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ORIGINAL ARTICLE

Investigation of viscous pressure forming for 6K21-T4 aluminum alloy car panels

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Abstract Aluminum alloy car panels are difficult-to-form, complex components, with low formability at room temperature and high springback, and are easily scraped after forming. Although several advanced forming technologies have been developed to improve the formability of aluminum alloys, currently, there are no viable and cost-effective methods for the manufacture of high-quality aluminum alloy car panels. In this paper, a newly-developed flexible die forming approach called viscous pressure forming (VPF) is proposed to manufacture car hoods with scaled-down dimensions. The use of VPF technology provides decreased springback and improved surface quality, and manufacturing expense can be decreased by taking advantage of the characteristics of this technology. Both forming experiments and the finite element method (FEM) were adopted to investigate the forming of the panels and to verify the accuracy of the simulation model. The FEM was then used to further investigate key forming process parameters, such as sheet blank shape and blank holder force (BHF), particularly their role in the main defect of local wall thinning. Results indicated that the maximum thinning of a formed hood was 32.4 % when using an initial sheet blank under a constant BHF of 40 kN, while it decreased by 41.7 % when using the optimized sheet blank under variable BHF with segmented binders. This is mainly because material flow can be efficiently controlled under variable BHF. VPF technology combined with an appropriate sheet blank and variable BHF is an advantageous approach for manufacturing high-quality aluminum alloy car panels.

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Keywords Aluminum alloy panels · Viscous pressure forming · Sheet blank shape · Variable blank holder force

1 Introduction

With the aggravation of energy crisis, there is a great demand for weight reduction in the automobile industry. This demand has led some new materials to replace traditional steels. High-strength aluminum alloys are becoming one of the ideal materials because of their low density, outstanding corrosion resistance, high strength-to-weight ratio, and so on [1, 2]. However, the formability of aluminum alloys is poor in traditional forming technologies at room temperature [3, 4], which can result in cracking and even an unacceptable level of springback. Hence, its extensive applications in automotive industry are restricted. Currently, only 9 % of an automobile's weight is composed of aluminum alloy parts, and most of them are cast alloys [5].Therefore, advanced forming technologies should be investigated to manufacture complex shape aluminum alloy parts with low formability.

Several advanced forming technologies, such as warm forming, incremental forming, and superplastic forming, have been developed to overcome these forming problems and to manufacture aluminum alloy parts [6]. Although aluminum alloys exhibit good formability [7] and low springback [8] at elevated temperature, it may lead to softening and destroy the desirable microstructure [9]. Complex shape parts can be manufactured by incremental forming and this method suits for small batch or single products forming [10]. In addition, superplastic forming has wide applications in aluminum alloy car inner panels and front wing outer panels [11]. However, up to now, there are no viable and cost-effective methods for manufacturing high-quality thin-walled aluminum alloy car exterior body panels, such as car hoods and outer doors.

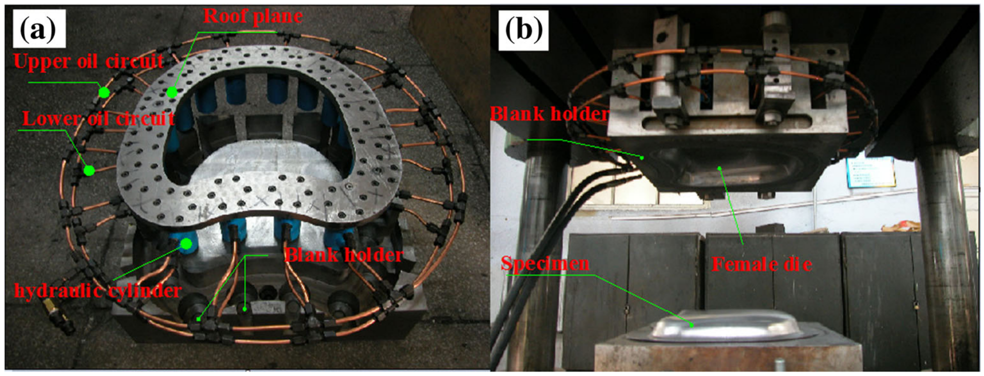

Fig. 1 Experimental setup

Viscous pressure forming (VPF) is a new flexible die forming process for metal sheets [12, 13], which uses a semi-solid, highly viscous, flowable, strain rate sensitive macromolecule polymer (called viscous medium) as a pressure-carrying medium. Because of these characteristics, the viscous medium can promote the flow of sheet blank, improve the stress distribution of sheet metal, reduce springback of formed parts, protect parts surface, and avoid scratching [14, 15]. Moreover, the viscous medium has no pollution to the environment and can be recycled. Previous researches show that VPF technology can improve the sheet formability at room temperature [16, 17] and especially suits for the forming of high-strength, difficult-to-form, complex component parts with low plasticity [14, 18]. Hence, the VPF process provides an opportunity to enlarge the application of aluminum alloy sheets in car exterior body panels and to reduce the manufacture costs of forming die.

Numerical modeling and simulation are important methods in the sheet metal forming process in recent years, which can decrease the efforts of experimental trials and reduce manufacturing costs [19]. Significant researches have been done through numerical simulation. Fu et al. [20] studied the deformation behaviors of flexible die forming using viscoplastic pressure-carrying medium through numerical simulation. It was found that the finite element method (FEM) could provide fundamental guidelines for the rational design and extensive practical applications of the process in industries. Cao et al. [21] analyzed the dynamic behavior of parts in the electromagnetic forming process (EMP) by FEM. The research indicated that this method could be accurate and simple for the analysis and optimum design of EMF systems. Cai et al. [22] investigated the wrinking, dimpling, and springback of sheet metal in the multi-point forming process through dynamic explicit FEM. Their study indicated that simulation results of curvature distribution on a cylindrical part agree well with experimental results and the numerical results could provide sufficient and valuable guidance on determining multi-point forming process parameters.

