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ORIGINAL ARTICLE

Hydroforming simulation and experiment of clad T-shapes

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Abstract Numerical simulations of the hydroforming process of Ti/Al clad T-shapes were conducted by using finite element analysis software. These simulations were used to optimize process parameters such as internal pressure, feed distance, and friction coefficient. Subsequently, hydroforming experiments were conducted based on these simulations. The results indicated that Ti/Al clad tubes could be obtained in the practical hydroforming process under the following forming conditions: internal pressure of 110 MPa, feed distance of punches of 25 mm, and a friction coefficient of 0.1. This resulted in well-bonded micro-interface between titanium and aluminum that is free from any delamination. The protrusion height of Ti/Al clad T-shapes were 25.5 mm and had high thickness uniformity.

Keywords Ti/Al clad T-shapes · Hydroforming · Numerical simulation · Practical forming

1 Introduction

Titanium/aluminum clad tubes are becoming more and more widely used in areas such as aviation, aerospace, and nuclear power engineering [1]. These two materials can be cladded by the explosive welding process. Through plastic deformation and subsequent oxidation of the aluminum layer, this material possess the outstanding advantages of high strength due to titanium and high hardness and wear resistance due to alumina (change the aluminum into the alumina by oxidation process).

At present, research has mostly concentrated on the preparation of clad tubes. However, more recently, research has focused on the deformation mechanisms and forming effects of clad tubes for the application of clad pipe-fittings in aerospace and nuclear power stations. Guo et al. investigated the law of plastic deformation and failure modes in Ti/Al clad bend tubes. Furthermore, the cold bending process of Ti/Al clad tube was simulated at room temperature and the variation law for maximum interface shear stress with different speed and friction coefficient [2, 3]. Islam et al. [4] performed numerical simulations and carried out experiments on the hydroforming process for the clad tube of specific clearance and was able to successfully fabricate X-shape cladding components. Hashmi et al. [5] investigated the deformation mechanisms of copper/brass clad tubes. The main failure mode of this clad tube is the delamination when the axial feed distance is large. Alaswad et al. [6] mainly discussed the effects of tube geometry on the protrusion height, thickness distribution, and wrinkle problem. Zhang et al. [7] carried out the hydroforming experiment for a clad metal spherical container. This investigation showed that the inner layer deformed first and slowly contacted with the outer layer. Eventually, both layers deformed simultaneously as the internal pressure was increased.

It is clear that the clad tube is difficult to form due to the difference in material properties between the outer and inner layer. Consequently forming defects, such as crack, wrinkle, and delamination commonly occurred during the forming process of clad tubes. In this paper, hydroforming simulations of Ti/Al clad T-shapes were conducted by FE simulation. Based on these simulation results, experiments were carried out to further optimize the forming effects. Finally, Ti/Al clad T-shapes were successfully manufactured [8–12].

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2 Hydroforming principle and FE model

2.1 Hydroforming principle

Hydroforming is an effective method for forming metal tubes into complicated shapes while maintaining excellent stiffness and precise geometry size. The stress mechanics of the process could be revealed by analyzing stress state of tube in the forming process as shown in Fig. 1. After the dies were closed, the increased internal pressure forced the material flow into the deformation zone. During the deformation process, F_1 and F_2, generated by the axial punches, provided an external force to compress the main tube. Additionally, a counterpunch was usually adopted to provide the counter pressure, F_3 on the top of the protrusion, in order to improve the stress state in the hydroforming process. In the conventional hydroforming process, crack defects usually occur due to the bi-axial tensile stress leading to excessive thinning of the wall thickness or even cracking. By application of the counterpunch, the tensile stress changed into the compressive stress in the protrusion area. This improved the stress state and related forming defects were avoided. However, the forming process with the counterpunch was complicated compared to the conventional hydroforming process. For this reason, the counterpunch was not utilized in the practical manufacturing process. By controlling the axial feed distance, loading path of internal pressure and the friction conditions, the high quality clad T-shapes could be fabricated.

