



Research article

Production readiness assessment of low cost, multi-material, polymeric 3D printed moulds

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HIGHLIGHTS

- The FDM AM procedure must be properly set up for the best outcome.
- The new generation FDM AM machinery gives the opportunity to explore new opportunities to reach manufacturing process efficiency to widen the target of this technology.
- Surface quality by FDM creation can be outstandingly improved with chemical smoothing process.
- Quality control by means of 3D scanning proved to be efficient with detection resolution in the order of 0.01 mm.

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ABSTRACT

Fused Deposition Modelling (FDM) technology allows to choose a large variety of materials and it is widely used by companies and individuals nowadays. The cost effectiveness of rapid prototyping is achievable via FDM, that makes this technology useful for research and innovation. The application of 3D printing to aid production is the most common approach. Moreover, the use of 3D printing in prototypes result in a waste of material since no reuse is considered. In the following manuscript, this technology is applied to mould fabrication by achieving a low surface roughness at a modest cost compared to conventional manufacturing methods. Moreover, the possibility to use a combination of thermoplastic materials is analysed by examination of the CAD model optimized for Additive Manufacturing (AM) from scratch and was verified using metrology tools. Several moulds were finally built and applied to the specific case study of carbon fibre laminated components. This manuscript aims to analyse the manufacturing process by comparing the mould surface geometry before and after the smoothing process. The achieved tolerance between the produced moulds is ± 0.05 mm that ensures the repeatability of the process from an industrial point of view; whilst the deviation between CAD and mould is ± 0.2 mm. To combine an accurate FDM process together with chemical smoothing proved to be a powerful strategy to produce high quality components that can be inserted in the production process by means of traditional manufacturing techniques. This will aid to reduce the cost of standard manufacturing for low production batches and prototypes of carbon fibre composites.

1. Introduction

Fused Deposition Modelling (FDM) [1] is one of the most renowned 3D printing method in the market due to its variety of possible printable materials from mainstream Polylactic Acid (PLA) up to more professional materials like Nylon [2] up to reinforced polymers like Acrylonitrile Butadiene Styrene (ABS) [3], PolyEther Ether Ketone (PEEK) [4], and

PolyPropylene (PP) [5] with carbon or glass fibers. This helped 3D printing to been known for its ability in creating complex geometries at low cost, especially for rapid prototyping applications; process of which was enlightened in the reviews of SAVU et al. [6] and Ngo et al. [7]. Nevertheless, FDM methodologies are still challenged for their exterior surface quality and internal structure anisotropy that makes this products difficult to be standardized for mechanical applications. Moreover, this

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technology ought to result in low productivity [8], but they proved to be a solid solution to create low-cost parts and small-lot production [9, 10, 11]. Additionally, FDM printing processes has been applied in different sectors like in biomedical, for tissue engineering, human bone repair, antibacterial, or other applications like electrical conductivity, electromagnetic, sensors, batteries, and other applications in the automotive, aviation, smart textile, environmental, and luminescence among other areas [12].

Moreover, researchers have used this technology to create tools for component production, especially in the case of very limited batches or prototypes. One of this application exploited the 3D printed moulds to manufacture polyurethane foam parts for the automotive industry [13]. The versatility of this process has turned it easily adaptable to a wide array of material types, among polymers, metal, and composites. A prove of this is the inclusion of a heated chamber in most modern printers, which in FDM is not always needed as in the case of Selective Laser Melting (SLM) printing method. Material supply to FDM printers is rather simple, and widely offered by dozens of manufacturers, that together to a large variety of thermoplastic polymers available on the market, in addition to other materials adapted to Fused Deposition [14]. Likewise, this printing method proved to be safer to other technologies like powder technologies that mandate personal protective equipment to avoid respiratory system problems during material handling and component cleaning, opposite to FDM that demonstrated no hassle during material handling since the material is wound on a spool, being easy to replace once the material is over. Additionally, FDM processes shown to be less environmental toxic [15] as the fumes produced can be successfully removed using small proper filters inside the printer. However, the main challenge of FDM printing ought to be the obtained surface quality of the created parts [16, 17, 18], in which other methods like SLM, Stereolithography (SLA) [19], and multi jet fusion from HP [20] have proven to be superior. This has been one of the reasons why Additive Manufacturing (AM) process repeatability is also a key research focus [21, 22, 23].

Moreover, other research results established that computer-aided engineering helps to portray efficient, cost effective mould manufacturing [24], and that polymeric-sourced moulds could be constructed by FDM printing [25], by using polymers like ABS to create a 3D-model accordingly to eliminate material shrinkage issues [26]. Moreover, the challenges of achieving a technical feasible product are often achieved by taking back knowledge from previous trials [27]; the research of Chen et al. [28], Mulan et al. [29], and Valerga et al. [30] proved that applying the method of polishing the surface of 3D-printed elements by solvent vapor is highly effective to reduce the surface roughness of the moulds.

1.1. Multi-material mould for carbon fibre component lamination

Historically, researchers have proposed complex information systems in order to aid a proper material selection in composites [31]. This advances have been led by the automotive sector, and in a more conservative way with the aerospace sector [32]. Past trial studies on the possibility of making moulds with FDM technology proved to be a clever solution [28, 33]. AM technology allowed the opportunity to exploit the full potential of rapid manufacturing with the versatility of FDM technologies. There are several FDM printers capable of multi-filament printing, besides a wide offering of filaments to portray multi-material printing. Hence, a novel proposal of component manufacturing with a wider range of functionality is possible. Moreover, the compatibility between filaments is crucial to allow the right adhesion, as well as guaranteeing a high surface finish. The latter result can be achieved by means of surface treatments that reduce exterior roughness of the moulds and guarantee a high surface finish to the moulded carbon fibre part [34, 35]. Moreover, the possibilities found in literature to obtain a good quality mould surface are mainly three: secondary machining, coating and

smoothing [36]. The first one has several drawbacks, in particular a material quantity to be removed must be considered, in addition to the extra equipment and tooling investments, hence the final cost and total build time increases, so then turns this approach more expensive than a single manufacturing process [37, 38]. The coating procedure changes the geometry of the component and thus the surface tolerance [39]. Because of the latter considerations, the smoothing process was chosen for this exercise, as it is known that thermoplastic polymers could be dissolved with certain chemical compounds. The research of Basha et al. [40], underlines the process of chemical polishing, as an outstanding procedure for enriching the appearance of a surface [41]. Chemical immersion is used for material abrasion or chemical polishing to increase surface finishing quality. The sharp details on the surface will diminish more if the chemical bath takes a longer period, hence its tolerances values are much determined on time [42]. The combination of chemical type and reaction time must be wisely taken to get a desired surface roughness quality [43]. Likewise, it is possible to smooth the surface of the parts by carefully controlling the action of the solvent. This surface modification usually occurs below the glass transition temperature, thus retaining the mechanical integrity of the component, and just reducing the outer surface roughness [44]. This process is highly valued to improve the overall surface quality of FDM-created elements [45]. The applied technique is commercially known as chemical smoothing and has been used by researchers to improve the quality of 3D printed surfaces, particularly in mould manufacturing exercises, like the previous work from Bin et al. [46] which guaranteed a watertight surface with this procedure. Additionally, adequate ventilation must be performed to evaporate the solvent residuals from the surfaces, finalizing the smoothing process and reobtaining the proper surface hardness. The process of Isopropyl Alcohol (IPA) smoothing has been validated with Polyvinyl butyral (PVB) material only. The vapor will interact with this material leaving other parts untouched in the case of multi-material printing. In particular, the IPA vapor breaks the weak bonds between molecules. On the opposite, when the alcohol is completely evaporated, this bonds are restored. This process makes surface smoothing possible, and it doesn't involve material removal. This is important since no removal rate is considered, and no waste of material is expected to occur. However, the effectiveness of this process is strictly related to the correct application of the vapor over the entire surface and most importantly, the overall action time of the solvent over the surface. A correct trade-off must be accessed in order to reach the desired quality of surface, but also to reach geometrical tolerance correlation with the original CAD values.

