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Kai Jin

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Xunzhong Guo

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Kai Jin
College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Qiwei Yuan
College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

Jie Tao
College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

Joseph Domblesky
Department of Mechanical Engineering, Marquette University, Milwaukee, WI 53005, USA

Xunzhong Guo
College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

Abstract
Tube spinning technology represents a process with high forming precision and good flexibility and is increasingly being used in the manufacture of bimetal composite tubular structures. In the present study, a forming analysis of clad tube and base tube in spinning process was conducted through numerical simulations and experiments. There was an equivalent stress transition on the interface since the stress transmission was retarded from clad tube to base tube. The yield strength became a main consideration during a design bimetal composite tube. Meanwhile, the strain distributions in axial direction, tangential direction, and radial direction were also investigated to determine the deformation characteristics of each component. As the press amount increased, the strain of clad tube changed more than base tube. As the feed rate increased, the strain decreased in axial direction and tangential direction but almost unchanged in radial direction. Simultaneously, a method for controlling the wall thickness of the clad tube and the base tube is proposed. These results to guide the design of bimetal tube composite spinning process have the certain meanings.

Keywords
Bimetal tube Tube spinning Interface effect Deformation characteristic

1 Introduction
Bimetal tubes are a high-performance, low-cost composite tube composed of two layers of metal materials which form a bond at the interface through plastic deformation or metallurgical bonding. Based on increasing demand to improve performance while reducing weight, the use of bimetal tubing is becoming more widely used in the aerospace, nuclear energy, and automotive and petrochemical industries. At the present time, bimetal tubes are mainly produced and fabricated using processes which includes hydraulic bulging [1], hot extrusion [2], hot rolling [3], mechanical drawing [4], explosive welding [5], as well as other plastic forming techniques by centrifugal casting methods [6], electromagnetic forming method [7], etc. Yet the above forming methods have some problems such as complex structure and low flexibility of the tooling.

Spinning represents a new bimetal tube forming technology that has the advantages of high precision, low cost, and high flexibility [8].

In recent years, a number of workers have carried out some research work on bimetal tubes spinning. Mohebbi et al. [9–11] were among the first to propose the method of spinning to form bimetal tubes. At the same time, the microstructure and interfacial strength of aluminum/aluminum, copper/aluminum, and stainless steel/aluminum bimetal tube spinning were studied to manufacture bimetal composite tube with interfacial bonding strength. To further improve the coordination of the two-layer tube, Jiang et al. [12] used ball spinning for forming Cu/Al bimetal tube. In addition, it was found that the yield strength of the inner and outer tube materials affects the coordination of the spinning of the bimetal tube and affects the elongation of clad tube and base tube. Concurrently, in order to research the stress conditions of spinning bimetal tube, an analytical model was established to provide theoretical guidance for spin-forming bimetal tubes by Zhang et al. [13]. Based on this model, theoretical stress distribution in the deformation zone can be calculated approximately. Furthermore, Zhang et al. [14, 15] also investigated the effect of spinning process parameters, heat treatment, and initial thickness ratio on spin bonding of Al/Al and steel/Al bimetal tubes.

Although an amount of bimetal tubes had been successfully manufactured by spinning, the relationship and differences between the clad tube and the base tube in spinning have not been studied. Yet they directly affect the forming quality and wall thickness control of the tube fittings which play a decisive role in adjusting the process parameters of the bimetal tube. In the present study, the objective was to analyze the connection and difference between the clad tube and the base tube through the research of the hardness change and the triaxial deformation of the clad tube and the base tube after spinning. The requirements for the material of the two-layer tube, the control of the wall thickness, and process parameter settings are summarized. Meanwhile, the deformation of the components of the bimetal tube and the wall thickness control methods was studied through a combination of experiment and simulation. The results showed there is a transition in the hardness change measured from clad tube to base tube. Afterwards, the effects of the process parameters including the press amount (ψ) and the roller feed rate (v) on the triaxial strain changes of bimetal tubes were studied as well. Bimetal tube is uniformly deformed in both tangential and axial directions. Only one set of experimental parameters is needed in a single pass spinning process. In the meantime, the deformation of clad tube in all directions is greater than base tube. During the spinning process, with the reduction of the press amount, the thinning is dominated gradually by clad tube. Therefore, it is possible to control the wall thickness distribution of clad tube and base tube by adjusting the press amount. Finally, the spinning test of bimetal tube was also carried out based on the optimal simulation results and the spinning tests are very close to the simulation results.

2 Experimental set-up and procedure

Spin forming process is relatively simple. The principle of bimetal tube spinning is that a high-speed spindle rotates the billet, while opposing rollers locally compress the surface and radially extrude the billet along the tube axial direction of movement to make coordinate plastic deformation of the two layers of metal as shown in Fig. 1a. In order to better fix the billets, the device clamps the mandrel and the blank together through a collet, as shown in Fig. 1b.

