Development of CAE system for predicting the heat crack in BMC compression molding

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Abstract

BMC (Bulk Molding Compound) having an excellent mechanical property, is a fiber reinforced thermosetting resin and is mainly formed in high temperature compression molding. It has widely been applied in the field in which mass production is required such as housing equipment for example and more recently for bath-tubs. However, after manufacturing a heat crack that is a molding defect often arises at the point where the cross section differs, such as a corner. During BMC compression molding, temperature and cure distribution in the material become complicated. At some points, surplus thermal strain or cure strain due to volume change during solidification of the resin is generated and a heat crack arises because of these strains. The purpose of this study is to construct the model of two-dimensional thermoelastic analysis by the finite element method considering inhomogeneous temperature and cure distribution and to develop a CAE system for predicting the heat crack. In this report, first, the analysis method was proposed. Secondly, numerical results in corner cross section; especially discussed is the degree of cure and maximum principal strain. Next, the mold temperature that was one of the forming parameter was changed and these results were discussed. Finally, it was concluded that the local strain could be suppressed by controlling the forming parameter.

1 Introduction

BMC has excellent mechanical properties and the high temperature compression molding is mainly on the molding. It has widely been applied in the field, which requires the mass production of housing equipment and so on.
During BMC compression molding, the temperature distribution in the material becomes inhomogeneous, since the material is rapidly heated from room temperature to the mold temperature. Also, the degree of cure distribution becomes complicated in order to transform by the polymerization reaction. By this heterogeneity, the volume change of thermal strain and cure strain is different in the place. The heat crack is a molding defect which often arises. Since this crack influences the molding parameter, the CAE system is required in order to efficiently decide the molding parameter which inhibits the crack.

In the past, Temperature and degree of cure distribution in the material during the cure process [1] have been predicted, furthermore residual stress distribution and deformation of warpage, deflections after cooling process [2][3] have been obtained. However, the aspects in the material after the molding considered heterogeneous thermal deformation and cure shrinkage in cure process have not been developed. The purpose of this study is to establish a system which can estimate the aspect in the material after the cooling process, consider various phenomena of the cure process and to investigate the generating factor of heat cracks.

2 Finite element formulation

2.1 Modeling

BMC compression molding consists of several stages: ensuring the material perfectly fills the mold, receiving heat transfer from the mold after it is charged in the mold, the cure process until the material perfectly cures, transmitting the heat sufficiently, and the cooling process until it cools to room temperature after the mold release. In each process, phenomena such as material flow, heat transfer, volume change, phase transformation and exothermic reaction are all related. Therefore, it becomes difficult to predict the aspect in the material after the forming. Then, following modeling was carried out in this study. Because the crack can be sufficiently observed in thickness direction cross section, we assumed two dimensional or plane strain problem. Since the material flow process is shortened in comparison with the forming time, we assumed that the flow does not influence the aspect in the material after forming, that the flow process can be neglected and that the material is regarded as having elasticity from the moment it is filled. In addition, since both fiber content and fiber length are low for BMC used in this study, the material was assumed the homogeneous isotropy.
2.2 Thermal transfer formulation

The thermal transfer analysis was carried out in order to obtain temperature distribution in the material. To solve two-dimensional non-steady heat transfer equation with the exothermic reaction term, it was made discrete by the finite element method.

\[
\begin{align*}
\left(\frac{1}{2}[k] + \frac{1}{\Delta t}[c]\right)\{T(t + \Delta t)\} \\
= (-\frac{1}{2}[k] + \frac{1}{\Delta t}[c])\{T(t)\} + \{f\}
\end{align*}
\]

\[\begin{align*}
[k] &= \int k(\frac{\partial N^T}{\partial x} \frac{\partial N}{\partial x} + \frac{\partial N^T}{\partial y} \frac{\partial N}{\partial y})dx\,dy \\
[c] &= \int \rho C_p N^T N \, dx\,dy \\
\{f\} &= \int \dot{Q} N^T \, dx\,dy
\end{align*}\]

Where, heat rate is obtained from reaction subroutine accurately expressed the unsaturated polyester resin (fumaric acid) / styrene polymerization reaction [4].

