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Viscous pressure bulging of aluminium alloy sheet at warm temperatures

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Abstract

Improving the formability of aluminium alloy sheet metal by using warm or elevated temperature has become a valid approach. In this paper, viscous pressure bulging (VPB) at warm temperature is proposed. The coupled thermo-mechanical finite element method and experimental method were used to investigate the VPB of aluminium alloy AA3003 at warm temperature. The temperature distributions of sheet metal and viscous medium were analyzed for non-isothermal VPB. The influence of forming temperature on thickness distribution, forming load and failure location of sheet metal were investigated. Research results show the temperature gradient field in sheet metal forms when the initial temperature of viscous medium is lower than that of sheet metal. The formability and failure location of sheet metal changes with initial temperature of viscous medium.

Keywords: Aluminium alloy; Viscous pressure bulging; Warm temperature; FEM

1. Introduction

In recent years, because of the requirements of weight reduction of structural component in aerospace, automobile area, the applications of many lightweight alloys become wider and wider, such as aluminium alloy, magnesium alloy and titanium alloy, and so on [1-2]. Because of these materials' low formability at room temperature, however, the forming of this alloy sheet metal has taken a challenge to conventional forming methods. The formability of these alloys can be improved by changing the forming temperature to either cryogenic or elevated temperatures [3]. This phenomenon makes the warm forming become a valid method for sheet metal with low formability. In recent literatures, warm deep drawing or warm hydroforming of aluminium alloy, magnesium alloy and titanium alloy have been presented in detail [4-6].

Viscous pressure forming (VPF) is a new sheet metal flexible-die forming process and has shown potential application for forming of low-plasticity material [7-8]. In this paper, viscous pressure forming at warm temperature is proposed. By using coupled thermo-mechanical finite element method and experimental methods, the characteristics of VPB at warm temperature for aluminium alloy sheet metal are analyzed. The temperature distributions of sheet metal and viscous medium were analyzed for non-isothermal VPB. The influence of forming temperature on thickness distribution, forming load and failure location of sheet metal were investigated. The VPB experiments were also conducted at different forming temperatures.

2. Finite element analysis

2.1 FE model

The commercial FEM software DEFORM2D is used for the simulation of the VPB of aluminium alloy sheet at warm temperature. FE model is shown in Fig. 1. Sheet metal is formed under the pressure of viscous medium pumped by piston. Analysis is re-

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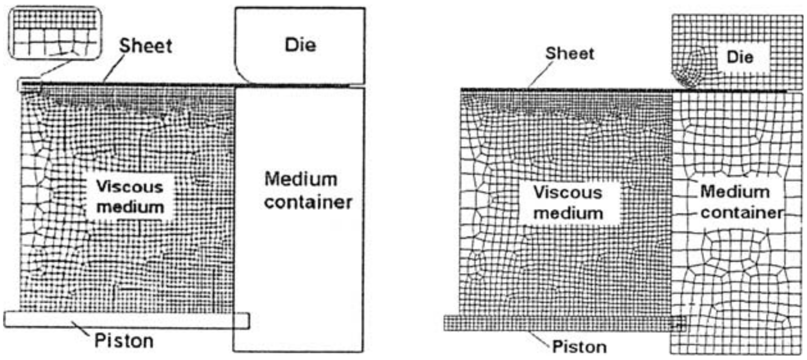
alized on half of the geometry because of the axisymmetry of the model. Sheet metal is discrete with quadrilateral element. The process parameters used in the simulation of VPB at warm temperature are shown in Table 1. In this study, aluminium alloy AA3003 was used to carry out the investigation. The flow stresses of AA3003 sheet at different temperatures are obtained by Abedrabbo [9], as shown in Fig. 2. Thermal parameters of aluminium alloy AA3003 sheet and viscous medium are shown in Fig. 3 and Table 3. The thermal parameters of viscous medium are obtained by doing experiments. The mean thermal conductivity of aluminium alloy sheet and viscous medium are 180 N/(s·°C) and 0.2 N/(s·°C), respectively. So, it can be said that the viscous medium is a poor heat conductor. The mechanical properties of viscous medium are considered to be non-sensitive to temperature.

