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Stress-State Reconstruction and Formability Enhancement of 2A12-T4 Aluminum Alloy Sheets via Double-Sided elastomer-Assisted Bulging

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Abstract

The limited room-temperature plastic deformability of 2A12-T4 aluminum alloy sheets and the severe strain localization and premature fracture caused by the lack of out-of-plane constraint in conventional bulging processes remain major challenges for sheet forming. To address these issues, an elastomer-assisted forming process based on the synergistic effect of double-sided flexible media and normal constraint is proposed. An analytical mechanical model of the double-sided encapsulation configuration was established and validated through bulging experiments using polyurethane punches with different hardnesses (60A–90A) and a rigid punch, combined with finite element simulations, full-field strain characterization using digital image correlation (DIC), and forming limit diagram (FLD) analysis, to elucidate the mechanism by which the double-sided flexible media reconstruct the stress state of the sheet. The results show that the double-sided flexible media generate dynamic normal compressive stress on the sheet, reconstructing the conventional plane biaxial tensile stress state into a triaxial stress state with two tensile and one compressive principal stresses, thereby suppressing rapid through-thickness thinning and microvoid damage evolution. Meanwhile, bidirectional interfacial shear friction promotes coordinated material flow from the sidewall toward the pole region, alleviating the stress and strain gradients. As the punch hardness

decreases, both forming uniformity and forming limit are significantly improved, with the 60A polyurethane punch exhibiting the most effective synergistic regulation. Compared with elastomer-assisted forming without double-sided coverage, the bulging height increased from 17.3 mm to 20.6 mm (19.1%), while the maximum thinning ratio decreased from 23.7% to 20.1%. Furthermore, the major forming limit strain reached 0.25, representing an approximately 78.6% improvement over that achieved with the rigid punch. This study provides new theoretical insight and an effective processing strategy for enhancing the cold formability of high-strength lightweight alloy sheets.

Keyword: 2A12-T4 aluminum alloy; elastomer-assisted forming; double-sided flexible media; stress-state reconstruction; forming limit

1 Introduction

2A12-T4 aluminum alloy components have been widely used in various fields owing to their low density and high strength. However, the limited room-temperature ductility and poor formability of this alloy hinder the fabrication of complex thin-walled components. Although high-temperature and low-temperature forming technologies have demonstrated certain advantages in the forming of such components, their practical applications remain limited [1]. Zheng et al. systematically reviewed the manufacturing technologies for lightweight aluminum alloy complex components and indicated that, despite the excellent specific strength of aluminum alloys, the insufficient room-temperature formability makes conventional cold stamping difficult to meet the requirements for high-precision manufacturing of complex thin-walled structures [2]. Dong Guo-jiang et al. replaced conventional flexible die media with granular media and proposed a novel flexible-die hot forming process, namely hot granular medium forming (HGMF). Through HGMF experiments, the limiting drawing ratio curves of AA7075 cylindrical components were obtained within the temperature range of 175–300 °C, and the maximum limiting drawing ratio of 1.71 was achieved at 250 °C [3]. X. Fan et al. developed an ultra-low-temperature gradient forming process, in which the coupled enhancement of material strength and ductility at low temperatures was utilized to regulate the stress–strain state. Experimental results

demonstrated that this process effectively improved the forming limit and wall-thickness uniformity, showing potential for the fabrication of large-scale aluminum alloy thin-shell components [4]. However, high-temperature and low-temperature forming processes generally involve complex processing conditions, difficulties in controlling the quality of formed components, and relatively high manufacturing costs. Consequently, these approaches have not been widely adopted, and cold forming remains the dominant manufacturing method for thin-walled components.

Due to the challenges associated with cold forming, pre-processing and preforming technologies have been extensively developed to improve the forming quality of aluminum alloy components [5]. Qingjuan Zhao et al. proposed an electrically assisted flexible forming method to address the issues of low forming accuracy and severe thickness reduction during sheet bulging. With increasing pre-treatment current, the fiber distribution along the thickness direction was homogenized, the work-hardening effect was alleviated, and the bulging depth under flexible-die conditions gradually increased with a more uniform wall-thickness distribution [6]. Tao et al. developed a multi-stage rubber forming method to overcome wrinkling defects during the rubber forming of convex-flanged 2A12 aluminum alloy sheets. By introducing additional lateral stresses based on the preliminary forming stage, this method effectively suppressed wrinkle formation [7]. Y.-K. Fuh et al. proposed a preform optimization approach based on finite element analysis and processing maps to address the unfavorable material flow, excessive forming loads, and localized defects encountered during the forming of complex aluminum alloy forgings. The results demonstrated that optimizing the preform geometry could improve die filling and strain distribution, reduce the maximum forging load by approximately 11%–12%, and simultaneously enhance material utilization and forming quality [8]. Y. Xu et al. investigated a pre-bulging-assisted deep drawing process for 2024 aluminum alloy sheets with poor ductility, aiming to overcome wrinkling and cracking during the deep drawing of complex components. It was found that appropriate pre-bulging could modify the stress state of the sheet, effectively avoid wrinkling and cracking, and improve wall-thickness uniformity and forming limit [9]. However, pre-treatment

forming and preforming technologies generally require additional tooling, resulting in increased mold costs, reduced production efficiency, and complicated process design.

Soft die forming and cover sheet-assisted forming technologies have gradually attracted increasing attention in the fabrication of thin-walled components. Quanwei Ma et al. proposed a soft-die roll forming process for microchannel structures, in which isotropic pressure was applied through a rubber pad during forming, enabling deformation of the entire microchannel profile. Experimental results demonstrated that no structural damage occurred in the formed microchannels. Moreover, a thinner and softer rubber pad, together with higher rolling pressure and velocity, resulted in an increased depth-to-width ratio of the microchannels [10]. Dong Y et al. employed a flexible hydroforming process to address the poor forming quality and low forming efficiency of multilayer deep-drawn 2A12 aluminum alloy fairings. By combining numerical simulation and experiments, the process parameters, including cavity pressure and blank-holder force, were optimized. The optimized process effectively controlled forming defects, improved wall-thickness uniformity, and significantly enhanced both forming quality and production efficiency [11]. Lingling Yi et al. proposed a hybrid bulging process for 5083 aluminum alloy cylindrical components, which significantly reduced the wall-thickness reduction ratio at the bottom region of the components [12]. To further understand the rubber pad forming process, Maziar Ramezani et al. conducted experimental and numerical investigations and developed theoretical static and dynamic friction models suitable for rubber pad forming. Compared with the conventional Coulomb friction model, the proposed friction model exhibited better agreement with experimental results [13]. Bin-Jun Zhou et al. investigated the wrinkling behavior and wall-thickness distribution characteristics of single-layer and double-layer aluminum sheets under different hydraulic pressures during hydroforming. The cooperative deformation of double-layer sheets effectively suppressed wrinkling, optimized the wall-thickness distribution, reduced the required forming pressure and tensile stress in the sheet, and provided potential energy-saving benefits [14].

In summary, existing studies have primarily focused on forming processes

involving unilateral flexible-die loading or the coordinated deformation of metallic laminated sheets. However, the contact-induced load transfer and deformation coordination mechanisms of metallic sheets subjected to double-sided elastomeric sheets remain insufficiently understood. In particular, the intrinsic effects of the stress-state reconstruction from plane stress to a triaxial stress state under double-sided constraints on the strain path, thickness uniformity, and forming limit of the sheet have not yet been systematically elucidated. To address these research gaps, a double-sided elastomer-assisted forming process is proposed in this study. Polyurethane sheets are introduced on both sides of a 2A12-T4 aluminum alloy sheet, whereby the inner elastomeric sheet homogenizes the punch load, while the outer elastomeric sheet imposes an opposing normal constraint. On this basis, a mechanical model is established to describe the regulation of the sheet stress state under double-sided constraints. Finite element simulations and full-field strain measurements using digital image correlation (DIC) are subsequently employed to investigate the strain evolution and thickness distribution of the sheet. Particular emphasis is placed on elucidating the physical mechanisms by which the double-sided flexible media suppress localized necking and delay the onset of plastic instability and fracture. This study provides a new mechanical perspective and technical support for the cold forming of aluminum alloy sheets with limited plastic deformability.

2 Experimental Materials and Methods

In this study, 0.5 mm-thick 2A12-T4 aluminum alloy sheets were employed, and their chemical composition is listed in Table 1. The 2A12-T4 aluminum alloy sheets were obtained from the 2A12 aluminum alloy substrate through solution treatment (holding at 500 °C for 2 h followed by water quenching) and natural aging (exposure at 25 °C for 30 days). The solution treatment promoted the dissolution of secondary phases, such as Al_2CuMg and Al_2Cu strengthening phases, into the aluminum matrix, while relieving residual stresses and microstructural defects generated during casting or rolling processes. Subsequently, natural aging induced the gradual precipitation of fine strengthening phases from the supersaturated solid solution through atomic

diffusion, avoiding excessive plasticity loss caused by rapid precipitation. After heat treatment, specimens were extracted for X-ray diffraction (XRD) analysis, as shown in Fig. 1. The results indicate that the 2A12-T4 aluminum alloy consists mainly of an α -Al matrix with secondary phases including α -Al, Al_2CuMg , and $\text{Al}_{20}\text{Cu}_2\text{Mn}_3$ (T phase). Strong diffraction peaks were observed at $2\theta \approx 38.6^\circ$ (111) and 44.8° (200), corresponding to the characteristic diffraction planes of the face-centered cubic (FCC) structure [15].

Table 1 Chemical composition of 2A12-T4 aluminum alloy/%

Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Al
0.07	0.18	4.75	0.58	1.64	0.08	0.02	0.06	Bal.

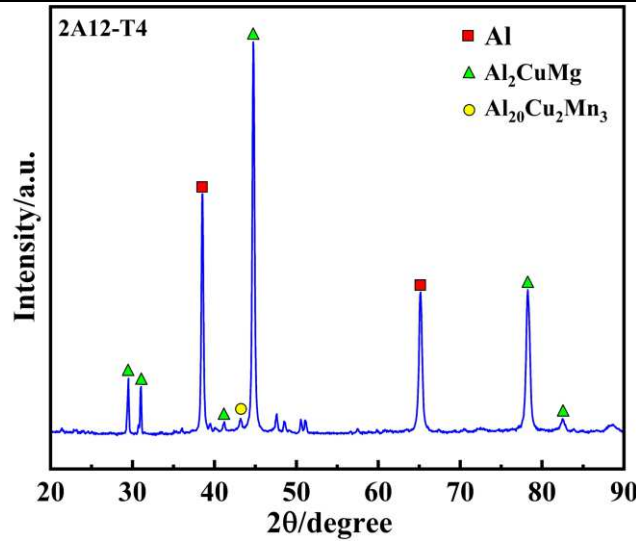


Fig. 1 XRD pattern of 2A12-T4

Fig. 2 presents the microstructural morphology of the 2A12-T4 aluminum alloy. The microstructure exhibits a relatively uniform and refined characteristic, consisting of typical equiaxed α -Al grains with a homogeneous grain size distribution. No obvious grain coarsening or segregation is observed. This microstructural feature can be attributed to the effective reduction of casting- and rolling-induced defects during the solution treatment at 500 °C, while the subsequent natural aging process prevented abnormal grain growth [16]. According to the XRD phase analysis, the strengthening phases, including Al_2CuMg and Al_2Cu , do not exhibit obvious continuous precipitation along grain boundaries and are mainly distributed as isolated particles within the grains. Such precipitation characteristics provide effective precipitation strengthening through

the pinning effect while avoiding grain boundary embrittlement, thereby establishing a favorable microstructural basis for achieving a balance between strength and ductility [17]. Meanwhile, no apparent metallurgical defects, such as shrinkage pores or inclusions, were observed in the microstructure, indicating the good quality of the 2A12-T4 aluminum alloy sheets used in this study and their suitability for subsequent bulging forming experiments.

