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CHARACTERISATION OF THE PREFORM THICKNESS VARIATION DURING INFUSION PROCESSES BY FRINGE PROJECTION

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SUMMARY: This paper deals with the problem of fluid progression during LRI (Liquid Resin Infusion) manufacturing processes. Recently, a finite element model has been developed by Celle et al. [2, 3] for studying the manufacturing process of composite materials by through-thickness infusion. In this infusion model, it is postulated that resin first fills in the draining fabric, and then infuses gradually in the transverse fiber direction. The fluid propagation is studied here using an optical full-field method to verify the two stage infusion scenario, but more generally to quantify the thickness variations during the infusion step. The method gives in-plane local information about the thickness variations of the stacking. The article will present details of the technique as well as preliminary results. Considering the most representative points, it is shown that the LRI stacking thickness varies in two times, the first one related to the resin in-plane propagation in the distribution layer, the second one to the swelling of the preform after all voids between fibers have been filled and resin keeps on infiltrating the system.

KEYWORDS: optical full-field technique, fringe projection, Liquid Resin Infusion (LRI), composite manufacturing, infusion process

INTRODUCTION

In the recent years, Liquid Resin Infusion (LRI) processes have become popular for the manufacturing of structural polymer-based composites. LRI has been identified as a cost-effective alternative to conventional autoclave manufacturing technique. With LRI it is possible, for example, to produce complex and thick parts with very good mechanical properties and with less waste than traditional methods [1]. However, the process is difficult to control, first because the mechanisms driving the infusion stage are quite complex, and second because the industrial technology does not permit to access easily the physical parameters such as thickness or resin front on small dimensions. Since industrially the thickness must be controlled precisely, understanding in details the filling stage of infusion is of prime importance.

In LRI-like processes resin infusion is performed through a highly permeable “draining” fabric placed on top of the preform stacking (Fig. 1). This stacking is then vacuum-bagged, and vacuum is made, it permits both to compact the stacking and to create a pressure differential which will pull out resin from the heating pot where it is initially placed. From what can be observed in some experiments, it seems that resin first fills in the draining blanket and then permeates across the thickness of the dry performs. This scenario has been retained to simulate LRI processes using a specific numerical model [2, 3], it must be confirmed and analyzed further.

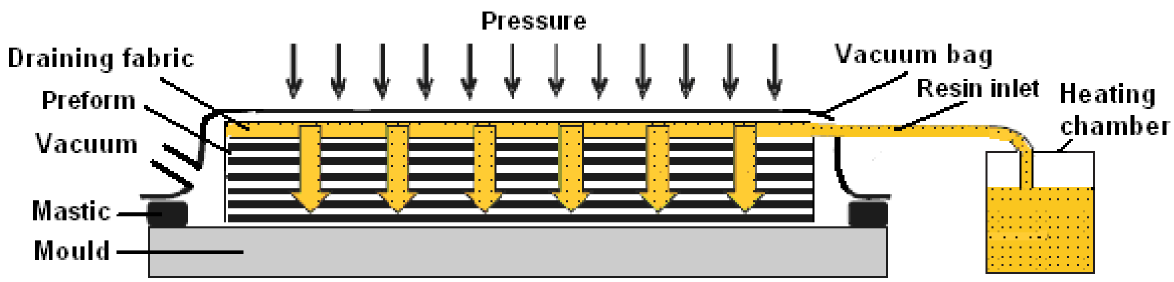

Fig. 1 Principle of LRI processes [1]

In order to analyze the preform filling and its spatial variations over the composite plate, an optical full-field technique is used to follow the thickness changes. These experiments are conducted using 24-ply composite plates $[90_6/0_6]_S$, made up of “UD fabric” reference G1157 E01 produced by Hexcel Corp. These carbon fabrics are plain weave with 96% weight in the warp direction and 4% weight in the weft direction. The preform stacking dimensions are 335 mm × 335 mm × 6mm. For the resin, the experimental LRI tests have been performed using an epoxy resin HexFlow© RTM-6. Before injection, the resin is preheated to 80-90°C in a heating chamber. The stacking (preforms + technical fabrics associated) is heated by a heating plate located below the molding. The external pressure is uniform and equal to the local atmospheric pressure. The filling temperature is 120°C and the curing temperature is 180°C maintained for a period of two hours. This temperature gap has been exploited on the same experiment to follow the resin front within the volume of the specimen [4].

