Experimental and simulation analysis of bubble deformation in foaming polypropylene

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Abstract

This paper investigates the bubble deformation in bubble growth using a self-made in situ visual injection molding device. The results show that the deformation degree of independent bubbles is kept within 0.015. Under the frame rate of 25 frames per second (FPS), it is found that adjacent bubbles with the same average diameter simultaneously pass through the deformation critical point, while adjacent bubbles with different average diameters can’t pass through the critical deformation point at the same time. The interaction in the process of adjacent bubble growth is simulated by finite element software, radial migration of bubbles is suppressed, the hoop stretch of bubbles is enhanced, and the deformation sequence of adjacent bubbles is determined by bubble radius and bubble pressure. On the basis of the bubble influence zone model and the bubble deformation model, a bubble deformation response model is established, used to reflect adjacent bubbles’ deformation response speed.

1. Introduction

Compared with unfoamed polymer materials, polymer foamed materials have the advantages of low density, low thermal conductivity, high specific strength, high impact energy dissipation, and good sound insulation. They have been widely used and play an essential role in the polymer industry [1–8]. For foaming materials, bubble structure is one of the main factors that determine the properties of foaming materials. Bubble deformation will lead to irregular bubble structure, and closed-bubble foamed plastics with regular structure have more advantages than foam plastics with irregular bubbles in elastic stiffness, yield strength, and energy absorption [9, 10]. The electrical conductivity and electromagnetic shielding properties of closed-bubble foam decrease with the change of bubble shape from spherical to polygonal and the increase of bubble size. When the bubble shape is polygonal, the percolation threshold only appears under the higher load of multi-walled carbon nanotubes [11, 12]. Hu et al.[13] founded that the closed-bubble foam with a spherical bubble shape has a good load-bearing capacity. When the bubble shape changes from spherical to polyhedral, the load-bearing capacity will decrease. The relative Young’s modulus and relative yield strength decrease rapidly with the increase of characteristic shape anisotropy in a specific range. In summary, bubble deformation will reduce the mechanical properties, electrical conductivity, and electromagnetic shielding properties of foaming materials. Therefore, it is vital to study the deformation mechanism and deformation law of bubbles to reduce the deformation of bubbles in foaming materials. It is crucial to improve the comprehensive properties of foamed products.

Tromm et al.[14] studied the filling phenomenon and the change of bubble structure of polystyrene/CO₂ system in high-pressure foam injection molding by in situ visualization technique. It is found that the filling pressure and its duration are the most critical parameters affecting the size and shape of nucleation bubbles in
the melt before mold opening. The higher the filling pressure and the longer the filling time of the melt in the mold filling process, the smaller the bubble size and the greater the bubble deformation. Zhang Lei et al. [15] established a three-dimensional mathematical model of incompressible, non-isothermal, and unsteady multiphase flow through numerical simulation and experiments. The effects of temperature field and velocity field on the evolution of bubble shape on the thickness section of the jet flow field are obtained. The deformation, rupture, and disappearance of bubbles with different initial sizes and positions in shear and fountain flow fields are predicted. The formation mechanism of pits, silver marks, and collapses on the surface of MFIM parts is revealed. Ataei et al. [16] studied the effect of viscosity distribution on bubble deformation by numerical simulation using the lattice Boltzmann method model. It is found that the change of viscosity reduces the deformation of bubbles under different capillary numbers.