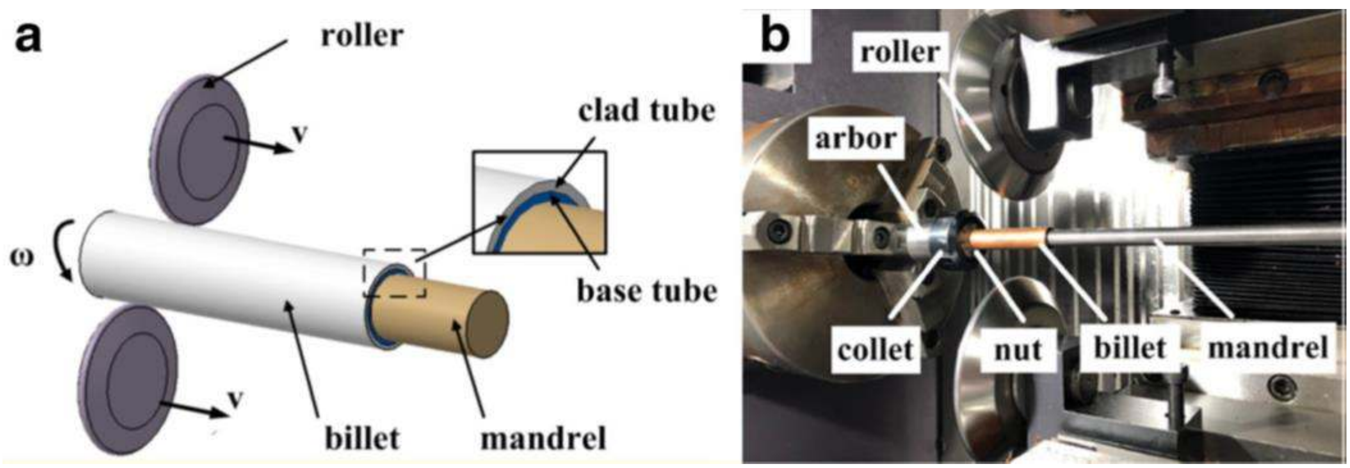

Fig. 1 Bimetal tube spinning. a Process schematic. b Experimental setup

Commercially, copper (T2) and aluminum (AA6061-T6) were selected as the billets. The outer diameter of clad tubes was 16 mm and wall thickness was 1 mm. At the same time, the outer diameter of base tubes was 14 mm and wall thickness was 1 mm. Simultaneous, single metal billet was used as a control group. The outer diameter of these tubes was 16 mm, and the wall thickness was 2 mm. The length of these tubes was all 100 mm. The actual forming part of the bimetal tube was 60 mm. An excessive gap between the mandrel and the preform resulted in bulging of the tube and should be avoided [16]. So here, we made the mandrel with a diameter of 13.8 mm.

In order to obtain the material parameters of the clad and base metal tube, according to ASTM E8M-01 interception of pipe samples, the true stress-strain curve was obtained after tensile test as shown in Fig. 2. Followed by according to the known stress-strain curve, this article used the second-order exponential decay function shown in Eq. (1) fitting the strain process.

$$\sigma = \sigma_0 + A \times e^{\varepsilon/a} + B \times e^{\varepsilon/b} \quad (1)$$

where σ is stress; ε is plastic strain; and σ_0, A, B, a, and b are

material coefficients.

The constitutive equation of the corresponding material is obtained though fitting.

$$\sigma_{Cu} = 449.32992 - 112.02652 \times e^{\frac{-\varepsilon_{Cu}}{0.00349}} - 20.82188 \times e^{\frac{-\varepsilon_{Cu}}{0.08268}} \quad (2)$$

$$\sigma_{A1} = 271.21823 - 27.95078 \times e^{\frac{-\varepsilon_{A1}}{0.03921}} \quad (3)$$

The resulting stress-strain curves for both materials are shown in Fig. 2.

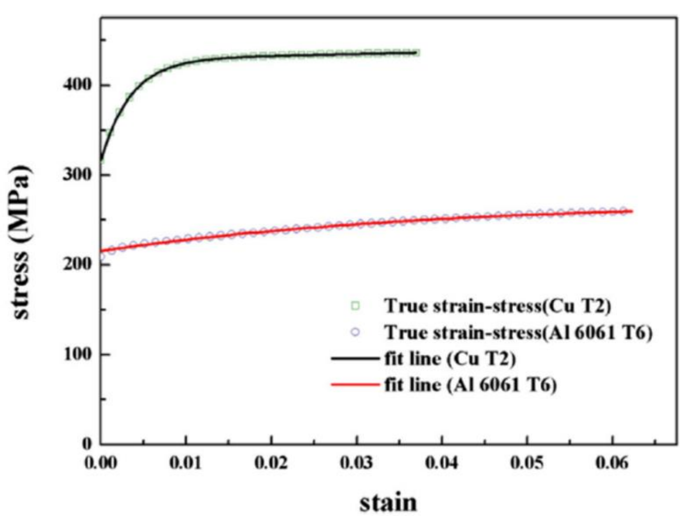

Fig. 2 Strain-stress curve of Cu tube and Al tube

In bimetal tube spinning experiment, the Cu/Al bimetal tube, Al/Al bimetal tube, and Al-based single metal tube were spinning in same process parameters. The characteristics of bimetal tube spinning process were analyzed by measuring the hardness variation in the wall thickness direction. The hardness of the corresponding position can be obtained by the HXS-1000AY microhardness tester as shown Fig. 3a.

