Evaluation of polycarbonate additive manufacturing molds for autoclave molding.

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Research Article

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Abstract

In Fiber Reinforced Plastics (FRP) molding, molds made of metal or epoxy resin blocks are commonly used, but the production time and material costs are high and not suitable for prototyping and small volume production. 3D printed molds have the potential to overcome these limitations, which would also enable frequent mold shape adjustment. The present study aimed to investigate the viability of the treated product as a mold for autoclave molding and establish a simple surface treatment method for additive manufacturing products produced by Fused Deposition Modeling. Polycarbonate resin was used to manufacture laminated male molds for the upper core and midsole of shoes, and the surface of the molds was treated with three different methods (clamping, treatment by aluminum tape and fluorine tape). The deformation of the molds due to autoclave molding was investigated by comparing the male molds before and after autoclave molding and computer-aided design data.

In the clamping treatment, it was difficult to remove the mold after autoclave molding due to resin getting into the mold and fiber exposure due to resin loss was also observed. In the aluminum tape treatment, the midsole mold was deformed. On the other hand, the fluorine tape treatment enabled easy mold removal, and little deformation and weight change of the molds were observed.

The results of this study suggest that the using laminated products made of polycarbonate resin can be used as molds for autoclave molding when combined with pre-treatment using fluorine tape.

1 Introduction

Fiber Reinforced Plastics (FRP) is essential to create lightweight, high-performance materials for modern society such as aerospace, automotive, railroad, marine, sports, medical, and civil engineering[1, 2]. Among FRP methods, autoclave molding has been used in many areas and is known for its excellent void removal ability and stability in product quality. On the other hand, the molds must withstand heat and pressure because autoclave molding is conducted under high temperature and high-pressure conditions. For this reason, traditional molds (metal or epoxy resin blocks) used in FRP molding are robust and durable, which are cost-effective for mass production. On the other hand, the production of molds from such materials involves a large amount of material waste and long production time.

In the case of low-volume production, multiple changes in shape and specifications are expected during the prototype stage. Therefore, making molds with low manufacturing costs associated with time, materials and equipment operation is required. 3D printed molds have the potential to reduce the cost and time for manufacturing molds for FRP molding. Especially, Fused Deposition Modeling (FDM) can be a practical approach as this technology has been developing rapidly due to its low production cost and a high degree of automation[3–6].

Lušić et al. used the finite element method (FEM) and concluded that thermoplastic molds, made of ULTEM 1010 created by FDM, can be used to produce carbon fiber-reinforced polymer (CFRP) parts in autoclave molding[7]. However, the results of FEM were not verified. Furthermore, engineered plastics, such as ULTEM 1010, can only be used with limited types of 3D printers and the material cost is high. Other studies have investigated the validation of the use of FDM layered products as molds for FRP molding by the hand layup method[8, 9] and autoclave molding[10]. Each study showed the potential of FDM layered products as a mold. On the other hand, carbon was used as FRP that required a temperature of up to only 120°C in autoclave molding. In reality, however, other materials such as Carbon Fiber Reinforced Plastics (CFRP) and Glass Fiber Reinforced Plastics (GFRP) are frequently used, which require the mold to be exposed to higher temperatures. Therefore, it is necessary to establish a method that can withstand higher temperatures than that used in previous studies.

Polycarbonate (PC), which is a relatively low-cost and general-purpose material used in 3D printers, has the potential to establish such a method. Even though PC has lower impact and heat resistance than engineering materials such as ULTEM 1010, PC has good dimensional stability, heat resistance, and impact resistance. Given its cost and performance, establishing the use of PC as a mold will be highly beneficial for future autoclave molding, especially for low-volume production. For the use of PC with FDM to create a mold, additional treatment is likely necessary as FDM additive manufacturing products generally have a rough surface due to the side-by-side line or staircase effect resulting from layer-by-layer deposition [11–14], which can be minimized by chemical treatment, laser treatment, heat treatment, and ultrasound treatment[15]. However, these processes require expensive equipment, and these processes might decrease the strength of the additive manufacturing product, meaning that such treatments might offset the potential benefits of the use of a PC product as a mold. Thus, for utilizing a PC product as a mold, it is also necessary to establish a cost-effective treatment method for the PC product surface. Therefore, this study aimed to establish a method to utilize PC as a mold together with a surface treatment method using a FDM 3D printer.

