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Tube shear hydro-bending of titanium alloys

Cong Han*, Yong Wang, Yongchao Xu, Shijian Yuan

School of Materials Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China

Abstract

A shear hydro-bending process was proposed to form the titanium alloys tubes with small bending radius, which can not be integrally formed by the conventional bending methods. Numerical simulation and experimental research were conducted to investigate effects of internal pressure and feeding ratio on defects, strain state and thickness distribution. The results show that the sound part can be successfully manufactured as the internal pressure ranges from $0.2\sigma_s$ to $0.6\sigma_s$ and the feeding ratio ranges from 1.0 to 1.3, while the defects occur if the internal pressure and the feeding ratio exceed to these scopes. The strain state of the inner and outer sides of the bend are tensile and compressive, and the thicknesses are thinning and thickening, respectively, which is influenced prominently by the internal pressure and the feeding ratio. The strain state of the lateral side is shear and the thickness is generally invariable. It can be conducted that shear hydro-bending method is suitable to manufacture the titanium alloys tube with small bending radius. There is a process window for the internal pressure and the feeding ratio, in which the tubes can be successfully formed without defects.

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Keywords: Tube forming; Hydroforming; Shear hydro-bending; Titanium alloys

1. Introduction

With the development of high reliability, high security and light weight, the requirement for structure integrality, structure style and occupied space are becoming stricter and stricter. The integral formed tubes with small bending

* Corresponding author. Tel.: +86-451-8641-5754; fax: +86-451-8641-5754.
E-mail address: conghan@hit.edu.cn

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radius (R/D<0.5) are often employed with the restriction of the space (Yuan et al., 2012). Especially, the integral titanium alloys tubes with small bending radius have a great application trend for its high strength, light weight and occupied narrow space (Schutz et al., 1998).

However, these tubes with small bend radius can not be manufactured integrally by the conventional bending methods for the limitation of relative bend radius. Whether numerical control (NC) bending (Li et al., 2006), press bending, push bending and other cold bending methods or laser and induction hot bending methods, the deformation mechanism is tensile-compressive, that is, the deformation is tensile at bend outside and compressive at bend inside (Yang et al., 2004). Consequently, there is a limited value of relative bending radius. For example, the limited value of titanium alloys is 1.0 (Zeng and Li, 2002). In case of exceeding 1.0, there are wrinkles at bend inside and fractures at bend outside. At present, these tubes are generally manufactured by welding two stamped halves. Therefore, reliability of tubes is influenced by the welding seams.

Shear bending method was proposed to manufacture tubes with small bending radius. Goodarzi et al. (2007) studied the shear bending method with mandrel for a Z-type pure aluminum tube. A shear hydro-bending process was proposed to form round (Yuan et al., 2011) and rectangular (Han et al., 2012) aluminum tubes with small bending radius as expanding application of hydroforming. The effects of internal pressure of liquid media, the ratio of axial feeding to transversal stroke, namely, the feeding ratio and the tooling corner radius were investigated on the defects, the thickness distribution and the microstructure of the hydro-bent tube.

In this work, a titanium alloy tube was expanded in shear hydro-bending process. Effects of internal pressure and feeding ratio on defects, thickness strain were investigated using numerical simulation and experimental method. Based on the research work, a process window was proposed for the internal pressure and the feeding ratio in tube shear hydro-bending of titanium alloys.

Nomenclature

F_t	force of transversal direction
F_a	force of axial direction
p	internal pressure
λ	feeding ratio
ε_t	thickness strain
R	bend radius of tube
φ	diameter of tube
t	thickness of tube
E	elastic modulus
σ_s	yielding strength
σ_b	ultimate strength
δ	elongation percentage

2. Deformation mechanism of proposed method

In the proposed process, a small bending radius tube can be formed by pushing a movable die along a fixed die and liquid medium is filled into the tube to support it. The die set is composed of the movable die and the fixed die. The movable die can move along the transversal direction of the fixed die. There are two punches to seal the tube end and push the material of the tube end into the bend corner area along the axial direction. During the process, the relationship of the axial feeding, the transversal stroke and the internal pressure can be controlled by a computer system. The small bending radius tube can possibly be shear hydro-bent if the relationship of the axial feeding, the transversal stroke and the internal pressure is appropriate.

In particular cases, in order to form the small corner radius, calibration process may be needed after shear bending process. In the process, the pressure is increased to a high value to calibrate the tube, however, the axial feeding and the transversal stroke is not changed.

