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TECHNICAL PAPER

Investigation into the overlapping sheet hydraulic bulge and its formability

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Abstract This paper presents the overlapping sheet hydraulic bulge, which can effectively improve the formability of low plasticity sheet metal by controlling or changing the force conditions and stress states of the target sheet. In the process, the material performance and thickness of the overlapping sheet play an important role in the formability of the target sheet. In this paper, the overlapping sheet hydraulic bulge process is theoretically analyzed. Also, limit bulging tests of no-overlapping sheet, different overlapping sheet materials and different overlapping sheet thicknesses are carried out by taking the aluminum alloy 2B06 as the research object, and the limit bulging heights of specimens are analyzed. Meanwhile, various aspects such as the specimen geometric shape and thickness distribution have been studied to verify the accuracy of the theoretical analysis. Finally, FEM is used to analyze the forming process to explain some results which were found in the test, and the comparison shows good agreement between the numerical results and test data. The results show that the overlapping sheet-forming method is beneficial for the formability attributes of target sheets. Deformation uniformity and the ability of plastic deformation can be improved by choosing higher strength coefficient *K*, larger work hardening exponent *n* and proper thickness of the overlapping sheet.

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Keywords Overlapping sheet · Hydraulic bulge · Target sheet · Aluminum alloy · Hollomon constitutive model · Formability

List of symbols

- P Hydraulic pressure (MPa)
- P_1 Reversed pressure in central area of target sheet (MPa)
- P_2 Reversed pressure in flange area of target sheet (MPa)
- K Strength coefficient of overlapping sheet (MPa)
- n Work hardening exponent of overlapping sheet
- t Overlapping sheet thickness (mm)
- K_1 Overlapping sheet strength coefficient (MPa)
- n_1 Overlapping sheet hardening exponent
- K_2 Target sheet strength coefficient (MPa)
- n_2 Target sheet hardening exponent
- σ_1 Stress of overlapping sheet (MPa)
- σ_2 Stress of target sheet (MPa)
- σ_ρ Radial stress of overlapping sheet (MPa)
- σ_θ Circumferential stress of overlapping sheet (MPa)
- σ'_ρ Radial stress of target sheet (MPa)
- σ_θ Circumferential stress of target sheet (MPa)
- σ_t Thickness stress of target sheet (MPa)

1 Introduction

In recent years, because of the requirements of weight reduction of structural components in the aerospace and automobile manufacturing fields, the applications of lightweight alloy sheets and profiles become wider and wider, such as aluminum alloy, magnesium alloy and titanium alloy, etc. However, most of the lightweight alloy materials are in low plastic deformation capacity and low elongation at room temperature (usually 5–20 %). The forming of these alloy sheets is a challenge to conventional forming methods. Therefore, in order to achieve such materials with high quality and low cost of manufacture, studies of new technology and new methods are needed [1–4].

For the methods of improving the ability of plastic deformation of sheet metals, one approach is to improve the composing structure and ingredients of the material by chemical means [5]. For example, some alloying elements such as manganese, titanium and niobium are added into molybdenum steel and nickel-based alloy, by which hot brittleness of steel is decreased and the ability of plastic deformation of materials is improved [6]. On the other hand, the plasticity of metal materials can also be enhanced by physical means. For example, plasticity can be improved by introducing heat, such as superplastic forming and warm/hot hydroforming [7, 8] or high speed forming processes such as impact hydroforming, explosive forming and electromagnetic forming [9–11]. In this paper, the method of changing loading mode of sheet metal is adopted to improve the formability of sheet metals. The goal of enhancing the ability of plastic deformation of materials is achieved by controlling or changing the force conditions and stress states of sheet metal [12–15].

The overlapping sheet hydraulic bulge process presented in this paper employs the use of same or different kinds of materials overlapped on one side of target sheet. Under the effect of hydraulic pressure, the overlapping sheet is formed together with target sheet, which is located on the liquid chamber side. So that the target sheet can be constrained and loaded with reverse pressure to achieve the biaxially-stretched and thickness compressed three-dimensional stress state. Also, the excessive thinning and fracture of the target sheet can be restricted effectively, and the microcrack caused by plastic deformation can be removed. Thus, the formability of the target sheet is improved. In the process, choosing the overlapping sheet with good plasticity can effectively constrain and control the deformation behavior of the target sheet, while the deformation rule between the target sheet and the overlapping sheet is identical or similar, the deformation uniformity and the formability of the target sheet can be improved correspondingly. The overlapping sheet hydraulic bulge process and stress states are shown in Fig. 1.

For the overlapping sheet forming method, Masanori et al. [16] used the rigid punch on overlapping sheets of the same material of pure aluminum in bulging test, and proved that the limit bulging height increased with the increasing thickness of the overlapping sheet by changing the thickness, and that the stress state of the target sheet and the overlapping sheet can lead to the changes of necking position by changing the contact conditions,

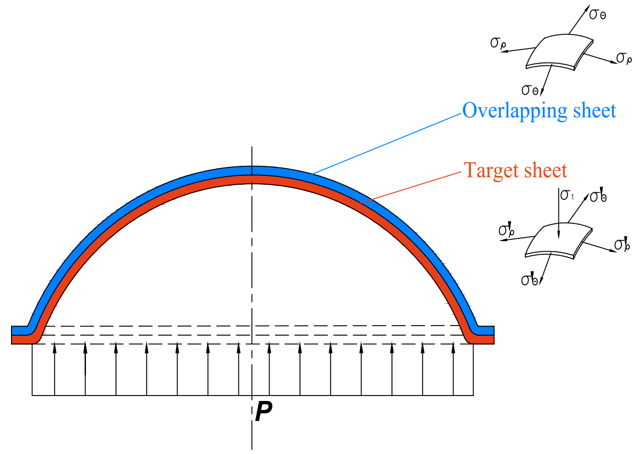
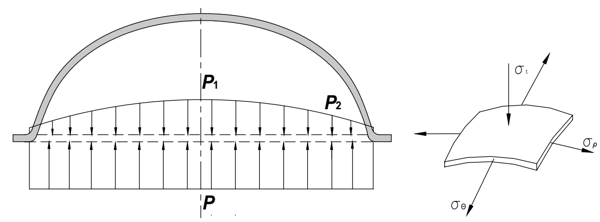