2 Methods

In the present study, two types of autoclave molding were used to verify the durability of PC additive manufacturing products 1) an upper core for shoes and 2) a plate resembling shoe midsoles. These forms were deemed adequate for the study as a foot shape has many free-form surfaces.

2.1 Molds of polycarbonate

Two types of PC additive molds were used as male molds rather than female molds because of the amount of resin used in the 3D printer, the build time, and the ease of reconfiguration for modified molds. Details of the PC resin used in this study (310-20100; Stratasys Japan Co., Ltd.) are as follows: Heat Distortion Temperature (HDT) @ 66 psi, 143.7°C; HDT @ 264 psi, 142.2°C; yield strength HDT @ 264 psi, 142.2°C; yield strength @ XZ orientation, 244 MPa; yield strength @ ZX orientation, 290 MPa. 3D printing was performed using a Fortus 400mc™ Large (Stratasys Japan Co., Ltd.). For additive manufacturing, GrabCAD (Stratasys Japan Co., Ltd.) was used to create the data with the internal shape of hexagonal star, 60% packing density, and surface thickness of 1.5 mm. For the upper core, the mold was divided into several parts for an easy demolding process after molding (Fig. 1).

2.2 Layup procedure

2.2.1 Material and Parts ply

A prepreg sheet (NS-Tepreg; Rate or resin contents, 40%; NIPPON STEEL Chemical & Material Co., Ltd.) made of glass fiber cloth (T-glass; plain weave; weight, 200g/m^2; Nitto Boseki Co., Ltd.) impregnated with a thermoplastic phenoxy resin was used. The prepreg sheets were divided into four parts in the upper core, and each sheet was laminated. For the midsole, three prepreg sheets were laminated.

2.2.2 Preprocessing of Mold

To prevent the resin from flowing in the lamination boundary of the 3D printed mold, three types of treatment were performed in advance: 1) surface treatment with a filling agent, 2) surface treatment with aluminum tapes and 3) surface treatment with fluorine tapes. These types of surface treatments were only first conducted for the midsole mold. When the surface treatment for the midsole mold was succeeded, an additional verification was conducted using the upper core mold..

For the surface treatment using the filling agent, the mold was polished to smooth the surface irregularities, and then the filling agent was applied (ES-31; Sika Ltd.) (Fig. 2a). The treatment with aluminum tape was done using an aluminum tape with 0.13 mm thickness, heat resistance temperature of 150°C (3M Japan Ltd.). The tape was applied over the entire mold to create a surface covered with metal and covering the boundary (Fig. 2b). For the surface treatment with fluorine tape, Teflon™ film tape (ASF-110 FR; thickness, 0.08mm; Chukoh Chemical Industries, Ltd.) was applied to the entire mold. Moreover, for the upper core, since the mold was divided into several parts, anelastic polytetrafluoroethylene (PTFE) tape (VALFLON® PTFE Strengthening Film; thickness, 0.08 mm; VALQUA, Ltd.) was applied to the joint (Fig. 2c). After surface treatment under each condition, i.e., before prepreg lamination, a release agent (Chemlease®2166; Chem-Trend L. P.) was applied to improve the mold release property.

2.3 Autoclave molding

A small autoclave machine (Hanyuda Co., Ltd.; Fig. 3) was used for GFRP molding. During the molding the maximum temperature and pressure were 130.0°C and 0.300 MPa, respectively. The detail of molding conditions is shown in Table 1.

Table 1
Setting autoclave molding conditions

Procedure	Machine display	Temperature setting, [°C]	Pressure setting, [MPa]	Duration, [min]
1	Temperature control 1	80.0	0.300	30
2	Temperature control 2	130.0	0.300	90
3	Cooling	60.0	After the temperature in the autoclave drops to 60°C, start decompressing.	-
4	Decompression	58.0		-

2.4 Verification of mold shape change

We examined the shape change of the male molds to confirm the deformation of PC resin additive manufacturing products and the effectiveness of three types of surface treatments. First, we measured the weight of the male mold before and after molding to check any weight loss due to some remaining resin on the male mold and deformed the mold. When the initial validation was succeeded, the molding process was repeated ten more cycles to check whether the mold could be used repeatedly. In addition, the shape of the upper core and midsole molds were compared among before the first autoclave molding, after the 10th molding and the computer-aided design (CAD) data for the molds.