The designed part is a bilateral symmetrical part with length of 130 mm in middle and 50 mm in each end. The round bending radius of the axis is 3 mm. The transversal width of the part is 70 mm and the centre line distance is 40 mm. The titanium alloy tubular blank of TA2 is used with 30 mm in outer diameter and 1.5 mm in thickness.

3. Numerical simulation

3.1. Finite element model

LS-DYNA software was used for simulating the shear hydro-bending process. The blank was discretized using shell element and divided into 7392 quadrilateral elements. The tool sets (punch and die) were modeled as rigid bodies as shown in Fig. 1. A displacement load was applied to the movable die and the punches in transversal and axial direction, respectively. Surface to surface contact procedure was used to model the complex interaction between the blank and tool set. Coefficient of friction in the blank die interface was assumed to be 0.05(Hezam et al, 2009).

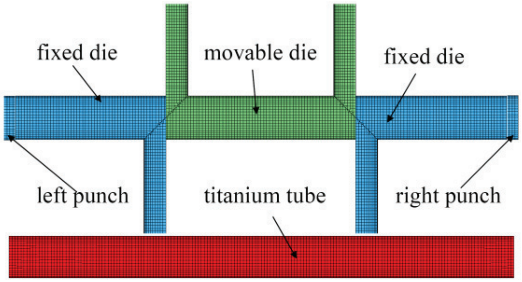

Fig.1. Finite element model of tube shear hydro-bending.

Standard specimens were tested on a uniaxial tensile testing machine to obtain mechanical properties of TA2. Common tensile properties like true yield stress and true ultimate tensile strength were obtained from the true stress strain curve. Yield strength was measured by taking the load at 0.2% strain by offset method. The mechanical properties of TA2 are given in Table 1.

Table 1. Mechanical properties of TA2 tubular blank

Elastic modulus *E* (GPa)	Poisson's ratio γ	Yield stress σ_s (MPa)	Ultimate strength σ_b (MPa)	Elongation δ (%)
103	0.35	227.8	334.1	43.6

3.2. Simulation program detail

Loading path is defined as the relationship of the internal pressure and the axial feeding in hydroforming process. If the loading path is not proper, the defects of buckling, wrinkling and splitting will occur (Yuan et al, 2011). In the shear hydro-bending process, there are three displacements as the left axial feeding, the right axial feeding and the transversal stroke. Because of the symmetry of the tube, the axial feedings of the left punch and the right punch are the same. The ratio of the axial feeding to the transversal stroke is defined as the feeding ratio, λ.

Effects of internal pressure and feeding ratio on defects were investigated using numerical simulation. The studied subject was varied while another subject was fixed. When the effect of the internal pressure was investigated ranging from $0.1\sigma_s$ to $0.7\sigma_s$, the feeding ratio was fixed to 1.0, that is to say, the axial feeding was equal to the transversal stroke. When the effect of the feeding ratio was investigated ranging from 1.0 to 1.6, the internal pressure was fixed to $0.4\sigma_s$, as shown in Fig. 2.

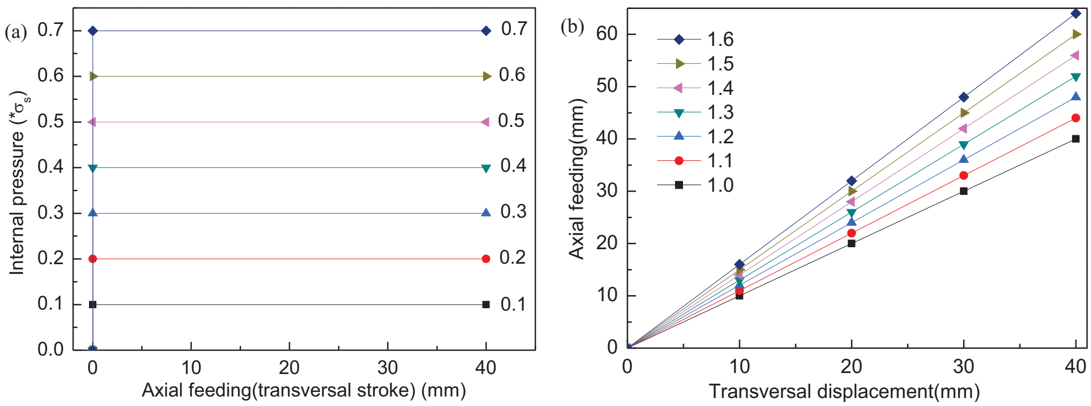

Fig.2. Loading paths for internal pressure and feeding ratio: (a) internal pressure versus axial feeding and transversal stroke, λ=1.0 and (b) axial feeding versus transversal stroke, p= 04σ_s.

