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Shear hydro-bending of 5A02 aluminum alloys rectangular tubes

HAN Cong, XU Yong-chao, WANG Yong, ZANG Chao, YUAN Shi-jian
School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

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Abstract: A shear hydro-bending process was proposed to solve the difficulties in forming aluminum alloy rectangular tubes with small bending radius, which cannot be integrally manufactured using conventional bending methods. Numerical simulation and experimental research were conducted on defects during shear bending process. Effects of the internal pressure, feeding ratio and die inner bend corner radius were comprehensively investigated. The results show that four defects including wrinkling, cracking, pitting and folding appear if the internal pressure and the axial feeding and transversal stroke are not appropriate. The shear hydro-bent tube is performed successfully as the internal pressure ranges from $0.2\sigma_s$ to $0.9\sigma_s$ and the feeding ratio ranges from 1.0 to 1.1. It can be concluded that the shear hydro-bending is suitable to form aluminum alloy rectangular tubes with small bending radius by controlling the internal pressure, the axial feeding and the transverse stroke. There is a reasonable process window of the internal pressure and the feeding ratio, in which the tube can be successfully formed without defects.

Key words: aluminum alloys; hydroforming; shear hydro-bending; rectangular tube

1 Introduction

In recent years, hydroforming has been widely used for manufacturing automotive hollow components in European and North America [1−3] and tubes for aerospace and aircraft in China [4−6] for its high reliability, light weight and space saving. An rectangular tube with small relative bending radius $R_b/d\leq0.5$ is often employed in narrow space. On the advanced waveguide, the integrated rectangular tubes made of copper alloys and aluminum alloys are widely used to meet the demands of lightweight and other special application [7]. At present, the rectangular tubes with small bending radius are usually manufactured by welding two stamped halves. Therefore, the reliability of tubes is influenced by the welding seams. At the same time, the surface finish of the inner tube is influenced by the welding process and is hard to be secondary operated for its narrow space. Integrally forming of the rectangular tubes with small bending radius can not only improve the reliability and inner surface quality, but also save weight and space [8].

However, the rectangular tube with small bending radius cannot be manufactured by conventional bending processes including numerical control (NC) bending, press bending and push bending [9−11]. The essential deformation of the conventional bending processes is tensile at outside and compressive at inside. Therefore, there is a limited value of relative bending radius. For example, the limited value R_b/d is 1.0 for 5A02 aluminum alloys round tube. In case of R_b/d <1, there are wrinkling at inside and thinning severely at outside.

Shear bending method was studied with mandrel for Z-type pure aluminum tube [12]. The zero bending method using liquid pressure as supporting media was investigated [13].

A shear hydro-bending process was proposed to form round tube with small bending radius as expanding application of hydroforming [14−16]. By using this method, the relative bending radius of the shear hydro-bent tube can be smaller than 0.1. The effect of internal pressure of liquid media was investigated on defects, thickness distribution and microstructure of the hydro-bent tube.

In this work, a shear hydro-bending process is proposed to form aluminum alloy rectangular tube with small bending radius. It is a new method to solve the difficulties in forming rectangular tubes with small bending radius which cannot be manufactured by conventional bending process. The effects of internal pressure of liquid media and axial feeding and transversal stroke on defects are investigated using

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Corresponding author: HAN Cong; Tel/Fax: +86-451-86415754; E-mail: conghan@hit.edu.cn
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numerical simulation and experimental method. The tooling corner radius that apparently influences the material flowing is also studied.

2 Principle of shear hydro-bending

In shear hydro-bending process, the liquid medium is employed as supporting die inside the tube. The deformation includes two main stages: filling and shear-bending, as shown in Fig. 1.

1) Filling. The tube is put into the die cavity composed of the fixed die and the movable die. Then the left punch and the right punch move to each tube end. After that, the liquid medium is filled into the tube and the punches are pushed forward to seal the tube end.

2) Shear hydro-bending. The pressure of the liquid medium is increased to a certain value. Then the movable die is going along the transverse direction of the tube, while the sealing punches are feeding axially. The tube is beginning shear deformation. The movable die and the sealing punches are stopped until the transverse stroke of the tube is up to the designed value.