Fig. 1 The overlapping sheet hydraulic bulge process and stress states

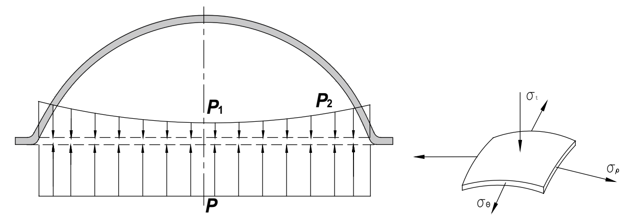
and the two measures mutually inhibited the development of necking, and thereby improved the formability of target sheet. Masashi et al. [17] studied the formability of aluminum sheet metal cemented by the overlapping sheet of copper sheet, and results showed that the formability with overlapping sheet performed better than that of the two sheet metals formed separately. Yourui Tao [18] successfully deep draw out the spherical shape part of FVSO812 with a thickness of 0.8 mm by packed-layer hot drawing (the FVSO812 sheet was coated by two layers of thicker metal sheets); the results showed that the packed-layer hot drawing could effectively prevent the generation of wrinkling and fracture and was a good forming method for high strength, low plasticity materials. Semiatin et al. [19] studied the forming limit on stainless steel clad aluminum without lubrication by experiment; the results showed that diffuse instability led to localized necking, and the unstable flow of the clad sheet material could lead to interface irregularities, which have been associated with local deformation, and then the local deformation determines the forming limit of clad sheet. Tseng et al. [20] obtained the overlapping sheets bulging limit diagram through bulge tests with Al/Cu overlapping sheets, determining its the forming limit for different thicknesses, and failure types such as localized necking and fracturing were predicted by the forming limit diagram. In this work, the overlapping sheet hydraulic bulge process is theoretically analyzed. Also, limit bulging tests of no-overlapping sheet, different overlapping sheet materials and different overlapping sheet thicknesses are carried out by taking the aluminum alloy 2B06 as the research object, and the formability of the target sheet was analyzed based on the Hollomon constitutive model. Finally, FEM is used to analyze the forming process to explain some results which were found in the test.

2 Analysis of the overlapping sheet hydraulic bulge

In overlapping sheet hydraulic bulge process, the reverse pressure provided by overlapping sheet, which is determined mainly by the material performance and thickness of the overlapping sheet, is constantly changing with the deformation of the overlapping sheet. The reverse pressure field distribution will influence the bulging specimen geometric shape and stress state of the deformation zone. Under the effect of hydraulic pressure P, assume that the two-layer sheet bulges from the lower upward, the reverse pressure field distribution on the target sheet can be divided into the following two cases: one case, the pressure in the center of the target sheet is higher than that close to the flange ($P_1 > P_2$), while the target sheet is formed by upper and lower pressure differences. Because the pressure difference in the center of specimen is lower than that close to the flange, the deformation is relatively smaller in the center zone, and that is relatively larger nearby the flange. Thereby the specimen geometric shape is approximately prolate ellipsoid and the stress state is shown in Fig. 2a). The other is that the pressure in the center of the target sheet is lower than that close to the flange ($P_1 < P_2$), the upper and lower pressure difference in the center zone and nearby the flange will lead to a short ellipsoid in specimen geometric shape and the stress state is shown in Fig. 2b).



(a) The reverse pressure distribution and stress state of target sheet (higher in center zone and lower nearby the flange)



(b) The reverse pressure distribution and stress state of target sheet (lower in center zone and higher nearby the flange)

Fig. 2 Geometric shape sketch and stress state of bulging specimen with different reverse pressure vector distribution of overlapping sheet

3 The overlapping sheet hydraulic bulge test

3.1 Test equipment and scheme

The test equipment is shown in Fig. 3. Diameter of the bulging die is Φ 100 mm. Material of target sheet is aluminum alloy 2B06 with thickness $t = 1.0$ mm. In order to compare the formability of the target sheet in overlapping sheet hydraulic bulge, hydraulic bulging tests of no-overlapping sheet, different overlapping sheet materials and different overlapping sheet thicknesses are carried out, respectively. Different materials used as overlapping sheet include aluminum alloy 2B06, 2024 and stainless steel SUS321. Mechanical properties of the materials are shown in Table 1. Sheet blank size is 190 mm × 190 mm. Hydraulic bulging tests were carried out on the self-developed 500KN sheet hydroforming equipment at Beihang University.

Fig. 3 Equipment of hydraulic bulging test

In the hydraulic bulging test of different overlapping sheet materials, three kinds of overlapping sheets 2B06, 2024 and SUS321 with thickness $t = 1.0$ mm were used; the material of target sheet is aluminum alloy 2B06 with thickness $t = 1.0$ mm. In the hydraulic bulging test of different overlapping sheet thicknesses, SUS321 overlapping sheet with thicknesses of $t = 0.5$, 1.0 and 1.5 mm (the thickness of 2B06 target sheet is 1.0 mm)

Table 1 Mechanical properties of overlapping sheet materials

Materials	Yield strength σ_s (MPa)	Tensile strength σ_b (MPa)	Strength factor K (MPa)	Strain hardening factor n	Elongation δ (%)	Elasticity modulus E (GPa)
2B06	71	234	275	0.16	10	66
2024	224	425	366	0.24	12	71
SUS321	230	520	890	0.45	40	200

Table 2 Hydraulic bulge test schemes

Test schemes		Overlapping sheet		Target sheet	
		Materials	Thickness (mm)	Materials	Thickness (mm)
1	Different overlapping sheet materials hydraulic bulge tests	2B06 2024 SUS321	1.0	2B06	1.0
2	Different overlapping sheet thicknesses hydraulic bulge tests	SUS321	0.5 1.0 1.5	2B06	1.0
3	No-overlapping hydraulic bulge tests	××	××	2B06	1.0

