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ON WETTING OF FIBER WITH A RESIN BY CAPILLARY FORCE

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ABSTRACT: VARTM (Vacuum Assisted Resin Transfer Moldings) is a potential method to realize low-cost processing of the composite materials. The objectives of the present study are to understand a wetting dynamic process in the vicinity of the solid-liquid-gas interface, and to evaluate flows in advancing resin along fiber(s).
In the present system, wetting process of glass fiber(s) of 25 μm in diameter on silicon substrate by epoxy resin is focused. After placing the fiber(s) on the substrate, a drop of resin is settled on the fiber. The leading edge of the resin is detected by high-speed CCD camera. Effect of the gap distance between the fiber and the substrate is discussed. Effect of micro- and nano-meter-scale particles suspended in the resin on the wetting process is also evaluated. In addition, we introduce processes of collision of the resin edges and their coalescence in the case of the opposing resin flows along fiber(s).

KEYWORDS: capillary force, fiber, wetting process, VARTM, particle

INTRODUCTION

One of potential methods for mass production of FRP (Fiber Reinforced Plastics) is the vacuum assisted resin transfer molding method, known as VARTM. In this method, the resin is driven by a pressure difference within fiber bundles. This method realizes a cheaper and faster-in-total process to from the FRP comparing to the conventional ways with designing and building metal molds. One of the problems in forming processes of the FRP is the void formation in the final products. Figure 1 indicates a cross-sectional views of the GFRP (Glass FRP). We do have several voids (see black area on Fig. 1), where the resin has not penetrated between the fibers in the process [1] [2] .We have proceeding works on the resin penetration in the fiber bundles by both experimental and numerical approaches [3] [4]. They studied it on a macroscopic view. There exist few experimental investigations of wetting fiber with resin for micro scale without numerical one [5]. The void formation process and the wetting/dewetting processes of the resin on the fiber(s), however, have not been understood well. On a wetting of fiber by the fluid due to the capillary force, we have fabulous works [6] [7] including the droplet migration along the fiber. The objective of this study is to accumulate knowledge on the wetting behaviors in the resin-fiber(s) system on the viewpoint of the interfacial thermo-fluid dynamics. This research aims at the development of the formation process of less-void and higher-functional composite materials.

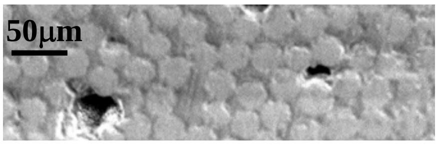

Fig. 1 A cross-sectional view of GFRP. Voids where the resin has never penetrated between the fibers are observed.

EXPERIMENTS

Figure 2 illustrates a schematics of the experimental apparatus. Fiber(s) are places on a silicon substrate, and irradiated with a collimated laser light. The laser light reflect by silicon wafer is captured with the CCD camera. The whole optical elements are settled on an optical rail, so that the incident angle of the laser light is arbitrarily changed without changing the optical path before the target. This system enables us to detect a resin flow between the fiber(s) and the substrate. Temperature of the substrate is varied from 5 °C to 50 °C. The test fluid is epoxy resin made by Japan Epoxy Resin Co., Ltd. The test fibers are glass fiber made of Mitsubishi Rayon Co., Ltd. We have varied the temperature of the resin, and the substrate in order to detect the effect of the viscosity and surface tension variation as a function of the temperature. In order to see the flow pattern in the advancing resin around the fiber on the substrate, another series of experiments are carried out by putting florescence particles of 1.0 μm in diameter in the resin.

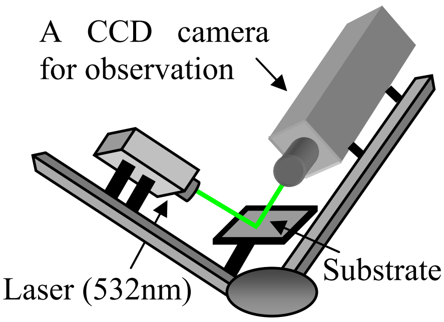

Fig. 2 Experimental apparatus

RESULTS & DISCUSSION

Typical example of the snapshot of the resin droplet placed on a single fiber placed on the substrate is shown in Fig. 3. The black line at the center is a glass fiber of 20 μm in diameter. The black part on the left-hand side in the frame is the resin, and the boundary line of the black part corresponds to the macroscopic contact line of the droplet. The resin flows around the wire from the left to right by the capillary force. The leading edge of the flowing resin is detected by evaluating the variations of the brightness of the detected image. Noted that the detected image is projected because of the incident angle of the laser light; the length scale in the horizontal and vertical directions are different.