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

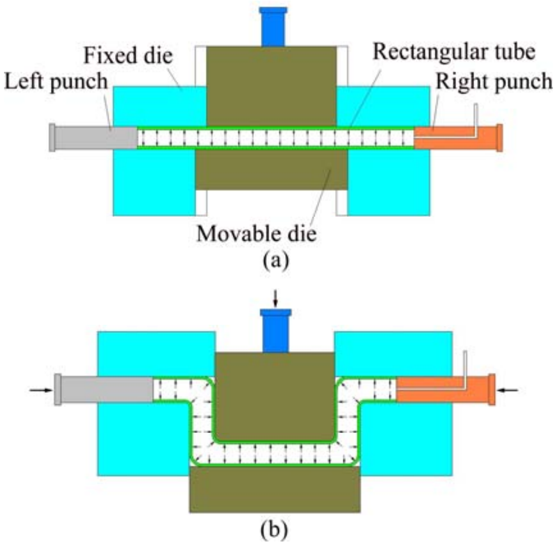

Fig. 1 Principle of shear hydro-bending: (a) Filling process; (b) Shear hydro-bending process

3 Simulation

3.1 Finite element model

The finite element model of shear-bending is shown in Fig. 2. Left and right punches, movable die and fixed die and rectangular tube are included. The die is shell rigid mesh and the mesh type is linear triangle and linear quadrangle, and the quantities are 118 and 24666, respectively. The tube is solid element and the mesh type is linear hexahedron, and the quantity is 113703. Tangential friction factor is used in the simulation. Elastic modulus is 75 GPa and Poisson ratio is 0.3. Yield stress is 76 MPa and elongation is 22.8%.

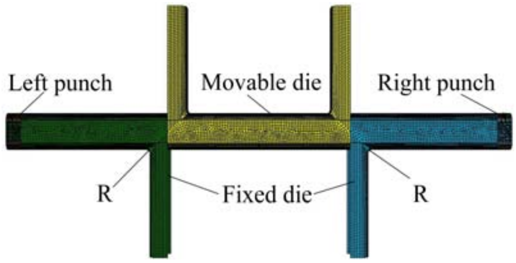

Fig. 2 Finite element model of shear hydro-bending

3.2 Parameters scheme

Three factors were investigated during the simulation progress. They are the internal pressure p, the ratio of the axial feeding of left and right punches to the transversal stroke of movable die and the inner bend corner radius R. Define the ratio of axial feeding to the transversal stroke as the feeding ratio λ. The load path for internal pressure is studied when the feeding ratio is fixed to be 1.0, which means that the axial feeding is equal to the transversal stroke, as shown in Fig. 3. The loading path of feeding ratio is studied when the internal pressure is $0.4\sigma_s$, as shown in Fig. 4. During the study process of internal pressure and feeding ratio, the inner bend corner radius is fixed to be 3 mm.

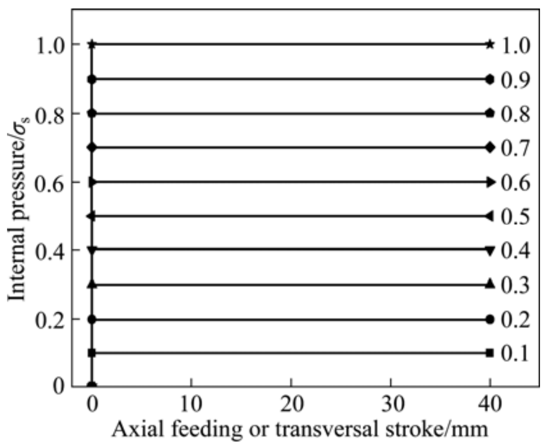

Fig. 3 Loading path for internal pressure when feeding ratio is fixed to 1.0

The inner bend corner radii of 1, 3 and 5 mm are studied and the internal pressure and feeding ratio are fixed to the $0.4\sigma_s$ and 1.0, respectively.