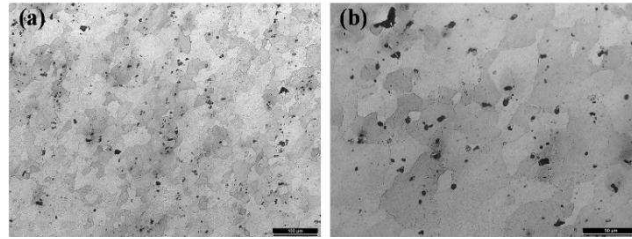


Fig. 2 Microscopic structure of 2A12-T4

According to the GB/T 228.1-2021 standard, the geometry and dimensions of the tensile specimens were determined, as illustrated in Fig. 3. The specimens were fabricated using electrical discharge wire cutting, and rectangular cross-section specimens were extracted from the 0.5 mm-thick sheets along three orientations, namely parallel to the rolling direction, perpendicular to the rolling direction, and at 45° to the rolling direction [18]. Uniaxial tensile tests were performed using a WDW-200 electronic universal testing machine. The tensile velocity was set within the range of 1–5 mm/min, corresponding to a strain rate range of $3 \times 10^{-4} \text{s}^{-1}$ – $1.3 \times 10^{-3} \text{s}^{-1}$. Three parallel tests were conducted for each condition to ensure repeatability. After testing, the obtained force–displacement curves were processed and converted into true stress–strain curves, as shown in Fig. 4.

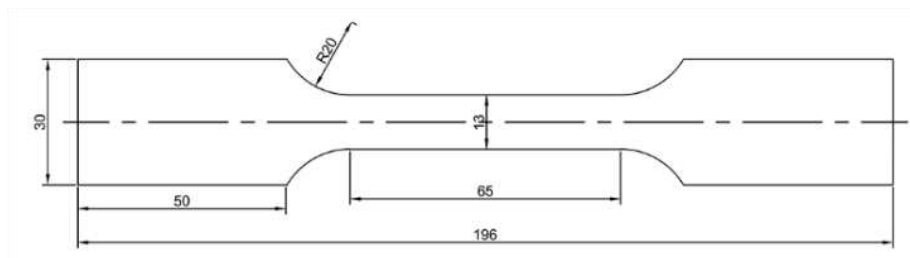


Fig. 3 Dimensions (in mm) of samples for tensile test

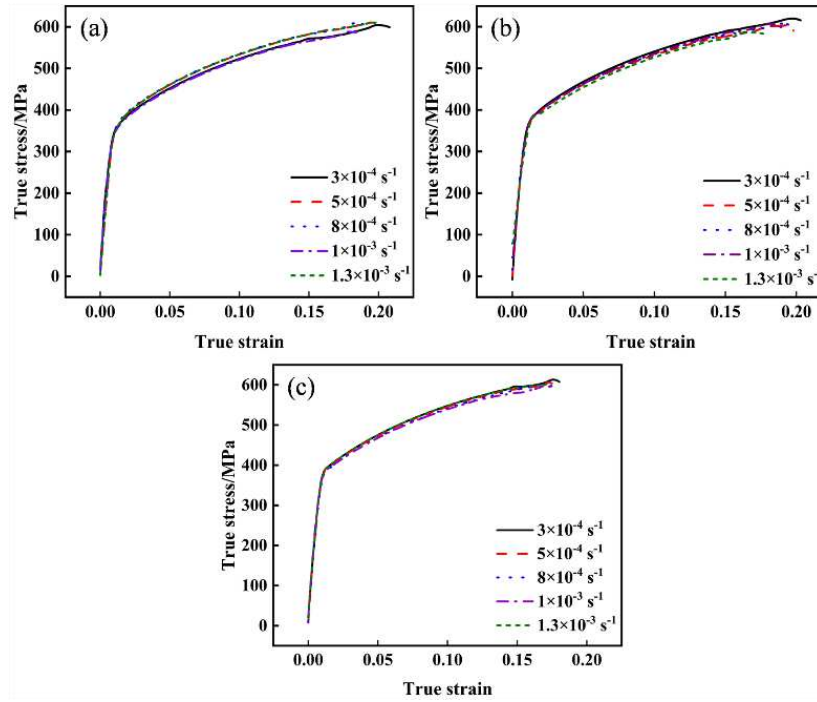


Fig. 4 True stress-strain curves of 2A12-T4: (a) parallel to the rolling direction, (b) perpendicular to the rolling direction, (c) at a 45° angle to the rolling direction

Fig. 5 shows the morphology comparison of the specimens before and after tensile deformation. The specimen oriented at 45° to the rolling direction exhibited the maximum elongation after fracture of 19.3% at a strain rate of $8 \times 10^{-4} \text{ s}^{-1}$. The true stress–strain curves obtained under different tensile loading rates show a high degree of overlap, indicating good repeatability and accuracy of the tensile test results. Based on the processed experimental data, the mechanical parameters of the 2A12-T4 aluminum alloy were determined, including an elastic modulus of $E=68 \text{ GPa}$, a yield stress of 392 MPa, and an ultimate tensile strength of 612 MPa. These experimentally obtained parameters were subsequently used as the material input parameters for finite element simulations.



Fig. 5 Comparative image of the 2A12-T4 aluminum alloy specimen before and after tensile testing

3 Results and discussion

3.1 Mechanical analysis

The sheet subjected to double-sided elastomer-assisted bulging is considered in this section, and its stress state during the forming process is analyzed, as illustrated in Fig. 6. Here, P denotes the normal constraint pressure; σ_1 , σ_2 and σ_3 , represent the radial tensile stress, circumferential tensile stress, and normal compressive stress, respectively; and τ denotes the tangential frictional stress at the interface.

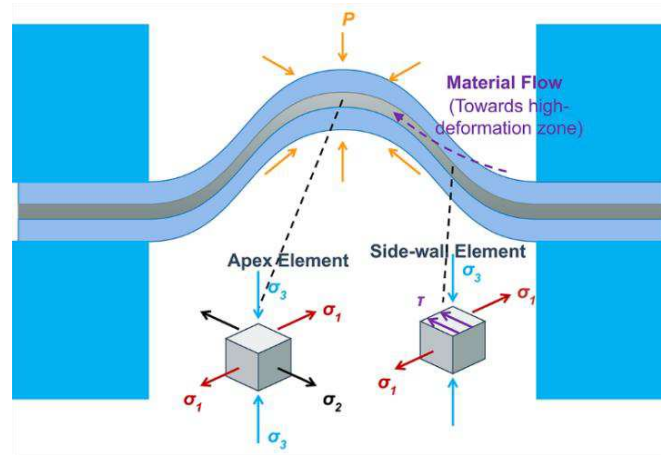


Fig. 6 Schematic illustration of the mechanical analysis of the sheet subjected to double-sided elastomer-assisted bulging

3.1.1 Analysis of meridional stress at an arbitrary point

During the double-sided elastomer cover sheet-assisted bulging process, the sheet is subjected to normal pressures generated by the constraints of the inner and outer cover sheets, as well as frictional forces at the contact interfaces. It is assumed that the forming pressure P applied to the sheet during bulging is axially distributed. The normal pressure exerted by the outer cover sheet and inner cover sheet on the sheet are defined as P_1 and P_2 , respectively. During the bulging of the laminated structure, friction forces exist at the contact interfaces. The meridional friction forces exerted by the outer and inner cover sheets on the sheet are defined as f_1 and f_2 , respectively. The force state of an arbitrary point on the sheet during the bulging process is illustrated in Fig. 7.

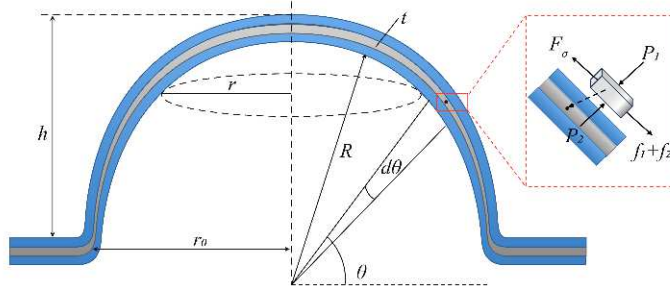


Fig. 7 Stress analysis for deformation at any point on the intermediate layer plate

The curvature radius of the sheet at the bulging height h is defined as R , and the corresponding wall thickness is t . θ represents an arbitrary angle, and r denotes the cross-sectional radius at the angle θ .

According to the condition of axial force equilibrium, the meridional friction forces exerted by the inner and outer cover sheets on the sheet are defined as f_2 and f_1 , respectively. The meridional stress at the position of θ is represented by F_σ . The normal pressures applied by the inner and outer cover sheets are defined as P_2 and P_1 , respectively, and the resultant normal pressure satisfies $P_1 + P_2 = 0$. The force analysis of the sheet with radius r is shown in Fig. 7 [19].

The axial component of the meridional friction force exerted by the outer cover sheet on the sheet is expressed as:

$$F_{f_1} = \int_{\theta}^{\frac{\pi}{2}} f_1 \cdot 2\pi r R \cos \theta d\theta \quad (1)$$

The axial component of the meridional friction force exerted by the inner cover sheet on the sheet is expressed as:

$$F_{f_2} = \int_{\theta}^{\frac{\pi}{2}} f_2 \cdot 2\pi r R \cos \theta d\theta \quad (2)$$

The axial resultant force of the meridional stress is expressed as:

$$F_\sigma = \sigma_r(\theta) 2\pi r t \cos \theta \quad (3)$$

The axial resultant force of the interfacial contact pressure exerted by the outer cover sheet on the intermediate sheet is expressed as:

$$F_{P_1} = \int_{\frac{\pi}{2}}^{\pi} P_1 \cdot 2\pi r R \sin \theta d\theta \quad (4)$$

The axial resultant force of the contact pressure exerted by the inner cover sheet on the sheet is expressed as:

$$F_{P_2} = \int_{\frac{\pi}{2}}^{\pi} P_2 \cdot 2\pi r R \sin \theta d\theta \quad (5)$$

The axial force equilibrium condition can be written as:

$$F_{\sigma} = F_{P_1} + F_{P_2} + F_{f_1} + F_{f_2} \quad (6)$$

Substituting Eqs. (1)–(5) into Eq. (6), the following equation is obtained:

$$\begin{aligned} \sigma_r(\theta) 2\pi r t \cos \theta = & \int_{\frac{\pi}{2}}^{\pi} P_1 \cdot 2\pi r R \sin \theta d\theta + \int_{\frac{\pi}{2}}^{\pi} P_2 \cdot 2\pi r R \sin \theta d\theta \\ & + \int_{\frac{\pi}{2}}^{\pi} f_1 \cdot 2\pi r R \cos \theta d\theta + \int_{\frac{\pi}{2}}^{\pi} f_2 \cdot 2\pi r R \cos \theta d\theta \end{aligned} \quad (7)$$

According to the geometric relationship, it can be obtained that:

$$r = R \cos \theta \quad (8)$$

$$R = \frac{r_0^2 + h_0^2}{2h} \quad (9)$$

Assuming that the meridional friction forces f_1 and f_2 are uniformly distributed over the entire contact surface of the bulged component, the meridional stress at the position θ can be obtained by integration[20]:

$$\sigma_r(\theta) = \frac{R(P_2 - P_1)}{2t} + \frac{R(f_1 - f_2)(\pi - 2\theta - \sin 2\theta)}{2t(1 + \cos 2\theta)}, \theta \in \left(0, \frac{\pi}{2}\right) \quad (10)$$

According to Eq. (10), the relationship between the meridional stress and θ can be obtained by taking $\frac{R}{t}$ as a parameter. For a given bulging height h , the meridional stress of the sheet increases with increasing θ . When $\theta = \frac{\pi}{2}$, the meridional stress reaches its maximum value, which is expressed as $\frac{R(P_2 - P_1)}{2t}$ [21,22]. Overall, the

application of inner and outer cover sheets can significantly improve the deformation uniformity of the sheet.

