Study on Draw Bending of Metal Tube Applied with Axial Thrust into A Small Bend Radius

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Abstract - With the ongoing trend toward the low carbon economy, the product design has headed towards thin, lightweight, and miniaturization. Therefore, under the considerations of not affecting the application functions and safety concerns, the space used for the metal tubes, if any in a product, should be as small as possible and, hence, tube bended in small radius has become more important. In this study, a rotary draw bending machine installed with a movable mandrel and a loadable axial thrust is used to investigate the influence of mandrel movement and axial thrust on the tube bend in small radius.

As a result, an appropriate axial thrust can improve the curvature of the outer wall of the metal tube and reduce the spring back after bending. However, if it's pushed too hard, the inner wall curvature could be enlarged and the improvement effect is then limited. A proper shifting of the mandrel into the metal tube shows also having an influence on spring back after bending. The farther the mandrel is pushed into the metal tube, the smaller the spring back is shown. If the tube is bended into small radius by combining the axial thrust and the mandrel shifting, the circular cross section of the metal tube is held better and the spring back is smaller than just by pushing mandrel into the tube. The axial thrust can reduce the kink effect in the inner wall generated by shifting the mandrel.

Keywords –Tube Draw Bending, Small Bend Radius, Axial thrust

I. PREFACE

The application of tube material in the industry or daily life is very common, and it is very diversified too, and the most commonly seen one is the metal tube. Generally, it contains stainless steel tube, cast iron tube, copper tube and Al tube, etc., and the functions are quite different too. Along with the advancement of technology, the requirement on the precision is much higher too, in the entire design, delicacy is usually the development trend, and small component as well as light weight component is always favored by the market. In order to adapt to the continuous compression of the utilization space of the metal tube and under the condition of not changing the tube diameter arbitrarily, the metal tube shape should be changed so as to achieve the design need, among them, the most commonly seen method is to reduce the bending radius to achieve this objective. And the forming characteristic of bending processing is that the external material of the work object has to take tensile stress and the internal material has to take compression stress, sometimes, even the geometrical shape of the cross section of the metal tube is going to show the defect of ellipse change [1,2]. These defects are going affect seriously the function of metal tube on the equipment, and its utilization value is going to be seriously reduced.

In literature, the mandrel can improve the outer tube wall flatness [3], and loading axial thrust can reduce the thinning of the outer tube [4,5]. Therefore, in this study, the widely used rotary draw bending is used to construct a set of automatic tube bending machine with online measurement function is to be used as the research platform, this study try to use different mandrel location and to add axial thrust in the tube bending process so as to investigate the effectiveness of mandrel and axial thrust in improving the defect in the tube bending process for tubes of small bend radius. It is hoped that the result can be used as reference for the industry.

II. ROTARY DRAW BENDING

Rotary draw bending has advantages such as simple mechanical structure and fast bending and forming, it has advantages such as massive production and geometrical precision in the bending process, hence, it is one of the bending processing methods that are widely adopted by the industry [6], and Fig. 1 illustrates the relative locations of the die and tube material in rotary draw bending.

Rotary draw bending is basically formed by bending die, clamp die and pressure die, and the bending die is fixed on the rotary stage of the machine, and the rotary stage will rotate under force driving. Before performing the bending process, it is needed to use clamp die to clamp the tube material onto the rotational die, then, bending die should be close to a pressure die and should get rotated to bend and form the tube material. During the bending process, the cross section shape will usually get kinked; hence, to avoid the generation of such defect, mandrel can be inserted into the tube before the bending.

During the bending of the metal tube, bending will occur due to the bending torque formed among three points of clamp die, bending die and pressure die, and during the bending process, the inner and outer wall will form respectively compression stress and tensile stress respectively.

And the geometrical shape of the cross section will become an ellipse as in Fig. 2, which is then represented by ellipticity f_k [7], and the ellipticity f_k is defined as:

$$f_k = (D_q - D_r) / D_o \qquad (1)$$

Wherein D_q and D_r are respectively the maximal outer diameter and minimal diameter after ellipse turning, and D_o is the original outer diameter of the tube material. Mandrel is very important component in tube bending device. Its main function is to support the inner tube wall through the internal part of the tube material so as to avoid any unexpected change of the tube cross section due to bending and the wrinkle on the tube wall, eventually, ideal tube shape is formed. Fig. 3 illustrates the shift of the mandrel center of semicircular shape relative to the centerline of the bending.