Subsequently, the effects of the internal pressure, the feeding ratio and the die bend corner radius are analyzed. In order to show the details, the quarter of the rectangular tube is selected and the simulation results are shown in the following.

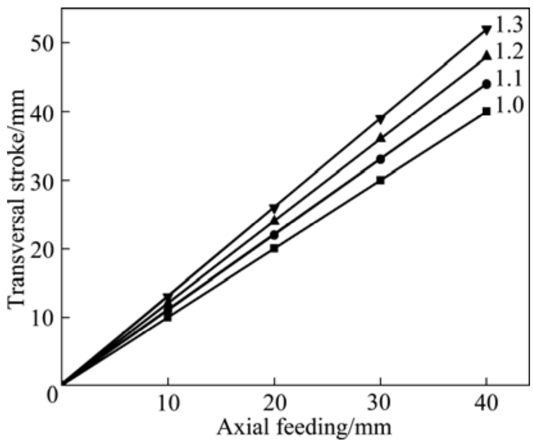

Fig. 4 Loading path for feeding ratio under internal pressure of $0.4\sigma_s$

3.3 Effect of internal pressure

The deformation results of different internal pressures are shown in Fig. 5. From Fig. 5, it can be seen that if the internal pressure is lower than $0.1\sigma_s$, the wrinkling will take place, as shown in Fig. 5(a). With the increase of the internal pressure, the supporting effect is becoming apparently. When the internal pressure is $0.2\sigma_s$, the process can be conducted but the supporting effect is limited and the pitting appears in the inner bend corner zone, as shown in Fig. 5(b). When the internal pressure is increased to $0.9\sigma_s$, the process can also be conducted but the supporting effect is excessive and the friction between the tube and the die surface is also increasing. As a result, the thinning becomes severely, as shown in Fig. 5(d). If the internal pressure is higher than $1.0\sigma_s$, the cracking will take place during the shear hydro-bending, as shown in Fig. 5(e). The successful rectangular tube can be obtained when the internal pressure is from $0.3\sigma_s$ to $0.8\sigma_s$, as shown in Fig. 5(c), in which the internal pressure is $0.5\sigma_s$.

3.4 Effect of feeding ratio

The loading path of feeding ratio is also important to the shear hydro-bending process. Four loading paths were studied as shown in Fig. 4. The deformation results are shown in Fig. 6.

From Fig. 6, it can be seen that if the axial feeding is smaller than transversal stroke, the tube end sealing will be failed and the shear hydro-bending process cannot be continued. With the increase of the axial feeding, more material of the tube end was pushed into the bend area. If the axial feeding is excessive, the material is accumulated in inner bend area and the pitting

