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Mechanics analysis of axisymmetric thin-walled part in warm sheet hydroforming

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KEYWORDS

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Abstract To obtain the influence of fluid pressure and temperature on warm hydroforming of 5A06-O aluminum alloy sheet, the unified mechanics equilibrium equations, which take through-thickness normal stress and friction into account, were established in spherical coordinate system. The distribution of through-thickness normal stress in the thickness direction was determined. The relation between through-thickness normal stress and fluid pressure was also analyzed in different regions of cylindrical cup. Based on the method of subtracting one increasing function from another, the constitutive equation of 5A06-O applied to warm hydroforming was established and in a good agreement with uniaxial tensile data. Based on whether the thickness variation was taken into account, two mechanic models were established to do the comparative study. The results for the studied case show that the calculated stress values are pretty close according to the two models and consistent with results of finite element analysis; the thickness distribution in flange computed by the second model conforms to the experimental data. Finally, the influences of fluid pressure on the flange thickness and radial stress were analyzed.

1. Introduction

Lightweight is the trend of aircraft, aerospace and automobile manufacturing. The application of lightweight materials such as aluminum and magnesium alloy is one of the important measures of realizing lightweight.[1] As is well-known, the formability of lightweight materials, which is poor at room temperature, would be improved at elevated temperature level.[2–4] Given that, warm sheet hydroforming is an innovative processing with the merits of both warm sheet forming and sheet hydroforming, which can solve the above problem.[5–7] Because this technology was proposed recently, many basic theories and key technologies exist as the black boxes. It will be of significance to investigate the forming mechanism and key technologies of warm sheet hydroforming, which will greatly improve the application of poor formability materials.[8,9]

In tremendous literature,[10–12] the elastic-plastic analysis of deep drawing has been made to conduct the forming process.

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To study the optimum blank-holder force, Zhao et al.[13] built the mechanic model for cylindrical cup hydroforming at room temperature. But the model assumed that the blank is in the plane stress state and ignored the variation of flange thickness. Choi et al.[14] studied sheet warm hydroforming with an analytic method to determine the stress and strain state in the flange and die corner. To simplify the analysis, the authors also did not consider through-thickness normal stress and utilized Swift type constitutive equation to describe the stress–strain curve. However, Nurcheshmeh et al.[15,16] pointed out that it will not be accurate enough to predict sheet forming limit for processes which lead to non-negligible out-of-plane stress, unless the prediction takes the through-thickness normal stress into account. Because of dynamic recovery and dynamic recrystallization at elevated temperature, the stress–strain curve of aluminum alloy will decline and cannot be described by simple exponential functions.[17] However, the complex expressions[18] are difficult to be applied to the mechanics analysis. In addition, the quantitative relation between through-thickness normal stress and fluid pressure should also be established and discussed.

In view of the above analysis, the unified mechanics equilibrium equations considering the through-thickness normal stress and friction were established in spherical coordinate system. The distribution of through-thickness normal stress in the thickness direction was determined. The relation between through-thickness normal stress and fluid pressure was also analyzed in different regions of cylindrical cup. Based on the method of subtracting one increasing function from another, the constitutive equation of 5A06-O aluminum alloy applied to warm hydroforming was derived. Meanwhile, two mechanic models were established to do the comparative study based on whether the thickness variation was taken into account. Finally, the influences of fluid pressure on the flange thickness and radial stress were analyzed and compared with finite element analysis and experimental data.

2. Generalized model in warm sheet hydroforming

2.1. Unified mechanics equilibrium equations

In the process of axisymmetric thin-walled sheet hydroforming, the through-thickness normal stress varies in the thickness direction from fluid pressure p to the contact stress σ_c and there is no stress-free surface on both sides of the blank. In the general case, the infinitesimal unit of arbitrary revolution shell with consideration of the through-thickness normal stress and friction is depicted in Fig. 1.