3.3. Effect of internal pressure

The internal pressure plays an important role in the shear hydro-bending process with round and rectangular aluminum alloys (Han et al., 2012). On one hand, the folding defect occurs if the internal pressure is smaller than a certain value for its insufficient supporting. On the other hand, the splitting occurs if the internal pressure is higher than another certain value for its bulge effect. These phenomena and rules are also suitable for titanium alloys tubes, but the absolutely critical pressure value for titanium is different from aluminum alloys. The simulation results are shown in Fig. 3. The folding occurred as the internal pressure was 0.1σ_s, while the splitting occurred as the pressure was 0.7σ_s. The forming processes were performed successfully as the pressure ranging from 0.2σ_s to 0.6σ_s.

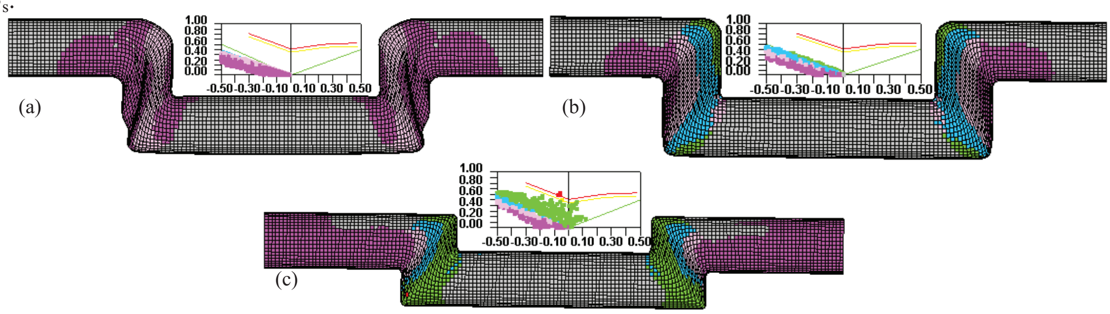

Fig.3. Effect of internal pressure on shear hydro-bending: (a) folding, p=0.1σ_s, (b) sound part, p=0.4σ_s and (c) splitting, p=0.7σ_s.

Fig.4 shows the thickness strain distribution with the internal pressure of 0.2σ_s, 0.4σ_s and 0.6σ_s. There were four critical lines which the strain was zero. By the division of these four lines, five typical zones were obtained, in which the thickness strain of the zone near the tube end and the inside of the second bend was bigger than zero, while the outside of the first and the second bend was smaller than zero, as shown in Fig. 4(a). With the increase of the internal pressure, the tensile and compressive states were different, as shown in Fig. 4 (b) and (c). The tensile area expanded and the compressive area decreased when the internal pressure varied from 0.2σ_s to 0.4σ_s, especially in the inside of the second bend. And it expanded further when the internal pressure reached to 0.6σ_s. The thickness strain state was compressive in the sealing area, in the inside corner of the first and the second bend and the wall thickness was thickening, while it was tensile in the outside of the first and the second bend and the wall thickness was thinning. In the shearing area, the upper side was different from the lower side, which was tensile near the upper side and compressive near the lower side. Although the thickness strain state in the middle of the part was tensile, there was no deformation and the thinning was small.

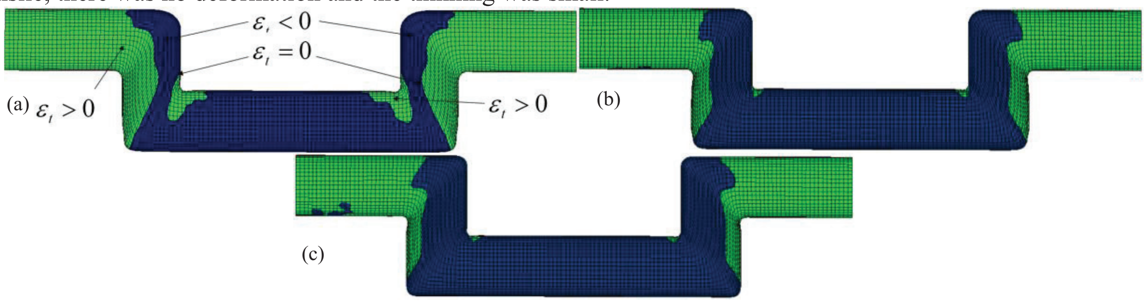

Fig.4. Effect of internal pressure on thickness strain: (a) p=0.2σ_s, (b) p=0.4σ_s and (c) p=0.6σ_s.

