SLOT-COATING FOR RAPID MANUFACTURING OF FIBRE-REINFORCED PARTS

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Abstract

Mechanical properties of parts manufactured through photolithography process are improved through the addition of short glass fibres. A lithography-based prototyping system for the manufacture of such composite parts has been under development in our laboratory. This paper will specifically detail a novel Liquid Layer Formation Subsystem (LLFS) for the creation of thin layers of glass-fibres/photopolymer mixture for this system. New LLFS combines a unique external mixing subsystem with a precisely controlled slot coater in order to deposit layers of uniform fibre volume fraction throughout the fabrication process. Evaluation of the mixing subsystem found it capable of delivering liquid with the expected fibre content, and examination of the geometric quality of the individual layers formed by the LLDS shows its ability to consistently build layers of correct height.

Introduction

In an effort to improve the mechanical properties of pure photopolymer-based parts, there have been several reports on introduction of discontinuous reinforcing fibres into the photopolymer matrix [1,2,3]. However, due to the difficulty of forming thin layers from the highly viscous photopolymer-fibre mixtures, only Zak et al. [3] have been able to achieve fully *automated* rapid manufacturing of fibre-reinforced polymer parts. The reported process fabricates fibre-reinforced polymeric components from a combination of UV-sensitive photopolymer liquid and short transparent glass fibres. In this process, the liquid photopolymer and the fibres are mixed, thin layers of this mixture are formed, and then selectively cured by a UV laser.

A key step required for the success of a Rapid Layered Composite Manufacturing (RLCM) process is formation of thin composite liquid layers. Creation of thin layers poses a unique set of challenges. Firstly, the combination of a high concentration of short glass fibres with a liquid photopolymer results in a highly viscous liquid with a shear-thinning rheology. High viscosity at low shear rates inhibits the ability of the liquid to spread uniformly over the surface of the previously solidified layer. Secondly, the density difference causes the fibres to settle continuously when no source of agitation is present, and, therefore, building layers with a homogeneous fluid becomes a challenge.

This paper proposes a novel solution to the problem of composite-liquid-layer formation which offers a number of improvements compared with the previously reported approach [3].

After a brief overview of our original design, the new design is introduced followed by the description of theoretical and experimental evaluations of the new design.

Original Process

The basic steps of the original RLCM process are shown in Figure 1: (a) the build platform is lowered into the vat; (b) the liquid-delivery system deposits the composite mixture onto the build platform below; (c) the liquid-levelling system forms a layer of desired height; and, (d) a UV laser selectively cures the part. Throughout the process, the fibre resin mixing subsystem continuously agitates the composite liquid.

The *fibre-resin mixing subsystem* in the original system, Figure 2, consisted of an open-top cylindrical container and a three-bladed axial-pumping impeller. The *composite-liquid-delivery subsystem*, Figure 2, consisted of two mechanically-linked, positive displacement peristaltic pumps, which transported the composite liquid from the mixing subsystem to the deposition nozzle located on an X-Y translator. The liquid was deposited onto the build platform in a controlled manner by synchronising the driving of the peristaltic pumps with the translation of the deposition nozzle. In order to cover the build platform thoroughly with composite liquid, the narrow deposition nozzle performed a raster scan over the area while running the pump (*area deposition*). A subsequent step, called *direct deposition*, involved delivering the composite liquid directly onto the solidified areas of the previous layer in order to ensure that the desired fibre content in parts could be achieved. The liquid deposited on the build platform surface was spread by the *liquid-levelling subsystem* to create a layer of consistent thickness. The latter system consisted of a wiper actuated by a pneumatic cylinder.

While the original RLCM system addressed many of the design challenges, the process still had numerous shortcomings: the deposition system was highly dependent on the underlying part geometry, and the performance of the fibre-resin mixing subsystem was affected as the liquid level was being depleted during the build.

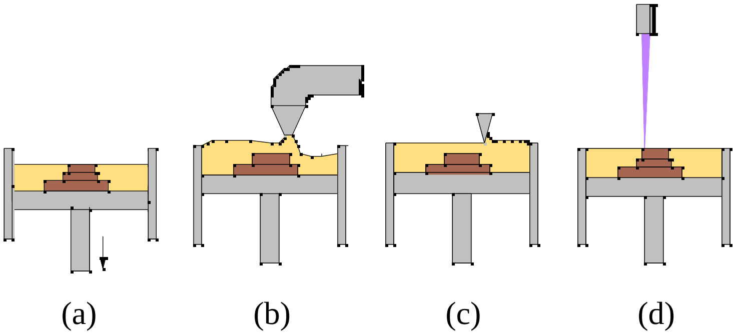


Figure 1. RLCM process steps.