The initial temperature parameters of each part of the model are listed in Table 3. Two deformation modes are investigated, isothermal forming and non-isothermal forming. In isothermal VPB, no heat exchange happens between each part. So rigid die needs not to be meshed, as shown in Fig. 1(a). On the contrary, rigid part must be meshed to calculate the heat exchange in order to investigate the influence of temperature distribution on deformation in non-isothermal VPB, as shown in Fig. 1(b). It is a thermo-



(a) (b)

Fig. 1. FE model of (a) Iisothermal VPB; (b) Non-isothermal VPB.

Table 1. Process parameters used in the simulation of VPB.

Tooling setup		Mechanical properties	
Inlet port radius (mm)	27.5	Sheet metal	Seen in Fig.2
Die corner radius (mm)	3	Viscous medium (MPa)	$\bar{\sigma} = 0.24\dot{\bar{\varepsilon}}^{0.25}$
Piston velocity (mm/sec)	0.2	Friction	Coulomb friction coefficient, μ \$0.1, at sheet/die interface Shear friction factor, m=0.2, at sheet/medium interface
Sheet blank diameter (mm)	86		
Sheet blank thickness (mm)	0.5		

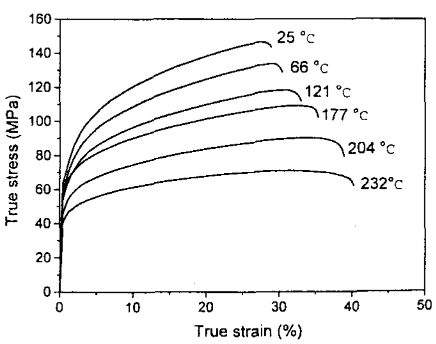


Fig. 2. Flow stress of aluminium alloy AA3003 at different temperature[9]

mechanical coupled deformation and different from isothermal VPB.

2.2 Results and discussions

2.2.1 Temperature distribution

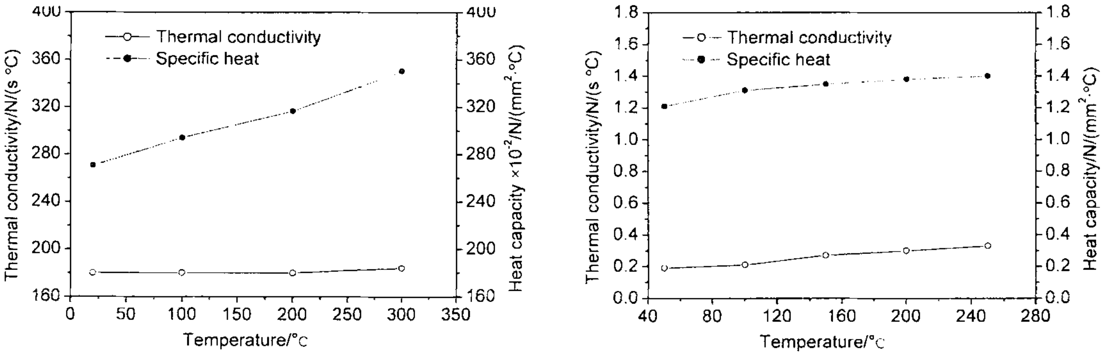
Ignoring the heat generation from the plastic work, the temperature of sheet metal keeps stable in the isothermal VPB process. Fig. 4 shows the temperature distribution of sheet metal and viscous medium at different bulging stage in the non-isothermal VPB, the initial temperature of viscous medium is 20°C. During forming, the sheet, which is initially at uniform temperature of 250°C, comes in contact with viscous medium at room temperature and looses heat rapidly due to its high thermal conductivity and low specific heat capacity. Thus, the region of sheet metal in contact with viscous medium has lower temperature compared to the sheet in contact with the die, as shown in Fig. 4. The temperature gradient is formed in sheet metal and the lowest temperature locates at dome centre areas and increases along the radial direction. As the deformation proceeds, the sheet looses heat continuously. A small increase in minimum temperature was observed in the dome area due to the heat generation from the plastic work during the process. On the contrary, the temperature of viscous medium increases slowly due to its low thermal conductivity. During the de-formation process, the centre area of viscous medium keeps the initial temperature. The temperature gradient affects the flow stress and deformation mode of sheet metal. It is different from warm hydro-forming which it is an isothermal forming process.

