Numerical Simulation of the Roll Forming Process of Aluminum Folded Micro-channel Tube

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Abstract. Micro-channel tube is the most important component of flat tube heat exchangers. The folded micro-channel tube is made of clad aluminum sheet through roll forming process, and has great advantage in the aspect of corrosion resistance over extruded tube. The folded tube's sub-millimeter channel size as well as tight dimensional precision requirement brings great challenge to roll forming process design. In this paper, the finite element model of the whole roll forming process of a ten-channel tube is established by using ABAQUS/Explicit. The deformation at different forming stands are investigated and compared with experiment. The hydraulic pressure test is carried out on the developed tube and its pressure bearing capacity is evaluated.

Keywords: Folded micro-channel tube; Finite element simulation; Roll forming; Pressure bearing capacity

INTRODUCTION

Micro-channel tube is a kind of heat exchanger tube with a row of sub-millimeter-diameter channels, and has been widely used in automobile air condition systems[1-6]. Most micro-channel tubes are extruded ones, as shown in Figure 1(a), i.e. they are formed by hot extrusion of cylindrical aluminum alloy ingot through a very small extrusion die, with an extrusion ratio over than 500[7-8]. The folded tube is a novel micro-channel tube that is formed by roll forming of thin aluminum plates, as shown in Figure1(b). It can be made of cladding aluminum plates, which consists of a 3XXX core aluminum alloy and a 4XXX aluminum alloy[9-10] on both sides, as shown in Figure 2. Therefore, the folded tube has great advantage in the aspect of corrosion-resistancy than extruded tube[11], and has great potential, as a substitute for extruded tube, in parallel flow heat exchangers, especially those used under harsh conditions.

A representative folded tube shown in Figure 1(b) is 16mm in width and 1.8mm in thickness. The requirement on high-precision overall dimension should be guaranteed for assembly with fins and header pipes in manufacturing heat exchangers. The sub-millimeter channel size poses challenge to roll forming of the folded tube. Moreover, reduction of wall thickness should be as small as possible to ensure the pressure bearing and anti-corrosion performance of the tube in future service.

(a) (b)

FIGURE 1. Micro-channel tube: (a) extruded tube; (b) folded tube

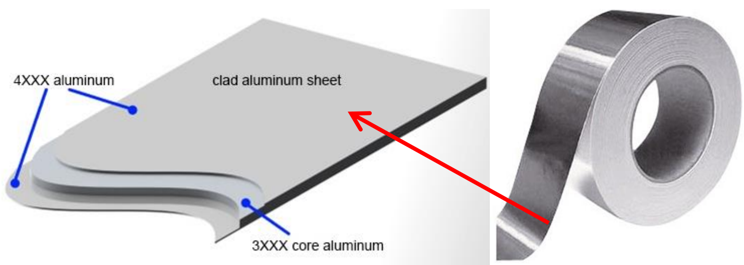
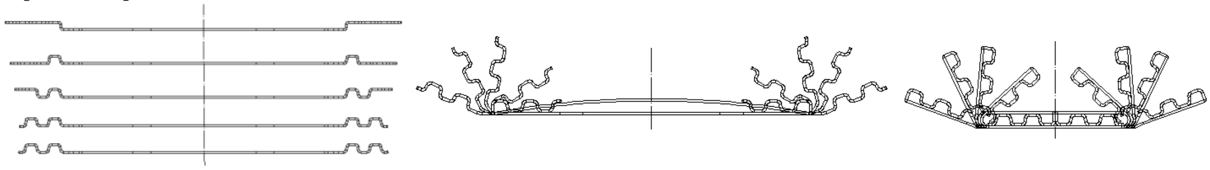


FIGURE 2. Clad aluminum alloy sheet

In the present work, the roll forming process of a ten-channel folded tube is numerically investigated by using the finite element method. First, the uniaxial tension test of clad aluminum sheet is carried out and a Swift type hardening model is established. A three dimensional finite element model of the whole roll forming process is then built by using ABAQUS/Explicit. The deformation behaviors of the clad aluminum sheet at different forming steps is analyzed. The experiment is carried out, and deformation configurations at different forming stages are measured and compared with simulated results. Finally, the formed folded tube is evaluated by pressure bearing test.

