Research on homogeneous deformation of electromagnetic incremental tube bulging*

Xiaohui Cui, Jianhua Mo, Jianjun Li

State Key Laboratory of Material Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan 430074, PR China

Abstract:

The electromagnetic incremental forming (EMIF) method is used for tube forming process. Suitable 2D FE models are designed to predict the forming process with a moving coil. In comparison with experimental values, simulation method can obtain accurate results. Then, effect factors named overlapping ration of adjacent discharge positions, discharge voltage, forming sequence and die dimension on tube homogeneous deformation are discussed. The result demonstrates that it is feasible to produce long-straight wall tubes using a small coil by electromagnetic incremental tube bulging.

Keywords

Electromagnetic incremental forming, Tube bulging, Process parameters, Numerical simulation

1. Introduction

Electromagnetic forming (EMF) is a kind of high-velocity forming technology based on the repulsive forces generated by opposing magnetic fields in adjacent conductors. In comparison with conventional forming processes, EMF has many advantages, including no lubricants, contact-free, high repeatability, improved strain distribution and reduction in wrinkling [1]. At present, the EMF method is mainly used in tube bulging, tube compression and tube connection, which could meet industry requirements to some extent [2, 3].

However, only some simple and small parts can be produced by EMF. This is because larger parts require more energy if using EMF to form the whole metal parts alone. But the electromagnetic forces cannot be arbitrarily enlarged to form large parts due to the limitation of strength of the working tool and the capacity of the capacitor bank. Yu et al. [4] analyze the effect of coil length on energy efficiency of tube forming. It is found that the longer of coil

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length corresponds to lower energy efficiency under the condition of the same discharge energy, which causes a higher equipment energy required under the same tube deformation.

Recently, Cui et al. [5] proposed a new method named electromagnetic incremental forming (EMIF). It is demonstrated that the EMIF technology is feasible to produce a large metal sheet part with small working coil and small discharge energy. In this paper,the EMIF method is used to produce a long tube with a small coil and small discharge energy.

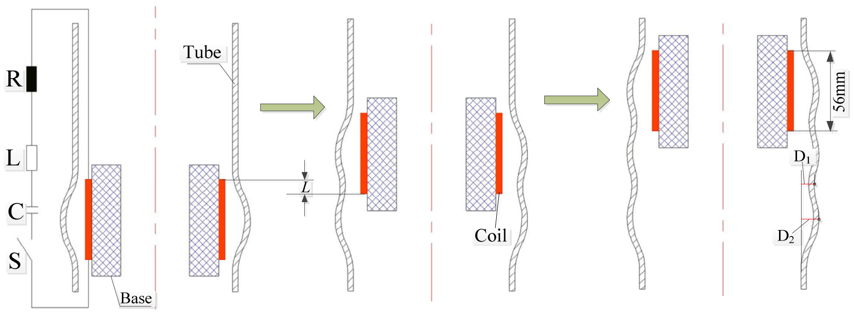
2. Principle of electromagnetic incremental tube forming

Figure 1 describes the principle of electromagnetic incremental tube bulging. The small coil causes workpiece local deformation at a high speed. Finally, all local deformations accumulate into large parts. There are two kinds of forming process: (1) the coil sequential discharge from a tube end to another end (Figure 1(a)); (2) the coil discharging make the tube ends deformation firstly, then the tube center deforms (Figure 1(b)). In order to produce long-straight wall tubes, it introduces two important concepts, as showed in Eq(1) and Eq(2): δ is overlapping ratio of adjacent two discharge regions; η is used to evaluate the tube deformation uniformity.

