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Numerical simulation of aluminum alloy ladder parts with viscous pressure forming ①

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Abstract: Viscous pressure forming (VPF), a recently developed flexible-die forming process that is suitable for difficult-to-form material, can obtain the better stress states of sheet blank during forming process in manufacturing complex shape parts. The process of manufacturing aluminum alloy ladder parts with VPF and solid metal punch was simulated by the FE software DEFORM. Under different blank holder pressure (BHP), the stress state, the strain state, the forming of small radius curved face and the distribution of thickness were analyzed. The simulation results show that, compared with solid metal punch forming, the sheet blank can flow into die cavity more easily with VPF due to the improvement of the stress states; the severe thickness reduction can be avoided, the sheet blank can contact the die perfectly and the parts have high dimensional accuracy.

Key words: viscous pressure forming; ladder parts; aluminum alloy; numerical simulation
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1 INTRODUCTION

The effect of stress states on axisymmetric sheet formability has been studied under the condition of solid metal punch forming [1-4], and the effect of blank holder pressure (BHP), friction coefficient and punch configuration on the stress states has been obtained. Because of the disadvantages of solid punch forming, new forming technology is needed to improve the stress states of the sheet in forming process and to meet the requirement of forming low plasticity, complex shape parts. Viscous pressure forming (VPF) is a recently developed flexible-die forming technology[5-11], which uses a kind of semi-solid, flowable, viscous and strain rate sensitive material (namely viscous medium) as the soft punch. Viscous medium has high pressure-resistance and can fill the die cavity well, so the parts can fit the die fully and have high dimensional accuracy. The schematic diagram of VPF is shown in Fig. 1. Adjusting the viscous medium injection pressure (i. e. forming pressure) and BHP, to real-time control the forming of the sheet blank, then the high formability can be obtained.

Aiming at forming of the aluminum alloy ladder parts, the finite element numerical simulation software, DEFORM[12], is used to analyze the differences of stress states and the effect of stress states on forming under the condition of VPF and solid metal punch forming. The reasons of VPF benefit to improving the stress states are explained.

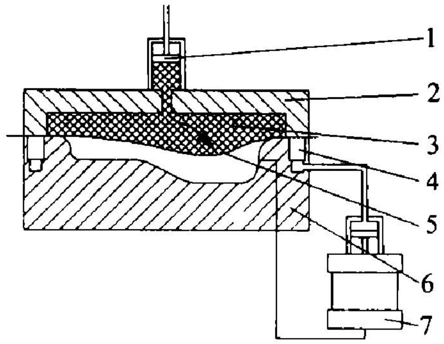

Fig. 1 Schematic diagram of viscous pressure forming
1—Piston; 2—Medium container; 3—Viscous medium; 4—Blank holder; 5—Sheet; 6—Die; 7—Blank hold hydraulic cylinder

2 LADDER PARTS AND MATERIAL PROPERTY

The main dimension of ladder part is shown in Fig. 2 (unit, mm). Its material is aluminum alloy (5A05M), the diameter of sheet blank is 150 mm, and the actual thickness is 1.05 mm. The parameters of material properties are listed in Table 1. When the

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ladder parts are made with solid punch forming, the typical defect is the severe thickness reduction, even fracture, at the center convex position (*A* area, Fig. 2). So as to avoid the location thickness reduction, the main method is to improve the stress states of the sheet blank in forming process.

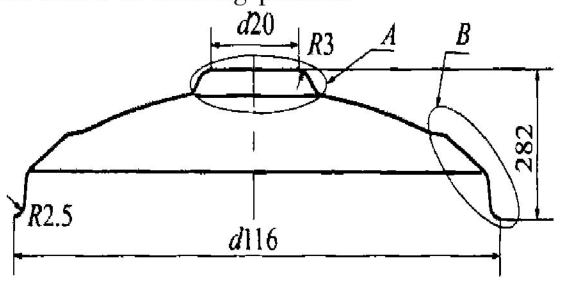

Fig. 2 Main dimensions of ladder part

Table 1 Parameters of material properties

Yield stress/ MPa	Elongation/ %	Elastic modulus/ GPa	Poisson's ratio	Strain hardening exponent	Thickness anisotropy
145	16	71	0. 3	0. 2	0. 61

3 NUMERICAL SIMULATION MODELS AND PARAMETERS

The forming process of the ladder part was studied with FE software DEFORM. The FE models used in simulation is shown in Fig. 3, and the simulation parameters are listed in Table 2.

