PROCESS SIMULATION OF FIBER REINFORCED PLASTICS

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Abstract

Advanced composite materials such as CFRP possess many characteristics that are superior to other structural materials. However, thermal strain and residual thermal stresses were generated together with heat molding during the thermoset molding process, leading to the issue that products could not be realized exactly according to design.

In this research, analysis simulation was developed that considers the effects of thermoset molding process in addition to mechanical design of products. The simulation consists of three kinds of analysis: 1) heat transfer analysis during molding; 2) curing temperature analysis of thermosetting resin; and 3) thermal deformation analysis during molding. Heat transfer analysis was developed that can be used even for complex heat inputs using apparent heat transfer coefficient. Curing temperature analysis was developed to judge curing temperature focused on the quantity of heat required until curing. Thermal deformation analysis was developed to find the thermal deformation during molding, considering the mold.

1. Introduction

Advanced composite materials such as carbon fiber reinforced plastics (CFRP) have distinctively superior specific strength and specific rigidity compared to other structural materials. In addition to being an indispensable part of satellite materials, they contribute significantly to rationalization of energy use in transportation equipment such as aircraft and high speed vehicles. CFRP further possess markedly low thermal expansion properties. Depending on the type of fiber, CFRP possess unique properties such as the ability to be utilized as high heat conductive materials surpassing even high heat conductive metals, therefore, an expansion in their applications is anticipated.

On the other hand, however, because of the generation of thermal strain and residual thermal stresses accompanying heat molding during the thermoset molding process that accounts for a major part of the manufacturing method of advanced composite materials, the molded body deformed and broke, and other problems have arisen, such as design strength could not be realized. This resulted in limitations on the material, such as the difficulty in molding large complex structures with high accuracy.

The present research aims to resolve such problems. In addition to estimating the mechanical performance based on conventional design in the design of structures made of advanced composite materials represented by CFRP, by analyzing the effects of the thermoset molding process, the condition of thermal strain and residual thermal stresses in the molded body was evaluated, and an analysis simulation method was developed enabling molding of composite materials with high accuracy.

2. Thermoset molding analysis simulation

Figure 1 shows an overview of the thermoset molding analysis simulation. The thermoset molding process was classified into three stages: heating, curing and thermal deformation, and the simulation was divided into three kinds of analysis: heat transfer analysis during molding, curing temperature analysis of thermosetting resin, and thermal deformation analysis during molding, based on the concept that thermal strain and residual thermal stresses accompanying heat molding of CFRP occur because of the temperature difference between curing temperature and operating temperature of molded body. Details of each of the analysis techniques is described below.

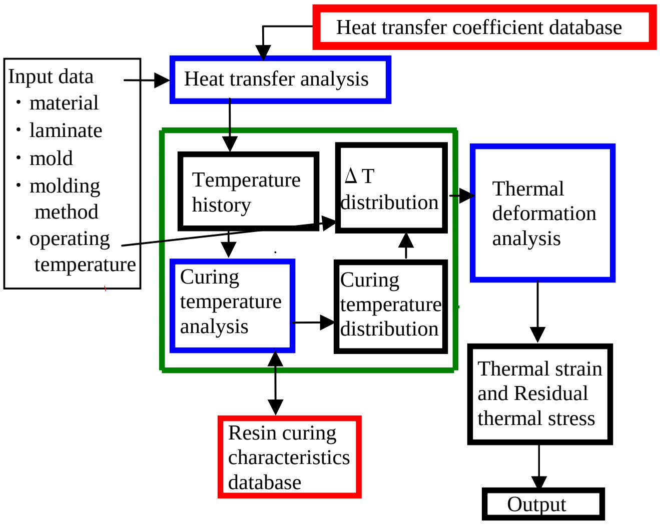


Fig.1 Overview of the thermoset molding analysis simulation.

3. Heat transfer analysis technique during molding

To determine the molding temperature distribution due to complex heat transfer phenomena that occur when large CFRP structures are made by thermoset molding, heat transfer analysis technique was developed wherein the product of the apparent heat transfer coefficient and environmental temperature within the molding apparatus was taken as heat input. A cylindrical body molded by autoclave molding is taken as an example and described hereafter.