2.2 FE model of hydroforming process for the clad tube

Figure 2 shows the initial mesh model of the tube blank, die, and punches in the MSC.MARC software. In the model, the titanium and aluminum tube blanks were meshed by hexahedral elements with element size of 1.5 and 2 mm, respectively. The quantities of outer layer and inner layer tube blanks after grid division were 15,660 and 62,400, respectively. In the simulation, an isotropic elastoplastic material model was applied. Additionally, the constitutive relation was chosen as $\sigma = E\varepsilon$ in the elastic deformation stage, while in the plastic deformation stage, Mises yield criterion was applied. The hardening law of the flow stress for the titanium and the aluminum tube were determined as $\sigma = K\varepsilon^n$. In the forming simulation, the K, n was calculated according to the data fitting of the true stress-strain curve (Fig. 3) obtained by the tensile experiments. Full Newton-Raphson iterations and Cauchy convergence criterion were adopted in the calculation process. The interface style was assumed as the smooth line to simplify the FE model; during the simulation, the contact type between two metal layers was set as “GLUE.” In addition, the displacement of the nodes on the symmetric plane (sym-xy and sym yz) was constrained. The internal pressure was loaded on the inner surface of the aluminum tube.

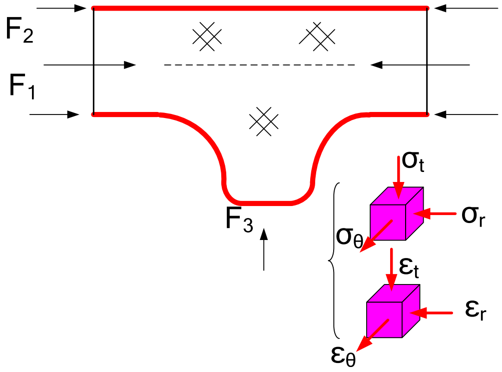

Fig. 1 Stress analysis for T-shapes in hydroforming process

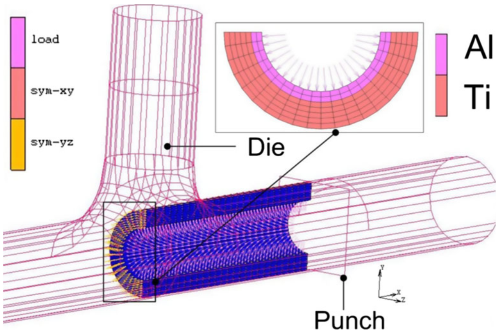

Fig. 2 Initial meshes of clad T-shapes hydroforming

3 Simulation results and discussion

3.1 Effects of internal pressure on the forming results

Internal pressure plays an important part in the hydroforming process for the Ti/Al clad tube, causing different mechanical properties of material. If the pressure is too small, the protrusion height may not be sufficient. Additionally, material accumulation occurred due to the hindrance of the material flow in the direction of the protrusion. Furthermore, the tensile stress caused by severe material accumulation could be found at the interface of the main tube of the clad T-shape. Therefore, forming defects such as micro-cracks and macro-delamination appear due to tensile stresses. However, if the internal pressure on the inner face of the clad tube is too large, the axial feed of the materials is not provided in time with the punches, causing the top of the protrusion to be the main deformed region including crack defects. In these conditions, the forming style is mainly a continued thinning of the wall thickness at the top of the protrusion.