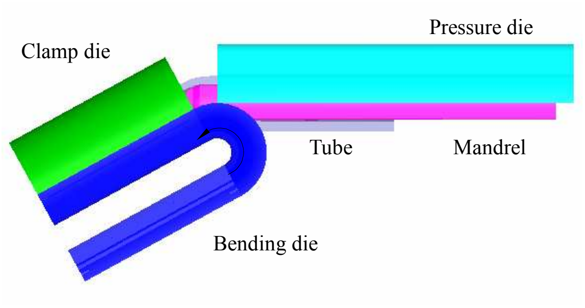

Fig. 1 Illustration of rotary draw bending

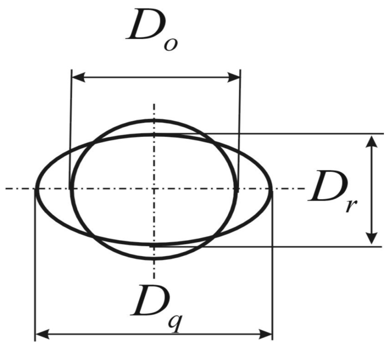

Fig. 2 Illustration of the ellipse of tube

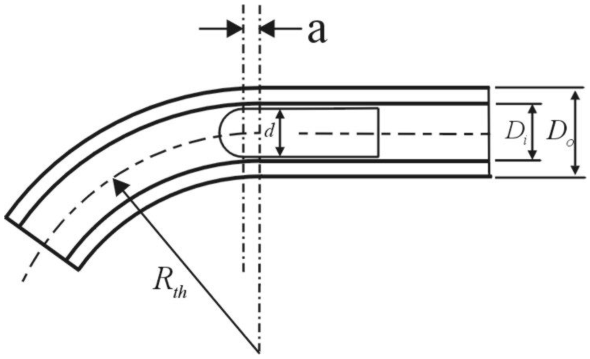

Fig. 3 Illustration of the shift of the mandrel

Wherein R_{th} is the ideal bending radius; D_o is the outer diameter of metal tube; D_i is the inner diameter of metal tube; *d* is the mandrel diameter; *a* is the semi-circular center of the round head mandrel relative to the bending center.

III. ROTARY BENDING TEST

In this study, different experimental parameters are controlled for the tube bending process of stainless steel tube. It includes: 1. Mandrel shift; 2. The adding of axial thrust; 3. The adding of axial thrust and mandrel shift, etc. This research is to plan a set of bending machine that can be added with axial thrust, can control the mandrel shift amount and possesses the online measurement function. Through a personal computer, including exercise control card and data acquisition card, servomotor can be controlled and the torque taken by the servomotor can be measured. It is as shown in Fig. 4.

The movement mechanisms of tube bending machine include rotational stage, mandrel movement unit and axial thrust unit. It needs three sets of servomotors. The rotational stage is driven by servomotor, and the torque can reach 175.5Nm. In the mandrel movement unit, servomotor will drive the linear module directly so as to convert the rotational movement into linear movement. Axial thrust unit is driven by another servo motor and linear module. The movement of each mandrel of control system is controlled by six-mandrel movement control card, in the measurement system, data acquisition card is used to acquire directly the torque sent out by the servo motor driver, then after conversion, the machine loading values can be obtained.

The tube materials used in the experiment is SUS 304 stainless steel tube. Tube outer diameter is 9.5mm, inner diameter is 6.2mm, length is 130mm, and the tube is bended into tube of small bending radius of 8.35mm (Bending ratio: The ratio between bending radius and outer diameter is 0.88). The semi-circular mandrel is of SK3 material and is heat-treated, and the diameter is 6mm with hardness in the range of HRC 48-52.

In the measurement of spring back angle, the metal tube is placed on horizontal work bench, then a digital camera is installed beside the work bench, meanwhile, level is used to calibrate the leveling so that the metal tube and camera lens will be vertical to each other, after the image is acquired, image processing is used to acquire the profile of the metal tube, then the bended tube angle is measured and the spring back angle is calculated.

For the application of axial thrust to the metal tube, please refer to literature [3]. The axial thrust for the improvement of the geometry of cross section of the metal tube is suggested to be 75MPa per unit area, after conversion, it is 3000N. To facilitate the comparison, axial thrust parameter is set up to be 1500N and 3000N. In the mean time, in order to analyze the metal flow change of the bended tube; first, in the outer wall of the unbent metal tube, at a division of 2.5mm, it is made into 12 divisions. It is as shown in Fig. 5.