In forming process, the viscous medium was pumped by piston and the sheet blank was pushed into the die cavity; in case of the solid punch forming, the metal punch contacted the sheet directly. Finally, the sheet blank was formed as required shape. The velocity of piston (or metal punch) is 5 mm/s, and the time increment is 0. 02 mm per step. The viscous medium is a kind of macromolecule polymer, and its stress vs strain curve is shown in Fig. 4.

Table 2 Process parameters used in simulation

Punch form	BHP/ MPa	Friction coefficient at sheet/ die interface	Friction factor at sheet/ medium
VM	1	0. 1	0. 2
VM	10		
Metal punch	1		
Metal punch	10		

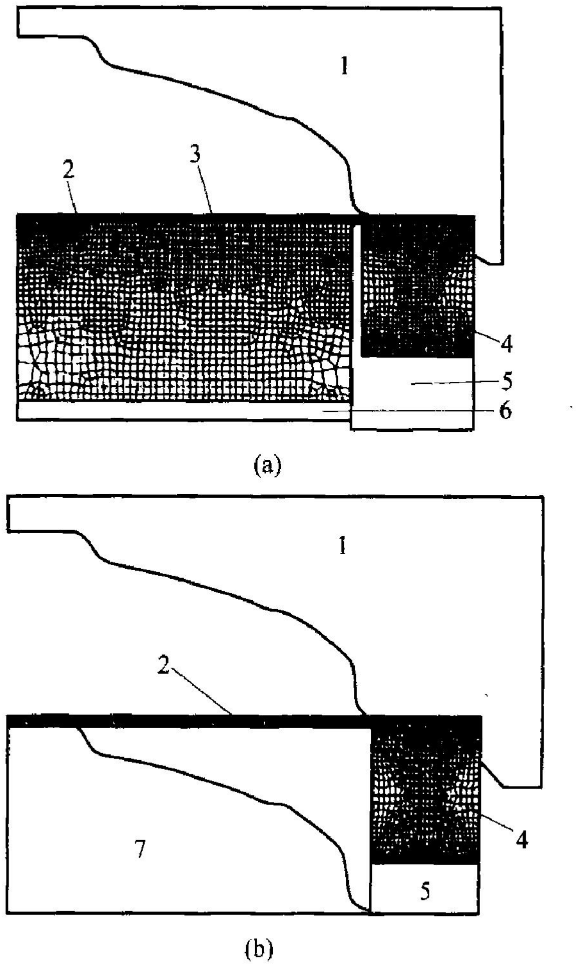

Fig. 3 FEM models used in process simulation
(a) —With VPF; (b) —With solid punch forming
1 —Die; 2 —Sheet; 3 —Viscous medium;
4 —Blank holder; 5 —Guiding device;
6 —Piston; 7 —Punch

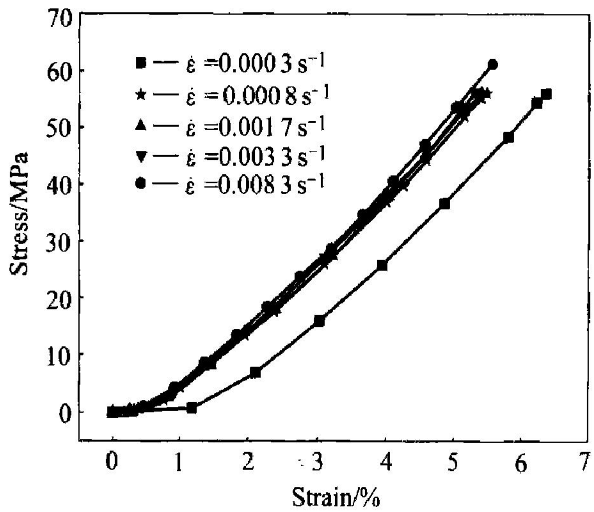

Fig. 4 Relationship between stress and strain of viscous medium

4 NUMERICAL SIMULATION RESULTS AND ANALYSIS

4. 1 Comparison of configurations with VPF and solid punch forming in forming process

An obvious difference between VPF and solid punch forming is the deformation configuration, and it can be visually displayed in whole forming process using numerical simulation method. The height, *h*, of the center point is selected as the parameter; the sheet blank configurations with VPF and solid punch forming are given in Fig. 5.

