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ScienceDirect
Trans. Nonferrous Met. Soc. China 21(2011) s465−s469
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Formability influenced by process loading path of double sheet hydroforming

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Received 10 May 2011; accepted 25 July 2011

Abstract: Double sheet hydroforming can be used to manufacture hollow part with complicated section geometries by allowing material draw-in under an appropriate process loading path. Two major parameters, clamping force and liquid pressure, were studied for hydroforming of unwelded double sheets. A proposed limit liquid pressure corresponding to different clamping forces was calculated theoretically, which can be used to reveal the influence of process parameters combination on deformation behaviors. The calculated results were studied and verified by FE analysis and experiments. Two linear loading paths and a multi-step loading path were applied to study the sheet deformation behaviors and formability. The experimental results illustrate that the multi-step loading path shows better formability than other loading paths.
Key words: double sheet hydroforming; clamping force; liquid pressure; formability

1 Introduction

In the last decades, double sheet hydroforming (DSH) as a new branch of sheet hydroforming was proposed and studied by some researchers [1−3]. Some initial applications, such as engine cradle, suspension triangle, B-pillar and crossmember [4−7], were found in the automobile industry for the special merits of good formability, reduced procedures and lower cost using DSH by contrast with stampings [8−10]. What's more, DSH has the advantage of forming parts with more complicated sections by allowing material to flow into die cavity in preforming stage under reasonable loading path [11−12]. ASSEMPOUR and EMAMI [13] tried to calculate the liquid pressure by using upper bound analysis method which was verified by single blank hemispherical hydroforming. GEIGER et al [14] studied the sealing curve varied by clamping force by experiments for the integration of the tube and double blank. NOVOTNY and HEIN [15] gave the process window determined by the leakage and rupture limit for hydroforming of double sheets by experiments. However, the process loading path combined by clamping force and liquid pressure is one big challenge which influences the material flow and part formability [12, 16], and few researchers focused on the relationship between the part formability and the process loading path.

In this work, unwelded double blanks were formed by high pressure liquid medium, the relationship between the liquid pressure and the clamping force was given by theoretical analysis, simulation and experiments, and different types of loading paths were used to study their effect on the formability.

2 Materials and model

The blank with material DC04 was used, and mechanical properties of the material are given in Table 1.

Table 1 Mechanical properties of DC04

Thickness/ mm	σ_s/ MPa	σ_b/ MPa	n	K	r
1	152	297	0.258	552.56	2.177

Foundation item: Project (50905041) supported by the National Natural Science Foundation of China; Project (20092302120079) supported by the Specialized Research Fund for the Doctoral Program of Higher Education, China; Project (09JD18) supported by Key Laboratory of Ministry of Education for Conveyance and Equipment (East China Jiaotong University)
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A double blank hydroforming device was designed to study the blank deformation behaviors affected by the combination of parameters of clamping force and liquid pressure. As shown in Fig. 1, the unwelded double blanks are placed and sealed between the upper die and the lower die, and then the liquid medium is introduced and fulfilled into the interface of the double blanks. At the same time the clamping force acts on the blanks of flange region, and the double blanks are bulged toward the negative directions by the high pressure produced by the filled liquid medium.

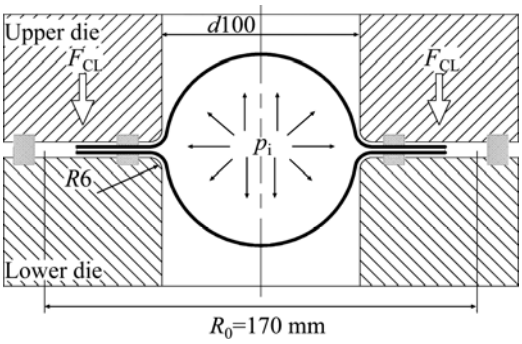

Fig. 1 Schematic diagram of unwelded double sheet hydroforming

3 Limit liquid pressure and its curve

3.1 Theoretical calculation

The clamping force and the liquid pressure are two important parameters for sheets deformation behaviors. Especially for the hydroforming of unwelded double blanks, the appropriate clamping force plays more important roles. One role is to maintain the fluid medium sealed between the upper die and the lower die, the other is to maintain a level to prevent wrinkles in the flange region and allow the blanks in flange region to flow into the die cavity at the same time. However, in the forming procedure, the actual clamping force applying on blanks of flange is reduced by resisting force caused by the increase of the liquid pressure, which results in the fact that the liquid medium flows out between the blank and die surface. So, the liquid pressure needed for the forming of blanks is decided by the appropriate clamping force. In this work, the limit liquid pressure was proposed when the moment of liquid medium leaks between the blank and the die under a constant clamping force.

The actual clamping force applying on blanks of flange can be expressed by

$$F_{AL} = F_{CL} - pS \tag{1}$$

where F_{AL} refers to the actual force applying on flange; F_{CL} refers to the clamping force given by press; p refers to the liquid pressure; and S refers to the square of liquid pressure applying on the die surface.