The internal pressure can be estimated by Eq. 1. It is well-known that the outer diameter is constant and the internal pressure mainly depended on the yield strength, σ_s and wall thickness t. According to Eq. 1, the internal pressure equation for clad tubes was built based on the thickness ratio, P shown

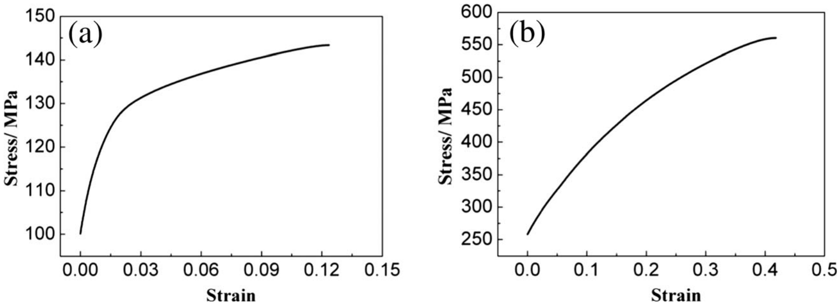

Fig. 3 The true stress-strain curve: **a** aluminum tube and **b** titanium tube

in Eq. 2.

$$P = kt\sigma_s \Big/ (D-t) \tag{1}$$

$$P = P_1 t_1 \Big/ (t_1 + t_2) + P_2 t_2 \Big/ (t_1 + t_2) \tag{2}$$

Where k is a constant, σ_s is the yield strength of the tube, D is the outer diameter, and t is the wall thickness. The initial internal pressure was calculated to be about 105 MPa by the Eq. 2.

Figure 4 illustrates the effect of internal pressure on the protrusion height and maximum thinning rate. The protrusion height increased initially then reduced with an increase in internal pressure, while the maximum thinning rate gradually increased throughout. At an internal pressure of 110 MPa, the maximum thinning rate exceeded 12.5 %. Figure 5 shows the effect of pressure on the interface shear stress of area A. Generally, the interface shear stress increased with an increase in pressure. Cracks were usually generated at the protrusion of clad T-shape. The optimum value of internal pressure for hydroforming, while avoiding delamination defects, was found to be 110 MPa.

3.2 The effects of feed distance on forming results

The punch feeding distance plays an important role in the hydroforming process that cannot be neglected. Generally, when the feed distance of the punch exceeds the normal value, material accumulation occurs at the end of the main tube, as shown in Fig. 6. This excessive thickening leads to the non-uniformity of the thickness distribution in the clad tube. However, if the axial feed of the materials is insufficient, the thinning or even local fracture occurs in this part of the protrusion. In addition, the coordination deformation between the outer and inner layer should be considered. An aluminum layer with excellent plasticity will improve the formability of the titanium layer because of the high bonding strength of the clad tube prepared by explosive welding method.

To investigate the effects of feed distance of punches on the protrusion height and maximum wall thickening rate, different feed distance values were selected individually. Figure 7 shows that with an increase in feed distance, the protrusion height and maximum thickening rate increased linearly. When the feed distance was less than 25 mm, the protrusion height was insufficient. However, when the feed distance exceeded beyond 25 mm, severe wall thickening occurred inevitably. Therefore, an axial feed distance of 25 mm was the optimal choice in the hydroforming simulation.