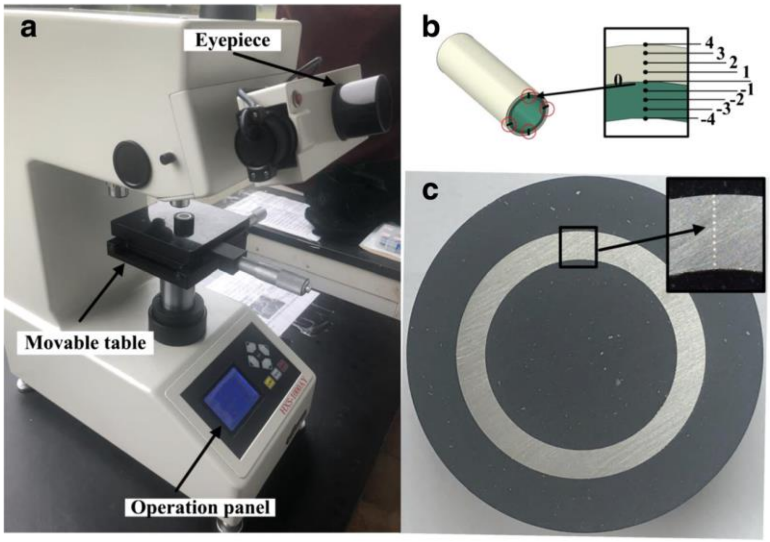

Fig. 3 Hardness testing

In addition, Cu/Al billets were spinning to study the triaxial strain changes, relation and differences of clad tube and base tube under different process parameters.

This paper used the control variable method to study the process parameters including the press amount (ψ) and the roller feed rate (v). Five sets of spinning experiments were performed on Cu/Al bimetal tubes for each process parameter. When studying a certain parameter, the other process parameters remain constant. Each process parameter selects five sets of data from small to large in a reasonable process interval which prevents the occurrence of forming defects to affect the experimental results.

Before spinning, the surface of clad tube and base tube was etched by the metal electrochemical marking machine as shown in Fig. 4. In spinning experiment, the strain in the axial and tangential directions of the tubes which were calculated by measuring the length change between the mesh etched on the clad tube and the base tube and in radial direction the strain which was calculated by measuring the wall thickness change after spinning forming was studied to analyze the deformation characteristic of bimetal tubes.

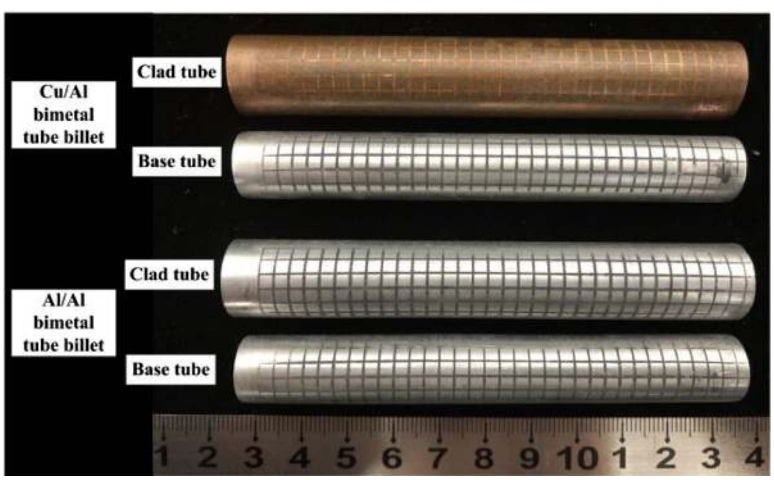

Fig. 4 Electrochemically clad tube and base tube of bimetal tube billet

3 FE model of tube spinning

Based on the ABAQUS/Explicit software, the plastic finite element model was established. Before the simulation, the CAD model of this study clad tube, base tube, rollers, and mandrel of was built by CATIA software, then imported to ABAQUS/explicit FE code, as depicted in Fig. 5. The fixed mandrel and the composite tube achieve an equivalent forming process through the rollers to do spiral movement around the tube to improve the accuracy of the calculation [17]. The penalty contact method was adopted to define the contact between the material and tools. The roller and mandrel were defined as analytical rigid bodies, and the clad tube and base tube were set as deformable bodies. The clad tubes and the base tubes used C3D8R entity unit which were eight-node linear brick and reduced integration elements [18]. Three layers of mesh are set in the thickness direction of the tubes, and both clad tube and base tube are divided into 12,000 meshes to ensure the accuracy of calculation. The analysis step was adjusted to dynamic explicit, and the interaction was set to face to face contact. In the finite element simulation, the billets removed the part which did not participate in the deformation of the length to reduce the calculation time. The end of the billets and the mandrel was fixed. Due to the complex trajectory of the two rollers, they are moved by a self-written subroutine. Two rollers were set symmetrically to rotate around the axis of the billets at the same rotation speed of the mandrel in the spinning experiments. In addition, all the dimensions of the FE model were same as the experimental process.