3.4. Effect of feeding ratio

The effect of the feeding ratio is also important for shear hydro-bending process. The leaking occurred as the feeding ratio was smaller than 1.0, while the folding occurred as the feeding ratio was 1.4, as shown in Fig. 5(a). With the increase of the feeding ratio, the folding defect became serious, as shown in Fig. 5(b). The severe folding appeared in the area between the two corners when the feeding ratio was 1.6. The forming processes were performed successfully as the feeding ratio ranging from 1.0 to 1.3. The thickness strain distribution was the same as that of the internal pressure except for the difference of the tensile and compressive area.

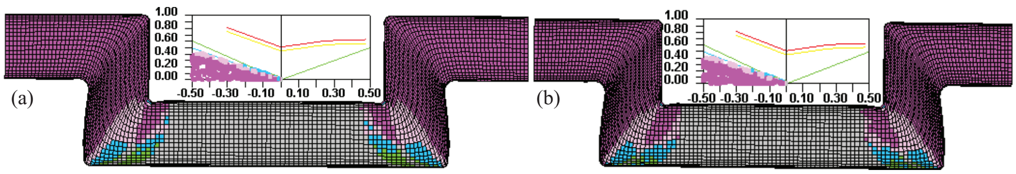

Fig.5. Effect of feeding ratio on shear hydro-bending: (a) folding, λ=1.4 and (b) severe folding, λ=1.6.

4. Experimental procedure

4.1. Equipment and tooling

Experiments were carried out on a 3150 kN hydroforming machine, which is composed of a press for die closing, a hydraulic intensifier, three horizontal servo oil cylinders and a computer system. The displacement of two punches and the movable die is driven by cylinders and the internal pressure of the tube can be controlled by a servo system according to the loading path from the computer system. Punch and movable displacements versus internal pressure is plotted and displayed on screen and saved on an Excel work sheet for later manipulation. The shear hydro-bending apparatus consists of a fixed die set, a movable die set, left and right punches set. The Teflon film is used to reduce the friction between the tube and the die cavity.

4.2. Experimental program detail

The effects of the internal pressure and the feeding ratio are very important on the thickness distribution and the corner radius. Seven groups of the internal pressure were conduced as 0.1σ_s, 0.2σ_s, 0.3σ_s, 0.4σ_s, 0.5σ_s, 0.6σ_s and 0.7σ_s. When the internal pressure was investigated, the feeding ratio was fixed to 1.0. At the same time, the feeding ratio was further studied under the condition of 1.0, 1.1, 1.2, 1.4 and 1.6 when the internal pressure was 0.4σ_s.

4.3. Effect of internal pressure and feeding ratio

When the feeding ratio was 1.0, the folding occurred as the internal pressure was $0.1\sigma_s$ and the folding place was located at the end of the first corner. Keeping the feeding ratio constant, with the increasing of the internal pressure, the folding was disappeared and the forming process could be conducted and the sound part could be successfully manufactured. When the internal pressure was $0.7\sigma_s$, the splitting occurred. The splitting appeared in the area of the 45° included angle to the axis of the tube between the first corner and the second corner. The splitting place was located at the middle of the two corners along the direction of 45°. The forming processes were performed successfully as the internal pressure ranging from $0.2\sigma_s$ to $0.6\sigma_s$, and the corner radius became smaller and smaller with the increasing of the internal pressure, as shown in Fig. 6(a).

The feeding ratio is important for the forming of the corner radius and the thickness distribution. If the feeding ratio is larger than 1.0, that is to say, the axial feeding is larger than the transversal stroke. It is beneficial to the forming of the corner radius and the thickness distribution. Howerer, if the axial feeding is too large, end folding will be appear and lead to wrinkle. If the feed ratio is small than 1.0, that means, the axial feeding is smaller than the transversal stroke. Leaking will occur and the forming process will not be continued. Fig. 6(b) shows the formed tube when the feeding ratios are from 1.0, 1.1, 1.2, 1.4, and 1.6. When the feeding ratio was 1.4, the end folding was very serious. When the feeding ratio increased to 1.6, the wrinkle appeared. The forming processes were performed successfully as the feeding ratio ranging from 1.0 to 1.3, and the corner radius became smaller and smaller with the increasing of the feeding ratio.