EXPERIMENTAL SET-UP

The measurement of out-of-plane displacements during the manufacturing process has been conducted by using an optical full-field technique, the fringe projection method. The physical principle of the fringe projection method is straightforward: a periodic pattern of white and black lines is projected on an object; the light is diffused by the object and captured by a CCD video-camera (Fig. 2).

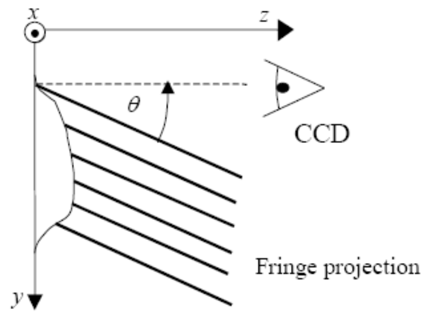

Fig.2 Basic principle of fringe projection.

The fringe projection technique exploits the light diffused by an object in order to measure its deformations; therefore the object must diffuse the light sufficiently. Moreover, in order to observe out-of-plane displacements, the angle between the projected fringes and the observed diffused light must not be null. Light intensities on an object illuminated by a set of fringes can be described by a periodic function I_{li}, with a perturbation φ corresponding to the object shape:

$$I_{li}(x,y) = I_0(x,y)\left[1+\gamma(x,y)\cos\left(\frac{2\pi}{p(x,y)}y+\varphi(x,y)\right)\right] \quad (1)$$

This equation involves an average intensity I_0 and a contrast γ. These values should be constant over the whole map, but some low-frequency variations due to illumination non homogeneities or diffusivity changes on top of the surface can occur. Consequently, both average intensity and contrast have to be considered as local quantities, typically calculated over few fringe periods, and can be denoted $I_0(x,y)$ and $\gamma(x,y)$. The pitch, p, is the distance between two light peaks on a flat surface. Again, due to perspective effects in particular, this pitch can change over the map, but this variation can be known either using a model or a calibration procedure.

Last, the object is responsible for a phase shift $\varphi = \varphi(x,y)$ at each point of the field. Consequently, eqn (1) is based on three unknown quantities ($I_0(x,y)$, $\gamma(x,y)$, $\varphi(x,y)$) which need at least three equations to be identified. The phase is extracted through the home-made code Photomecanix and the out-of-plane position $w(x,y)$ can be calculated according to the following basic equation:

$$\varphi(x,y) = \frac{2\pi\tan(\theta(x,y))}{p(x,y)}w(x,y) \quad (2)$$

In this expression, the sensitivity characterized by the slope of the linear relationship between $\varphi(x,y)$ and $w(x,y)$, can be adjusted by modifying the pitch p or the angle θ between the CCD video-camera and the video-projector .

It has to be noted that the sensitivity can vary locally. In particular, in the present experiment, the video projector and the CCD camera used divergent beams, leading to a more complex situation than described in Fig. 2. An *in situ* calibration procedure has been developed based on prescribing a known translation of a reference object, here a glass plate.

Time dependent effects are expected, so a temporal phase extraction is not adapted. Besides, since the sensitivity must be very high compared to more classical experiments [5], the fringe density is also high, close to 12 pixels per fringe. So we were able to use a spatial phase extraction algorithm [6] to derive $\varphi = \varphi$ (i, j), where (i, j) are the pixel coordinates over a given area corresponding to the extraction procedure, typically 1 or 2*p*. Again, a calibration procedure has been developed to correlate (i, j) position in the camera frame of reference to the (x, y, z) coordinates in the global frame of reference.

The experimental set-up is shown in Fig. 3. The images diffused by the plate are captured by a CCD video-camera connected to a personal computer. Finally, the displacement field is obtained. A Basler A113P CCD video-camera (1296×1030 pixels, 8 bits) and a Sony video projector (1024×768 pixels) were employed. Spatial phase extraction is performed using a wavelet repeating 3 times a 12 pixels sine wave.

An estimation of resolution based on a repeatability test on a given stable situation gives a value of 0.8 % of one fringe, *i.e.* the noise level is 36 µm. The spatial resolution, *i.e.* the mean distance between two statistically independent data, has been determined using the noise autocorrelation function, with a cut-off set to 0.5. The value is 25 pixels, or 5.7 mm. Of course, these value result from the spatial phase extraction, leading to more averaged data but more spread data.

