Int J Adv Manuf Technol (2015) 80:1149–1157
DOI 10.1007/s00170-015-7126-y

ORIGINAL ARTICLE

Research on hydro-pressing process of closed section tubular parts

W. C. Xie[1] · C. Han[1] · G. N. Chu[1] · S. J. Yuan[1]

Received: 17 September 2014 / Accepted: 6 April 2015 / Published online: 15 April 2015

Abstract A hydro-pressing method was proposed to solve the problems in tube hydroforming process, such as too high pressure, nonuniform thickness distribution, and difficult forming of section corners. The process of hydro-pressing a tube seems like pressing of a solid bar. Theoretical analysis was performed, and the calculation formulas of hydro-pressing process parameters were given. Experimental research was conducted on hydro-pressing process of rectangular cross section with curved sides and bowtie cross-sectional components. The effects of supporting pressure, displacement of the pressing on section shape, and thickness distribution were investigated. The difference was compared between the hydro-pressing forming and the conventional mechanical pressing. It is demonstrated that the supporting pressure and pressing displacement are the essential parameters that influence cross-sectional shape and thickness. The dent defect disappears gradually as the supporting pressure increases and the thickness varies unobvious during hydro-pressing process of a rectangular cross section with curved sides. When the supporting pressure is 15 MPa, the maximum thinning of the rectangular cross section with curved sides is only 1.92 %. For a bowtie cross section, the required pressure is far less than that of conventional hydroforming for the same corner radius. Thickness distribution of section corner zone is more uniform than that formed by conventional hydroforming. Compared with conventional hydroforming, the hydro-pressing is a valid method to form the closed section tubular parts with the same perimeter and different cross-sectional shapes, which remarkably improves thickness distribution and reduces the forming pressure.

Keywords Hydro-pressing · Hydroforming · Tubular part · Section shape · Thickness distribution

1 Introduction

Tube hydroforming is a competitive and advanced technology to form hollow automotive components due to its advantages such as weight reduction and high utilization of strength and stiffness [1–4]. From pressure standpoint, tube hydroforming involves two major processes: preliminary forming stage and final forming stage. The required pressure is low for preliminary forming stage, but much higher for final forming stage. For most of automotive components, the required pressure generally needs to reach 100–200 MPa during final forming stage. When forming complex section component or high strength material, it is up to 300 MPa. Higher pressure induces serious problems, such as over thickness thinning near corner zone, excessive wear of the die, and worse maneuverability for pressure control [5–7]. Such problems limit further broad use of hydroforming technology. In response to these problems, scholars have made great efforts and proposed many measures [8, 9].

To solve these problems mentioned above, Vari-form put forward a new forming technology-pressure sequence hydroforming (PSH) [10, 11]. Its idea is the pressure induces and increases as die closing and internal liquid compressing and then provides the force for plastic deformation. The significant feature is the required pressure that has been decreased by 30–50 %. The main reason is that friction plays active roles during pressure sequence hydroforming.

✉ C. Han
conghan@hit.edu.cn

[1] National Key Laboratory of Precision Hot Processing of Metals, Harbin Institute of Technology, P.O. Box 435, 92 West Da-Zhi Street, Harbin 150001, People's Republic of China

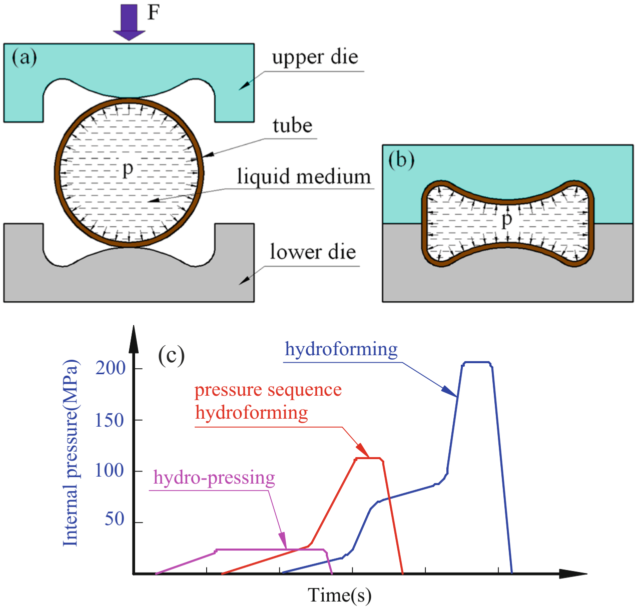

Fig. 1 Schematic of hydro-pressing process: **a** filling and pressured, **b** pressing period, and **c** loading paths

However, it is complex and difficult to control pressing displacement and hydraulic pressure simultaneously, because the pressure in the tube is going up during the die closing. Meanwhile, precision equipment is necessary to achieve precise control. Yuan et al. proposed a preform method, named as "petal preform" [12–15]. As a flower-like section shape was preformed, the central zones of the four sides of the section would not contact with the die surface before calibration. Thus, the tube material is easy to flow into the transition radius areas in the calibration stage. Moreover, a positive force along the sides, whose direction is opposite to that of the friction force, is produced by hydraulic pressure and is beneficial to overcome the friction force and to push the material into the radius area. Therefore, pressure for forming the transition radii can be greatly reduced by 50–80 %. However, the petal preform takes effect only during initial forming stage. It has no effect after petal cross section that is flattened. In recent years, warm hydroforming was studied and demonstrated some advantages for low plasticity material forming [16–18]. Required pressure drops to a lower degree by heating the material to a certain temperature. Nonetheless, hot process is of long period, inefficient, and higher cost. As a result, it still does not match mass volume production in the automobile industry.

