A LAYERED-MANUFACTURING PROCESS FOR THE FABRICATION OF GLASS-FIBER-REINFORCED COMPOSITES

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ABSTRACT

In this paper, we present a rapid manufacturing process for the layered fabrication of polymer-based composite parts using short discontinuous fibers as reinforcements. In the recent past, numerous research efforts, similar to ours, have been made to produce fiber-reinforced plastic parts via layered manufacturing methods. However, most of these attempts have not resulted in the development of an effective commercially-viable manufacturing process. Our proposed fabrication process on the other hand has been experimentally verified to yield composite parts comparable in quality to pure polymer parts manufactured on a commercial stereolithography system.

This process uses a UV-laser-based system for the selective solidification of the composite liquid. The primary components of the prototype are: (1) fiber-resin mixing subsystem, (2) composite-liquid deposition subsystem, (3) liquid leveling subsystem, (4) laser-light delivery subsystem, and (5) contour-milling subsystem.

Extensive microscopic examination of composite parts, built by the proposed prototype system, has been conducted to evaluate the parts' layer quality. Results indicate that the prototype system can yield comparable layer quality, in terms of accuracy and uniformity, to that of pure-resin parts made by a photopolymer-based commercial system.

INTRODUCTION

Reinforcement of plastics by fibers has been used successfully for over fifty years as means of improving the mechanical properties of the manufactured products [1]. Combining high-modulus, high-strength fibers with a polymeric matrix produces a composite material with higher stiffness and strength, and lower thermal-expansion coefficient. The reinforcing fibers can be introduced either in continuous (long) or discontinuous (short) form. While continuous fibers provide greater relative improvement of the mechanical properties, they also significantly complicate composite-material processing. Short-fiber composites on the other hand can be easily manufactured by automated, and hence more economical, methods.

Since the late 1980's, several Rapid Layered Manufacturing (RLM) techniques have been investigated, and some commercially developed. These techniques allow free-form fabrication of complex-geometry parts directly from their CAD models [2]. The most commonly used RLM technique for the production of plastic parts is Stereolithography (SL). As a building material, it employs a liquid photosensitive resin, which is selectively solidified by an ultraviolet (UV) laser beam. The SL technique is used as a basis for the rapid manufacturing of short-fiber reinforced parts proposed herein.

There has been some recent work performed on improving the mechanical properties of polymer-based parts produced by SL methods. For example, in [3], long fibers were added to the polymer matrix by stacking rings with arrays of parallel horizontal fibers stretched across, and then curing the polymer via a standard SL procedure. In another approach [4], continuous fibers were laid out by a dedicated apparatus before curing each layer of the part. Other approaches include using solid inserts within the polymer [5], or building fiber-reinforced shells around solidified resin part [6].

Feasibility studies were also reported regarding the use of discontinuous reinforcements in the form of either 10-15 mm chopped glass fiber bundles or 55 μm diameter glass microspheres [7, 8]. Composite samples several-layers thick were produced by manually spreading the glass fibers over the liquid resin on each layer. Fibers were not premixed due to the very high viscosity of the resulting mixture. Improvements of material mechanical properties were reported for fiber-based reinforcements, while no improvement was attained by using microspheres.

The above methods of reinforcement (especially those using medium-length or continuous fibers, as in [3, 4, 7, and 8]) are suitable for the rapid layered manufacturing of objects with relatively simple geometric shapes. However, significant difficulties may arise when applying these methods to the production of objects with small-scale features, thin walls or intricate shapes.

Thus, herein, we propose reinforcement of SL-made complex-geometry objects by short fibers introduced directly into the photopolymer matrix. The fact that the resin remains liquid at room temperature simplifies the process of adding the fibers, storing and handling the mixture, as well as controlling the amount of fibers added. Due to its transparency (for photo-curing) and relatively low cost [1], glass fiber was selected for reinforcement.

INCORPORATING FIBERS IN THE SL PROCESS

The benefits of reinforcements are limited by the maximum volume fraction that can be accommodated by the matrix. This limit is in turn governed by the uniformity of the fiber orientation and the fiber length. For uniformly oriented fibers, the concentration can reach 50-60% by volume; for randomly oriented fibers, the limit can be 10-40%, depending on the fiber length.

Below, we briefly review the suitability of the SL process for fabrication of *fiber-reinforced* parts.

(i) Mixture Viscosity

Adding fibers to the liquid resin creates a highly viscous liquid. When used in a standard SL process, such a liquid is likely to have difficulty in flowing to form an even layer after the part is submerged. A subsequent wiping operation may also encounter problems because of the presence of fibers, as was confirmed in our preliminary investigation into the wiping of various fiber-resin mixtures.