2.2.2 Thickness distribution

The predicted thickness distributions of bulging specimens at different forming temperature are shown

Table 2. Thermal parameters used in the simulation of VPB.

Thermal expansion 10^{-6}/°C	Viscous medium	Sheet metal
20-100	235.	23.2
20-200	672.2	24.1
20-300	-	25.1
Interface heat transfer coefficient (N/(s·mm·°C))	10 at sheet/die interface 1 at sheet/medium interface	
Factor to convert plastic deformation energy to heat	0.9	



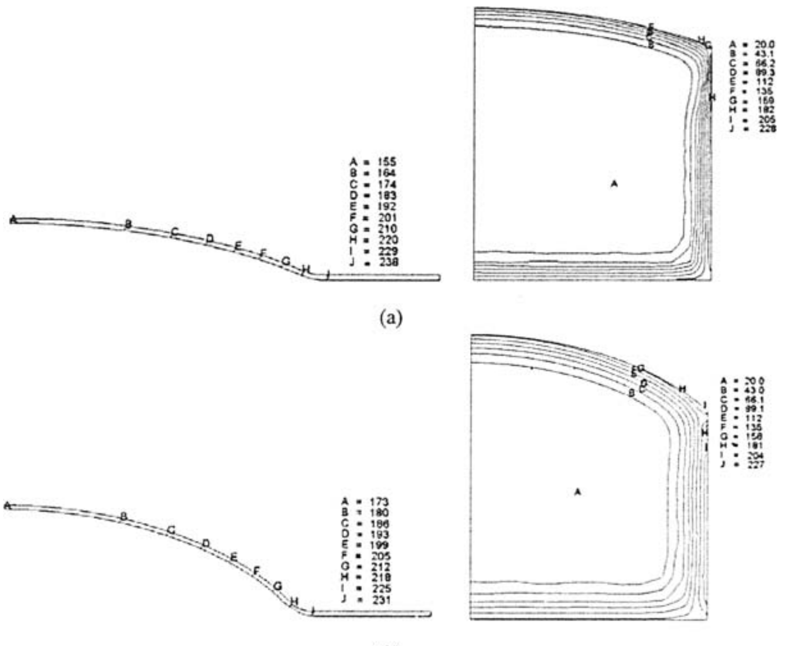
(a) (b)

Fig. 3. Thermal properties of aluminium alloy and viscous medium at different temperature: (a) Aluminium alloy AA3003; (b) Viscous medium.

Table 3. Deformation modes used in the simulation of VPB.

Deformation modes	Viscous medium initial temperature (°C)	Sheet, die, medium container and piston temperature (°C)
Non-isothermal	20 100 150 200 250	250
Isothermal	20 100 150 200 250	

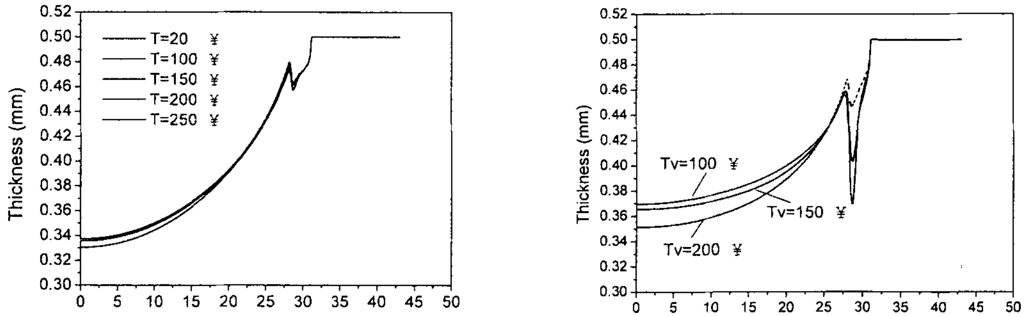
in Fig. 5. In all cases, the dome height is 15mm. In isothermal VPB, the forming temperature (*T*) has no obvious effect on the thickness distribution of bulging specimens. The maximum thinning point locates at dome center and thickness increases along the radial direction. On the contrary, the initial temperature of viscous medium (T_V) has great influence on the thickness distribution of bulging specimen for the non-isothermal VPB. The thickness of bulging specimen at the dome center increases with increasing initial temperature of viscous medium and the maximum thinning point varies. When the initial temperature of viscous medium is 100°C, the maximum thinning point occurs at die corner. When the initial temperature of viscous medium is 200°C, the maximum thinning point occurs at dome center. For the non-isothermal VPB case, the homogeneity of thickness distribution does not vary monotonously with the variation of initial temperature of viscous medium. The homogeneity of thickness distribution is better than the other two forming conditions when the initial temperature of viscous medium is 150°C.