In injection foam molding, the above bubble deformation can be avoided by selecting the appropriate injection molding process. For example, the secondary open mold foaming process can often eliminate the bubble deformation caused by resin flow. However, in bubble growth, a large amount of deformation is usually produced due to the interaction between bubbles. The study of the interaction between bubbles began with the fluid. Then the phenomenon of bubble deformation was observed and widely studied by scholars in the process of polymer foaming. Hallez et al. [17] studied the interaction between two spherical bubbles rising in a liquid. The resistance and lift of each bubble are analyzed. According to the physical description of the interaction, a simple model of the resistance and lift of each bubble is given. Michael et al. [18] studied the interaction between two deformable bubbles. The results show that the horizontally staggered bubbles are aligned due to the deformation caused by the interaction between the hydrodynamics and the bubbles, thus increasing the coalescence speed. Peng et al. [19] used the modified single-component multiphase lattice Boltzmann method to simulate the weak interaction, strong interaction, and interaction between adjacent cavitation bubbles. It is found that under the interaction of two bubbles, the interaction changes from strong to weak with the increase of the initial distance of bubbles. Yang et al. [20] studied the effect of the interaction between bubbles on the radial pulsation of bubbles and numerically simulated the cavitation bubbles by considering the model of interaction between bubbles through radiation pressure waves. The results show that the inhibition of amplification of bubble expansion ratio by bubble interaction mainly depends on ultrasonic parameters, bubble radius, bubble distance, and bubble number.

In these studies, researchers mainly studied the bubble deformation from the aspects of the injection molding process and resin rheological properties. Still, they rarely studied the deformation mechanism and deformation law caused by the interaction between bubbles. The purpose of studying bubble deformation is to provide a theoretical basis for reducing the bubble deformation and improving the quality of foamed materials in the actual injection molding process, so this paper directly studies the bubble deformation in the actual injection molding process with the help of in situ visualization technology. We explained the deformation mechanism of adjacent bubbles and simulated the changes in surrounding stress and displacement after the bubbles were subjected to the action of adjacent bubbles during the growth process by finite element software. Simultaneously, we simulated the effects of bubble size and intra-bubble pressure on the deformation of adjacent bubbles. In addition, based on the bubble influence area model and the bubble deformation model, a bubble deformation response model is established to reflect the speed of the bubble deformation response in the actual injection molding process.

2. Theoretical foundation

The research group [21] observed the rotation and deformation of the fibers with different characteristics around the growth bubble and found that the growth bubble had the effect of hoop stretch and radial migration on the surrounding resin. The mathematical models of bubble influence range and bubble deformation are established. The influence range of growing bubbles is calculated by the mathematical model of bubble influence range, which is calculated by equation (1).

$$r^* = r_{n+1} = (\sqrt{n + 1}) r$$  \hspace{1cm} (1)

where $n$ is the number of resin layers in the bubble influence zone and $r$ is the bubble radius. The deformation of adjacent bubbles is judged by equation (2).

$$r_1^* + r_2^* = L$$  \hspace{1cm} (2)

where $r_1^*$ is the influence range of bubble 1, $r_2^*$ is the influence range of bubble 2, and $L$ is the center distance between bubble 1 and bubble 2. When $r_1^* + r_2^* = L$, that is, the sum of the radius of influence of the two bubbles is equal to the distance between the centers of the bubbles, at this time, the influence areas of the two bubbles are tangent, and the bubbles reach the critical point of deformation and are about to deform.
3. Experiment

3.1. Materials and equipment
Polypropylene (L5E89) with an MFR $= 3.1$ g min$^{-1}$ was provided by China National Petroleum Corporation (Beijing, China). The foaming agent masterbatch was self-prepared [22].

An injection molding machine with visual function (TTI-205Ge, Dongguan Donghua Machinery Co., Ltd, China) was assembled, which observed the bubble deformation in injection molding, as shown in figure 1(a). Figure 1(b) shows the visualization mold developed and designed by our team [23]. Two transparent sapphire sheets were installed in the center of the mold fixing plate and the moving plate. High-speed microscopic cameras and light sources perpendicular to the sapphire sheet were installed on the mold fixing plate and the moving plate.

3.2. Injection molding experiment
Polypropylene and blowing agent masterbatch are blended in a ratio of 100:6, and the visual foam injection molding experiment was carried out according to the injection molding process in table 1.