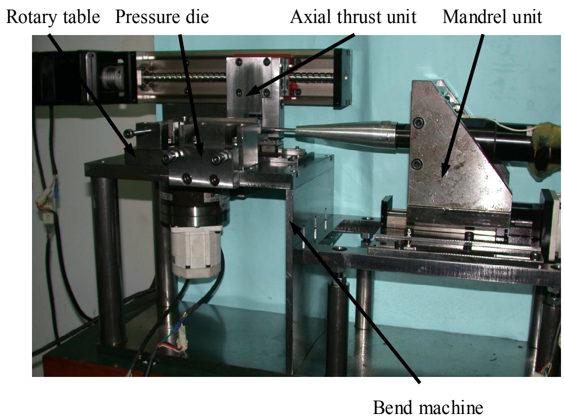

Fig. 4 Rotary tube bending machine

Fig. 5 Metal flow field mark and analysis (30°, 60°, 90°)

Then the metal tube is bended respectively into 30°, 60° and 90°; meanwhile, the real outer diameter change of each mark is measured to be used as the metal flow field analysis of the metal tube.

Finally, this study will evaluate the stress of metal tube in the tube bending process and the reliability of metal flow field change through finite element analysis software and reference experimental model, and the tube material is set up to be elasto-plastic, the friction setup at the contact boundary is Coulomb friction, and the friction coefficient of bending die and the clamp die and metal tube is 0.3, but for mandrel and metal tube, it is 0.096. Angular speed of the bending die is 3 radians per second.

IV. EXPERIMENTAL RESULT AND DISCUSSION

In this section, description and discussion will be applied to the experimental result and finite element analysis. In the experimental part, mandrel shift amount and the adding of axial thrust are used parameters, discussions are made to metal flow field analysis, ellipticity, outer tube wall thickness ratio and spring back angle of bended tubes of all kinds of parameters; finite element analysis includes bended tube flow field analysis and stress analysis.

First, in the metal flow field analysis part, the cross section of bended tube not added with parameter is as shown in Fig. 6, it can be seen that during the tube bending process, ellipse-turning will occur in the metal tube, meanwhile, due to the enlargement of the long axis diameter, it cannot be included in the shape forming slot of the bending die, and at the bending site, there will be out-shifted phenomenon.

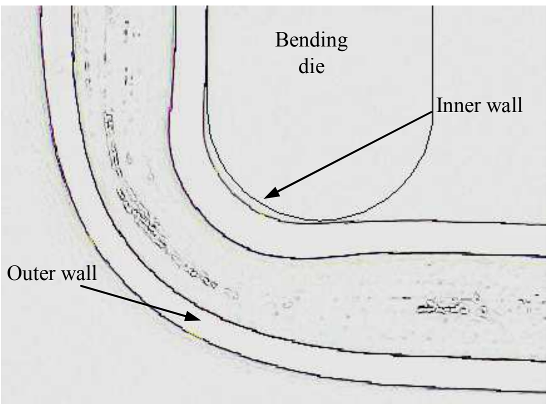

Fig. 6 Cross section of bended tube not added with parameter

When taking axial cross section on the metal tube, will be find that a gap as shown in the figure will be generated between bending die and the inner wall.

To analyze the flow fields of one bent metal tube, this experiment divided the metal tube into 12 segments (Fig. 5) by marking the tube's outer diameter, then the tube will be bended respectively to 30°, 60° and 90°, and the flow field situation of the metal tube is observed, then the short axis outer diameter of each division ring at different bended tube angle is measured, and the result is as shown in Fig. 7. From the curve in the figure, it is clear that in the bending process of rotary draw bending, the deformed area will continue the deformation due to stress.

For the semi-spherical mandrel used in the experiment, the shift a is the distance from the sphere center to the bending center. Fig. 8 and Fig. 9 are respectively the bending torque and mandrel loading at different mandrel location support, the A, B curve in the figure is respectively mandrel location set up at 0.5mm and 1.5mm. Mandrel loading, before 15° of tube bending, will have no draw action on mandrel due to the gap between mandrel and metal tube. The larger the mandrel shift, the larger the draw loading on the mandrel, relatively, the bending process will need more bending torque to achieve tube bending and forming process. From the bending loading curve at different mandrel shift, it is clear that the larger the bending angle, the larger the bending torque needed. This is because for a clamp die, the larger the tube bending angle, the larger the partial stress in the axis of the metal tube, which will in turn lead to larger torque in tube bending process.

