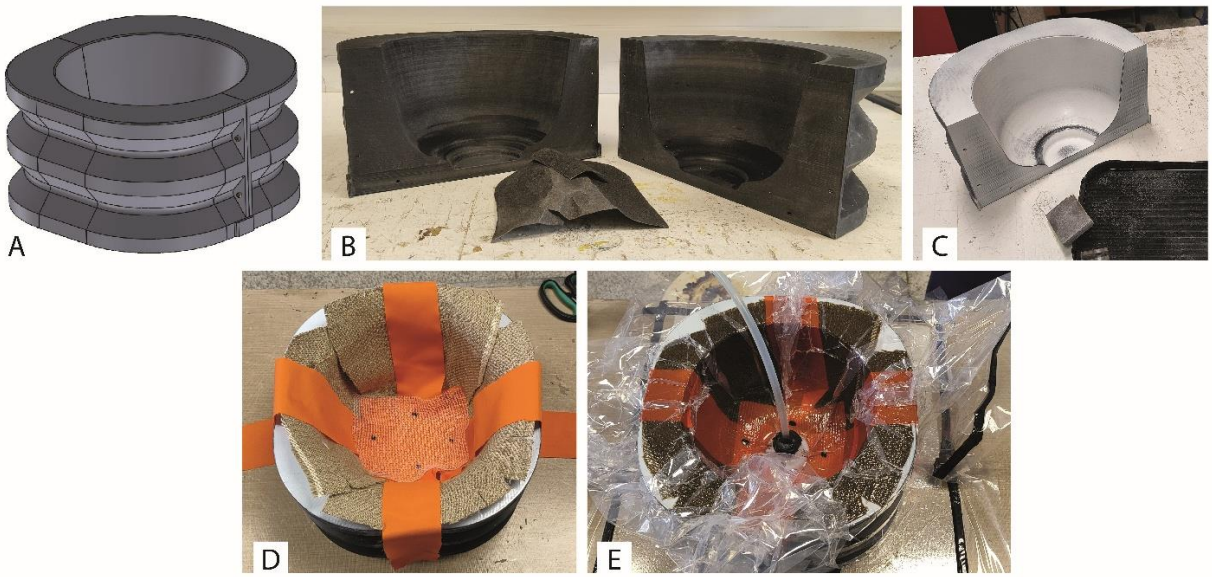


Fig. 3. Final mold, CAD model (A). Final mould after the water sanding process (B). Middle of the mould primed and polished (C). Vacuum infusion process: fibers preparation (D) and resin entrance (E).

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After the redesign, the process shown in figure 1 (B) is repeated. Subsequent to the printing of the mould, a water sanding (figure 3 (B)) is carried out in order to polish the surface and avoid any impurities being transferred to the engine cover. After the surface has been polished, two coats of primer are applied in order to make the sur-face as even as possible (figure 3 (D)). Thereafter, the mould is waxed, by applying 6 layers of wax, to allow the correct demoulding of the engine cover. Once the wax is cured, a three PVA layers are applicated to improve the demoulding process. The two parts of the mould are connected by a silicone cord to ensure the correct infusion process. Then, the infusion process is carried out.

The vacuum infusion process was utilised to facilitate the production of the second composite engine cover (figure 3 (D and E)). The entrance piece that enables the resin to enter is designed with meticulous precision and printed using an FDM process. The outcome of this process is a uniform and consistent distribution of the resin, ensuring its even dispersion throughout the fibre composition of the component under consideration. This process entailed the implementation of a composite reinforcement layer stack, meticulously layered within the designated additive manufacturing mould. Subsequent to this stage, the configuration was augmented with the incorporation of flow media and infusion grid, culminating in the sealing of the mould with a vacuum bag. Following this process, the resin-curing stage took place at ambient temperature.

Following the redesign of the final mould, two prototypes were obtained that exhibited satisfactory demoulding properties. The first two prototypes were fabricated through the superimposition of four flax patterns. The last prototype is constituted by the placement of two layers of the same flax, with a layer of wool of 400 g/m2 by TOMTEX S.A. positioned intermediately. Each layer is composed of four patterns of fabric as shown in the left of figure 3 (D), with the layers being positioned on top of each other. Subsequent to the demoulding process, the edge and the upper area are machined to achieve the desired shape. This is achieved by utilising a laser cutting machine, which ensures the precise geometry of the components.