3.3. Characterization of bubble deformation degree
The degree of bubble deformation [15, 24–26] is given by equation (3).

$$D = \frac{A - B}{A + B}$$  \hspace{1cm} (3)

The screenshot software was adopted to capture images from the visual video with 25 FPS frame by frame. The image analysis software was used to measure the bubble axis length A, B, and the bubble center distance L by measuring the pixels of the image [27]. A schematic diagram of the measurement of the A-axial and B-axial of a single bubble is shown in figure 2(a). Figure 2(b) shows the measurement diagram of the axis length and center distance of the adjacent bubbles.

3.4. Finite element simulation
3.4.1. Model setup

(1) Governing equation
Using the standard linear solid model [21] is shown in figure 3(a).
Boundary condition setting

A fixed constraint is added around the model to simulate the constraint of the mold on the foaming material, and a pressure load is applied inside the bubble to simulate the pressure provided by the gas in the bubble, as shown in figure 3(b).

Physical parameters of PP foaming

The physical parameters of PP foaming are shown in table 2.

### Table 2. Physical parameters of PP foaming.

| Density/g/cm³ | Poisson’s ratio | Young’s modulus/Pa | Shear modulus/Pa | Viscosity/Pa’s |
|---------------|----------------|--------------------|-----------------|---------------|
| 0.91          | 0.34           | 713                | 266             | 2020          |

(2) Boundary condition setting

A fixed constraint is added around the model to simulate the constraint of the mold on the foaming material, and a pressure load is applied inside the bubble to simulate the pressure provided by the gas in the bubble, as shown in figure 3(b).

(3) Physical parameters of PP foaming

The physical parameters of PP foaming are shown in table 2.

3.4.2. Finite element simulation of stress and displacement

Using the finite element software, the physical parameters [28–30] in table 1 are input into the corresponding interface, and the time was set to 1s. Firstly, the stress and displacement of resin around the growing bubble under the action of adjacent bubbles were simulated. Then the effects of gas pressure and initial radius of bubbles on bubble deformation are simulated, and the results are analyzed and discussed.
4. Results and discussion

4.1. Discussion and analysis of independent bubble deformation

In the actual foaming process of injection molding, independent bubbles will also produce slight deformation due to uneven growth, so we have made a statistical analysis of the deformation caused by independent bubble growth.

Figure 4 is a video screenshot of the process of independent bubble growth. The independent bubbles are approximately circular and do not appear macroscopic local concave deformation during the entire growth process. Figure 5(a) shows the deformation degree ($D$) distribution of independent bubbles with time. It can be seen from the figure that the deformation degree ($D$) of independent bubbles is basically maintained within 0.015 (remove three non-repeatable points). During the unrestrained growth of bubbles, the deformation degree changes with growth time, and the bubble deformation does not have a steady growth trend. It changes randomly (shown in figure 5(b)). Therefore, to eliminate the error caused by bubble deformation in the process of free growth, $D = 0.015$ is used as the symbol of deformation degree. In the follow-up study, keeping the deformation degree above 0.015 and maintaining stable growth is the analysis basis for evaluating the reliability of adjacent bubble deformation.

4.2. Discussion and analysis of adjacent bubble deformation

Based on eliminating the deformation error caused by independent bubble growth, the deformation of adjacent bubbles in growth is studied. Start timing from the appearance of the bubble, select the first two frames and the last two frames, and the last one second of the video observation screenshot when the bubble reaches the critical point of deformation. The frame rate of the video is 25FPS, and the time interval between two adjacent screenshots is 0.04s.

Figure 6 shows a screenshot of the video of adjacent bubbles with the same average diameter. The adjacent bubbles cross the critical point of deformation at 2.92s, and the bubble deformation becomes more and more severe with the growth of bubbles. The bubble appears to have apparent macroscopic deformation at 3.96s. Figure 7 is the deformation trend chart of adjacent bubbles counted in the video observation screenshot. Under
the frame rate of 25FPS, the axial length A and axial length B of bubbles in the video screenshot are measured frame by frame, and the deformation degree of bubbles is calculated. We find that the adjacent bubbles with the same average diameter pass the critical deformation point simultaneously. The time for each group of bubbles to cross the critical deformation point is different, mainly due to the different central distances of the adjacent bubbles.