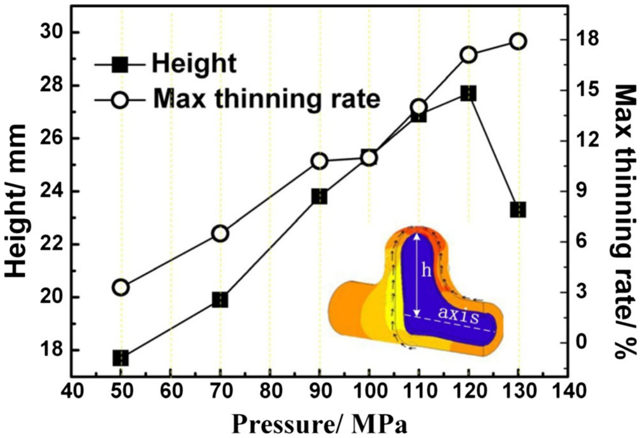

Fig. 4 Internal pressure vs. the protrusion height and maximum thinning rate

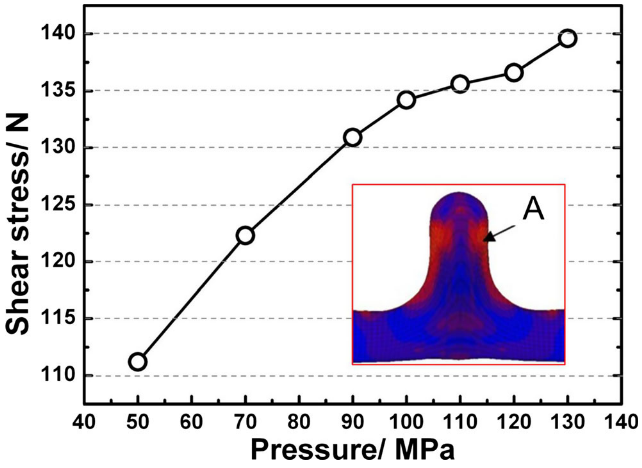

Fig. 5 Pressure vs. the interface shear force

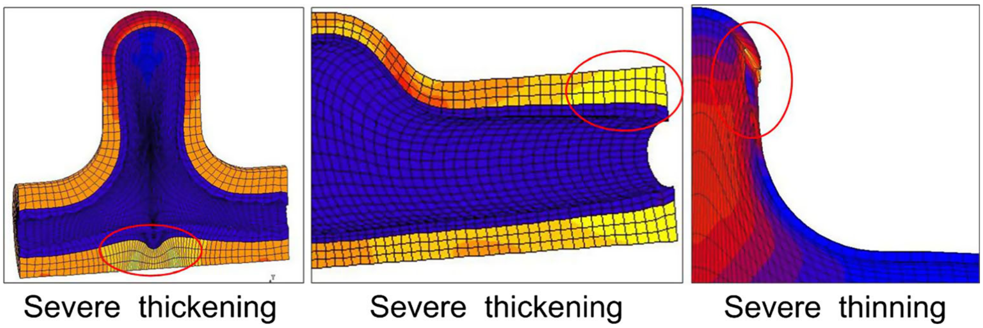

Fig. 6 Common defects in hydroforming process for the clad T-shape

3.3 The effects of friction on the forming results

From Fig. 8, it is clear that, an increasing friction coefficient causes the protrusion height to gradually decrease while the maximum thickening rate increases. At a friction coefficient of 0.1, the protrusion height was 26 mm and the maximum thickening rate was 58 %. When the friction coefficient exceeded 0.1, the protrusion height was insufficient. The friction coefficient had little effect on the maximum thinning rate. Consequently, a coefficient of 0.1 was chosen as the optimum. Clearly, the protrusion height and thickness distribution of the Ti/Al clad tube depend on the comprehensive action of internal pressure, feed distance, and friction coefficient. From the above simulation results, the optimized parameters were are as follows: internal pressure of 110 MPa, axial feed distance of punches of 25 mm, and a friction coefficient of 0.1.

3.4 The effect of bonding strength on the forming results

The bonding strength between titanium and aluminum layers has a significant impact on the hydroforming process. From Fig. 9, we can see that, the protrusion height increased with an increase in bonding strength. When the bonding strength is lower, the coordination deformation effects of the aluminum and titanium layer were restricted. During the deformation process, as the aluminum layer were delaminated from the titanium layer, fracture defects commonly occurred in the aluminum because of its lower strength and thinner wall thickness. This allowed oil used in the hydroforming process to entered into the gap between the inner and outer layer. In this case, the forming failed due to delamination and facture of the aluminum layer. From the simulation results, we know that the main delamination area was near the protrusion area and the end of main tube of the clad T-shapes. For the Ti/Al clad tube blank prepared by the explosive welding method, the bonding strength was in the range from 70 to 75 MPa. Therefore, the clad tube blank could endure the large deformation during the hydroforming process.