In this paper, VPF technology is adopted to form complex shape aluminum alloy car panels. In order to research the formability of the panels in VPF, we selected the aluminum alloy car hoods with scaled-down dimensions as test parts for the panels. Both the experiments and numerical simulation were utilized to research the forming process of the hoods. The forming experiments were carried out by means of a 4000-kN hydraulic press with a multi-point flexible blank holder force (BHF) loading system, and the reliability and validity of the simulation model were verified through the comparison between simulation results and experimental data obtained from the forming tests. Subsequently, the FEM was used to further investigate the forming process and to predict the panel formability under different forming parameters. It is significant in this research to promote the application of VPF technology in the industry to manufacture high-quality aluminum alloy car panels.

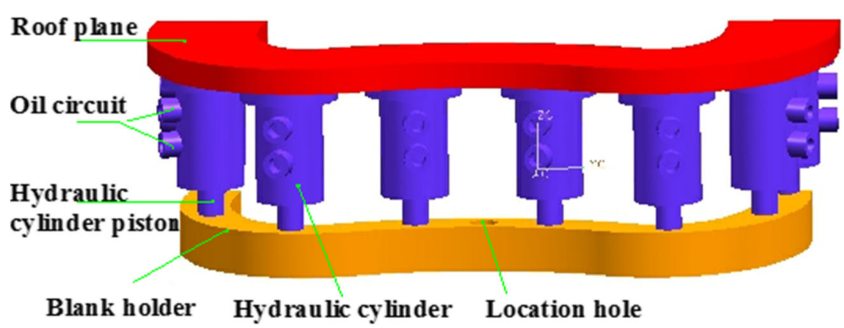

Fig. 2 Schematic diagram of the flexible BHF loading system

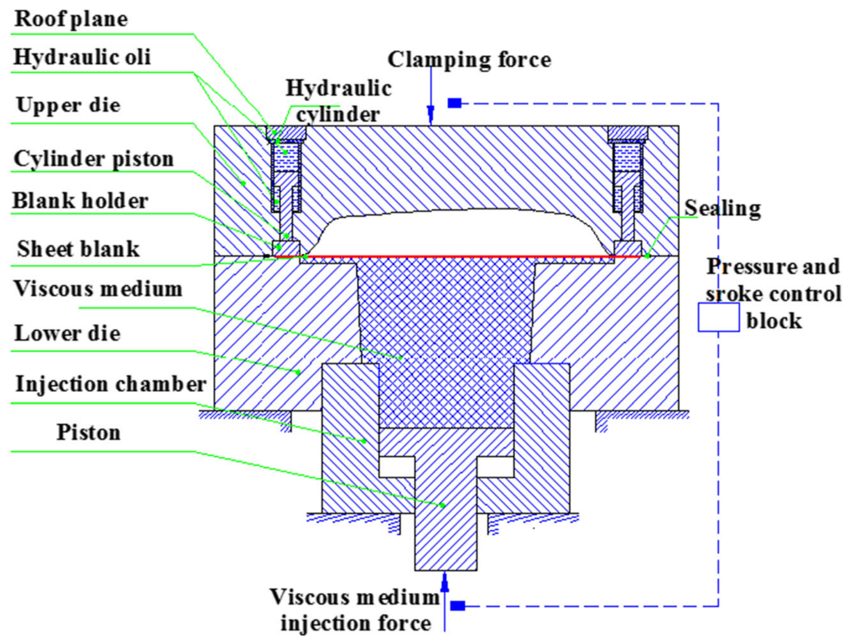

Fig. 3 Schematic drawing of the VPF process for aluminum alloy panels

2 Methods and materials

2.1 Experimental setup

In this work, a multi-point flexible BHF loading system, which has 16 hydraulic cylinders, was developed to manufacture the aluminum alloy car hoods, as shown in Figs. 1a and 2. Variable BHF can be applied by changing hydraulic pressure and the action numbers of hydraulic cylinders. The forming experiments of the hoods in VPF were conducted in the authors' laboratory, as shown in Fig. 1b. The results of the experiments were used to verify the simulation model in VPF.

The principle sketch of the aluminum alloy hood in VPF is shown in Fig. 3. The sheet blank is placed on the medium chamber, and then an appropriate BHF is applied by 16 hydraulic cylinders which can provide constant BHF and variable BHF. The sheet blank begins to form under the pressure which is generated with the upward movement of the viscous medium. In sheet metal forming processes, the effect of sheet blank shape [23] and BHF [24–26] is of significant importance, especially for difficult-to-form aluminum alloy hoods.