3. – RESULTS AND DISCUSSION

3.1.- INFUSION PART: ENGINE COVER MADE WITH FLAX AND BIORESIN

3.1.1.- Initial mold and first prototype

The initial prototype exhibited numerous surface imperfections arising from discrepancies in the polishing of the mould and the print quality, which was determined by the layer height. Thus, the mould was unusable due to peeling of the layers resulted from the demoulding problems as shown in figure 4 (A and B).

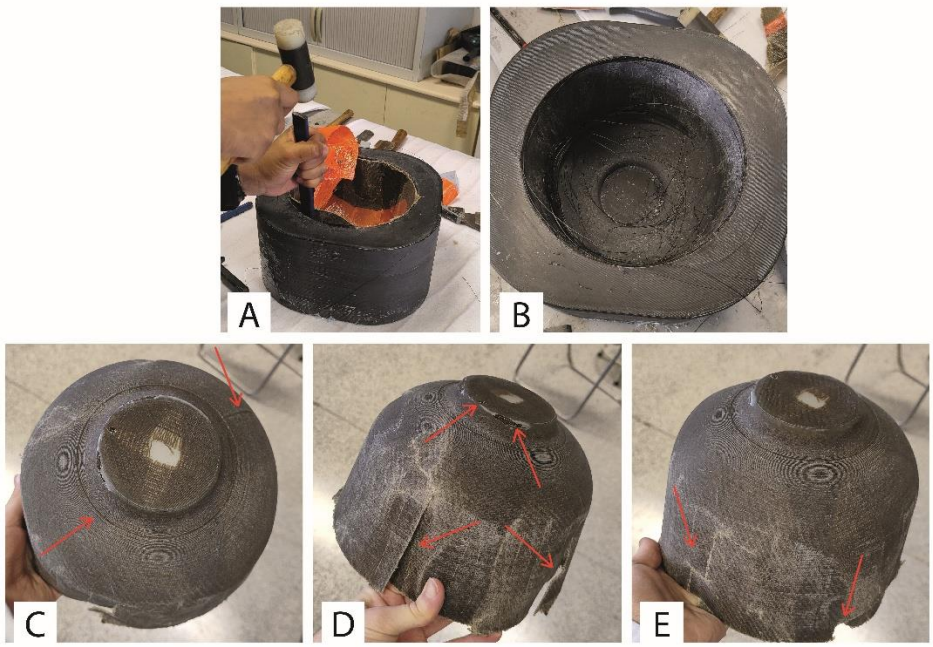


Fig. 4. Demoulding first prototype problems (A). Mould after demoulding process (B). First prototype imperfections (C, D, E).

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Additionally, the prototype sustained substantial damage during the demoulding process due to the direction of the subtraction. This was attributed to the inadequate demoulding angle, which resulted in excessive adhesion of the walls to the mould.

As a result of demoulding problems, the force exerted on the engine cover was excessive, resulting in cuts and fractures on the surface of the component. Additionally, the presence of mould lines on the final component is indicative of substandard printing quality. It was also noted that there was an absence of resin in certain curved areas of the mould. The aforementioned imperfections are illustrated in figure 4 (C, D, E).

3.1.2.- Improved mold part and final prototypes

The final prototype represents a significant enhancement over the previous iteration. The redesign was improved to facilitate the process of demoulding, and its reusability was demonstrated by the production of two engine covers. As demonstrated in figure 5 (A), the prototype fabricated from flax was successfully demoulded. This prototype exhibits a surface with a significantly reduced number of imperfections when com-pared to the original prototype.