Among automotive components, there is a kind of part which is different only in section shape but basically unchanged in section perimeter, such as side rail, roof member, and A-pillar. In term of such specific structural characteristics, mechanical pressing forming is regarded as an appropriate method to manufacture these components [19, 20]. However, instability and local dent defect are easy to happen due to lack of internal supporting so that the section shape and dimensional precision cannot be guaranteed.

Aiming at solving the problems above, a new method of hydro-pressing process is proposed. The major idea of the hydro-pressing process is that pressing of a tube with internal supporting pressure, which seems like pressing of a solid bar. The effects of supporting pressure and pressing displacement on section shape and thickness distribution were experimentally investigated.

2 Principle of hydro-pressing process

The process of hydro-pressing is that a tube is formed into the designed section shape as die closing and hydraulic pressure applying simultaneously. Because of the supporting action of

Fig. 2 Tube blank and section dimension (mm): **a** tube blank, **b** rectangular cross section with curved sides, and **c** bowtie cross section

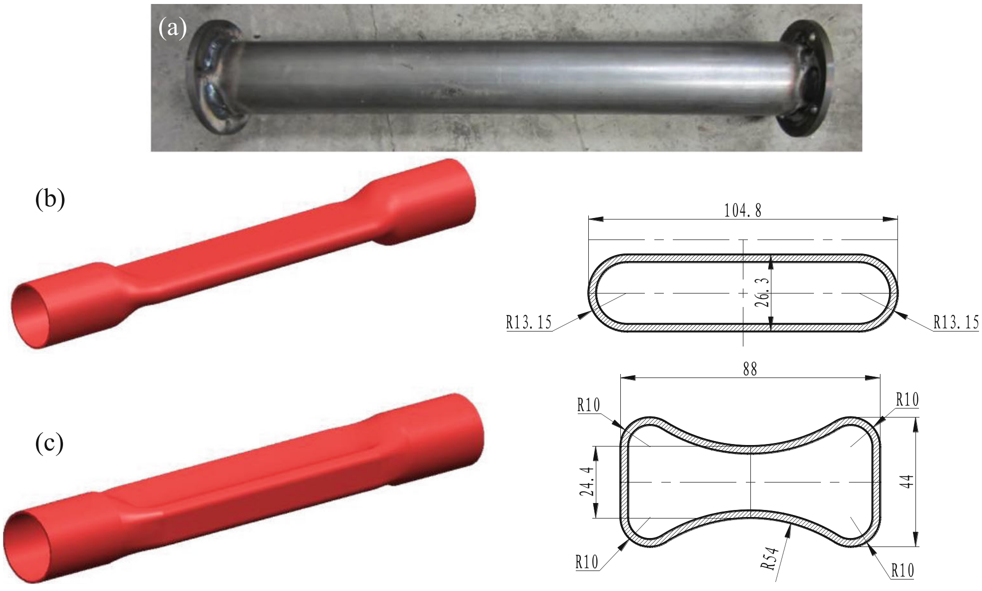

Table 1 Mechanical parameters of mild steel tube

Material	Tensile stress σ_b (MPa)	Yield stress σ_s (MPa)	Hardening exponent n	Strength coefficient K	Elongation (%)
STKM11A	345	295	0.104	492	44.2

hydraulic pressure, the instability and wrinkle defects can be avoided. The schematic of hydro-pressing process is illustrated in Fig. 1. It consists of two major periods, filling period and pressing period. During the filling period, a tube is put into the die, then sealed by plugs, and filled with liquid. In the pressing period, hydraulic pressure is increased to a design value; after that, the upper die closes and presses the tube into the design cross section. The pressure in the tube is kept constant by a relief valve and an oil–water pressure transducer when it goes up as the press moving down. In the opposite way, it is maintained by the oil–water pressure transducer to the required value if the pressure drops. Moreover, there is no expansion of the tube in the process. It differs from the PSH method of Vari-form, which the internal pressure is going up and there is an expansion of the tube. Hydro-pressing process is easy to control, and the cycle time is usually shorter than the PSH process.

3 Specimen and experimental schemes

3.1 Specimen and material

In view of the fact that rectangular cross section is the primary shape element of automobile components, a rectangular with curved sides and a bowtie cross section are selected to be the specimen section shapes. The bowtie cross-sectional specimen end is designed as a round shape to avoid shifting, as shown in Fig. 2. Tube material is mild steel STKM11A, and the mechanical properties obtained through uniaxial tensile test are listed in Table 1. The outer diameter of the tube blank is 76.3 mm, and the thickness is 2.6 mm. The total length is 600 mm, and the length of pressing zone is 300 mm.

3.2 Experimental schemes

The supporting pressure and pressing force are the primary factors of the hydro-pressing process. As the ratio of thickness to radius is much bigger than 20, the mechanical model of hydro-pressing process can be regarded as a thin wall cylinder shell, as shown in Fig. 3. According to the principle of force equilibrium, the axial stress σ_z and hoop stress σ_θ can be described as

$$\sigma_z = \frac{r}{2t}p, \quad \sigma_\theta = \frac{r}{t}p \tag{1}$$

where r is the radius of the cylinder, t is the thickness, and p is the hydraulic pressure.