PATTERN DESIGN

As shown in Figure 3, roll forming process of folded micro-channel tube can be divided into three stages: the trapezoidal grooves on both hands of the plate section are formed at the first stage (from step 1 to step 5); at the second stage (from step 6 to step 14), parts of sheet with trapezoidal grooves are folded to form the first four micro channels; The rest of six channels, as well as the two semi-circular arcs of micro-channel tube, are formed by folding the sheet once more at the stages from step 15 to step 22.



(a) #1 ~ #5 (b) #6 ~ #14 (c) #15 ~ #22

FIGURE 3. Pattern design of roll forming

FINITE ELEMENT MODEL

The clad aluminum sheet studied in current work is an AA4343/AA3003/AA4343 sandwich sheet, in which AA3003 is an Al-Mn base alloy and AA4343 an Al-Si base alloy. The thickness of the sheet is 0.265mm. The uniaxial tension test of the clad aluminum sheet is carried out. The Von Mises associated plasticity model with the exponential hardening is used to describe the stress-strain response, as below.

$$\sigma = K(\varepsilon + \varepsilon_0)^n \tag{1}$$

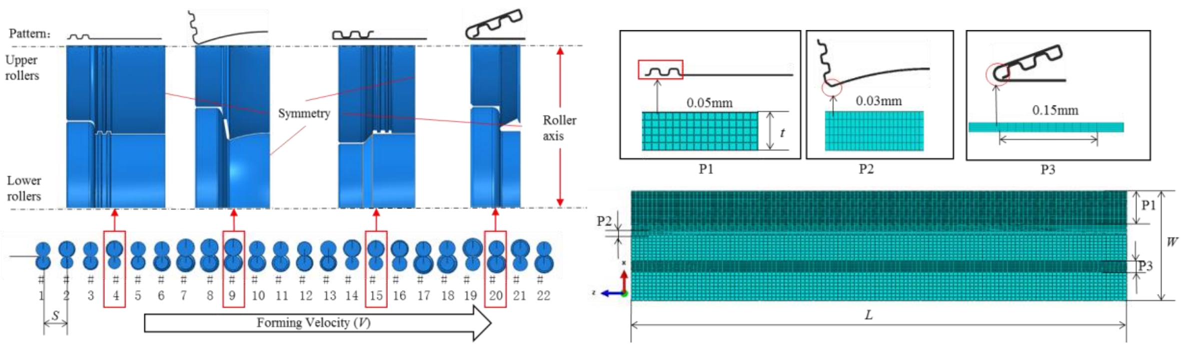
where K and n are material parameters of the exponential hardening model.

Based on data fitting of the material test, the mechanical properties of clad aluminum sheet are obtained as listed in Table 1, where E, σ_s and ν are elastic modulus, yield stress and Poisson's ratio respectively.

TABLE 1. Mechanical properties of clad aluminum sheet

Parameters	E (Gpa)	σ_s(Mpa)	ν	ε_0	K(Mpa)	N
Values	65.5	180.7	0.33	0.00494	296.8	0.09336

The three dimensional finite element model of the roll forming process is established by using ABAQUS/Explicit[12], as shown in Figure 4. Only a half of aluminum sheet is modeled due to the symmetry of geometry, boundary and loading conditions. According to the pattern design, the plate is formed in a folded tube after experiencing deformation at total 22 forming stands. Upper and lower rollers are installed on each forming stand, as shown in Figure 4(a). The aluminum sheet is discretized by 3D stress elements (C3D8R) with different sizes according to various forming radii, as shown in Figure 4(b). The total element number is 135000 and the minimum element size is 0.03mm. The dimension of metal sheet and forming parameters are listed in Table 2. All forming tools are modeled as analytical rigid surfaces. The contact between tools and aluminum sheet is set as a strict "master-slave" algorithm. The penalty function model with friction coefficient of 0.1 is employed.



(a) (b)

FIGURE 4. FE modeling: (a) assembling and boundary conditions; (b) meshing of aluminum sheet

TABLE 2. Sheet dimension and forming parameters

Parameters	L(mm)	$W(mm)$	t (mm)	V (mm/s)	S(mm)
Values	120	26.5	0.26	2000	100

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NUMERICAL SIMULATION RESULTS

In order to verify the finite element simulation, the comparison between FE simulation and experimental results is carried out. Some forming results in both of experiment and simulation are compared in figure 5. In the first five steps, the edges of the aluminum sheet are gradually formed into two trapezoidal grooves, as shown in Figure 5(a). Figures 5(b) and (c) show the second stage of the forming sequence and Figures 5(d) and (e) show the third forming stage. The final shapes of the folded tube are demonstrated in Figure 5(f). As can be seen from the figures, simulation results show good consistency in the geometric configurations comparing with the experimental ones.