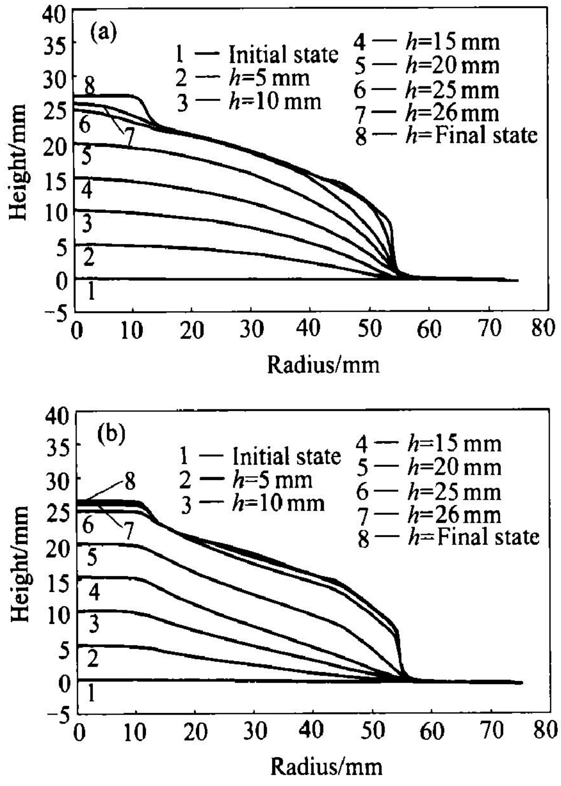

Fig. 5 Configurations of specimens in forming process

(a) —With VPF; (b) —With solid punch forming

The configuration of sheet blank with VPF is upward convex surface and the sheet blank begins to contact the die at h= 25 mm; however, the configuration of suspend area of the sheet in solid punch forming is downward concave surface, and the sheet blank begins to contact the lateral surface of solid punch (corresponding to B area in Fig. 2) at h= 20 mm and to contact the die surface at h= 25 mm. Because of no existence of suspend area with VPF, the possibility of occurring body wrinkles is reduced.

4. 2 Comparison of stress distribution in forming process

The reason of fracture and wrinkling can be obtained by researching on the stress states of ladder parts in process. The stress distributions of sheet blanks with VPF and solid punch forming under different BHP are shown in Figs. 6 ~ 9. Before sheet blank formed entirely at A area, it can be seen that the meridional stress with solid punch forming is higher than that with VPF, and has a peak value at punch profile radius. At this point, when BHP is 1 MPa and 10 MPa, the meridional stresses of sheet blanks with solid punching are 44. 4 MPa (Fig. 6(a) and Fig. 8(a)) and 24. 2 MPa (Fig. 7(a) and Fig. 9 (a)) higher than that with VPF respectively. The sheet blank occurs stress concentration earlier, and this leads to the bigger local deformation and thinning. While these phenomenon can be restrained with VPF. After the sheet blank begins to touch the die, the meridional stress of A area and B area of sheet blank increase, and finally the small radius curve surface at A area of the sheet blank is formed. However, there are severe thinning of sheet blank at this area and non-uniform thinning of whole body with solid punch forming, and the solid punch can not push the sheet blank to the die continually because of the gap between solid punch and die. The result is that the meridional stress is smaller than that of with VPF slightly (Figs. 6 ~ 9(b)) and the radius at A area is not formed entirely. So the flowablity of viscous medium ensures the specimen's dimensional accuracy.

The meridional stress and latitudinal stress are nearly equal and vary gently in the center portion (radius is about 20mm). This area can be called as equibiaxial tensile stress region, and the sheet blank is in bulging state (Fig. 10(a)). Out of this area, the latitudinal stress decreases quickly to zero and becomes as compressive stress. The circle (radius is about 40 mm), that the latitudinal stress equals zero, is called as stress dividing circle. The meridional stress, which has a peak value at die profile radius, decreases slowly along with radius, and is tensile stress all the time. After the sheet