Moreover, the chosen smoothing process for this project is not the only one available. Table 1 shows a comparison between 3 different surface enhancement methods found in the literature: Chemical Smoothing [47, 48], Epoxy Resin Smoothing [49, 50], and Abrasive Smoothing [51]. The epoxy smoothing method applies a thin coat layer of resin to fill the gaps between lines and layers. On the opposite side, abrasive smoothing involves removing material from the surface of the geometry using abrasive powders. The six parameters shown on Table 1 (Automation of the process, ability to deal with complex geometry, toxicity of the used chemicals, the need for safety equipment, overall costs and printing times) have been analysed from a quality point of view assigning to them a specific weight (high, medium, low). Therefore, benchmark properties for each parameter have been highlighted in green. Chemical smoothing showed more benefits compared to the other processes, specially to epoxy resin smoothing. Therefore, chemical smoothing has been chosen by the authors.

Therefore, the aim of this study is to portray an exercise of a FDM part manufacturing aimed to achieve a low surface roughness by means of exploiting the chemical smoothing process for polymeric FDM elements. Moreover, the repeatability and the possibility to use a combination of thermoplastic materials are analysed with a 3D laser scanning method, which is used to verify the validity of the proposed manufacturing procedure.

Table 1. Comparison between different smoothing processes. The best result is shaded in green for each parameter considered.

	Automation	Complex geometry	Toxicity	Safety	Costs	Time
Chemical smoothing [47, 48]	High	High	High	Medium	Low	Low
Epoxy Resin Smoothing [49, 50]	Low	Medium	High	Low	Medium	Medium
Abrasive Smoothing [51]	Low	Medium	Low	Medium	Low	High

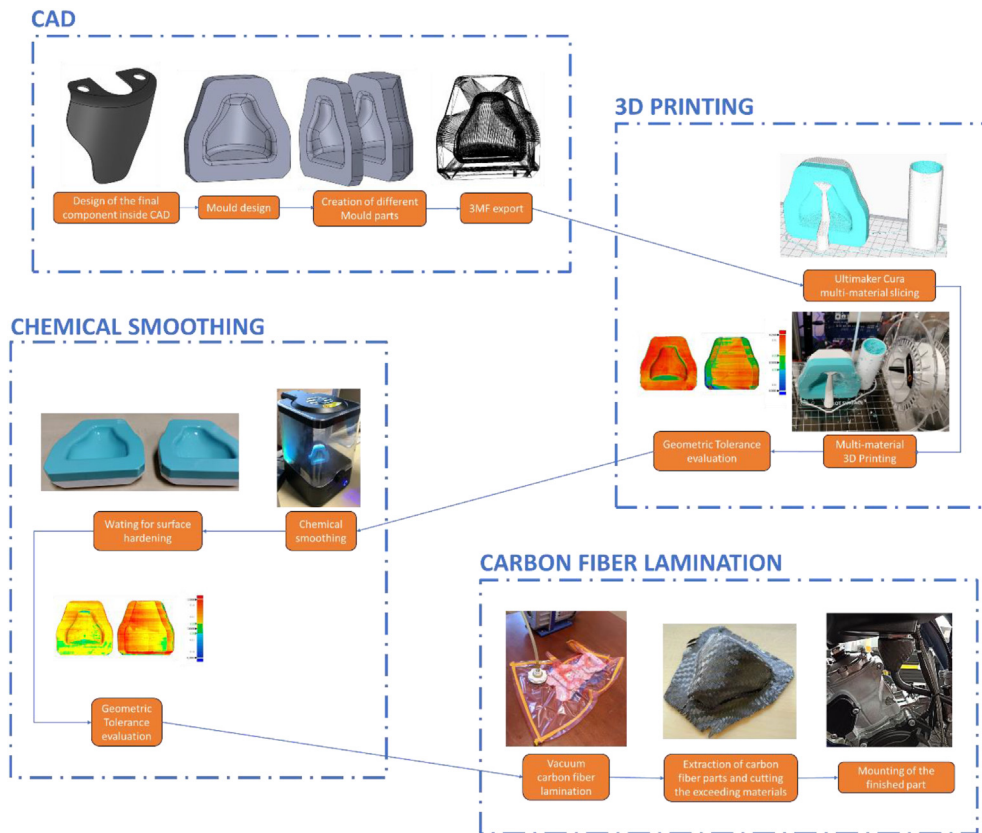


Figure 1. Process workflow starts from the design of the object, passing through the mould design, the mould fabrication, until the manufacturing of the carbon fibre component.

2. Materials and methods

2.1. Methodology

Figure 1 shows the methodology proposed for the design, manufacturing and postprocessing tests. The equipment for vapor smoothing used in this study is the Polymaker Polishear (Polymaker Inc., China), developed specifically for PVB polymers. The input of the pipeline is a 3D CAD model of the carbon fibre part, and the final output is the manufactured carbon fibre component.

2.2. Materials choice

This study considered a combination of two polymeric FDM filaments: Polyvinyl butyral (PVB) (produced by Polymaker with the commercial name of Polsmooth®) in addition with PLA produced by Filoalfa®. This study proposes to fabricate a mould with PVB material in order to laminate carbon fibre components. PVB is usually applied for safety glass manufacturing [52] due to its transparency properties [53], but it is unknown for FDM applications. Its use in the mechanical field is also unknown except for the latter example. Nowadays, the cost of PVB filament is almost double the price of the most common PLA but is still rather low than that of Nylon and other engineering polymers. However,

the print quality is excellent whilst keeping its printability and mechanical behaviour comparable to PLA [54]. Nevertheless, the lower glass transition temperature (Tg) of PVB implies low warping behaviour,

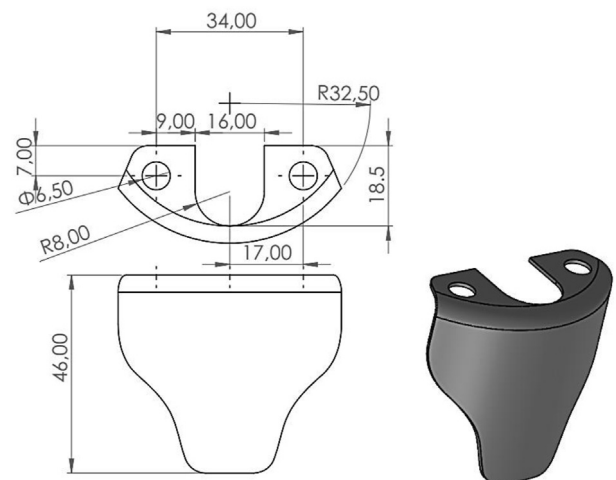


Figure 2. 2D drawing of the fuel tap protection with the main dimension and isometric view for the Husqvarna tc85 MY 2022.