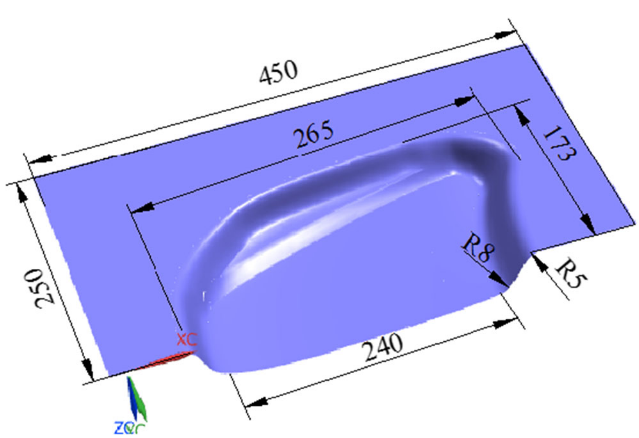

Fig. 4 Shape and main sizes of the half female die (unit: mm)

2.2 Finite element analysis model

The geometry and main sizes of the half female die are shown in Fig. 4. The bottom of the female die is a curved surface, and its maximum depth is 45 mm. In order to have a deep understanding of the deformation behavior of the aluminum alloy hood in VPF, we employed the commercially available finite element analysis (FEA) code ABAQUS/Explicit to simulate this forming process. The FEA model of the hood in the VPF process consists of a viscous medium, a blank holder, a sheet blank, a chamber, and a female die, as shown in Fig. 5. According to the symmetry of the geometry model and boundary conditions, one half of the whole model was selected to reduce the computational expense. The blank holder, the chamber, and the female die were meshed as 4-node-quadrilateral discrete rigid element with an assumption of not having any deformation in the VPF process. The sheet blank was defined as 4-node-quadrilateral shell element with reduced integration (S4R), and the mesh dimension of 2×2 mm^2 was used. The viscous medium was designated as 8-node-hexahadron body element. The Hill's quadratic yield criterion was utilized to define the

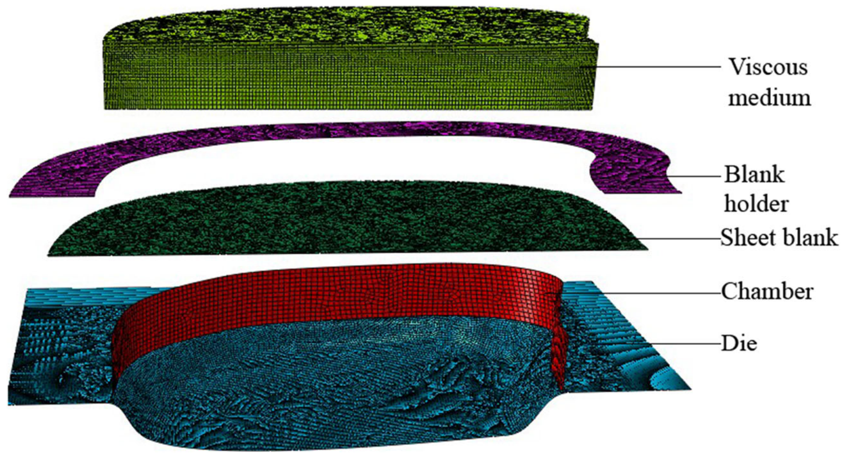

Fig. 5 FEA model of the VPF process

anisotropy of the sheet blank. Contact interactions were defined between the viscous medium and the sheet blank. The tangential behavior was defined as penalty with friction coefficient of 0.2 [18]. The normal behavior of the contact was hard contact which meant no penetration between the sheet blank and the viscous medium. Moreover, the mass scaling feature was considered to decrease the computational costs with influencing inertial effects.

2.3 Materials model

The aluminum alloy sheet used in this work was 6K21-T4 with a thickness of 1.2 mm. The uniaxial tensile properties of this material are summarized in Table 1. The viscous medium is a semi-solid, flowable, highly viscous, strain rate sensitive macromolecule polymer. Its flow stress versus the strain rate curve is shown in Fig. 6.

3 Results and discussion

3.1 Verification of the finite element model

The verification of the finite element model is carried out through the energy conservation principle and the comparison of simulation results with experimental results under the same conditions. Thinning is defined as the ratio of the amount of wall thickness reduction and original sheet blank thickness, expressed as the following (1):

$$\Delta = (t_0 - t)/t_0 \times 100\% \quad (1)$$

$$\varepsilon_T = \ln(t/t_0) = \ln(1-\Delta) \quad (2)$$

$$\Delta = 1 - \exp(\varepsilon_T) \quad (3)$$

where Δ is the thinning. ε_T is thickness strain. t_0 and t are the wall thickness before and after deformation.

For explicit dynamic simulation of the quasi-static VPF process, it is well known that the kinetic energy should be monitored to ensure that the ratio of kinetic energy to internal energy does not get larger than 10 % [27]. Compared with the internal energy variation, the kinetic energy keeps a smaller value during the whole explicit dynamic simulation of VPF process, as shown in Fig. 7. Thus, on the basis of the energy conservation principle, the inertia effects could be neglected and the quasi-static VPF process is ensured.

As shown in Fig. 8a, b, the geometry of the experimental aluminum alloy hood corresponds well with the

Table 1 Material properties of 6K21-T4 sheet

Young's modulus, E	73,390 MPa
Poisson's ratio, μ	0.34 MPa
Tensile strength	220 MPa
Yield strength	118 MPa
Flow stress $\overline{\sigma} = K\overline{\varepsilon}^n$	K=424 MPa, n=0.22
Anisotropy	r_0=0.78, r_{45}=0.61, r_{90}=0.66