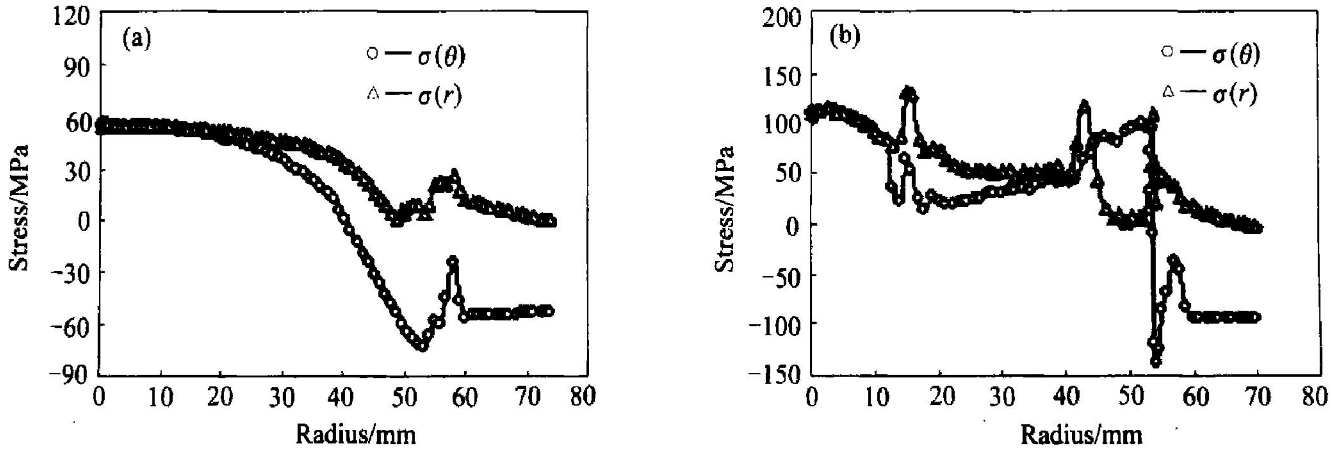

Fig. 6 Stress distribution curves with VPF and BHP= 1 MPa

(a) —h= 15 mm; (b) —Final state

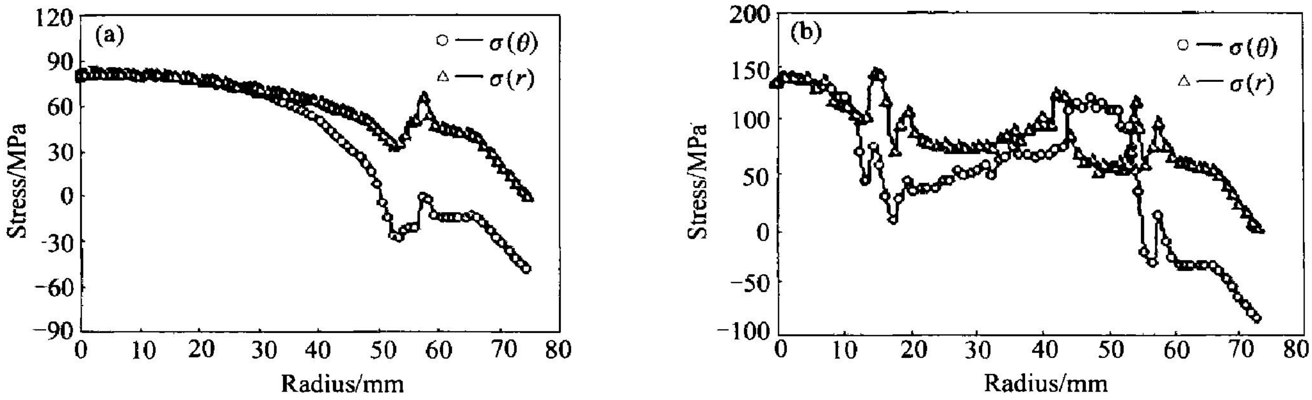

Fig. 7 Stress distribution curves with VPF and BHP= 10 MPa
(a) —h= 15 mm; (b) —Final state

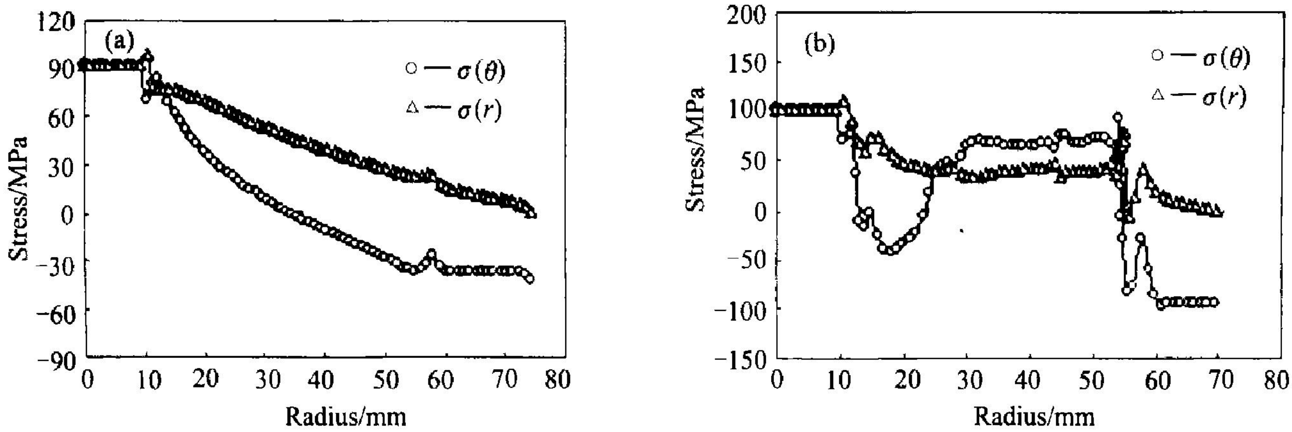

Fig. 8 Stress distribution curves with punch forming and BHP= 1 MPa
(a) —h= 15 mm; (b) —Final state