3.1 Overview

The estimated accuracy of temperature distribution of a body molded by autoclave molding depends on the convective heat transfer coefficient used. However, there are practically no examples of measurement of convective heat transfer coefficient for CFRP thermoset molding by autoclave, and conditions for using data corresponding to various molding conditions do not exist.

In the present study, the heat transfer coefficient to be used in the analysis was determined as an inverse problem [1]. Using the environmental temperature within the molding apparatus and the heat transfer coefficient, a method to estimate the temperature distribution of the molded body was used. However, the heat transfer coefficient determined in this case is the apparent heat transfer coefficient that includes the effects of equipment such as vacuum bags, breeder, and so on.

3.2 Procedure to specify the apparent heat transfer coefficient

In this study, the apparent heat transfer coefficient was specified as an inverse problem. That is, as shown in Fig. 2, the actual temperature history during molding was measured. Temperature analysis, taking the heat transfer coefficient as parameter, was performed for this measurement system, and the temperature history of the position corresponding to the actually measured value was obtained. The measured data was superposed on this value. The heat transfer coefficient when the analysis value practically coincided with the measured value was specified as the apparent heat transfer coefficient.

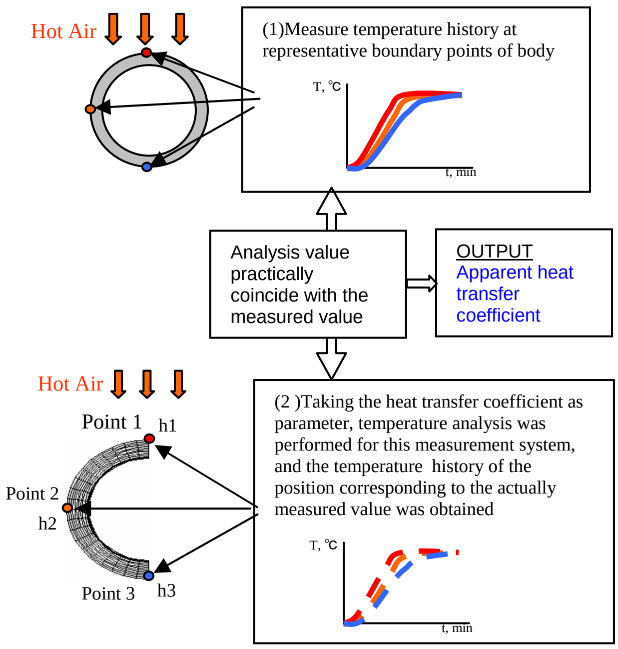


Fig. 2 Procedure to specify the apparent heat transfer coefficient

3.3 Heat transfer analysis during molding

To confirm that the analysis by the method mentioned above is effective, a cylinder with sandwich construction with the configuration of Table 1 was molded, and heat transfer analysis during molding was performed.

The state of molding is shown in Fig. 3. The temperature at the air outlet was controlled from ambient temperature to 120 ˚C at the heating rate of 3.0 ˚C/min, and hot air was blown in one direction to mold the body. The temperature history at each measurement point at this stage was measured using a thermocouple, and the measured values were superposed on the analysis values. In the analysis, a model was prepared including the mold to be used for molding, the heat transfer coefficient was assigned as shown in Fig. 4, and the analysis values were superposed on the actually measured values at each of the three points in the circumferential direction on the outside and the inside of the analysis model.

Table 2 shows the results, namely the specified apparent heat transfer coefficient. An example of the results of superposition of the analysis values of temperature history and the actually measured values is shown in Fig. 5. Since the values practically coincided, it was confirmed that the present method is applicable to the molding of CFRP structures.

An example of temperature distribution when heat transfer analysis was carried out during molding using the results of Table 2, is shown in Fig. 6. The analysis model at this stage was made by solid elements. The number of solid elements was 5280, and the number of nodes was 6075.