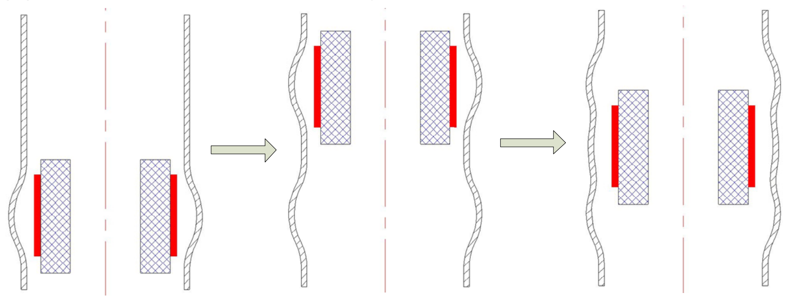
$$d = \frac{L}{L_{coil}} \tag{1}$$

$$h = \frac{D_2 - D_1}{D_2} \tag{2}$$

Where, L is the overlapping region of the coil discharge in two adjacent positions. L_{coil} is the length of coil. In this paper, L_{coil} is equivalent to 56mm. D_1 is the smallest radial displacement at the valley region of the tube. D_2 is the maximum radial displacement.



(a) the coil sequential discharge from a tube end to another end



(b) the tube ends deform firstly and then the tube center deforms

Figure 1 The principle of electromagnetic incremental tube bulging

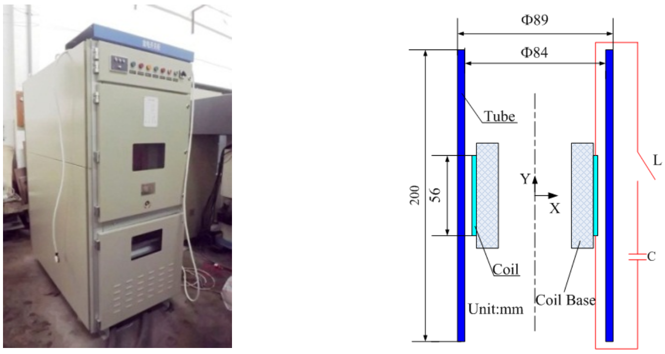
3. Numerical simulation of electromagnetic incremental tube forming

3.1 Finite element models

EMF equipment was made by Huazhong Univeristy of Science and Technology (Figure 2). The main parameters in the current experiments were: capacitance-900μF, rated voltage-10KV. A thirteen solenoid coil in conjunction with capacitor banks was used to make the tube deforms by magnetic force. The section area of the coil is 1×4mm^2. The inner radius of the coil is 38mm. The coil length is 56mm. The distance between coil and tube is 3mm. The discharge current, I(t), flowing in the coil is approximately described by the following equation:

$$I(t) = U\sqrt{\frac{C}{L}}e^{-bt}\sin wt \qquad (3)$$

Where, U is the initial voltage, C =900μF is the capacitance, L=14.6μH is the inductance, β =616.44s^{-1}is the current damping factor and ω=8723.7 rad/s is the current angular frequency.



(a) (b)

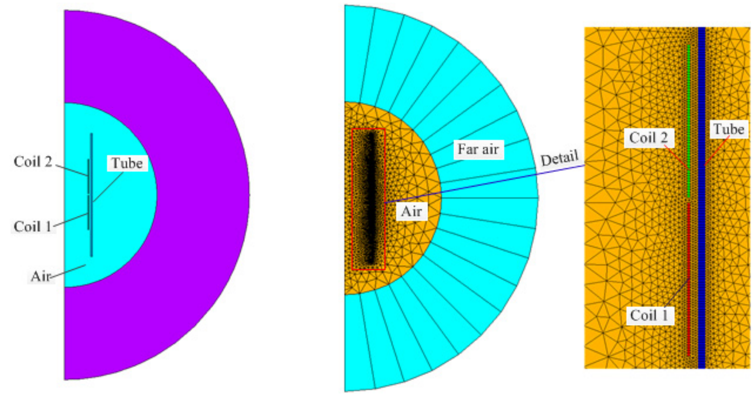
Figure 2 Equipment condition for electromagnetic tube bulging (unit: mm): (a) Capacitor bank and vacuum switch; (b) Tube and solenoid coil

To predict the electromagnetic incremental tube forming by FEM, a method like "birth-death element" was proposed. Many coil models was required to be established and the coil does not move in the simulation process. The magnetic forces are calculated on the basis of stationary coil condition in the ANSYS/EMAG model.