3.1.2 Analysis of circumferential stress at an arbitrary point

During the elastomer-assisted cover sheet bulging process, the sheet is subjected to normal pressures from the inner and outer cover sheets due to their constraining effects. In addition, meridional friction forces exist at the contact interfaces during the bulging process of the elastomer–metal multilayer structure. Assuming that all materials in the multilayer structure are isotropic, the relationship between the flow stress and the applied fluid pressure, curvature radius, and sheet thickness can be described by the Laplace equation based on membrane theory [23]. For an axisymmetric element of the sheet, the equilibrium equation under uniform pressure can be expressed as Eq. (11).

$$\frac{\sigma_1}{\rho_1} + \frac{\sigma_2}{\rho_2} = \frac{P}{t} \quad (11)$$

For the force analysis of the metal sheet, the resultant normal pressure exerted by the inner and outer cover sheets on the sheet is $P_2 - P_1$, and the current sheet thickness is t_0 . The meridional and circumferential stresses at an arbitrary point are denoted by σ_r and σ_θ , respectively. Substituting these parameters into Eq. (12) yields:

$$\frac{\sigma_r}{\rho_r} + \frac{\sigma_\theta}{\rho_\theta} = \frac{P_2 - P_1}{t_0} \quad (12)$$

Substituting Eq. (12) into Eq. (13), the circumferential stress in the sheet can be expressed as:

$$\sigma_\theta = \left[\frac{(P_2 - P_1)}{t_0} - \frac{\frac{R(P_2 - P_1)}{2t} + \frac{R(f_1 - f_2)(\pi - 2\theta - \sin 2\theta)}{2t(1 - \cos 2\theta)}}{\rho_r} \right] \cdot \rho_\theta, \theta \in \left(0, \frac{\pi}{2}\right) \quad (13)$$

Analysis of Eq. (13) indicates that, as θ decreases, corresponding to a position closer to the outer peripheral region, the ratio $\frac{R}{t}$ increases, whereas $\frac{(P_2 - P_1)}{t_0}$ remains approximately constant. Consequently, with decreasing θ , the circumferential stress σ_θ initially decreases and subsequently increases in the opposite direction [24,25].

3.1.3 Stress state and mechanism analysis during the bulging process

For the sheet without cover sheets, the spherical top region exhibits the smallest curvature radius and is mainly subjected to equibiaxial tensile stresses, including the radial tensile stress σ_1 and circumferential tensile stress σ_2 . The thickness direction (normal direction) is unconstrained, and the material is therefore under a plane stress state. After introducing the double-sided cover sheets, the spherical top region is subjected not only to in-plane biaxial tensile stresses but also to normal compressive stress P generated by the compression of the inner and outer polyurethane cover sheets. Consequently, the material state changes from a biaxial tensile stress state to a triaxial stress state consisting of two tensile stresses and one compressive stress. This normal constraint effectively reduces the increasing rate of local equivalent plastic stress and suppresses the rapid thinning of the sheet in the thickness direction, thereby delaying the occurrence of localized necking (excessive thinning) [26]. In the transition region between the spherical top and the sidewall, the curvature varies significantly. Without cover sheets, contact with the rigid punch in this region results in uneven normal loading and generates a large stress gradient [27]. Under the double-sided cover sheet configuration, the sheet is subjected to normal pressure and becomes "flexibly clamped" in this region. The continuous normal pressure enhances the interfacial contact and reduces the abrupt stress variation between the spherical top and sidewall, leading to a more gradual deformation process. In the sidewall region, the relatively large curvature radius results in a lower deformation degree during conventional bulging. Consequently, the material cannot fully participate in plastic flow, causing preferential thinning in the spherical top region [28]. Under the action of double-sided cover sheets, the sidewall is continuously constrained by the upper and lower cover sheets in the normal direction, allowing the sheet to maintain contact with the flexible medium. Meanwhile, the interfacial friction τ provides tangential constraint, promoting coordinated material flow from the sidewall region toward the highly deformed region and improving material utilization [29].

3.2 Finite element simulation

Based on the mechanical properties obtained from the tensile tests of the 2A12-T4

aluminum alloy, the bulging process of the 2A12-T4 aluminum alloy sheet was numerically simulated using ANSYS software. In the finite element model, the 2A12-T4 aluminum alloy was described using an elastoplastic constitutive model and the Hill48 anisotropic yield criterion. The hardening behavior was defined by the experimentally obtained true stress–true strain relationship. The polyurethane punch and cover sheets were modeled using the hyperelastic Mooney–Rivlin constitutive model. The material parameters of polyurethane rubbers with hardness values ranging from 60A to 90A are listed in Table 2, and the Poisson’s ratio was set to 0.49 [30]. According to the requirements of the elastomer-assisted cover sheet bulging experiments, a circular blank with a diameter of 98 mm was selected as the metal sheet, and elastomer cover sheets with the same dimensions were employed. Since the bulged component exhibits axisymmetric geometric characteristics, a one-quarter model, as shown in Fig. 8, was established for finite element simulation, and symmetry constraints were applied to reproduce the overall loading conditions. The element size was set to 1 mm. The friction coefficients between the punch and sheet, and between the cover sheets and sheet were set to 0.2 and 0.15, respectively, while the dynamic friction coefficient was set to 0.22. The medium chamber and blank holder were defined as rigid bodies to simplify the computational process [31].

Table 2 Mechanical properties parameters of the polyurethane rubber

Polyurethane rubber	Hardness Shore A	Mooney–Rivlin constant C_{10}	Mooney–Rivlin constant C_{01}
Type 1	60	0.501	0.123
Type 2	70	0.736	0.184
Type 3	80	1.782	0.445
Type 4	90	2.824	0.706

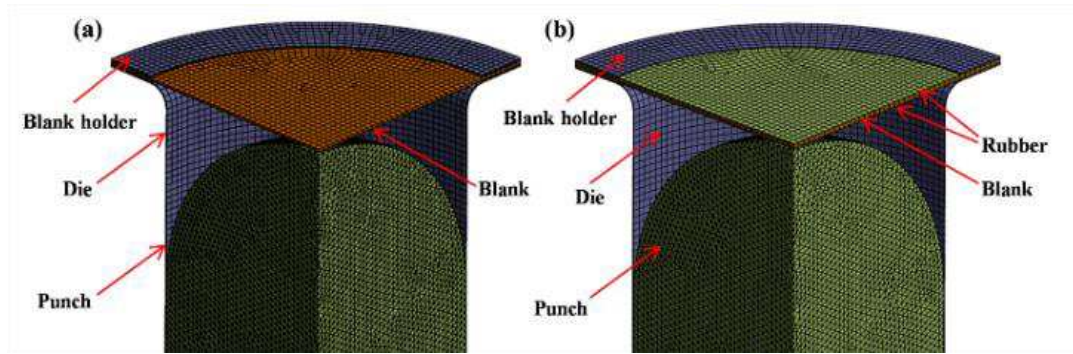


Fig. 8 Deformation numerical simulation model:

(a) deformation without a cover elastomer and (b) deformation with a cover elastomer

Fig. 9 shows the equivalent stress distributions during the bulging process using punches with different hardness values under the condition without cover elastomer. The equivalent stress exhibits an obvious concentration feature at the spherical top region. The peak stress is located at the top area and gradually decreases toward the sidewall, resulting in a relatively large stress gradient. For the steel punch, the high-stress region is limited mainly to the spherical top area, while the equivalent stress in the sidewall region rapidly decreases to below 100 MPa, indicating a highly non-uniform stress distribution. The peak equivalent stress at the spherical top reaches 404.9 MPa, which is slightly higher than the yield strength of the 2A12-T4 aluminum alloy (392 MPa), indicating that plastic deformation has occurred. Due to the high rigidity of the steel punch, it cannot accommodate the deformation of the sheet, resulting in non-uniform pressure transmission. Consequently, severe stress concentration occurs at the spherical top region, where plastic strain accumulates rapidly and the material reaches its forming limit earlier, leading to plastic cracking [32].

For polyurethane punches, the high-stress region expands with decreasing punch hardness. For the 60A polyurethane punch, the high-stress region extends from the spherical top to the middle section of the sidewall, accompanied by a smoother stress transition and a reduced stress gradient. Meanwhile, the peak equivalent stress increases with decreasing polyurethane hardness. The peak equivalent stress of the 60A punch reaches 430.3 MPa, which is 25.4 MPa higher than that of the steel punch. This phenomenon is attributed to the enhanced deformability of the polyurethane punch, which promotes more sufficient plastic deformation of the sheet. The increased plastic

deformation further raises the stress level through strain hardening effects [33]. Compared with the steel punch, although the 60A polyurethane punch does not reduce the peak equivalent stress at the spherical top region, it enlarges the high-stress area and decreases the stress gradient from the spherical top toward the sidewall. This is because the flexible polyurethane undergoes elastic deformation during the bulging process, thereby dispersing the contact pressure [34]. These results demonstrate that the flexible polyurethane punch can effectively improve the load transfer range and spatial uniformity of plastic deformation. However, under the condition without cover sheet constraints, the excessive stress gradient cannot be fundamentally eliminated [35].

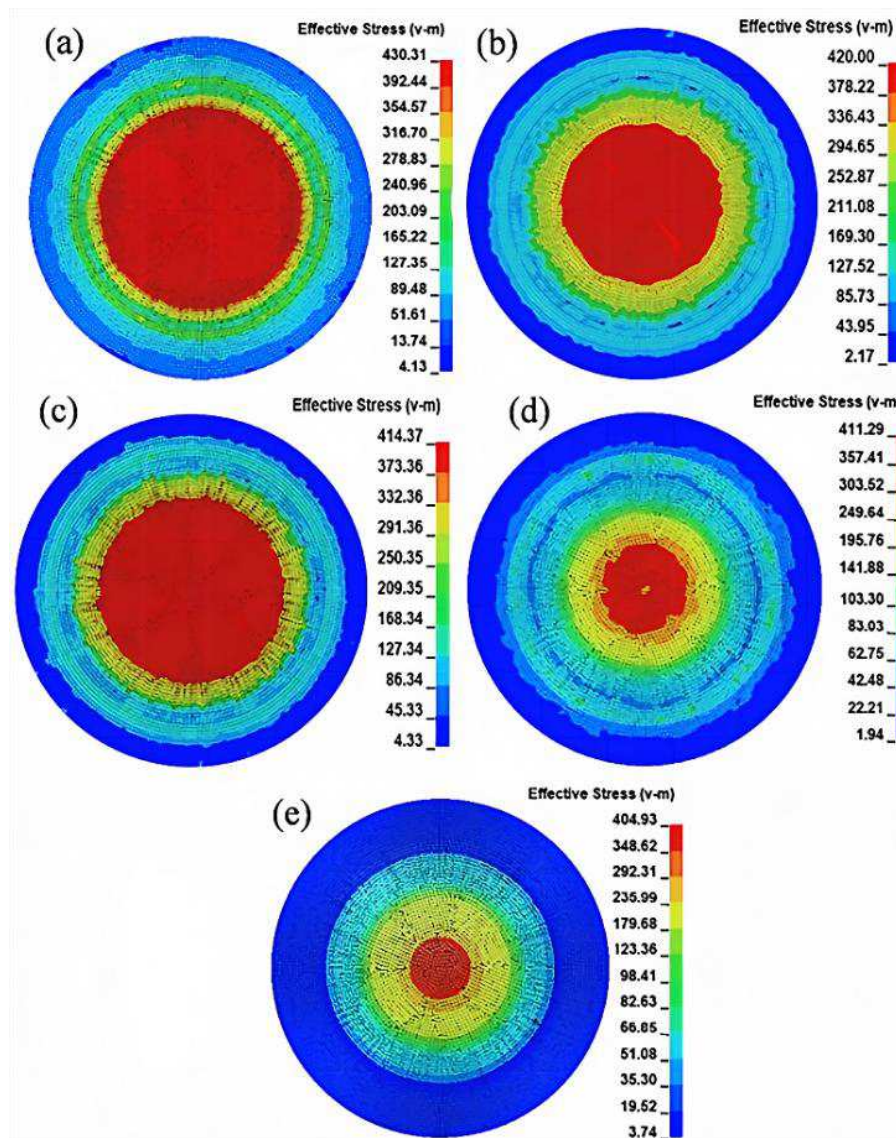


Fig. 9 Stress distribution under uncovered elastomer loading conditions:
(a) 60A, (b) 70A, (c) 80A, (d) 90A, (e) Rigid punch

Fig. 10 shows the equivalent stress distributions of the 2A12-T4 aluminum alloy

sheets during elastomer-assisted cover elastomer bulging simulations with different punch hardness values. In these simulations, 90A polyurethane elastomer cover sheets were bonded to both sides of the 2A12-T4 aluminum alloy sheet. The coordinated regulation of the sheet deformation behavior was achieved through the bidirectional normal constraints and interfacial friction forces provided by the inner and outer cover sheets. Compared with the cases without cover elastomer, the equivalent stress distribution under the cover elastomer condition becomes significantly more uniform, and the stress concentration phenomenon is almost eliminated. This improvement is attributed to the synergistic regulation of the stress state by the double-sided cover elastomer. The cover elastomer applies uniform normal constraints to both surfaces of the aluminum alloy sheet, allowing the sheet to maintain a relatively stable deformation state during the bulging process and preventing local stress concentration. Meanwhile, the bidirectional interfacial friction between the cover elastomer and the sheet provides a dual-directional traction effect, promoting more uniform and sufficient material flow from the sidewall region toward the spherical top region. As a result, a more uniform pressure transmission and stress distribution over the entire forming region are achieved. For the steel punch, the peak equivalent stress at the spherical top region is 413 MPa, and the high-stress region expands uniformly from the spherical top toward the middle section of the sidewall. The peak equivalent stress of the polyurethane punches increases slightly, reaching 432 MPa for the 60A polyurethane punch. The equivalent stress decreases smoothly and approximately linearly from the spherical top to the sidewall, without obvious stress mutation or localized concentration. Among all cases, the 60A polyurethane punch exhibits the most uniform equivalent stress distribution, achieving a desirable homogeneous loading state.

