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Control and use of wrinkles in tube hydroforming

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Abstract

The common defects in tube hydroforming are buckling, bursting and wrinkling. Wrinkling occurs as the axial force reaches a critical value, which was considered as one of defects in the past. In this paper, theoretical analyses, numerical simulation and experiment were conducted to investigate wrinkling behavior in tube hydroforming and how to control and use wrinkles. Effect of loading path and length to diameter ratio on the number of wrinkles and part shape is discussed. It has been shown from the research results that not all wrinkles are defects and tube can be successfully formed after wrinkling in some cases. The key issue is obtaining useful wrinkles instead of dead wrinkles. However, the thickness distribution is not even along the longitudinal direction. Accumulation of material in the expanding area by formation of wrinkles is an effective method for obtaining preform. By use of this method, process window can be enlarged for hydroforming.

Keywords: Internal high pressure forming; Hydrofoming; Wrinkles; Numerical simulation

1. Introduction

Tube hydroforming (THF) or internal high pressure forming (IHPF) has been widely used in automotive industry to manufacture hollow components with variable cross-sections. The basic process is that tube is formed into complex shapes with a die cavity using internal pressure and axial feeding simultaneously. Its main advantages over the conventional stamping processes are weight and cost reduction, better structural integrity, increased strength and reduction in part numbers [1]. Due to unreasonable combination of internal pressure and axial feeding, one of the defects such as buckling, bursting and wrinkling occurs in tube hydroforming.

Dohmann et al. [2] pointed out that wrinkles are unavoidable in the intake region of the expansion tool and can be eliminated by increasing the internal pressure in calibration stage. In addition, as a result of excessively axial feeding, wrinkles can be also formed in the center of the workpiece in the case of long expansion tools, which can be avoided by controlling the forming process carefully.

Defects during the hydroforming process are predicted by numerical simulation and the adjustment of loading paths is presented to smooth the forming process [3]. According to the maximum feeding length and the minimum internal pressure, the loading path is optimized to keep the tube in the critical status before wrinkling. As a wrinkle is about to be formed, the internal pressure should be increased to avoid it. This method is very difficult in the real-time control process.

Xing et al. [4] analyzed the instability of tubular blank under axial stress and the effect of loading path and material properties on hydroforming process. An idea is proposed that some tiny and eliminable wrinkles are acceptable to avoid the excessive thinning of the tube thickness, which could be eliminated during calibration. No experiment was conducted to verify this idea.

Yuan and his colleagues [5,6] conducted an initially experimental and numerical analysis of wrinkling behavior in hydroforming of aluminum alloy tubes. Various shape and number of wrinkles are obtained in different loading paths.

In this paper, control and use of wrinkles in tube hydroforming and the affecting factors on wrinkling behavior are comprehensively investigated by FE simulation based on geometrical analysis of wrinkling and the stress and strain state and thickness variation after wrinkling. It is pointed out that not all wrinkles are defects. Some wrinkles can be used as preform to increase formability. It is proposed that accumulation of material in expanding area by formation of wrinkles is an effective method for obtaining preforms. The key issue is to obtain “useful” wrinkles instead of “dead” wrinkles.

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Nomenclature

d	outside diameter of initial tube
D	outside diameter of part
h	height of sine curve of wrinkle wave
l	length of forming area with the maximum expansion
l_0	length of initial tube
l_1	length of part
l_w	length of single wrinkle wave
l'	whole length of die cavity
n	number of wrinkles
S	surface area of part
S_0	surface area of initial tube

Greek symbols

Δ	ideal feeding length
Δ'	theoretical feeding length
α	semi-angle of cone-shaped transition area
ε_t	thickness strain
ε_θ	circumferential strain
ε_z	longitudinal strain

2. Theoretical analysis

2.1. Geometrical analysis of wrinkling in tube hydrofoming

As shown in Fig. 1, the procedure using a tubular blank with wrinkles as a preform is that wrinkles (3) are formed whereby the tube (1) is pushed inward a distance (Δ') by punches (2) under certain internal pressure, these wrinkles are then expanded to die cavity (4) so that the part is formed.