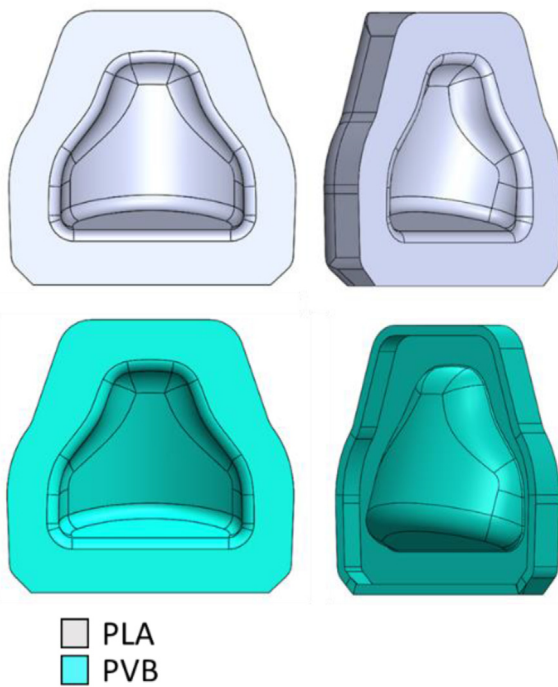


Figure 3. CAD model of the two parts of the mould, the PLA part in white and the PVB part in light green.

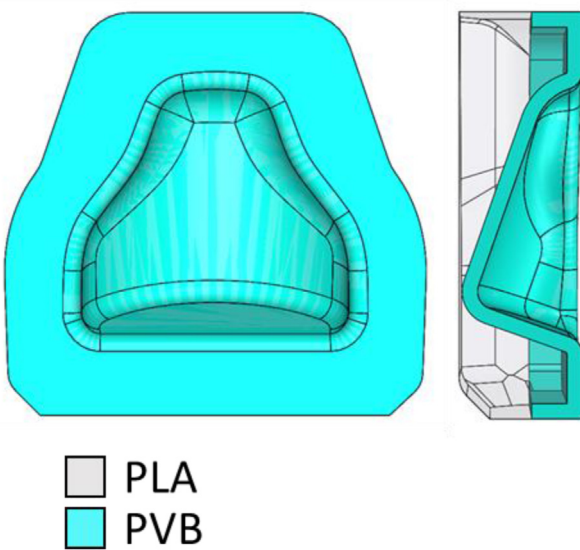


Figure 4. CAD model of the two parts assembly.

plus the capacity of manufacturing bigger-sized components is possible with a not enclosed printer, alike PLA. However, the main drawback of PVB is the high hygroscopic behaviour that constrains its storage in humidity-controlled containers. Furthermore, it is soluble only with specific solvents, as isopropyl alcohol (IPA). Other polymers like PLA are soluble in chloroform [55], but this process is rather dangerous. Other materials such as ABS and ASA are soluble in acetone [48], but need more specialized printing tooling like an enclosed heated chamber to avoid layer delamination, higher printing temperatures and fume filtering. The fumes originated by these polymers could lead to various respiratory system issues [56]. All these problems would increase the overall cost of production of the mould inevitably if ABS or ASA are used though their cost is compatible PVB.

Table 2. Slicing printing parameters applied in Ultimaker Cura.

Parameter	Unit	PLA	PVB
Layer Height	mm	0.2	0.2
Line width	mm	0.4	0.4
Wall Line Count	-	2	2
Z seam position	-	Shortest	Back
Top Layers	-	1	1
Bottom Layers	-	1	1
Infill Density	%	15	35
Infill Patten	-	Grid	Grid
Printing Temperature	°C	205	210
Build Plate Temperature	°C	70	70
Flow	%	100	100
Print Speed	mm/s	60	60
Travel Speed	mm/s	200	200
Retraction Distance	mm	4	4
Fan Speed	%	100	100
Regular Fan Speed at Height	mm	0.4	0.4
Support Structure	-	Tree	Tree
Support Overhang Angle	°	45	45

However, a smooth internal surface of the mould must be ultimately ensured to guarantee a carbon fibre component with an acceptable surface finish. Additionally, manufacturing costs of the element were minimized by limiting the use of PVB only where a smoothed surface is needed, hence reducing the overall mould cost. This has led to create a multi-material hybrid print in which the PVB is used as a “coating material”, by means of creating a small surface layer, only in the strictly necessary areas. Therefore, the rest of the mould structure and the internal infill would be constructed in PLA, that would not undergo any changes due to IPA alcohol and therefore remains unaffected. Though polymer adhesion characteristics between PLA and PVB is very good. This combination has been already analysed by Prusa [57] concluding that the two materials are compatible, they could be combined without risk of nozzle clogging and they are able to adhere to each other with no problems. Additionally, they both share similar printing parameters, making a more stable and predictable additive manufacturing process.

2.3. From solvent bonding to chemical smoothing

It is known that Thermoplastics could dissolve gradually with a given chemical compound, and that the surface of a polymeric element would be diminished by a controlled process. Also, a strong surface adhesion could be obtained when both surfaces are treated with a solvent, as a polymeric chain diffusion is created when the solvent is helped with a compression force between both treated areas. Furthermore, the solvent bonding properties just happens when attached to a surface, being different from adhesive bonding methods; this surface relaxing usually occurs below T_g, thus maintaining the mechanical integrity of the component, and therefore it could be used to smooth the surface of a given thermoplastic [44]. This process was known to improve the overall surface quality of FDM-created elements [45]. This procedure is commercially called chemical smoothing, and has been used by researchers to improve the quality of 3D printed surfaces, particularly in mold manufacturing practices, like previous work from Bin et al. [46] which assured watertight surfaces with this procedure. Additionally, the component must be cooled down at open air or with proper ventilation to achieve even results, so the alcohol residuals would evaporate from the surface appropriately. The process of Isopropyl Alcohol (IPA) smoothing is applicable only to PVB material so then the vapor interacts only with this material, leaving other materials untouched in the case of multi-material printing. The scope of this study would not consider possible effects of vapor interaction with other materials for the case of

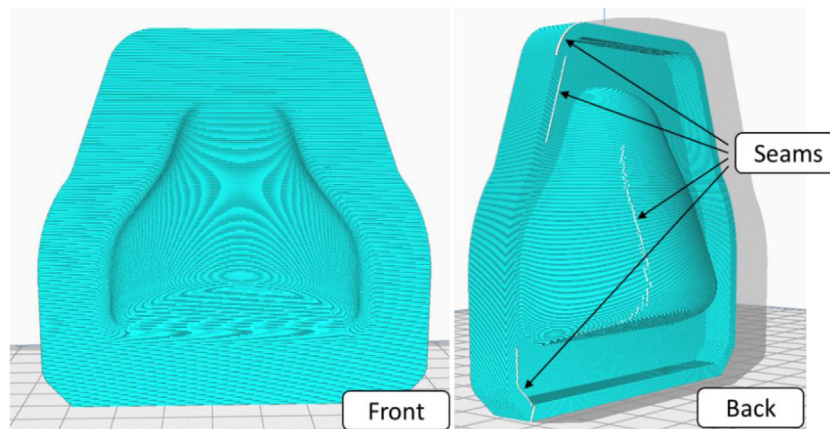


Figure 5. Seams position for the PVB part.

