International Journal of Mechanical Sciences 120 (2017) 70–80

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Analysis of wrinkling during sheet hydroforming of curved surface shell considering reverse bulging effect

Y.Z. Chen[a,b], W. Liu[a,b,*], Z.C. Zhang[b], Y.C. Xu[a,b], S.J. Yuan[a,b]

[a] National Key Laboratory for Precision Hot Processing of Metals, Harbin Institute of Technology, Harbin 150001, China
[b] School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

A R T I C L E I N F O

Keywords:
Unsupported wrinkling
Sheet hydroforming
Reverse bulging effect
Curved surface shell
Energy method

A B S T R A C T

Wrinkling in unsupported region is a worthy problem to be solved in sheet metal forming process. Sheet hydroforming is advantageous in the prevention of unsupported wrinkles. However, the simply increasing of liquid pressure is not enough to suppress the wrinkling even though with the occurrence of "reverse bulging effect" .[1] In order to predict and control the wrinkling quantitatively in unsupported region for thin-walled shells with curved surface, a theoretical model on critical wrinkling stress was proposed by considering proper "reverse bulging effect" based on energy method. The influence of liquid pressure and other parameters on the critical wrinkling stress was analyzed. The critical loading path of the liquid pressure to control wrinkling was obtained by combining critical wrinkling stresses and circumferential stresses. An experimental setup for an extremely thin-walled shell with semi-ellipsoidal geometry was designed and manufactured to verify the theoretical model. It is found that at a certain punch stroke, the magnitude of the critical wrinkling stress increases and that of circumferential compressive stress decreases with the improvement of the liquid pressure. The critical loading path can be utilized to get well formed shells with a ratio of thickness to diameter equals 0.27% in the experiments. The proposed method can be applied to predict and control wrinkling in unsupported region for hydroforming of thin-walled shell with high accuracy and considerably reduced simulation time.

1. Introduction

With the great usage of thin-walled shells with curved surface recently, wrinkling defect appears to become more prevalent during forming processes [1]. For some components with large area of unsupported region, the absence of normal constraint makes the suppression of unsupported wrinkling more difficult. Thus deep considerations are in need to predict and prohibit any wrinkling occurred in the sheet metal forming process [2,3]. Many efforts were made to control the wrinkling occurred in the thin-walled sheet components, such as sheet hydroforming process (SHP), modified deep drawing process [4], high speed forming [5], spinning and incremental forming et al. [6,7]. SHP is somewhat different from the conventional drawing method [8,9], which has been proved efficient and reliable in controlling wrinkles as a result of a controllable liquid pressure. For the SHP of some curved surface shells using aluminum alloys and low carbon steel, the sheet metals in unsupported areas are easy to be deformed with proper liquid pressure, then the sheet can be bulged along the reverse direction of the deep drawing. This deformation was called "reverse bulging deformation" by Zhang et al. [10]. Therefore, the term "reverse bulging effect" is used in this study to illustrate the mentioned phenomenon. Generally, this effect can be generated for the hydroforming process of curved surface shells with an appropriate combination between liquid pressure and blank holder pressure. Proper "reverse bulging effect" is the key to control the development of unsupported wrinkles, which changes the unsupported area into different stress state at a certain drawing period because of the effect of proper liquid pressure [11,12]. Furthermore, it has been proved from our previous study that sometimes the unsupported wrinkles cannot be controlled completely even though with insufficient "reverse bulging effect" under lower liquid pressure (as shown in Fig. 1), especially for deep drawn shells with large unsupported area [10,12]. In our published work, a theoretical liquid pressure path was obtained to control the wrinkling. However, the calculated path was just the one that big enough to suppress the defect, the critical wrinkling stress and critical loading path considering the "reverse bulging effect" are still unknown. This problem is urgent to be solved to offer suggestions in academic research and industrial applications.

