Comparison of Three Additive Manufacturing (AM) Techniques for Manufacturing Complex Hollow Composite Parts

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Additive manufacturing (AM) is well known for supporting the manufacturing of composites through the 3D printing of lay-up tools, sacrificial mandrels, trim molds, etc. The fused deposition modeling (FDM) is a pioneer in composite tooling. This technique is advantageous in many scenarios in which it is convenient to obtain hollow composite parts by dissolving sacrificial mandrels, removing the use of expensive and heavy metal molds. However, the effects that the removal process has on the thermomechanical properties of the composite must be considered. The convenience of another AM technique, liquid crystal display (LCD) printing, has also recently been demonstrated. The present work aims to compare three different techniques, FDM, fused filament fabrication (FFF), and LCD, each using different materials and, therefore, different mandrel removal processes. DMA analyses have highlighted the impact of some dissolution processes on thermomechanical properties. Further mechanical analysis is conducted to support what is found in the thermomechanical characterization tests. Finally, an economic analyses highlight the time and cost savings of some AM technologies compared to the conventional method for manufacturing composite parts.

1. Introduction

Additive manufacturing (AM) has demonstrated its ability to enable composite manufacturing by developing a vast tooling family that includes lay-up tools, sacrificial mandrels, trim molds, and other components.[1,2] Stratasys' fused deposition modeling (FDM) is the AM method that pioneered composite tooling (FDM). This technology is particularly suitable for composite tooling applications that involve the production of hollow and complicated geometries. Our study team used this technique to create a realistic sacrificial mandrel production scenario for producing intakes.[3] After a preliminary cost comparison, this technology showed to be significantly more cost effective than the standard steel mold method. However, because the dissolution procedure necessitates the use of a basic solution at specific temperature and ultrasonic conditions, this post-processing influenced the final composite, resulting in a loss of the observed thermomechanical characteristics (e.g., glass transition temperature, T_g). Our research continued with the study of a new AM technology called liquid crystal display (LCD) printing.[4] This method employs daylight resins that crosslink when exposed to a specific wavelength (460 nm). The first advantage is that LCD printing develops a full layer at once, without the usage of print heads, by simply irradiating more dots in the same amount of time. Benefits in terms of time and cost were seen. FDM, fused filament fabrication (FFF), and LCD are the three AM techniques used to make mandrels in this study. Male lamination and curing followed the acquisition of the s-shape and box-shape mandrels. The samples were then acquired in accordance with the ASTM 7264 standard for flexural testing. Finally, the mechanical features that were observed were compared. AFM microscopic measurements were used to further assess the quality of the internal surfaces of the composites. The comparative analysis of times and costs was carried out to compare the three AM techniques.

2. Experimental Section

In order to test geometries with a higher degree of complexity than those studied at Amphora in previous studies,[3] S-shaped geometries were designed. The materials chosen are of three types depending on the AM technologies investigated. As for the FDM printing, a Fortus 400 mc printer (Stratasys, Los Angeles, USA) was used. The FDM mandrels were molded in SR-100 soluble support material (**Figure 1**a). The FFF printed mandrels were obtained using a desktop printer outsourced by Crea3D Srl (Ruvo di Puglia, Italy) and built in Aquasys180 material (Infinite Material Solutions, Wisconsin, USA), a filament used as a support for PEEK printing, Figure 1b. The LCD mandrels were printed on

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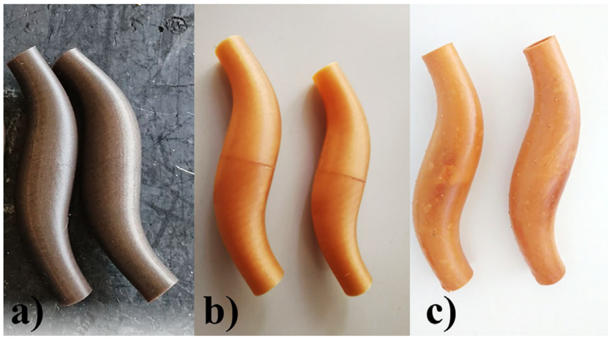

Figure 1. AM mandrels S-shaped built in: a) SR-100 by FDM; b) AquaSys180 by FFF; c) Cream Hard by LCD. AM, additive manufacturing; FDM, fused deposition modeling; FFF, fused filament fabrication; LCD, liquid crystal display.