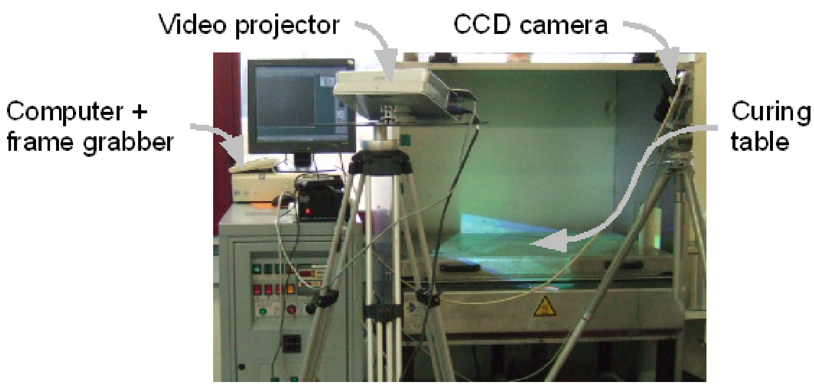

Fig.3 Experimental testing device

RESULTS AND DISCUSSION

Measurements of Thickness Variation

The thickness variations are recorded over time for the whole field. The reader may note that the measured thickness corresponds to the sum of any change occurring in the LRI arrangement, including some shape variations due to temperature changes. For the sake of clarity, 5 areas were selected to follow the thickness change over time: the four corners, and the middle of the cured plate. Results are presented Fig. 4.

As it can be verified in Fig. 4, the process can be split in 3 parts. First, the resin goes through the draining blanket (Zone A in Fig. 4), reaching the side opposite to the resin inlet after 2'40", with a moon shape (Fig. 5). A first thickness change is seen at this very first step (160 µm for points 1, 2, 4 and 5 and 95 µm only for point 3). Point 5, the nearest from the inlet pipe, reaches its height first, then point 2 and 4, point 1 and last point 3. Globally, the resin propagates in the draining fabric first on the contours, and then in the centre. Within zone A, a second thickness increase only concerns point 1 and 4 (for 160 to 340 µm). Note that these points are close to the omega outlet. The reason of this second increase is still questionable, but let us retain that an impervious film is placed in this area in order to avoid a direct output of the resin in the omega outlet. Among the more realistic possibilities, we think that this film may provoke a local pressure increase and the whole system (draining blanket in particular) swelling.

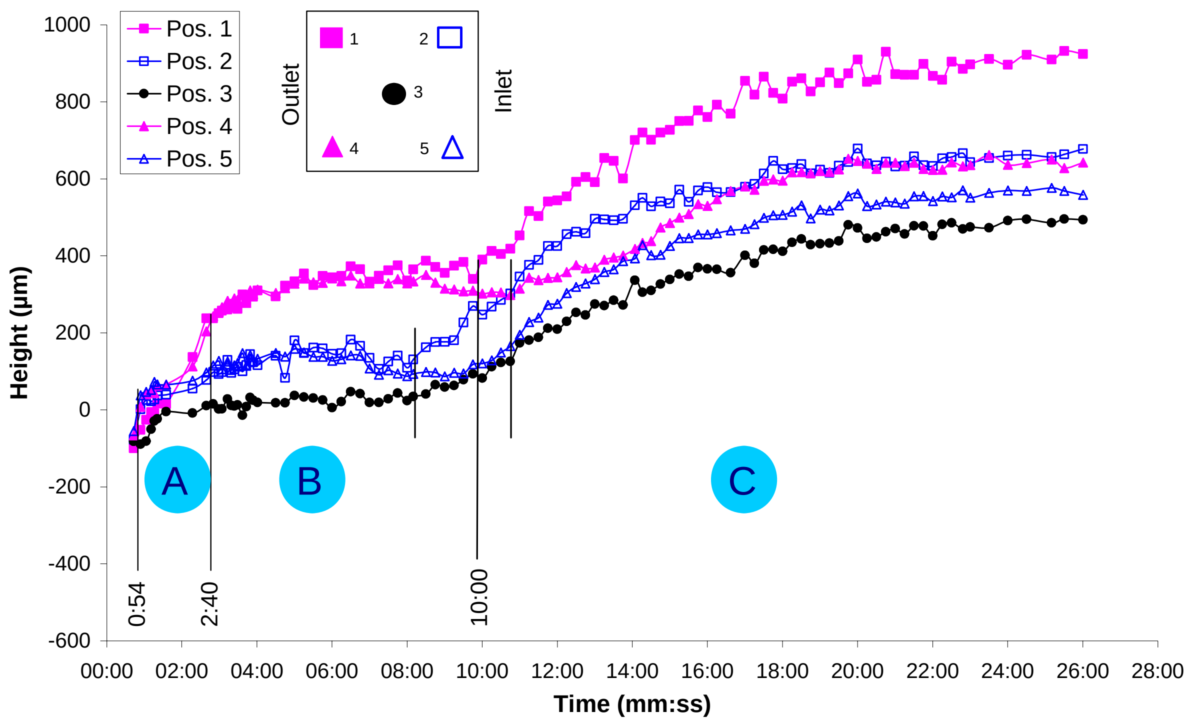

Fig. 4 Thickness change as a function of time measured at 5 locations over the plate during infusion.