Table 1 Configuration of molded body

iron mold(t=8mm)→release tape→inner skin(0/0/0)(K13C/Cyanate) →honeycomb core(Al1/4-5052-.001P t=15.1mm) →outer skin(0/0/0)(K13C/Cyanate)→release film→bleeder →vacuum bag film

*cylinder circuit direction is 0° direction

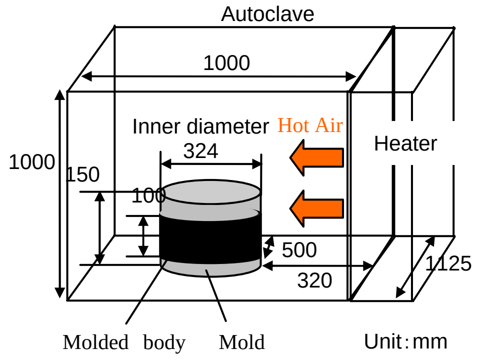


Fig. 3 State of autoclave molding

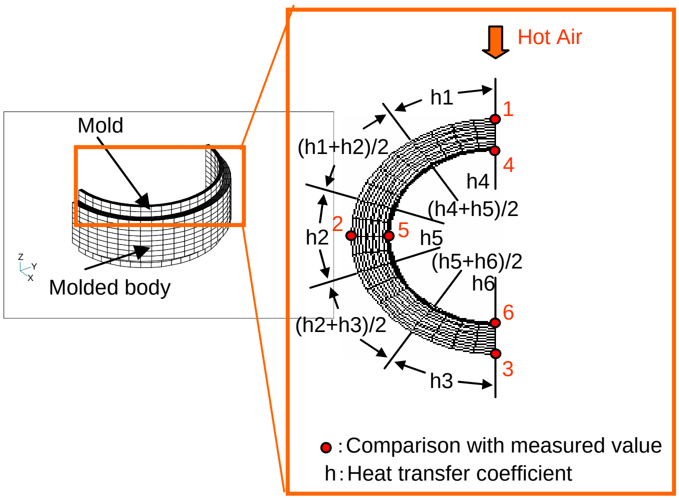


Fig. 4 Preparation of analysis model

Table 2 Apparent heat transfer coefficient

Apparent heat transfer coefficient	W/(K・mm2)
h1	2.14E-5
h2	1.46E-5
h3	2.00E-5
h4	0.71E-5
h5	0.75E-5
h6	1.00E-5

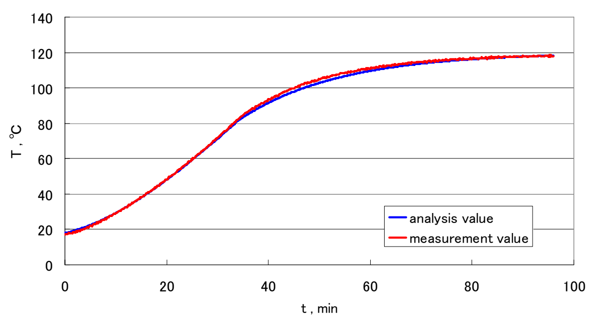


Fig. 5 An example of the results of coincidence of temperature history values

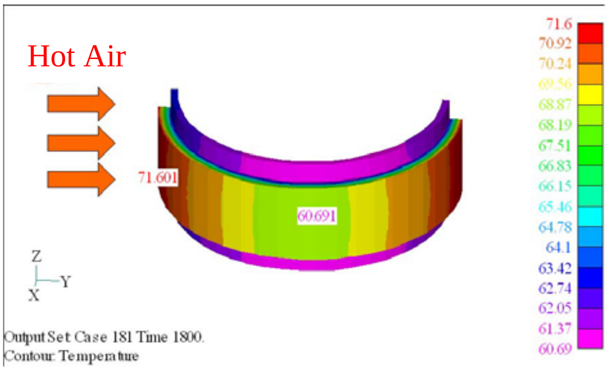


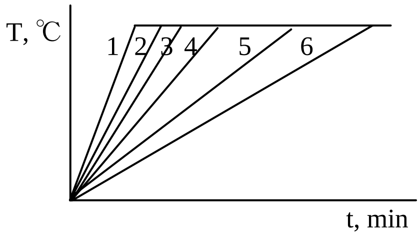
Fig. 6 Temperature distribution contour diagram from heat transfer analysis