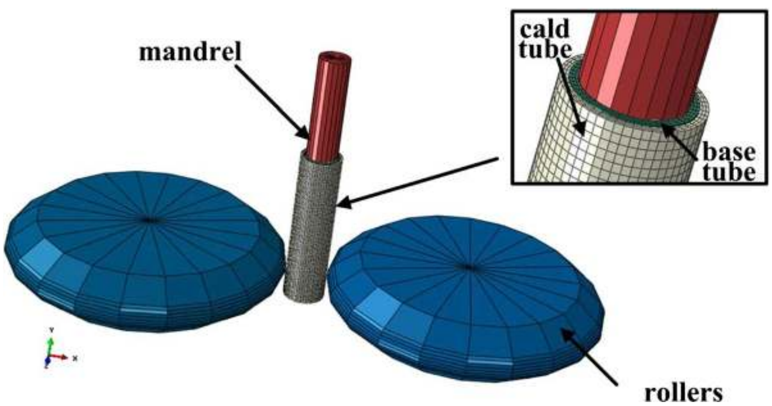

Fig. 5 FE model of bimetal tube spinning

4 Forming analysis

The deformation of metal during the spinning process of bimetal tube is extremely complicated. The bimetal tube not only has two layers of metal inside and outside but also there is an interface between the corresponding two layers. During the forming process, the internal and external fittings can be better combined with the spinning pressure. However, the material between the two layers does not have strong binding force as same as the neutral layer material of the single tube, since the clad tube and base tube will be in different stress conditions as Fig. 6 shows. From the partially enlarged cloud image, it can be seen that the stress appears fault from the clad tube to the base tube instead of the stepwise diffusion. The analysis considers that there is a stress transition between the clad tube and the base tube in the interface area.

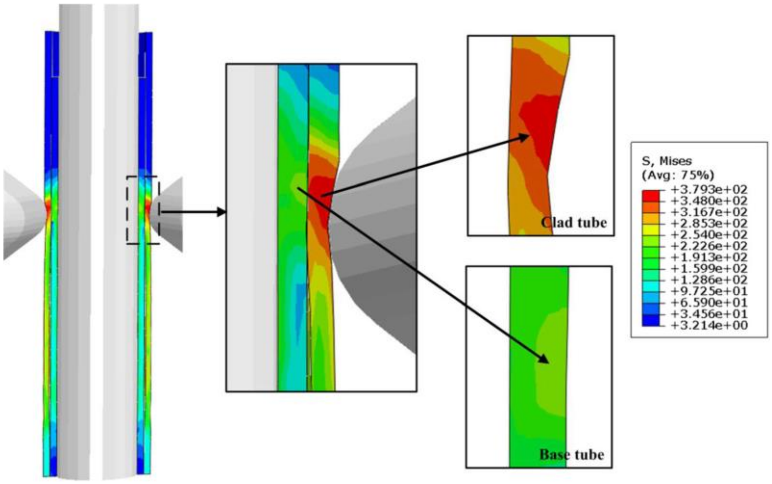

Fig. 6 Equivalent stress distribution of Cu/ Al bimetal tube between clad tube and base tube in spinning area

In this paper, the stress transition was studied during the forming process of the clad tube and base tube of the bimetal tube; the single metal tube and the bimetal tube were respectively subjected to spinning simulation and extract the equivalent stress on the radial point of the situation. Simultaneously, each point is an arithmetic mean of four points evenly distributed across the cross section. Figure 7 shows the Al tube, Al/ Al, and Cu/Al bimetal tube radial points of the equivalent stress changes in the same process parameters.

It can be seen from Fig. 7 that there is a larger stress transition from the clad tube to the base tube comparing with single metal tube. Concurrently, the magnitude of the stress transition changes at the interface with the material of the clad tube changing correspondingly. By comparing, we can also find clad tube is subjected to greater stress than base tube.