(ii) Fiber Settling

Since the fiber density is more than twice that of a typical resin (2.54 g/cm^3 for glass vs. 1.13-1.15 g/cm^3 for resin), the fibers tend to sink if left undisturbed. For spheres in liquid, the terminal sinking velocity is given by [9]:

$$V = (\rho_s - \rho_l)\frac{gd^2}{18\mu} \tag{1}$$

where g is the gravitational acceleration, d sphere diameter, ρ_s density of sphere, ρ_l density of liquid, and μ viscosity of liquid. Using a typical resin viscosity of 200 cP, a fiber length of 1.5 mm and diameter of 15 μm, and calculating the diameter of a sphere equal to the fiber volume, yields a sinking rate of about 85 mm/hr. Thus, if the mixture was left undisturbed in a vat during part building, the fibers would settle continuously, which would lead to lower fiber concentration near the surface.

(iii) Fibers on the Part Surfaces

When short fibers are added to polymers as reinforcements in a typical manufacturing process (e.g., injection molding), the solidification of the matrix always takes place within a mold with solid boundaries surrounding the composite part. These boundaries guarantee that the fibers will not protrude from the surface of the finished part. On the other hand in our case, when the fiber-resin mixture is solidified by the laser beam, the boundary between the solid and the liquid will always fall across some fibers. Preliminary experiments showed that the parts produced by an SL method had protruding fiber filaments on their vertical surfaces.

THE NEW RAPID LAYERED MANUFACTURING PROCESS

One key novel feature distinguishes the proposed RLM process from the standard SL: the composite liquid is not stored in a vat but instead deposited from above for each layer (Figure 1). The primary fabrication steps of the current process are as follows:

(1) The composite liquid is continuously stirred in a separate container during the part building.

(2) A known volume of the composite liquid is deposited from above for each layer (Figure 1b).

(3) A wiper levels the liquid at the required height (Figure 1c).

(4) The layer is selectively cured by a UV laser (Figure 1d).

(5) A milling tool is used to remove the fibers protruding from the solidified walls of the current layer (Figure 1e).

(6) The part is lowered into the vat (Figure 1f), and the process steps 2 and 5 are repeated.

Once the part-building process is completed, the platform is raised, and the part is removed, cleaned, and post-cured.

This process solves all three primary problems addressed in the earlier section, namely, settling of fibers, spreading of a highly viscous composite liquid, and removing the fibers protruding from the finished part's vertical surfaces. The fiber-removal solution proposed herein is the use of a vertical milling tool. At each layer, a small-diameter, numerically controlled end-mill traces the perimeter of the part. The cut could be made to remove just a part of the solidified perimeter, thus assuring precise horizontal dimensions of the layer.

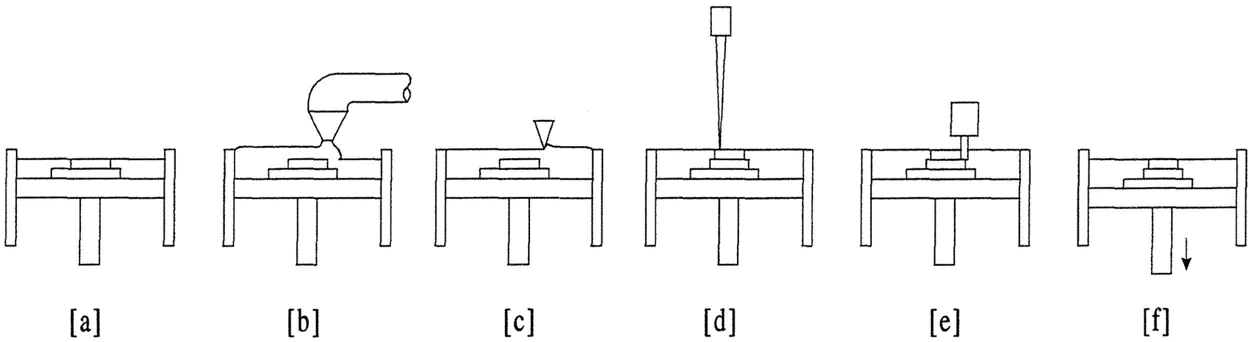


Figure 1: Steps of the Proposed RLM Process.

THE CURRENT EXPERIMENTAL SYSTEM

An experimental system was designed and built to serve as a tool for the process development. The first prototype was described briefly in [10]. The current prototype is capable of automatically building composite layered parts from the data provided by a CAD software. The main components of the system are (Figure 2):

(1) Fiber-resin mixing subsystem,

(2) Composite-liquid deposition subsystem,

(3) Liquid leveling subsystem,

(4) Laser-light delivery subsystem,

(5) Z-platform translation subsystem, and

(6) Milling subsystem.