\[
\dot{Q} = \dot{Q}_M + \dot{Q}_O
\]

\[
\begin{align*}
\dot{Q}_M &= [CM] (k_{MM}[CR_M] + k_{OM}[CR_O]) q_M \\
\dot{Q}_O &= [CO] (k_{MO}[CR_M]) q_O \\
[CR_M] &= [CR] r_{OM}/(1 + r_{OM}) \\
[CR_O] &= [CR] / (1 + r_{OM}) \\
r_{OM} &= k_{OM}[CM]/k_{MO}[CO]
\end{align*}
\]

Where, \( \dot{Q}_M \) and \( \dot{Q}_O \) are styrene and fumaric acid polymerization reaction heat, respectively, \([CM]\), \([CO]\) styrene, fumaric acid remainder monomer concentration, \(q_M, q_O\) styrene, fumaric acid activation energy, \([CR_M]\), \([CR_O]\) styrene, fumaric acid reaction concentration respectively. \([CR]\) is fumaric acid / styrene equilibrium radical concentration, \(k_{MM}, k_{OM}\) and \(k_{MO}\) is styrene
radical / styrene, fumaric acid radical / styrene and styrene radical / fumaric acid rate constant of reaction respectively. In addition, degree of cure $\beta$ is obtained from fumaric acid and styrene remainder monomer concentration.

$$\beta = 1 - \frac{([CO] + [CM])}{[CMO]}$$  \hspace{1cm} (2-3)$$

$[CMO]$ is initial fumaric acid / styrene monomer concentration. Since the material temperature is higher than the mold one by the exothermic reaction, heat transfer to mold was also calculated. In the cure process the calculation was repeated at time step $\Delta t=0.01$ by 360 seconds, in the cooling process at $\Delta t=0.1$ by the material became perfectly a room temperature. Thermal property used in this study is shown at Table 2-1.

<table>
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<tr>
<th></th>
<th>BMC</th>
<th>Mold</th>
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<tbody>
<tr>
<td>$k$</td>
<td>$0.1 \text{ J/(m·sec·K)}$</td>
<td>$80.4 \text{ J/(m·sec·K)}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$1.93 \text{ g/cm}^3$</td>
<td>$4.2 \text{ g/cm}^3$</td>
</tr>
<tr>
<td>$C_p$</td>
<td>$2.3 \text{ J/(g·K)}$</td>
<td>$3.5 \text{ J/(g·K)}$</td>
</tr>
</tbody>
</table>

### 2.3 Thermoelastic formulation

The thermoelastic analysis was carried out in order to obtain the deformation aspect in the material. The problem was the plane strain with thermal strain and cure shrinkage, it was made discrete by the finite element method.

$$[k]\{d\} = \{f_s\} + \{f_t\} + \{f_c\}$$  \hspace{1cm} (2-4)$$

$$[k] = \int_{\Delta} B^T D B dxdy$$

$$\{f_s\} = \int_{\Delta} N^T F ds$$

$$\{f_t\} = \int_{\Delta} B^T D \varepsilon_c dxdy$$

$$\{f_c\} = \int_{\Delta} B^T D \varepsilon_c dxdy$$

Where, since elastic property depends on degree of cure, it was approximated like Fig.2-1 by the straight line. Elastic property used in this study is shown at
Table 2-2. Also the elastic modulus before curing was obtained by the upper mold displacement of React Meter as mold pressure fluctuated, while it retained the material at 140° after the uncured material was laid in it. Cure shrinkage $\varepsilon_c$ showed the volume change during solidification, it was approximated by the upper mold displacement before and after cure of the material laid in React Meter.

Like the above, heat transfer and thermoelastic analysis were constructed, and corner cross section where the heat crack was comparatively easy to generate was calculated. The analysis parameter is shown in Table 2-3. Additionally flowchart of this system is shown at Fig.2-2.