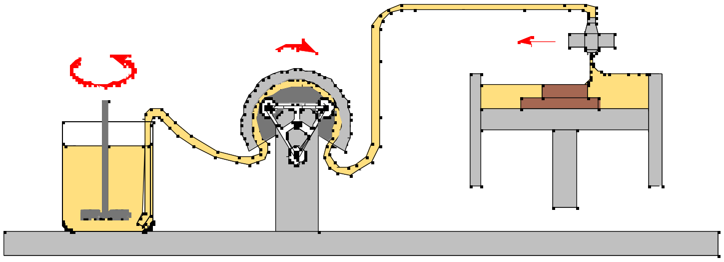


Figure 2. The original fibre-resin mixing and composite-liquid deposition subsystems.

New Liquid-Layer Formation Subsystem (LLFS)

The latest iteration of the slot-coating LLFS design is shown in Figure 3. The fibres are maintained in suspension by an axially pumping impeller located in a small mixing chamber, which remains filled with constant volume of composite liquid. A conical hopper feeds the mixing chamber. A peristaltic pump forces the mixture through tubing, which runs from the bottom of the mixing chamber to the top of the hopper in order to maintain fluidisation within the system. The mixer and peristaltic pump run at constant speeds throughout the RLCM build.

During deposition, an array of mechanically linked, peristaltic pumps drives fluid through flexible tubing, which runs from draw-off points along the circumference of the mixing chamber, to deposition inlets at the front of the coater. Once the fluid enters the coater through the inlets, the flows are merged in internal distribution chamber and extruded downwards through the slot as a wide film which covers the width of the build platform. Material is metered in a controlled manner as the coater moves from right to left so that a uniform layer of composite liquid is deposited. Once the coating sequence is complete, the pumps are reversed in order to empty the coater and tubes of the remaining composite liquid to prevent fibre settling during the laser layer scan.

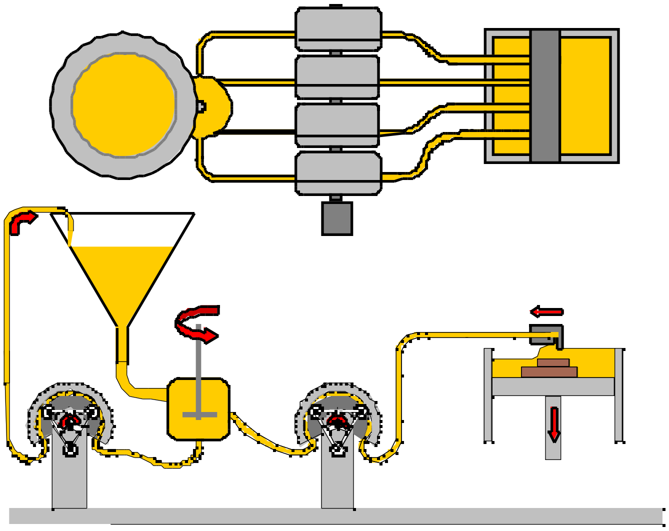


Figure 3. The new Liquid-Layer Formation Subsystem.

Fibre-Resin Mixing Subsystem

In the original system, as the build progressed, and as layers were deposited, the amount of fluid in the batch decreased steadily, and, thus, the liquid level in the system dropped which affected the circulation pattern and the fibre concentration at the draw-off point. Clearly, the mixing apparatus for the RLCM must be designed in such a way that the mixing process is repeatable regardless of the liquid level. To address this problem, in the proposed new RLCM system, a separate *agitation subsystem* produces a homogeneous mixture, thus, creating a zone where the desired concentration of mixture can be drawn off, and a separate *recirculation subsystem* ensures consistent process parameters throughout the build by acting as a buffer as mixture is drawn off for layer deposition.

The design parameters of the new fibre-resin mixing subsystem are: impeller type, geometry and position, vessel geometry, agitation speed, draw-off point location, hopper geometry, and recirculation flowrate. Only a few key parameters are discussed below:

Impeller type: Two impeller types, radial and axial, can be used. Axial impellers produce far more flow, for a given power, compared to radial impellers and are far more effective in solid suspensions applications [4, 5]. Furthermore, studies comparing axial impeller shapes report that downward pumping, three bladed, high flow propellers are the most efficient shapes for solid suspension [6, 7]. Thus, the mixer prototype of the proposed design utilises a downward pumping marine propeller with a 1.5 pitch ratio.