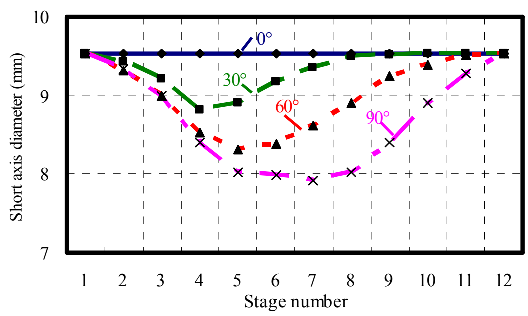

Fig. 7 Ellipse-turning short axis diameter curve of each stage by flow field analysis

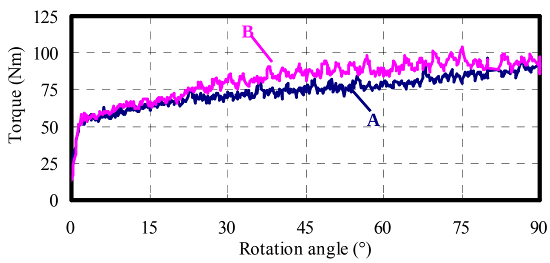

Fig. 8 Bending torque for different mandrel shift

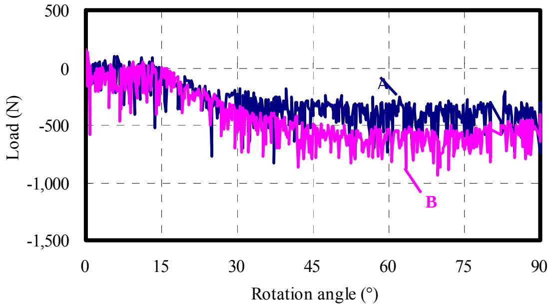

Fig. 9 Mandrel loading for different mandrel shift

The analysis of ellipticity of tube bending of different mandrel shift is as shown in Fig. 10. Test 001 is the bended tube without adding any improvement parameter, and it is clear that at 60° position, the ellipticity is largest. Test 002 is the case when mandrel shift is 0.5mm, at 60° position; the ellipticity is improved from 25% to about 16%. Test 003 is for mandrel with shift of 1.5mm, at 60° position; the ellipticity is even reduced to 7.5 %. In these three experiments, it was found that when mandrel has fixed shift, there is not too much improvement on 30° position, and this is because in the tube bending process, when the tube bending angle is increased, there is no mandrel support, and the deformed area will continue the deformation due to the stress. Test 004 is the case when mandrel shift is reduced from 4mm to 1.5mm, it is clear that at 30° position, the ellipticity is reduced from 22.5% to 15.2%, and the improvement effect at 60° does not show too much difference due to this.

Tube wall thickness, under the safety consideration of metal tube utilization, has become a very important factor. However, in the metal tube bending process, the tensile stress in the outer tube wall and other factor will all lead to the thinning of the tube wall. In this study, the outer tube wall thickness ratio is used to represent the tube wall thickness variation analysis, and the thickness ratio is the ratio between the tube outer wall thicknesses to the original thickness. Fig. 11 is the outer tube wall thickness ratio at different mandrel shift, and each experiment number parameter is the same as before. From each curve, it is clear that when mandrel gets deeper, although the ellipticity can be improved, yet the outer wall thickness becomes thinner too. Fig. 12 is the axial cross section of bended tube when mandrel shift is changed from 4mm to 1.5mm.