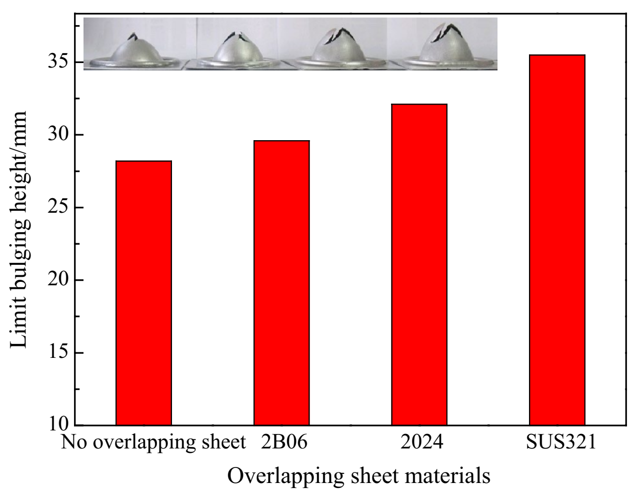


Fig. 4 Limit bulging height of bulging specimens with different overlapping sheet materials

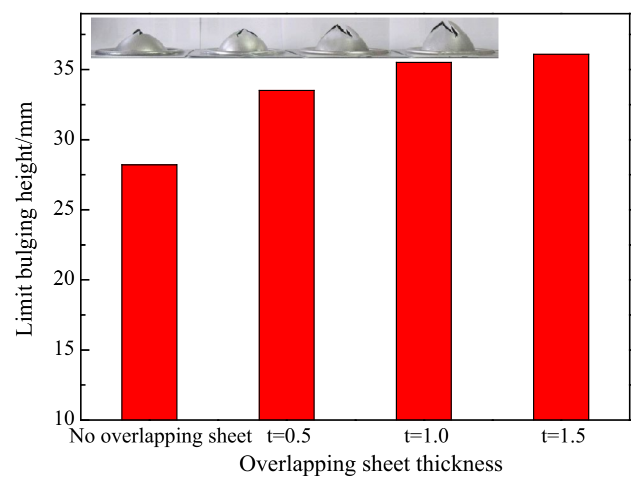


Fig. 5 Limit bulging height of bulging specimens with different overlapping sheet thicknesses

was chosen to carry out the bulge test. In no-overlapping sheet hydraulic bulging test, the material of target sheet is aluminum alloy 2B06 with thickness of 1.0 mm (as shown in Table 2).

3.2 Limit bulging height

The test results are shown in Figs. 4, 5. As can be seen, the fracture all appeared around the curvature peak areas and the forming limit is increased significantly by using the overlapping sheet forming method. In hydraulic bulge process, the intensifying pressure cannot be cut off immediately while the sheet metal is approaching its critical point of instability and still exists until the fracture, hence, resulting in a larger crack. When no overlapping sheet is used, the specimen limit bulging height is 28.2 mm. With the overlapping sheet material of 2B06, the specimen limit bulging height is 29.6 mm, a 4.96 % improvement in formability. With the material of 2024, the specimen limit bulging height is 32.1 mm, a 13.83 % improvement in formability. With the material of SUS321, the specimen limit bulging height is 35.5 mm, a 25.89 %

improvement in formability. By comparison, with the overlapping sheet material of SUS321, the formability of 2B06 target sheet is the best, followed by the overlapping sheet 2024 having better, and 2B06 having inferior limit height and formability among the three overlapping sheet materials. Besides, the limit bulging heights of target sheet with different overlapping sheet thicknesses are 33.5, 35.5 and 36.1 mm, respectively. Compared with the no-overlapping sheet hydraulic bulge, the formability of target sheet is improved by 18.79, 25.89 and 28.01 %, respectively. Thereby, the larger the thickness of overlapping sheet, the greater the limit deformation capacity of target sheet is improved.

3.3 Analysis of formability of target sheet

The aforementioned limit bulge tests show convincingly that the overlapping sheet forming method is beneficial for the formability attributes of target sheets. Next, the mechanism of formability improvement of target sheet is further investigated. In the overlapping sheet hydraulic bulge process, the thickness normal stress and the constraint function, which are applied to the target sheet by the overlapping sheet, play the key role for the improvement of target sheet formability. Meanwhile these factors are closely correlated with the mechanical performance parameters and thickness of the overlapping sheet. During this research, it has been assumed that the stress and strain of the overlapping sheet and target sheet satisfy the Hollomon constitutive model. The stress–strain relationship of overlapping sheet:

$$\sigma_1 = K_1 \varepsilon^{n_1} \quad (1)$$

where K_1 is overlapping sheet strength coefficient, n_1 is overlapping sheet hardening exponent.

The stress–strain relationship of target sheet:

$$\sigma_2 = K_2 \varepsilon^{n_2} \quad (2)$$

where K_2 is target sheet strength coefficient, n_2 is target sheet hardening exponent.

According to the stress–strain curve of material, in the overlapping sheet hydraulic bulge, the size of reverse compressive stress at any point is related with the deformation stage of target sheet and overlapping sheet. Since the thicknesses of overlapping sheet and target sheet are small, we can assume that the deformation of any point is similar. In this way, the deformation degree of overlapping sheet and target sheet can be calculated from the derivation of formula (1) and (2):

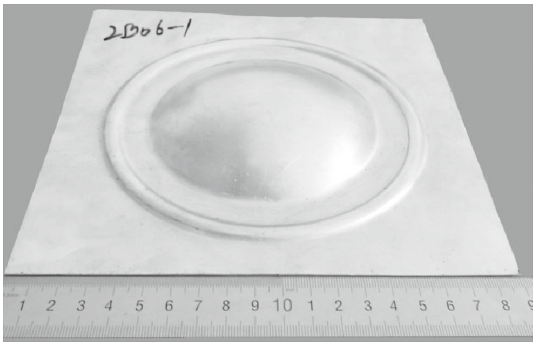
$$\sigma_1' = K_1 n_1 \varepsilon^{n_1 - 1} \quad (3)$$

