DEVELOPMENT OF MULTI-FUNCTIONAL SENSOR FOR RESIN TRANSFER MOLDING

S. Motogi[1], T. Itoh[1], T. Fukuda[1],
K. Yamagishi[2], S. Kitade[2] and H. Morita[2]

[1] Department of Intelligent Materials Engineering, Osaka City University
3-3-138, Sugimoto, Sumiyoshi-ku, Osaka, 558-8585, Japan
[2] Research Institute, Ishikawajima-Harima Heavy Industries
Shin-nakahara, Isogo-ku Yokohama 235-8501, Japan

SUMMARY: A multi-functional sensor for RTM process monitoring is developed. The sensor can be used for flow front detection of the resin at the resin filling stage as well as for conventional cure monitoring at the curing stage by measuring dielectric properties of the matrix resin. A comb-shaped electrode sensor has been used for cure monitoring *e.g.*, in autoclave processing of advanced composites. It measures the dielectric response of resin existing in the vicinity of electrodes between which one applies an alternating voltage. The newly developed sensor is also comb-shaped electrodes but sufficiently long to cover the RTM die dimensions. It is found that the dielectric loss factor response of the sensor linearly changes with the wet length of long array of electrodes, therefore it serves as the resin front sensor if it is embedded in the die of RTM. It is also shown that the two dimensional flow can be monitored with sufficient accuracy by the newly developed sensors.

KEYWORDS: RTM, resin front sensor, cure monitoring, dielectric sensor, permeability, Darcy's law, smart manufacturing

INTRODUCTION

Resin transfer molding (RTM) is now expected to be a promising manufacturing technology for the next generation advanced composite materials because of its high cost performance in making complex shape parts [1]. Namely, it is comparatively easy to make curved, twisted parts, and the fiber volume fraction can be as high as 60%; therefore, the strength requirement meets well with the RTM fabricated composite parts. RTM processing is divided into three stages: a near net shape preform of fibers is made and set to a cavity of the mold, and melt resin is injected to fill completely the cavity and then the composite is cured at elevated temperature. There are many factors which influence the performance of the RTM fabricated composite parts, *e.g.*, temperature, resin flow, void content, thermal residual stresses *etc*. The resin filling stage is effectively a penetrating process of resin into preform, therefore it is now widely accepted that the flow is described by Darcy's law with the analogy of liquid flow through porous media [2]. Darcy's law is a constitutive equation and a

mechanics version of Fourier's law relating the heat flux and the temperature gradient. It says that the average velocity v of the resin penetrating the fiber preform is given by

$$v_i = -\frac{k_{ij}}{\mu}\frac{\partial P}{\partial x_j} \tag{1}$$

where P is the pressure, μ is the viscosity of the resin and k_{ij} is the permeability tensor [3]. This last quantity depends on the density and geometry of the fibrous preform and also on the wettability of the fiber with the resin. Therefore the measurement of value of the permeability tensor is extremely important for simulation of filling stage of RTM process. Such simulation is of course necessary for automation and control as well as better understanding of molding process, *i.e.*, for the intelligent or smart manufacturing. But the exact and precise measurement of the permeability tensor may be extremely laborious task using *e.g.*, the so-called short-shot technique, and the data has in general large scatter. Automation and process control of RTM using simulation technique might be an indispensable key technology for the development of RTM technique.

This paper describes the development of a new type sensor for RTM processing. The sensor is a dielectric measuring devise which is effectively a comb shape electrodes of copper printed on a flexible board (in fact, it is a rather thick resin film). The dielectric response of matter in the vicinity of the electrodes is measured upon application of alternating voltage, therefore the response changes with wet length of the sensor with liquid (in this case, the melt resin). If we can make a long sensor, and set it to the cavity of RTM mold, it can give an information of the position of the penetrating resin front. Because the information can be a continuous one, we can measure very precisely and locally the value of permeability.

Moreover, the same sensor can serve as a cure monitoring devise in the elevated temperature curing stage after the filling of the resin. The sensing principle (also the dielectric loss measurement) is now widely accepted as a standard and robust but sensitive technique for degree of cure of resin.