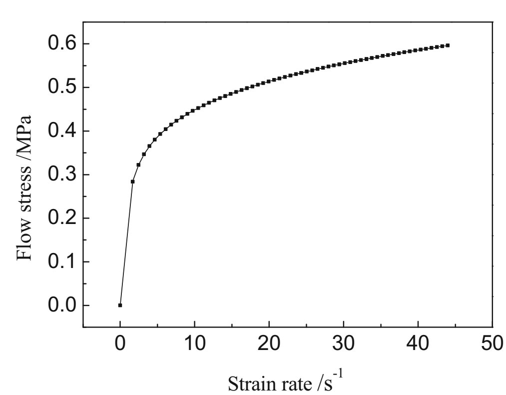

Fig. 6 Flow stress vs. strain rate curve of the viscous medium

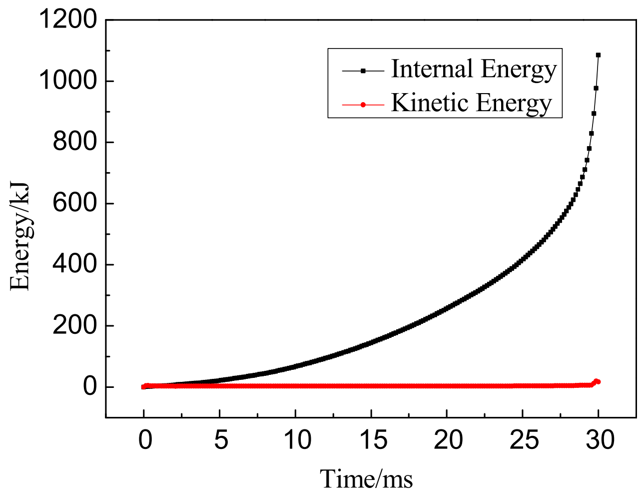

Fig. 7 Energy transformation in the VPF process

simulation part under the same processing conditions. The maximum equivalent plastic strain appears in region A (Fig. 8d), which is a dangerous area and most likely to fracture with the increasing of BHF, and the predicted result of simulation part can be verified by the experimental specimen, as shown in Fig. 8c. The thickness strain distribution of the experimental hood at a dangerous corner under a constant BHF of 80 kN is measured through The Automated Strain Analysis and Measurement Environment (ASAME), as shown in Fig. 9a. When it is transformed into wall thickness thinning according to Eq. (3), the maximum thinning of the hood is 20 %. Under the same conditions, the wall thickness distribution of the simulation part is shown in Fig. 9b. Its maximum thinning is 21 %, and the relative error is 5 % compared with that of experimental hood. This discrepancy is mainly caused by simplifying the real model and measuring errors.

3.2 Effect of material flow velocity distributions on the formability of the hood in VPF

As shown in Fig. 9a, b, the corner of the formed aluminum alloy hood is seriously thinned in the VPF process. Thus, this corner is selected to research its deformation behavior in VPF. Material flow velocity distributions of the viscous medium and sheet blank in the VPF process are shown in Fig. 10. It is found that the flow directions of the sheet blank and the viscous medium which act on the surface of the sheet blank are coincident during

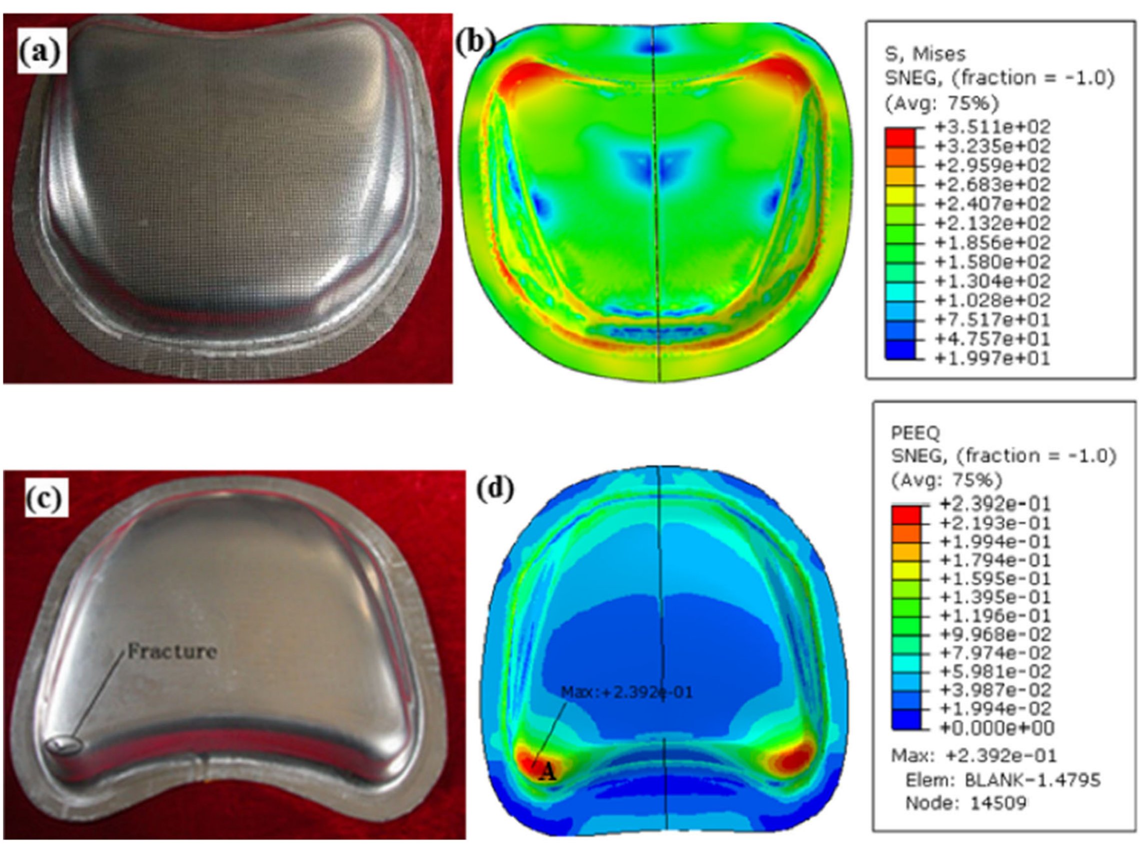

Fig. 8 Specimens from experiment and simulation. **a** Experimental hood. **b** von Mises equivalent stress contour of simulation part. **c** Fracture experimental hood. **d** Equivalent plastic strain contour of simulation part