(a)

(b)

Fig. 4. Temperature distributions of sheet metal and viscous medium at different bulging height (*H*): (a) *H*=6.0 mm; (c) *H*=13.0 mm.



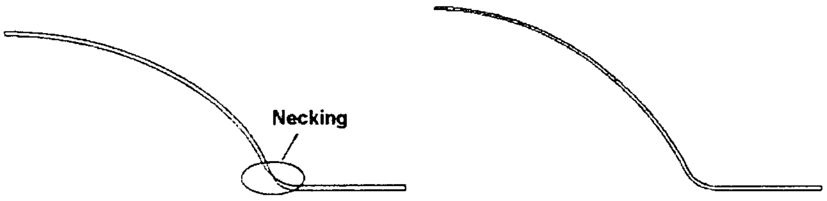
(a)

(b)

Fig. 5. Thickness distributions of bulging specimens at different forming conditions: (a) Isothermal VPB; (b) Non-Isothermal VPB (the temperature of sheet metal is 250°C).

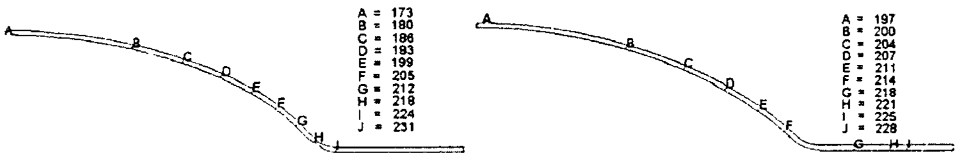
2.2.3 Fracture location

In non-isothermal VPB, the temperature of viscous medium has obvious effect on the fracture location of bulging specimen. The predicted geometry of the dome at the height of 14.3mm is shown in Fig. 6 for the case that the initial temperature of viscous medium are 20°C and 150°C, respectively. For the former case, the necking occurred at the die corner. For the latter case, the fracture located at the dome center. This difference can be explained by analyzing



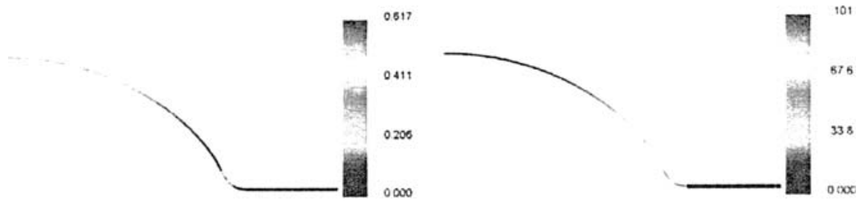
(a) (b)

Fig. 6. Location of maximum thinning of sheet metal: (a) *Tv*=20°C; (b) *Tv*=150°C.