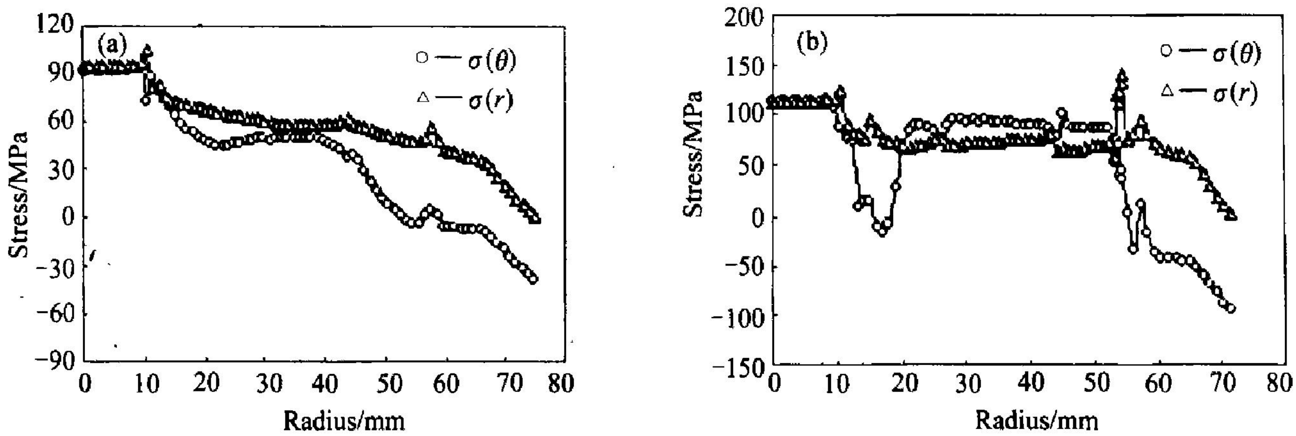

Fig. 9 Stress distribution curves with punch forming and BHP= 10 MPa
(a) —h= 15 mm; (b) —Final state

blank begins to touch the die (Fig. 6 (b) and Fig. 7 (b)), the latitudinal stress is tensile stress in die cavity and has a relative big value at die top convex profile radius (corresponding to A area in Fig. 2).

As to solid punch forming (Fig. 10(b)), because of the role of friction, the meridional stress equals to the latitudinal stress approximately. The latitudinal stress is tensile stress in whole suspend area with the higher BHP; there is a stress dividing circle (radius is about 34 mm) in this area while BHP is low. On the range of stress dividing circle, the latitudinal stress is tensile stress, and com- pression stress out of the circle. The compression stress can lead to body wrinkles easily.

The smaller radius of stress dividing circle is beneficial to the flow of the sheet blank. However, this means the bigger area of latitudinal compressive stress that can increase the possibility of puckers. The higher BHP, the bigger stress dividing circle with both VPF and solid punch forming. This fact states that the higher BHP benefits to eliminating the puckers to a certain extent . On the

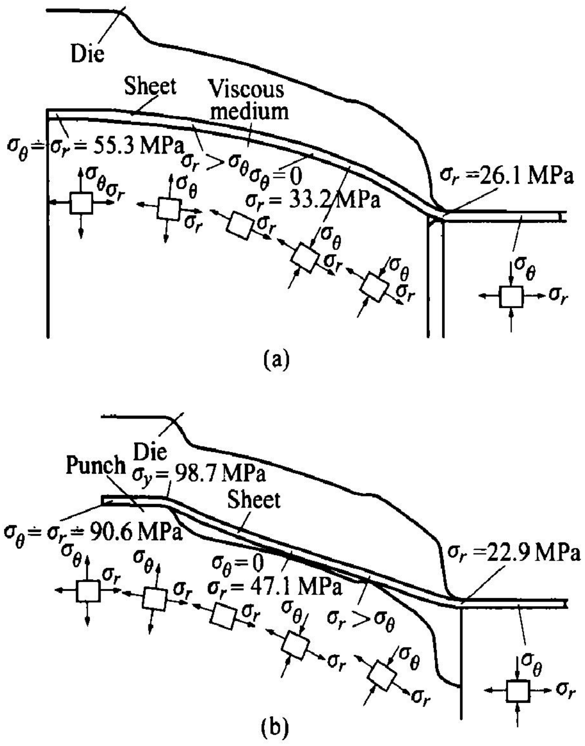

Fig. 10 Stress states with BHP= 1 MPa in deformation process
(a) —VPF, h= 15 mm;
(b) —Punch forming, h= 15 mm