SENSOR PROPERTIES

Making Sensor and Measuring Principle

The newly developed sensor is a comb shape pair of electrodes of copper foil (35mm thick) printed on a flexible circuit board. The board is made of plyimide film and the dimension of the sensor is 13mm(W)*85mm(L) *50μm(T). The scheme of the sensor geometry is shown in Fig.1. Making process of the sensor is none other than an usual one of making electric circuit board using ultra-violet light and etching techniques. Two ends of the electrodes are connected with the measuring amplifier (Eumetric 100A of Micromet Instrument Inc.) of dielectric response of the matter existing in the vicinity of the two electrodes. It can measure the real and imaginary part of the permeability of the dielectric materials. The specific complex dielectric constant ε can be written as

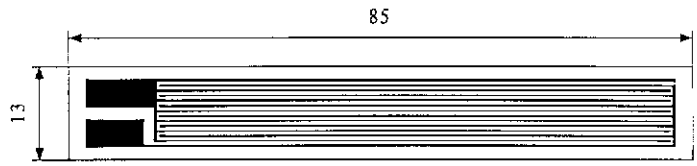

Fig.1 Sensor pattern.

$$\varepsilon = \varepsilon' - i\varepsilon'' \tag{2}$$

under AC electric field, where the ε' denotes the real part (permeability) and ε'' is the loss factor. This latter loss part can be written as, in the low frequency limit,

$$\varepsilon'' = \frac{\sigma}{\omega \varepsilon_0} \tag{3}$$

where σ is the ionic conductivity, ω the angular frequency of the external field and ε_0 is the permeability of the vacuum [4]. The reciprocal of conductivity $1/\sigma$ is particularly convenient to estimate the degree of cure of resin since its minimum (maximum) corresponds to the maximum (minimum) mobility of ions in polymers. The resistance $1/\sigma$ is called the ionic viscosity. We use the dielectric loss factor for resin front detection and the logarithmic ion viscosity for the cure monitoring [5].

As a Resin Front Sensor

The sensor is attached to a steel plate and it was very slowly sunk into melt resin bath. Figure 2 shows the change in the dielectric loss factor with the wet length of the sensor by melt resin. The abscissa is the distance from the very front of the sensor to the resin front in Fig.1; therefore, at about 10mm, electrode part first meet the melt resin. The upper thick copper part of the sensor was covered by a piece of scotch tape so as to ensure that the response rate does not change at that part. The maximum (or saturation) value of loss factor does not change if the resin property does not change as is shown in Fig.2.

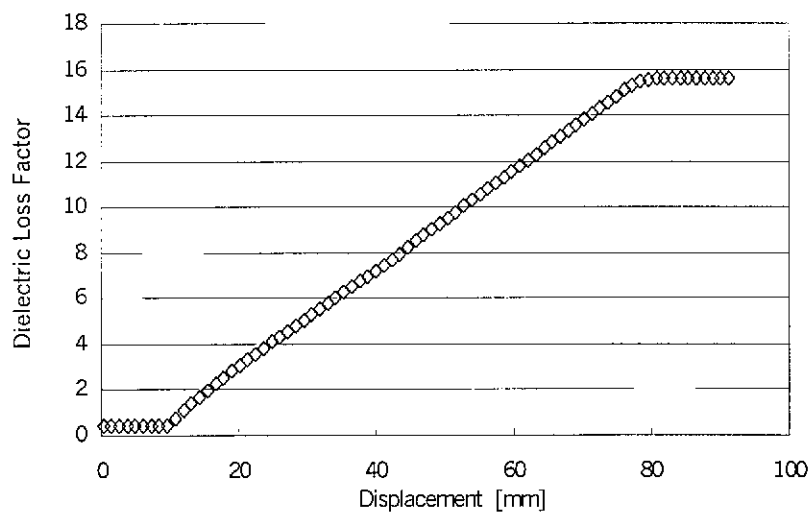

Fig.2 Dielectric loss factor response of new sensor.

The response is nicely linear with the wet length; therefore, if we can measure the loss factor, the position of the resin front can be easily known. It happened that the suitable frequency of the external electric field was 100Hz for the materials we used, but it can change for other material systems.

The response time has a certain limitation, because we used a commercially available measuring devise. It requires several seconds for one cycle of measurement, but we expect that it can be much reduced if the device is specially designed for the purpose of this paper. Therefore the measurement may be made almost continuously in the longitudinal direction of the sensor. This is a great advantage of this new sensor in comparison with already existing discrete methods.