Because of axial symmetrical placement of coil and tube in Figure 1 (b), only the half of forming system is taken into account in 2D FE model. Figure 3 shows meshes and boundary conditions for the EM model. The ANSYS/EMAG is used to calculate the magnetic force on the sheet. The EM model consists of far field air, air, coil and sheet. Regions of sheet, coil and far field air are all meshed into four-node quadrangular elements. The region of air is meshed into three-node triangular elements. The element types of sheet, coil and air are axisymmetric with plane 13. The element types of far field air is axisymmetric with infin110. As showed in Figure 3, the simulation process can be simply described as follows:

(1) The models of coil 1 and coil 2 are both built-in FEM. Both of the element types for coil 1 and coil 2 are plane 13.

(2) The current density in only loaded into the model of coil 1 to make the tube deform. The material property of air is assigned to the model of coil 2. This means the coil stays in the same position with coil 1 at present. And the model of coil 2 is the air region.
(3) Then, the current density is only loaded into the model of coil 2 to make the tube deform. The material property of air is assigned to the model of coil 1. This means the coil moves from the position of coil 1 to the position of coil 2. And the coil1 is the air region.



(a) Geometric model (b) Finite element model
Figure 3 Electroomagnetic field model

3.2 Material properties

The material used in this experiment is the aluminum alloy 3003 tube with 2.5mm in thickness. The annealing technology is: annealing temperature is 450℃, holding time is 3h. The yield strength of the material is 74Mpa. Properties of materials is measured by tensile tests at room temperature, in which 2.5mm thickness standard specimens were used. The true stress-strain curve of the aluminum alloy 3003 tube under quasi-static condition is shows Eq. (4):

$$s_y = 472(e + 0.0017)^{0.293} \tag{4}$$

Where, σ_y is the quasi-static constitutive behavior of the sheet, e is the plastic strain.

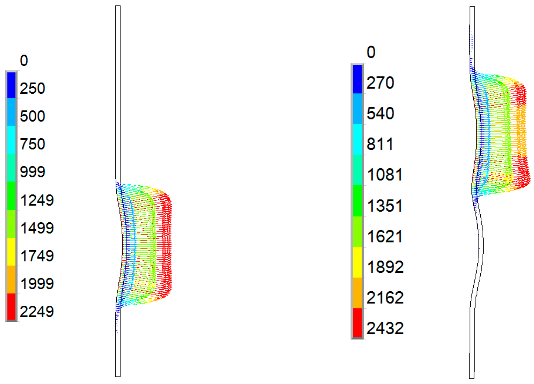
In order to consider the effect of high strain rate on the forming process, some scholars used the viscoplastic material behavior with rate-dependence law (Cowper-Symonds constitutive model) in the ANSYS software to analyze the EMF process. Liu et al. [6] established an experimental scheme according to the conventional stamping of cylindrical parts to analyze the formability of 5052 aluminum alloy sheet. The experimental results show that the EMAS technology can successfully produce an aluminum cup with smaller bottom corner radius than the one by conventional deep drawing process. Moreover, a “multi-step, loose coupling” numerical scheme was proposed to simulate the deformation behaviors of EMAS. The predicted and experimental profiles of cylindrical parts are in good agreement. Yu et al. [4] investigated the tendency of homogeneous radial deformation during electromagnetic compression. It is defined the R is length ratio of the tube to coil. There exists a critical value, 0.93≥R≥0.92, corresponding to the uniform radial deformation. A good agreement between the predicted and the experimental data is obtained. Thus, the Cowper-Symonds constitutive model (Eq.5) is also used to predict high speed forming process in this paper:

$$s = s_y(1 + (\frac{\dot{e}}{P})^m) \quad (5)$$

Where, σ is the dynamic flow stress, σ_y is the quasi-static constitutive behavior of the sheet, $\dot{e}$ is the strain rate. P=6500 s-1 and m=0.25 are the special parameters for aluminum alloy.