4 Hydroforming experiment of Ti/Al clad T-shape

To manufacture Ti/Al clad T-shapes in practice, hydroforming experiments were conducted using the hydroforming machine designed by Nanjing University of Aeronautics and Astronautics. The parameters of this machine are given in Table 1.

Ti/Al clad tube prepared by the explosive welding method was chosen as the original tube blank. The manufacturing route of clad tubes through explosion is as follows: Firstly,

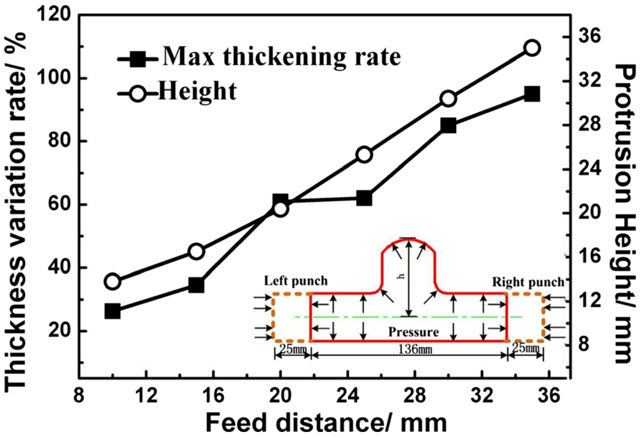

Fig. 7 Feed distance vs. the protrusion height and maximum thickening rate

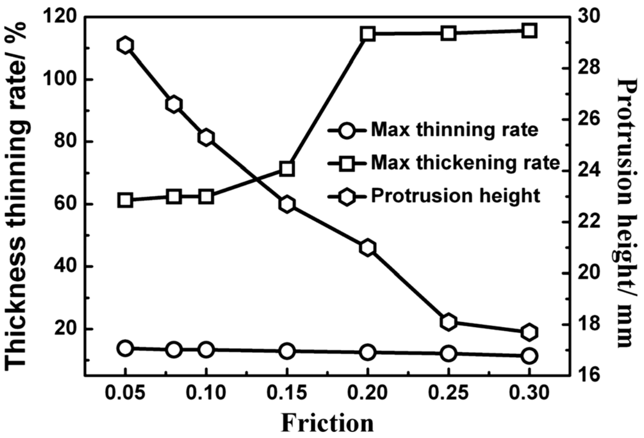

Fig. 8 Friction vs. the protrusion height and thickness thinning rate

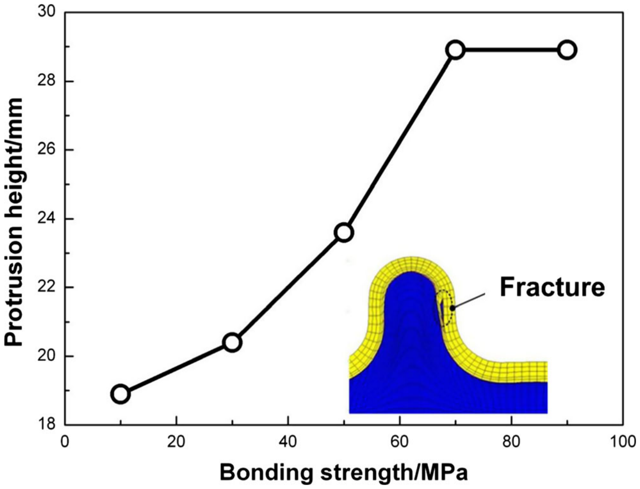

Fig. 9 Bonding strength vs. the protrusion height

the inner wall of the titanium tube was ground and polished. Moreover, the coaxiality is required during assembling for the aluminum tube. Secondly, the outer surface of the titanium was constrained by the Cr12MoV steel mould. Thirdly, the electrical blasting cap was used to detonate explosives in the aluminum tube. High-speed detonation wave and kinetic energy of explosion product were transferred to the aluminum tube, forcing high-speed movement of the aluminum tube towards the titanium tube. Plastic deformation, local metal melting, and atomic mutual diffusion subsequently occurred at the explosive cladding interface, and finally metallurgical bonding was formed [13].