As a Cure Monitoring Sensor

The sensor structure is essentially as same as the conventional commercial one; therefore, it must be able to monitor the cure of resin. Figure 3 shows a comparison of the log ion viscosity response of the conventional and newly developed sensors using neat resin (Epoxy) cure process. The minimum point indicates the resin begins the gelation and the saturation means the completion of cure. Two sensors exhibit essentially identical responses. This shows that the new sensor can be used also as a cure monitoring sensor.

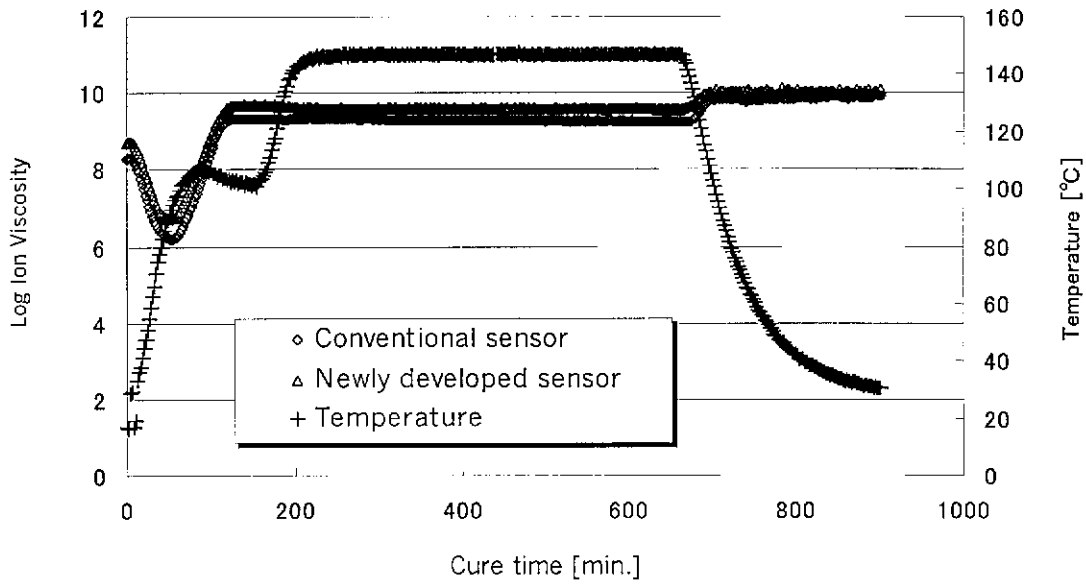

Fig.3 Comparison of dielectric loss factor response of new sensor and conventional sensor.

Because of involved geometry of RTM composite parts, it is well conceivable that the degree of cure differs from point to point. We should then naturally ask how the sensor response is if the degree of cure of the resin is different along the length of the sensor. We made a sensor pattern on a wide circuit board as shown in Fig.4.

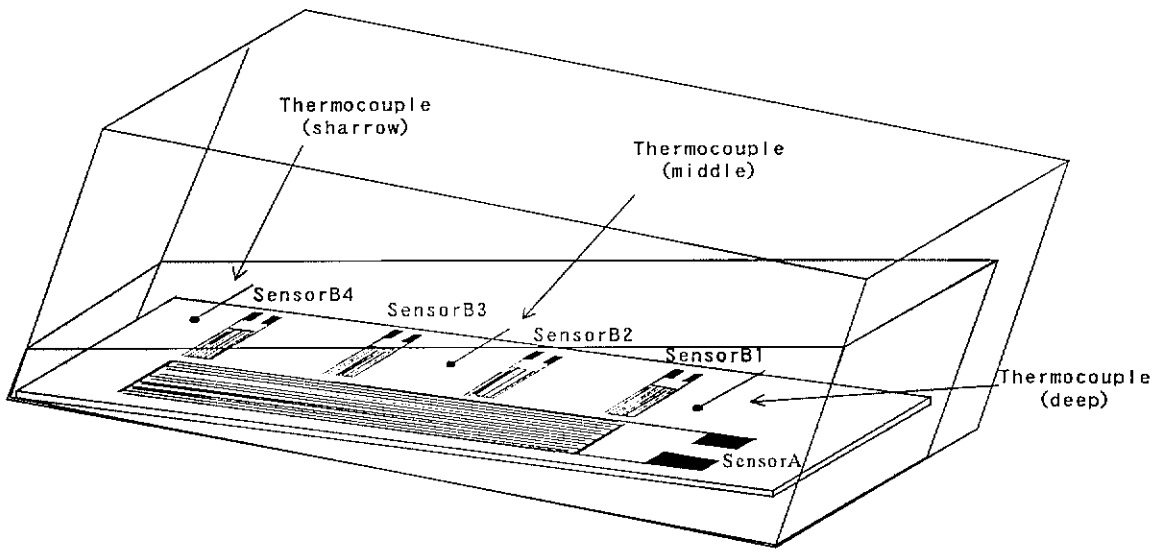

Fig. 4 Resin pan for distributed degree of cure and the sensor configuration.

