ESTIMATION OF RESIN FLOW FOR FRP BASE ON MPS METHOD

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1 Introduction
Because carbon fiber-reinforced plastics have the characteristics such as high strength and lightweight, they have been used in a wide range of fields such as automobiles and airplanes. The further increase in demand is expected in the future, and the capacity of high production is also needed to significantly reduce the time required for molding. The current molding method is categorized by the nature of the resin. The thermosetting resin is used for Resin Transfer Molding (RTM), and the thermoplastic resin is being carried out for press forming. The mechanical properties of FRP are dependent on the microscopic behaviors such as resin impregnation and void formation. It is difficult to estimate the behavior of the resin flow considering the microscopic structure. In order to solve the problem, the numerical analysis to estimate the resin flow in microscopic structures has carried out in various studies [1] [2] [3]. The analysis is based on 2D estimation of resin flow, however, the actual resin flow is 3D phenomenon. In this study, the 3D simulation of resin flow has been developed based on Moving Particle Semi-implicit (MPS) method which is one of the particle methods, and the occurrence of the non-impregnated parts into the fiber bundles is estimated considering the effects of surface tension and wettability on resin flow.

2 Numerical method
2.1 Governing equation
The governing equation for incompressible fluid, Navier-Stokes equation and Equation of continuity are given by the following equation (1), (2).

\[
\frac{Du}{Dt} = -\nabla P/\rho + \nu \nabla^2 u + g + A \quad (1)
\]

\[
\frac{Dp}{Dt} = 0 \quad (2)
\]

Where, \( \rho \) is the density, \( P \) is the pressure, \( v \) is the viscosity coefficient, \( u \) is the velocity, \( g \) is acceleration of gravity, \( A \) is external force term due to surface tension and wettability.

2.2 MPS (Moving Particle Semi-implicit) method
In the MPS method, the governing equation is discretized with the interparticle interaction model. In this model, it is necessary to consider a weight function calculated by the distance between the particles (3), (4).

\[
W(r) = \frac{r_i^3}{r} - 1 \quad (0 < r < re) \quad (3)
\]

\[
W(r) = 0 \quad (re \leq r) \quad (4)
\]

Figure 1 shows a description of the elements of the formula. In the equation, \( r \) is the distance between two particles and \( re \) is the effective distance for the interaction of particles.

![Fig.1 Effective distance (2D)](image)

The incompressibility of the corresponding particle \( i \) is expressed by \( n_i \), the sum of weight functions of particle \( j \) in effective distance in Eq.(5), when a constant mass of each particle. The corresponding particle\( (n_0) \) is a constant.

\[
n_i = \sum_{j \neq i} W(|r_j - r_i|) \quad (5)
\]
By using the value obtained by Eq.(5), the gradient, divergence and Laplacian are calculated in the following equations. It is MPS method flow. As the result, the governing equations (1) and (2) can be discretized as MPS method.

\[
\langle \nabla \phi_i \rangle = \frac{d}{n_0} \sum_{j \in \mathcal{N}_e} \frac{\phi_j - \phi_i}{|r_j - r_i|^2} (r_j - r_i) w(r_j - r_i) \tag{6}
\]

\[
\langle \nabla \cdot u \rangle_i = \frac{d}{n_0} \sum_{j \in \mathcal{N}_e} \left( \frac{(u_j - u_i)}{|r_j - r_i|^2} (r_j - r_i) w(r_j - r_i) \right) \tag{7}
\]

\[
\langle \nabla^2 \phi \rangle_i = \frac{2d}{\lambda n_0} \sum_{j \in \mathcal{N}_e} (\phi_j - \phi_i) w(r_j - r_i) \tag{8}
\]

2.3 Calculation of external force term

The external force term is calculated based on a method of exerting inter-particle potential force [4]. In this study, the inter-particle potential force function is calculated by using the following formula equations (9)(10).

\[
A = C_1 \sum p_1 (r) + C_2 \sum p_2 (r) \tag{9}
\]

\[
p(r) = - \left( r - r_0 \right)^2 \left( r_1 + r_1^2 / 2 + r_1 / 2 \right) \tag{10}
\]

where \( r \) is the distance between the particles, \( r_0 \) is the distance between the particles of the initial state, \( r_1 \) is the effective radius. Using the fluid inter-particle potential coefficient (\( C_1 \)) as surface tension and inter-particle potential coefficient between the fluid and solid (\( C_2 \)), Fig.2 shows a description of the elements of the formula.