Figure 8 is a video screenshot of the deformation process of bubbles with different average diameters. The large bubble crosses the critical deformation point at 3.04 s, and the small bubble lags 0.08 s relative to the large bubble and crosses the critical deformation point at 3.12 s. The deformation of the two bubbles became more and more serious with their growth, and the two bubbles of different sizes appeared to have obvious deformation at 4.04 s. Figure 9 shows the deformation trend of adjacent bubbles with different average diameters. It can be seen from figures 9(a) and (b) that the larger bubble first passes the critical deformation point, and then the small bubble crosses the critical deformation point, while in figure 9(c), the deformation order of bubbles is the opposite.
The statistical results show that at the frame rate of 25FPS, the adjacent bubbles with the same average diameter pass the critical deformation point at the same time. In contrast, the adjacent bubbles with different average diameters show that one bubble lags behind the other to cross the critical deformation point. The growth
power and resistance provided by the system control the growth of bubbles. The growing power of the bubble comes from the gas dissolved in the resin, which is provided for the bubble by diffusion. The resistance in the process of bubble growth mainly comes from the limitation of the mold, the surface tension of the resin, and the interaction between bubbles. Whether the effect of the mold on the foam is isotropic depends on the uniformity of the resin distribution in the mold. The effect of the mold on the foam is isotropic if the resin is uniformly distributed. The uniformity of resin distribution in the mold cavity is determined by the complexity of the shape of the cavity and the size of the part. The more complex the mold cavity and the larger the size of the part, the worse the uniformity of resin distribution. At the same time, the larger injection pressure will increase the flow speed of the resin in the mold cavity, thereby making the resin distribution more uniform. We carried out visualization experiments through high-pressure injection molding. The shape of the mold cavity used is a simple plane and the visual observation area is less than 1 cm², so the resin can be uniformly distributed in this area, so the effect of the resistance of the mold on the foam can be approximated as isotropic. The surface tension of pure polymers is only related to temperature and resin properties. However, the resin/gas mixture is used for foaming, and it can be seen from equation (4) that the surface tension of the resin/gas mixture is a function of the resin surface tension and gas content [31, 32].

\[
\gamma_{\text{mix}} = \gamma_{\text{polymer}} \left( \frac{\rho_{\text{mix}}}{\rho_{\text{polymer}}} \right)^4 (1 - W_{\text{gas}})^4
\]

Where \(\gamma_{\text{polymer}}\) is the surface tension of the resin, \(\rho_{\text{polymer}}\) and \(\rho_{\text{mix}}\) are the mass density of polymer and polymer/gas mixture, respectively, and \(W_{\text{gas}}\) is the mass fraction of gas absorbed in the polymer. From formula (4), it is known that the surface tension of the resin/gas mixture increases with the decrease of gas content. In the process of bubble growth, the gas in the resin continuously diffuses into the bubble, and the gas content in the resin around the bubble shows a gradient distribution. The gas concentration increases gradually from the bubble boundary to the outside. That is, the gas concentration on the bubble boundary is the lowest. The bubbles were dissolved back into the resin by higher injection pressure, and the gas was uniformly distributed in the resin and then foamed by the secondary mold opening process. For the adjacent bubbles with the same average diameter, the two bubbles consume the same gas, so the resin around the two bubbles has the same gas concentration gradient, so the growth power and surface tension of the two bubbles are the same. At this time, the total growth resistance and the growing power of the two bubbles are the same. Adjacent bubbles of the same size have the same physical properties and cross the critical deformation point simultaneously. For the adjacent bubbles with different average diameters, because the atmospheric bubbles consume more gas in the surrounding resin, the gas concentration of the resin around the atmospheric bubbles is less than that of small bubbles. That is, the growing power of large bubbles is less than that of small bubbles, and the surface tension of large bubbles is greater than that of small bubbles. The adjacent bubbles of different sizes have different physical properties, so they cannot cross the critical point of deformation simultaneously.