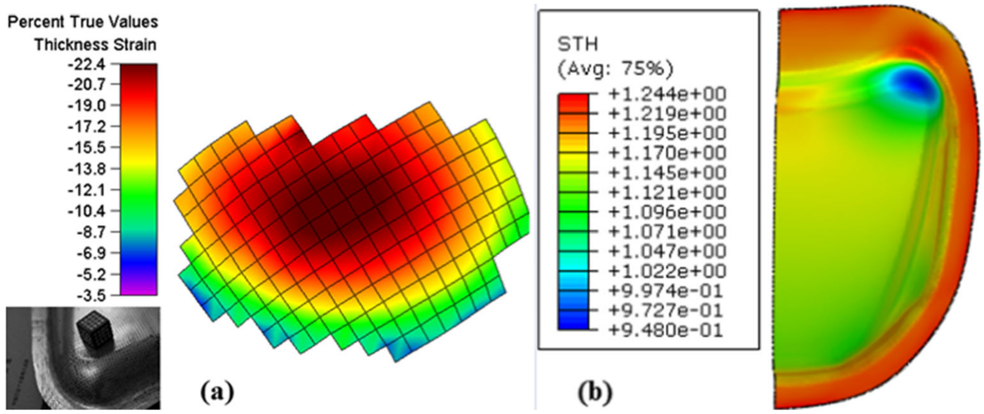

Fig. 9 Comparison of maximum wall thickness reduction. **a** Thickness strain distribution at dangerous area of experimental part. **b** Thickness distribution of simulation part

the whole forming process. Thus, more material flows is supplied into the corner of the female die, and then the maximum thinning is decreased for the formed aluminum alloy hood. In addition, the viscous medium wraps on the surface of the sheet blank in the whole VPF process; therefore, the surface quality of the formed aluminum alloy hood is improved and the advantages of VPF technology are showed.

3.3 Effect of sheet blank shape on the formability of the hood in VPF

It is important to choose a reasonable sheet blank shape for fabricating aluminum alloy car panels. As shown in Fig. 11, two kinds of sheet blanks are chosen to analyze the effect of sheet blank shape on the formability of the hood in VPF under a constant BHF of 40 kN. The first one is estimated through DYNAFORM and the second one is obtained from many times of optimization. The wall thickness distributions of formed aluminum alloy hoods in these two conditions are shown in Fig. 12a, b. The maximum thinning of the formed hood reaches at 32.4 % when using the initial sheet blank; thus, fracture usually appears in this corner area. However, the maximum thinning of the formed hood changes to 21 % when using the optimized sheet blank. This is mainly because the stress state at the dangerous corner of the formed hood is efficiently adjusted when using the optimized sheet blank

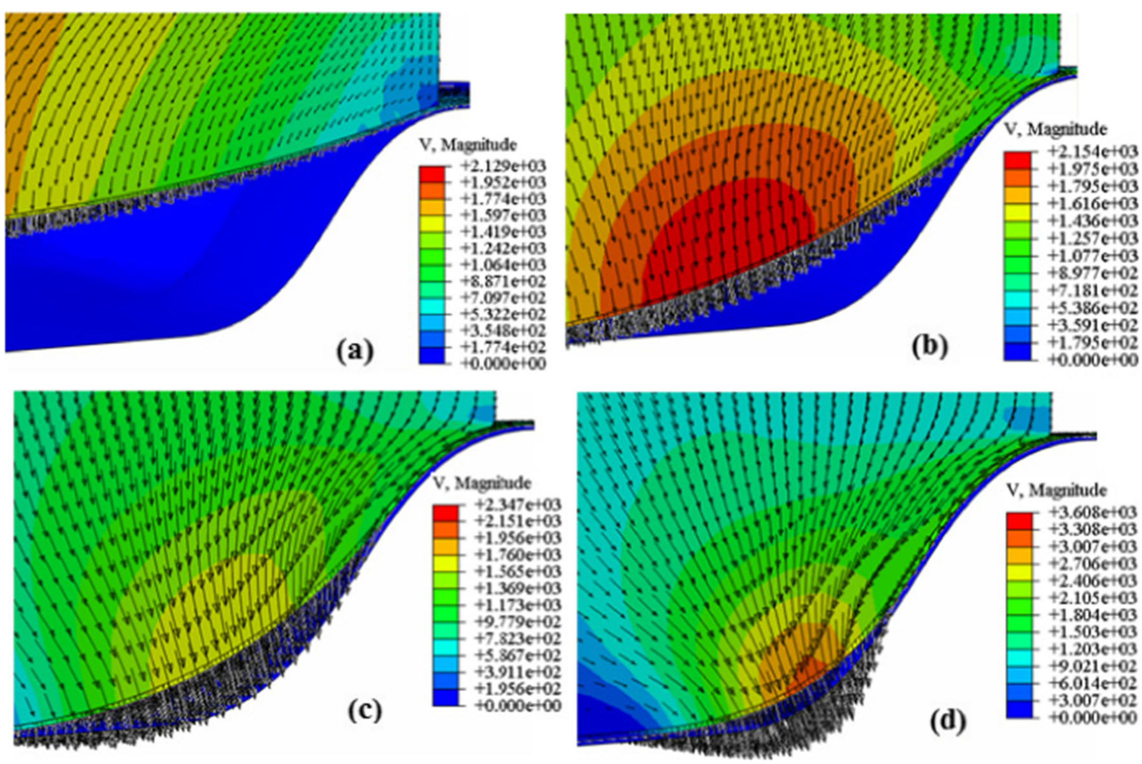

Fig. 10 Material flow velocity distributions at dangerous corner of sheet blank and viscous medium in VPF process. **a** 1/7 stroke of punch. **b** 3/7 stroke of punch. **c** 5/7 stroke of punch. **d** 6/7 stroke of punch