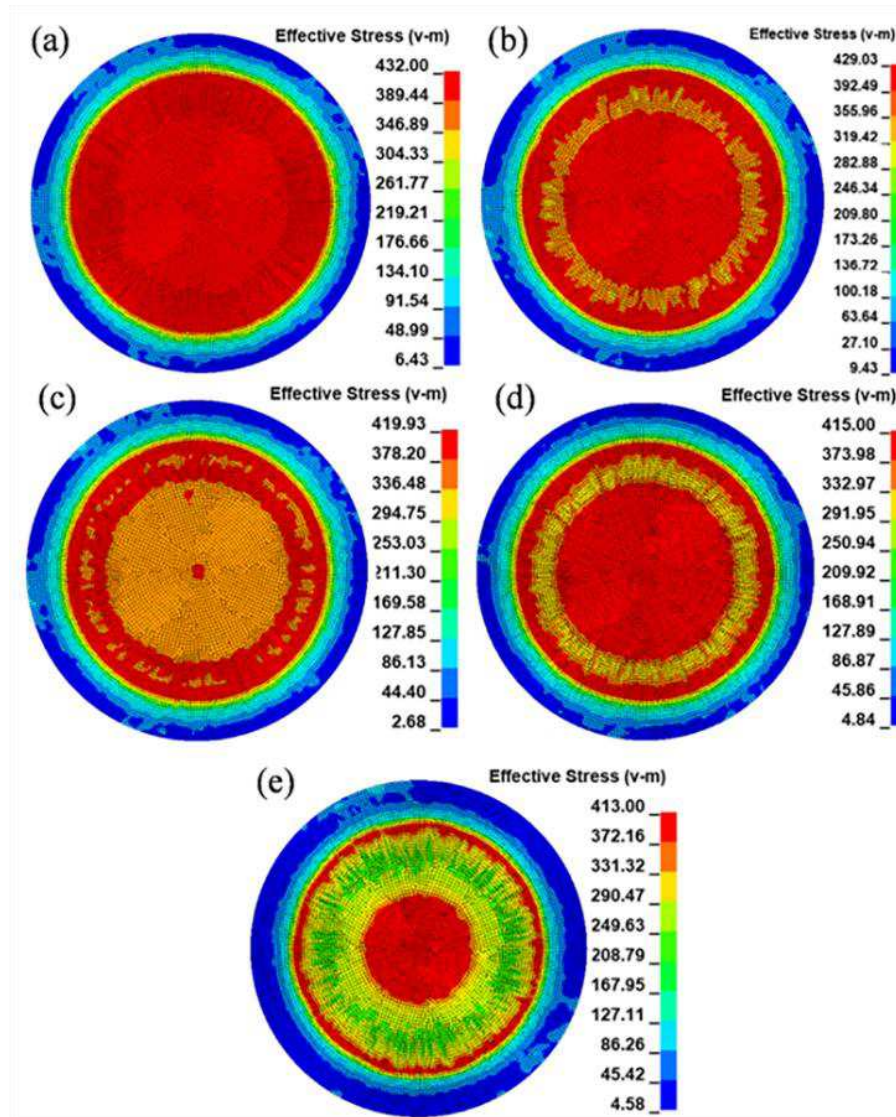


Fig. 10 Stress distribution under covered elastomer loading conditions:
(a) 60A, (b) 70A, (c) 80A, (d) 90A, (e) Rigid punch

Wall thickness reduction is an important indicator for evaluating the forming quality of bulging processes. Fig. 11 shows the wall thickness reduction distributions of the 2A12-T4 aluminum alloy sheets during the bulging process with punches of different hardness values under the condition without cover sheets. The distribution of wall thickness reduction exhibits a high degree of consistency with the equivalent stress distribution. The maximum thickness reduction occurs in the spherical top region, and gradually decreases from the spherical top toward the sidewall, resulting in a non-uniform wall thickness distribution.

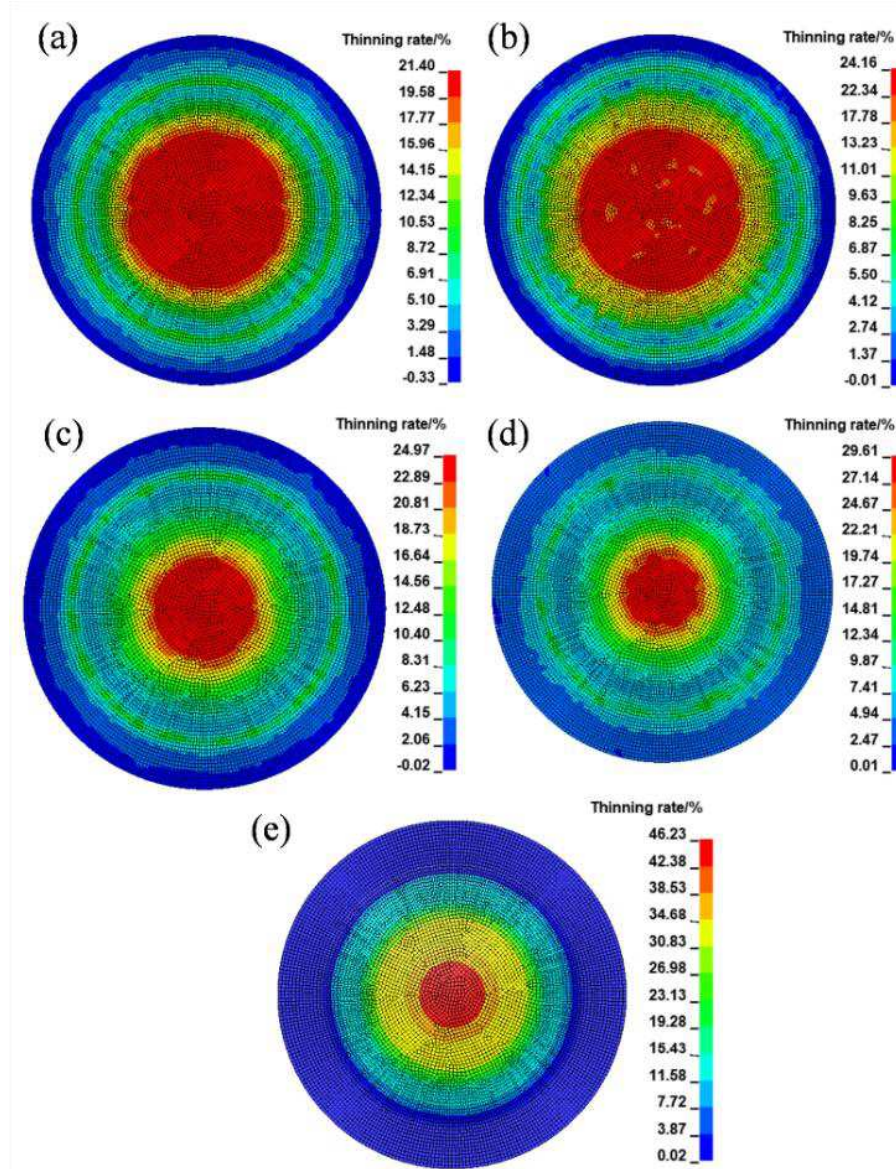


Fig. 11 Thinning rate distribution under uncovered elastomer loading conditions:
(a) 60A, (b) 70A, (c) 80A, (d) 90A, (e) Rigid punch

The wall thickness reduction distributions of the 2A12-T4 aluminum alloy sheets bulged with punches of different hardness values under the cover elastomer condition are shown in Fig. 12. The bidirectional synergistic regulation provided by the cover sheets results in an almost uniform distribution of wall thickness reduction. The maximum thickness reduction in the spherical top region is significantly reduced, and the uniformity of wall thickness distribution is optimized. This represents the core advantage of the elastomer-covered sheet-assisted forming process.

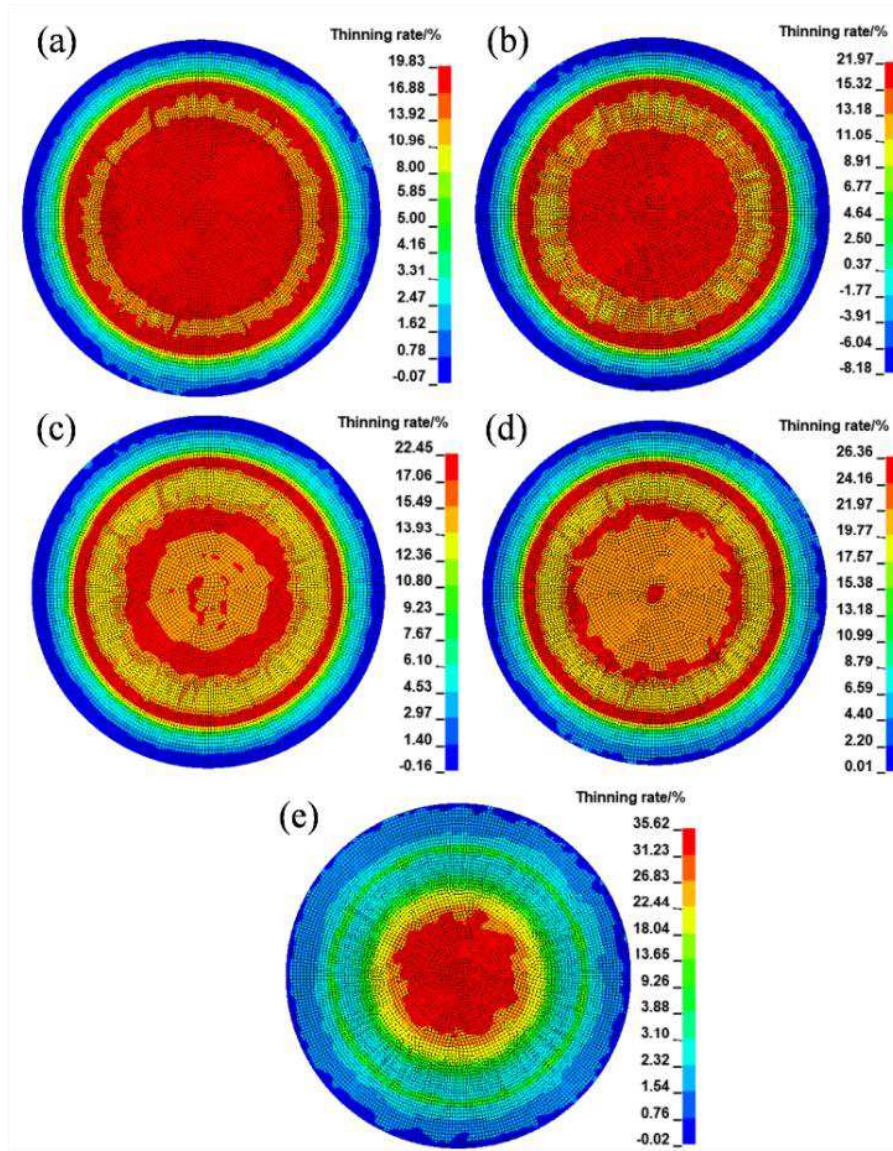


Fig. 12 Thinning rate distribution under covered elastomer loading conditions:
(a) 60A, (b) 70A, (c) 80A, (d) 90A, (e) Rigid punch