Impeller geometry and location: A too low ratio of impeller to vessel diameter (D/T) would result in accumulation of solids at the fillet region between the walls and the bottom; while a too high D/T ratio will cause the transition from a desirable axial flow pattern to an undesirable dual-loop reversed flow [7]. A D/T ratio of 0.38 was selected for the proposed design based on the literature references. A proper ratio of off-bottom clearance to vessel diameter (C/T) would result in the desired axial flow which sweeps the bottom of settled solids [8]. A C/T ratio of 0.25 was chosen to achieve the desired effect.

Draw-off point location: It has been shown that the concentration of solids as a function of height has a maximum just above the impeller for both radial and axial types [9]. The draw-off point location selected is, therefore, at a point just above the impeller.

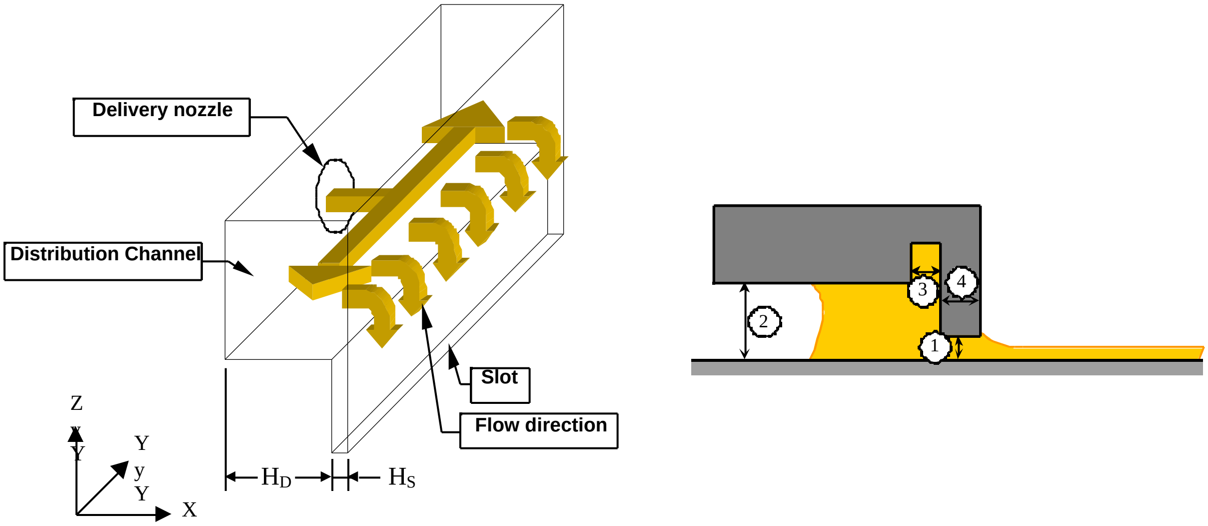
Recirculation flowrate: To counteract fibre settling, the recirculation flowrate must match the fibre-settling rate. A peristaltic pump, which has no direct contact with the fibres, is used to drive the recirculation flow through flexible plastic tubing.

Liquid Deposition Subsystem (LDS)

The LDS is required to form thin layers of composite liquid characterised by prescribed thickness, minimum height variability, and fibre content equal to that in the externally supplied liquid raw material. In our original system, the direct deposition step was dependent on the part profile. Namely, the total volume of liquid deposited over the entire vat, as well as the total time for deposition, fluctuated from layer to layer as the part's cross-sectional geometry changed. Also, in order to deposit fibre-resin mixture directly onto solid surfaces, a very precise coordination between rotation of the peristaltic pump and the translation of the X-Y table was required. In order to address these problems, in the new system, wide-film deposition is responsible for spreading the liquid uniformly over the surface of the platform during layer formation. Multiple-nozzle delivery ensures that liquid with the correct fibre content is deposited over the solidified sections in a manner that is insensitive to the contour geometry of the part.

Let us consider the distribution channel and the slot of the proposed coater design (Figure 4(a)). By choosing a small slot gap, H_S, a large resistance to flow is created in comparison to the resistance to flow in the distribution channel, where a large gap, H_D, is selected. The one-dimensional flow entering the system from the delivery nozzle will therefore be distributed uniformly along the Y direction in the distribution channel before entering the narrow slot. It is also expected that the pressure difference across the distribution channel will be negligible compared to that along the slot. This means that the pressure along the slot entrance will be fairly uniform with respect to the Y direction, so that the slot gap adjustment will also minimise the film variability along the length of the coater.