An ideal feeding length Δ is defined as a feeding value to keep the constant tube thickness before and after the hydrofoming process. According to the surface area of the formed part being equal to that of the original tube, the ideal feeding length is obtained from next equations:

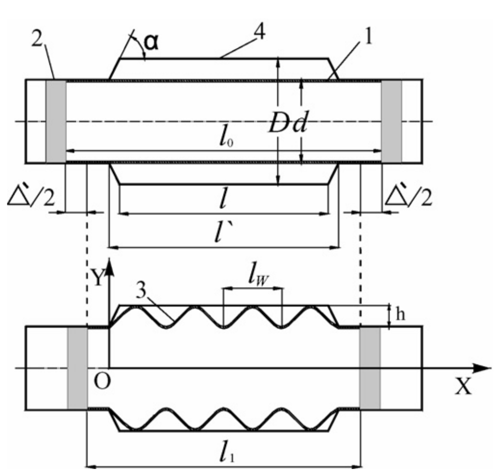

Fig. 1. Wrinkling in tube hydroforming: (1) tube, (2) punch, (3) wrinkled tube, (4) die.

Surface area of the formed part :

$$S = \pi Dl + \frac{\pi(D^2 - d^2)}{2\sin\alpha} + \pi d(l_1 - l') \quad (1)$$

$$\text{Surface area of the original tube : } S_0 = \pi d l_0 \quad (2)$$

Theoretical feeding length :

$$\Delta = l_0 - l_1 = \frac{2Dl\sin\alpha + D^2 - d^2}{2d\sin\alpha} - l' \quad (3)$$

It is assumed that wrinkles are evenly distributed in the die cavity, the wave shape of the wrinkle is described by a sine curve, the top of the wrinkle wave is closed to the die and its bottom is on the outside surface of the original tube. Fig. 1 shows a case with four wrinkles. If the feeding length is different, the number of wrinkles is also different.

The maximum value of height of the sine curve of the wrinkle wave h is $(D-d)/2$ and smaller than the maximum one in the cone-shaped transition area.

Let the axial length of single wrinkle wave $l_w = l'/n$, the sine curve is described by

$$y = h\sin\left(\frac{\pi}{l_w}x\right) + \frac{d}{2} \quad (0 \le x \le l_w) \quad (4)$$

The surface area of single wrinkle wave:

$$S' = 2\pi\int_0^{l_w}\left[h\sin\left(\frac{\pi}{l_w}x\right) + \frac{d}{2}\right]\sqrt{1 + \frac{h^2\pi^2}{l_w^2}\cos^2\left(\frac{\pi}{l_w}x\right)}\,dx \quad (5)$$

The explicit solution cannot be given from this definite integral, but the answer is available by numerical integration method.

The whole surface area of the formed part $S_n = nS'$ when there are n wrinkles. Then the theoretical feeding length Δ' can be obtained from next equation.

$$\Delta' = \frac{S_n}{\pi d} - l' \quad (6)$$

For the case that $D = 88$ mm, $d = 65$ mm and $\alpha = 20°$, three different length of the forming area $l = 65$, 97.5 and 130 mm, i.e. the length to diameter ration $l/d = 1$, 1.5 and 2, the wrinkles number, real feeding length, average thinning rate are calculated, as shown in Table 1.

It can be seen from Table 1 that the thinning rate of wall thickness becomes small and even thickening occurs with increasing the number of wrinkles and the feeding length. This is true for all parts with three different length to diameter ratio. The needed forming materials can be accumulated in advance in the forming area through formation of wrinkles. The key point is number of wrinkles. As long as the number of wrinkles is appropriate, the minimum thickness of part can be kept to meet the required value.