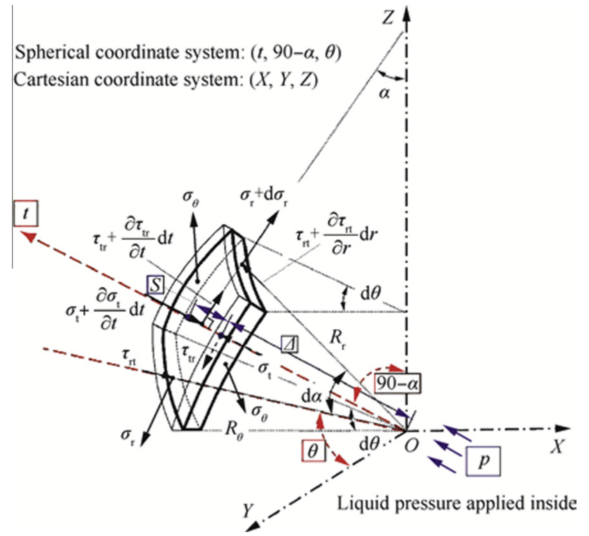

Fig. 1 Infinitesimal unit with consideration of through-thickness normal stress and friction.

In the following study, as we know: $\sin\frac{d\alpha}{2} \approx \frac{d\alpha}{2}$ and $\sin\frac{d\theta}{2} \approx \frac{d\theta}{2}$, the equilibrium equation in the normal and radial direction can be derived:

$$\frac{\partial \sigma_t}{\partial t} + \sigma_t\left(\frac{1}{R_r} + \frac{1}{R_\theta}\right) - \frac{\sigma_r}{R_r} - \frac{\sigma_\theta}{R_\theta} + \frac{\partial \tau_{tr}}{\partial r}\sin\alpha = 0 \quad (1)$$

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} + \frac{1}{\sin\alpha}\left(\frac{\tau_{rt}}{R_r} + \frac{\tau_{rt}}{R_\theta} + \frac{\partial \tau_{rt}}{\partial t}\right) = 0 \quad (2)$$

where S is the blank thickness and Δ the inner radius of the blank; σ_r, σ_θ, σ_t denote the radial, circumferential and through-thickness components of the stress respectively; τ_{rt} and τ_{tr} are the radial shear stress induced by friction, R_r, R_θ are the radial and circumferential radii of curvature in neutral layer of thickness respectively; r denotes the radius away from symmetric axis to infinitesimal units, and α the angle between the plane tangential to the neutral layer and symmetric axis.

2.2. Stress–strain curves at elevated temperature

Because of dynamic recovery and dynamic recrystallization at elevated temperature, it is difficult to describe precisely the stress–strain curve of aluminum alloy by the simple exponential functions, $\sigma = \alpha_1 \varepsilon^n \dot{\varepsilon}^m e^{-bT}$ (n is the hardening exponent, m the strain rate sensitivity exponent and T the celsius temperature; α_1, b are the fitting parameters).[14] In this paper, based on the method of subtracting one increasing function from another, the constitutive equation of 5A06-O aluminum alloy was derived to be applied to warm sheet hydroforming. Fig. 2 shows the schematic diagram of the modeling of softening part that will simplify the mechanics analysis. The hardening curve σ and test data $\sigma - \Delta\sigma$ represent the stress–strain curve of aluminum alloy at room temperature and high temperature, respectively. $\Delta\sigma$ is the difference between σ and $\sigma - \Delta\sigma$, which can also be described by increasing function.

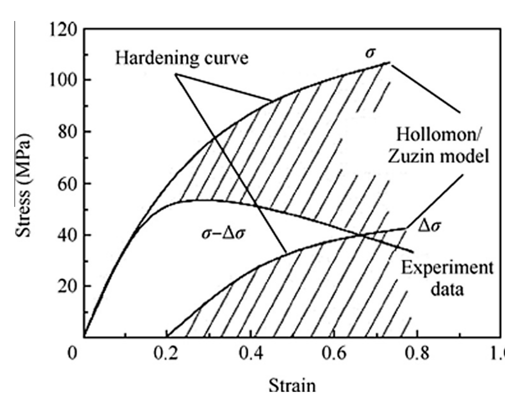

Fig. 2 Schematic diagram of modeling of softening part.