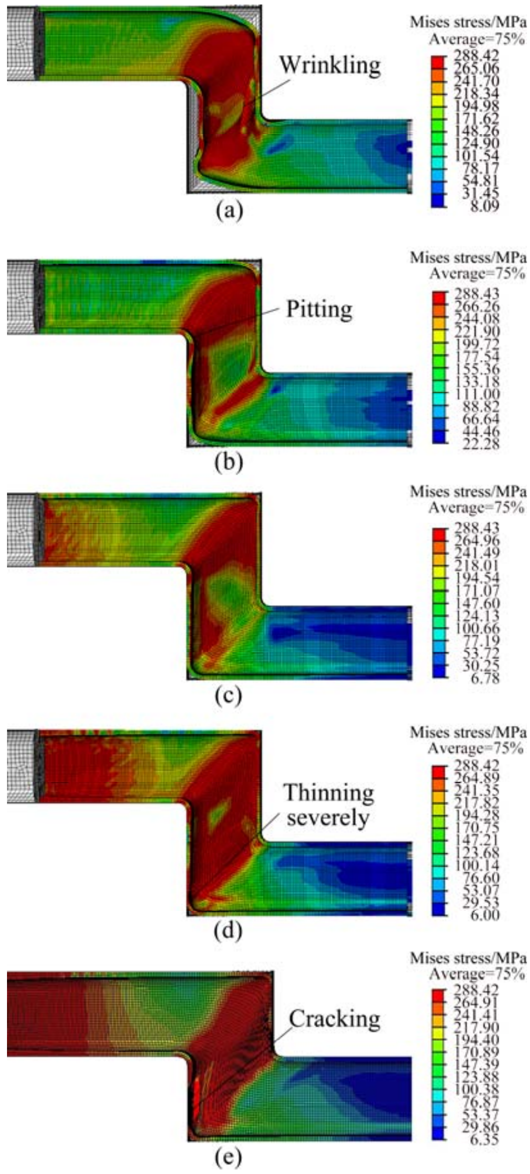

Fig. 5 Deformation results under different internal pressures: (a) $p=0.1\sigma_s$; (b) $p=0.2\sigma_s$; (c) $p=0.5\sigma_s$; (d) $p=0.9\sigma_s$; (e) $p=1.0\sigma_s$

will take place during the shear hydro-bending, as shown in Fig. 6(a) and Fig. 6(b), where the feeding ratios are 1.2 and 1.3, respectively. The more the material is pushed into the bend area, the more the pitting will take place. The shear hydro-bent rectangular tube can be successfully manufactured, only when the feeding ratio is appropriate, as shown in Fig. 6(c) and Fig. 6(d).

3.5 Effect of die inner bend corner radius

The die inner bend corner radius plays an important role on material flowing. Three corner radii of 1, 3 and 5 mm were simulated. The simulation results are shown in Fig. 7. When the inner bend corner radius is 1 mm, the material is difficult to flow into the corner radius and the material is accumulated excessively in the inner corner zone and pitting appears, as shown in Fig. 7(a). When the

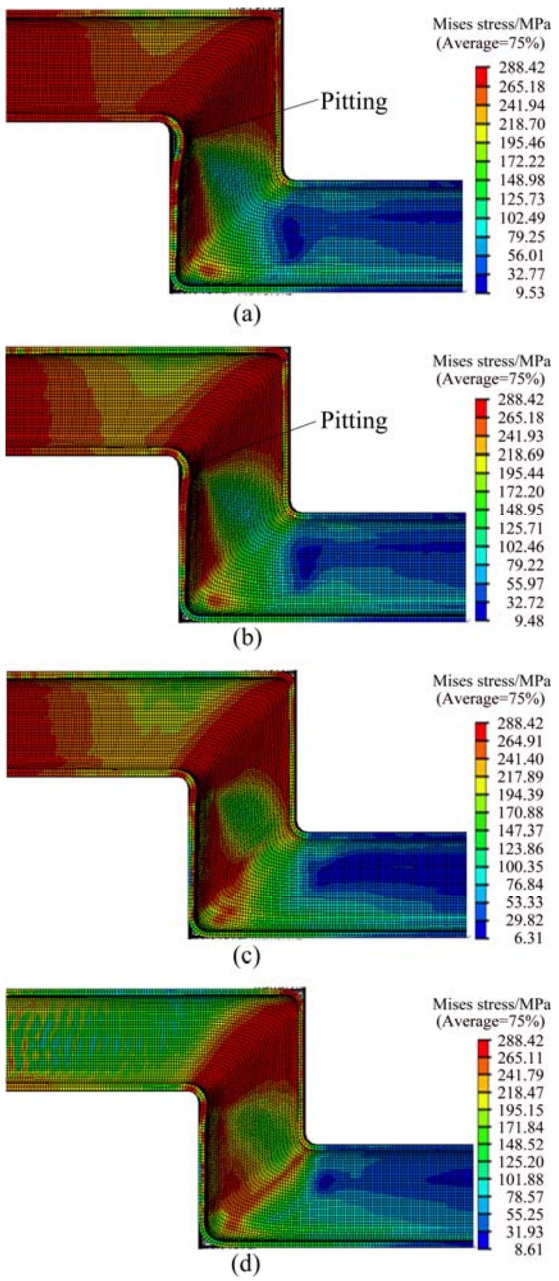

Fig. 6 Deformation results in case of different feeding ratio: (a) pitting for high feeding ratio (λ=1.3); (b) λ=1.2; (c) λ=1.1; (d) successful shear hydro-bent rectangular tube (λ=1.0)

inner bend corner radius is increased to 3 and 5 mm, the rectangular tube is successfully formed, as shown in Fig. 7(b) and Fig. 7(c). It can be seen that with the increase of corner radius, the material is easy to flow into the inner bend corner radius and benefit to tube shear hydro-bending.