$$\sigma_2' = K_2 n_2 \varepsilon^{n_2 - 1} \quad (4)$$

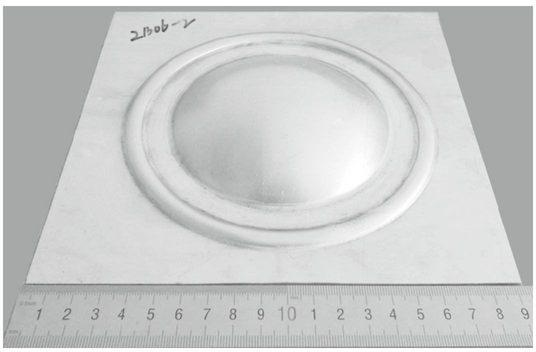
Assume that the overlapping sheet and the target sheet have the same work hardening exponent $n_1 = n_2$, when $K_1 > K_2$, the strength of overlapping sheet is higher and its deformation is more difficult than that of the target sheet under certain hydraulic pressure. Therefore, the target sheet is affected by the high reverse compressive stress from the overlapping sheet, and the reverse compressive stress increases with the increasing of thickness of overlapping sheet. So the formability of target sheet is improved correspondingly. Meanwhile the higher value of K of the overlapping sheet is, the greater the reverse compressive stress is and the better the target sheet can be formed. When $K_1 < K_2$, with low strength of the overlapping sheet and high strength of the target sheet, the deformation of the overlapping sheet is easier, the target sheet is affected by the low reverse compressive stress from the overlapping sheet and cannot facilitate the formability improvement.

If it is assumed that the overlapping sheet and the target sheet have the same strength coefficient $K_1 = K_2$, when $n_1 > n_2$, strain hardening effect, deformation resistance ability and deformation uniformity of the overlapping sheet is better than that of the target sheet. Under similar forming conditions, the deformation behavior of target sheet can be constrained by that of overlapping sheet, and the deformation uniformity and the formability of target sheet are also improved correspondingly. The higher value of n of the overlapping sheet is, the more significant the aforementioned constraint effect is and the better the target sheet can be formed. However, when $n_1 < n_2$, strain hardening effect of overlapping sheet is poor, the deformation is relatively easy, while deformation resistance of the target sheet is higher, the deformation is relatively difficult. So it can do little influence on the formability of the target sheet.

For the hydraulic bulge test with different overlapping sheet materials, specimens of aluminum alloy 2B06 with the same bulging height $h = 26$ mm are shown in Fig. 6. Profile shapes measured from the center vertex of the specimen are shown in Fig. 7. As shown in the figures, heights of the bulging specimens are similar, but the geometrical shapes are changed noticeably. With the overlapping sheet material SUS321, the bulging height of the specimen is the highest in the flange region, the deformation uniformity and the formability is the best, followed by the overlapping sheet 2024 having better and 2B06 having inferior formability among the three overlapping sheet materials. In no overlapping sheet hydraulic bulge, the curvature radius of bulging specimen around the peak is small, and the bulging height is low in the flange region, the specimen curvature radius gradients are changed noticeably. Using the overlapping sheet forming method, the distribution uniformity of curvature radius of bulging



(a) With overlapping sheet material 2B06



(b) With overlapping sheet material 2024

(c) With overlapping sheet material SUS321

Fig. 6 2B06 specimens with different overlapping sheet materials ($h = 26$ mm)

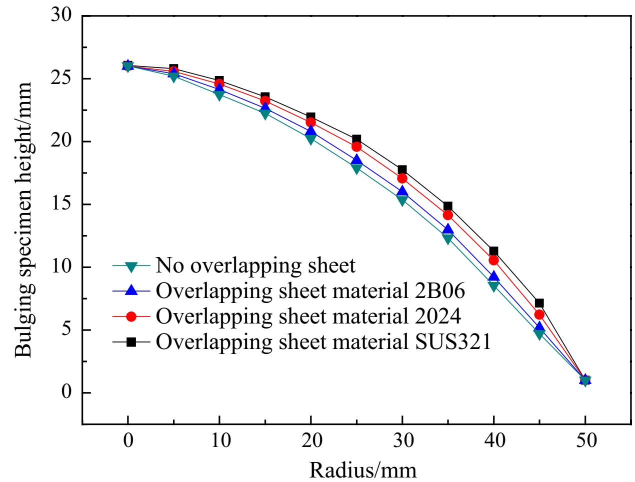


Fig. 7 Profile shapes of bulging specimens with different overlapping sheet materials ($h = 26$ mm)

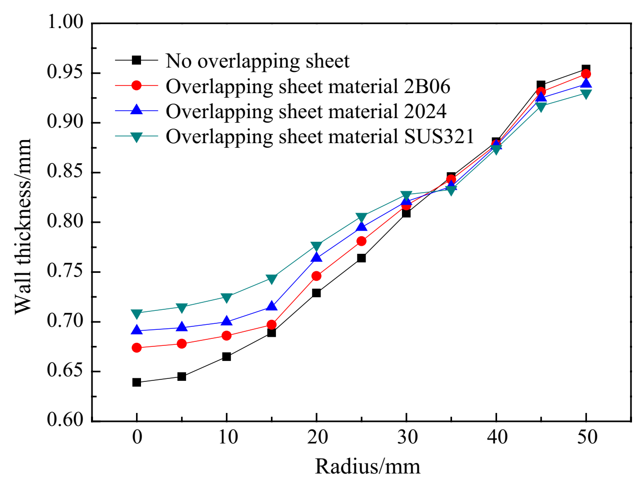
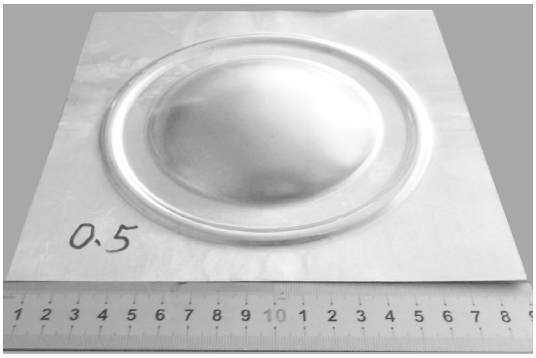


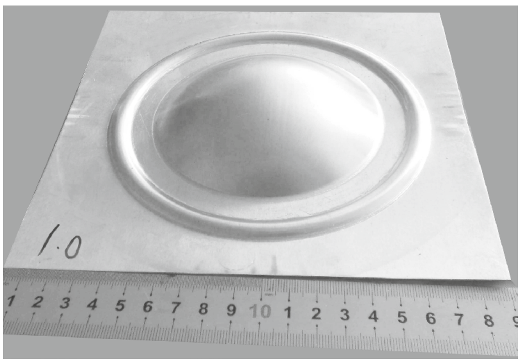
Fig. 8 Wall thickness distributions of bulging specimens with different overlapping sheet materials ($h = 26$ mm)

specimen is improved significantly (the same as the analysis in the second section). Wall thickness distributions of the aluminum alloy 2B06 specimen along the radial direction are shown in Fig. 8. The maximal thickness thinning all appeared around the peak of the specimens, and the thickness thinning of target sheet can be restrained obviously by the overlapping sheet function with improved wall thickness distribution uniformity. Therefore, during the forming process, choosing the materials of overlapping sheet with higher strength coefficient K and larger work hardening exponent n, which can improve the reverse compressive stress and can be more advantageous in constraining and controlling the behavior of the target sheet for distributing larger deformations and improving thickness uniformity, is helpful to improve the formability of target sheet.