3.3 Numerical simulation and experimental results

Figure 4 shows the magnetic force acting on the tube at the different time if there was no overlap region for the coil discharge in different position. The total time for forming process is N×400μs. N stands for the number of discharge regions. The simulation time for the coil discharge in a fixed position is 400μs.



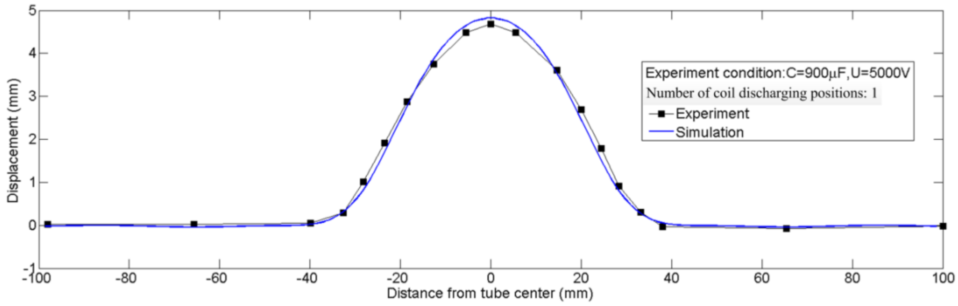
(a) t=200μs (b) t=600μs

Figure 4 Magnetic force on the tube at different time

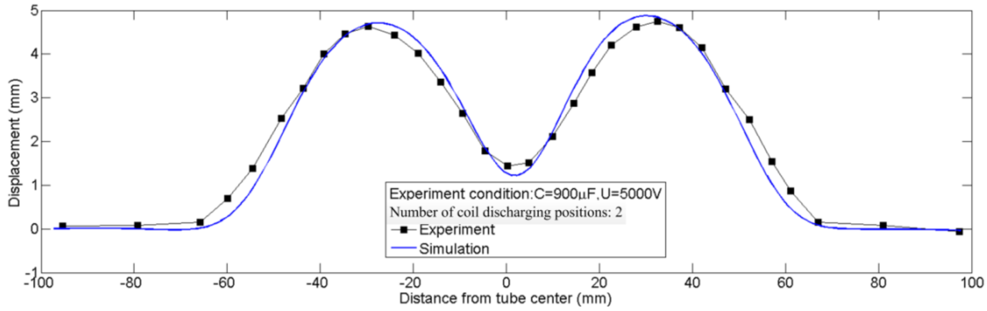
Figure 5 shows the experimental results with different discharge parameters: (1) the coil discharge in one position and the discharge voltage is 5000V; (2) the discharge voltages are 5000V in two positions and there is no overlap region for the two discharge regions; (3) the coil sequential discharge from a tube end to another end. The discharge voltages are 5000V in three positions and the overlap ratio is 50% of the adjacent two discharge regions. Figure 6 shows the comparison between the experimental and simulation results. These show the simulation method has a high accuracy to analyze the electromagnetic incremental tube forming process.

(a) One-step forming (b) two-step forming (δ=0) (c) three-step forming (δ=50%)

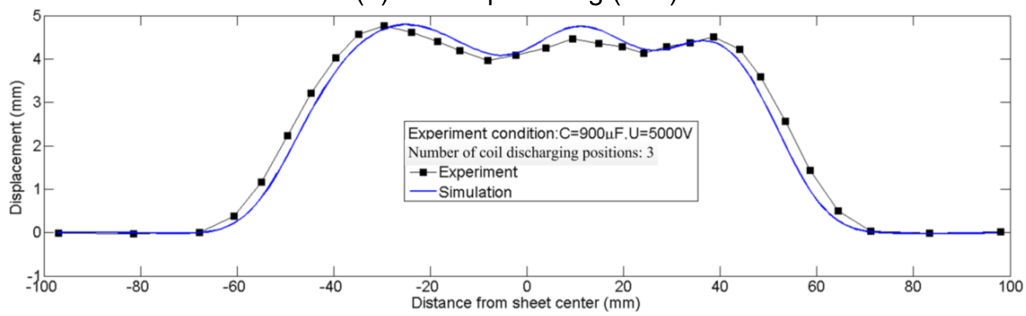
Figure 5 Experimental results



(a) One-step forming



(b) two-step forming (δ=0)