4. Curing temperature analysis technique

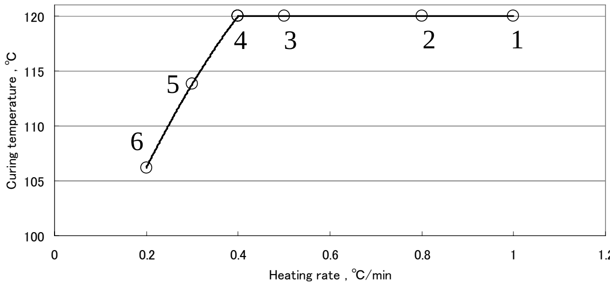
To determine the temperature at which the molded body cured from the temperature history during molding, the quantity of heat required until the resin in the base material (prepreg) cures was focused on. The characteristics data and the quantity of heat found from arbitrary temperature history were matched, and a method to determine the curing temperature was developed. Details of the method are given below.

4.1 Overview

The temperature at which the thermosetting resin cures varies depending on the heating process during molding. M55J/ epoxy-based resin prepreg was used as the test sample, DMA equipment was used, and resin curing temperature in prepreg was measured when the heating rate was systematically varied. The results are shown in Fig. 7. It can be observed that the lower the is heating rate, the lower is the temperature at which the resin cures. Based on this result, the quantity of heat required until the resin in prepreg cures was studied, and a method to determine the temperature at which the resin in the base material cures from an arbitrary temperature history was developed.



(a) Profile of heating rates

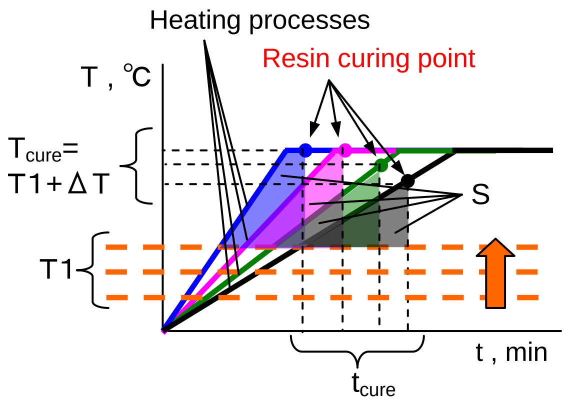


(b) Change in resin curing temperature

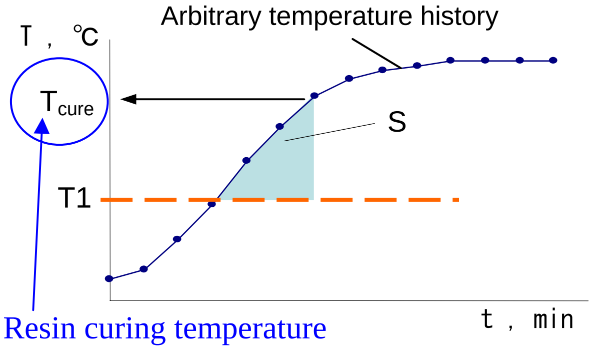
Fig. 7 Relationship between heating rates and curing temperature

4.2 Method of calculating the curing temperature

As shown in Fig. 8(a), the temperature and time required until the resin in the base material cures are measured corresponding to the heating process of any pattern. The temperature and time at curing at this stage are taken as resin curing points. Here, the two assumptions below are made in relation to the resin curing reaction. 1) The quantity of heat required from the time the resin in the base material reacts until it cures is fixed and does not depend on the heating process. 2) Resin curing reaction does not occur at low temperatures. Based on the two assumptions above, the threshold temperature T1, which is the lower limit at which regular area S that forms the product of the time and temperature until the curing point in each heating process, is determined from the relationship of resin curing point corresponding to heating process for multiple measurements. T1 at this stage, refers to the temperature at which the resin curing reaction mainly starts. S is the quantity of heat required from the time the resin curing reaction starts until the time the curing is complete. T1 and S determined in this way, possess generality in base materials using the same resin, are assumed to hold good for resin curing in arbitrary heating processes as shown in Fig. 8(b), and the curing temperature is determined.