4 Experimental

4.1 Machine and tooling

The experiment research was conducted in the machine manufactured by Harbin Institute of Technology.

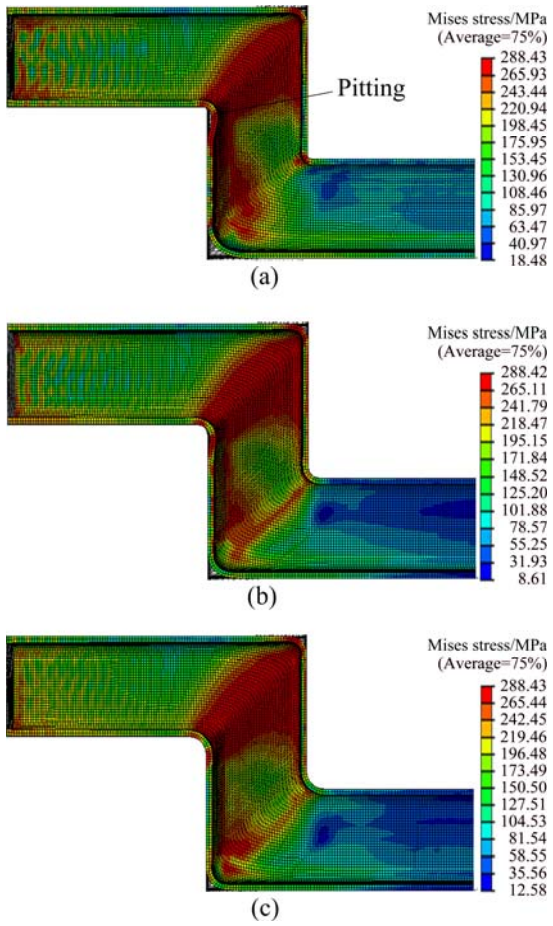

Fig. 7 Effect of die inner bend corner radius: (a) R=1 mm; (b) R=3 mm; (c) R=5 mm

It consists of pressure intensifier, closing machine, computer control system and three servo cylinders, which was used to control the internal pressure and the movement of the left punch, the right punch and the movable die. The tooling of shear hydro-bending is composed of left punch, right punch, upper die, lower die and transverse movable die.

4.2 Rectangular tube and mechanical properties

The material used in the experiment was 5A02 aluminium alloy. The yield stress of the material is 76 MPa and the elongation is 22.8%. The width of the rectangular tube section is 26 mm and the corner radius is 4 mm, the thickness is 1.5 mm, as shown in Fig. 8.

Fig. 8 Rectangular tube and its section used in process of shear hydro-bending

The experimental process step by step with the transversal stroke of 5, 10, 20 and 40 mm is shown in Fig. 9. The rectangular tube can be successfully hydro-bent by controlling the internal pressure, the axial feeding and the transversal stroke. The relationship of the internal pressure and the feeding ratio plays an important role during the shear hydro-bending process. The loading path of internal pressure and feeding ratio are studied subsequently.

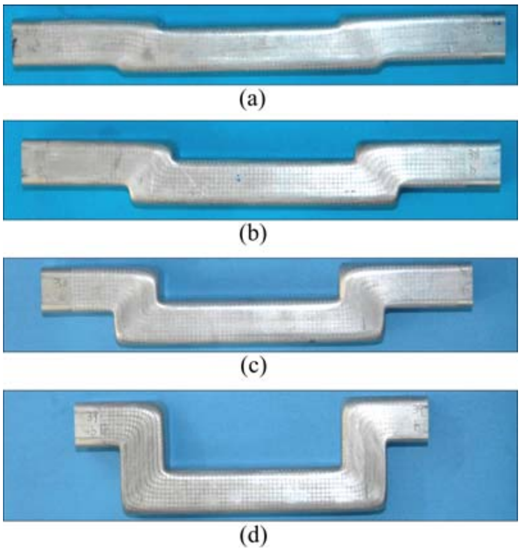

Fig. 9 Hydro-bending steps with different transversal strokes: (a) 5 mm; (b) 10 mm; (c) 20 mm; (d) 40 mm