When the liquid leaks before the fracture of blanks, the actual force applying on the blanks of flange is reduced to zero,

$$F_{AL} = F_{CL} - pS = 0 \tag{2}$$

So, limit liquid pressure p_l without the liquid leakage can be calculated by

$$p_l = \frac{F_{CL}}{S} \tag{3}$$

However, under a higher clamping force on the flange with few blank flowing into the die cavity, more stretching deformation on double blanks will produce creaking before the liquid leakage, and the liquid pressure at the moment of fracture can be given by

$$p_f = \frac{2t}{R}\sigma_b \tag{4}$$

where t refers to the thickness of blank; R refers to the radius of the hemispherical cup.

According to Eqs. (3) and (4), a set of limit liquid pressure corresponding to different clamping forces can be calculated.

3.2 FE analysis and experiments

Both FE analysis and experiments were conducted to verify the theoretical calculations. The FE model was built up with the commercial code DYNAFORM, as shown in Fig. 2. The upper die and lower die were modeled as rigid bodies. Belytshko-Tsay element was used to discrete the blanks with a diameter of 170 mm, and the minimum element size of blank was set to 2.0 mm. To exert the loading paths, a pressure varied with forming time was applied in the circle range with diameter of 100 mm, corresponding to the inner diameter of the two dies.

In the experiments, the double blanks were bulged in a hydromechanical press with the maximum clamping force of 1 MN and the maximum liquid pressure of 100 MPa. In the forming procedure, the clamping force and liquid pressure can be controlled on time. The experimental equipments and mould are shown in Fig. 3.

With various clamping forces ranging from 200 kN to 900 kN, a calculated limit liquid pressure curve can be obtained from Eq. (3) and Eq. (4). Similarly, a set of FE analysis and experiments with different clamping forces were done in order to achieve the limit liquid pressure. The results show good agreements with the theoretical calculation results, as shown in Fig. 4.

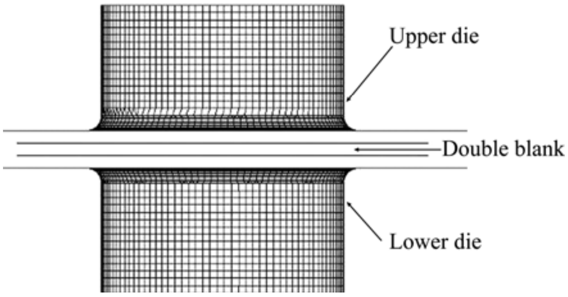

Fig. 2 FEM model of double sheet hydroforming

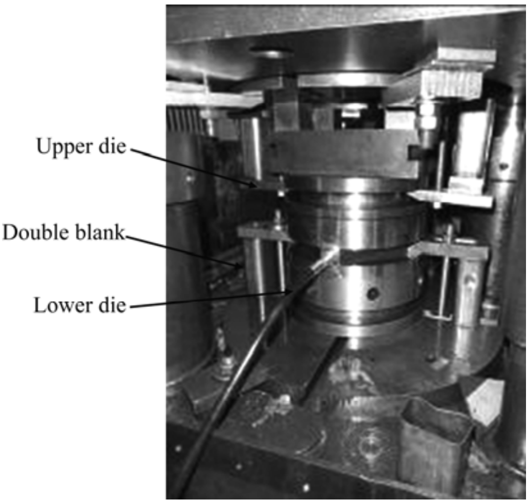

Fig. 3 Experimental tool

3.3 Deformation behaviors

From Fig. 4, there are four different deformation behaviors (A, B, C, D) under different combinations of the clamping force and the liquid pressure at least. For example, in the region above the limit liquid pressure curve, liquid leaks from flanges for the low clamping force (A). However, in the region above the fracture limit curve, fracture occurs at the top of hemispherical for pure stretching strain caused by high clamping force (B). So, the appropriate forming process loading path should be below the limit liquid pressure curve and the fracture limit curve. But, the blank deformation behaviors are much different in the regions. For example, the region near the curve means that materials draw-in easily and little stretch forming occurs under the process parameters combination of lower clamping force and higher liquid pressure (C). On the contrary, the region far from the curve means that materials draw-in hardly and more stretch forming occurs under the process parameters combination of higher clamping force and lower liquid pressure (D). So, in the center, the deformation behavior is the combination of deep drawing and stretch forming. By this way, the forming window decided by clamping force and liquid pressure was obtained, which can be very useful to reveal different deformation behaviors.

4 Loading path and formability

Three different process loading paths were used in the experiments, as shown in Table 2 and Fig. 5. In the two linear loading paths, Path 1 and Path 2, the clamping forces are maintained as a constant value, while the liquid pressure increases continuously up to a value. From the samples formed with Path 1 and Path 2, wrinkles and fracture occur on different parts. However, with the multi-step loading path, Path 3, good formability is realized.