Fig. 13 presents the maximum thickness reduction distributions of the bulged components under different forming conditions. Without cover sheets, the maximum thickness reduction at the spherical top region of the component formed by the steel punch reaches 46.2%. For polyurethane elastomer punches, the maximum thickness reduction at the spherical top region increases with increasing punch hardness, while the value decreases to 21.4% for the 60A polyurethane punch. A lower punch hardness results in a more uniform stress distribution, a smaller thickness reduction gradient, and a more homogeneous wall thickness distribution. Without cover sheets, the sheet lacks external constraints, and the spherical top region undergoes excessive plastic deformation under biaxial tensile stress. Meanwhile, the sidewall material cannot

effectively flow toward the spherical top region due to the lack of support, resulting in a non-uniform thickness distribution and a higher tendency for cracking at the spherical top region, thereby limiting the forming quality. Under the cover elastomer condition, the maximum thickness reduction at the spherical top region formed by the steel punch is reduced by 10.6% compared with that without cover sheets. Moreover, the thickness reduction gradually decreases from the spherical top region to below 5% at the sidewall region, resulting in a more uniform wall thickness distribution. For polyurethane elastomer punches, the maximum thickness reduction at the spherical top region is significantly reduced compared with the uncovered condition, and the minimum value of 19.8% is achieved with the 60A punch. The cover elastomer improves the stress state through bidirectional normal constraints, preventing localized deformation. Meanwhile, the bidirectional interfacial friction generates a clamping–traction effect, promoting uniform material flow from the sidewall toward the spherical top region, compensating for the material consumption at the top region and suppressing excessive thinning [36].

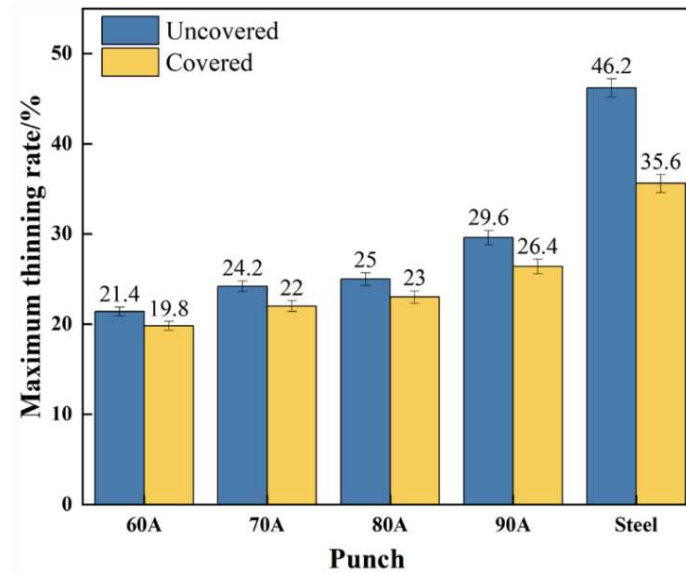


Fig. 13 Thinning rate in different punch conditions

3.3 Bulging experiments and forming limits

3.3.1 Bulging experiments

The structure of the sheet bulging die is shown in Fig. 14(a), which consists of a medium chamber and a blank holder. The medium chamber was designed as a cylindrical structure with a flange, which was used to accommodate the punch and

transmit the applied pressure. This study mainly focuses on the elastomer-covered sheet-assisted forming process. Therefore, a steel punch and polyurethane punches with hardness values of 60A, 70A, 80A, and 90A were selected as the forming punches. Polyurethane exhibits high elasticity, excellent wear resistance, and good pressure transmission capability. Under the action of medium pressure, polyurethane can undergo uniform expansion and subsequently drive the sheet deformation [37]. The geometries of the punches are shown in Fig. 14(b).



Fig. 14 Sheet bulging die

The bulging sheet was prepared using a circular 2A12-T4 aluminum alloy blank with a diameter of 98 mm and a thickness of 0.5 mm, as shown in Fig. 15(a). The elastomer cover sheets were fabricated from transparent polyurethane with a hardness of 90A, and their dimensions were identical to those of the 2A12-T4 aluminum alloy blank, as shown in Fig. 15(b). The elastomer cover sheets can effectively suppress defects commonly occurring in elastomer forming without cover sheet constraints, such as localized wrinkling, excessive thinning, and cracking, thereby improving the smoothness of the formed component profile [38].

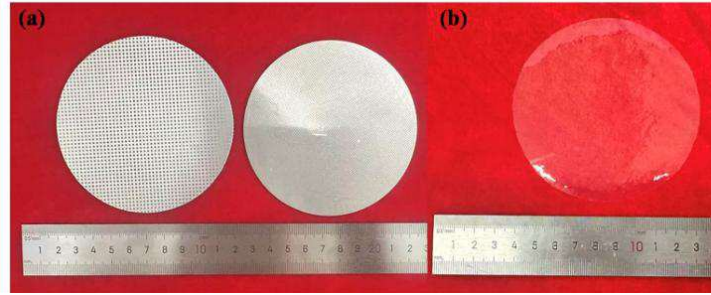


Fig. 15 Deformed plates and soft-molded coated plates

The bulging experiments were conducted by applying a constant displacement through the punch until the forming limit was reached. After maintaining the pressure for 30 s, the pressure was released and the formed components were removed. The elastomer bulged components without cover elastomer are shown in Fig. 16(a). An arc-shaped crack appears at the center of the spherical top region of the component formed by the steel punch. This is attributed to the inability of the rigid punch to accommodate the sheet deformation, resulting in non-uniform pressure transmission and local stress overload. For all polyurethane punch cases, cracks are located in the region of concentrated biaxial tensile strain and severe thickness reduction at the spherical top. Among them, the component formed by the 60A polyurethane punch exhibits the best surface quality, whereas the components formed by the 80A and 90A polyurethane punches only exhibit slight plastic deformation.

The elastomer bulged components with cover sheets are shown in Fig. 16(b). Under the cover sheet condition, the surface quality of the bulged components is significantly improved. The component formed by the 45# steel punch exhibits a relatively smooth surface, with only slight annular indentation occurring at the boundary between the spherical top and sidewall regions. The overall geometry is closer to a hemispherical component compared with the single-layer cover sheet-assisted bulging component. The forming quality of the components formed by polyurethane elastomer punches is further improved. No macroscopic cracks are observed, and the formed components exhibit smooth surfaces, regular profiles, and uniform deformation in the spherical top region without localized excessive deformation. The component formed by the 60A polyurethane punch shows no visible deformation defects and

achieves the best surface quality among all investigated conditions. The components formed by the 70A, 80A, and 90A polyurethane punches exhibit only slight plastic deformation in the spherical top region, satisfying the appearance requirements for engineering applications.

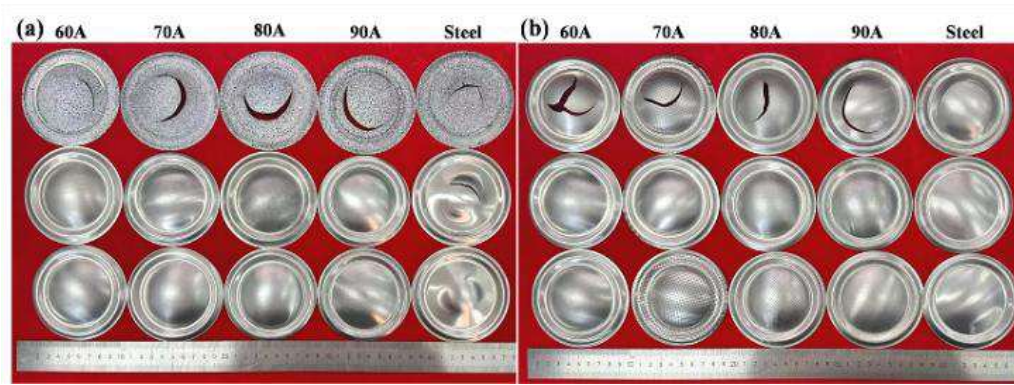


Fig. 16 Forming parts: (a) blank forming parts without cover elastomer;
(b) blank forming parts with cover elastomer

The three-dimensional geometries of the bulged components were reconstructed using a 3D laser scanner, as shown in Fig. 17. The bulged components formed with cover sheets exhibit higher bulging heights than those formed without cover sheets. Under the uncovered condition, the component formed by the 45# steel punch presents a relatively small curvature at the spherical top region. The transition region between the sidewall and spherical top is relatively flat, resulting in a large suspended area and a lower bulging height. Compared with the uncovered condition, the geometrical accuracy of the components formed with cover sheets is improved. The profiles of the components formed by elastomer punches are approximately semicircular, and their bulging heights are significantly higher than those obtained with the steel punch. Moreover, the bulging height increases with decreasing polyurethane hardness. The use of cover elastomers enables the formed components to closely approach the ideal hemispherical shape. No distortion is observed in the transition region between the sidewall and the spherical cap, indicating a smooth geometric transition. Consequently, the formed components exhibit excellent symmetry and shape integrity.

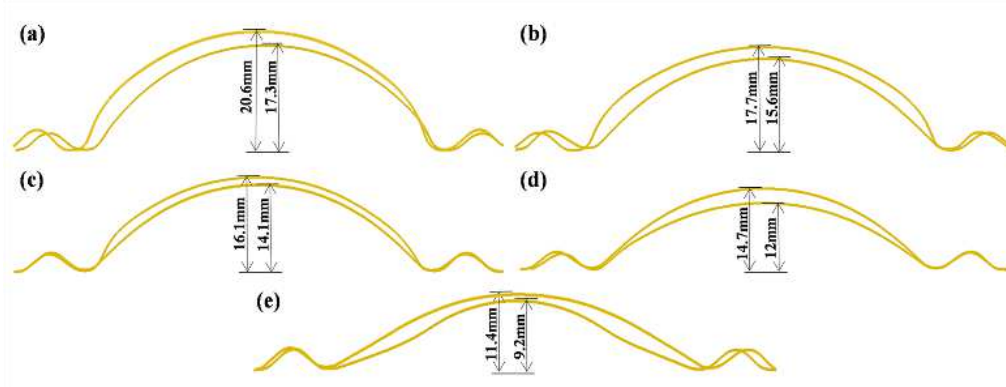


Fig. 17 Deformed blank configuration: (a)60A,(b)70A,(c)80A,(d)90A,(e)Rigid punch

Fig. 18 shows the bulging heights of the formed components. Under the condition without cover elastomer, the bulging height of the component formed by the steel punch is 9.2 mm, while that formed by the 60A polyurethane punch reaches 17.3 mm, representing an increase of 88% compared with the steel punch. During the bulging process, the plastic deformation of the sheet is completely driven by the pressure applied from the punch. When local stress concentration occurs, the profile of the formed component cannot maintain a regular hemispherical shape, resulting in geometric distortion. In contrast, the flexible deformation capability of the polyurethane elastomer punch improves the material plastic flow behavior, leading to a higher bulging height than that achieved with the steel punch.

Under the cover elastomer condition, the bulging height also increases with decreasing punch hardness. The bulging height of the component formed by the 45# steel punch increases from 9.2 mm without cover sheets to 11.4 mm with cover sheets, and the geometry becomes closer to an ideal hemispherical shape. The increase in bulging height is more significant for polyurethane elastomer punches. The component formed by the 60A polyurethane punch reaches a bulging height of 20.6 mm, which is 19.1% higher than that without cover sheets (17.3 mm).

The bidirectional clamping–traction effect provided by the cover sheets is the primary reason for the increase in bulging height. During the bulging process, the bidirectional interfacial friction between the inner and outer cover sheets and the aluminum alloy sheet promotes more sufficient material flow from the sidewall region, providing additional material supply for plastic deformation. Meanwhile, the

bidirectional normal constraint maintains a stable deformation state of the sheet during bulging, prevents local geometric distortion, and ensures the forming quality of the components.