The system is controlled by custom-written software running on an Intel-processor-based PC. The PC is interfaced to a motion controller, which drives four stepper motors, activates solenoid air valves, and receives feedback signals from several limit switches.

The *fiber-resin mixing subsystem* keeps the fibers in suspension throughout the building process. It consists of an open-top container and a helical-screw stirring device inserted into the container from above. The helical-screw arrangement achieves adequate mixing, when turning slowly, without causing agitation or foaming of the liquid.

The *composite-liquid deposition subsystem* delivers repeatable desired amounts of resin into the vat. This function is performed via a peristaltic pump, which uses rollers to squeeze the liquid through a flexible plastic tube. One end of the tubing is inserted into the container of the mixing subsystem; the other end is attached to the platform of the X-Y translator. The pumping action is combined with the simultaneous translation of the dispensing nozzle in front of the wiper to assure even spreading of the composite liquid. The advantages of delivery via a peristaltic pump are: (i) accurate metering of the liquid volume delivered, since the pump is of a positive displacement type and (ii) simplified system maintenance, since there is no contact between the pump mechanism and the liquid, and since the tubing is easily replaceable. Evaluation of the current version has shown significantly improved consistency of the liquid volume delivered, relative to our earlier system described in [10].

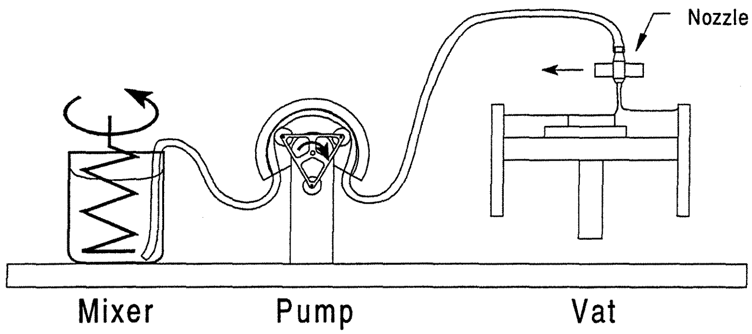


Figure 2: Current Version of Composite-Liquid Deposition and Fiber-Resin Mixing Subsystems.

The *liquid leveling subsystem* assures uniform spreading of the liquid over the vat's top surface to create a layer of consistent thickness. This is achieved by translating a wiper with a triangular edge profile. The wiper movement is actuated by a pneumatic cylinder. Two forward-and-return wiping stroke sequences are performed to form each layer: the first stroke sequence is carried out after the platform has been lowered by a depth of several layers, and the second stroke sequence when the platform has been raised back to the height one-layer lower than the last layer built.

The *laser-light delivery subsystem* delivers a focused beam of UV light to the surface of the composite liquid and moves the beam spot in the X-Y plane. The laser-light source is a 20 mW He-Cd UV laser, Omnichrome 3056-10M. The light is delivered via a fiber-optic cable. At the output end of the cable, a lens focuses the light beam. The X-Y motion of the beam is achieved by attaching the focusing lens and fiber-optic cable to an X-Y translator.

The *Z-platform subsystem* moves the supporting platform vertically. Since the height of the platform directly affects the layer thickness, its vertical displacement must be accurately controlled. To achieve the required accuracy, the Z platform is actuated by a stepper motor driving a micrometer attached to a vertical translation stage.

The *milling subsystem* removes surface fibers by a portable milling tool attached to the platform of the X-Y translator. The milling tool is driven remotely through a flexible shaft attached to an externally-mounted motor.

EXPERIMENTAL RESULTS

Since parts produced by an RLM process are formed out of individual layers, good surface quality and dimensional accuracy can be achieved only by building *high-quality individual layers*. The experimental system described above was therefore used to build a set of pure and composite rectangular parts (25×30×4.8 mm), and the layer cross-sectional profiles of these parts were then examined microscopically. The composite liquid comprised the 2202SF photopolymer by Allied Signal and 15% by volume 737BD 1.6 mm milled glass fibers by Owens Corning. It was noted that for 1.6 mm long fibers the maximum achievable volume fraction was about 15-20%. An additional pure-resin test part was built on a commercial SL machine (Sony JSC-2000 Solid Creator) from DeSolite SCR310 photopolymer. The measurements obtained from this part served as a benchmark for the layer quality of our own parts.

Several vertical sections of each part were made. Figure 3 shows the layer profiles for one section of the pure-resin part built on a commercial SL machine ("SL_PURE"). Figure 4 shows the layer profiles for sections of a pure-resin part ("RLM_PURE") and a composite part ("RLM_COMP") built on our prototype system. Ideally, the plots should consist of straight horizontal lines representing layer boundaries separated by the nominal layer thickness of 0.3 mm.