For the male molds after surface treatment and demolding, the shape was measured in 3D using a non-contact 3D scanner (RANGE7; KONICA MINOLTA, INC.), and the obtained shape information was aligned using Image Viewer (KONICA MINOLTA, INC.), and then converted to mesh data after alignment (best fit method, 25% sample rate) using Design X (3D Systems Corporation). The obtained mesh data were aligned using the best-fit alignment of Geomagic studio (3D Systems Corporation). Then the differences in the shape of the male molds before and after the molding were compared. A positive average distance indicates that the point is bulging relative to the reference point, while a negative average distance indicates that the point is dented relative to the reference point. The mean was calculated for each bulging and concave part for the entire mold, and the standard deviation (SD) was calculated for the entire mold.

3 Results

The print time was about 18 hours for the upper core and 8 hours for the midsole. In the clamping process for the mid-sold mold, the resin was embedded in the mold, making it difficult to demold. In addition, the GFRP resin was shed, and the glass fibers were exposed (Fig. 4a). In the case of aluminum tape treatment, the mold release was easy, but the mold was significantly deformed (Fig. 4b). From these results, we concluded that the surface treatment with a filling agent and aluminum tape was a failure, and the subsequent processes such as GFRP molding for the upper core mold and the investigation of the shape change of the male mold, were not conducted. In the surface treatment with fluoroplastic tape, the mold release was easy, and no mold deformation was visually observed. Therefore, surface treatment with fluoroplastic tape was concluded to be a success, and further analyses were performed. In the following sections, therefore, results from only fluoroplastic tape treatment are reported.

3.1 Weight of molds

We measured the weight before and after prepreg lamination and after demolding (Table 2). The weight of the upper core mold increased by 4g, and the weight of the midsole mold increased by 2g before and after molding.

Table 2
Weight change before and after FRP molding

	Weight of molds with Teflon taps	
	Upper, [g]	Midsole, [g]
Before laminating prepregs	1,477	239
After laminating prepregs	1,647	277
Weight of prepregs	170	38
After de-molding	1,480	239
Weight of FRP	166	36
Amount of resin release	4	2

3.2 Mold shape change

Table 3 shows the comparison between the mold and CAD data before and after molding. For the upper core mold, the average distance between the concave and convex areas was 0.09 mm and − 0.09 mm, respectively, before and after molding, and the overall SD was 0.12 mm. The mold and CAD data after molding showed that the overall SD was 0.22 mm, and the average distance between the concave and convex areas was 0.22 mm and − 0.11 mm, respectively.

Table 3
Shape comparison of 3D scan data and CAD data of molds before and after molding

				Convex part	Concave part	
		Mean distance, [mm]	(SD)	Mean distance, [mm]	Mean distance, [mm]	RMS
Before molding – After-molding	Upper	-0.02	(0.12)	0.09	-0.09	0.12
	Midsole	0.03	(0.37)	0.34	-0.25	0.38
After-molding – CAD data	Upper	0.14	(0.22)	0.22	-0.11	0.26
	Midsole	0.14	(0.27)	0.27	-0.21	0.39
Before molding – CAD data	Upper	0.14	(0.24)	0.25	-0.12	0.28
	Midsole	0.10	(0.12)	0.14	-0.07	0.15

Note. SD, standard deviation; RMS, root mean square.

In the midsole type, the average distance between the concave and convex areas before and after molding was 0.34 mm and − 0.25 mm, respectively, and the overall SD was 0.37 mm, which was slightly larger than that of the upper core mold. In the comparison between the post-molding data and the CAD data, the average distance between the uneven parts was 0.27 mm and − 0.21 mm, respectively, and the overall SD was 0.27 mm.