Fig.2 Scheme of resin droplet

In this study, the fall of water droplets is simulated by changing the three types (Table 1) of potential coefficient \( C_1 \) to verify the validity of the proposed method. Figure 3 shows analysis result. It was observed that the spread width of a water droplet is smaller by increasing \( C_1 \). This result was noted that the proposed method works normally.

<table>
<thead>
<tr>
<th>Case</th>
<th>( C_1 ) (surface)</th>
<th>( C_2 ) (wettability)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>( 1.0 \times 10^7 )</td>
<td>( 1.0 \times 10^6 )</td>
</tr>
<tr>
<td>Case 2</td>
<td>( 7.0 \times 10^6 )</td>
<td>( 1.0 \times 10^6 )</td>
</tr>
<tr>
<td>Case 3</td>
<td>( 4.0 \times 10^6 )</td>
<td>( 1.0 \times 10^6 )</td>
</tr>
</tbody>
</table>

In the analysis, \( \rho \) is \( 1200 \text{kg/m}^3 \), \( \nu \) is 0.05, \( g \) is \( 9.8 \text{m/s}^2 \).
3 Estimation of wettability

3.1 Determination of potential coefficient

Each potential coefficient is an important factor to represent the surface tension and wettability, however, the value cannot be investigated completely by comparison with the actual behavior of the fluid. In this study, a three-dimensional model of the resin droplet is developed and compared with the droplet particle as shown in Fig. 4. By using the model, the optimal potential coefficient is determined. Furthermore, the relation between various kinds of fibers and the resin can be estimated only by changing the potential coefficient. Here, numerical analysis is carried out by using three types of $C_2$ to confirm the validity of the proposed technique.

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In the analysis, $\rho$ is $1200 \text{kg/m}^3$, $\nu$ is 0.05, $g$ is $9.8 \text{m/s}^2$.

3.2 Determination of potential coefficient

In Fig. 5, the clinging of resin on a fiber is different due to the effect of wetting parameter $C_2$. The tendency of affinity on the fibers increases with increasing of wetting parameter. In case 1, accumulated part of resin appears at the bottom side of the fiber due to the low value of wetting parameter. On the other hand, the resin is accumulated on the upper surface of fiber in case 3. The numerical results are similar to the actual phenomena. By using drip of the resin from a pipette that can adjust the capacity to the actual fiber, the evaluation of wetting behaviors can be performed with the actual behavior. The measurement of dripping behavior of resin can be performed with a high-speed microscope, and the relation between the contact angle of resin on fiber and wettability can be estimated. In order to estimate the correct value of wetting parameters, the parameter fitting with the measurement of dripping and numerical analysis is necessary. The proposed three-directional simulation is very useful for the parameter fitting because the parameter fitting is not enough with the conventional two-directional simulation.
4 Numerical analysis of resin flow in UD FRP

4.1 Periodic model

Figure 6 shows the microscopic structure of periodic alignment of fibers in UD composite. The resin flow analysis is carried out and the non-impregnate parts are estimated. Here, in order to clarify the effect of wettability of the fibers on the resin flow, three-dimensional resin flow analysis is performed. The geometrical parameters are shown in Table 3. Two types of the model are prepared by changing the wetting parameter $C_2$ in Table 4.

![Figure 6 Periodic model](image)

**Table 3 Parameter of periodic model**

<table>
<thead>
<tr>
<th>$l$ (μm)</th>
<th>$w$ (μm)</th>
<th>$h$ (μm)</th>
<th>$D$ (μm)</th>
<th>$l_f$ (μm)</th>
<th>$a$ (μm)</th>
</tr>
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<tbody>
<tr>
<td>45.0</td>
<td>75.0</td>
<td>24.0</td>
<td>10.0</td>
<td>150.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

In the analysis, $\rho$ is 1200 (kg/m$^3$), $\nu$ is 0.05, $g$ is 9.8 (m/s$^2$). Table 4 means of the coefficients $C_1$ and $C_2$.