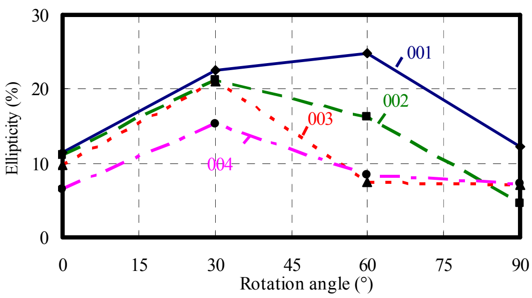

Fig. 10 The ellipticity of bended tube at different mandrel shift

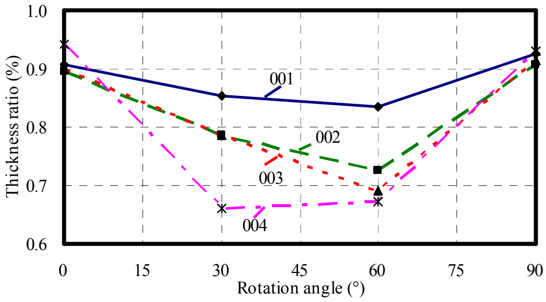

Fig. 11 The outer tube wall thickness ratio at different mandrel shift

In the figure, the inner wall shows an increase in the curvature, the reason might be because in the tube bending process, when the mandrel is supporting the outer tube wall, it will simultaneously change the metal flow in the inner tube wall of the metal tube; hence, the inner tube wall will have larger curvature. And this phenomenon has caused very large limitation on the improvement of the ellipticity.

At different mandrel shift, the analysis of spring back angle of the bended tube is as in Fig. 13. When mandrel is supporting the outer wall, the tube wall will generate larger stress, from spring back amount curve, it can be seen that due to the support of mandrel, spring back amount will be reduced, meanwhile, the deeper the mandrel, the lower the spring back amount.

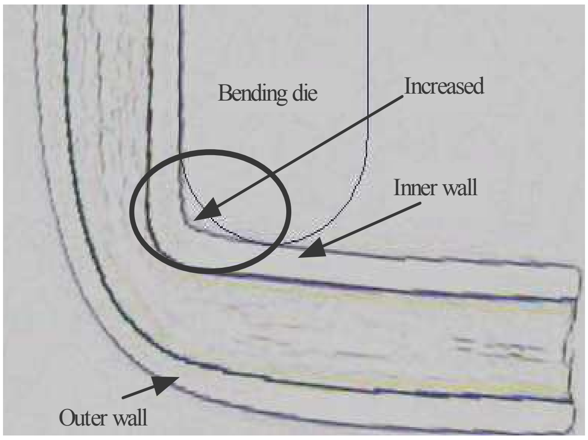

Fig. 12 The axial cross-section of bended tube when the mandrel shift is changed from 4mm to 1.5mm

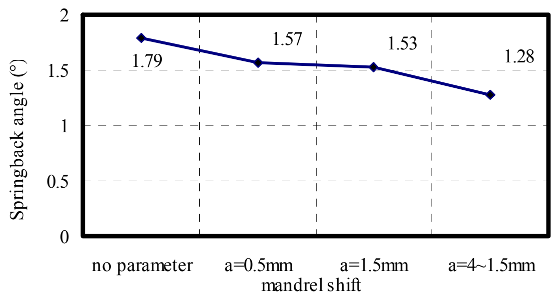

Fig. 13 Springback angle for bended tube at different mandrel shift

The ellipticity analysis with the adding of axial thrust is as in Fig. 14. Test 005 is bended tube with the adding of axial thrust of 1500N, due to the adding of axial thrust, the ellipticity at 30° position is improved, yet at 60° position, the ellipticity generated has become larger. Test 006 is the bended tube with the adding of axial thrust of 3000N, the ellipticity-changing trend is the same as that added with axial thrust of 1500N, in the mean time, the ellipticity at 30° is reduced from 22.5%to 12%. The adding of axial thrust can only improve 30° position, but at 60° position, the ellipticity is increased. The reason might be because at small angle of tube bending, axial thrust will reduce the axial partial force of the clamp die to the metal tube, and relatively, the generation of the tube bending stress will be reduced, then the ellipticity of the cross section of the bended tube will be reduced. At large tube bending angle, due to the change in the direction of the action force, axial thrust will have smaller action on the clamp die too, in the mean time, in the inner tube wall, the axial thrust will increase the compressive stress, which will in turn cause more serious ellipticity in the cross section of the bended tube.

Fig. 15 is the outer wall thickness ratio of bended tube when it is added with axial thrust. The experiment number is the same as above, and it is clear from the figure that the larger the added axial thrust, the smaller the thinning of the outer tube wall of the bended tube. This is because the added axial thrust can reduce the tensile stress acting on the outer tube wall due to tube bending process, hence, the tensile strength taken by the outer tube wall will be reduced, and the thinning of the tube wall will be relatively reduced.