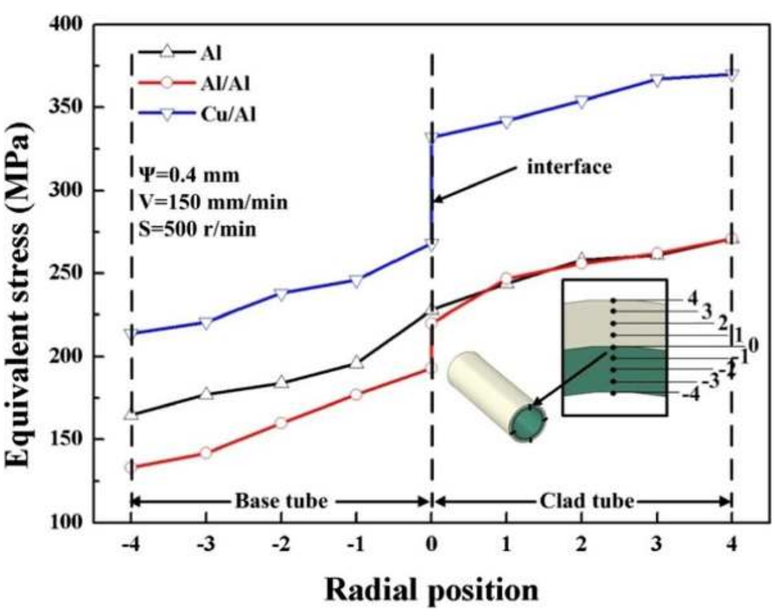

Fig. 7 Equivalent stress of the radial point changes of the cross section of single Al tube, Al/Al and Cu/Al bimetal tube

Figure 8 shows the change in hardness in the radial direction of single Al tube, Al/Al, and Cu/Al bimetal tube. It can be seen from the figure that the hardness gradually changes in the wall thickness direction, and the hardness in the interface area changes drastically. Material hardness changes, and deformations correspond to each other. As the amount of deformation of the material increases, hardness increases accordingly [19]. The hardness change also verifies the clad tube has a greater deformation than the base tube.

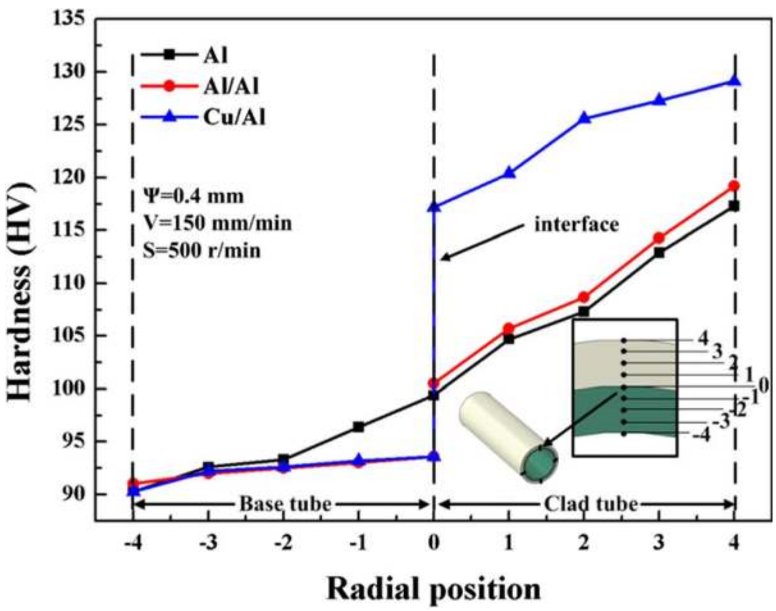

Fig. 8 Hardness of the radial point changes of the cross section of single Al tube, Al/Al and Cu/Al bimetal tube

In the spinning process, the clad tube cannot drive the base tube occurs completely same deformation occurs with different materials and different sizes of stress. Due to the existence of the interface, energy loss caused by metal interaction between interfaces and different force areas between the clad tube and the base tube which lead to large differences in the deformation of the clad tube and the base tube for bimetal tube. So under the same force, the stress of the base tube is smaller. Regardless of what the material of the base tube is, the clad tube in the spinning process will must be deformed. It is necessary to take into account the strength relationship between the material of clad tube and base tube. Since the stress of the base tube is smaller in spinning, the yield strength of clad tube should be at least higher than the yield strength of base tube. Otherwise, base tube will not undergo plastic deformation which causes tubes to not have a good combination.

According to the deformation of clad tube and base tube, bimetal tubes are divided into two types of spinning: both clad tube and base tube undergo plastic deformation and only clad tube undergoes plastic deformation. According to the film theory [20], only the internal pure matrix of clad tube and base tube should be in good contact, and bimetal tube can have bond strength. Therefore, base tube must be deformed so that the inner base body of the clad tube and base tube are in full contact. For better integration, in this paper, we mainly study the second type. Figure 9 shows a comparison of Al/Cu, Cu/ Al bimetal tubes, and an original base tube. Since the yield strength of Cu is greater than Al in Al/Cu bimetal tube, the stress of the base tube cannot meet the requirement of plastic deformation. It can be seen that even after a multi-pass spinning, the axial length of Cu tube did not changed, that is, the base tube was not deformed as the same as the mandrel for the clad tube.

Fig. 9 Difference of Al/Cu and Cu/Al bimetal tube after spinning

5 Results and discussion

There are many factors that affect the formation of bimetal tube spinning, such as process parameters, tube size, roller size, and material properties. This paper focuses on effect of key process parameters [21] in the spinning compound process including the press amount (ψ), the roller feed rate (v) and spindle revolutions(s) in the bimetal tube spinning forming. Through research, we found that the spindle speed changes have little effect on the deformation of the tube. So this article mainly focuses on research and analysis of press amount (ψ) and roller feed rate (v).