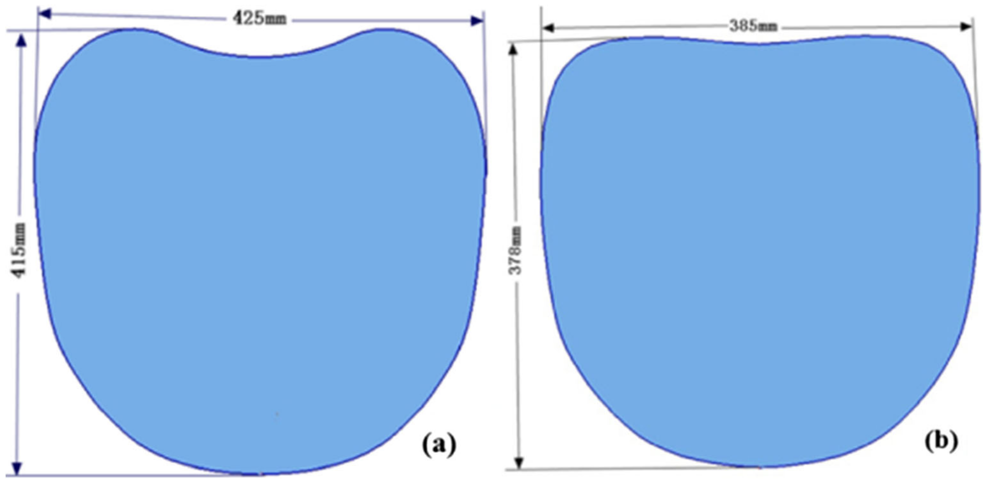

Fig. 11 Geometry of sheet blank. **a** Initial sheet blank. **b** Optimized sheet blank

compared with the initial one. According to the Levy-Mises incremental strain theory,

$$d\varepsilon_1^p/\sigma_1^{'} = d\varepsilon_2^p/\sigma_2^{'} = d\varepsilon_3^p/\sigma_3^{'} = d\lambda \quad (4)$$

With the decrease of $\sigma_3^{'}$ from 250.7 to 244.7 MPa in thickness direction, the plastic strain increment $d\varepsilon_3^p$ would be decreased; the thickness strain ε_3 then decreases from 0.35 to 0.27 in these two conditions. With the decrease of the