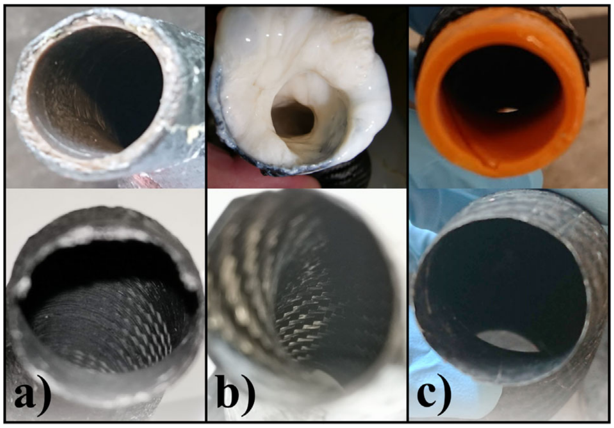

Figure 2. Mandrel removal for the three AM techniques: a) FDM; b) FFF; c) LCD. AM, additive manufacturing; FDM, fused deposition modeling; FFF, fused filament fabrication; LCD, liquid crystal display.

the LC-Precision Ceramic printer of Photocentric (Peterborough, UK) using Cream Hard resin in daylight (Figure 1c). Using the same approach, in order to obtain geometries useful for thermomechanical comparisons, box-like geometries ($25 \times 25 \times 80$ mm^3 and 2 mm thick) were designed and printed (Figure 4a).

Male lamination was carried out using carbon fiber prepreg named GG200TDT121R by Torayca was used in the experiments using the following cure cycle: ramp at 2°C min^{-1} from room temperature to 135°C; hold at 135°C for 120 min applying 5 bar of pressure in the autoclave; after 120 min of curing reduce the temperature to 35°C at 3°C min^{-1}. The obtained FDM parts were dissolved in the proprietary Stratasys Waterworks solution (**Figure 2**a), while the FFF mandrels were dissolved in water at 60°C (Figure 2b). The LCD mandrel was removed by mechanical breakage with a hammer (Figure 2c). As for the SR-100 samples, one batch was shipped to a company specializing in the removal of AM support materials called PostProcess (Buffalo, USA). The removal process was carried out using DECI system, a machine having flow jet streams spraying bidirectionally, coupled with a perpendicular linear motion for mechanically assisted support removal. The mandrel was removed in 45 min at 65°C. The observations of the removing times and the related thermomechanical characteristics of the composites were recorded to make the

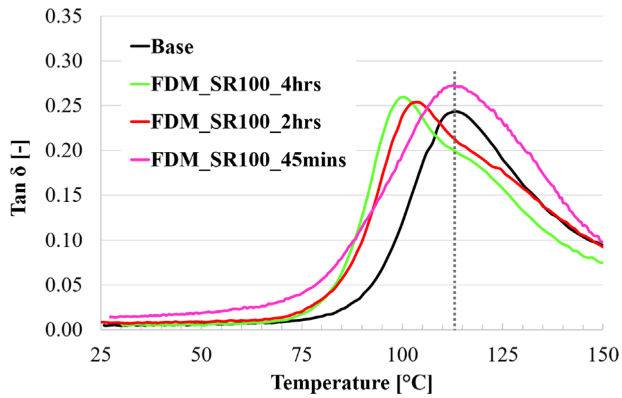

Figure 3. Tanδ versus temperature curves for the base and SR-100 composites.

comparisons referred to in the next section. The composites thus obtained from the box-shaped mandrels were cut by Dremel in the dimensions determined by the ASTM 7264 standard for the flexural testing of laminated samples ($77 \times 13 \times 2$ mm^3). Mechanical tests were performed using an Instron 5985 universal testing machine (Instron, Milan, Italy) equipped with a load cell of 10 kN. The tests were carried out in strain control at the speed of 1.0 mm min^{-1} and a span length of 64 mm.