5.1 The effect of press amount

In the spinning process, the press amount directly affects the change of wall thickness and stress condition of bimetal tube. So it is a very important forming parameter for bimetal tube spinning. In this paper, a method for controlling the wall thickness of clad tube and base tube is proposed. In the case of other process parameters unchanged (the spindle speed is 500 r/min, the feed rate of the roller is 150 mm/min), this part mainly investigates the deformation of Cu/Al bimetal tube under different press amounts and press amount influence on the wall thickness change of clad tube and base tube. Five different press amounts of 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, and 0.5 mm were respectively adopted to simulate the spinning process.

In order to explore the deformation in three directions, in simulation, the length changes of the deformation unit and the position of the corrosion points on the tube surface changes of the experiment in each direction were measured. By calculating the strain in each direction of the bimetal tube under different press amounts, the strain trend in each direction is studied.

Through the observation of Fig. 10, it can be found that the triaxial strain of clad tube is much larger than base tube and the triaxial strain of bimetal tube also increases accordingly with the increase of the press amount. In the three strains, the radial strain changes the most. In Fig. 10a, c, it is found that the amount of depression of 0.3 mm is a coordination point. As can be seen from the figure, when the pressing amount is less than 0.3 mm, the strain conditions of the clad tube and the base tube are largely different. When the amount of depression is larger than 0.3 mm, the strain tendency of the clad and base tube becomes consistent. According to the analysis, when the pressing amount is less than 0.3 mm, the material of the clad and base tubes will slide relatively during the deformation process, and the consumption of a part of the energy will cause a large difference in the strain trend. Figure 11 is the ratio of the actual thinning of clad tube and base tube under different press amounts obtained by sorting and calculation. When the press amount is small, the plastic deformation occurred in base tube is smaller. But with the increase of the press amount, the ratio slowly becomes smaller. Thus, in the process of bimetal tube spinning, it can control the thickness distribution of clad tube and base tube to a certain extent by adjusting the press amount.

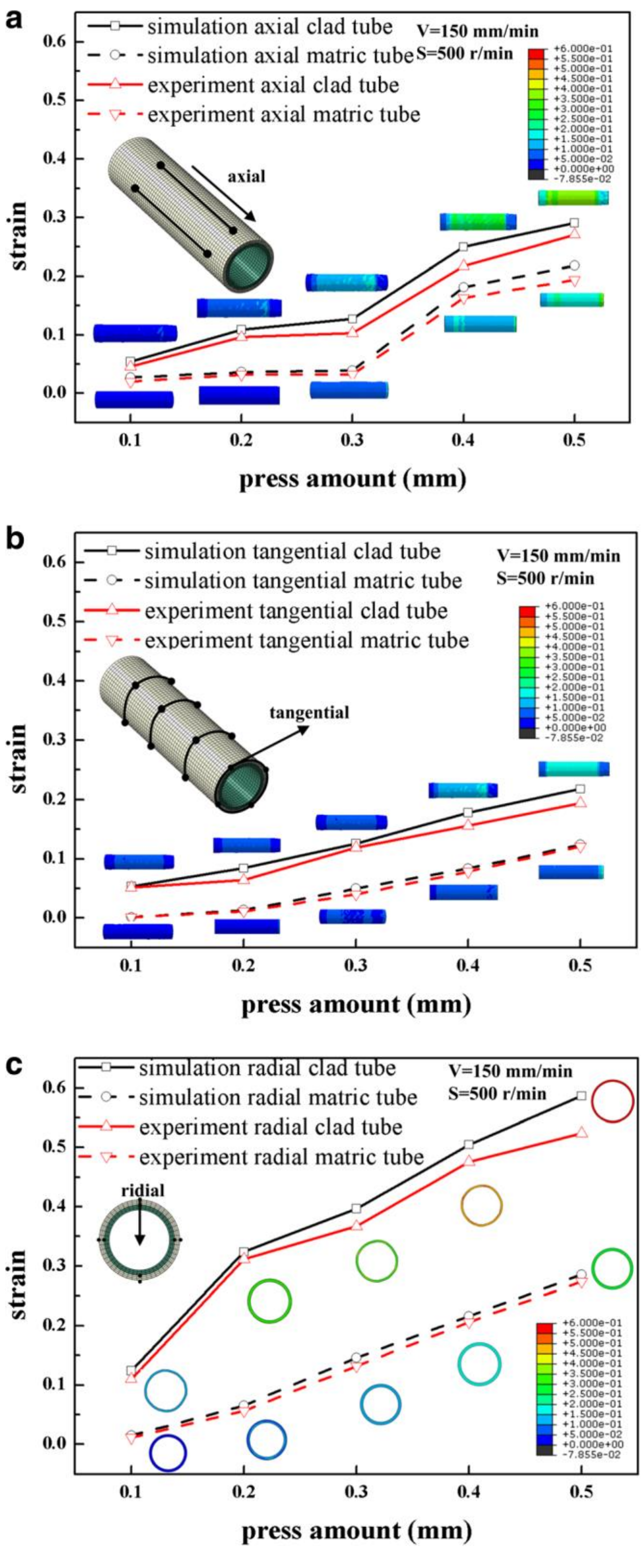

Fig. 10 Comparison of the simulated and experimental triaxial strain distribution of clad tube and base tube under different press amounts. a Axis direction. b Tangential direction. c Radial direction