(a) Method of setting S and T1



(b) Determination of curing temperature for arbitrary temperature history

Fig. 8 Method of calculating curing temperature

4.3 Method of obtaining the curing point

In this study, the curing point of resin in prepreg was measured using dynamic mechanical analysis (DMA). Although measurements may be performed using DSC or rheometer, DMA was used because the curing of base material was to be judged from the change in mechanical characteristics. DMA measurements were performed in the resonance frequency measurement mode using the Dynamic Mechanical Analyzer DMA 983 of T. A. Instruments.

DMA is originally a system for measuring resonance frequency of samples by directly fixing the solid samples in two arm units and vibrating the arms. Accordingly, there were many cases in which samples became soft with the rise in temperature like prepregs and changed easily, so that measurements could not be made without resonance. The measurement method was modified to use aluminum plate so that the sample resonated even if the prepreg became soft.

The method of fixing the sample after the modification is shown in Fig. 9. The prepreg was sandwiched between two aluminum plates at the center. The state of change in rigidity when the two aluminum plates adhered to the prepreg before and after the prepreg cured was evaluated.

The sample was fixed by the method described above. The resonance frequency of the sample was measured with the heating process. An example of the measured results is shown in Fig. 10. This is a graph showing the resonance frequency of the sample made from prepreg and aluminum plates in time series when the temperature was raised up to 120 ˚C at a heating rate of 1.0 ˚C/min and was retained at 120 ˚C for 180 min. As shown in Fig. 10, the intersection of the tangent of the part at which the resonance frequency of the sample changes abruptly and the tangent of the part after the change in resonance frequency is the curing point of the resin in prepreg.

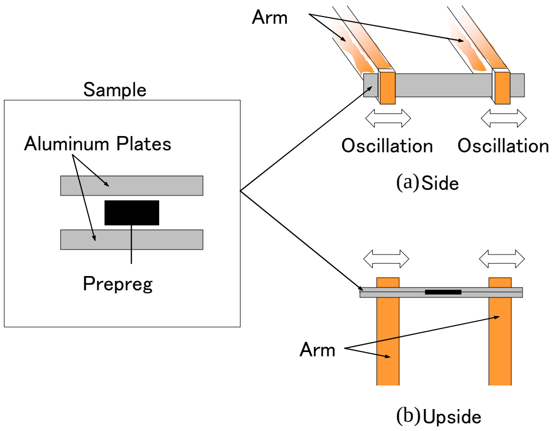


Fig. 9 Method of fixing DMA test specimen

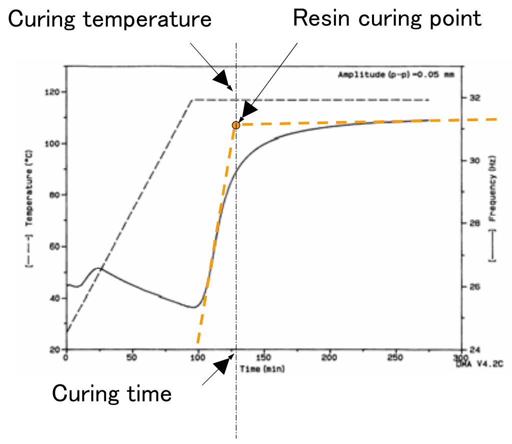


Fig. 10 An example of the DMA measured results

4.4 Acquisition of parameters (S, T1) for calculating the curing temperature

To confirm the effectiveness of the curing temperature calculation method according to this study, M60J/ epoxy-based resin prepreg was used and the parameters S and T1 required for calculating the curing temperature were determined.

Table 3 shows the selected heating process taken as test condition. The following cases have been considered: heating rate is varied systematically (No. 1 to 6); temperature duration enters during heating (No. 7 to 10); and at this stage, the temperature and time vary. Table 4 shows the results of measurement of curing point in relation to the heating process shown in Table 3. The size of the prepreg specimen used in the measurements was 2 mm x 2 mm x 0.1 mm (2 ply), and its mass was 2.3 mg.

Based on the method of calculating curing temperature, the relationship between the threshold temperature value T1 and the area S, is shown in Fig. 11. From this figure, if T1 is set as 73 ˚C, then the area S becomes 2900 ˚C・min for all the results of the measurement. These results indicate that the resin in the base material mainly starts the curing reaction from 73 ˚C, does not depend on the heating process, and curing is completed from that point when heat equivalent to 2900 ˚C・min is received. Moreover, since the point of intersection is observed in Fig. 11, the assumptions used in this method are shown to be valid, thus confirming the effectiveness.