(c) three-step forming (δ=50%)

Figure 6 Experimental and simulation data of electromagnetic incremental tube bulging

4. Effect factors on tube homogeneous deformation

According to the results of the coil discharge in two or three different positions in Figure 6, it shows there exist the peak and valley on the deformed tube. Therefore, the sequency coupling method is used to analyze the effect named overlapping ratio of adjacent two discharge regions, discharge voltage, forming sequence and die structure on tube deformation uniformity.

4.1 Forming sequence and overlapping ratio

Figure 7 shows the effect of overlapping ratio on tube homogeneous deformation if the coil discharging in two different positions with the discharge voltage is 5000V. With the increase of the overlap ratio, the displacement at the position of 28mm away from the tube center slight increase due to the second discharge make the deformed region deform again. Higher of overlap ratio δ, the tube homogeneous deformation η is improved. However, there exists only one peak if the overlap ratio is higher than 70%.

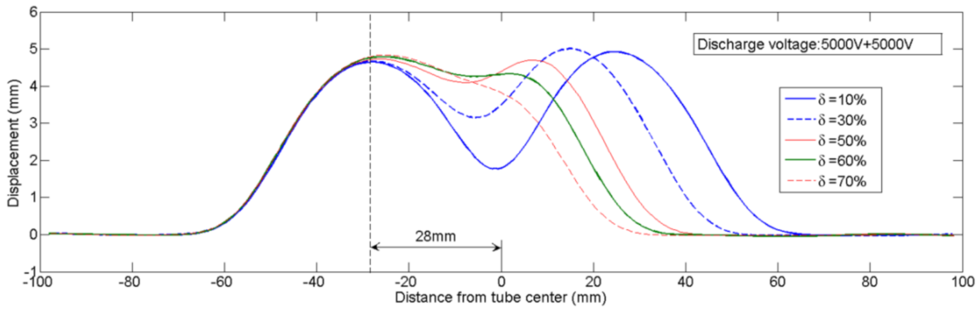
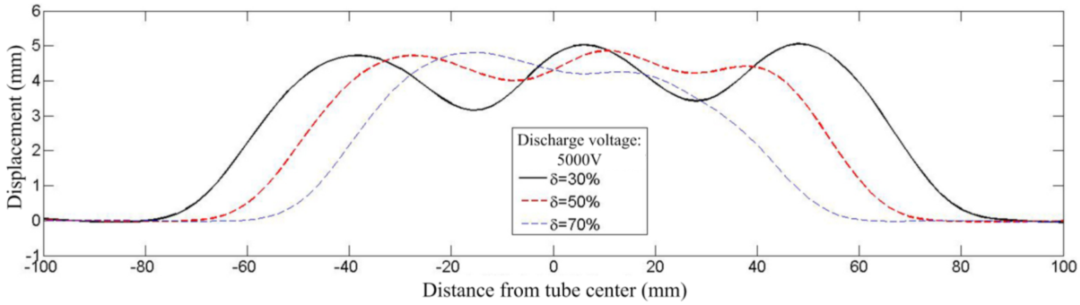
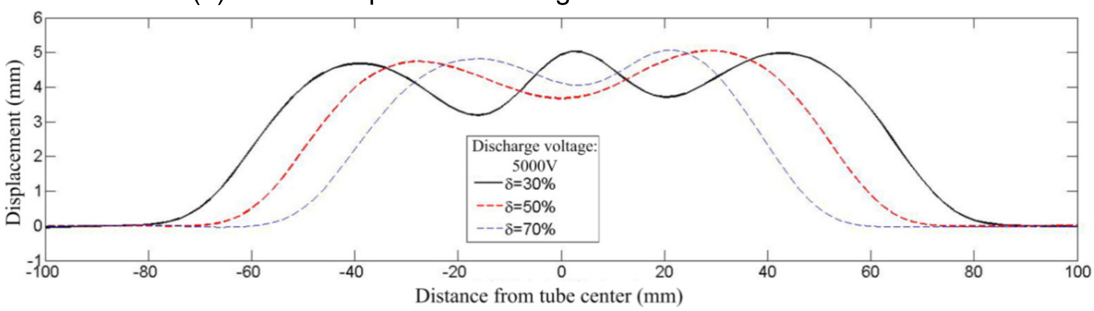