It was found that both the midsole and upper core molds could withstand autoclave molding for 10 times. Therefore, as additional verification, five molding cycles were conducted. As a result, no visible deformation occurred in either of the male molds.

4 Discussion

This study investigated the viability of laminated molds made with an FDM 3D printer as molds for autoclave molding of GFRP. Our results suggest that PC molds are effective as male molds for autoclave molding when a fluorine-coated tape is used for surface treatment.

4 − 1 Male molds for autoclave molding by 3D printing

This study created the upper core and midsole with a hexagonal star structure inside a 3D printed mold. The print time for each mold was about 18 hours for the upper core and 8 hours for the midsole of one foot. It is expected to take more than 24 hours for a mold made by the cutting process. Therefore, the molding in this study contributes to shortening the manufacturing time and reducing the mold's weight due to its hollow structure. A previous study of 3D printing compared honeycomb and solid structures and reported that the honeycomb structure reduced the molding time by about half and the material consumption by about 80%[7]. Despite the difference in the material used, the result from the present study generally agreed with the previous study, and it is likely that a structure with vacant space is appropriate to reduce molding time and material consumption. On the other hand, it should be noted that it is necessary to carefully consider the conditions for printing, such as the internal shape of the molded product, in high temperature and pressure conditions.

The PC additive manufacturing used in this study did not show any significant deformation even after more than 15 autoclave molding cycles. Compared to ULTEM 1010, which was confirmed to be a valid material for autoclave molding[7], PC is low-cost but has a lower heat resistance and impact resistance. Therefore, PC is a great material to be used to create a mold for autoclave molding, and the use of general materials such as PC will have a positive impact on projects that involve small lot production and many shapes and specification changes such as tailor-made equipment. However, even with the same structure, the success or failure of molding differs depending on the surface treatment method, suggesting that appropriate surface treatment is necessary as described in the following sections.

4 – 2 Surface treatment

The surface roughness of the part is a defect in the FDM additive manufacturing product. This is caused by the side-by-side line or staircase effect that results from layer-by-layer deposition, which results in a rough surface, and is most noticeable on inclined or curved surfaces[11–14]. In general, these defects can be minimized or eliminated by chemical treatment, laser treatment, heat treatment, and ultrasound treatment[15]. On the other hand, each process requires expensive equipment and specialized techniques, and another potential issue is that such processes might decrease the strength of the additive manufacturing product. Therefore, in the present study, three types of surface treatment methods were tested to investigate a low-cost and simple treatment method.

Among the surface treatment methods tested in the present study, the fluorine tape was the easiest for demolding. As for the clamping process, there is a possibility that additional finer polishing would have improved demolding. However, the polishing process requires great skill to erase the stacking marks in the FDM method completely, and excessive polishing causes a change in the shape of the mold. Therefore, it can be concluded that the use of fluorine tape as a surface treatment method is an easy and practical way that enables the use of a laminated PC product as a mold for autoclaving molding.

The use of aluminum tape deformed the mold significantly. Since the aluminum tape is a metal, it has high thermal conductivity. Therefore, the large deformation with the aluminum tape was likely caused by the excessive temperature rise that went beyond the thermal deformation temperature of the PC as well as the exposure to high pressure. On the other hand, there was little deformation with the fluorine tape, and it might be the case that the tape served as insulation. Even though a surface treatment with tape might increasing the size of the mold, the thickness of the tape is collapsed under high pressure, and the risk is likely minimal.

Our results suggest that fluorinated tapes are a convenient and effective surface treatment. However, if the overlapping of the tapes is insufficient, there is also the issue of resin entering through the gaps between the tapes. In this study, the weight of the upper core mold increased by 4g, and the weight of the midsole mold increased by 2g before and after molding, suggesting some amount of resin being stuck on the mold surface. Therefore, the mold must be polished to remove the resin before it is used again.

5 Conclusion

The current study successfully autoclave-molded GFRP using a PC mold that was manufactured using FDM. The PC mold could withstand autoclave molding with a temperature up to 130°C and a vacuum pressure of 0.3 MPa. Covering the mold surface with fluorine tapes prevented the resin from getting into the laminated surface of the FDM and enabled easy mold removal. Our results suggest that the 3D printer's additive manufacturing products made of general materials are as practical and effective as FRP molds by autoclave molding when combined with pre-processing by covering fluorine tape.