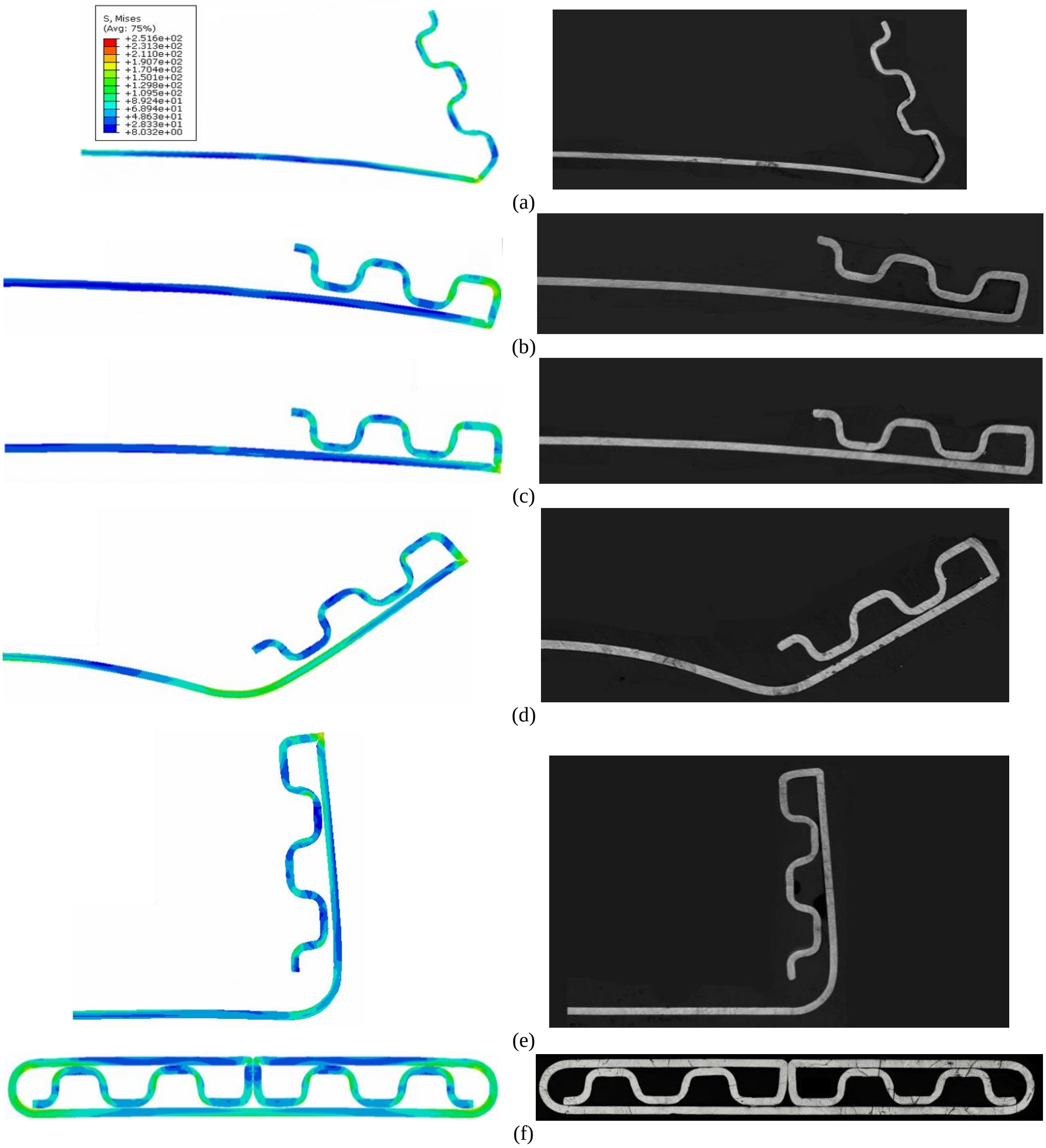
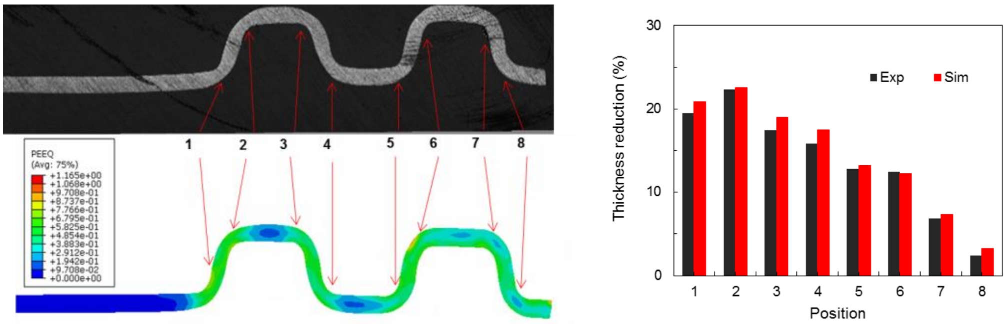