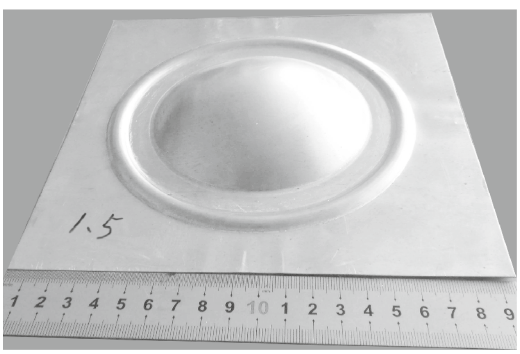
For the hydraulic bulge tests with different overlapping sheet thicknesses, specimens of aluminum alloy 2B06 with the same bulging height $h = 26$ mm are shown in Fig. 9. The specimen profile shapes and wall thickness distributions are shown in Figs. 10, 11, respectively. As can be seen, the minimum wall thickness of the bulging specimen is 0.639, 0.684, 0.709 and 0.718 mm, respectively. At the same bulging height and increasing thickness of the overlapping sheet condition, the deformation degree of target sheet near the flange region also increases



(a) With overlapping sheet thickness t=0.5mm



(b) With overlapping sheet thickness t=1.0mm



(c) With overlapping sheet thickness t=1.5mm

Fig. 9 2B06 specimens with different overlapping sheet thicknesses ($h = 26$ mm)

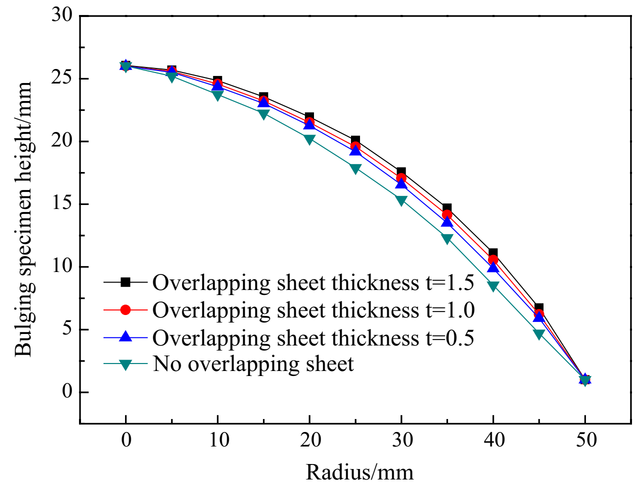


Fig. 10 Profile shapes of bulging specimens with different overlapping sheet thicknesses ($h = 26$ mm)

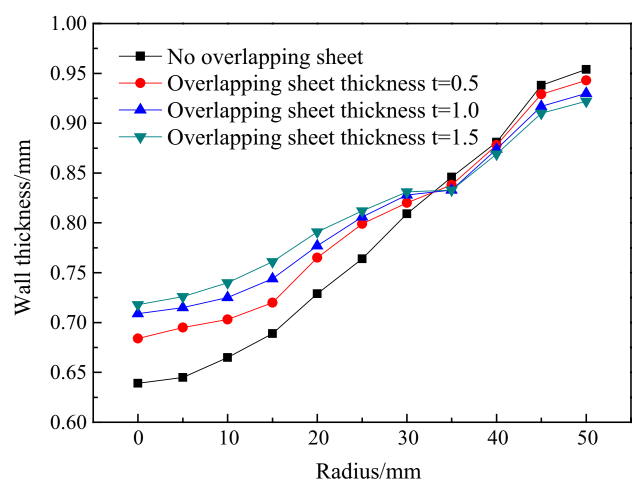


Fig. 11 Wall thickness distributions of bulging specimens with different overlapping sheet thicknesses ($h = 26$ mm)

correspondingly and hence, the formability is improved. At the same time, higher hydraulic pressure is also needed for increased thicknesses of overlapping sheets. The observed bulging pressures when the bulging height $h = 26$ mm are 10.5, 14.8, 17.3 and 19.6 MPa, respectively. Therefore, the reverse compressive stress on target sheet exerted by the overlapping sheet also becomes higher, which is conducive for improvement in the deformation uniformity and formability of the target sheet. But considering the production cost and forming difficulties, it is recommended that the thickness of the overlapping sheet be chosen as similar with the target sheet.

4 Simulation and analysis

4.1 FEM model

Finite element analysis software Dynaform 5.8.1/LS-DYNA3D was used in the numerical simulation. The finite element model is shown in Fig. 12. Diameter of the bulging die is Φ 100 mm. Material of target sheet is aluminum alloy 2B06 with thickness $t = 1.0$ mm. Different materials used as overlapping sheet include aluminum alloy 2B06, 2024 and stainless steel SUS321. In the simulations, the material models of the target sheet and overlapping sheet were obtained by the uniaxial tension tests. All tools were modeled using a rigid shell element. The overlapping sheet and the target sheet were discrete using the B–T shell element.

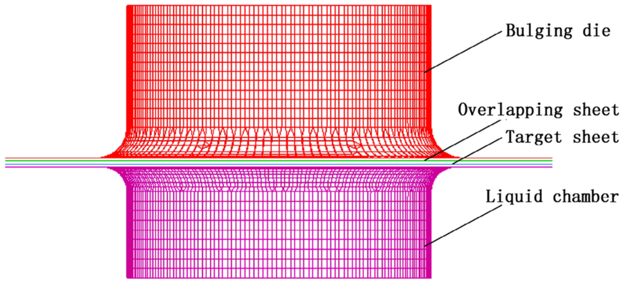


Fig. 12 FEM model

A friction coefficient of 0.10 was used for the interfaces between the target sheet and the overlapping sheet, and 0.12 for that between the target sheet and the liquid chamber and between the overlapping sheet and the bulging die, respectively.