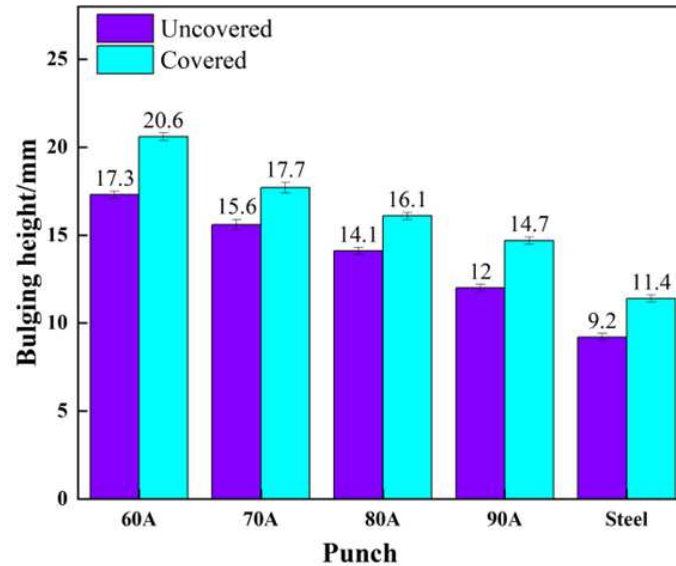


Fig. 18 Expansion height in different punch conditions

The strain distributions of the elastomer bulged components without cover elastomer were measured using a digital image correlation (DIC) system, and the results are shown in Fig. 19. Regardless of whether a steel punch or a polyurethane elastomer punch was used, the 2A12-T4 aluminum alloy sheets exhibited obvious strain concentration under the uncovered condition. The maximum strain was always located in the spherical top region, and the strain gradually decreased from the spherical top toward the sidewall, resulting in a large strain gradient.

For the component formed by the 45# steel punch, the maximum strain in the spherical top region reaches 10.7%, indicating the most significant strain concentration. The strain difference between the spherical top and sidewall regions exceeds 40%. The maximum strain of the component formed by the 60A polyurethane punch reaches 19.2%. With increasing punch hardness, the strain decreases, and the strain difference between the spherical top and sidewall gradually becomes smaller. This phenomenon is attributed to the stronger flexibility of the low-hardness polyurethane punch. During the bulging process, the larger deformation of the punch itself may still result in locally excessive pressure. As the polyurethane hardness increases, the deformation of the punch decreases, improving the uniformity of pressure transmission and partially

mitigating strain concentration [39]. During the uncovered bulging process, the spherical top region of the sheet is mainly subjected to biaxial tensile strain, and the circumferential tensile strain is significantly higher than the meridional tensile strain. This strain state easily leads to localized excessive thinning of the sheet, which is the primary cause of cracking defects in the uncovered bulging process. In contrast, the sidewall region mainly experiences uniaxial tensile strain, and its deformation degree is much lower than that of the spherical top region. Consequently, the plastic flow capability of the material is not fully utilized, resulting in poor overall forming performance [40].

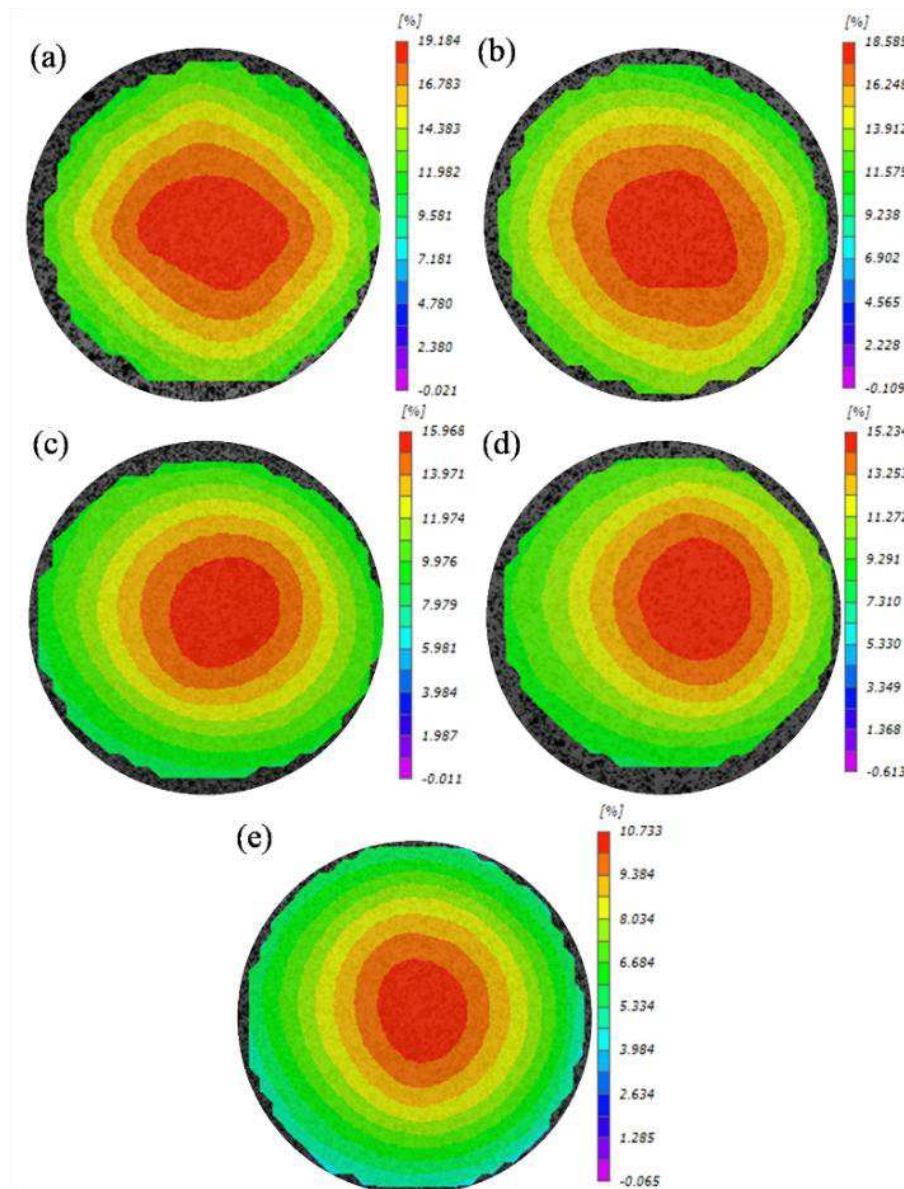


Fig. 19 Strain distribution under no cover elastomer loading conditions:
(a) 60A, (b) 70A, (c) 80A, (d) 90A, (e) Rigid punch

The full-field strain distributions of the formed components under the double-sided cover elastomer condition are shown in Fig. 20. Compared with the uncovered condition, the strain distribution exhibits significantly improved uniformity. The strain concentration phenomenon in the spherical top region is almost eliminated, and the strain distribution over the entire forming region becomes more homogeneous. As a result, the plastic flow capability of the material is fully utilized, achieving uniform deformation throughout the component.

For the component formed by the 45# steel punch, the maximum equivalent strain in the spherical top region increases from 13.7% with a single cover sheet to 16.4% with double-layer cover sheets. The strain decreases smoothly and approximately linearly from the spherical top toward the sidewall, and the strain difference between the spherical top and sidewall regions is reduced to only 10%. This indicates that the bidirectional traction effect generated by the double-layer cover sheets effectively promotes the participation of sidewall material in plastic flow. The strain distribution uniformity of the components formed by polyurethane elastomer punches is further improved. The component formed by the 60A polyurethane punch exhibits the highest maximum strain of 21.8% among all investigated conditions, while also achieving the most uniform full-field strain distribution. The strain difference between the spherical top and sidewall regions is only 5%, and no obvious strain concentration region is observed. This strain distribution characteristic results from the bidirectional synergistic regulation provided by the double-layer cover sheets. The bidirectional normal constraints improve the stress state of the sheet and prevent excessive deformation along a single direction. Meanwhile, the bidirectional interfacial friction promotes sufficient plastic flow of the sidewall material, enabling uniform deformation throughout the component. Compared with the uncovered condition, the elastomer-covered forming process achieves full-field homogeneous deformation and significantly enhances the plastic deformation capability of the 2A12-T4 aluminum alloy sheet.

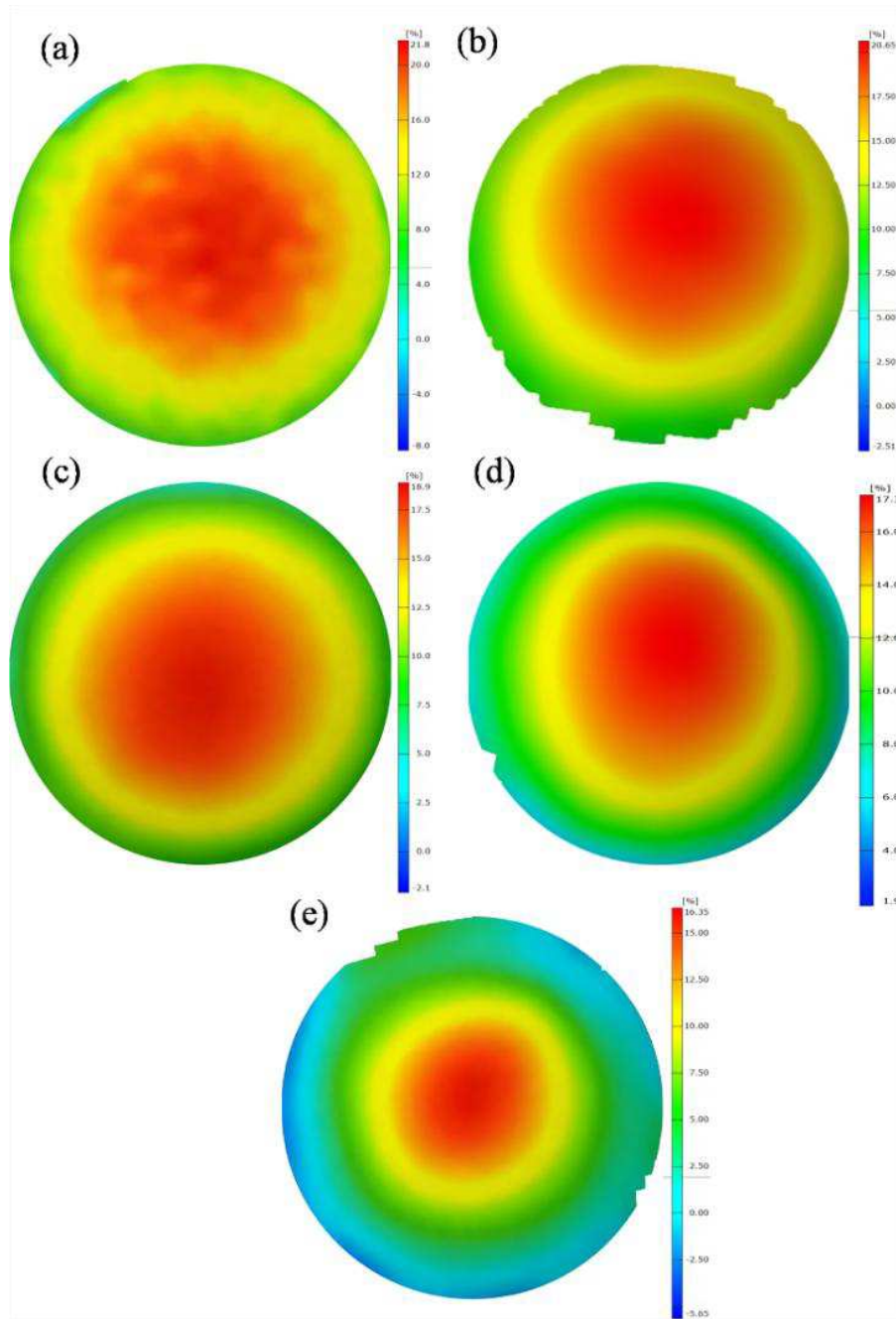


Fig. 20 Strain distribution under cover elastomer loading conditions:
(a) 60A, (b) 70A, (c) 80A, (d) 90A, (e) Rigid punch

Thickness reduction is an important criterion for evaluating the forming performance of bulging components. As shown in Fig. 21, for the bulged components without cover elastomer, the maximum thickness reduction occurs in the spherical top region where strain concentration is located. From the spherical top toward the sidewall, the thickness reduction gradually decreases, indicating significant non-uniformity in the thickness distribution. This result is consistent with the thickness reduction distribution obtained from the finite element simulation in Fig. 10.