other hand, the stress dividing circle radius increases with the forming process, so the tendency of puckers decreases. The difference between VPF and solid punch forming is that the sheet blank has no non-contact area in VPF, and the normal pressure of viscous medium acting on the sheet blank can reduce the occurrence of body wrinkles. So the stress states of sheet blank with VPF do well to restrain the wrinkling.

4.3 Comparison of effective strain in forming process

The effective strains of sheet blanks with VPF and solid punch forming are shown in Figs. 11 – 16. Before the sheet blanks contact the die surface, the highest effective strains are 7.95% (with VPF) and 12.2% (with solid punch forming) respectively under the condition of BHP= 1 MPa; and 8.61% (with VPF) and 18.5% (with solid punch forming) respectively with BHP= 10 MPa. At the end of simulation, though the parts still need to be formed at sharp corner (R3 of A area, Fig. 2) with solid punch forming (the reason has been stated before), the peak value of effective strains are higher than that with VPF about 1.3% – 7.1%.

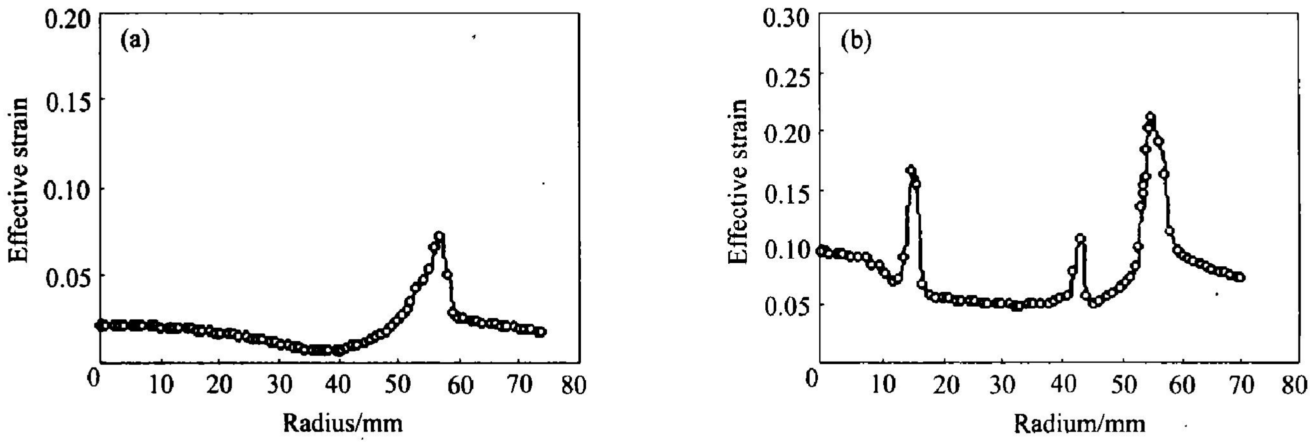

Fig. 11 Effective strain distribution curves with VPF and BHP= 1 MPa in deformation process
(a) —h= 15 mm; (b) —Final state