Statistical analysis of the observations from all sections of the above three parts was carried out after discarding the data for the first 8-10 layers in order to allow for process stabilization (Table 1). Three parameters are shown for each part: the average layer thickness, which is the mean of layer boundary separation values observed across all the part sections; the standard deviation within layers, which is a measure of the unevenness of the layers; and the standard deviation between layers, which is a measure of the layer-to-layer variability of the average layer thickness. The results show that our prototype is able to build layers with a mean thickness very close to the nominal value. Also, the variabilities in the building process of the layers are quite close to those obtained on the Sony machine, especially when one considers that our system is still in its prototype stage. The composite part layer variability is only slightly higher than that for the pure-resin part. Process refinements should reduce the difference even further.

Parts built on our prototype system have somewhat higher variability of the layer thickness than those built on a commercial SL machine. However, the standard deviation values are within the same order of magnitude. Also, note that the composite part layer variability is only slightly higher than that for the pure-resin part built on our prototype system. Process refinements should reduce the variability even further.

Table 1. Statistical Data for Layer Profiles of Multiple Sections.

	Average Layer Thickness (mm)	St. Dev. Within Layers (mm)	St. Dev. Between Layers (mm)
SL_PURE	0.313	0.008	0.002
RLM_PURE	0.306	0.016	0.007
RLM_COMP	0.315	0.021	0.010

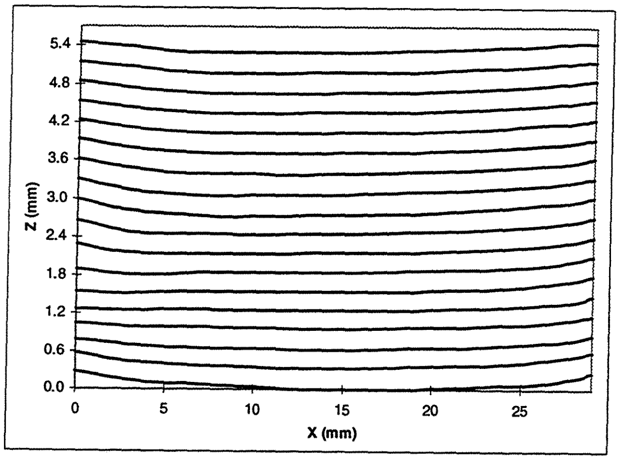
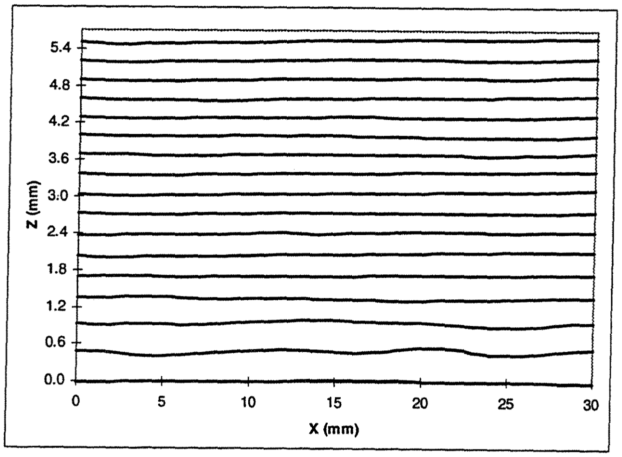
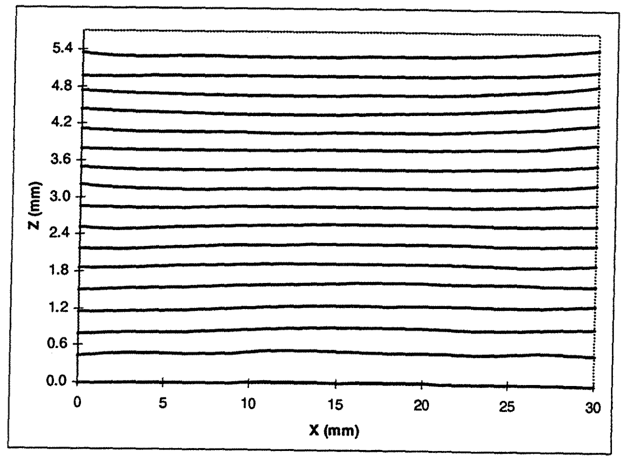


Figure 3. Layer Profiles for a Pure-Resin Part Made on a Commercial SL Machine.



(a)



(b)

Figure 4: Layer Profiles for (a) a Pure-Resin and (b) a Composite Test Part.

CONCLUSIONS

This paper presented a new RLM process for the fabrication of glass-fiber-reinforced plastic composites. This process is based on a layer-by-layer selective solidification of composite liquids comprising photopolymers and glass-fibers. An experimental system was developed to verify the proposed RLM process and is currently capable of producing high quality glass-fiber-reinforced composite plastic parts.

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