Table 3 Heating pattern

No	Heat Rate (℃/min)	Duration (℃)/(min)	Heat Rate (℃/min)	Duration (℃)/(min)
1	0.2	120 / 180	–	–
2	0.3	120 / 180	–	–
3	0.4	120 / 180	–	–
4	0.5	120 / 180	–	–
5	0.8	120 / 180	–	–
6	1.0	120 / 180	–	–
7	1.0	80 / 60	1.0	120 / 180
8	1.0	80 / 30	1.0	120 / 180
9	1.0	70 / 30	1.0	120 / 180
10	1.0	90 / 60	1.0	120 / 180

Table 4 Base material curing point (M60J/ epoxy-based resin)

No	Curing temperature (℃)	Curing time (min)
1	106.2	409.5
2	113.8	299.0
3	120.0	239.6
4	120.0	209.1
5	120.0	146.8
6	120.0	129.7
7	120.0	184.0
8	120.0	155.4
9	120.0	186.2
10	120.0	176.8

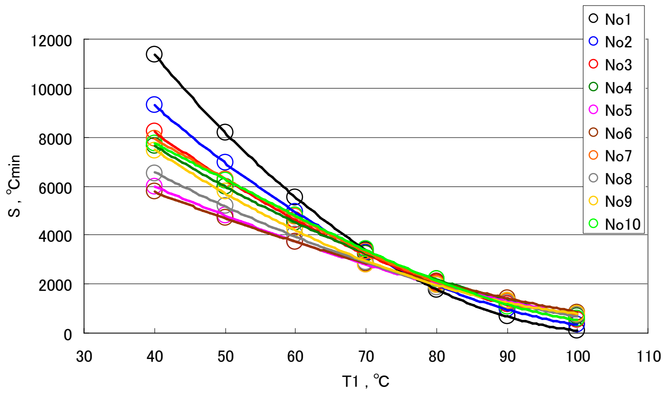


Fig. 11 Relationship between S and T1

4.5 Curing temperature analysis

Using the curing temperature calculation parameters T1 and S, analysis software for determining the base material curing temperature from arbitrary temperature history was developed.

From the settings screen of Fig. 12, the values of T1 and S for the prepreg used are entered in the block. In addition, if any arbitrary temperature history is taken as input data, then the curing temperature will be output as shown in Fig. 13. The results of curing temperature distribution found from this software from the temperature distribution determined by heat transfer analysis are shown in Fig. 14.