Figure 7 Deformed tube profiles vs δ if the coil discharging in two positions

Figure 8 shows the effect of overlapping ratio and forming process on tube homogeneous deformation if the coil discharging in three different positions with the discharge voltage is 5000V. It can be found there exist obvious peak and valley values on tube no matter what kinds of forming process or overlapping ratio of adjacent two discharge regions, which caused the tube has a low deformation uniformity.



(a) the coil sequential discharge from tube end to another



(b) the tube ends deform firstly and then the tube center deforms

Figure 8 Deformed tube profiles vs δ with different forming process (three-step forming)

4.2 Discharge voltage

As showed in Figure 7, there exist obvious peak and valley values on tube if $\delta \leq 50\%$ and the coil discharge in two different positions. Figure 9 shows the effect of the discharge voltage in the second position on deformed tube profiles. With the discharge voltage increased, the value of the tube deformation uniformity is increased firstly and then decreased. The great value of tube deformation uniformity η=3.3% if the discharge voltages are 5000V and 5125V in two different positions with theδ is equal to 60%.

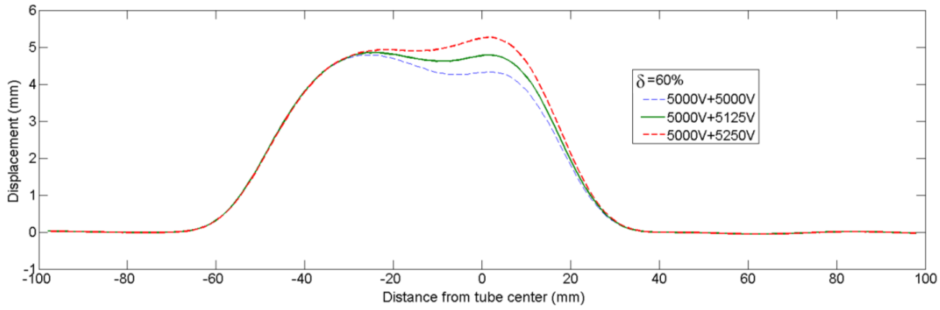


Figure 9 Deformed tube profiles vs discharge voltage (two-step forming)

In Figure 8, the displacement at the tube center is lower than its adjacent regions with δ =50% if the tube ends deform firstly then the tube center deforms. In order to improve the tube deformation uniformity, the higher discharge voltage is needed to increase the displacement at the tube center. As showed in Figure 10, with the discharge voltage increased, the displacement at the tube center is increased, while value of the tube deformation uniformity is increased firstly and then decreased. The value of tube deformation uniformity η=8.7% if the discharge voltages are 5000V, 5000V and 5250V in three different position and δ =50%.