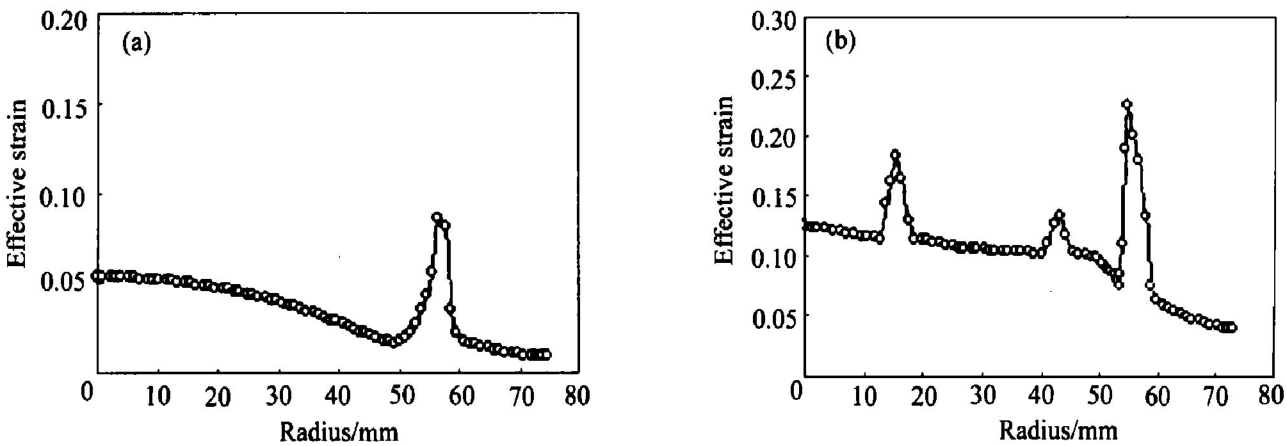

Fig. 12 Effective strain distribution curves with VPF and BHP= 10 MPa in deformation process
(a) —h= 15 mm; (b) —Final state

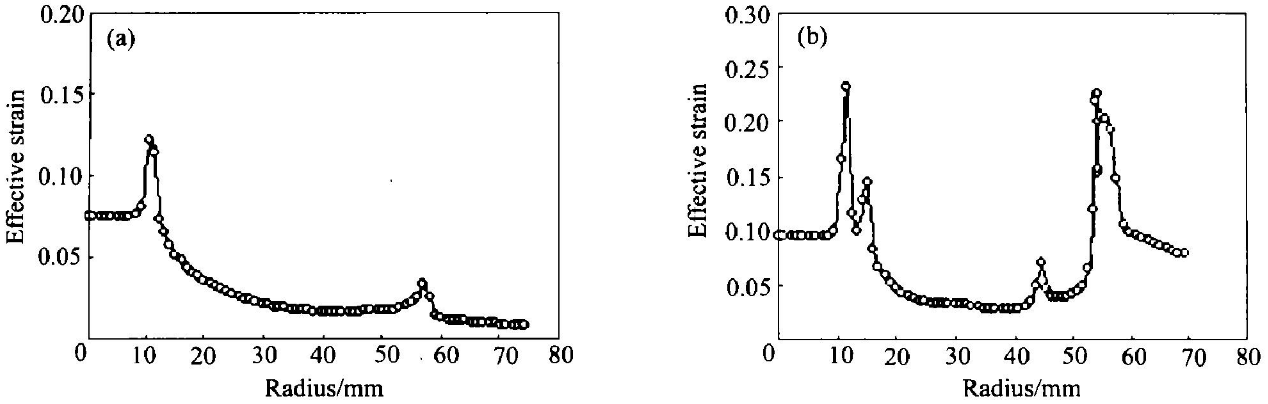

Fig. 13 Effective strain distribution curves with punch forming and BHP= 1 MPa in deformation process
(a) —h= 15 mm; (b) —Final state

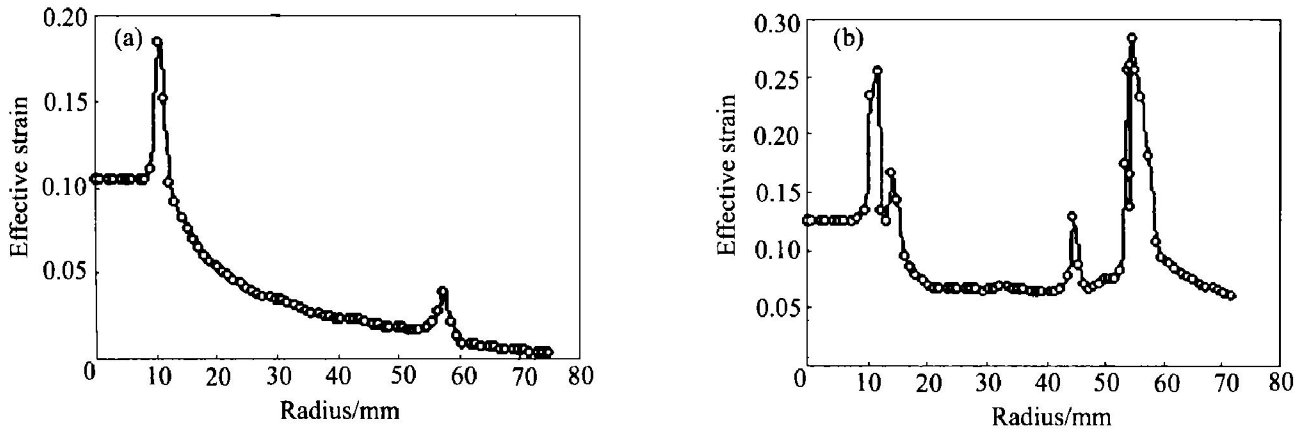

Fig. 14 Effective strain distribution curves with punch forming and BHP= 1 MPa in deformation process
(a) —h= 15 mm; (b) —Final state