3. Results and Discussion

3.1. Composite Characterization

3.1.1. DMA Analysis

The samples on which a worsening of the thermomechanical properties was found[2] are those in SR-100, subjected to the process of dissolution in a basic solution containing NaOH at temperatures of 85°C and ultrasound at 75% power. From the composites obtained from these mandrels, therefore, samples were obtained to investigate the viscoelastic behavior of the four composites: the base composite, the one obtained by dissolving in proprietary WaterWorks solution for 2 and 4 h, the one obtained by PostProcess. The thermomechanical analyzes were performed using a DMA Tritec 2000 (Triton Technology Ltd., Nottinghamshire, UK) by single cantilever geometry and sample size $(10 \times 5 \times 2)$ mm^3. The tests were carried out at 1 and 10 Hz with 2°C min^{-1} heating rate from 25°C to 150°C. The tanδ versus temperature plot is reported in **Figure 3**. For the composites obtained from PostProcess, unlike the two obtained by dissolving in basic solution, no shift in the peak was observed with respect to the base composite.

3.1.2. Mechanical Testing

The composite pieces were cut into bar samples (**Figure 4**) and evaluated after they were obtained from the box-shaped samples. The FFF and LCD samples show the most similarities in terms of observed responses, according to the statistical analysis performed on the data obtained. In fact, the FFF and LCD samples have average Flexural moduli of 6.59 and 6.56 GPa, respectively,

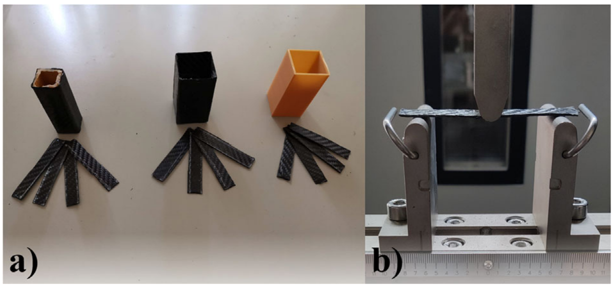

Figure 4. a) Bar samples cut from box-shaped composites for b) flexural testing.

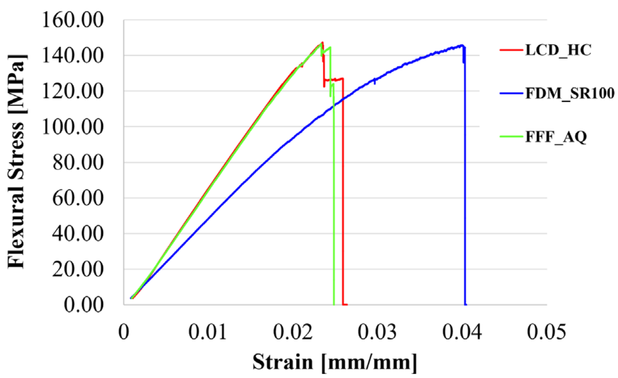

Figure 5. Average flexural stress versus strain curves.

as shown in **Figure 5**, while the FDM samples have average values of 5.07 GPa. There were no significant variations in flexural strength, with average values of 142.09, 140.90, and 145.07 MPa for the FDM, FFF, and LCD samples, respectively. However, there was a substantial difference in the elongation at break response, with the FDM samples showing the highest values of all, at 4.12% versus 2.50% and 2.58% for the FFF and LCD samples, respectively. Following what DMA analysis revealed, this conclusion was predicted. The sodium hydroxide solution impacted the matrix of the composite generated by dissolving the FDM mandrel, resulting in lower T_g values than the composite untreated, indicating matrix plasticization.

Table 1. Values of roughness measured.