4.3. Analysis of finite element simulation results
4.3.1. Finite element simulation of stress and displacement of resin around independent and adjacent bubbles during growth

The stress and displacement of the resin around the bubble were simulated to reflect the hoop stretch and radial migration of the resin around the bubble. In the actual injection molding process, it is observed that the independent bubbles will not appear obvious deformation, but when other growing bubbles appear near the independent bubbles, the independent bubbles will deform obviously. Therefore, in the resin with a radius of 300 μm, we establish independent bubbles with an initial radius of 100 μm and adjacent bubbles with an initial radius of 100 μm and 50 μm, respectively, and apply 50Pa pressure to each bubble.

Figure 10 shows the stress cloud map of individual and adjacent bubbles. Figure 10(a) shows that the stress around the independent bubble is uniformly distributed in a ring. With the distance away from the bubble boundary, the stress of the resin gradually decreases. That is, the hoop stretch reduces. The stress distribution of the resin around the adjacent bubbles is uneven, and the stress at the adjacent positions of the two bubbles is much higher than that at other locations (as shown in figure 10(b)). Because the single bubble is subjected to uniform resistance of the same size around the growth process, for two bubbles that are close to each other, due to the interaction between the bubbles, the bubble produces the largest resistance at the adjacent proximal end.

Figure 11 shows the displacement cloud map of the resin around a single bubble and adjacent bubbles. The displacement of the resin around the independent bubbles is uniformly distributed, as shown in figure 11(a). For adjacent bubbles, due to the interaction between the bubbles, the radial migration of the bubbles is suppressed and the hoop stretching is enhanced, so the displacement distribution of the resin around the adjacent bubbles is not uniform and the resin displacement at the adjacent positions of the two bubbles is the smallest, the resin displacement at both ends of the bubble is the largest (as shown in figure 11(b)).
4.3.2. Effect of growth dynamics on the deformation of adjacent bubbles with equal diameter

In this section, a two-dimensional model of adjacent bubbles with equal diameter was established in a resin with a radius of 600 μm. The initial radii of the three groups of adjacent bubbles are all 100 μm, and the center distance of the bubbles is 300 μm. The pressure was applied to

1. 100Pa and 80Pa;
2. 100Pa and 90Pa;
3. 100Pa and 100Pa.

Figure 12 shows the stress and displacement of each point on the boundary of adjacent bubbles with the same diameter at different pressure, and the selection of points on the boundary of bubbles and bubbles is shown in figure 13. As shown in figure 12(a), the stress at point a and point c of Bubble1 increases with the increase of pressure inside Bubble2, but the stress at point c increases faster than at point a. In contrast, the stress at point b and point d of Bubble1 decrease with the increase of pressure inside Bubble2. The stress at all points on the boundary of Bubble2 increases with the increase of its internal pressure. As shown in figure 12(b), the displacement of Bubble1 at point a, point b, and point d increases with the increase of pressure inside Bubble2, while the displacement of point c decreases with the increase of pressure inside Bubble2. The displacement of each point on the boundary of Bubble2 increases with the increase of pressure. It is found that when the pressure of Bubble2 is less than that of Bubble1, the stress and displacement of each point on the boundary of Bubble1 are larger than that of Bubble2.

Table 3 shows the A-axis, B-axis, and the deformation degree (D) of the adjacent bubbles. The A1-axis increases with the increase of pressure inside Bubble2. The B1-axis decreases with the rise of pressure inside Bubble2. The D1 increases with the rise of pressure inside Bubble2. The A2-axis and B2-axis increase with the increase in Bubble2 internal pressure, and the D2 decreases with the rise in Bubble2 internal pressure. When the pressure applied to bubble2 is less than bubble1, the D2 is always greater than that of D1, and the deformation degree of the two bubbles is not equal until the pressure applied to bubble2 is equal to that of bubble1.
4.3.3. Effect of growth dynamics on the deformation of adjacent bubbles with different diameters

In this section, a two-dimensional model of adjacent bubbles with a radius of 100 μm and 80 μm was established, and pressures of (1) 100 Pa and 90 Pa; (2) 100 Pa and 100 Pa; (3) 100 Pa and 110 Pa; (4) 100 Pa and 120 Pa; (5) 100 Pa and 130 Pa; (6) 100 Pa and 140 Pa; (7) 100 Pa and 150 Pa; (8) 100 Pa and 160 Pa were applied to the adjacent bubbles.