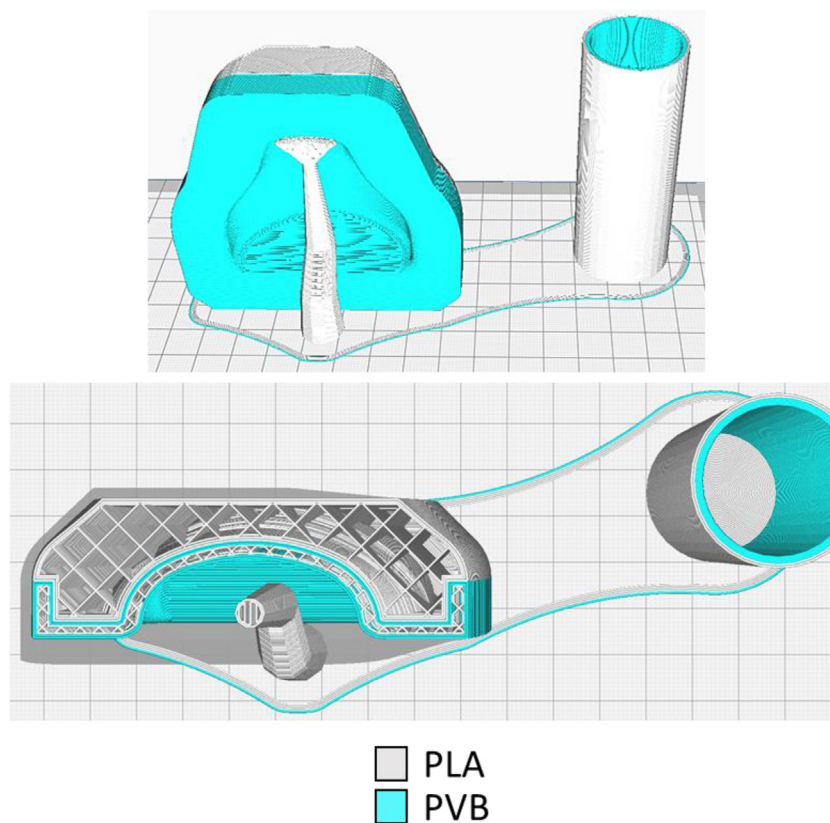


Figure 6. Preview of the created G-code inside Ultimaker Cura.

multi-material printing at this stage. Additionally, the equipment for vapor surface smoothing is the Polymaker Polishear (Polymaker Inc., China), that was developed specifically for PVB polymers.

3. Case study: carbon fibre fuel tap cover for a racing motorbike

The outlined methodology can be applied to diverse exercises such as the production of carbon fibre trims for luxury cars, produced in low batches of small to medium carbon fibre parts and prototypes. The same idea can be applied to different sectors such as automotive, naval, aerospace among other general industry applications. The chosen case study to prove the methodology is a small batch of carbon fibre cover for the automotive field.

The need of a lightweight cover in racing bikes that protects exposed components from debris that can cause damage to the vehicle brought the decision of applying the proposed methodology to a real case application. This is the case of the Husqvarna TC 85 2022 motorbike, in which the fuel tap is exposed, and the introduction of a protection element should avoid potential fuel leakage by damage to the cap. This exercise would be followed by other components ought to be designed and produced for the exclusive usage of the racing team.

3.1. Mould geometry

The geometry was gathered by means of the CAD 3D model of the stock fuel tap protector cover. PTC Creo 3D is modelling software that

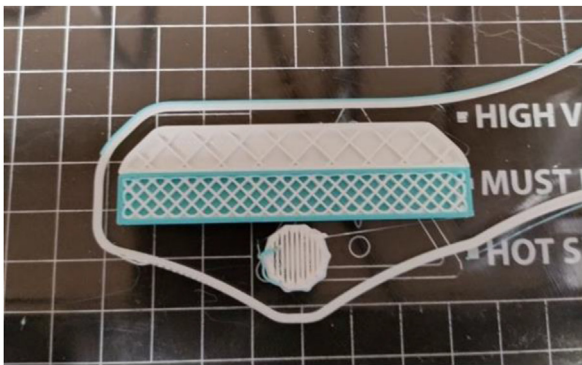
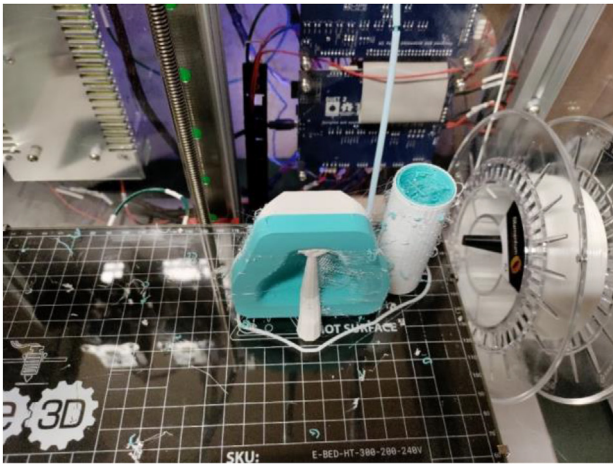


Figure 7. Initial layers of the FDM mould at the top, the final result at the bottom.

was used to create the protection cover model according to the dimensions acquired directly on the fuel tank by means of a calliper; the 2D drawing and 3D detail is shown in Figure 2.

The CAD file of the mould was created with a Boolean operation starting from the outer surface of the actual part. This procedure allowed to create a cavity with the desired geometry. Special attention was carried out in the creation of proper draft angles (5° on all surfaces of interest) and elimination of undercuts. In addition, it was decided to create a tool insertion space all around the cavity of the mould to ease the extraction of the component and to avoid cavity damage. The part was designed to be reused. Additionally, three flat areas have been added on the base, on the back and on top to ensure proper positioning inside the smoothing machine. Finally, the addition of large fittings made it possible to avoid ripples in the fabric during lamination that could transmit defects to the final component as well.

Furthermore, to achieve a multi-material solution it was necessary to divide the initial mould into two overlapping parts, as required by the slicing software to be able to assign different settings to overlapping

volumes, one in PVB and one in PLA. Figure 3 shows the CAD model of the two parts. The final thickness value of the PVB part was obtained in order to minimize the use of this material only in the areas of actual interest and at the same time to maximize the quality of the internal mould surface. It was decided to proceed with a design that allowed to have the least amount of visible printing path lines in PVB, but at the same time avoided visible joints in the cavity of the mould or on the surfaces of interest, thus maximizing the final quality. This approach created a surface with the desired thickness starting from the front face of the mould. Finally, the two components were put into an assembly and saved, as can be seen in Figure 4 and imported later into the slicer software (Cura v4.11.0) for printing setup.