Declarations

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The authors declare that they have no conflict of interest.

Author contributions:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Osamu Takeda, Keita Suzuki, Ryoichi Nakajima, and Kei Maeda. The first draft of the manuscript was written by Osamu Takeda and all authors commented on previous versions of the manuscript. Tomohiro Gonjo edited the manuscript with additional evidence in addition to correcting the English grammar and expressions. All authors read and approved the final manuscript.

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Figures

Figure 1

Polycarbonate split upper core molded by FDM method

Figure 2

Surface treatment methods. (a) Coating the filling agent, (b) Covering the aluminum tape, (c) Covering the upper core with the fluoroplastic-coated tapes, (d) Covering the mid-sole with the fluoroplastic-coated tapes

Figure 3

Autoclave molding

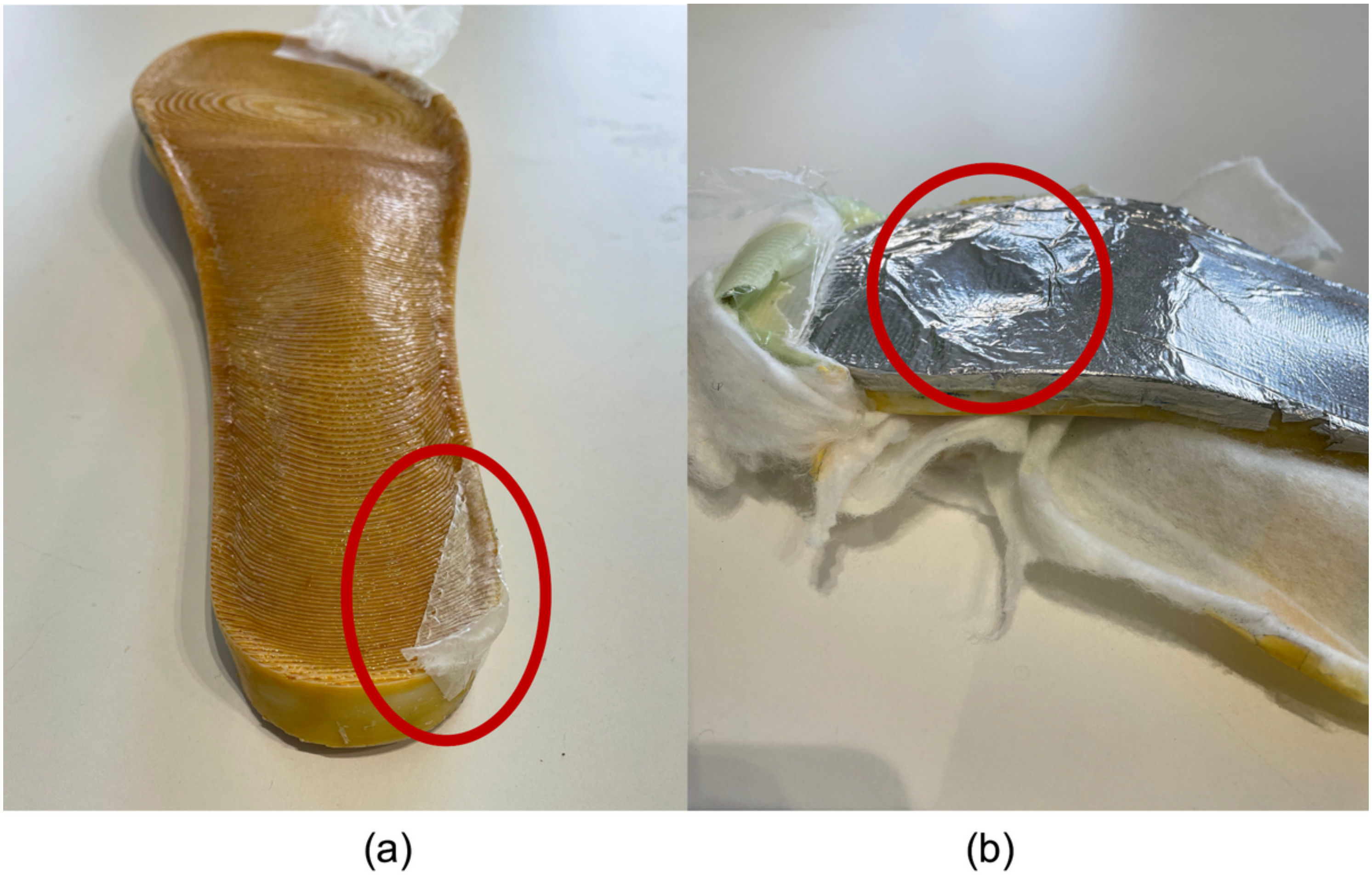

Figure 4

Polycarbonate molds after autoclave molding by surface treatment. (a) Coating the filling agent, (b) Covering the aluminum tape. * The circles indicate areas where the resin got into the mold and was difficult to demold or where the mold was greatly deformed

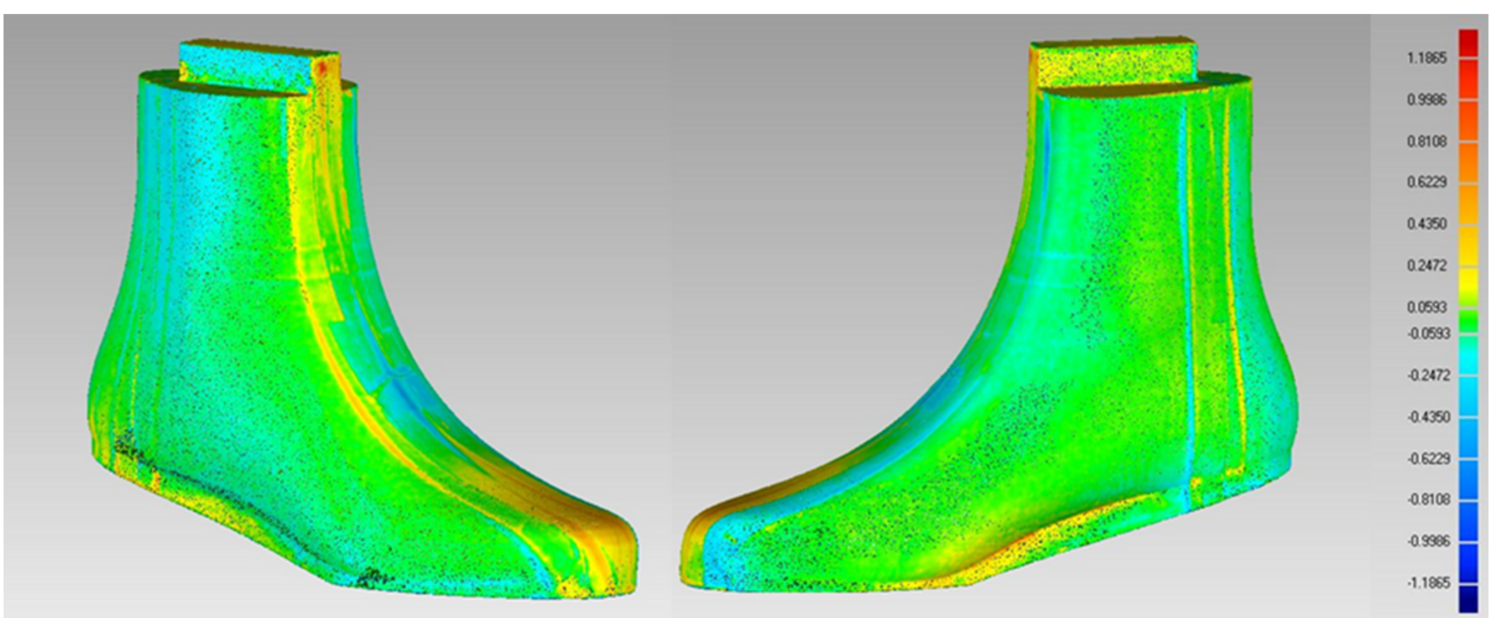

Figure 5

3D scanning for polycarbonate molds covering the fluoroplastic-coated tapes after autoclave molding.