The sensor board is sunk into a resin pan with variable depth as shown in Fig.4, and then the cure of resin was monitored. The result is shown in Fig.5, and evidently shallow part of resin cures fast. The small sensors well indicate the local nature of cure of resin. Comparison of the deepest sensor and long one is shown in Fig.6. The long sensor seems to show the completion of cure (saturation of log ion viscosity) as does the deepest sensor, *i.e.*, the latest response. This is an advantageous property as a cure monitoring sensor, since we can recognize from the long sensor response that all part of the composite is cured without under-cured region.

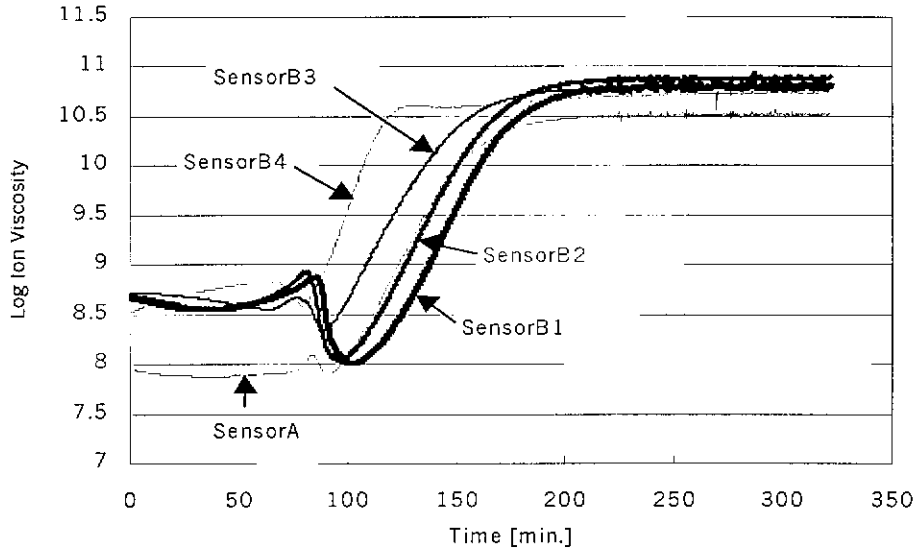

Fig.5 Comparison of responses of new long sensor (A) and from deep to shallow (B1 to B4) sensors

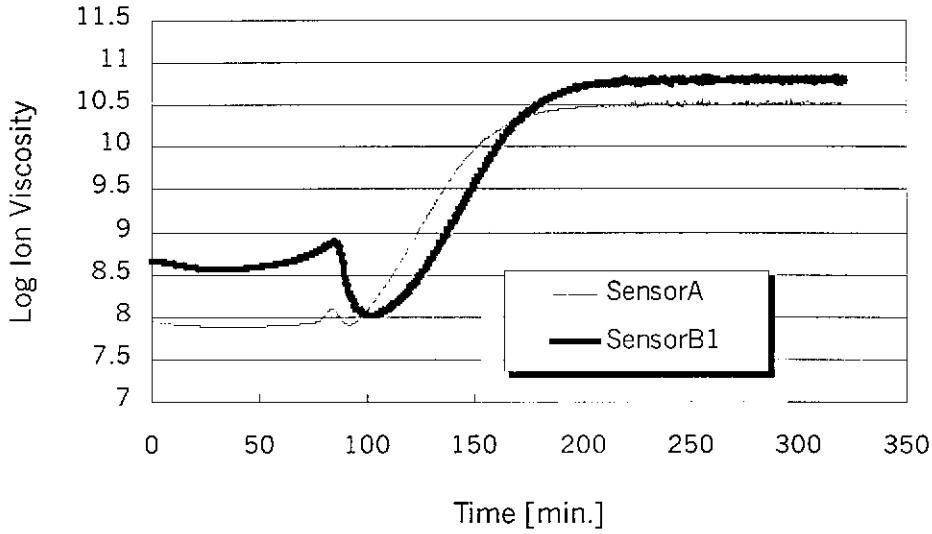

Fig.6 Comparison of responses of long sensor (A) and deepest one (B1).