3.2. Printing strategy and settings

The printer used for this application was the E3D toolchanger. It is a multi-extruder device that allows multi-material or multifilament part manufacturing using FDM technology. The printing strategy developed for this component can be easily applied to parts with similar material characteristics and component properties requests. Table 1 summarizes the printing parameters used to create the multi-material part, splitting the printing parameters between PLA and PVB. PLA was used to create the back part of the mould, as well as the infill of the overall part and the supports. This resulted in two different infill percentage areas, the first section is the closest to the mould cavity and the other at the most distant part. This allowed to avoid possible collapses of the mould around the areas of greatest interest, and at the same time, helps to reduce the overall extrusion, hence the build time of the PLA part.

Moreover, the parameters and settings in Table 2 were adopted to improve the quality of the mould before the chemical smoothing process and to reduce possible internal cavity defects as shown in Figure 4. Additionally, Figure 5 shows that the PVB seams have been specially

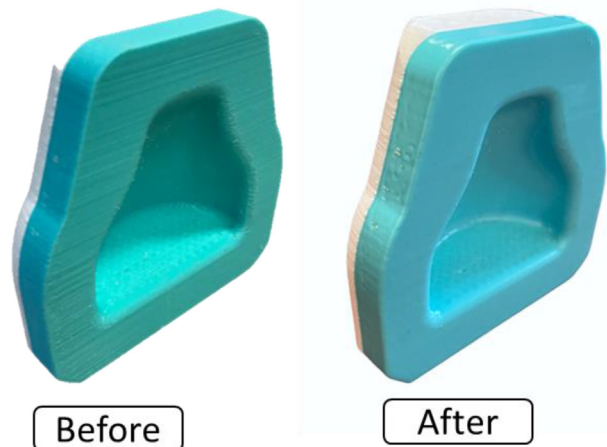


Figure 9. Surface comparison before and after smoothing.

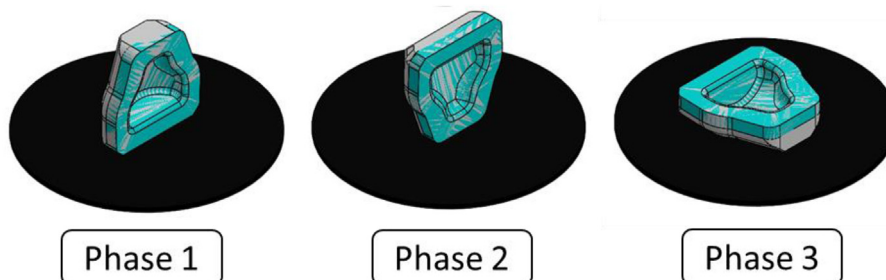


Figure 8. Position of the moulds during the three 20-minute smoothing cycles.

positioned in the internal hidden part of the mould to avoid any possible defect on the surface. The seams of the PLA part were chosen to maximize the printing speed by reducing the travel movement and sacrificing little of the print quality of the PLA part. A purging tower was placed close to the part in order to purge the extruders and to stabilize the material flow before printing the layers of the part.

Afterwards, a preview of the G-code can be seen in Figure 6, showing the multi-material part, the tower, and the different infill percentage areas. A Figure 7 shows the first layers in which are visible the base of the support, the differentiated density infill at the top and the result at the bottom. Finally, a 100% PVB mould was also printed to make an evaluation of the multi-material additive process. In this way, it was possible to portray an overall tolerance comparison with respect of the CAD and PLA-PVB moulds, allowing to verify the advantages of this multi material solution.

3.3. Chemical smoothing of the mould cavity surface

The Chemical Smoothing (CS) process was performed on all 3D printed parts described in 3.2, by using the Polymaker Polyshear post-processing device. Each part positioned inside the machine in the same position as printed, then an initial 20-minute smoothing cycle was performed. Next, the moulds were flipped over and a second 20-minute run was completed. Finally, the moulds were rotated upside down and a final 20-minute cycle was applied. Smoothing in multiple positions allows a better uniformity of the final surface. The chosen cycle time and part positioning were decided after reviewing the smoothing parameters given by the PVB filament manufacturer. Part positioning must guarantee the clear path for the fumes to the desired treated surfaces.

Moreover, Figure 8 summarizes the three positions in which CS was performed. All parts are then left to dry for 72 h at room temperature to

allow the alcohol to completely evaporate from the surface. Alternatively, this process can be accelerated by keeping the moulds in a ventilated environment to accelerate alcohol evaporation. Furthermore, Figure 9 shows the comparison between the PVB-PLA 3D printed mould after support removal with material residuals on the cavities, opposite to the one after the smoothing cycle. The PLA surfaces remained unmodified after the smoothing cycle since there's no reaction of such polymer with IPA.

4. Result and discussion

4.1. Dimensional verification of 3D-Printed mould just after printing with an optical 3D scanner

To assess the obtained quality level of the process, a dimensional tolerance and replicability assessment of the multi-material printing and smoothing processes were portrayed thru a Faro 3D Quantum Max ScanArm 3D Scanner was used. Two PLA-PVB moulds were printed using the same G-code file and one all-PVB mould was printed using only the PVB setting provided on Table 1. Two measurement-scenarios were taken for all the printed moulds, one after printing and the other one after CS, as shown in the workflow (Figure 1). Moreover, a dimensional evaluation was carried on by comparing the point clouds obtained with the 3D scanner and the original CAD file.

Therefore, the results shown in Figures 10 and 11 demonstrate a slightly oversized geometry respect to the CAD file. About 95% of all the surfaces have a positive value less than 0.2 mm with respect to the reference geometry. Figure 12 reveals a high level of reproducibility since the two PLA-PVB mould surfaces exhibited differences in the range of ± 0.05 mm, with the major deviation value appearing outside the surfaces of the cavity.

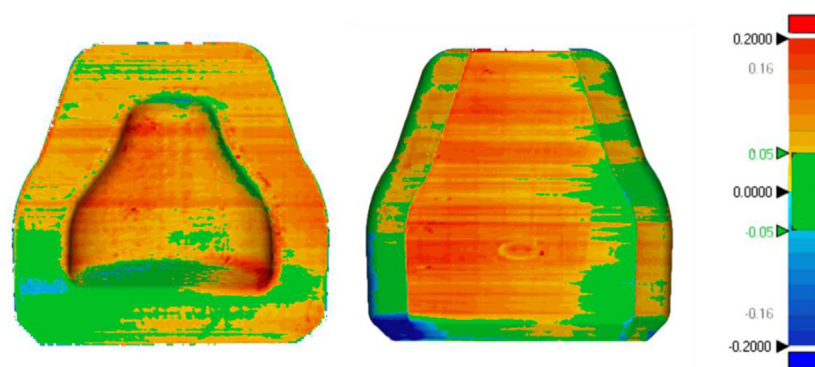


Figure 10. Reference: mould CAD geometry; Object: mould 1 PVB-PLA after printing.