According to Tresca yield criterion, the limit of supporting pressure P_s can be derived as

$$p_s = \frac{t}{r}\sigma_s \tag{2}$$

where σ_s is the yield stress of the material.

Pressing force F_P can be derived as

$$F_p = 2rLp_s = 2Lt\sigma_s \tag{3}$$

where L is the length of the pressing zone.

The experiment schemes are given in Table 2. According to Eq. (1) and Table 1, the maximum supporting pressure is 20.1 MPa. Then, six different values of the supporting pressures, which are all less than 20.1 MPa, were selected and studied to show effects on cross-sectional shape, thickness distribution, and corner filling during hydro-pressing process. In addition, four different values of pressing displacements were experimented to investigate the primary evolution course of hydro-pressing process.

3.3 Experimental setup and die

A special apparatus was developed to carry out experiment on the hydro-pressing, as shown in Fig. 4, which is composed of a 2000 kN hydraulic press for die closing, a hydraulic drive system, an oil–water pressure transducer, and a control system. The role of the oil–water pressure transducer is transferring 25-MPa oil pressure into the water pressure, so that the tube can be formed by a clear fluid medium.

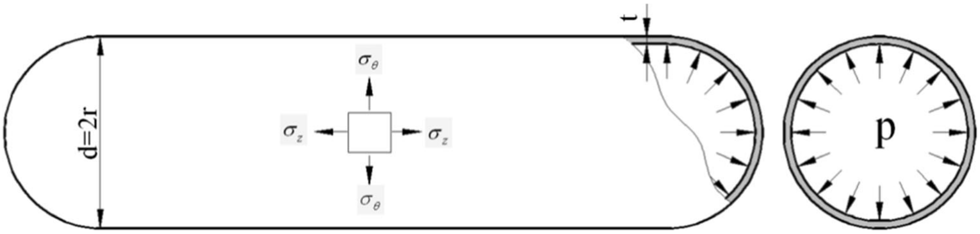

Fig. 3 A thin-walled cylinder shell subjected to hydraulic pressure

Table 2 Experimental schemes

Type of section	Supporting pressure P/MPa	Displacement of pressing H/mm
Rectangular with curved sides	0, 6,	20, 30, 40, 50
	0, 3, 6, 9, 12, 15	40
Bowtie cross-section	0, 3, 6, 9, 12, 15	–

The hydro-pressing die set consisted of an upper die, a lower die, left and right plugs. The material of the die was one kind of tool steels. Both the upper and lower dies were quenching and tempering. The upper die was assembled and mounted on the upper base plate, which was fixed with the upper movable plate of the hydraulic press. The lower die was mounted on the lower base plate. The flanges were welded on the tube end, and they were assembled with the plugs to seal the tube end. After the tube was put into the die cavity, the water medium was filled into the tube from the oil–water pressure transducer by a pipe through a plug. There is no axial feed during the pressing process. The pressure of the tube inside could be controlled by a servo system according to the loading path from the computer control system. The tube is not lubricated in the test.

4 Results analysis and discussion

4.1 Hydro-pressing of rectangular cross section with curved sides

4.1.1 Effect of supporting pressure on cross-sectional shape

Figure 5 shows the effect of the supporting pressure on the cross-sectional shape. It can be seen that a serious buckling defect appears and the side arc is sharp quietly when the supporting pressure is zero, i.e., the conventional mechanical pressing forming. On the contrary, a sound rectangular cross section with curved sides is achieved when the supporting pressure applied. For different supporting pressures, the difference is that only polar axis varies slightly.

Figure 6 shows the arc shape of the cross section formed under different supporting pressures. It can be observed that the shapes of side arcs are all curved. Major semi-axis changes slightly as the supporting pressure increasing, but minor semi-axis is almost invariable. Major semi-axis increases from 14 to 15.5 mm during the supporting pressure increasing from 3 to 15 MPa.

In order to quantify buckling degree, the depth of dent is defined as the difference between h_1 and h, as shown in Fig. 7. It can be seen that there is an obvious dent for traditional mechanical pressing forming without supporting pressure, and the depth of dent reaches to 0.24 mm. Depth of dent decreases with high pressure. The dent defect disappears when the supporting pressure reaches to 6 MPa. It is worthwhile to be noted that springback happens when the supporting pressure reaches to 15 MPa. These results illustrate that the dent defect can be eliminated only under an appropriate supporting pressure. Too higher pressure would induce more springback. As for mild steel STKM11A tube with 76.3-mm diameter and 2.6-mm thickness, the appropriate supporting pressure is 6 MPa.