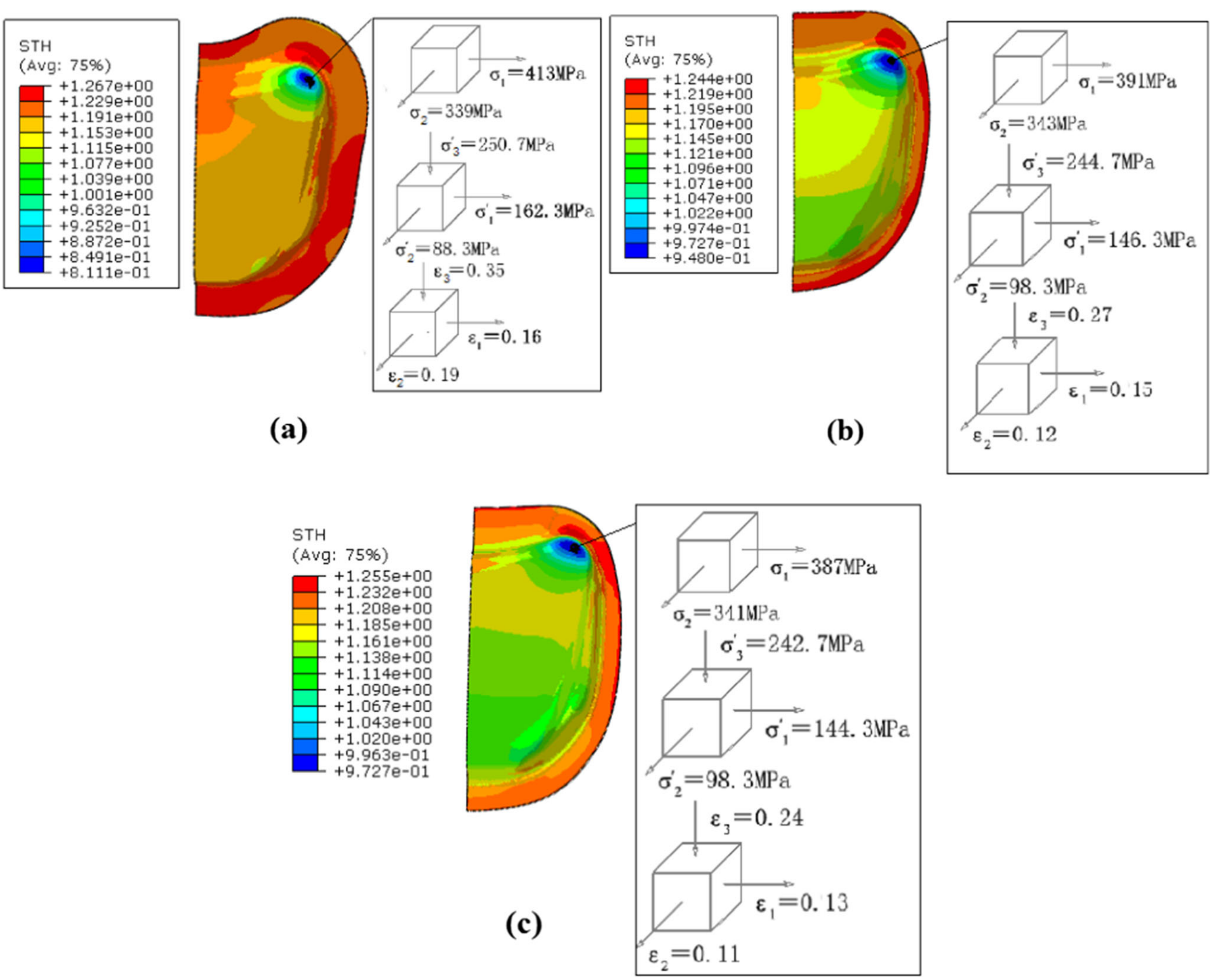

Fig. 12 Wall thickness distributions under different conditions. **a** Initial sheet blank. **b** Optimized sheet blank. **c** Variable BHF with segmented binders

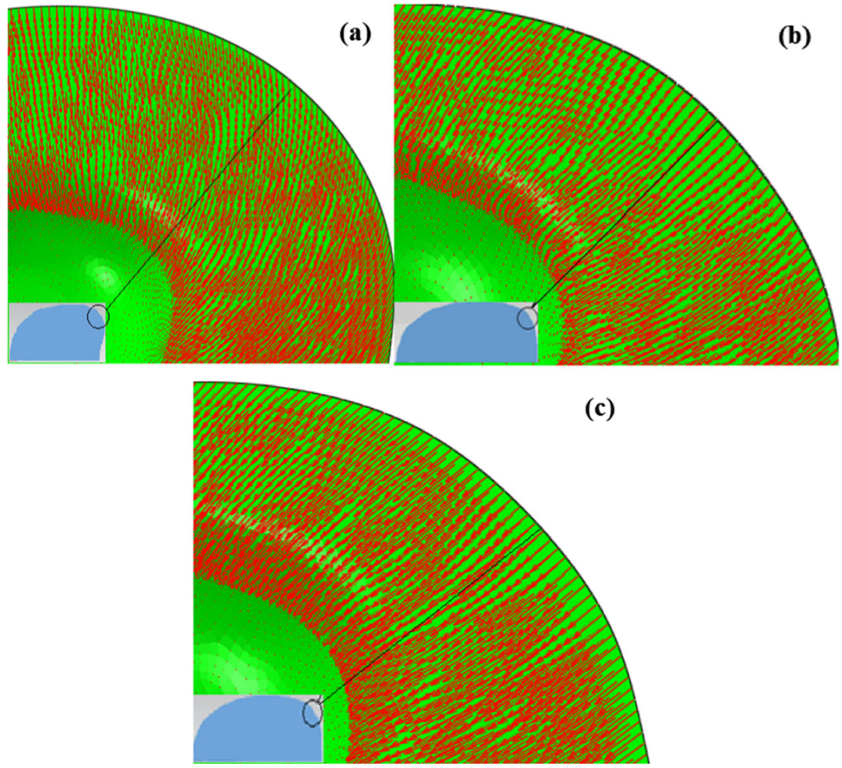

Fig. 13 Flange material flow of dangerous corner under different conditions. **a** Initial sheet blank. **b** Optimized sheet blank. **c** Variable BHF with segmented binders

thickness strain ε_3, the maximum thinning is reduced. In addition, material flow is another important factor, as shown in Fig. 13a, b. It can be found that the material flow direction at the corner flange is changed. When using the optimized sheet blank, the material flow direction is perpendicular to the rim of the corner flange and the material flows directly into the female die along the radical direction. Thus, the formability of the aluminum alloy hood is improved when using the optimized sheet blank.

3.4 Effect of BHF on the formability of the hood in VPF

The BHF is an important factor which influences the formability of the aluminum alloy hood in VPF. Therefore, two kinds of BHFs are chosen to research the effect of BHF on the formability of the hood in VPF. The first one is a constant BHF of 40 kN which are analyzed above, and the other one is a variable BHF with segmented binders, as shown in Figs. 14 and 15. The BHFs applied on block2 and block3 are both 10 kN. The maximum thinning of the formed hood is 18.9 % when using the optimized sheet blank under variable BHF with segmented binders, as shown in Fig. 12c. This is mainly due to the fact that material flow is efficiently controlled under variable BHF with segmented binders, as shown in Fig. 16. Besides, the changed stress state (Fig. 12c) is also beneficial to the increase of material flow at the corner flange. Figure 16a shows the flange material flow displacement under constant BHF of 40 kN. It can be found that the