Fig.5 Resin propagation in the draining fabric.

On a second step corresponding to zone B in Fig. 4, the thickness remains almost constant for 8 minutes. This means that the resin impregnates the system without any significant volume variation. Resin is still injected in the system, and no resin flow could be observed in the outlet tube. During all the period, resin is filling the voids between the fibers. Then another thickness increase is clearly identified at about 10 minutes. It begins simultaneously near the inlet and in the centre of the plate (points 2, 3 and 5), and afterward at the outlet (points 1 and 4). This order is the same as the one found using thermocouples (see [4] in this conference), but one should note anyway that this increase, as well as the previous one, is almost simultaneous at each point of the plate compared to the total filling time.

Last, the whole preform is inflated (zone C in Fig. 4). Points 1 and 2 and points 3 and 5 are submitted to a similar variation respectively, the increase being less marked at point 4, i.e., just beside the outlet pipe. Now, all the voids between fibers should be filled, and the resin keeps on penetrating the system tends to separates the fibers, giving the final resin volume fraction. This step of the process ends when a resin flux is observed in the outlet pipe (28 min). In fact, thickness variations are very weak at this time showing that equilibrium is found between external pressure (1013 hPa) and resin dynamic pressure.

Discussion

Finally, the total thickness varies during the filling procedure, in a range [600, 1006] µm, depending on the zone. Spatial variations are of about 400 µm, half related to the second swelling (from phase B to phase C), half to the first swelling (from phase A to phase B). Thickness measurements realized by a contact method after cooling and demoulding of the plate yields thickness spatial variations of 195 µm. Note that the thickness variations recorded by the fringe projection technique integrates all the possible variations in cure and in the composite preform itself of course. However, the different fabrics (draining blanket, peel ply, etc.) and possible deformations occurring during the curing/cooling process are ignored.

Regarding the mean thickness variation, complementary information comes from the simulation of this experiment using the numerical model developed [2, 3]. After the filling stage, computations show a 0.63 mm expansion for the plate alone, while a mean value of 0.73 mm is assessed experimentally with the fringe projection for the whole stacking. Moreover, the mass of resin received by the system (plate + distribution layer + pipes + …) is 470 g experimentally and 410 g numerically for the plate alone. These results show some correlation between measurements and predictions; they tend to confirm that the variation of the plate thickness on its own is well captured. No further conclusion can be drawn at this stage, but the swelling of the preforms is demonstrated, and its magnitude should be lower than the total thickness increase observed for the whole system. This is verified here, but complementary experiments must be carried out to dissociate the plate behavior from the rest of the technical plies surrounding; during infusion as well as during curing and cooling.

CONCLUSIONS

Resin film infusion (RFI) is a very promising process for structural applications of composite materials, but for an optimal use there still misses a deep understanding of the phenomena encountered, especially during the infusion stage. We have used here, in industrial conditions, an optical full-field technique to follow the thickness variations of the staking during the filling process in conjunction with thermocouple sensors (see [4]). This experiment aimed at better understanding the process, and tries to draw a possible scenario of the filling process.

This method gave access to very sensitive measurements (resolution of 36 µm), and to local in-plane thickness variation measurements. Interpretation of these results is still tricky, and some additional experiments should be performed. One of the more interesting point outlined during the experiment is a 3-step filling procedure: 1^{st} – draining blanket filling, 2^{nd} – void filling without global volume change, 3^{rd} – plate swelling due to resin separating the fibers in the preform network. Even if some slight differences may be seen, the three phenomena occur almost simultaneously over the whole plate area. This observation advocates for a unidirectional through-thickness resin flow.

Eventually, these are very first results, and further experiments will be conducted to show the repeatability of the observed phenomena. The method will also be validated, and now attention must be paid to dissociate the plate behavior from the rest of the technical plies surrounding. Optical method used to follow the resin front can help in understanding the behavior of the composite from curing to cooling. This implies to ensure more representative curing conditions, by using an oven for instance.

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