* Corresponding author at: National Key Laboratory for Precision Hot Processing of Metals, Harbin Institute of Technology, Harbin 150001, China.
E-mail address: liuw@hit.edu.cn (W. Liu).

[1] Normally, the unsupported areas of sheet metals during hydroforming are easy to be bulged along the reverse direction of deep drawing, this phenomenon can be regarded as a "reverse bulging effect".

http://dx.doi.org/10.1016/j.ijmecsci.2016.10.023
Received 13 June 2016; Received in revised form 25 October 2016; Accepted 26 October 2016
Available online 28 October 2016
0020-7403/

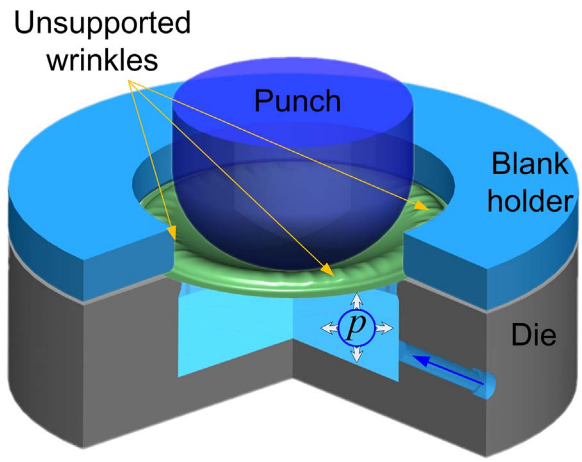

Fig. 1. Unsupported wrinkles in the sheet hydroforming process with insufficient "reverse bulging effect".

Theoretically, the wrinkling is unavoidable when the magnitude of its circumferential stress is beyond the critical wrinkling stress (means the critical circumferential compressive stress of the sheet during forming) [13,14]. Geckeler et al. [15] firstly focused on calculating the critical wrinkling stress based on one-dimensional calculation model. Then a prediction method named "energy method" was proposed by Senior et al. [16]. By calculating the bending energy of wrinkled plate and the work done by the in-plane membrane force, the critical wrinkling stress can be obtained. Consequently, an important expression to predict the wrinkling in deep drawing was developed by Yu et al. [17]. Using this method in predicting wrinkling has been proved efficient and practicable [18,19]. Numerical simulation method has been applied widely in predicting wrinkles for the merits of lower cost, more convenience and higher computation capability. However, for the complicated plastic forming process with large strain variation, the accurately numerical simulation works rely on complex boundary conditions and appropriate selection of model and mesh [2], which limits the independent application of simulation results. Furthermore, some nice works on the prediction of critical states of wrinkling have been made combining the analytical and numerical simulation results [18,20,21]. Therefore, the combination and comparison between the theoretical critical wrinkling stress and actual circumferential stress in simulation are feasible in predicting wrinkling defect.

For the SHP of sound cylindrical parts, an analytical model was firstly proposed by Yossifon et al. based on the energy method to predict proper liquid pressure [22], the experimental results agreed well with their theoretical prediction [23,24]. Then the wrinkling defect of hemispherical parts was investigated by Lo et al. [25] and Abedrabbo et al. [26] to get a proper loading path. However, the mentioned works didn't take the "reverse bulging effect" into account in their theoretical models to optimize loading paths. Therefore, considering the presence of "reverse bulging effect" of curved shells with large area of un-supported region, there is still no sufficient theoretical and quantitative model to get the critical wrinkling stress and critical loading path of the liquid pressure. What's more, for the forming process of thin-walled curved parts with the ratio of thickness to blank diameter lower than 0.3%, the eliminating of the wrinkles still faces great challenge.