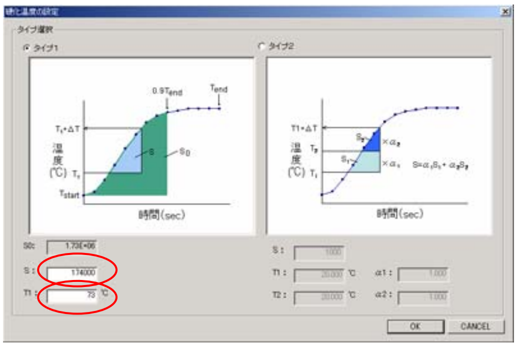


Fig. 12 Settings screen of curing temperature analysis software

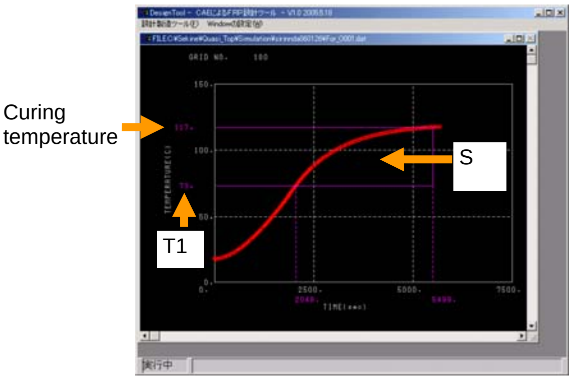


Fig. 13 Output of curing temperature by curing temperature analysis software

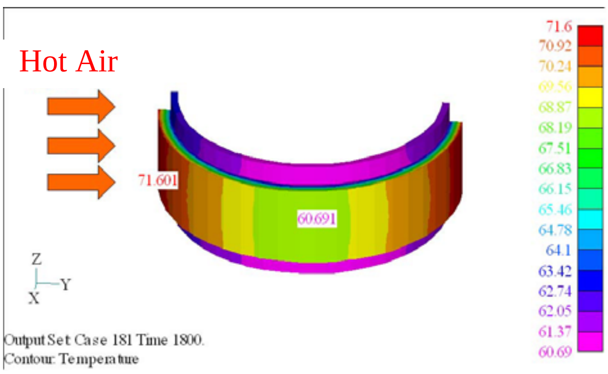


Fig. 14 Base material curing temperature distribution

5. Thermal deformation analysis technique during molding

The mold used for molding is modeled in addition to the molded body in thermal deformation analysis during molding. In this way, thermal deformation analysis technique that can also consider the effects due to thermal deformation of mold was developed. Details are given below.

5.1 Overview

During the thermoset molding of CFRP, the resin in the base material becomes soft due to heating of the base material until the resin cures; moreover, the mold used in the molding deforms due to heat when heated, therefore, the base material deforms following the thermal deformation of the mold. For this reason, the dimensions of the molded body differ from the designed values. For instance, when a cylindrically-shaped molded body as shown in Fig. 15 is thermoset molded, if the heating of the mold is uniform all over, the mold deforms uniformly due to the heat. If heating is non-uniform, the thermal deformation is also non-uniform, and the shape becomes strained. In case of the latter, not only will the dimensions of the molded body change, but the thermal strain will also become non-uniform.

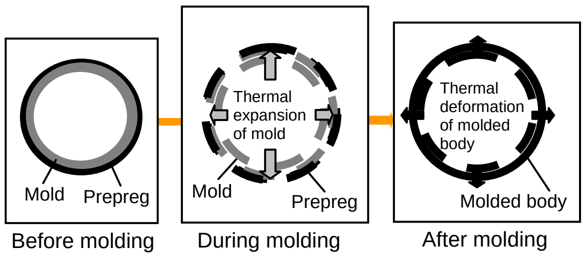


Fig. 15 General sketch of thermal deformation that occurs during thermoset molding

5.2 Thermal deformation analysis during molding

In the present study, an analysis model was developed considering the effects of thermal deformation of die, by adding the coefficient of thermal expansion of the mold to the coefficient of thermal expansion of the base material in the analysis model of the molded body in order to perform the thermal deformation analysis of the molded body considering the effects due to the thermal deformation of the mold.

The developed analysis model is shown in Fig. 16. The laminate configuration of this model is shown in Table 5. The analysis model at this stage was made by solid elements. The number of solid elements was 5280, and the number of nodes was 6075. Thermal deformation analysis was performed taking the heat transfer analysis results of Fig.17 as the temperature load conditions. The results of analysis at this stage are shown in the form of thermal strain contour diagram in Fig. 18. Figure 18(a) shows the analysis results considering the effects of thermal deformation of mold, while Fig. 18(b) shows the analysis results not considering the mold. It can be observed that the thermal strain changes when the effects of thermal deformation of the mold are considered.

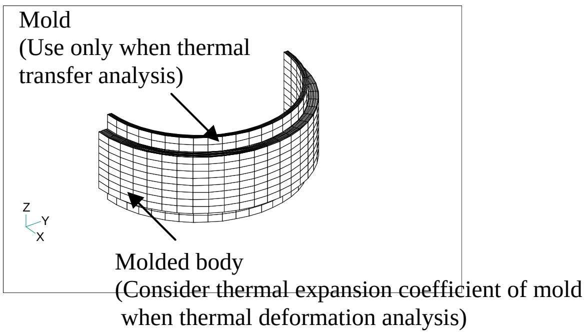


Fig. 16 Thermal deformation analysis model of molded body considering thermal deformation of mold

Table 5 Laminate configuration of thermal deformation analysis model

inner skin(90/0/0/90)(M55J/Epoxy)
→honeycomb core(Al1/4-5052-.001P t=15.1mm)
→outer skin(90/0/0/90)(M55J/Epoxy)