4.2 Influence of overlapping sheet materials on target sheet

The main factors that affect the formability of target sheet in the practical application process of the overlapping sheet forming method include the material performance and thickness of the overlapping sheet. In the simulations of different overlapping sheet materials, the thicknesses of overlapping sheets are all 1.0 mm. The forming limits of 2B06 target sheet with different overlapping sheet materials are obtained and compared with the test data, as shown in Fig. 13, the numerical results agree well with test data. The fracture all appeared around the curvature peak areas. When no overlapping sheet is used, the limit bulging height obtained by numerical simulation is 27.8 mm, the test result is 28.2 mm. With different overlapping sheet materials, the specimen limit

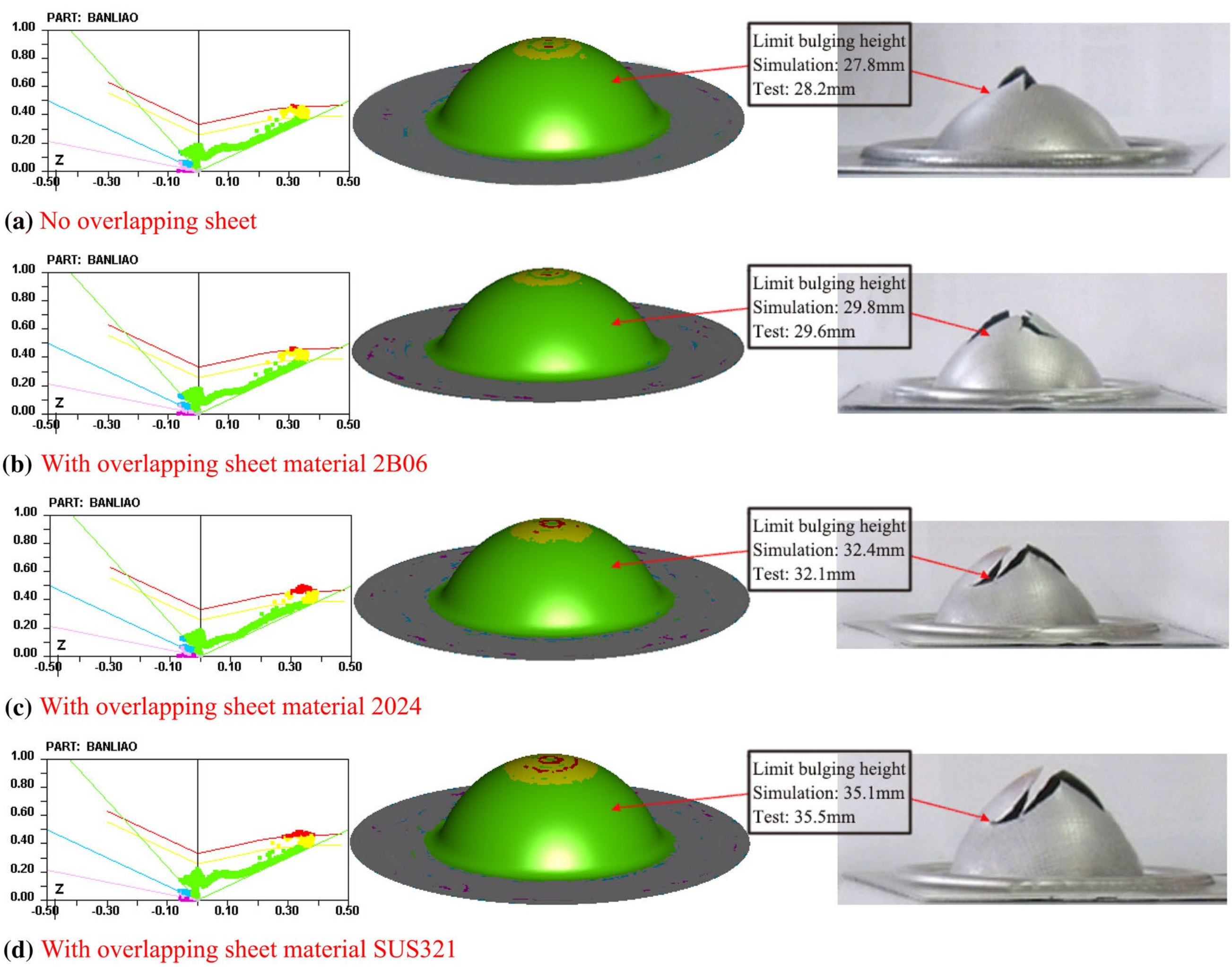
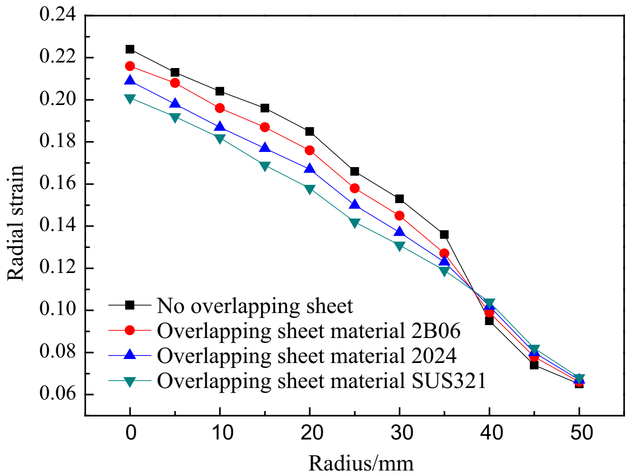
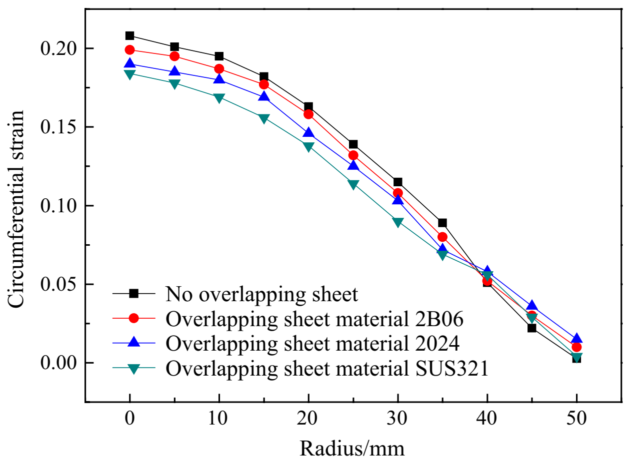