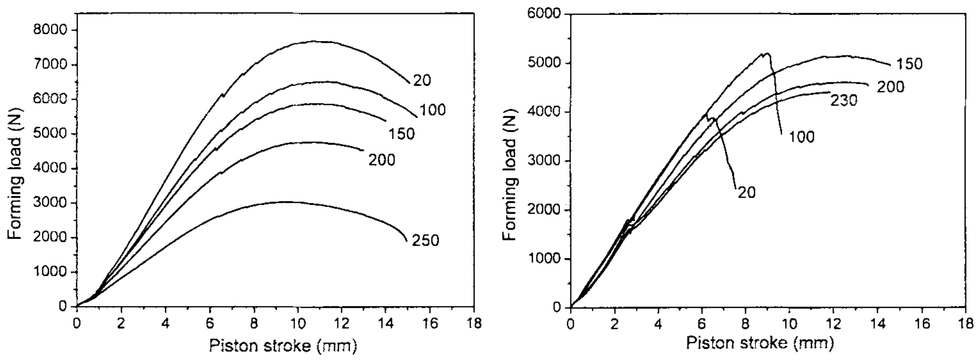
(a) (b)

Fig. 7. Temperature distribution of sheet metal: (a) *Tv*=20°C; (b) *Tv*=150°C.



(a) (b)

Fig. 8. Effective strain and effective stress distribution of sheet metal: (a) Effective strain; (b) Effective stress.



(a) (b)

Fig. 9. Forming loads obtained from the simulations of AA3003 sheet metal VPB at different temperature for: (a) Isothermal VPB; (b) Non-isothermal VPB.

the temperature distribution of sheet metal of the two cases, shown in Fig. 7. The lowest temperature is located at the dome center, and increases along the radial direction and it is 173°C and 197°C, respectively for the two cases. Because the flow stress decreases with increase in temperature, the sheet metal at die corner area become the preferential deformable area. The effective strain and effective stress distributions of bulging specimen are shown in Fig. 8 when the necking occurred. Although the maximum effective strain locates at necking, the maximum effective stress is at dome center. It is due to the influence of temperature on flow stress. The main deformation happened at die corner and necking occurs at this location due to the temperature difference between dome center and die corner when the initial temperature of viscous medium is 20°C.

2.2.4 Forming load

The predicted piston loads for isothermal bulging and non-isothermal bulging at different deformation conditions are shown in Fig. 9. In non-isothermal VPB, when the initial temperatures of viscous medium are 20°C and 100°C, the fracture occurred at die corner at low bulging height, so the piston load is low. In isothermal and non-isothermal conditions, the piston load decreases with increasing the forming temperature or viscous medium temperature. Because of the low thermal conductivity of viscous medium, however, the heat exchange between sheet metal and viscous medium can not conducted quickly. In non-isothermal bulging process, the dominating factor

Table 4. Process parameters of AA3003 sheet VPB process at warm temperature.

Parameter / Case	Viscous medium temperature (°C)	Sheet, die, medium container temperature (°C)
Case 1	20	20
Case 2	150	150
Case 3	180	180
Case 4	200	200
Case 5	20	200

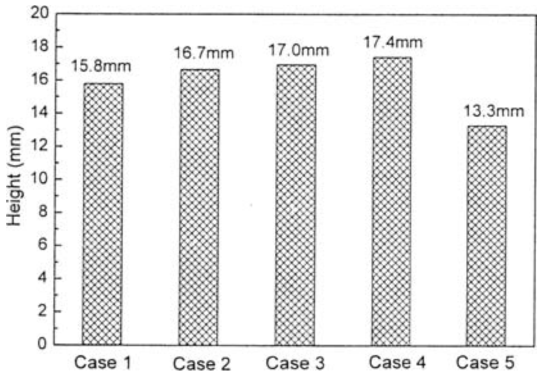


Fig. 10. Comparison of VPB limit dome height at each forming case.

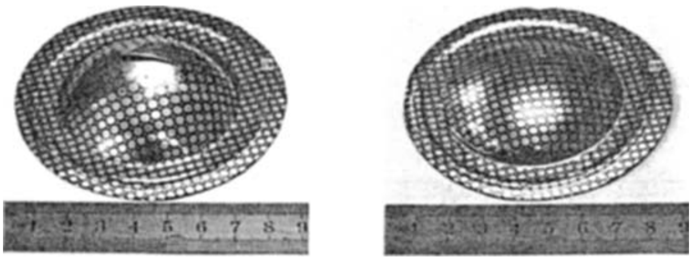

(a) (b)

Fig. 11. VPB specimens at two forming conditions: (a) Case 4 and (b) Case 5.

affecting the piston load is the temperature of sheet metal.