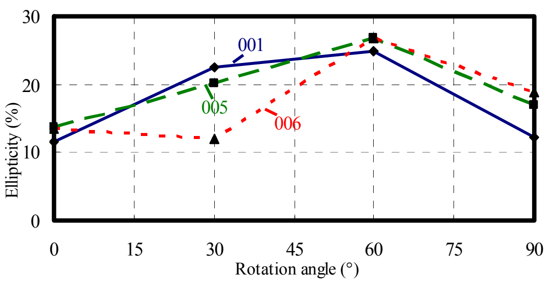

Fig. 14 The ellipticity of bended tube added with axial thrust

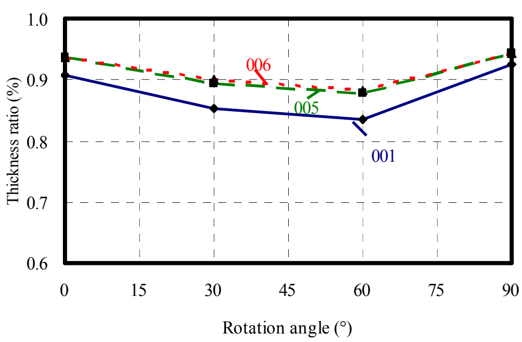

Fig. 15 The outer tube wall thickness ratio of bended tube added with axial thrust

The ellipticity analysis of bended tube added with axial thrust and mandrel shift is as shown in Fig. 16. Test 007 is the bended tube added with axial thrust 1500N and the change of mandrel shift from 4mm to 1.5mm. Test 008 is the bended tube added with axial thrust 3000N and with the change of mandrel shift from 4mm to 1.5mm, and the improvement on ellipticity for Test 008 is only slightly larger than Test 007. Fig. 17 is the axial cross section drawing for bended tube added with axial thrust 3000N and the change of mandrel shift from 4mm to 1.5mm, as compared to the inner tube wall of Fig. 9, it can be seen that the inner tube wall, due to the adding of axial thrust, will not change the metal flow field direction due to the drawing strenght caused by the mandrel on the metal tube in the tube bending process, Hence, the adding of axial thrust can improve the drawback of increase in curvature due to the influence of mandrel.

The spring back angle analysis of multiple parameter bended tube is as shown in Fig. 18, from the curve, it can be clearly seen that the larger the axial thrust, the smaller the spring back amount, in accompanied use with mandrel, the spring back amount will be reduced to even smaller value, in the mean time, the larger the mandrel shift, the smaller the spring back amount we obtained. It can be clearly seen that mandrel and axial thrust has additive effect on spring back amount.

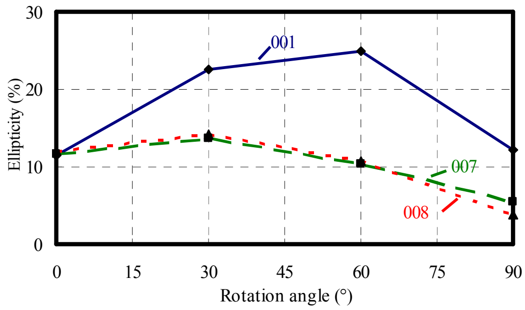

Fig. 16 The ellipticity of bended tube added with axial thrust and mandrel shift

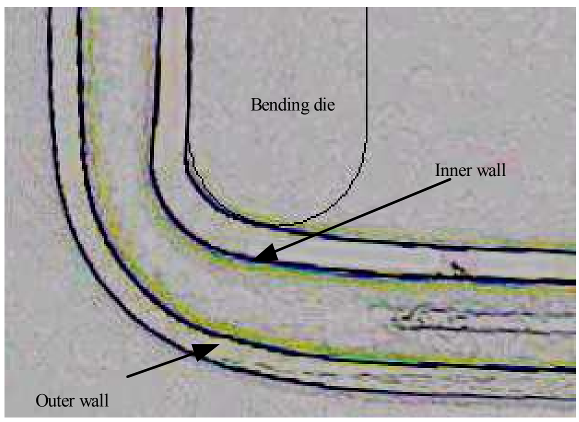

Fig. 17 Axial cross section of bended tube added with axial thrust and mandrel shift