AM Technique	Parameters		
	RMS [nm]	RA [nm]	Peak-to-peak [nm]
Base	12.714	10.292	81.661
FDM	35.357	29.287	259.168
FFF	48.101	40.843	261.412
LCD	18.264	14.472	114.707

AM, additive manufacturing; FDM, fused deposition modeling; FFF, fused filament fabrication; LCD, liquid crystal display.

3.1.3. Morphology

The surfaces of the composite samples obtained by traditional method (called base) and by AM were analyzed by an atomic force microscopy (AFM, NTEGRA by NT-MDT). The AFM measurements were carried out in different locations. As an example, in **Figure 6** the colormap of the roughness distribution in a square surface of 2 μm side is shown, the colorbar reports the surface height in the range [0; 250] nm.

The values of average roughness measured are reported in **Table 1**. Base samples show the lowest rugosity in terms of RMS and RA parameters. LCD samples show good surface quality and values of rugosity similar to the base. The worst values were observed for the composites obtained from FDM and FFF, which showed a layer-like surface morphology.

3.2. Cost and Time Evaluation

Times and costs related to the printing of the mandrels and their dissolution have been recorded to evaluate the most economically

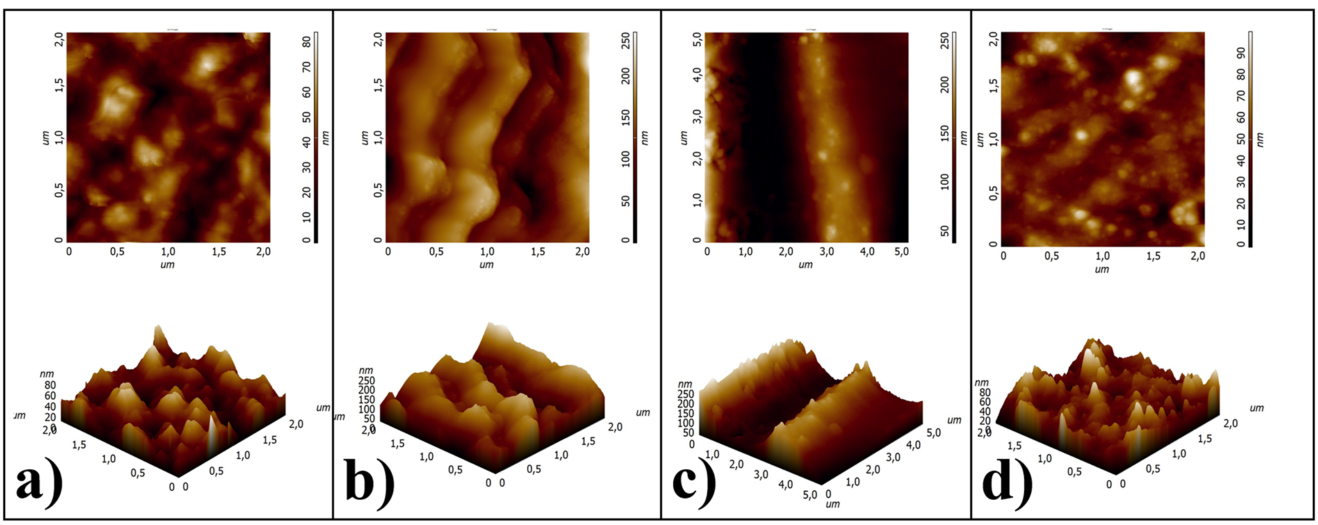

Figure 6. The roughness distribution of the composites: a) base; b) FDM; c) FFF; d) LCD. FDM, fused deposition modeling; FFF, fused filament fabrication; LCD, liquid crystal display.