![Fig.2-1 Approximation of elastic property.](image-url)

### Table 2-2 Elastic property

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>$E_{\text{solid}}$</td>
<td>$7200$ MPa</td>
</tr>
<tr>
<td>$E_{\text{fluid}}$</td>
<td>$560$ MPa</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$0.29$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$7.5 \times 10^{-5}$ 1/K</td>
</tr>
<tr>
<td>$\varepsilon_c$</td>
<td>$0.026$</td>
</tr>
</tbody>
</table>

### Table 2-3 Analyzing parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen thickness</td>
<td>4mm</td>
</tr>
<tr>
<td>Mold pressure</td>
<td>$5$MPa</td>
</tr>
<tr>
<td>Forming time</td>
<td>$360$sec</td>
</tr>
<tr>
<td>Mold temperature(upper/lower)</td>
<td>$130^\circ /130^\circ$</td>
</tr>
<tr>
<td>Room temperature</td>
<td>$20^\circ$</td>
</tr>
</tbody>
</table>
3 Numerical results and discussion

Since the crack seemed to arise by the local strain in the material, maximum principal strain was used as evaluation in this study. Maximum principal strain distribution after cure process of the mold temperature $130^\circ /130^\circ$ (upper/lower) is shown in Fig.3-1. This figure shows that high strain occurs in region A that is close to the boundary with mold and in region B in the material. Curve [a] which parallels the mold boundary is drawn in region A, straight line [b] to the thickness direction in region B (reference Fig.3-2.). Time history of degree of cure and principal strain on each line are shown at Fig.3-3 and Fig.3-4. While the difference of the point for degree of cure in not found in Fig.3-3 (a), it is found in (b) that degree of cure at the points (b2, b3) which is far from the mold is slow. Fig.3-4 (a) shows that strain rises at a3 and a4. Since there was no difference in the cure history, it was considered that this strain was caused not by the inhomogeneity in the material, but by the mold pressure began to greatly act.
from this points and by stretching the boundary. In Fig.3-4 (b) the strain rises at b2. Since the peak of the strain at b1 and b3 near b2 existed further than b2 in a past, it seemed to occur by straining b1 and b3 early. In addition, because the time difference of these strains corresponded with one of cure history in Fig.3-3 (b), it was considered that this was greatly due to the quantity of cure shrinkage, that is, slowness and fastness of the cure. From cure and strain history, the strain increases until cure is started and is stabilized when the cure finishes to some extent. This is directly due to the low of the elastic modulus in the uncured material. From the above, it was considered that strain increase of region A influenced the geometry of the products and increase of region B influenced the inhomogeneity of slowness and fastness of the cure in cure process.

The strain of region A can be restrain by heightening the mold temperature, hastening the cure and raising the elastic modulus. Also, in region B, the inhomogeneity can be restrained by slacking the temperature gradient of thickness direction, as the result the local strain can be prevented. From the above consideration, the analysis was carried out at the various mold temperature.
The effects of the maximum principal strain for mold mean temperature (the mean temperature of upper and lower mold) and mold temperature gradient (when upper mold temperature is high is defined as plus) after cure process is shown in Fig.3-5. (a) of this figure shows that the strain is reduced with the increase of the mold mean temperature and the temperature gradient. However, comparison of upper mold temperature near region A (the dotted line in Fig.3-5.(a)), the strain increased when the lower mold temperature was high. Also, (b) shows that the strain is reduced with increase of the mean temperature and with the decrease of the temperature gradient. The temperature gradient of thickness direction slacked by decreasing temperature gradient and seemed to suppress the strain. The decrease of the strain of when the mold mean temperature is higher in both regions, since the cure is early started in the higher temperature, is due to the reduction of the time in which the elastic modulus is low to make the strain increase. However, in this report, the analysis was carried out at the product thickness 4mm constant, it seemed to become the result of differing from the above since the change of the thickness influenced the temperature gradient in the material.

Fig.3-3 Degree of cure VS time
Fig. 3-4 Maximum principle strain VS time

4 Conclusions

The inhomogeneous aspect in the material in cure process can be expressed by using degree of cure as the parameter that shows phase transformation of BMC and by regarding the elastic modulus as degree of cure dependence. In addition, the local strain in the material that can cause the heat crack can be sufficiently restrained by changing the mold temperature that is the forming parameter.

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Fig. 3.5 Maximum principle strain VS mold temperature

References