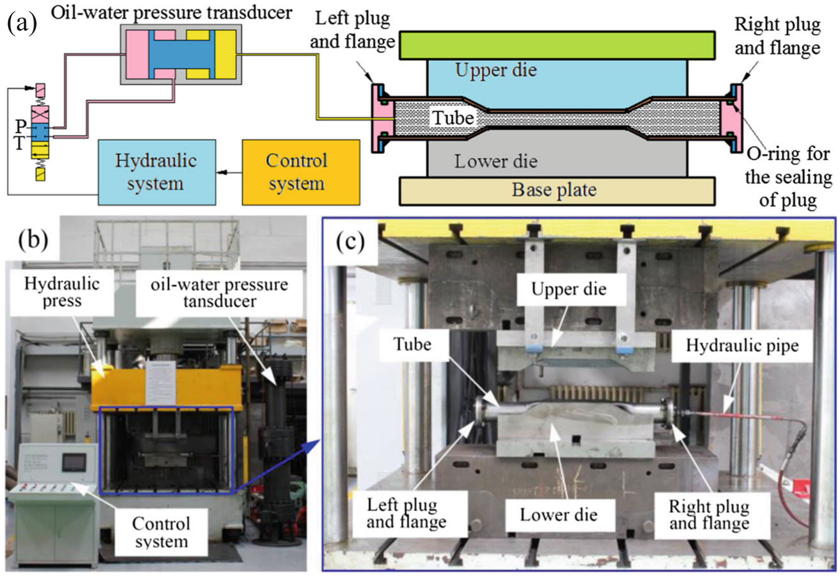

Fig. 4 Experimental setup and die: **a** schematic of hydro-pressing press and tooling, **b** hydraulic press, and **c** die set

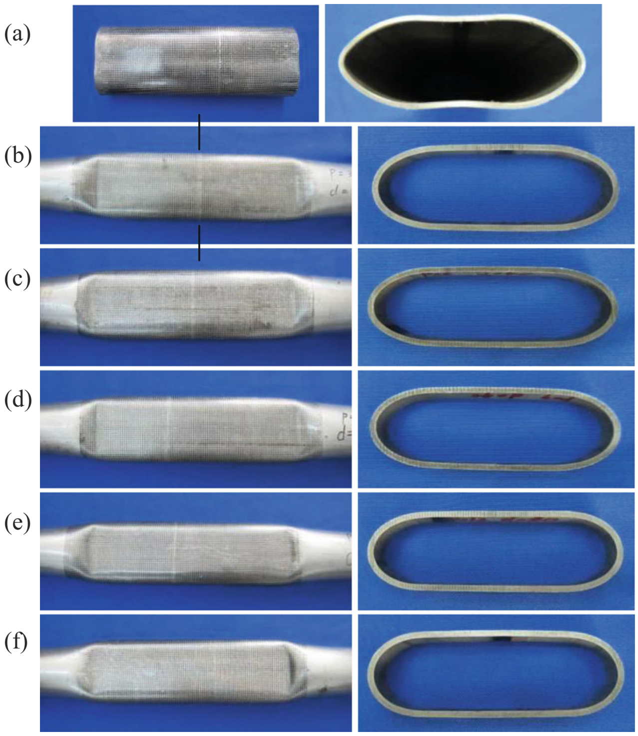

Fig. 5 Shape change of rectangular cross section with curved sides: **a** p= 0 MPa, **b** p=3 MPa, **c** p=6 MPa, **d** p=9 MPa, **e** p=12 MPa, and **f** p= 15 MPa

4.1.2 Effect of supporting pressure on thickness distribution

The formed each part is cut from the center, and typical points are selected along the circumferential direction of section and the thickness of each point is measured by a micrometer. Figure 8 shows the effect of the supporting pressure on the thickness distribution. It can be seen that thickness is virtually unchanged when the supporting pressure is 0 and 3 MPa and varies unobviously even when the supporting pressure is bigger than 6 MPa. Thickness is symmetrical distribution, and thinning ratio increases as the supporting pressure is rising. Thinning ratio increases from 0.3 to 1.92 %, when the supporting pressure is increasing from 6 to 15 MPa. For a certain supporting pressure, the maximum thinning happens in the vertically symmetrical plane (points 1 and 13), and the minimum thinning locates in the horizontally symmetrical plane (point 7). In view of thickness distribution, the appropriate supporting pressure is also 6 MPa. A FE simulation was conducted to analyze the reason for the thickness distribution. Figure 9 is the thinning ratio and equivalent stress at the initial stage that the die contacts with the tube and the final stage, respectively. The equivalent stress of the top point reaches the maximum value when the die contacts with the tube, which is bigger than that of other points. There is a stress concentration on the tube top; so, the maximum thinning occurs at the top point. When the contact area is bigger, the equivalent stress on the top point becomes small and the thickness is no longer changed due to the friction between the tube and the die. However, the maximum thinning ratio is about 2 %; so, the thickness distribution of the hydro-pressing is more uniform than that of the conventional hydroforming.

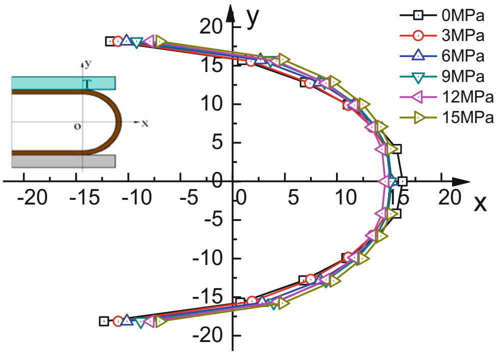

Fig. 6 Side arcs shape under different supporting pressure

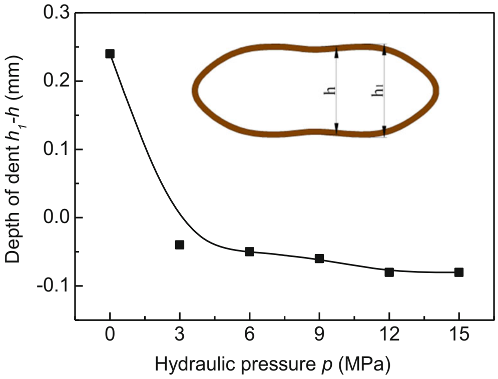

Fig. 7 Depth of dent in different supporting pressure

4.1.3 Effect of pressing displacement on cross-sectional shape

Figure 10 shows the main evolution course of traditional mechanical pressing and hydro-pressing process. For traditional mechanical pressing, the dent defect appears even when the