Figure 14 shows the stress and displacement of each point on the boundary of adjacent bubbles with unequal diameters with different gas pressures, and the selection of points on the edge of bubbles is shown in figure 13. As shown in figure 14(a), the stress of Bubble1 at point a and point c increases with the increase of the internal pressure of Bubble2, while the stress of point b and point d decrease with the rise in the internal pressure of Bubble2. The pressure at all points on the boundary of Bubble2 increases with its pressure increase. The stress of each point on the boundary of Bubble1 increases with the increase of its pressure. As shown in figure 14(b), the displacement of Bubble1 at points a, b and d increases with the increase of the pressure of Bubble2, while the...
displacement of point c decreases with the increase of the stress of Bubble2. The displacement of each point on the boundary of Bubble2 increases with the rise in its pressure.

Table 4 shows the A-axis and B-axis and the deformation degree of adjacent bubbles with different gas pressures and different bubble radii. The A1-axis increases with the increase of Bubble2 pressure, the B1-axis decreases with the increase of Bubble2 pressure, and the D1 increases with the increase of Bubble2 pressure. The A2-axis and B2-axis increase with the rise of Bubble2 pressure, and the D2 decreases with the rise in Bubble2 pressure. With the rise of the pressure applied to Bubble2, the D1 increases while D2 decreases. When the pressure of Bubble2 is less than or equal to 130Pa, the D1 is less than that of D2, and when the pressure of Bubble2 is greater than or equal to 140Pa, D2 is less than that of D1.

It can be seen from sections 4.3.2 and 4.3.3 that the deformation sequence of adjacent bubbles is determined by the radius of bubbles and the gas pressure. When the radius of the two bubbles is equal, the deformation degree of the bubbles with relatively low gas pressure is larger. When the gas pressure of the two bubbles is equal, the deformation degree of the small bubble is larger. Still, as the internal pressure of the small bubble continues to increase to a certain value, the deformation degree of the two bubbles will be equal. When the gas pressure inside the small bubble continues to increase, the deformation degree of the atmospheric bubble will be larger than that of the small bubble.

4.4. Establishment of bubble deformation response model

The bubble radius and bubble center distance ($L^*$) when the adjacent bubbles reach the critical point of deformation are measured. Using the model of bubble influence region and model of bubble deformation, the size of the bubble influence region ($r_1^*$, $r_2^*$) is calculated and compared with $L^*$.

As shown in figure 15, the central distance of the bubble ($L^*$) is much less than the sum of the radii of the influence zone of the two bubbles ($r_1^* + r_2^*$) that is, the observable deformation of the adjacent bubbles in the actual injection foaming process requires varying degrees of overlap of the bubble influence zone before the bubble deformation can be observed. Therefore, to describe the relationship between the critical deformation distance ($L^*$) of adjacent bubbles and the influence range of bubbles in the actual injection molding process, the correlation between ($r_1^* + r_2^*$) and ($L^*$) was analyzed. When the bubble reaches the critical deformation point,
**r**^*_1^* + **r**^*_2^* is selected as the independent variable X and **L**^*_1^* is selected as the dependent variable Y for the scatter plot. According to the distribution trend of the scatter graph, we choose the linear function, quadratic function, and power function model to analyze the data (**r**^*_1^* + **r**^*_2^*, **L**^*_1^*). Figure 15 shows the fitting of function and experimental data. As shown in Table 5, the adjusted R^2 of the linear function, quadratic function, and power function all reach more than 0.90, and they all can describe the functional relationship between **L**^*_1^* and **r**^*_1^* + **r**^*_2^*. However, because the quadratic coefficient of the quadratic function is negative and the opening of the function is downward, it shows that the influence zone of the bubble does not increase with the increase of the bubble radius, which is not consistent with the actual situation. The standard estimation error of the linear function is

![Figure 15](image15.png)

**Figure 15.** Comparison between **L**^*_1^* and **r**^*_1^* + **r**^*_2^* when adjacent bubbles reach the critical point of deformation.