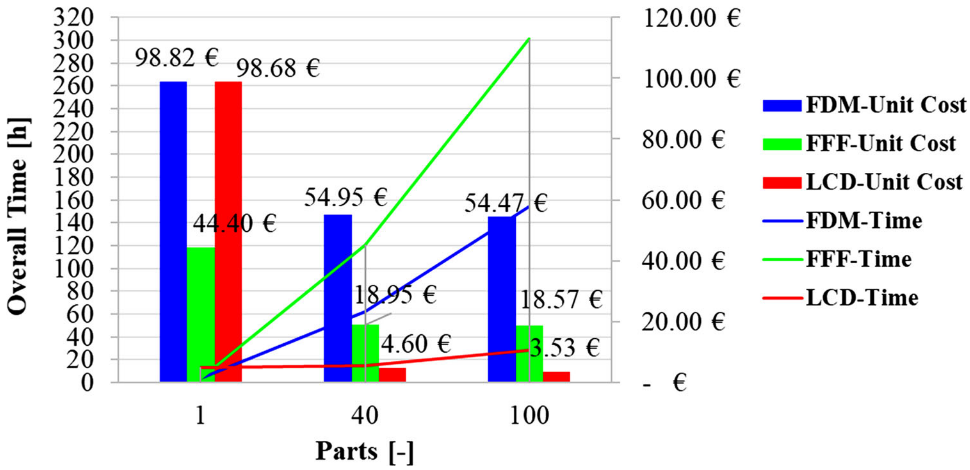

Figure 7. Cost and time evaluation.

and productively advantageous solution. Using the cost model adopted in ref.,[3] the three AM techniques were compared. The graph in **Figure 7** summarizes the results obtained.

Three scenarios were simulated: the printing of one single mandrel, of 40 pieces (as previously investigated in ref.[3]) and of 100 pieces. The three printers considered are the Fortus 400 mc for FDM technology, the Ultimaker S5 for FFF technology and Photocentric's LC-Magna for LCD technology. In Figure 7, it is possible to see how the overall time is proportional especially for the two filament techniques. This trend is not observed for the LCD technique because the build time is not directly proportional to the parts introduced into the printing plate, but to the maximum height of the printed part. Furthermore, in this print each layer is printed at the same instant, by means of photoreticulation of the resin areas affected by the light source, therefore without moving the print heads on the surface. The overall time, therefore, includes both the printing time and the spindle dissolution time. For the production of a single mandrel, in particular, it is obtained that the FDM technique takes 1.5 h for printing and 2 h for dissolution, the FFF technique takes 3 and 0.5 h, while the LCD technique takes 13 h and 2 min. For 40-part printing, as the LC-Magna printer is capable of printing 56 parts per job, the printing time remains 13 h, while this increases considerably in 60 and 120 h for FDM and FFF, respectively. Finally, for the printing of 100 parts, two print jobs are required for the LCD technique for a total of 26 h of printing, while three jobs and 150 h of printing will be required for FDM and five jobs and 300 h for FFF.

As for the costs, however, these were calculated also taking into account the energy absorbed by the removal processes. The results shown in Figure 7 show the unit costs. For small-volume printing, FFF technology has proved cost-effective. The considerable cost savings, however, can be seen once again in the LCD technique, which leads to a saving of 93% and 81% compared to the FDM and FFF techniques, respectively, with a unit cost of the part of only € 3.53.

4. Conclusions

In conclusion, composite components were created with the aid of AM. Three AM techniques were employed: two identical procedures, FDM and FFF, which differed mainly in the construction materials used (SR100 and Aquasys180 for FDM and FFF printing, respectively), and a daylight resin (Cream Hard) for printing the mandrels in the LCD approach. The AM mandrels were laminated with prepreg and cured in autoclave. The removal techniques were investigated in terms of time and how they affected thermomechanical characteristics and surface finish. Flexural testing revealed that the mechanical behavior of the produced composites was affected. In fact, the composites produced using FDM mandrels showed a T_g lower than base and LCD composite. A possible solution to this problem would be to reduce the removal time of the mandrel to 45 min. Furthermore, as reported by the company, the cycle could be further reduced by directing more nozzles into the mandrel. The composite samples from FDM had much lower flexural modulus values (about 20%) than the others, as well as larger (around 60%) elongations at break.

It is evident that alternative procedures and materials can provide considerable benefits to traditional composite manufacturing, but it is also important to remember that the effects of these processes on the finished composite item must be well studied.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

additive manufacturing, composites, FFF, LCD, tooling

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