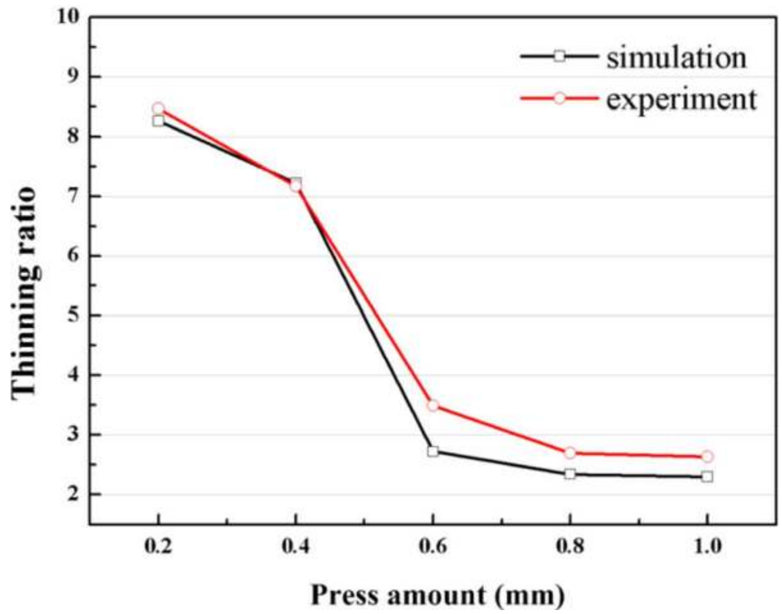

Fig. 11 Ratio of thickness reduction of clad tube to base tube in different press amounts

5.2 The effect of roller feed rate

Feed rate is the rollers along the tube axial movement speed during spinning. This paper investigates the influence of roller feed rate on the deformation of Cu/Al bimetal tube and the triaxial strain change of clad tube and base tube with different roller feed rates in other process parameters under the same conditions (the press amount was 0.6 mm, the rotary speed is 500 r/min). Respectively, set the feed rate of 50 mm/min, 100 mm/min, 150 mm/min, 200 mm/min, and 250 mm/min. Through the observation of Fig. 12a, b, it is found that lower roller feed rate can effectively reduce the rebound of the bimetal tube in forming process. As the roller feed rate increases, the axial and tangential strain of the bimetal tube decreases accordingly. And the radial strain of the clad and base tube is basically unchanged. However, with the increase of the feed rate, the strain decreases correspondingly in the axial and tangential direction.