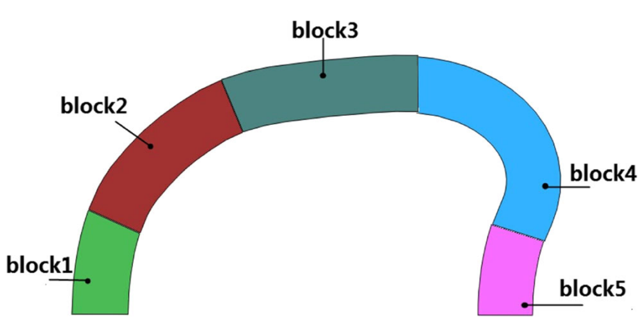

Fig. 14 Geometry of segmented binders

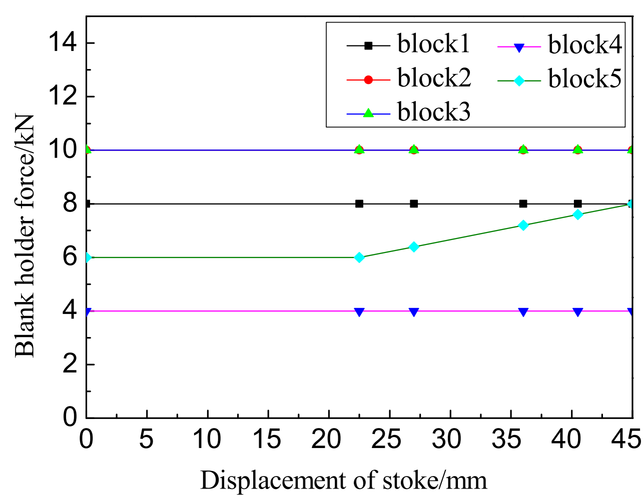

Fig. 15 Loading curves of variable BHF with segmented binders

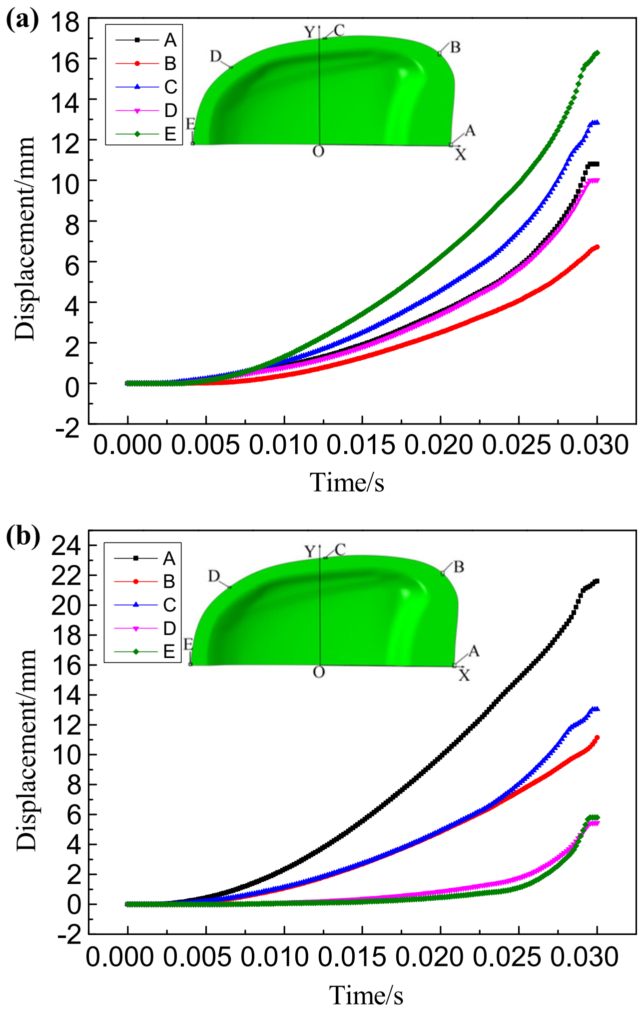

Fig. 16 Displacement of different flange regions under different BHFs. **a** Constant BHF of 40 kN. **b** Variable BHF with segmented binders

maximum and minimum material flow displacements of the flange appear in region E and region B, respectively. However, the flange material flow is efficiently regulated for the aluminum alloy hood in VPF under variable BHF with segmented binders. The maximum material flow region of the flange changes to region A. Material flow displacement of the region B is increasing from 6.7 to 11.2 mm, as shown in Fig. 16b, which significantly decreases the local thinning of the formed aluminum alloy hood. Therefore, the formability of the aluminum alloy hood in VPF is improved under variable BHF with segmented binders.

4 Conclusion

VPF technology is an advantageous approach for the fabrication of high-quality aluminum alloy car panels with low formability at room temperature. In this paper, the FE model of aluminum alloy hood in VPF was established in the commercial FE code ABAQUS, and the accuracy of the simulation model was verified by comparing the experimental and numerical geometry and the maximum thinning of the formed hood. There was a very close geometric match and a good agreement between the maximum thinning, with a deviation of 5 % from the experimental result. The model was then used to investigate the influence of sheet blank shape and BHF on the formability of the aluminum alloy hood in VPF. The main conclusions derived from this study are as follows:

1. The material flow directions of the sheet blank and the viscous medium acting on the surface of sheet blank are coincident in the whole VPF process so that more material flows are supplied into the corner of the hood. Therefore, the thinning at the dangerous area of the formed hood is reduced.
2. When using the optimized sheet blank, material flow direction is perpendicular to the rim of the corner flange and the material flows directly into the die cavity along the radical direction, which is in favor of improving the hood formability.
3. The maximum thinning of the formed aluminum alloy hood is 21 % when using the optimized sheet blank under constant BHF of 40 kN, while it decreases by 10 % when using the optimized sheet blank under variable BHF with segmented binders.
4. The corner flange material flow is controlled and the stress state is efficiently adjusted at the dangerous corner of the formed hood under variable BHF with segmented binders. Thus, the formability of the aluminum alloy hood in VPF is significantly improved.

This research can provide fundamental guidelines for automotive industry to produce high-quality aluminum alloy panels through VPF technology and benefit for researchers who study on the major of flexible die forming.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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