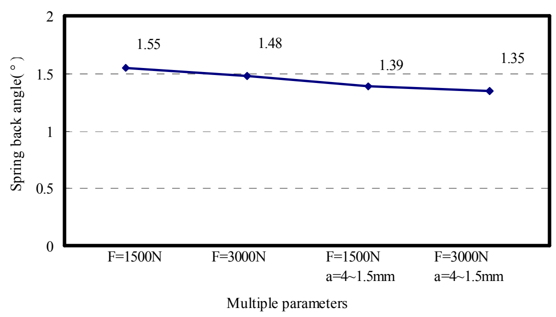

Fig. 18 Spring back angle of bended tube of multiple parameters

In order to confirm the reliability of the experimental effect, this study has finally adopted finite element analysis. The result of metal flow and the influence of the adding of axial thrust on tube material is simulated, Fig. 19(a) is the cross section of bended tube not added with axial thrust, in the inner wall, due to the bending of the tube wall, the metal tube will be streamlined and the metal tube will shift outwards, and a gap will then be generated between bending die and the inner tube wall of the metal tube. Fig. 19(b) is the cross section of bended tube added with axial thrust 3000N, as compared to Fig. 19(a), due to the adding of axial thrust, the streamlining of the inner tube wall can be improved, from the figure, it is clear that there is only small gap between the inner tube wall of metal tube and bending die. The simulation analysis of the maximal main stress vector when the tube is bended to 30° is as in Fig. 20. The stress change shows that the adding of axial thrust does not reduce the stress of the bended tube but instead, increase it. Moreover, axial thrust will instead cause the enhancement of the compression stress of the inner wall, hence, the geometry of the cross section of the metal bended tube will

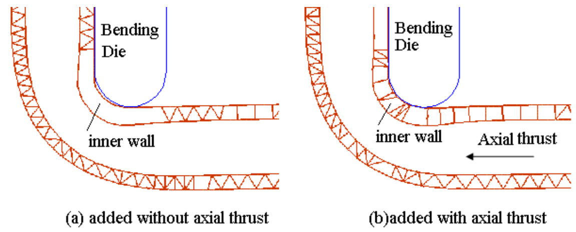

Fig. 19 Cross section of bended tube

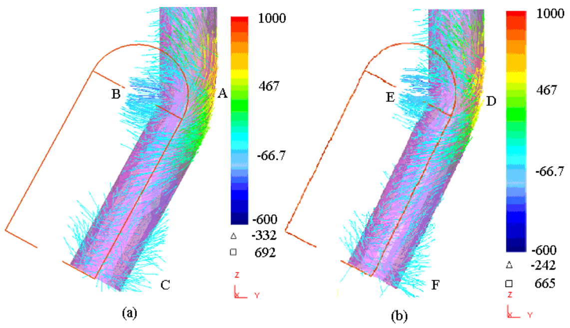

Fig. 20 The maximal main stress vector chart when it is bended to 30°

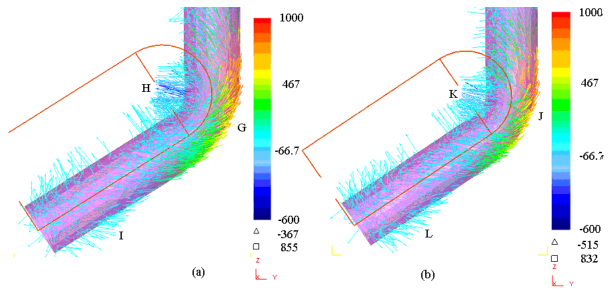

Fig. 21 The maximal main stress vector chart when it is bended to 60°

not be improved at 60° due to axial thrust, instead, it becomes worse.

V. CONCLUSION

In this study, a rotary draw bending machine installed with a movable mandrel and a loadable axial thrust is used to investigate the influence of mandrel movement and axial thrust on the tube bend in small radius. Meanwhile, the loading can be measured online, and the influence of mandrel and axial thrust on the bended tube can be observed.

As a result, an appropriate axial thrust can improve the curvature of the outer wall of the metal tube and reduce the spring back after bending. However, if it's pushed too hard, the inner wall curvature could be enlarged and the improvement effect is then limited. it was found from the experiment that a proper shifting of the mandrel into the metal tube shows also having an influence on spring back after bending. The farther the mandrel is pushed into the metal tube, the smaller the spring back is shown. If the tube is bended into small radius by combining the axial thrust and the mandrel shifting, the circular cross section of the metal tube is held better and the spring back is smaller than just by pushing mandrel into the tube. The axial thrust can reduce the kink effect in the inner wall generated by shifting the mandrel.

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