It is the goal of this work to develop a theoretical and quantitative model about the critical wrinkling states considering "reverse bulging effect" in SHP. The critical wrinkling stress during the SHP was analyzed and obtained based on the energy method. The influence of liquid pressure and other experimental parameters on the critical wrinkling stress in SHP was discussed. The mechanism of the wrinkling suppression was analyzed. A 2D simulation model was built to offer stress distribution and save large amount of simulating time. Combining the theoretical and numerical results, a critical loading path of the liquid pressure was built. As the final step, some very thin-walled components with curved surface (the ratio of thickness to diameter is 0.27%) without wrinkling could be formed smoothly according to the analytical critical loading path of the liquid pressure.

2. Theoretical analysis

In modern industry, semi-ellipsoidal parts are widely utilized as many kinds of key components such as propellant ellipsoidal storage tank and pressure vessels [27]. However, the wrinkling defect in the forming of semi-ellipsoidal parts is extremely hard to predict and control. Apparently the unsupported wrinkling defect is caused by the absence of normal constraint in the forming process. It is meaningful to carry out some research on the wrinkling suppression of semi-ellipsoidal parts. Therefore, the analytical model in this paper was built based on this kind of shell. In order to carry out the theoretical analysis more clearly, some assumptions were introduced to render this process. 1) The bending and unbending effects of the blank during the SHP are neglected. 2) The thickness and the volume of the blank are keep unchanged during the whole process. 3) The normal stress can be ignored because of very small normal stress compared with in-plane stress. 4) The strain rate sensitivity of aluminum alloy at room temperature is neglected in the current study [28].

As shown in Fig. 2, the theoretical model and the simplified wrinkling deflection can be seen clearly. The vertical section of the semi-ellipsoidal shell is an ellipse with radius of long axis a and radius of short axis b. The magnitude of the wrinkling is w_0, and N presents the number of wrinkles on the formed parts. The touching point of the blank with the punch, as well as the left boundary of the reverse bulging area under various conditions is assumed as $A_m(x_{hm}, y_{hm})$. For the SHP of complex curved shells, it seems that the position of $A_m(x_{hm}, y_{hm})$ cannot be fixed. When there is no liquid pressure, the touch point of the blank and the punch can be confirmed according to the geometrical characteristics, which is defined as $A_0(x_{h0}, y_{h0})$. Thus $A_0(x_{h0}, y_{h0})$ is the left limitation of A_m during SHP. For the moment that the drawing distance is h, the calculation of $A_0(x_{h0}, y_{h0})$ is shown below:

$$\begin{cases} \frac{x_{h0}^2}{a^2} + \frac{y_{h0}^2}{b^2} = 1 \\ \frac{y_{h0} - y_h}{x_{h0} - a} = y'_{h0} = -\frac{b^2 x_{h0}}{a^2 y_{h0}} \end{cases} \tag{1}$$

Where

$$y_h = -b + h \tag{2}$$

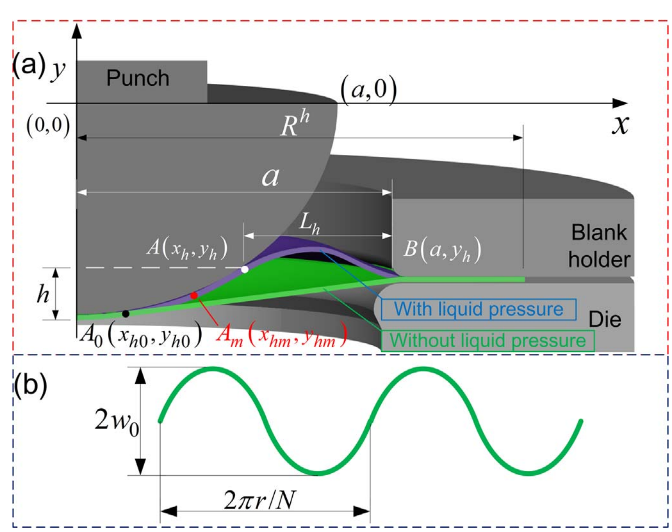

Fig. 2. (a) Section view for the calculation of critical wrinkling stress and (b) the deflection of unsupported wrinkles in Fig. 1.