Fig. 13 Numerical and testing limit bulging height of 2B06 target sheet with different overlapping sheet materials



(a) Radial strain



(b) Circumferential strain

Fig. 14 Strain distributions of the specimen along the radial direction with different overlapping materials ($h = 25$ mm)

bulging height obtained by simulation is 29.8, 32.4 and 35.1 mm, respectively, the maximum relative error with test results is only 1.4 %. It shows that the numerical simulations can correctly reflect the results of the tests. Meanwhile, choosing higher strength coefficient and larger work hardening exponent of the overlapping sheet can improve the forming limit and is helpful to improve the formability of target sheet.

With the same bulging height $h = 25$ mm, strain distributions of the aluminum alloy 2B06 specimen along the radial direction are shown in Fig. 14. As can be seen, the overlapping sheet materials have a great influence on the strain distribution of bulging specimens, the maximal value of strain and the strain distribution uniformity along the radial direction of the bulging specimen can be remarkably improved by choosing stainless steel SUS321 as the

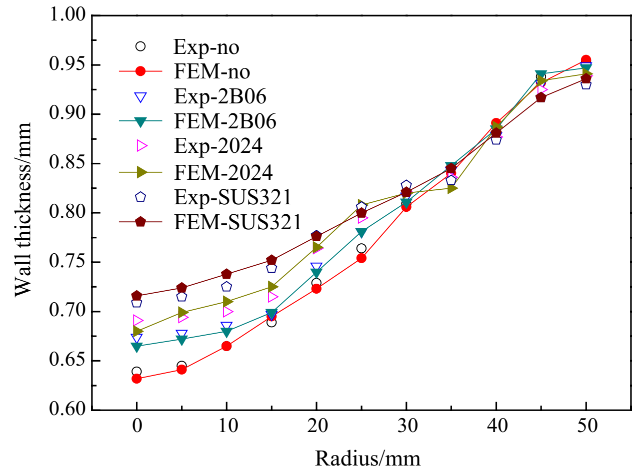


Fig. 15 Numerical and testing thickness distributions

overlapping sheet material. This is caused by the differences of geometric shapes. Therefore, with the selection of materials with good plasticity and high strength for the overlapping sheet, the reverse compressive stress on the target sheet increases and the three-dimensional stress state enhances. Also, the local excessive deformation of the specimen is restricted effectively with decreased radial strain and circumferential strain in the central area, and the microcrack caused by plastic deformation is removed. Thus, the formability of the target sheet is improved correspondingly. Thickness distributions of the specimen obtained by numerical simulation are shown in Fig. 15, the comparison shows good agreement between the numerical results and test data.

4.3 Influence of overlapping sheet thickness on target sheet

In the simulations of different overlapping sheet thicknesses, SUS321 overlapping sheet with thicknesses of $t = 0.5$, 1.0 and 1.5 mm were chosen to carry out the bulge test. The forming limits of 2B06 target sheet with different overlapping sheet thicknesses are obtained and compared with the test data, as shown in Fig. 16, the numerical results agree well with test data, the maximum relative error is only 1.5 %. Figure 17 illustrated the strain distributions of the aluminum alloy 2B06 specimen along the radial direction, as can be seen, with the increasing of the overlapping sheet thickness, the radial strain and circumferential strain of the specimen in the central area decreases, and the strain distribution uniformity remarkably improves. Also, the reverse compressive stress on the target sheet is also increased and the stress state of target sheet is improved with reduced tensile stress, and then the