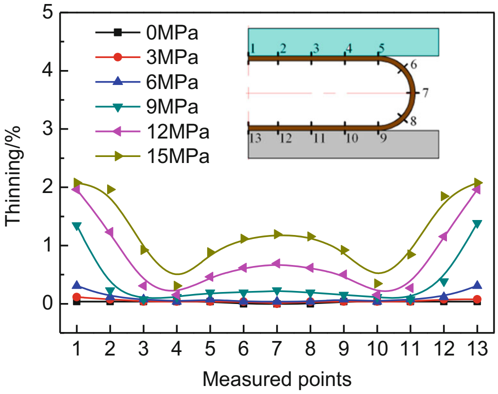

Fig. 8 Thickness distribution of rectangular cross section with curved sides

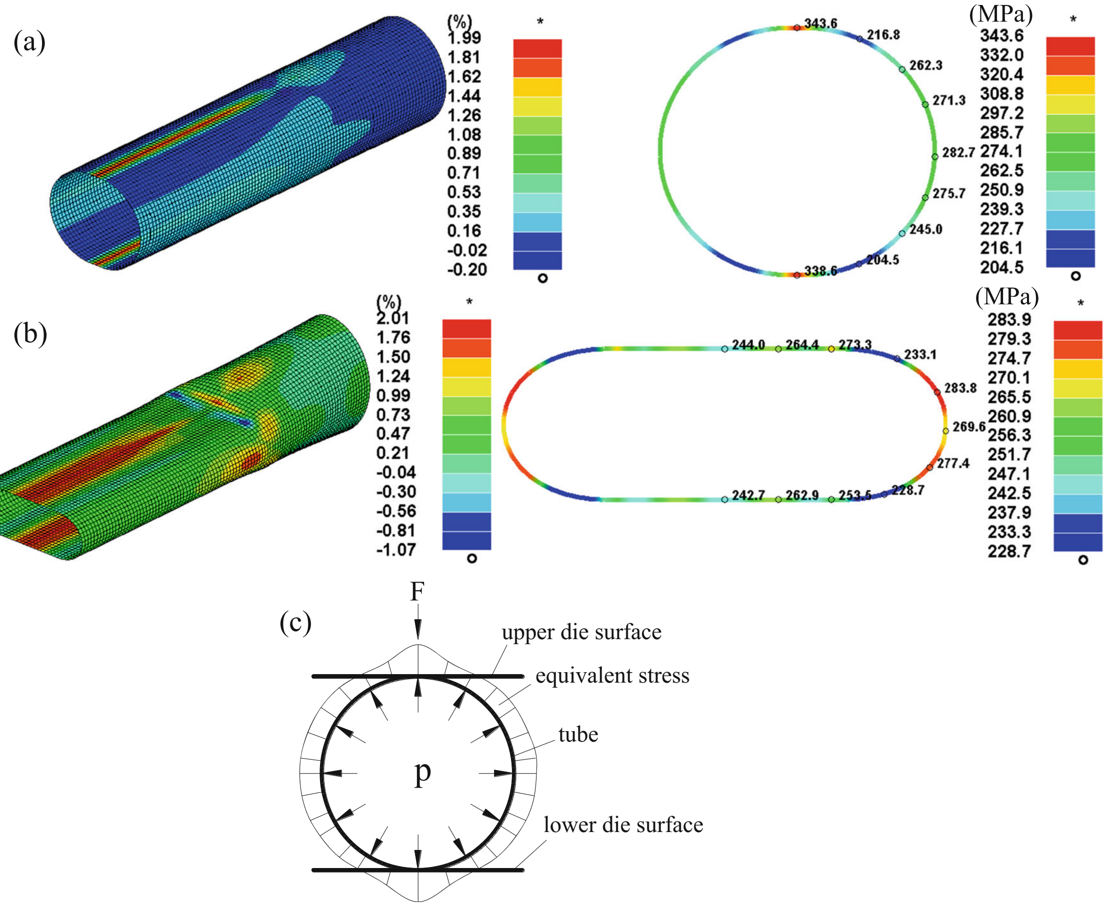

Fig. 9 Thinning ratio and equivalent stress of rectangular cross section with curved sides: **a** thinning ratio and equivalent stress at the initial stage, **b** thinning ratio and equivalent stress at the final stage, and **c** schematic of stress concentration as the die contacting with the tube

pressing displacement is 20 mm and worsens as the pressing displacement increasing. Serious dent happens when the pressing displacement reaching 50 mm. As for hydropressing process, there is no dent defect that happens at any pressing displacement amount, and a sound rectangular cross section with curved sides is well formed.