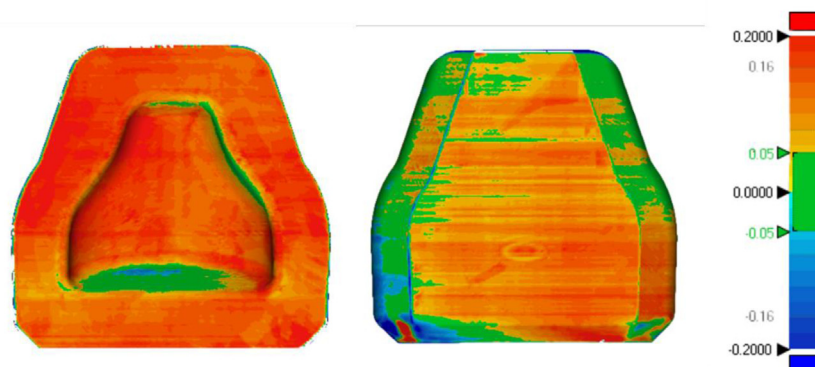


Figure 11. Reference: mould CAD geometry; Object – mould 2 PVB-PLA after printing.

Moreover, the results shown in Figure 13 compare the values from the all-PVB mould with the CAD geometry. The areas coloured in blue represent the zones that are slightly undersized with respect to the CAD one. As can be seen from the results, a full PVB part has led to a more accurate internal cavity surface. The comparison between the mesh of the all-PVB mould and the two PLA-PVB moulds is shown in Figures 14 and 15. The results of this comparison with respect to those obtained from the single material compared to the CAD show that the PLA-PVB moulds are oversized by a few tenths of a mm with respect to the all-PVB one. Repetition trials revealed that different material removal rates could be a cause of it.

4.2. Dimensional verification of 3D-Printed mould after smoothing with an optical 3D scanner

The chemical smoothing procedure was performed according to section 2.3 and the parts were scanned after 72 h. The comparison before and after CS is shown in Figures 16 and 17. In this case, a different approach for the comparison of the two-point clouds was adopted to minimize the overall distance between the meshes. Since PLA surfaces remained untouched by the IPA smoothing process, the alignment was done referring to such surfaces.

However, Figure 18 instead shows the effect of CS on the all-PVB mould. Figures 16–18 show that there is an swelling on the surface

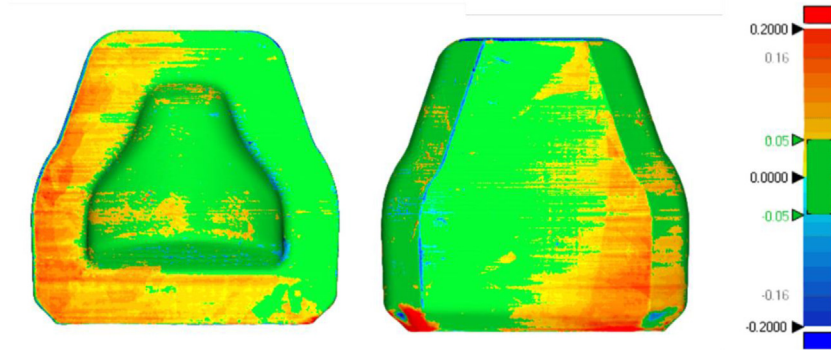


Figure 12. Reference: mould 1 PLA-PVB after printing; Object: mould 2 PLA-PVB after printing.

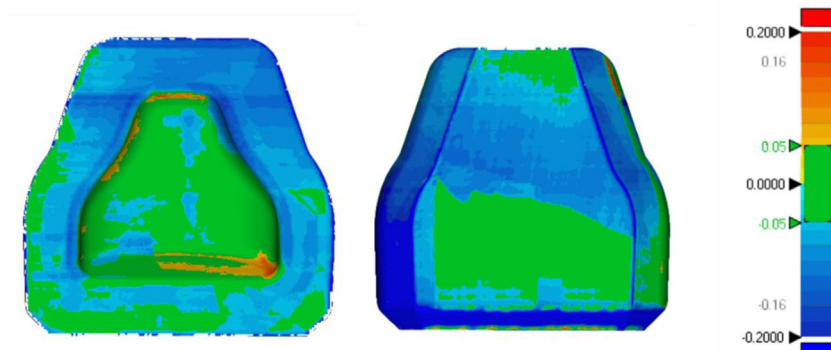


Figure 13. Reference – CAD geometry Object – 100% PVB mould after printing.

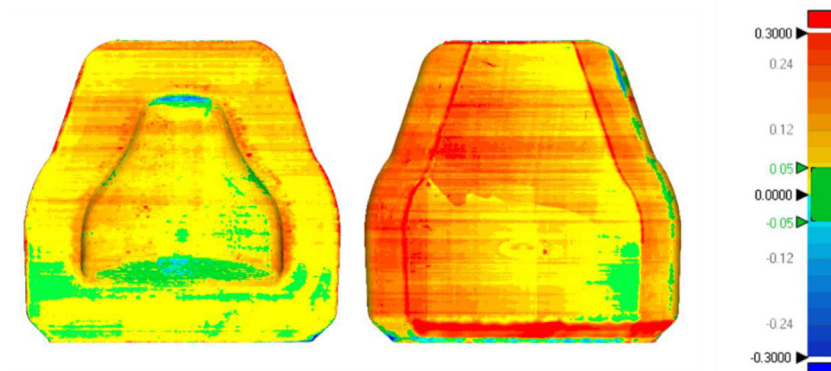


Figure 14. Reference: mould 100% PVB after printing; Object: mould 1 PLA-PVB after printing.

after the smoothing process due to a residual content of solvent that is still present in the surface. On the opposite, forcing the evaporation inside an oven can generate the blistering phenomenon.

However, Figure 19 shows that the smoothing process, performed following the aligning of Figure 7, was able to flatten the minor differences exhibited in Figure 12. Nevertheless, the moulds expanded due to the residual alcohol content but remained almost completely identical afterwards with a final tolerance in the range of ± 0.05 mm.

Nevertheless, the overall final tolerances obtained by comparing the results after CS with the CAD geometry were evaluated after leaving the smoothed moulds in free air at ambient temperature. Figures 20 and 21

show the PLA-PVB moulds, oversized with respect to the CAD geometry. The final tolerance values obtained with respect to the CAD geometry are mostly within the absolute range of 0.3 mm. The most important result is reported in Figure 22, where the undersized geometry of the all-PVB mould got closer to the CAD geometry values after the smoothing process.