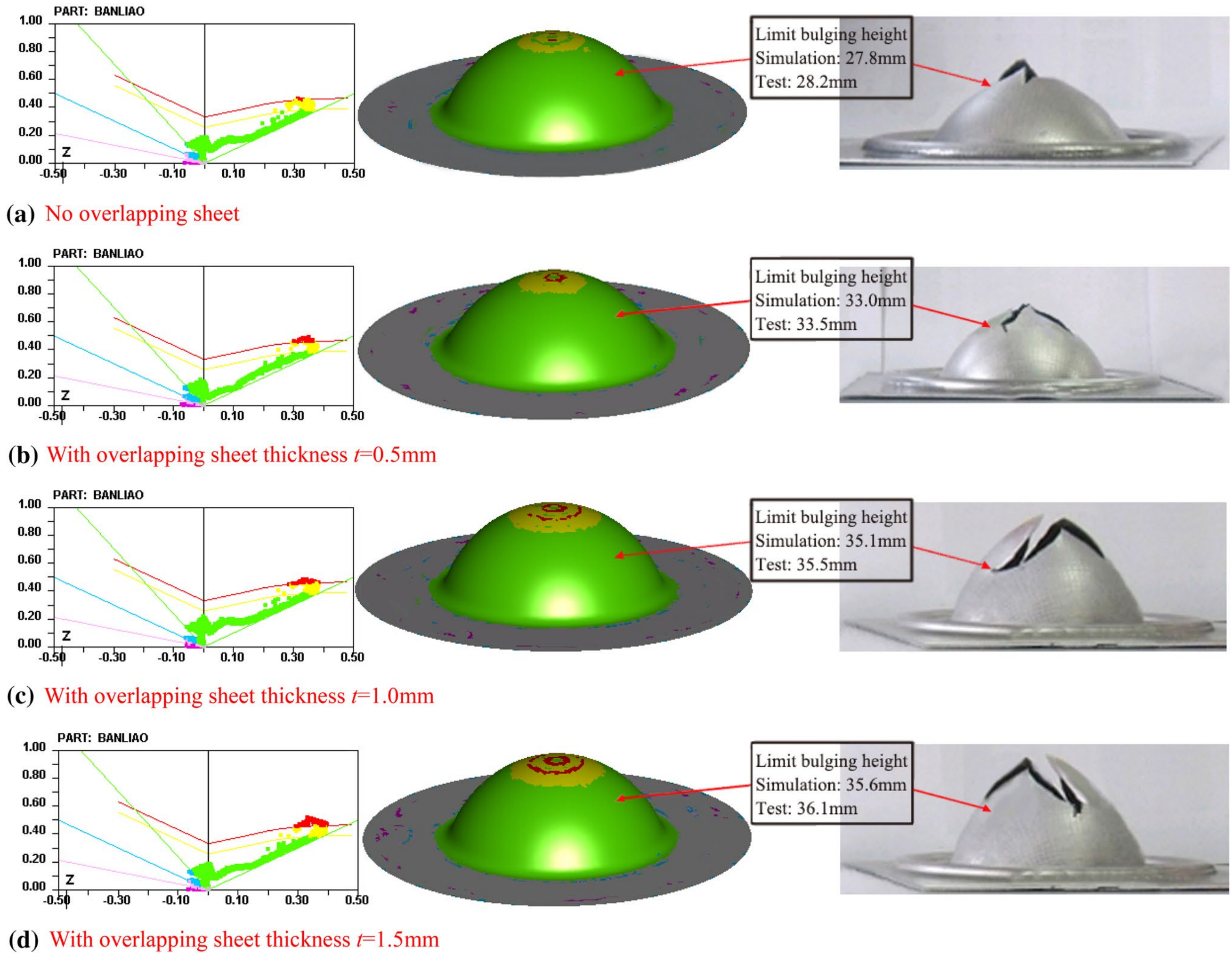


Fig. 16 Numerical and testing limit bulging height of 2B06 target sheet with different overlapping sheet thicknesses

formability of the target sheet is improved correspondingly. Comparison of the specimen thickness distributions with different overlapping sheet thicknesses of numerical simulation and test results are shown in Fig. 18, as seen in the figure, the numerical results agree well with test data.

5 Conclusions

- Compared with the no-overlapping sheet hydraulic bulge, the overlapping sheet hydraulic bulge process is more conducive to the improvement of target sheet formability;
- In overlapping sheet hydraulic bulge process, the material of overlapping sheet has great influence on the formability of target sheet. For the material that meets the Hollomon constitutive model, the reversed pressure provided by overlapping sheet is related with the strength coefficient K of overlapping sheet, and the deformation uniformity of target sheet is influenced by the work hardening exponent n of overlapping sheet. The overlapping sheet materials with higher strength coefficient K and work hardening exponent n are helpful in improving the deformation uniformity and the limit deformation capacity of target sheets. Meanwhile, this regularity is heightened with the increasing of the overlapping sheet thickness;
- For commercial scale production, the formability of target sheet can be improved by using the overlapping sheet hydraulic bulge process, however, the production cost and process conditions must be taken into consideration. The thickness of the overlapping sheet is recommended to be chosen as similar to that of the target sheet metal.

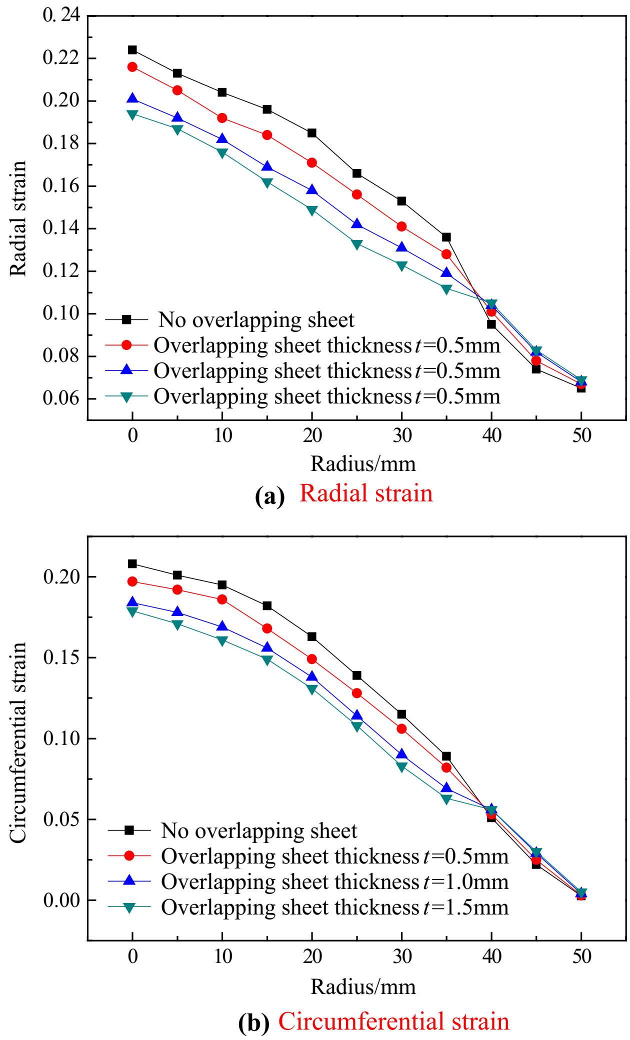


Fig. 17 Strain distributions of the specimen along the radial direction with different overlapping thicknesses ($h = 25$ mm)

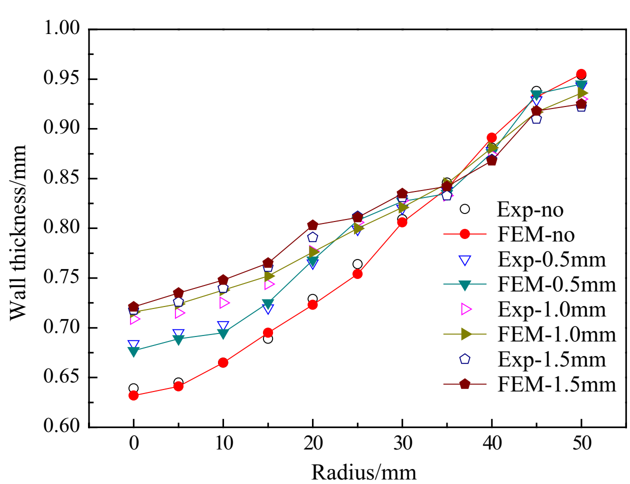


Fig. 18 Numerical and testing specimen thickness distributions ($h = 25$ mm)

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