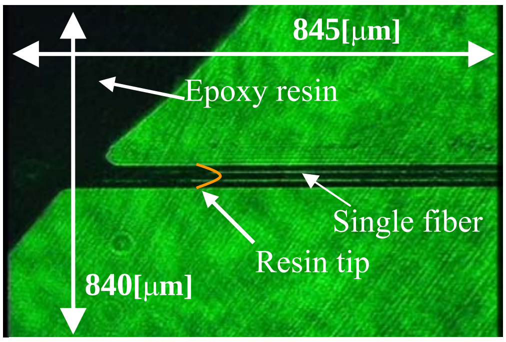

Fig. 3 Snapshot of the resin flow along a fiber; the resin flows from left to right in the frame.

1. Wetting of resin around single fiber

As shown as a schematic image in Fig. 4, we detect the resin flow at the tip position of the resin. Then we evaluate the velocity of the resin tip around the wire as a function of time as shown in Fig. 5. The time t = 0 corresponds to the instance when the droplet is placed on the wire. In this figure one can find the temporal variations the velocity of the resin tip on the substrate at different temperatures, T = 20, 40 and 50 °C. The velocity gradually decreases as elapse of time to converge into null. It must be reminded here that the temperature coefficients of the viscosity and the surface tension are both negative for the present test fluid. The velocity of the resin tip increases as the substrate temperature increases at the same instance. We will refer the result under the condition at 20 °C as the basic result in the following.

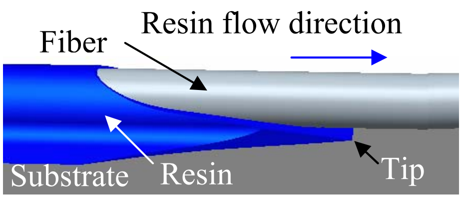

Fig. 4 Schematic image of the resin flow along a fiber

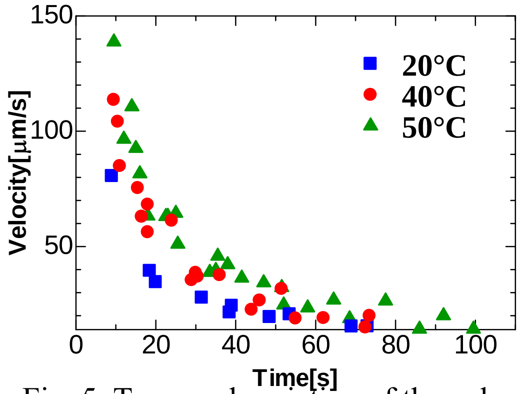

Fig. 5 Temporal variation of the velocity of the resin tip on the substrate at different temperatures.

2. Effect of the gap distance of two fibers (top point)

In the case of two fibers, we vary the gap distance between the fibers, ΔL, to see the effect of the capillary force. We align the two fibers with a designated gap distance on or above the substrate, and drop a single droplet on the both simultaneously. Figure 6 expresses a snapshot of the resinous flow between two fibers. The resin droplet is placed in the left-hand side out of the frame, and the resin flows from left to right in this frame. One can clearly see that the resin advances along the fibers by the capillary force, which pulls the resin between the fibers to follow the preceding tip of the resin. Figure 7 indicates the temporal variations of the velocity of the resin edge between the fibers (thick arrow in Fig. 6) as a function of the gap distance between the fibers. The black dashed line shows the velocity of the basic flow in the case of a single fiber as aforementioned. The valley between the fibers advances with a similar profile in quality of the velocity of the resin along the fiber. If the gap is narrower than about 50 μm, the resinous velocity between the two fibers is faster than that in the case of the single fiber. As the ΔL becomes larger, the effect of the capillary force pulling the resin between the fibers becomes rather small to reduce the velocity.

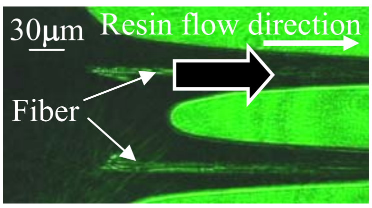

Fig. 6 Snapshot of the resin flow between the fibers; the resin flows from left to right in the frame.

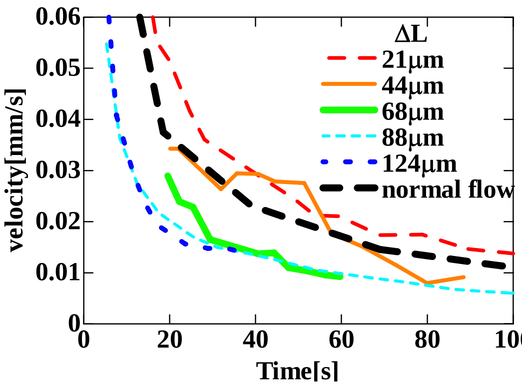

Fig. 7 Temporal variations of the velocity of the resin between the fibers as a function of the gap distance ΔL. Dashed line corresponds to the basic flow in the case of a single fiber at 20 °C as shown in Fig. 5.