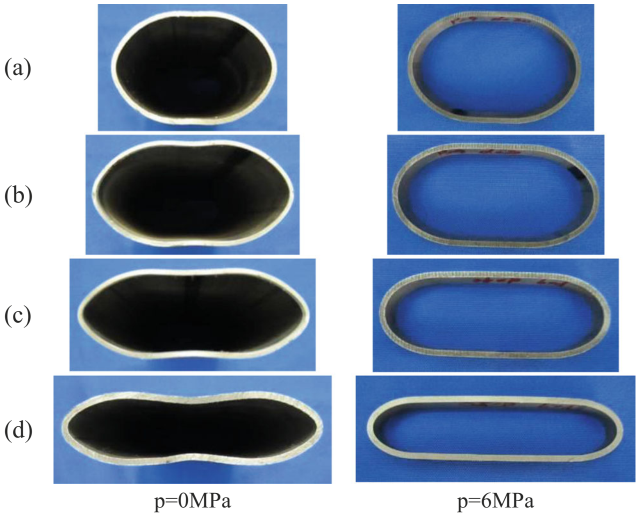

Fig. 10 Effect of pressing displacement on cross-sectional shape under the condition of 0 and 6 MPa: **a** H=20 mm, **b** H=30 mm, **c** H=40 mm, and **d** H=50 mm

Figure 11 shows the effect of the pressing displacement on the dent degree. As for traditional mechanical pressing, the dent degree worsens as the pressing displacement increasing. The relationship between depth of dent and pressing displacement is almost linear. The maximum depth reaches 2.2 mm when the pressing displacement is 50 mm. In contrast, the

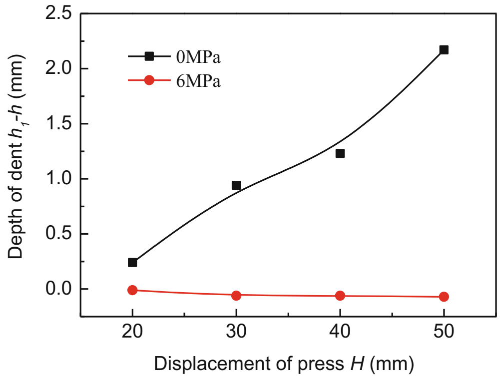

Fig. 11 Effect of the pressing displacement on dent depth

depth of dent is always about zero at any pressing displacement for hydro-pressing process. It can be concluded that the supporting pressure plays a key role in preventing dent defects during hydro-pressing process.

4.2 Hydro-pressing of bowtie cross section

4.2.1 Effect of supporting pressure on bowtie cross-sectional shape

Figure 12 shows the effect of the supporting pressure on the bowtie cross-sectional shape. It can be seen that when no supporting pressure applied, the dent and flash defects also appear and disappears until the supporting pressure 3 MPa was applied. From Fig. 12b, it also can be seen that there is fairly straight side formed as the supporting pressure reaches 6 MPa. The length of straight side becomes longer as the supporting pressure rising. A sound bowtie cross section was obtained when the pressure reached 12 MPa.

In view of geometrical precision, the corner radius is the key parameter for the bowtie cross-sectional component, which is often used to evaluate the formability of process. The corner radii of different supporting pressures are shown in Table 3. It can be seen that the value of the corner radius formed is 11 mm although the supporting pressure is only 3 MPa, which is slightly smaller than the designed radius 10 mm. The corner radius decreases as the supporting pressure rising. It reaches 10.67 mm when the supporting pressure is 15 MPa, but it is still smaller than the designed radius. The major reason is the expansion ratio that happened during hydro-pressing process that is only about 1.04 %, which is less than the designed expansion value of 6 %.

Table 3 Corner radius by different supporting pressures

Supporting pressure (MPa)	3	6	9	12	15
Radius (mm)	11.0	11.0	11.0	11.0	10.67

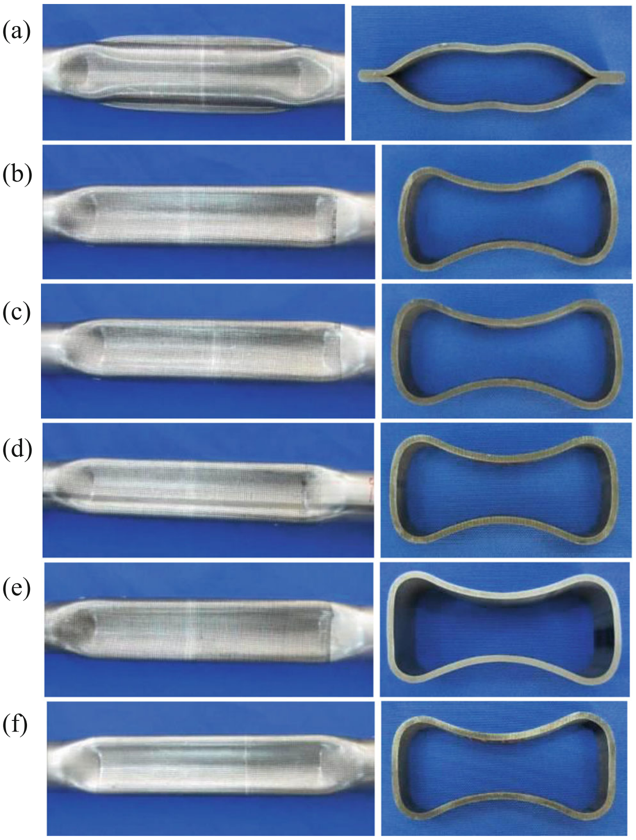

Fig. 12 Shape change of bowtie cross section: **a** $p=0$ MPa, **b** $p=3$ MPa, **c** $p=6$ MPa, **d** $p=9$ MPa, **e** $p=12$ MPa, and **f** $p=15$ MPa

4.2.2 Effect of supporting pressure on thickness distribution

Figure 13 shows the effect of the supporting pressure on the thickness distribution. It can be seen that thickness is almost unchanged when the supporting pressures are 0, 3, and 6 MPa. As the supporting pressure is bigger than 6 MPa, the thinning ratio begins to be bigger. The maximum thinning happens on the vertically symmetrical plane (point 1 and 21). The maximum thinning ratio is only 1.62 % when the supporting pressure is 15 MPa, which is far less than that of the hydroforming process.