DETECTION OF 2-DIMENSIONAL FLOW BY NEW SENSOR

In order to estimate the actual applicability of the new sensor to real RTM flow, we made an RTM die as shown in Fig.7. The resin penetrates from the resin reservoir into glass fiber preform by suction force from the other side. The resin used here is epoxy of room temperature cure type. The sensor is set just beneath the fiber preform. The geometry of the sensor is also shown in Fig.7. Three long sensors are used in this case for a qualitative estimation of two dimensional flow. The preform used here is 14 layers of glass fiber plain woven cross. The upper die is made of thick glass plate so that the resin front can also be determined by direct observation of photographs taken in the course of resin flow.

By photographical observation, we can easily see that the early stage of the flow is apparently 2-dimensional in the plane of preform. Then the resin front gradually becomes flat to be one dimensional. We measured the sensor response of dilelectric loss factor. Figure 8 shows three sensor response, which clearly indicates the center sensor a little proceeds than other two particularly in the early stage of the flow. Figure 9 compares the center sensor response (transformed to resin front position) and directly observed one through the upper die. The sensor response proceeds a little than upper resin front. This might be due to the three dimensionality to the thickness direction because of the effect of gravity.

Although precise aspects should be further investigated, we can say that the newly developed sensor can actually detect the resin flow front