![Figure 16](image16.png)

**Figure 16.** Comparison between numerical results and experimental results.

| Function   | Adjusted R^2 | Standard estimation error | Standardized coefficient | Significance  |
|------------|--------------|---------------------------|--------------------------|--------------|
| Linear     | 0.984        | 39.376                    | Coefficient of the first order 0.372 | P < 0.001 |
|            |              |                           | constant 244.421          | P < 0.001 |
| Quadratic  | 0.988        | 34.460                    | Coefficient of the first order 0.460 | P < 0.001 |
|            |              |                           | Quadratic coefficient −2.132E-5 | P = 0.015 |
|            |              |                           | constant 175.179          | P < 0.001 |
| Power      | 0.974        | 0.060                     | Exponential coefficient 0.701 | P < 0.001 |
|            |              |                           | constant 4.900            | P < 0.001 |

Table 5. Evaluation of function fitting results.
39.376, which is much larger than that of the power function, so the power function is chosen as the function model to describe the relationship between bubble center distance and bubble. The expression of the bubble deformation response model could be written in the form of equation (5).

\[ L^* = a \times (r_1^* + r_2^*)^b \]  

(5)

Where \( L^* \) represents the response speed of bubble deformation, \( r_1^* \) represents the radius of the influence zone of bubble 1, and \( r_2^* \) represents the radius of the influence zone of bubble 2. Compared with \( r_1^* + r_2^* \), \( L^* \) is smaller, indicating that bubble deformation can be observed only when the degree of resin superposition in the bubble influence zone is higher, indicating that the response speed of bubble deformation is slower; On the contrary, when \( L^* \) approaches \( r_1^* + r_2^* \), bubble deformation can be observed when the superposition degree of the bubble influence zone is low, indicating that the response speed of bubble deformation is fast.

### 4.5. Effect of injection temperature on bubble deformation response model

Figure 17 shows the fitting results of experimental values and power functions at injection temperatures of (a) 165 °C–185 °C and (b) 185 °C–205 °C. At injection temperatures of 165 °C–185 °C and 185 °C–205 °C, the deformation degrees of single bubbles were maintained within 0.017 and 0.018, respectively. After eliminating the error, it is found that the deformation response model of adjacent bubbles still conforms to the power function, and the adjusted correlation coefficient decreases slightly, but remains above 0.9, as shown in table 6. Parameter \( a \) of the deformation response model decreases with the increase of injection temperature, and parameter \( b \) increases with the increase of injection temperature. Considering the increase in injection temperature, reducing the solubility of the gas in the resin leads to a decrease in the growth kinetics of bubbles, and at the same time causes a decrease in the viscoelasticity of the resin, resulting in the fluctuation of parameters \( a \) and \( b \) with the change of injection temperature.

### 5. Conclusion

(1) At a frame rate of 25FPS, adjacent bubbles with the same average diameter have similar physical characteristics, so they cross the critical deformation point simultaneously. On the contrary, because the physical properties of adjacent bubbles with different average diameters are different, they can’t cross the critical deformation point simultaneously.
(2) The finite element simulation results showed that the deformation of the adjacent bubbles is caused by the uneven stress distribution around the bubbles due to the interaction between the bubbles. Bubble size and bubble pressure together determine the deformation sequence of adjacent bubbles.

(3) The Bubble deformation response model was established based on the bubble influence zone model and bubble deformation model, which is used to reflect the deformation speed of bubble interaction. The deformation response model of the bubble still conforms to the power function at different injection temperatures.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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