4.2.3 Comparison of the forming pressure between hydro-pressing and hydroforming

To compare the forming pressure between hydro-pressing and hydroforming, an experiment was also carried out on hydroforming of the same bowtie cross-sectional specimen. The hydroforming die and measurement of the corner radius are shown in Fig. 14. The diameter of the tube is the same as that of hydro-pressing process, while the curve length of the die section is different and the expansion ratio is 11.0 %. Four displacement sensors were installed at the die corner to measure the relationship

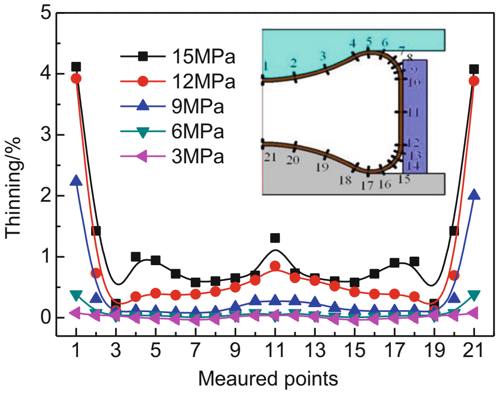

Fig. 13 Thinning ratio of bowtie cross section

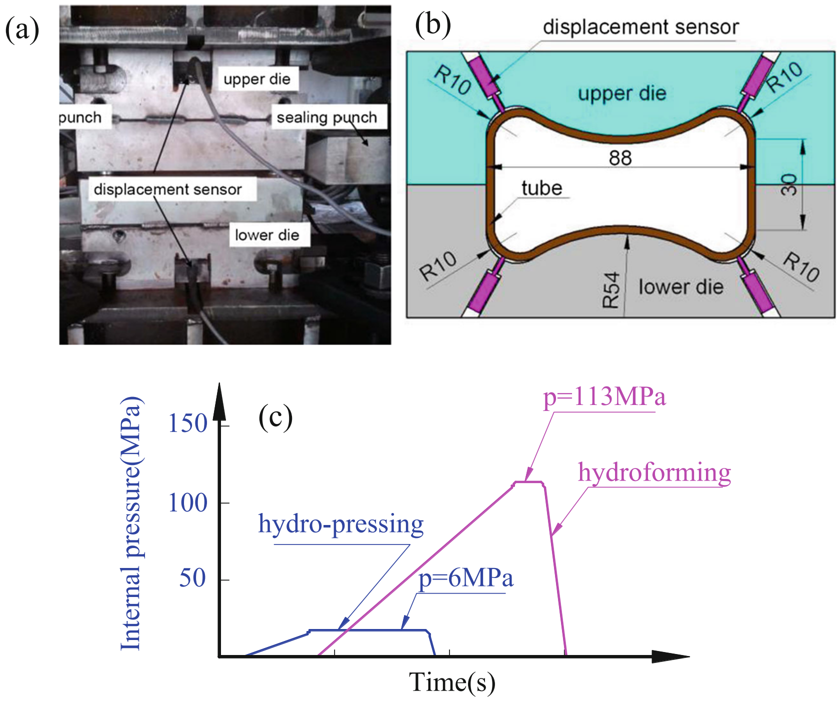

Fig. 14 Hydroforming dies and measurement of the corner radius: **a** hydroforming dies, **b** schematic of measurement and section dimensions, and **c** loading path of hydro-pressing and hydroforming process

between the corner radius and the pressure during the corner filling.

The relations between the corner radius and the pressure are illustrated in Fig. 15. It can be observed that the required pressure of the hydroforming is about 113 MPa to form a corner with 11-mm radius, which is far bigger than that of hydro-pressing process. As above discussed, the required pressure is only 6 MPa to form the same size radius for hydro-pressing process. This result attests that hydro-pressing really has significant advantages in the corner forming and also results in greatly reducing forming pressure. As a result, the designed radius could be achieved just by a very low pressure. At the same time, the cracking never happens due to the corner filling, which means that the hydro-pressing is an effective technology.

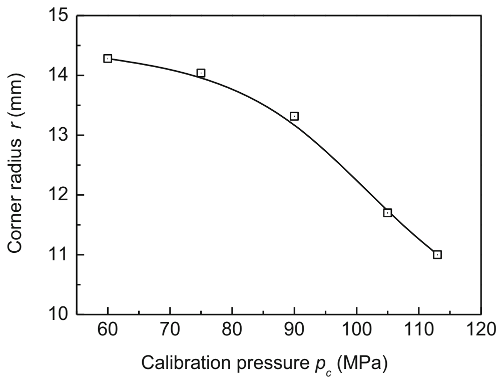

Fig. 15 Relation between the radius and the hydraulic pressure

5 Conclusions

In order to solve the problems in tube hydroforming process, a hydro-pressing method was proposed. A preliminary experimental research was conducted on hydro-pressing of typical sections. Conclusions can be drawn from this work as following:

(1) The calculation formulas for parameters of the hydro-pressing process were given, which provides reference for equipment selection and die design. The supporting pressure is the essential parameter that influences the shape, the thickness distribution, and the corner radius of the cross section.