Layer formation with the composite-liquid coater works on the same principles as industrial slot coaters; however, in the case of the RLCM application, it is the coater which moves rather than the substrate. The slot-coater geometry parameters (Figure 4(b)) include the gap height (1), reservoir height (2), slot width (3) and blade width (4).



(a) (b)

Figure 4. The new coater design: (a) flow within the coater; (b) coater geometry parameters.

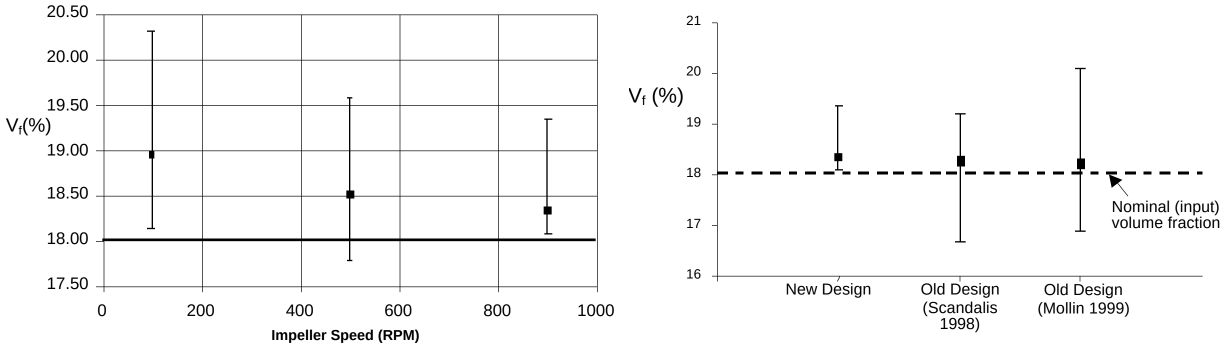
Design Verification

In order to verify the improved operation of the proposed new LLFS, first, tests of the mixer component were performed by evaluating its ability to consistently deliver composite liquid with correct fibre content; second, overall performance of the system in building sample parts was evaluated through the examination of their layer quality.

Fibre-content tests in composite liquids

The mixer was tested with a full factorial experiment. The first control factor was the impeller speed, which was varied through 100, 500 and 900 RPM. The second control factor was the recirculation rate, represented by the speed of the pump, with levels of 8, 20 and 35 RPM. A mixture of 18% Owens Corning 737 1/16" glass fibres and Cibatool 5170 photopolymer was used. After manual mixing for 1 minute, the suspension was poured into the mixer and allowed to mix at the specified control factor level for 30 minutes. Four samples were then taken and UV cured. Next, the mixture was drained back into the beaker and allowed to stand for 60 min before being poured into the hopper for the new trial. The fibre volume fraction in each sample was obtained by measuring its specific gravity via ASTM Standard Test Method D792-91.

Analysis of Variance revealed that the effects of the impeller speed are significant at $\alpha=0.05$, while the effects of the pump speed ($\alpha=0.77$) and pump/impeller interactions ($\alpha=0.99$) are not significant. As the impeller speed is increased, the average fibre volume fraction converges to a value that is just above the nominal amount of fibres added to the mixture (18%) (Figure 5(a)). Also, with the increase of impeller speed, the range of variation decreases significantly. Volume fraction tests of our original design [10, 11] compared with the new system show similar mean volume fractions, but the range of variation for the new mixer design is well under half that of the old design (Figure 5(b)).



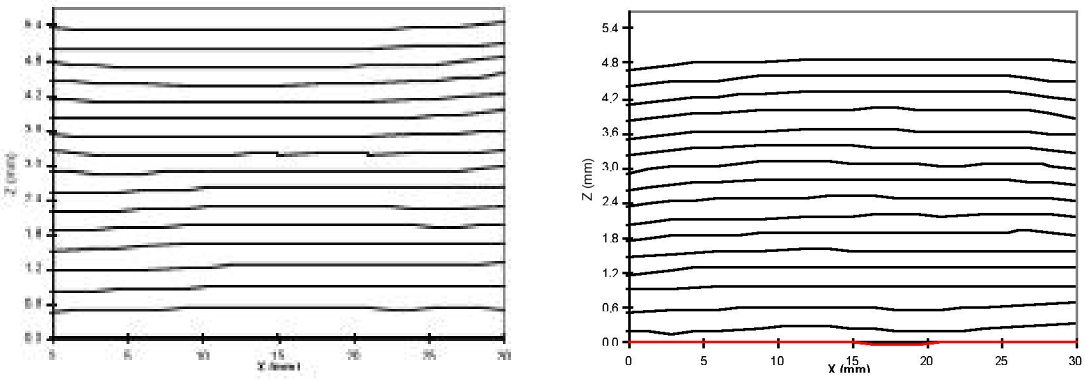
(a) (b)

Figure 5. Verification of the new mixer: (a) effect of impeller speed on fibre volume fraction; (b) comparison with the original design (error bars indicate range of measurements).