Table 1 Parameters of the hydroforming machine

Index	Unit	Value
Main capacity	Ton	315
Main stroke	mm	400
Transverse press	Ton	56×2
Transverse stroke	mm	220
Cushion capacity	Ton	180
Cushion stroke	mm	80
Table dimensions	mm	915×750
Intensifier pressure	kg/cm^2	200
Total power	KW	42.7

Before the hydroforming experiment, the clad tube was annealed in argon atmosphere and insulated for 1~3 h at 500~580 °C to avoid fracture defects, as shown in Fig. 10a. From Fig. 10b, c, we know that large quantities of the twin crystal were observed in the titanium base. The twin crystal was formed during the explosive bonding process because of the high deform velocity. After the annealing process, the equiaxed crystal was obtained owing to the recrystallization effects under the high temperature.

The tube blank was then oiled and coated with a polyethylene film to reduce the friction coefficient between the die cavity and the clad tube. After the heat treatment and lubrication, the hydroforming process of the clad tube was executed in three steps in order to observe the individual stage forming effects. Firstly, the axial feed distance of the punch was set to a third of the total feed displacement. The forming result is shown in Fig. 11a. When the axial feed distance is not sufficient, the protrusion height is lower. When the axial feed distance was then set to two thirds of the total feed distance, the protrusion height increased. The clad T-shape was obtained without any obvious defects when the feed distance reached the default value, as shown in Fig. 11c.

Figure 12 shows the hydroformed Ti/Al clad T-shapes after sectioned processing. The height of the practical part of the protrusion was 25.5 mm, compared to the simulation result of 26 mm, demonstrating a good agreement between the numerical model and experimental results. Figure 12 also shows a maximum thinning rate of 11.3 % in area A. Area C is likely to crack easily due to the high stress and strain in this area. From the SEM image, it can be seen that area C is free from any delamination. Furthermore, the thickness distribution of clad T-shapes between experimental and simulation results matched well, as shown in Fig. 13.

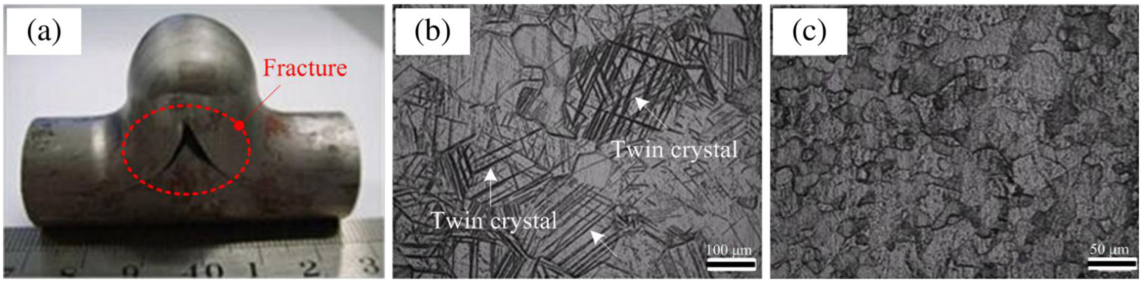

Fig. 10 Titanium tube: **a** fracture defect in hydroforming process without heat treatment, **b** twin crystal formed in the clad process, and **c** equiaxed crystal after the annealing process

Fig. 11 Forming results in three steps: **a** the first step, **b** the second step, and **c** the third step

5 Conclusion

1. Simulation of the Ti/Al clad T-shape hydroforming process allowed optimization of process parameters. The optimized internal pressure was 110 MPa, feed distance of punches was 25 mm, bonding strength was 60 MPa, and friction coefficient was 0.1.
2. Crack and delamination defects of Ti/Al clad T-shapes were avoided by optimizing hydroforming process parameters.
3. In the experiment, a protrusion height of 25.5 mm was achieved and T-shapes with high-thickness uniformity were obtained. In addition, there was good agreement between the numerical and experimental results of the thickness distribution and protrusion height.