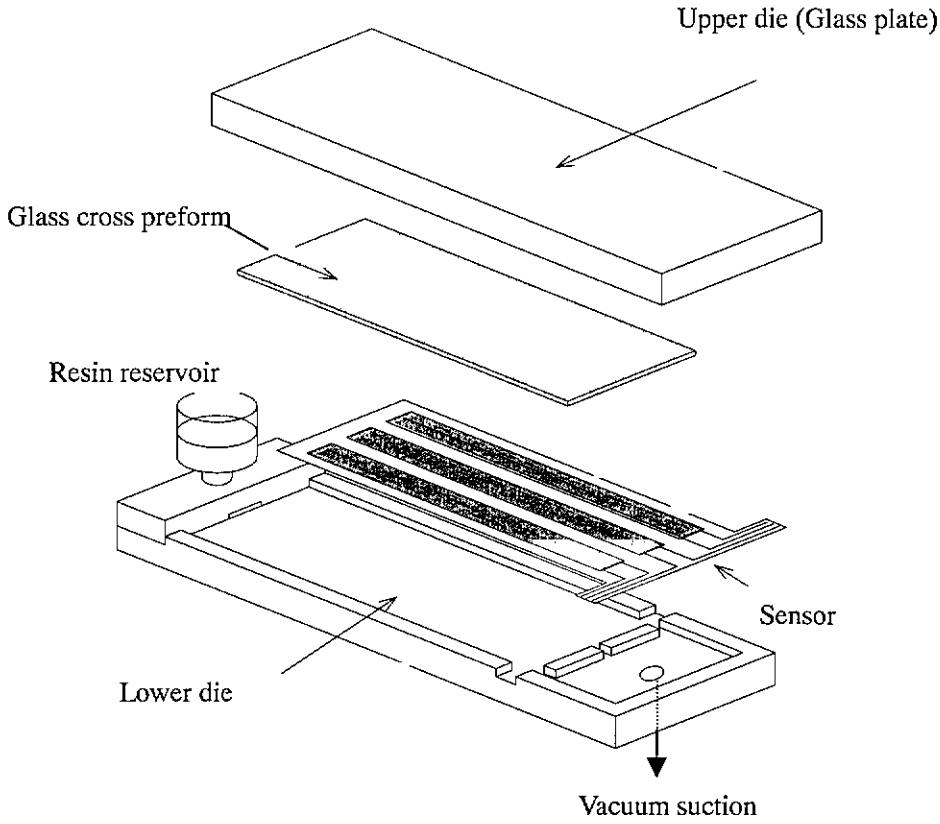

Fig.7 Configuration of RTM die and sensors

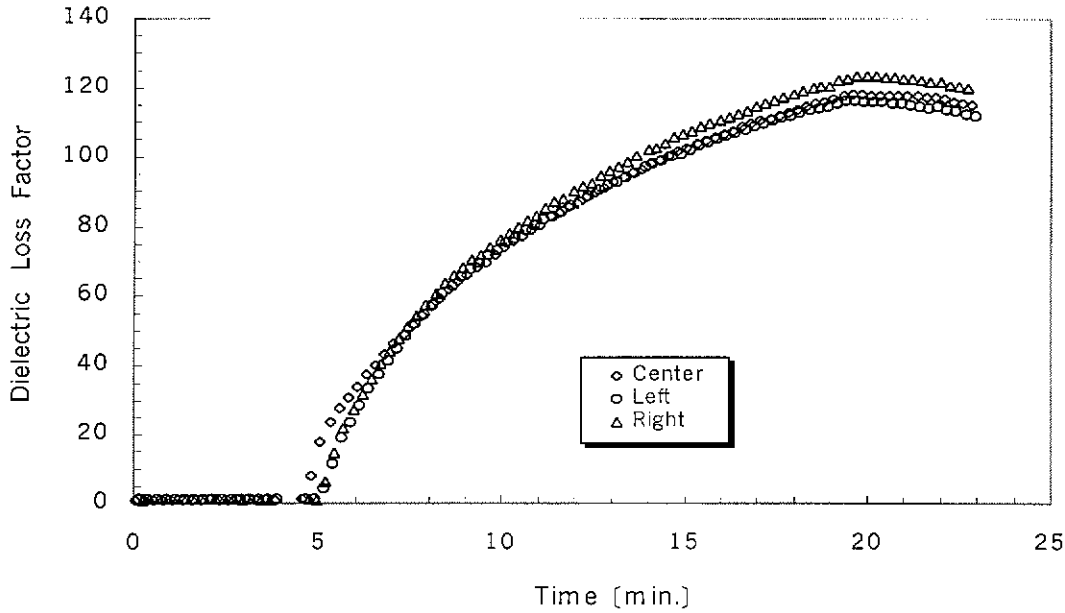

Fig.8 Comparison of three sensor response

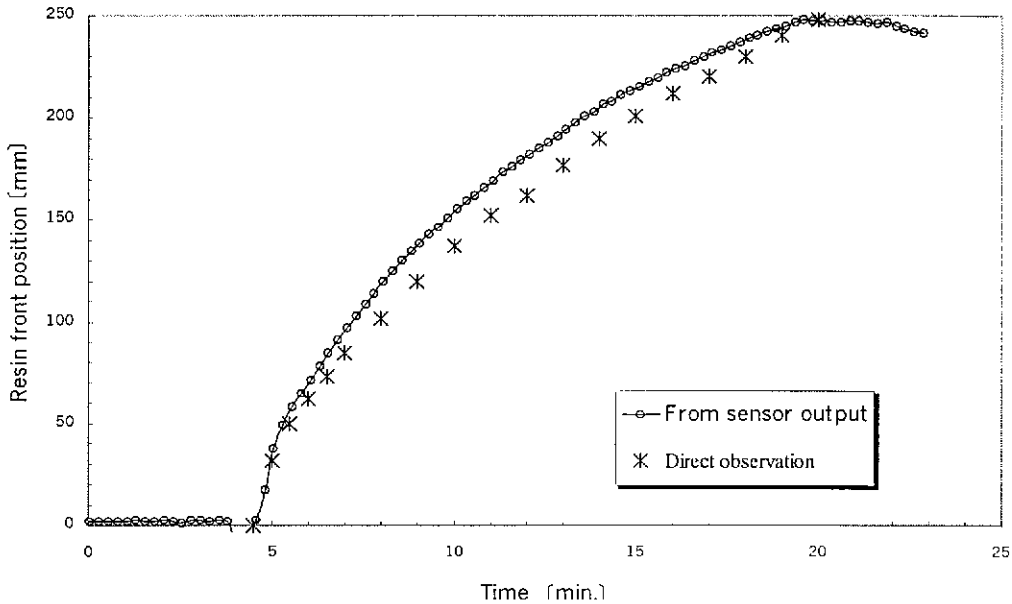

Fig.9 Comparison of resin front position detected by center sensor and direct observation.

CONCLUSIONS

We obtained the following conclusions. The newly developed sensor can almost continuously detect resin flow front at the RTM resin filling stage. The sensor is also available for the cure monitoring of resin and composites. The latest cure completion can be detectable along the sensor length. It can thus be used for confirmation of the end of cure of all part of the composite. Two dimensional flow in a simple RTM die was actually detected with good agreement with the direct observation.

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