*cylinder circuit direction is 0° direction

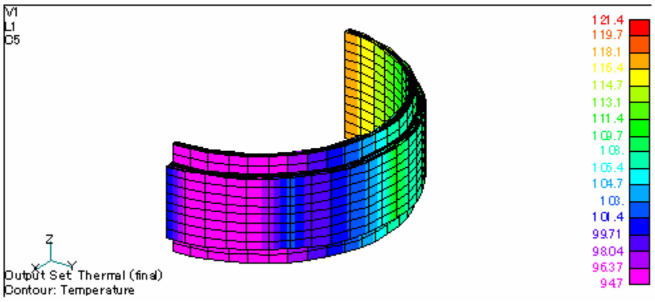
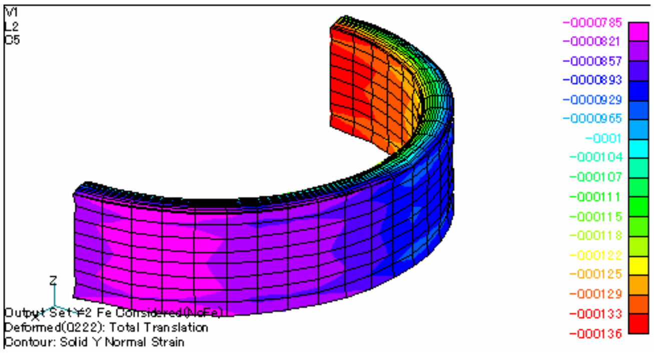
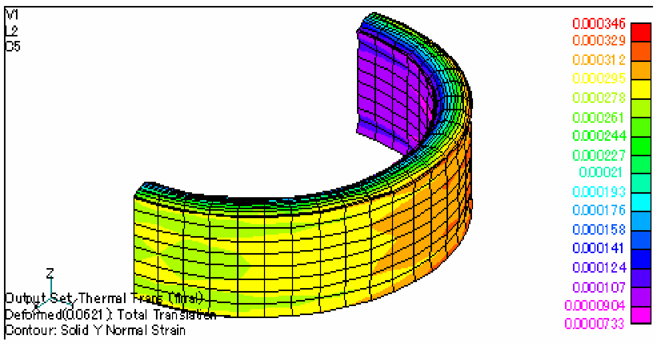


Fig. 17 Temperature boundary conditions



(a) When the effects of thermal deformation of the mold are considered



(b) When the effects of thermal deformation of the mold are not considered

Fig. 18 Contour of thermal strain along the circumference of cylinder

6. Conclusions

Advanced composite materials such as CFRP possess many beneficial characteristics that are not present in other structural materials, and an expansion in its applications are anticipated. However, because of the thermal strain and residual thermal stress that accompany heating molding during the thermoset molding process, which is its main method of manufacture, the molded body deforms or breaks, or the design strength may not be realized. In view of such issues, there were constraints in its use in large complex structures because molding this material with high accuracy was difficult.

To resolve such problems, an analysis simulation was developed in this study that can consider not only mechanical design aspects of the molded body, but also process dependency in thermoset molding during the design stage of CFRP. In this analysis simulation, the thermoset molding process was classified into the three stages of heating, curing and thermal deformation, and each of these were developed as heat transfer analysis during molding, curing temperature analysis, and thermal deformation analysis during molding, respectively. The conclusions arrived at as part of the results of this study are given below.

- To analyze easily the complex heat transfer phenomena that occur when large CFRP structures are made by thermoset molding, a heat transfer analysis technique was established wherein the product of the apparent heat transfer coefficient and environmental temperature within the molding apparatus is taken as heat input.

- To determine the temperature at which the resin in the base material cures from the temperature history added to the base material in case of thermoset molding, the fixed quantity of heat necessary for curing the resin was studied and the characteristics data was matched with the heat quantity determined from arbitrary temperature history, and the technique for determining the curing temperature was developed.

- By preparing an analysis model of the molded body including the mold used for molding, thermal deformation analysis technique was established that considered also the effects of thermal deformation of mold on the base material in case of thermoset molding.

ACKNOWLEDGEMENTS

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