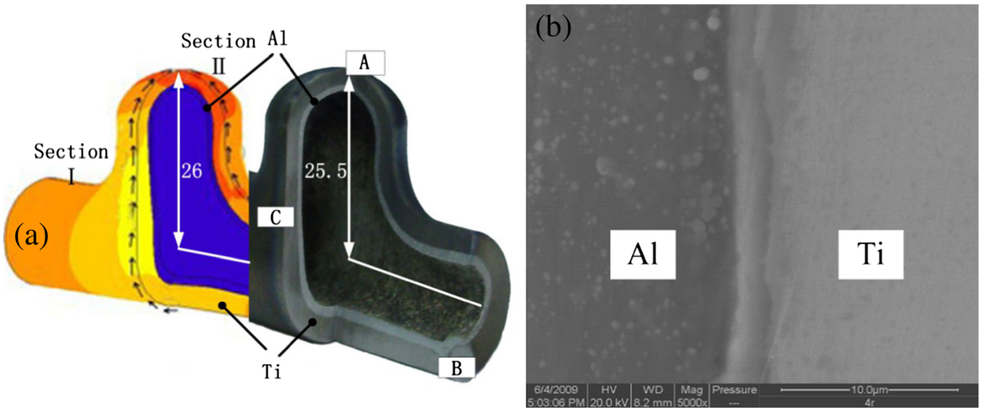

Fig. 12 Forming effects: **a** comparison between experimental and simulation results and **b** SEM image of the interface morphology of area C

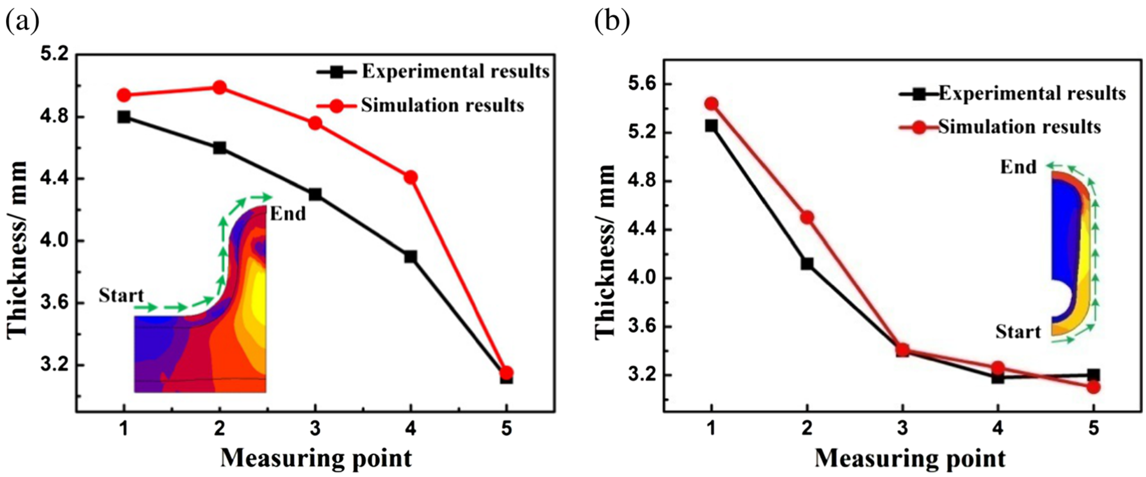

Fig. 13 Thickness distribution of different sections for experimental and simulation results: **a** thickness distribution of section A and **b** thickness distribution of section B

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