(2) For a rectangular cross section with curved sides, the dent defect gradually disappears as the supporting pressure increases. However, too higher pressure would induce springback. As for mild steel STKM11A tube with 76.3-mm diameter and 2.6-mm thickness, the appropriate supporting pressure is 6 MPa. For a bowtie cross section, the required pressure is far less than that of the hydroforming to form the same corner radius. The required pressure for forming a corner with 11-mm radius is only 6 MPa for hydro-pressing process, which is about 5.3 % of that of the hydroforming.

(3) Thickness distribution is symmetrical, and the thinning is unobvious for hydro-pressing process. The maximum thinning happens at the midpoint of each side. The maximum thinning ratios are about 1.92 and 1.62 % for rectangular cross section with curved sides and bowtie cross

section, respectively. It means that the thickness distribution of the hydro-pressing is more uniform than that of the conventional hydroforming.

This research reveals that the advantages of the hydro-pressing process are low forming pressure, no wrinkling and bursting defects, and good thickness uniformity. Large–tonnage presses are no longer necessary, so that the cost of presses, tools, and parts can be remarkably reduced as opposed to conventional tube hydroforming. It means that the hydro-pressing is a valid method to form the tubular parts with the same perimeter and different cross-sectional shape. Further research will be conducted on hydro-pressing of advanced high strength steel (DP780/DP980) tubes, magnesium alloy tubes, and aluminum alloy tubes with curved axis and complex section shapes.

Acknowledgments This work was financially supported by the National Key Technology R&D Program, Development of Advanced Forming Technologies of High Strength Steel and Integration Applications in Target Car, and the National Natural Science Foundation of China (project number: 51075097, 51175111). The authors would like to take this opportunity to express their sincere appreciation.

References

1. Dohmann F, Hartl C (1997) Tube hydroforming-research and practical application. J Mater Process Technol 71(1):174–186
2. Koç M, Altan T (2001) An overall review of the tube hydroforming (THF) technology. J Mater Process Technol 108(3):384–393
3. Ngaile G, Jaeger S, Altan T (2004) Lubrication in tube hydroforming (THF) part I: lubrication mechanisms and development of model tests to evaluate lubricants and die coatings in the transition and expansion zones. J Mater Process Technol 146(1):108–115
4. Hashimi S (1996) Computer-monitored hydraulic bulging of tubes. J Mater Process Technol 57:182–188
5. Daniel EG, Tirumala SA, Morteza N, Thomas W (2012) A practical method to evaluate the forming severity of tubular hydroformed parts. Int J Adv Manuf Technol 62:965–980
6. Tabatabaci SA, Panahi MS, Mashhadi MM, Tabatabee SM, Aghajanzadeh M (2013) Optimum design of preform geometry and forming pressure in tube hydroforming using the equipotential lines method. Int J Adv Manuf Technol 69:2787–2792
7. Yang C, Ngaile G (2008) Analytical model for planar tube hydroforming: prediction of formed shape, corner fill, wall thinning, and forming pressure. Int J Mech Sci 50:1263–1279
8. Ahmadi BSY, Khalili K, Eftekhari SSE, Kang BS (2014) Loading path optimization of a hydroformed part using multilevel response surface method. Int J Adv Manuf Technol 70:1523–1531
9. An H, Green DE, Johrendt J (2010) Multi-objective optimization and sensitivity analysis of tube hydroforming. Int J Adv Manuf Technol 50:67–84
10. Morphy G (1998) Tube hydroforming: efficiency and effectiveness of pressure sequence hydroforming. SAE Technical Paper. doi: 10.4271/982328
11. Morphy G (1998) Tube hydroforming: dimensional capability analysis of a high volume automotive structural component production process. SAE Technical Paper. doi: 10.4271/980450
12. Yuan SJ, Han C, Wang XS (2006) Hydroforming of automotive structural components with rectangular-sections. Int J Mach Tools Manuf 46(11):1201–1206
13. Han C, Yuan SJ (2008) Reduction of friction and calibration pressure by section preform during hydroforming of tubular automotive structural components. Adv Mater Res 44–46:143–150
14. Liu G, Yuan SJ, Teng BG (2006) Analysis of thinning at transition corner in tube hydroforming. J Mater Process Technol 177:688–691
15. Teng BG, Li K, Yuan SJ (2013) Optimization of loading path in hydroforming T-shape using fuzzy control algorithm. Int J Adv Manuf Technol 69:1079–1086
16. Elsenheimer D, Groche P (2009) Determination of material properties for hot hydroforming. Prod Eng Res Dev 3:165–174
17. Hashemi SJ, Naeini HM, Liaghat G, Tafti RA, Rahmani F (2013) Numerical and experimental investigation of temperature effect on thickness distribution in warm hydroforming of aluminum tubes. J Mater Eng Perform 22:57–63
18. Yuan SJ, Qi J, He ZB (2006) An experimental investigation into the formability of hydroforming 5A02 Al-tubes at elevated temperature. J Mater Process Technol 177:680–683
19. Nikhare C, Weiss M, Hodgson PD (2010) Die closing force in low pressure tube hydroforming. J Mater Process Technol 210:2238–2244
20. Nikhare C, Weiss M, Hodgson PD (2009) FEA comparison of high and low pressure tube hydroforming of TRIP steel. Comput Mater Sci 47:146–152