**Table 4 Potential Coefficient**

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<td><strong>Case2</strong></td>
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![Fig. 7 Resin flow and non-impregnated area (Case1) (X-Z cross section)](image)
Results and Discussion (Periodic model)

As the numerical results of case 1 and 2, the different behaviors appear due to the effect of wetting parameter $C_2$. The distinguishing feature of the numerical results is that non-impregnated parts due to each resin flow are different. In case 1 (low wettability), non-impregnated parts appear behind the fibers toward flow direction in Fig. 7(b). On the other hand, the fibers are wrapped in resin flow in case 2 (high wettability) in Fig. 8(b).

In practice, inter-particle force between resin and fiber in case 1 is low, resulting in non-impregnated part is generated on the back side of the fiber with respect to the flow direction. On other hand, it isn’t generated by high inter particle force in case 2. The results confirm that the wetting parameters affect the impregnation of resin.

In order to estimate the detail of impregnation on the fiber, the spread width of resin is investigated as shown in Fig. 9. The results showed the wetting parameters affect the impregnation of fiber direction of resin. Consequently, in the case 2, the resin impregnated width behind the fiber is wider than that of case 1.

The width of resin impregnation is very important for RTM because determination of position of resin injection. In this future, it is necessary to clarify relationship between width of resin impregnation and difference in wettability.
4.3 Random model

Numerical analysis with random alignment model is carried out to investigate the effects of space and width of flow path between the fibers on the resin flow. The fibers are aligned irregularly in the actual molding. The geometrical parameters of the random alignment model are shown in Table 5. Two types of the model are prepared by changing the wetting parameter $C_2$ in Table 6. The diameter of a fiber is unified, and the width of the channel is set randomly.

![Fig.10 Random model](image)

In the random alignment model, the minimum proximity distance between fibers is 1.0μm as narrow path in Fig.10. The potential coefficients and other dimensions are the same of the periodic model. Figure 11 and 12 show the numerical results with the random alignment model.

**Table 5 Parameter of random model**

<table>
<thead>
<tr>
<th>l(μm)</th>
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Fig.11 Resin flow and non-impregnated area (Case1) (X-Z cross section)

(a) 0.0003 [s]
(b) 0.0009 [s]
(c) 0.0020 [s]
(d) 0.0026 [s]
4.4 Results and Discussion (Random model)

As shown in Figs.11 and 12, characteristic resin flow was discovered, though it wasn’t discovered in periodic model. This resin flow was confirmed around big space and narrow path in Fig.10. Around narrow path, the non-impregnated area tends to be generated as shown in Figs.11, 12. Furthermore, non-impregnated area continues to remain around narrow path in case 2. This result shows that each of the resin behavior in front and back of narrow path attributed to non-impregnation. In front parts, the resin doesn’t pass through between the fibers because of high interface potential force of both fibers as shown in Fig.12(b). Figure13 shows X-Y cross section of Fig.12(d) to investigate resin flow in back parts. From this result, resin particles in back parts were found to be moved toward fiber direction.

Fig.13 Resin flow and non-impregnated area (Case2 (d))

Comparing Fig.11(d) and Fig.12(d), whole impregnation tendency is different due to C2. In case1 (low wettability), non-impregnated parts appear at many parts around fibers. On the other hand, resin wraps around fibers in case2 (high wettability). The difference in this result depends on the behavior of the resin in a large space as yellow area in Fig.10. In case1, the resin isn’t able to remain in large space because of low inter-particle force applied to fibers around large space. The behavior becomes inception, then leads to excessive non-impregnation. However, the resin of case2 remains in the space due to the high inter-particle force (C2).

In the future, it is necessary to clarify relationship between resin impregnation and size of space among the fibers.
5 Conclusion

The 3D simulation of resin flow was developed based on MPS method, and the occurrence of the non-impregnated parts into the fiber bundles is estimated considering the effects of surface tension and wettability on resin flow. The two types of particles is considered to estimate the effects of surface tension and wettability with a three-dimensional droplet model. From the numerical results of resin flow around fibers in random alignment, the proposed method can represent the flow conditions even any resin and fibers by changing the potential coefficients.

References