4.3. Vacuum lamination process and final mounting of the part

Consequently, the manufactured moulds were used to create parts by lamination; this was carried out by using 120 g/m² twill carbon fibre

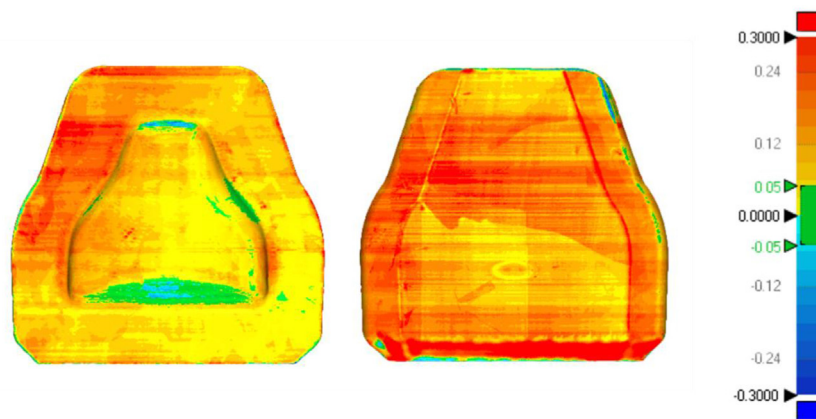


Figure 15. Reference: mould all-PVB after printing; Object: mould 2 PLA-PVB after printing.

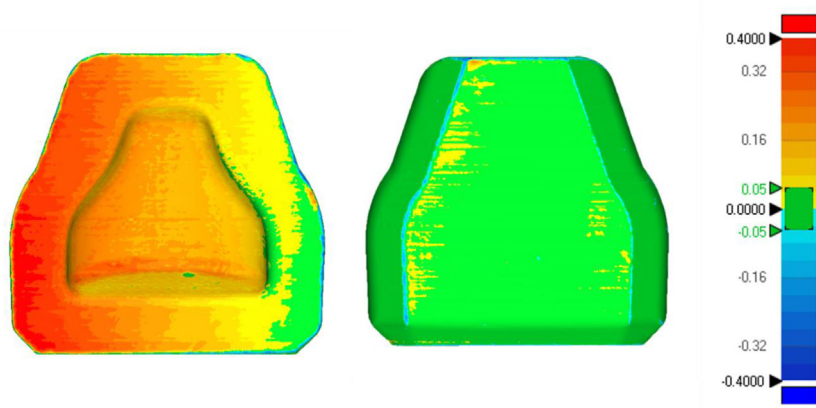


Figure 16. Reference: mould 1 PLA-PVB after printing; Object: mould 1 PLA-PVB after smoothing.

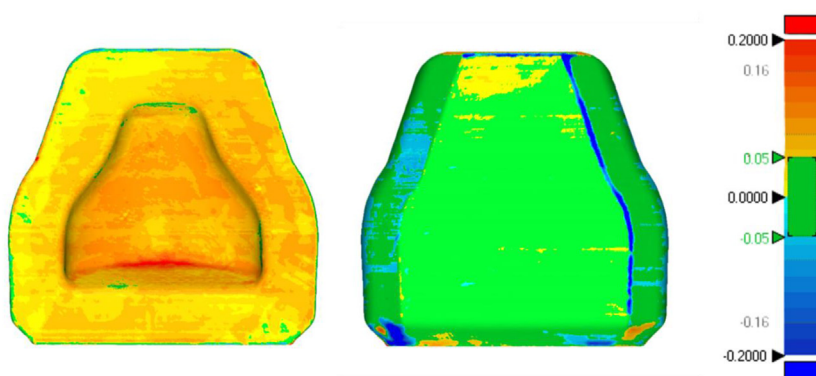


Figure 17. Reference: mould 2 PLA-PVB after printing; Object: mould 2 PLA-PVB after smoothing.

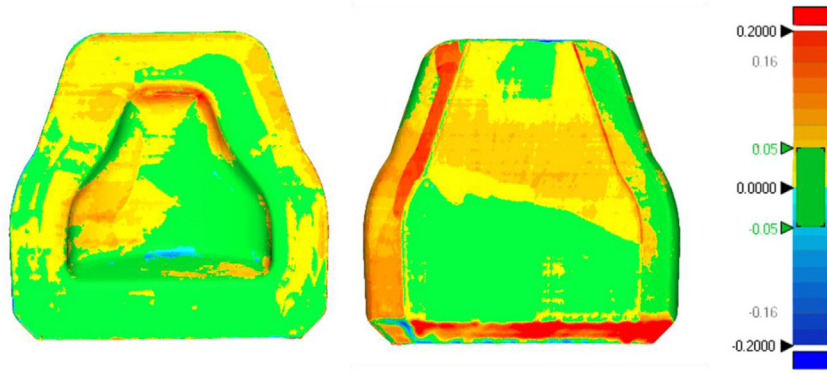


Figure 18. Reference: mould all-PVB after printing; Object: mould all-PVB after smoothing.

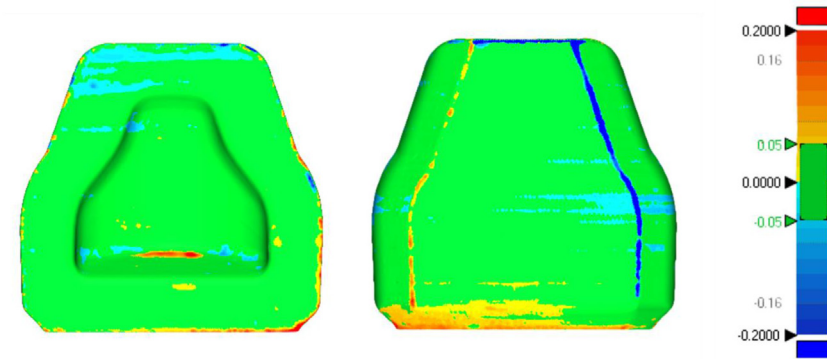


Figure 19. Reference: mould 1 PLA-PVB after smoothing Object: mould 2 PLA-PVB after smoothing.

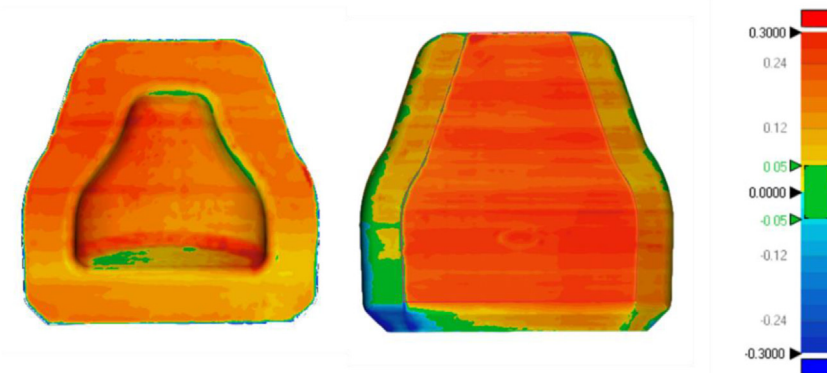


Figure 20. Reference: mould CAD geometry; Object: mould 1 after smoothing.