FIGURE 5. Comparison of simulation results with experimental ones: (a) #5 step; (b) #10 step; (c) #14 step; (d) #17 step; (e) #19 step; (f) #22 step (The left is simulation configurations and the right one is measured ones.)

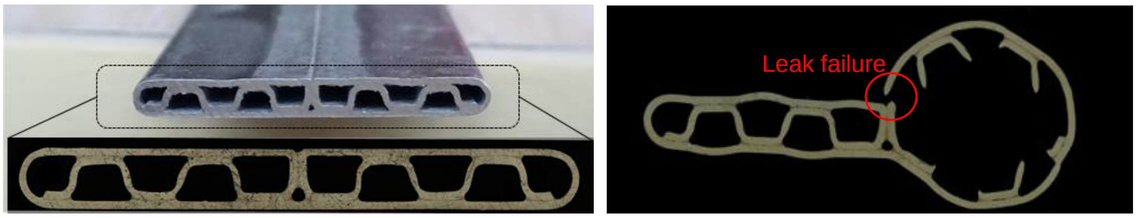
Pressure bearing capacity is one of the most important performance indicators of micro-channel tubes. The location of burst failure is always at the weaknesses of the micro-channel tube. Therefore, wall thickness reduction of the folded tube in roll forming process directly affects its bearing capacity. Generally, the smaller bending radius will lead to more severe thickness reduction. As can be seen from the forming pattern, small bending radii are at the corner of trapezoidal grooves which is formed during the first five steps. Therefore, it is necessary to evaluate the thickness reduction of sheet wall at these bending corners. The thickness reductions at the eight corners in experiment and simulation are compared in Figure 6. The thickness reduction shows a decreasing trend from the center to the edge and the most server thickness reduction (23%) appears at the first bending corner. The simulation results agree with the experimental ones very well.



(a) (b)

FIGURE 6. Compared results of thickness reduction between experiment and simulation: (a) forming shape; (b) thickness reduction

In order to evaluate the pressure bearing capacity of folded micro-channel tube, NOCOLOK brazing[13] and hydraulic pressure tests are carried out. The folded tube is firstly heated to 605 ℃ in SECO/WARWICK Nitrogen protection brazing furnace, then held for 3~5 minutes at this temperature. The welded micro-channel tube is obtained after air cooling, as shown in Figure 7(a). Hydraulic pressure tests show that leak failure occurs at the top center of the tube when the pressure increases to about 18MPa. The tube cross section after hydraulic pressure test is shown in Figure 7(b), which indicates that the fracture areas are at the bending corners of the trapezoidal grooves and corresponds to the positions with thickness reduction.



(a) (b)

FIGURE 7. Hydraulic pressure test: (a) brazed folded tube; (b) folded tube after hydraulic pressure test

CONCLUSIONS

Numerical simulation of the roll forming process of a clad aluminum folded micro-channel tube is carried out. The deformation characteristics of the sheet during the forming processes are analyzed. The simulation results show good consistency with the experimental ones in the geometric configurations and thickness reductions. In addition, the pressure bearing capacity of the folded micro-channel tube is evaluated by the hydraulic pressure test. The failure mode indicates that the bending corners of the trapezoidal grooves formed in the first five steps are the weakness of the folded tubes. Future work will focus on the pattern design optimization for alleviating the wall thickness reduction.

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