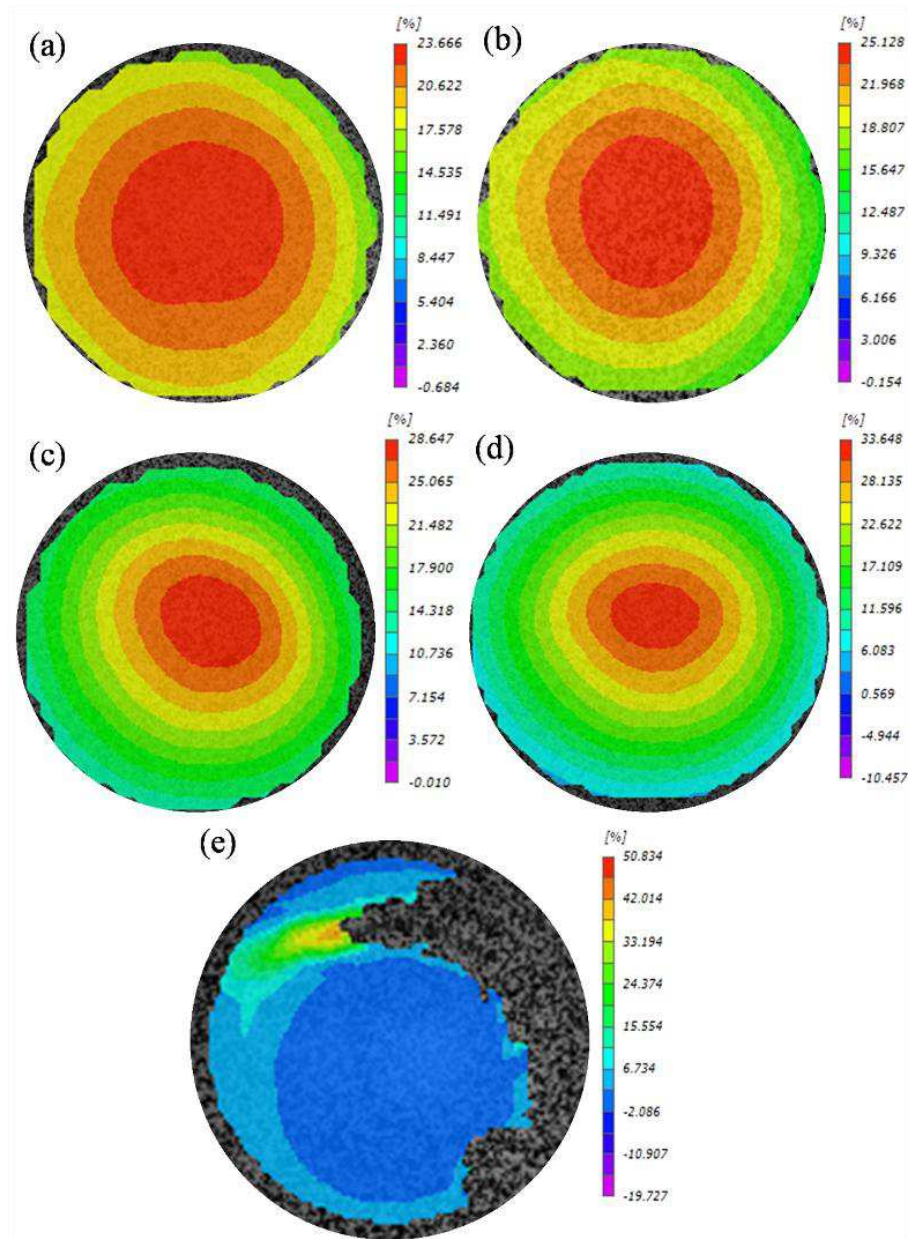


Fig. 21 Distribution of thinning rate under no cover elastomer loading conditions:
(a) 60A, (b) 70A, (c) 80A, (d) 90A, (e) Rigid punch

The wall thickness reduction distributions of the formed components under the cover sheet condition are shown in Fig. 22. Compared with the uncovered condition, the thickness reduction is significantly reduced, and the uniformity of wall thickness distribution is greatly improved. The wall thickness remains nearly consistent throughout the entire forming region, without localized excessive thinning, resulting in a uniform thickness distribution. The overall wall thickness variation of the components formed with cover sheets is controlled within 0.05 mm, which is lower than the 0.12 mm variation observed without cover sheets. Among all investigated conditions, the

component formed by the 60A polyurethane punch exhibits the smallest wall thickness variation of only 0.02 mm, approaching an ideally uniform thickness distribution.

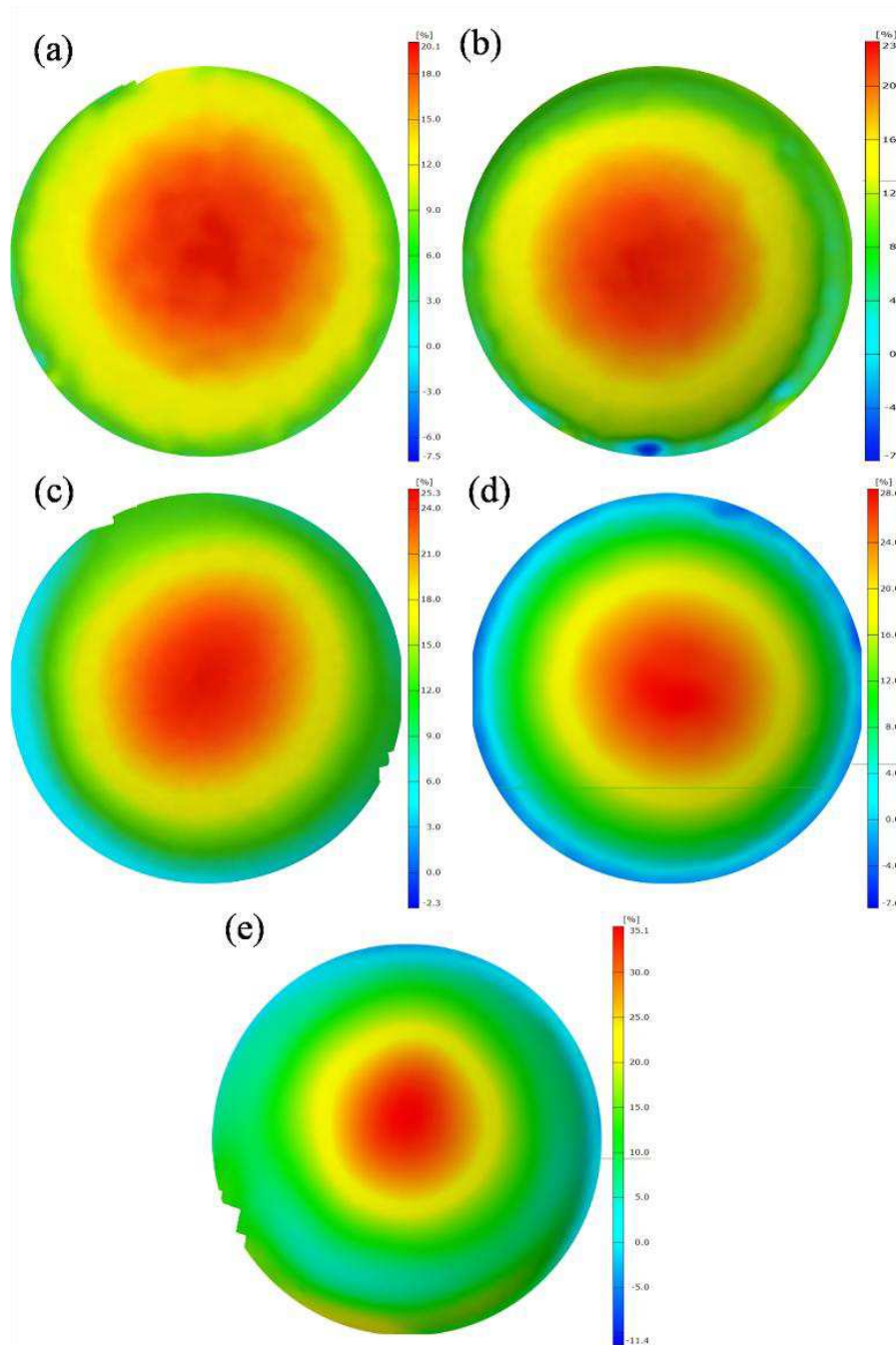


Fig. 22 Thin film distribution under cover elastomer loading conditions:
(a) 60A, (b) 70A, (c) 80A, (d) 90A, (e) Rigid punch

As shown in Fig. 23, under the uncovered elastomer condition, the maximum thickness reduction of the steel punch-formed component reaches 50.8% in the spherical top region. This is attributed to the friction between the steel punch and the sheet, which restricts deformation at the top region. As a result, deformation becomes

highly localized in the unsupported sidewall region, leading to an abnormally high local thickness reduction. Meanwhile, the maximum thickness reduction gradually decreases with decreasing polyurethane punch hardness, and the component formed by the 60A polyurethane punch exhibits a maximum thickness reduction of 23.7%.

Under the cover elastomer condition, the maximum thickness reduction at the spherical top region of the steel punch-formed component decreases from 50.8% without cover sheets to 35.1%. Meanwhile, the thickness reduction in the sidewall region reaches 10–12%, indicating that material flow from the sidewall toward the spherical top region is significantly enhanced, effectively compensating for the material consumption at the top region. For polyurethane elastomer punch-formed components, the maximum thickness reduction in the spherical top region is significantly reduced compared with the uncovered condition, and it decreases continuously with decreasing punch hardness, which is consistent with the simulation results. The component formed by the 60A polyurethane punch exhibits a maximum spherical top thickness reduction of only 20.1%, representing the lowest value among all experimental conditions.

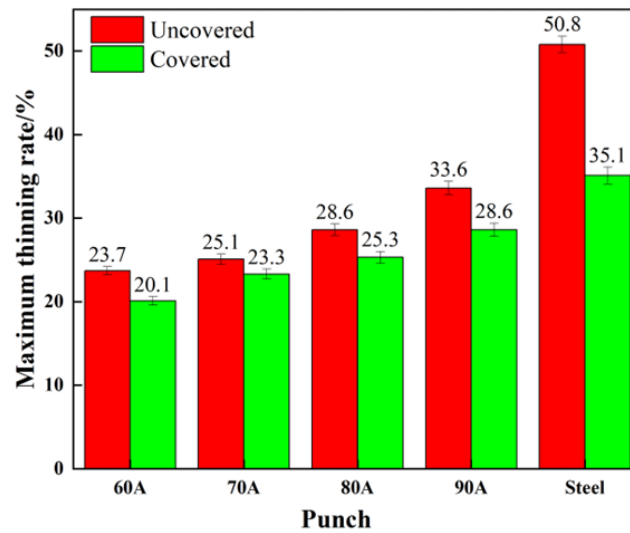


Fig. 23 Maximum thinning rate in different punch conditions

3.3.2 Forming limit

The forming limit is a critical indicator for evaluating the plastic deformation capability of metallic sheets [41]. In this study, the elastomer-covered sheet-assisted bulging process was taken as the research focus, and forming limit tests were conducted on 2A12-T4 aluminum alloy sheets to investigate the forming limit characteristics

under the cover sheet condition. Circular 2A12-T4 aluminum alloy forming limit specimens with a diameter of 98 mm were prepared, as shown in Fig. 24. The forming limit experiments were performed using 90A polyurethane elastomer cover sheets, combined with a 45# steel punch and polyurethane elastomer punches with hardness values of 60A, 70A, 80A, and 90A.