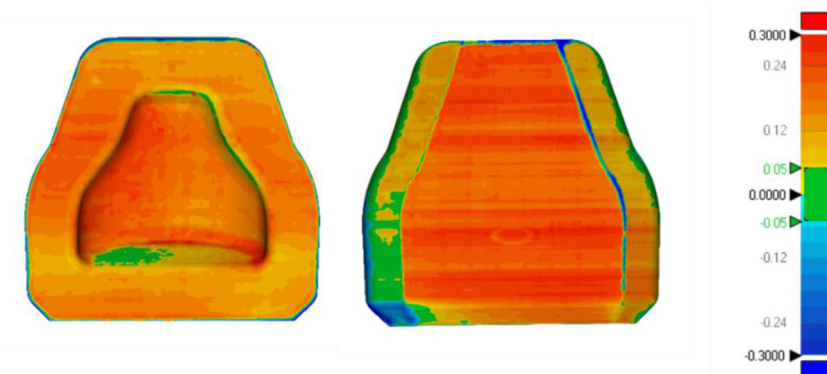


Figure 21. Reference: mould CAD geometry; Object: mould 2 after smoothing.

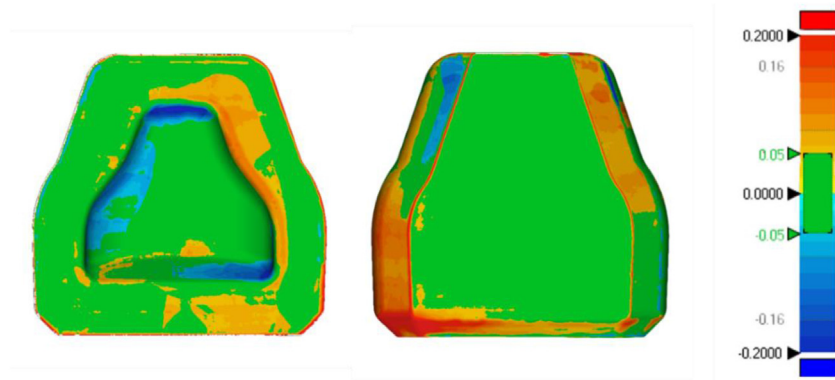


Figure 22. Reference: mould CAD geometry; Object: mould all-PVB after smoothing.



Figure 23. Vacuum procedure in the lamination process with the created moulds.



Figure 25. Part mounted on the motorbike.

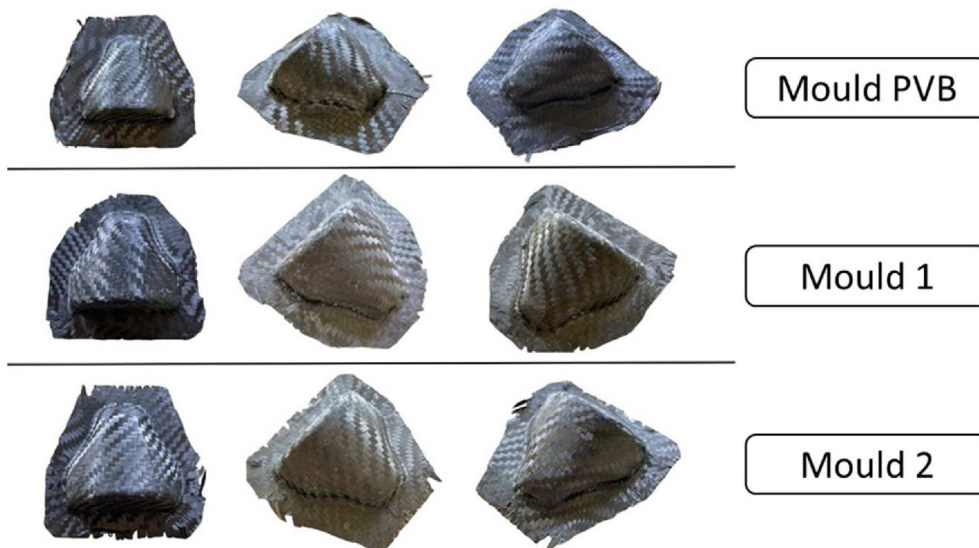


Figure 24. Laminated parts by using the moulds.

cloth combined with C-system CFS 1010 epoxy resin. Three layers of the cloth were applied to each mould inside the relative cavity, then a perforated tissue and a breather cloth were applied on the mould and then put in a vacuum bag at a pressure of 5 Pa, as can be seen in Figure 23. The resulting parts made from the three fabricated moulds are shown in Figure 24 and the result with the refined part mounted on the bike is seen in Figure 25.

4.4. Discussion

This document covered the main process steps required to fully develop a part by means of exploiting manufacturing 4.0 technologies, some of which are key drivers of rapid prototyping and have great opportunity to become an important production technique for small lots or highly complex parts with customized requirements, aimed to help industry applications.

Moreover, the ability of using a multi-material AM strategy led to a reduction of production costs compared to the all-PVB version of the part but achieved the high surface finish, achieved with the smoothing process. A further reduction of cost can be obtained using recycled PLA filaments since this material is only used as a skeleton for PVB.

However, the given moulds were evaluated 72 h after the smoothing procedure. This time frame was chosen from the filament manufacturer and found to create two counterbalancing factors: a residual amount of unevaporated alcohol found to remain on the surface; additionally, the CS process itself found to have 2 effects on the material structure on the surfaces. The first one is that dilatate the surfaces, while the second one reduces the roughness. This analysis led to the conclusion that the alcohol evaporation time is important to maintain tolerances. It is suggested to develop an additional evaporation time or forced ventilation cycle so the alcohol remains will not change the surface geometry.

Nevertheless, the residual alcohol content found in the surface has not shown issues in the case of rapid prototyping of the carbon fibre parts except for the possible gain of surface tolerances. This phenomenon can be compensated in advance with a correct scaling of the printed part for upcoming trials.

However, the limitation of the non-autoclavability of this type of moulds is specifically related to the maximum temperature and not to the pressure applied. Anyway, temperature would not become a real limitation since nowadays there are prepreg fabrics on the market that cure at low temperatures, allowing to obtain components with higher mechanical properties, without defects in texture and microporosity.

Finally, the main limitations found for this process were: the dimension constraints on the printing plate and smoothing chamber, as well as printing orientation and the difficulty found to reach higher tolerances values than those reported, especially for great size parts due to the materials used.

5. Conclusion

This multi-material manufacturing and repeatability trial demonstrated good functional capabilities. The obtained mean dimensional tolerance of the case studied is in the range of 0.1 mm and could be closer to the CAD dimensions by scaling the initial printing input file. Likewise, the smoothing process performed in multiple steps and orientation led to an overall homogenization of the mould surface with no visible sign of the layer-by-layer construction.

The process described in this study can be successfully reproduced to create custom components for the industry, as parts for automotive interiors, whenever specific modifications are needed compared to the mass production offering, or when the customer requires special characteristics. Moreover, this procedure can be applied to create parts in limited series where the time and cost of creating a conventional mould would be higher otherwise.

Future developments with this process would engage the accurate prediction of the vapor smoothing process tolerances and the possibility of reusing moulds after the first lamination procedure.

Declarations

Author contribution statement

Patrich Ferretti, Gian Maria Santi: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Christian Leon-Cardenas: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Elena Fusari: Performed the experiments; Analyzed and interpreted the data.

Mattia Cristofori: Performed the experiments.

Alfredo Liverani: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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