3. Experiment

The VPB experiments were conducted at different temperatures. The experimental setup is the same with that used in numerical simulations. The blank was placed over a draw bead and clamped with a blank holding force (BHF) to insure no material will draw in during the stretch experiments. Heating elements with an active control device were added to the VPB machine in order to raise the temperature to the desired elevated temperature. The active control was achieved by using two thermocouples linked to the die and blank system. Using the temperature control device, the desired temperature was set and maintained for a period of about 20 min or until a constant and isothermal condition was achieved.

3.1 Experimental parameters

The process parameters used in VPB experiments are shown in table 4. According to the mechanical properties of aluminium alloy AA3003 sheet metal, five forming temperatures are used to investigate the influence of temperature distribution on sheet deformation.

3.2 Experimental results

Limit dome height (LDH) is one of the important characters to reflect the bulging property of sheet metal. The LDH of VPB specimens at various forming temperature are shown in Fig. 10. In isothermal bulging, the LDH increases with increasing forming temperature. The LDH of bulging specimen at 200°C attained 17.4mm and increased 10.3% higher than that at room temperature. In non-isothermal bulging, the LDH is far lower than that in isothermal bulging when the initial temperature of sheet metal and viscous medium are 200°C and 20°C. The bulging specimens by experiments for case 4 and case 5 are shown in Fig. 11. For case 4, the fracture locates at dome center, but the maximum thinning point occurs at die corner area for case 5. It agree well with numerical simulations (shown in Fig. 8)

4. Conclusions

In non-isothermal viscous pressure forming process, the non-uniform temperature distribution is formed in sheet metal and viscous medium. The temperature is low at dome center of sheet metal and increases along the radial direction. So, the flow stress is decreased along the radial direction and the formability is improved.

In VPB at warm temperature, when the initial temperature of viscous medium is much lower than that of sheet metal, the maximum thinning was observed at the die corner radius. This is different from the observation in conventional VPB test where the thinning occurs at the dome center.

The location of maximum thinning in numerical simulations has a good agreement with experiment observations.

References

[1] G.S. Cole and A.M. Sherman, Lightweight materials for automotive applications, *Mater. Charact.* 35 (1995) 3-9.

[2] R.T. Holt, A.K. Koul, L. Zhao, W. Wallace, J.C. Beddoes, J.P. Immarigeon, Lightweight materials for aircraft applications, *Mater. Charact.* 35 (1995) 41-67.

[3] Daoming Li, Amit Ghosh, Tensile deformation behavior of aluminium alloys at warm forming temperatures, *Mat. Sci. Eng. A.* 352 (2003) 279-286.

[4] M. Keigler, H. Bauer, D. Harrison, S. De, K.M. Anjali, Enhancing the formability of aluminium components via temperature controlled hydroforming, *J. Mater. Process. Tech.* 167 (2005) 363-370.

[5] H. Palaniswamy, G. Ngaile, T. Altan, Finite element simulation of magnesium alloy sheet forming at elevated temperatures, *J. Mater. Process. Tech.* 146 (2004) 52-60.

[6] Fuh-Kuo Chen, Kuan-Hua Chiu. Stamping formability of pure titanium sheets, *J. Mater. Process. Tech.* 170 (2005) 181-186.

[7] Liu J, Westhoff B, Ahmetogla M, and Altan T, Application of Viscous Pressure Forming (VPF) to Low Volume Stamping of Difficult-to-forming Alloys - Results of Preliminary FEM Simulations, *J. Mater. Process. Tech.* 53 (1996) 49-58.

[8] Z.J. Wang, J.G. Liu, X.Y. Wang, Z.Y. Hu, B. Guo, Viscous pressure forming (VPF): state-of-the-art and future trends, *J. Mater. Process. Tech.* 151 (2004) 80-87.

[9] N. Abedrabbo, F. Pourboghrat, J. Carsley, Forming of aluminium alloys at elevated temperatures – Part 1: Material characterization. *Int. J. Plasticity.* 22 (2006) 314-341.