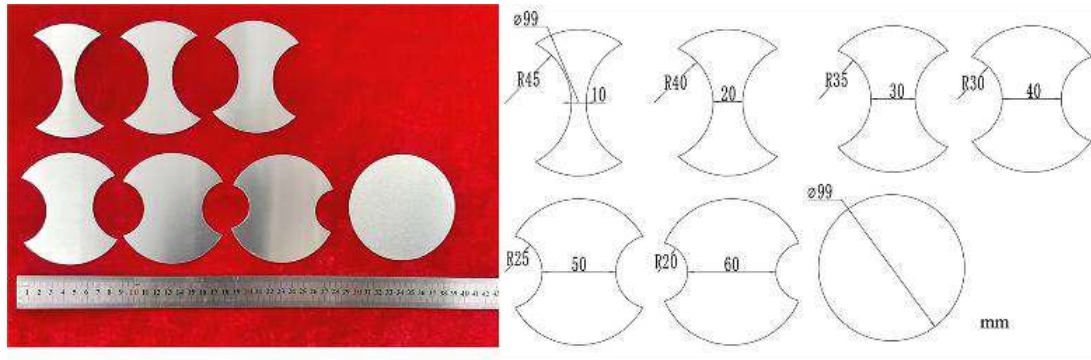


Fig. 24 Forming limit specimen

Representative forming limit specimens formed using the 45# steel punch and the 60A polyurethane punch are shown in Fig. 25, revealing a pronounced difference in deformation behavior. For the component formed by the 45# steel punch, the macroscopic failure appears as a short arc-shaped through crack with a limited crack propagation length. In addition, the bulging height is relatively low, indicating that the sheet fractured before sufficient plastic deformation could be achieved, resulting in a relatively low forming limit. For the components formed by the polyurethane elastomer punch, the cracks are consistently located in the spherical top region and exhibit a significantly larger propagation range. The compliant load-transferring characteristic of the polyurethane elastomer effectively delays crack initiation, thereby substantially improving the forming limit of the sheet. Among all investigated conditions, the component formed by the 60A polyurethane punch exhibits the greatest deformation capacity and achieves the highest forming limit.

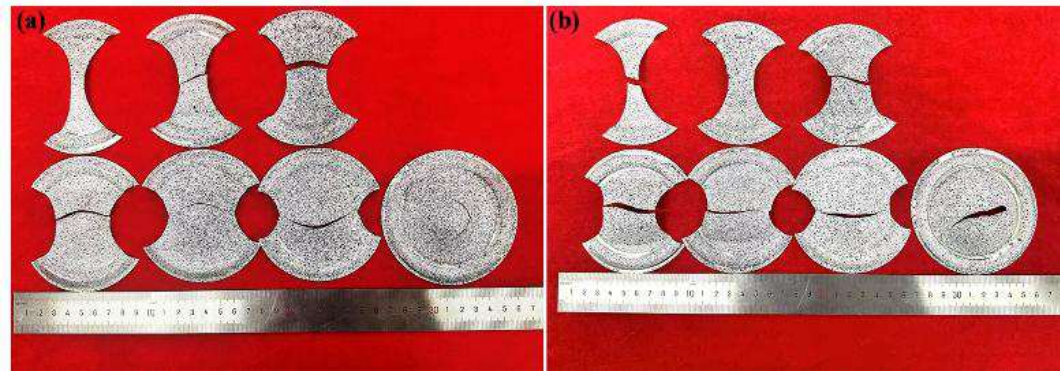


Fig. 25 Forming limit bulging parts: (a) Rigid die and (b) 60A

The strain distributions of the forming-limit specimen were measured using a digital image correlation (DIC) system. Taking the optimal forming condition, i.e., the double-layer cover sheet condition with the 60A polyurethane punch, as an example, the major and minor strain distributions at the forming limit are presented in Fig. 26. The maximum major strain occurs at the location where microcracks initiate in the spherical top region, reaching 23.7%. From the spherical top toward the sidewall, the major strain exhibits a smooth and approximately linear decreasing trend without obvious abrupt strain localization, indicating that plastic deformation occurs throughout the entire sheet and that the material flow capability is fully utilized. The minor strain at the crack initiation region of the spherical top exhibits a slight compressive strain characteristic, while gradually transforming into tensile strain toward the sidewall. The overall variation of minor strain is limited, and its distribution remains relatively uniform. This demonstrates that under the constraint of double-layer cover sheets, the strain state of the sheet becomes more balanced, and the biaxial tensile strain ratio is optimized. Consequently, premature cracking caused by excessive deformation along a single direction is effectively suppressed.

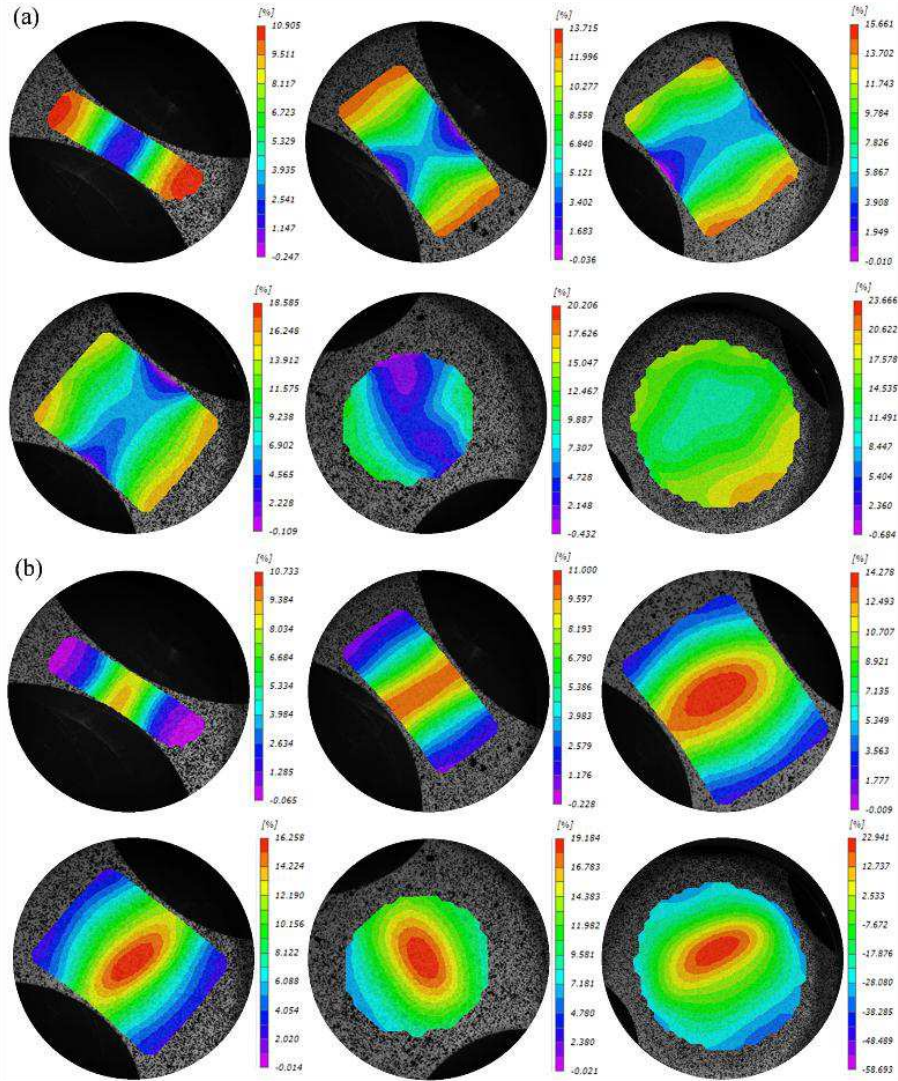


Fig. 26 Distribution of forming limit strain at 60A under cover elastomer condition:
(a) major strain and (b) minor strain

The forming limit strains obtained under different punch conditions in the elastomer-covered bulging process were plotted in the major strain–minor strain coordinate system to establish the forming limit diagram (FLD) of the 2A12-T4 aluminum alloy sheet, as shown in Fig. 27. The forming limit curves under different punch conditions exhibit an obvious gradient characteristic. The sheet exhibits the lowest forming limit when formed with the rigid steel punch, with a maximum major strain of only 0.14. In contrast, the forming limit curves obtained with polyurethane elastomer punches gradually shift upward as the punch hardness decreases. The 60A polyurethane punch produces the highest-positioned forming limit curve, with a maximum major strain of 0.25, indicating the highest forming limit among all

investigated conditions.

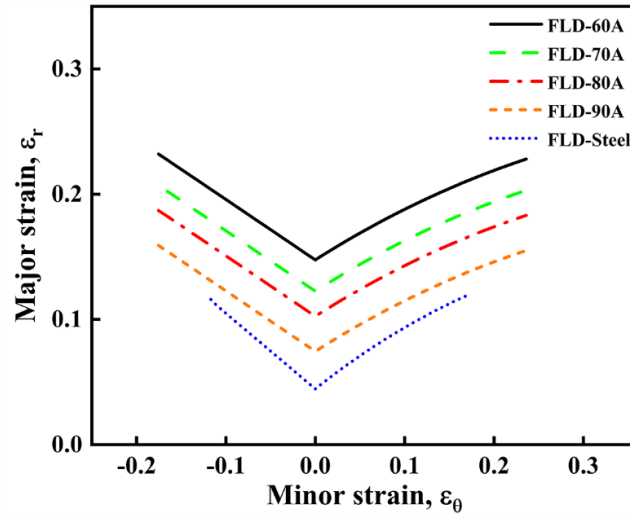


Fig. 27 Forming limit diagram of cover elastomer

4 Conclusions

Based on the results obtained, the following conclusions can be highlighted:

1. The elastomer-covered sheet-assisted forming process regulates the load transfer and relative sliding behavior of the sheet through the normal contact constraints and interfacial friction provided by the double-sided cover sheets. The high-stress and high-strain regions gradually extend from the spherical top toward the sidewall, accompanied by a reduction in stress gradient and an expansion of the high-stress-bearing region. This mechanism suppresses localized excessive thinning, improves the uniformity of stress distribution, and enhances the overall forming performance of the sheet.
2. Within the polyurethane hardness range of 60A–90A, decreasing punch hardness enlarges the effective contact area between the elastomer and the sheet, resulting in smoother pressure transmission and progressive improvements in bulging height and thickness uniformity. Among all investigated conditions, the 60A polyurethane punch exhibits the best forming performance. Compared with the uncovered forming condition, the bulging height increases from 17.3 mm to 20.6 mm, representing a 19.1% improvement. Meanwhile, the maximum experimental thickness reduction decreases from 23.7% to 20.1%, corresponding to a reduction

of 3.6 percentage points and a relative decrease of 15.2%. The overall wall thickness variation is controlled within 0.02 mm, with no localized excessive thinning or macroscopic cracking defects.

3. The double-sided cover sheet configuration significantly improves the forming limit of the 2A12-T4 aluminum alloy sheet. Under the 60A polyurethane punch condition, the forming limit curve (FLD) is located at the highest strain region among all investigated conditions, with a maximum major forming limit strain of 0.25. Compared with the steel punch condition (0.14), the maximum major strain increases by 0.11, corresponding to a relative improvement of approximately 78.6%. This demonstrates that the synergistic effect of the low-hardness flexible punch and double-sided cover sheets effectively delays localized instability and fracture of the sheet.
4. The high-stress, high-strain, and maximum thickness reduction regions obtained from finite element simulations are in good agreement with those observed experimentally. Both simulation and experimental results demonstrate that the cover sheets reduce the deformation gradient from the spherical top toward the sidewall. Furthermore, the decreasing trend of maximum thickness reduction with decreasing polyurethane punch hardness is consistent between simulations and experiments. These results confirm that the established finite element model can reasonably describe the contact load-transfer behavior and sheet deformation characteristics during double-sided cover sheet-assisted bulging.

Statements & Declarations

Author Contributions Zhang Rui: Writing – original draft, Writing – review and editing, Validation, Methodology, Investigation, Supervision, Funding acquisition. Hu Shuai: Writing – review and editing, Methodology, Investigation, Formal analysis, Data curation. Wang Xianxi: Writing – review and editing, Visualization, Data curation. Chen Shiyao: Writing – review and editing. Zhou Haofei: Writing – review and editing. Wang Pengyi: Writing – review and editing. Sui Qi: Writing – review and editing. Han Ying: Writing – review and editing. Ran Xu: Writing – review and editing.

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