Layer quality by sectioning

As part of the initial experimental validation of the new mixer and coater designs, the RLCM system was used to build a composite rectangular part (25×30×4.8 mm), whose cross-sectional profiles were examined microscopically. The part was made from a composite liquid comprising Cibatool 5170 photopolymer and Owens Corning 737BD 1/16" milled glass fibres (18% by volume). It consisted of 16 layers, each 0.3 mm thick nominally.

Three vertical sections of the part were made. Figure 6 shows the layer profiles for one cross-section of composite parts built on (a) original and (b) new RLCM systems. Ideally, the plots should consist of straight horizontal lines, representing layer boundaries, separated by the nominal layer thickness of 0.3 mm.



(a) (b)

Figure 6. Layer profiles for composite parts made on (a) original and (b) new RLCM systems.

Figure 7 allows comparison between performances of both systems. For both versions, statistics are displayed for all layers ("overall") and for layers 6-16 only of the sixteen-layer part ("stabilized"). In the latter case, the data for the first several layers is discarded to allow the process to stabilize. Three parameter types are shown: (1) the average layer thickness error, which is the mean of layer boundary separation measured less the nominal layer thickness; (2) the standard deviation within the layers, which is a measure of the uniformity of the layers; and (3) the standard deviation (SD) between the layers, which is a measure of the layer-to-layer variability. The new version is better able to build layers of correct thickness. One can also note the significant decrease in the average thickness error. Most other parameters are also either better than or equal to those of the original system. It must be emphasized here that the current results for the new system represent early trials. With refinement of the new system further improvements are expected.

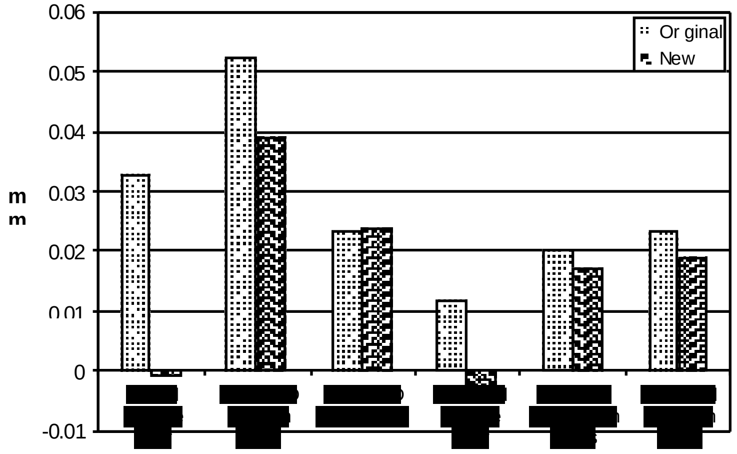


Figure 7. Statistical comparison between the layer quality for original and new systems.

Conclusions

Paper reports on the latest progress in the development of the Rapid Layered Composite Manufacturing process. Specifically, a new design of the liquid-layer formation subsystem is presented. This subsystem must form thin layers of composite liquid with prescribed thickness, minimum height variability, and correct fibre content. This task is accomplished by separate subsystems, one responsible for the fibre mixing and the other for liquid deposition. With the new design, the fibre mixing subsystem is capable of maintaining fibres in suspension and deliver composite liquid with correct fibre content throughout the build. This is achieved through implementing separate *agitation* and *recirculation* subsystems. The new liquid deposition subsystem can form thin layers of composite liquid with correct fibre content. This is accomplished through wide-film deposition and multiple-nozzle delivery which ensures that liquid with the correct fibre content is deposited over the solidified sections in a manner that is insensitive to the contour geometry of the part.

Early performance verification tests of the fibre mixing subsystem confirmed its ability to deliver consistent composite liquids at approximately 18% by volume fibre content. Layer quality evaluations showed the new system capable of building layers with an average thickness within 1% of the nominal value, and with layer-to-layer and within-layer variability of 5-6% (expressed in terms of standard deviation). While the improvements brought about by the new design are a benefit, it must be emphasized here that the main advantage of the new design is that it achieves greater process automation by not requiring a special deposition strategy dependent on the part geometry and by delivering composite liquid of uniform fibre content throughout the build.

Acknowledgements

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