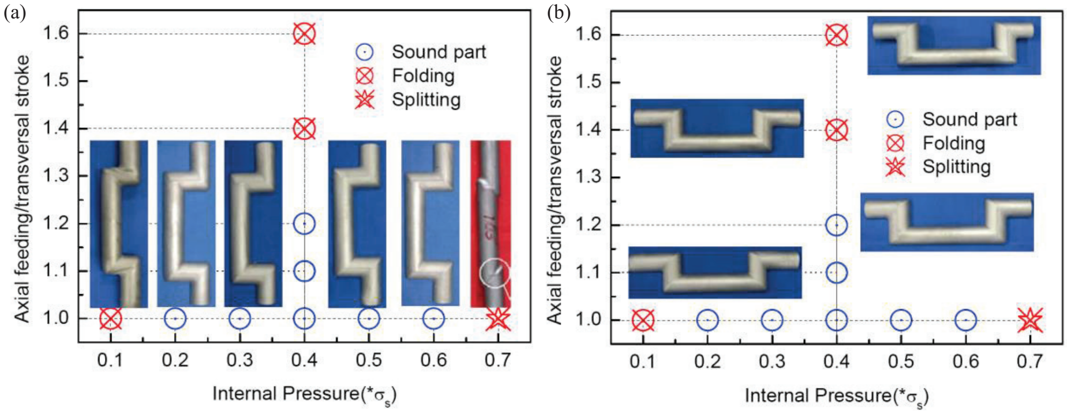

Fig.6. Effect of internal pressure and feeding ratio on deformation: (a) internal pressure (λ=1.0) and (b) feeding ratio (p=$0.4\sigma_s$).

4.4. Thickness distribution

Fig. 7 shows the thickness distribution along the axial direction under the internal pressure of $0.2\sigma_s$, $0.3\sigma_s$, $0.4\sigma_s$ and $0.5\sigma_s$ at the lower side and the upper side of the tube. Because of the symmetry of the part, only one half of the tube was selected. And twenty points were selected along the upper side and the lower side, which were uniformly distributed in each zone.

It can be seen from Fig. 7(a) that the thickness at the lower side was increased in the sealing zone, the first corner zone and the shearing zone. In the sealing zone, the thickness was becoming bigger with the increasing of the distance from the tube end. The maximum thickness was located in the first corner zone. The tendencies of thickness variation of two corner zones were different. The thickness of the first corner zone was thickened for the compressive stress state, while that of the second corner zone was thinning for the tensile stress state. The thickness of the shearing zone was a transition of two corner zones. The thickness of the holding zone was approximate to the original thickness. When the internal pressure was $0.2\sigma_s$, the minimum thickness was 1.47 mm and the thinning was 2%, while the maximum thickness was 1.85 mm, and the thickening was 23.3%. The differential quantity of the maximum and the minimum was 0.38 mm. When the internal pressure was $0.5\sigma_s$, the minimum thickness was 1.27 mm and the thinning was 15.3%, while the maximum thickness was 2.07 mm, and the thickening was 38%. The differential quantity of the maximum and the minimum was 0.8 mm. With the increase of the internal pressure, the thickness distribution was becoming more non-uniform. The normal pressure was increasing with the internal pressure, thus the friction between the tube and the tools and the material flowing was becoming difficult. At the same time, the location of the maximum thinning occurrence was hysteretic with the increasing of the internal pressure. Because the friction prevented the material in the feeding zone to the shear zone and the bulging effect at the first corner.