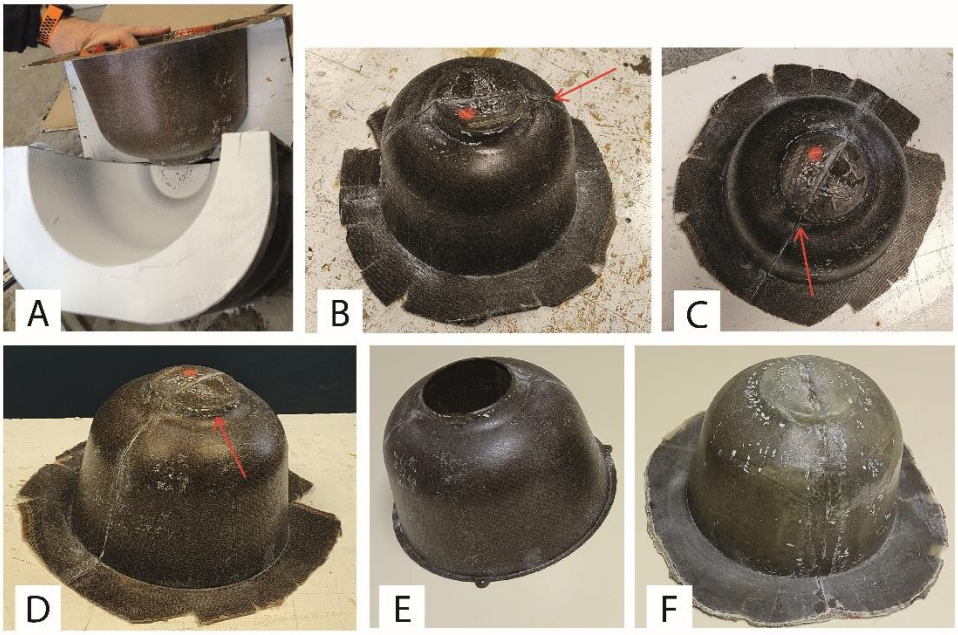


Fig. 5. Final mould and the initial prototype (second prototype) made with this mould (A). Imperfections of second prototype (B, C, D). Prototypes obtained from the final mould: first prototype (after laser CNC mechanised) (E), second prototype after demoulding (F).

The flaws observed are attributable to the integration of the two components of the mould, as illustrated in figure 5 (B, C). Additionally, the upper curvature exhibits a minor deficiency in resin, attributable to the curvature (figure 5 (D)).

A comparison of the two prototypes obtained with the final mould (figure 5 (E and F)) reveals that the last prototype consisting of three layers (flax-wool-flax) exhibits a less precise geometry. This is attributed to damage sustained by the mould during the initial demoulding process, as well as the challenges associated with the infusion process, which hindered the effective implantation of the fabrics. Additionally, the thicker nature of wool renders it more challenging to manipulate during the infusion process.

As is evident in the third prototype (fig. 5 (F)), a small deformation has occurred on the top surface of the prototype due to the deformation of the mould at the join between the two pieces that constitute the prototype. This phenomenon can be attributed to the fact that the resin attains a higher thermal peak when utilising a greater number of layers. In this instance, flax and wool are utilised. Furthermore, wool is a material that absorbs a greater amount of resin, which in turn causes higher thermal peaks to be reached. These higher temperatures result in deformations in the PLA mould because excess its glass transition temperature.

4. - CONCLUSIONS

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The findings of this study provided the team with the opportunity to examine the efficacy of a FDM additive manufactured composite mould. This investigation in-volved the production of three engine covers for a particular drone. The first cover was produced by using the initial mold while the last two covers were manufactured utilizing the redesigned final mold.

The deterioration of mold surfaces can result from a variety of factors. It is evident that a number of these factors are directly related to the printing parameters that are set in the slicer software, thereby impacting the printing process. Of these parameters, layer height is observed to have the most significant influence, given its direct relationship with the roughness of the mould. This factor has a direct impact on the post-processing time of the mould, as well as resulting in a superior or inferior polishing outcome. Mould polishing defects are therefore reflected in the surface imperfections observed on the resulting prototypes manufactured of composite materials made in this study.

Another critical factor that must be given full consideration is the glass transition temperature of the mould material, which determines the temperatures to which the additive manufactured mould can be subjected during the infusion process. It is therefore essential to select resins that do not exhibit significant thermal peaks and do not necessitate high curing temperatures while the cover is in the mould. Ideally, these resins should be capable of being cured at room temperature or below 40°C in order to prevent mould deformation due to that the PLA glass transition temperature is around 55ºC. Future studies will require a more comprehensive evaluation of in-mold temperature profiling during cure and dimensional stability data versus cycles.

In addition, it is recommended to refrain from utilising surfaces that exhibit intricate geometries, including substantial roundings or corners. This is due to the fact that such surfaces hinder complete adaptation by the fabrics, which consequently im-pedes the accurate delivery of the resin. This, in turn, results in defects manifesting on the final surface of the component. In future research, it is hoped that the impact on the surface of the prototype caused by joining the two parts of the mould can be reduced by improving the joining methods.

The creation of moulds utilising materials capable of withstanding elevated temperatures would be a fascinating endeavour. Such an approach would serve to prolong the service life of the mould and facilitate the execution of additional production cycles.

In conclusion, the utilisation of FDM technology facilitates the fabrication of moulds for small part runs in a manner that is more accessible and economical in comparison to conventional expensive methodologies.

In subsequent studies, it would be worthwhile to examine the environmental impact and recyclability of the moulds produced by this technology. Furthermore, additional research is required to ascertain the viability of this manufacturing process for the production of components with alternative geometries.

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