So, under the condition of the same BHP, the parts with VPF have lower effective strains than that with solid punch forming. On the other hand, the higher BHP leads to the higher effective strain for both VPF and solid punch forming. The highest effective strain of parts with VPF lies at die profile radius, but at punch profile radius (A area) at incipient stage with solid punch forming. It can be derived that the fracture areas are the die profile radius (with VPF) and the punch profile radius of A area (with solid punch forming) separately.

4.4 Comparison of thickness distribution

The parts' thickness distribution by numerical simulation and experiment is shown in Fig. 15. The thickness distribution of both VPF and solid punch forming has great relationship with BHP. The higher the BHP, the bigger the thickness thinning is. In addition, with the same BHP, the thickness thinning of the parts with VPF is smaller than that with solid punch forming. Especially at die profile radius and punch profile radius (A area), the thickness of parts with solid punch forming decreases severely, however, the thinning is gentle with VPF. This phenomenon matches the difference of stress states between VPF and solid punch forming that stated before. So, the more uniform thickness of parts can be obtained by improving the stress state. The dotted line in Fig. 15 is the thickness distribution curve by experiment with VPF, and it is in good agreement with simulation results.

Fig. 16 illustrates examples of the specimens made with VPF. If the BHP is too low, the wrinkling will occur (Fig. 16(b)); and if the BHP is too high, the fracture will occur (Fig. 16(c)). Directed by the numerical simulation results, the perfect

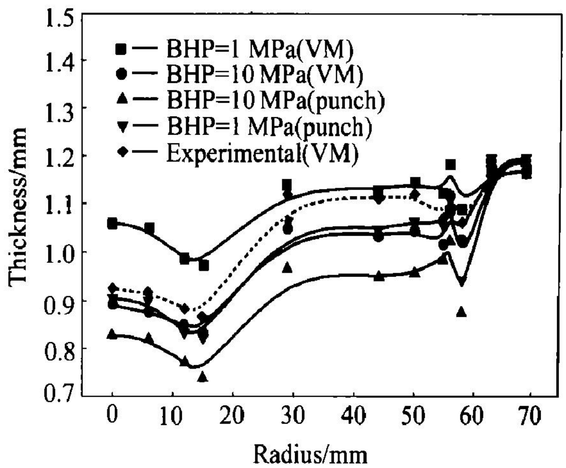

Fig. 15 Thickness distribution by simulation and experiment

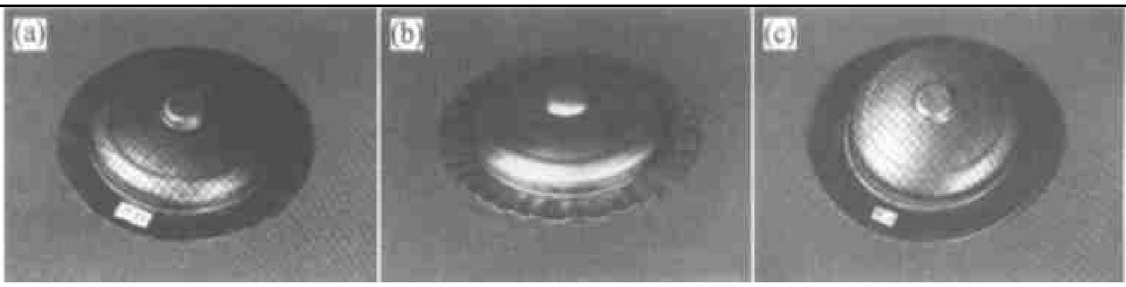

Fig. 16 Specimens made with VPF
(a) —Perfect; (b) —Wrinkling; (c) —Fracture

specimen was made with VPF under appropriate BHP (Fig. 16(a)). It can be seen that the specimen has no defect and has good surface quality.

5 CONCLUSIONS

1) The stress states are improved because the sheet blank contacts with viscous medium entirely in VPF process. And the fracture at central area which often occurs in solid punch forming process is eliminated.

2) With VPF, both the meridional stress and latitudinal stress are high at die profile radius, which is the dangerous area.

3) Unlike solid punch forming, VPF has no suspend area, so the tendency of puckers is reduced.

4) Compared with solid punch forming, the thickness distribution is more uniform by VPF, and the parts have higher dimensional accuracy.

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