Table 2 Experimental parameters of loading path

Loading path	Clamping force/ kN	Liquid pressure/ MPa	Formability of parts
Path 1	400	0−10	Wrinkling
Path 2	700	0−12	Fracturing
Path 3	300−700	0−12	Good

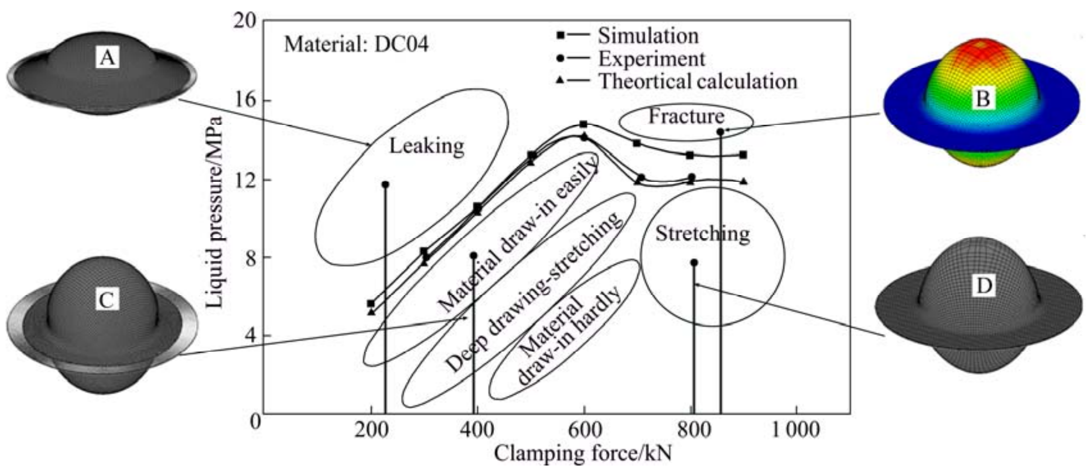

Fig. 4 Limit liquid pressure and its curve

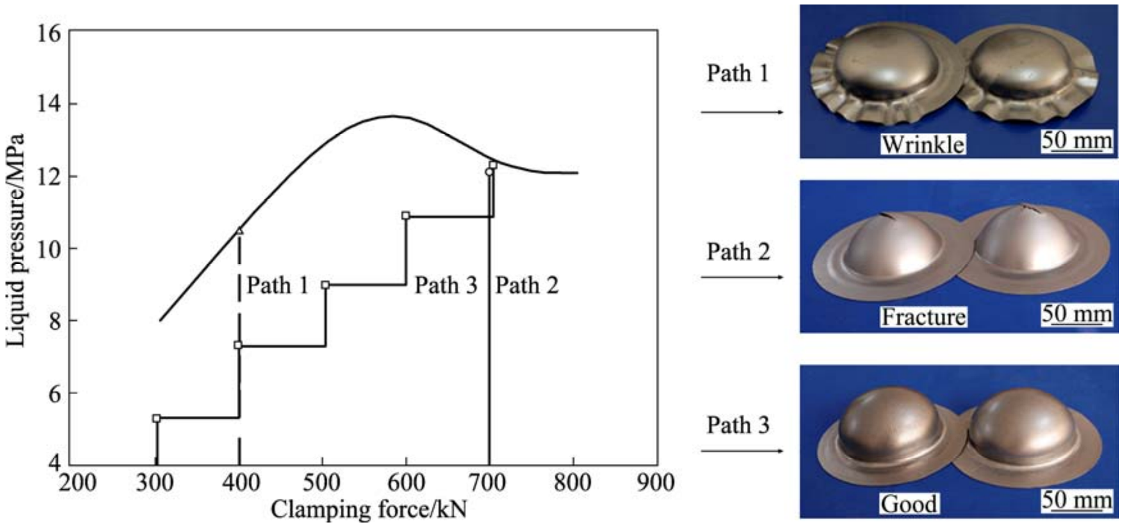

Fig. 5 Results of experimental parts with three different loading paths

5 Conclusions

1) The proposed limit liquid pressure curve is obtained by the theoretical calculation, FE analysis and experiments. Good agreements among three kinds of results verify the limit liquid pressure curve equations.

2) The deformation behavior changes with different process parameter combinations. By using the limit liquid pressure curve, appropriate loading path can be selected to improve the formability according to the deformation behaviors presented in the figure of limit liquid pressure curve.

3) Experimental results show the multi-step loading path is better than the linear loading paths for allowing more materials draw-in and avoiding liquid leakage.

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板材成对液压成形工艺加载路径对成形性的影响

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摘 要：板材成对液压成形可以用于制造复杂几何截面的空腔构件，通过合理的工艺加载路径可以实现板材的流动控制。研究非焊接板材成对液压成形工艺以及两个主要工艺参数(合模力和液压力)的影响。通过理论计算研究不同合模力对应的极限液压力，得到极限液压力曲线，揭示不同工艺参数组合对变形行为的影响规律。通过有限元分析和实验研究验证了理论值，结果表明它们之间具有较好的一致性。实验采用 2 种线性加载路径和 1 种阶梯型加载路径研究加载路径对变形行为和零件成形性的影响，结果表明采用阶梯型加载路径可以得到很好的成形性。

关键词：板材成对液压成形；合模力；液压力；成形性

(Edited by CHEN Wei-ping)