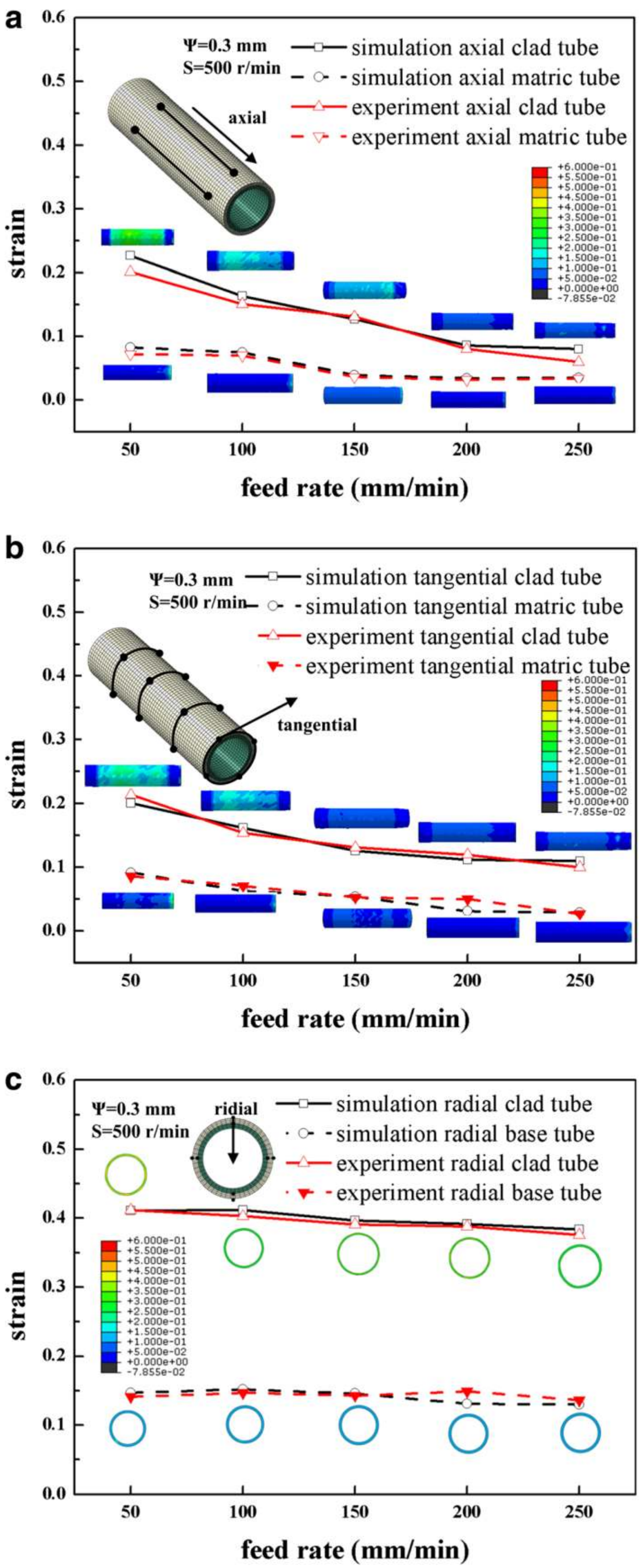

Fig. 12 Comparison of the simulated and experimental triaxial strain distribution of clad tube and base tube under different roller feed rates. a Axis direction. b Tangential direction. c Radial direction

The analysis considers that the low roller feed rate effectively increasing the intensive degree of the forming trajectory. Due to the number of contacts per unit length become more, the deformation of the movement trajectory overlaps more closely as shown in Fig. 13. The value of L decreases correspondingly with the decrease in roller feed rate. The material in the area is fully formed.

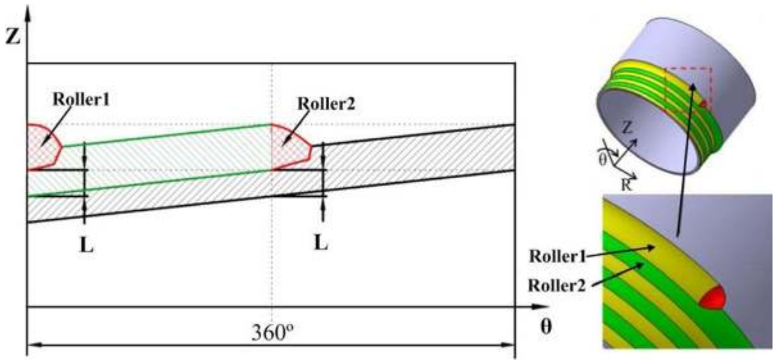

Fig. 13 roller track of spinning

Through the observation of Fig. 10, the tangential and radial deformations of the tubes change greatly in different amounts of depression. When the amount of depression is 0.5 mm, the strain in the radial direction reaches 0.58. The actual percentage of breaking elongation of the clad tube was 0.54. Therefore, the bimetal tubes have the possibility of breaking. There are indeed some breaks in the experiment as shown in Fig. 14. At the same time, by further increasing the amount of pressing, it is found that the bimetal tubes have basically broken. Therefore, the amount of pressing of 0.5 mm is a pole of fracture, and the further increase of the amount of pressing will cause the tubes to break due to excessive deformation. However, under different roller feed rates, the radial deformation of the tube is basically unchanged. The axial and tangential strain is decreasing, but the degree of change is small. At the same time, the strain in all three directions is lower than percentage of breaking elongation of the material. So, the roller feed rate will not affect the fracture of the bimetal tube.

Fig. 14 Fracture of bimetal tube

6 Conclusion

In the present study, a forming analysis of clad tube and base tube in spinning process was conducted through numerical simulations and experiments. Based on the results obtained, the following conclusions can be made:

(1) The hardness change in wall thickness direction indicated that there is a stress transition between clad tube and base tube due to the existence of the interface. Clad tube is subjected to a greater stress than base tube. It is necessary to take into account the strength relationship between the material of clad tube and base tube. Only base tube undergoes better plastic deformation; there is a better combination in bimetal tubes. So it is better that the yield strength of clad tube is higher than the yield strength of base tube.

(2) The influence of different forming parameters on the triaxial strain variation of bimetal tube by spinning is different. It is found that the amount of depression of 0.3 mm is a coordination point. And lower roller feed rate can effectively reduce the rebound of the bimetal tube in forming process. In addition, in the single pass spinning process, the forming parameters cannot be changed to ensure that bimetal tube can be evenly distributed in three directions.

(3) It is reliable to control wall thickness of clad tube and base tube by adjusting the amount of press. In the small press amount, the thinning of the bimetal tube is mainly covered by clad tube. The wall thickness of clad tube can be changed by using a small amount of press in the multipass spinning process.

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