4.3 Effect of internal pressure

The wrinkling occurs as the internal pressure is $0.1\sigma_s$, while the splitting occurs as the internal pressure is $1.0\sigma_s$, as shown in Figs. 10(a) and (b). The forming processes are performed successfully as the internal pressure ranges from $0.2\sigma_s$ to $0.9\sigma_s$. Figure 10(c) shows the rectangular tube obtained under the internal pressure of $0.4\sigma_s$. Figure 10(d) shows the rectangular tube obtained under the internal pressure of $0.5\sigma_s$. Figure 10(e) shows the rectangular tube obtained under the internal pressure of $0.6\sigma_s$. It can be seen that although the rectangular tube can be obtained without defect under the condition of different internal pressure, the round corner radius of outer bend is different. It becomes smaller with the increase of internal pressure.

4.4 Effect of feeding ratio

The tube end sealing is failed and the leaking occurs and the shear hydro-bending process could not be continued as the feeding ratio is smaller than 1.0. The pitting occurs in inner bend corner area as the feeding ratio is larger than 1.2, as shown in Fig. 11(a), in which the feeding ratio is 1.2. If the axial feeding is excessive,

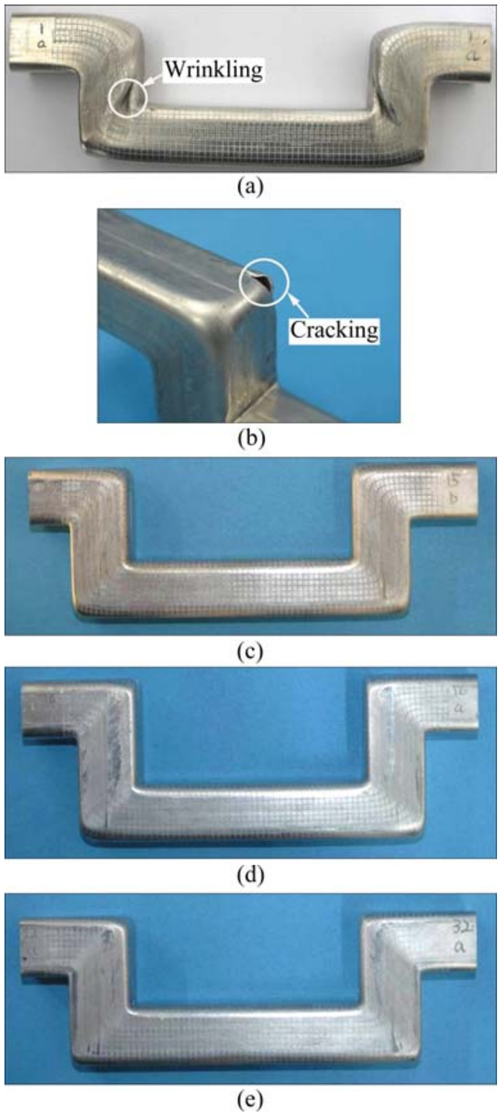

Fig. 10 Shear hydro-bending rectangular tubes under different internal pressures: (a) $p=0.1\sigma_s$; (b) $p=1.0\sigma_s$; (c) $p=0.4\sigma_s$; (d) $p=0.5\sigma_s$; (e) $p=0.6\sigma_s$