3. Effect of the gap distance of two fibers (Rear resin from top point)

In order to see the effect of suspended particles in the resin, we put fluorescence particles of 1.0 μm in diameter. Figure 8 shows a typical example of the snapshot of the resinous flow with the particles. Each arrow in the valley region of the resin indicates a velocity vector derived by the particle tracking from the successive images. Length of the arrow is proportional to the absolute value of the velocity. Figure 9 indicates the velocity distribution in the valley. The color corresponds to the vector in Fig. 8. In this figure the position between the centers of the fibers is expressed from 0 to 100. Note that we have a tiny gap between the fiber and the substrate, we have particles flowing in the region beneath the fiber as indicated at the position of 0 and 100. In this case the particles flow in the bulk region of the valley. It is noted that the resin in the bulk between the fibers flows faster than that at the edge of the valley. The resin speed in the vicinity of the fiber is low, because of the shear stress in this region where the resin is filled in between. The average velocity in the valley bulk almost corresponds to the velocity at the edge of the bulk.

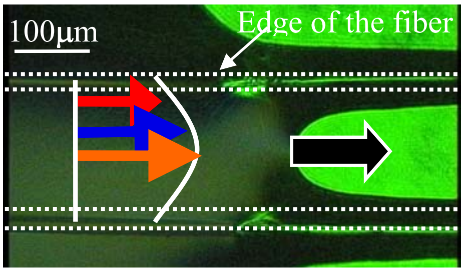

Fig. 8 Snapshot of the resinous flow with the particles. Each arrow in the valley region of the resin indicates a velocity vector derived by the particle tracking from the successive images. Length of the arrow is proportional to the absolute value of the velocity

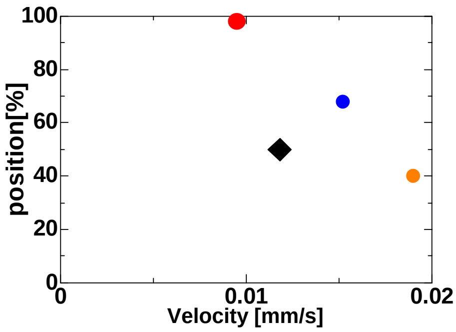

Fig. 9 Velocity distribution in the valley of the resin between the fibers. The color corresponds to the vector in Fig. 8. The position between the side edges of the fibers is expressed from 0 to 100.

4. Resinous collision (fibers)

It is seldom to see an entrainment of air bubbles in a collision of the resins along a single fiber. In the case of the resin collision in a bundle of fibers (Fig. 10), we do have a bubble entrained in the resin (Fig. 11). Figure 12 indicates a temporal variation of the behaviors of the bubble and particles after the collision of the resin. In the figure the positions of the center of the mass (blue) and the edges (orange) of the bubble are indicated. Note that the bubble exhibits its shape elongated parallel to the fibers, then gradually its shape into spherical one. At the instance of the collision of the resin, the bubble stays at the collision point with shrinking its shape, and then strays back and forth. It is noted that the bubble strays almost laterally without crossing neighbor fibers.

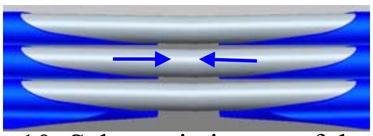

Fig. 10 Schematic image of the resin collision along the fibers

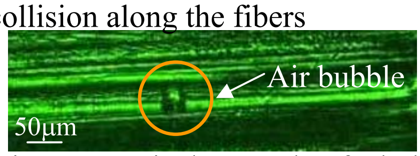

Fig. 11 Typical example of a bubble entrained in the resin.

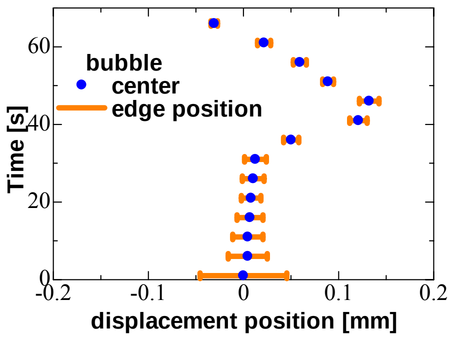

Fig. 12 Behavior of a bubble entrained in collided resin.

CONCLUDING REMARKS

The objective of this study is to accumulate knowledge on the wetting behaviors in the resin-fiber(s) system. We especially focus on the wetting process of the fiber(s) on the smooth substrate by the resin as a fundamental study for vacuum assisted resin transfer molding (VARTM) processes. We have tested wetting of a single fiber and of multiple fibers by the resin droplet on the substrate at a designated temperature. Behaviors of advancing tip of the resin along a single fiber and advancing valley between the fiber are described. Behaviors of suspended particles in the resin are also discussed. We also focus on collision of the resin advancing along the fiber(s) and resultant bubble entrainment.

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