The thickness distribution of the upper side was different from that of the lower side in some zones, as shown in Fig. 7(b). The thickness of the upper side was reduced in the sealing zone, the first corner zone and the shearing zone and thickened in the second corner zone. In the sealing zone, the thickness was increased and the value was becoming smaller with the increasing of the distance from the tube end and became thinning near the first corner zone. It was continuing to thin and reached the minimum in the shearing zone. Then it started thickening again and reached the maximum in the second corner zone. The maximum thinning of the bent tube was becoming serious with the increasing of the internal pressure. The distribution of the holding zone of upper side was the same as that of the lower side. When the internal pressure was $0.2\sigma_s$, the minimum thickness was 1.48 mm and the thinning was 1.3%, while the maximum thickness was 2.02 mm, and the thickening was 34.7%. The differential quantity of the maximum and the minimum was 0.54 mm. When the internal pressure was $0.5\sigma_s$, the minimum thickness was 1.18 mm and the thinning was 21.3%, while the maximum thickness was 2.09 mm, and the thickening was 33.3%. The differential quantity of the maximum and the minimum was 0.63 mm.

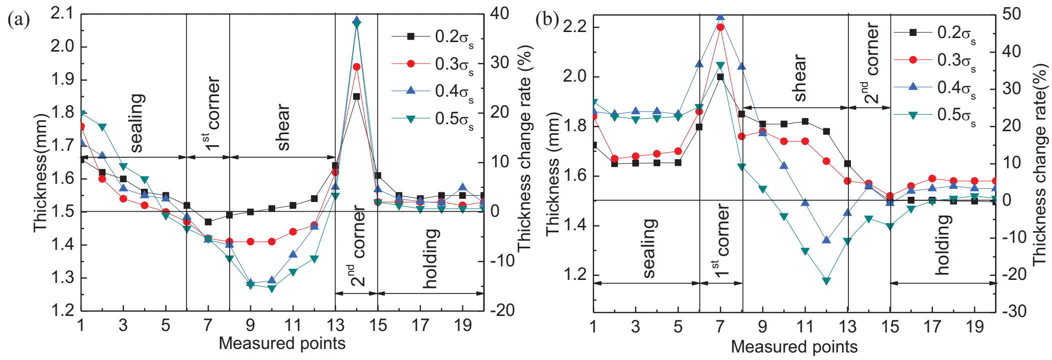

Fig.7. Thickness distribution with different internal pressures in the area of (a) the lower side and (b) the upper side.

4.5. Process window

From the above analysis, it can be seen that there is a process window of the internal pressure and the feeding ratio that the process can be successfully performed. Fig. 8 shows a schematic diagram of the process window of the internal pressure and the feeding ratio, which has two critical lines and three typical zones, namely folding zone, splitting zone and forming zone. The folding critical line is presented for the critical state of folding defect occurrence, above which folding defect appears for high feeding ratio. The splitting critical line is presented for the critical state of splitting defect occurrence, under which splitting appears for high internal pressure. There is a forming process window between the folding and the splitting critical line, in which the sound parts can be successfully manufactured.

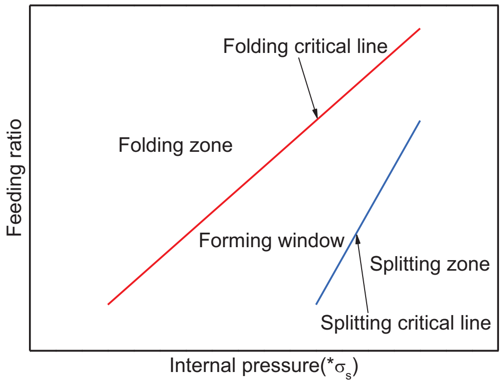

Fig.8. Process window of the internal pressure and feeding ratio.

Conclusion

1) Shear hydro-bending method is suitable to manufacture the titanium alloys tube with small bending radius by a reasonable combination of the internal pressure and the feeding ratio. There is a process window for the internal pressure and the feeding ratio, in which the tube can be successfully formed without defects.

2) There are four thickness strain unchanged lines between the thinning and the thickening, whose strain is zero. The shear hydro-bent tube can be divided into two typical zones in which the thickness strain is different. The thickness strain states are compressive in the sealing area and the bend inside, while it is tensile in the bend outside. Although the thickness strain state is tensile in the middle of the part, there is no deformation and the thinning is small. With the increase of the internal pressure, the tensile area expands.

3) As for TA2 titanium alloys, the tubes with small bending radius can be successfully manufactured under the condition of the internal pressure ranging from $0.2\sigma_s$ to $0.6\sigma_s$ when the feeding ratio is 1.0. The outside corner radius is becoming smaller with the increasing of the internal pressure. And it also can be successfully manufactured under the condition of the feeding ratio ranging from 1.0 to 1.3 when the internal pressure is $0.4\sigma_s$.

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