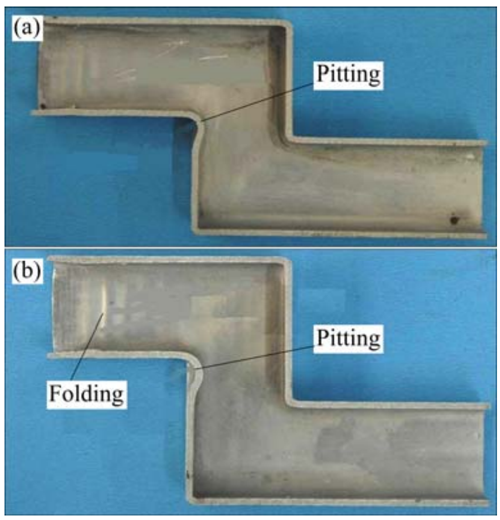

Fig. 11 Effect of feeding ratio on shear hydro-bending: (a) $\lambda=1.2$; (b) $\lambda=1.3$

the material is also accumulated in tube end area and the folding will take place, as shown in Fig. 11(b). The shear hydro-bent rectangular tube can be successfully conducted without any defect, only when the feeding ratio is appropriate.

4.5 Process window of shear hydro-bending

The simulation and experiment results show that there is a process window of internal pressure and feeding ratio, in which the defects can be avoided, as shown in Fig. 12. The plane of $p_{\min}$ is presented for the low limit of the internal pressure, under which wrinkling appears for insufficient support. The plane of $p_{\max}$ is presented for the upper limit, above which cracking appears for high pressure. There is also a process window for the feeding ratio. Pitting and folding appear when the feeding ratio is above the upper limit $\lambda_{\max}$. Leaking appears when the feeding ratio is below the low limit $\lambda_{\min}$ for insufficient feeding. The window which is made up of the plane of $p_{\min}$, $p_{\max}$, $\lambda_{\min}$ and $\lambda_{\max}$ is the forming process window of the internal pressure and feeding ratio, in which the sound rectangular tubes can be successfully manufactured.

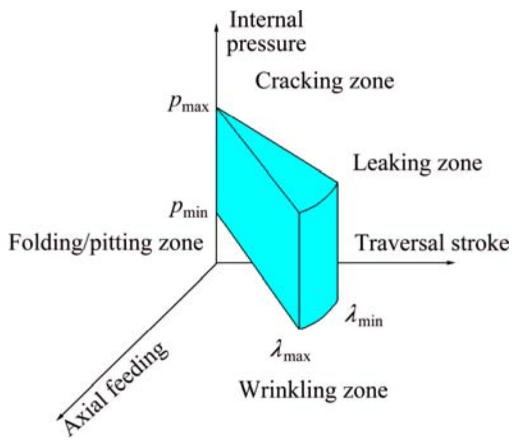

Fig. 12 Process window for internal pressure, axial feeding and transversal stroke

5 Conclusions

1) Shear hydro-bending is suitable to manufacture the aluminum alloy rectangular tube with small bending radius by controlling the internal pressure in combination with the axial feeding and transversal stroke.

2) The defect of the rectangular hydro-bent tube mainly includes wrinkling, pitting, folding and cracking. The relationship of internal pressure and axial feeding and transversal stroke plays an important role in the defects.

3) There is a process window for the internal pressure and the feeding ratio of axial feeding and transverse stroke, in which the rectangular tube can be successfully formed without defects.

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5A02 铝合金矩形管充液剪切弯曲成形

韩 聪，徐永超，王 勇，臧 超，苑世剑

哈尔滨工业大学 材料科学与工程学院，哈尔滨 150001

摘 要：为了解决传统弯曲方法无法整体成形铝合金小弯曲半径矩形管的难题，提出了一种充液剪切弯曲成形方法。通过数值模拟和实验方法研究成形过程中内压、补料比和模具弯曲内侧圆角对成形缺陷的影响。结果表明：在不同工艺参数下，分别出现起皱、开裂、凹陷和堆积 4 种缺陷。内压在 0.2σ_s 至 0.9σ_s 以及补料比在 1.0 至 1.1 的区间内，都可以顺利成形剪切弯曲管件。通过控制内压、轴向进给和横向行程，充液剪切弯曲成形方法可用于制造铝合金小弯曲半径矩形管。并且存在一个合理的内压和补料比成形窗口，在此窗口内，管材可顺利成形。

关键词：铝合金；液压成形；充液剪切弯曲；矩形管

(Edited by HE Yun-bin)