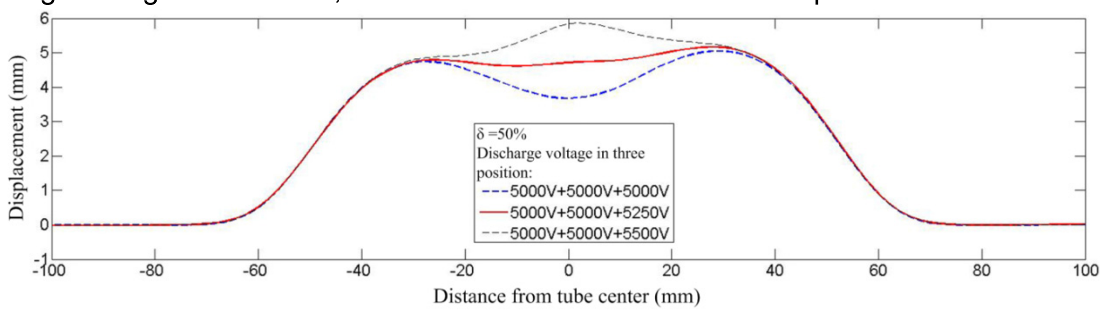
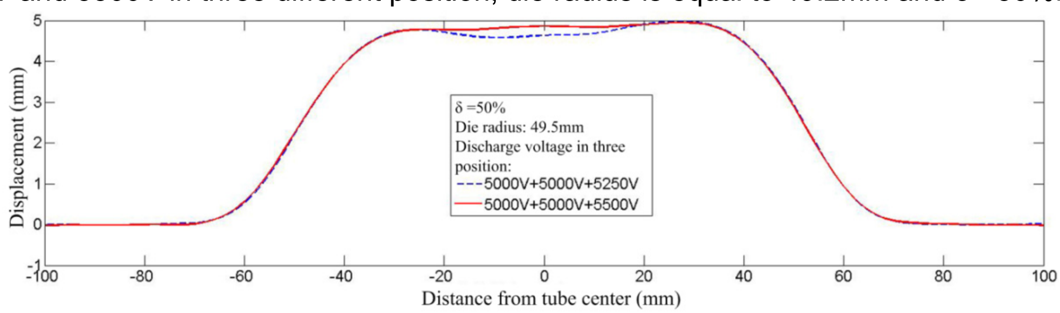


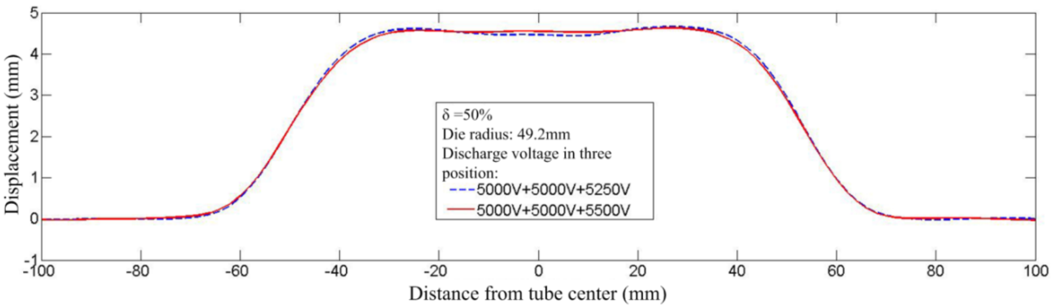
Figure 10 Deformed tube profiles vs discharge voltage (three-step forming)

4.3 Die dimension

In order to control the deformed tube shape, a die structure with reasonable inner radius is needed. Figure 11 shows the effect of die dimensions on deformed tube profiles. Under the condition of same discharge voltage, the value of the tube deformation uniformity under the condition of the die radius is 49.5 is lower than the one if the die radius is 49.2. In addition, the optimum value of the tube deformation uniformity η =1.3%if the discharge voltages are 5000V, 5000V and 5500V in three different position, die radius is equal to 49.2mm and δ =50%.



(a) the distance between the tube and die is 5mm in the initial state



(a) the distance between the tube and die is 4.7mm in the initial state

Figure 11 Effect of die dimension on deformed tube profiles (three-step forming)

5. Conclusion

In this paper, the EMIF method is used in this paper to produce a long tube with a small coil and small discharge energy. A method like "birth-death element" is used in 2D FE model to predict the forming process with a moving coil. In comparison with experimental values, simulation methods can obtain accurate results. Then, it is found that the overlapping ratio of coil discharge positions, discharge voltage, forming sequence and die dimension has great influence on tube deformation uniformity. Finally, the value of the long tube deformation uniformity η is equal to1.3%if the discharge voltages are 5000V, 5000V and 5500V in three different positions, die radius is equal to 49.2mm and δ =50%.

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