Development of Space-Time-Controlled Multi-Stage Pulsed Magnetic Field Forming and Manufacturing Technology at the WHMFC*

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Abstract

In November 2011, the Project of Basic Research of Forming by Space-Time-Controlled Multi-Stage Pulsed Magnetic Field (Stic-Must-PMF) was supported by the National Basic Research Program of China (973 Project, 2011.11-2016.08). It is aimed at achieving breakthroughs in manufacturing technology to solve current problems in forming large-scale and complex sheet and tube parts and components, imposed by the limitations of existing equipment and materials forming properties. The objective of our research group focuses on the design principles and structural layout optimization of Stic-Must-PMF facility. And this paper will report the development of Stic-Must-PMF forming and manufacturing technology at the Wuhan National High Magnetic Field Center (WHMFC) including numerical modeling, experimental setup and experimental studies.

Keywords

Electromagnetic forming, Space-time-controlled, Finite element method

1 Introduction

Electromagnetic forming (EMF) is a high-speed forming technique that reshapes metal workpieces by means of pulsed electromagnetic force. Compared with conventional

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quasistatic forming processes, the EMF technology has been proved that it can efficiently improve the forming limits of metal workpieces and reduce wrinkling and springback [1]. And the technology has been investigated with various numerical and experimental studies for a long time. However, two problems have restricted its extensive applications in forming large-scale and complex sheet: 1) how to generate strong pulsed electromagnetic force (i.e., the design of high-field drive coils; 2) how to generate a space-time-controlled electromagnetic force acting on the workpiece in the EMF process.

To solve the current bottleneck problems of the EMF technology, a Space-Time-Controlled Multi-Stage Pulsed Magnetic Field (Stic-Must-PMF) forming and manufacturing technology has been proposed in our previous work [2]. And in the past two years, our work has focused on the three research aspects for developing the technology: (1) Numerical modeling for the full coupling of EMF process with a large-scale deformation, which can consider the effects of the sheet geometry and velocity on the circuit parameters and the electromagnetic force distribution on the workpiece as well as the effect of sheet-die. This research is a prerequisite for accurately predicting the dynamic behavior of the workpiece under the action of the multi-stage and multi-direction pulsed high magnetic field. (2) Building the key components of an experimental setup for Stic-Must-PMF forming system, including pulsed power supplies, forming magnets and control and measurement system. (3) Carrying out preliminary experiments by the use of the high pulsed magnetic field. And more details of these developments of the technology at the Wuhan National High Magnetic Field Center (WHMFC) will be reported in this paper.

2 Numerical modeling and simulation

To better understand the dynamic deformation behavior of the workpiece for designing the EMF system well, numerous numerical methods have been performed by using developed codes or commercial finite element method (FEM) [3]-[7]. Due to the fact that the numerical simulation based on FEM is much easier to implement, more researchers have used the finite element method to investigate the EMF process, mainly including the loose coupling method and sequential coupling method. Compared with the former, the sequential coupling method is more accurate since it can consider the effect of workpiece deformation on the electromagnetic force distribution. However, the effect of the change in system inductance, caused by the deformation of the workpiece, on the coil current was not considered in the method as well as the effect of the workpiece velocity. To consider the point, an efficient FEM using multi-physics software COMSOL has been developed [8], which can consider the effects of the sheet geometry and velocity on the circuit parameters and the electromagnetic force distribution on the workpiece. Unfortunately, it cannot consider the effect of sheet-die. Meanwhile, remeshing the airgap region situated between the coil and the workpiece in the method to eliminate the distortion introduces additional complication and inconvenience, and its convergence is getting worse as the deformation increases. And these are also the drawback of the sequential coupling method.

To overcome these problems for a fully coupled analysis, a numerical method based on a combination of Matlab and FEM models has been developed by our group, as shown in Figure 1. The mechanical model in the method is an ordinary structures problem involved large deformation, high strain rate and contact, which can be solved using the finite element method. This part is similar with other numerical simulation methods. A distinguishing feature of this method is that the whole electromagnetic part of EMF is regarded as an accurate equivalent circuit network problem. Then only the coils and workpieces are considered in the model without considering the air meshes, and thus there are no convergence problems in the deformation process in our method. In the calculation, the solid conductors of the system are divided into a large number of current filaments, in which uniform distribution of current is assumed. Because the magnetic field generated by these current filaments can be calculated in the 2D model using the semi-analytical or semi-analytical formulas, the problem of electromagnetic force distribution in the workpiece can be effectively solved in Matlab. It should be noted that the displacement and velocity values of the calculation nodes in the deformed workpiece are updated at each simulation step to reflect their effects on the current and the magnetic force distribution in the forming process.

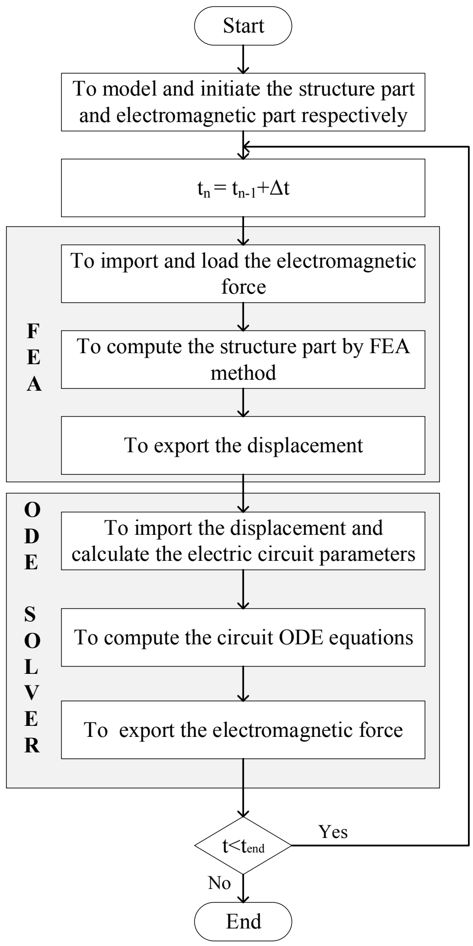

***Figure 1**: Flowchart of the implemented algorithm for the EMF model.*

Figure 2 shows the prediction profiles of the deformed workpiece in an EMF model for the three cases: (a) the workpiece end is assumed to be fixed and it can be calculated by use of ANSYS based on a sequential coupling method; (b) the workpiece end is free and the simulation is based on our numerical method; (c) the workpiece end is free and the simulation is based on a loose coupling method. Contact conditions are considered between the die and the sheet as well as the sheet and holder in the simulations. It can be seen a radial indent will exist when the workpiece end is assumed to be free in the simulation and that should be highly problematic for air meshing and the calculation of electromagnetic field in the sequential coupling method. This problem can be sovled well by our method and the loose coupling method. However, the accuracy of the calculation result is low in the loose coupling method due to the effect of the workpiece deformation on the magnetic analysis is neglected. And it can be seen from Figure 2 that the simulation deformation of the workpiece is much larger than that in the other methods. More detailed results about the axial displacement at the sheet center for the three cases are shown in Figure 3. In summary, our numerical method can avoid the problem of the air mesh processing and study the impact contact behavior between the workpiece and die with considering the effects of the workpiece deformation on the circuit parameters and the electromagnetic force distribution on the workpiece.

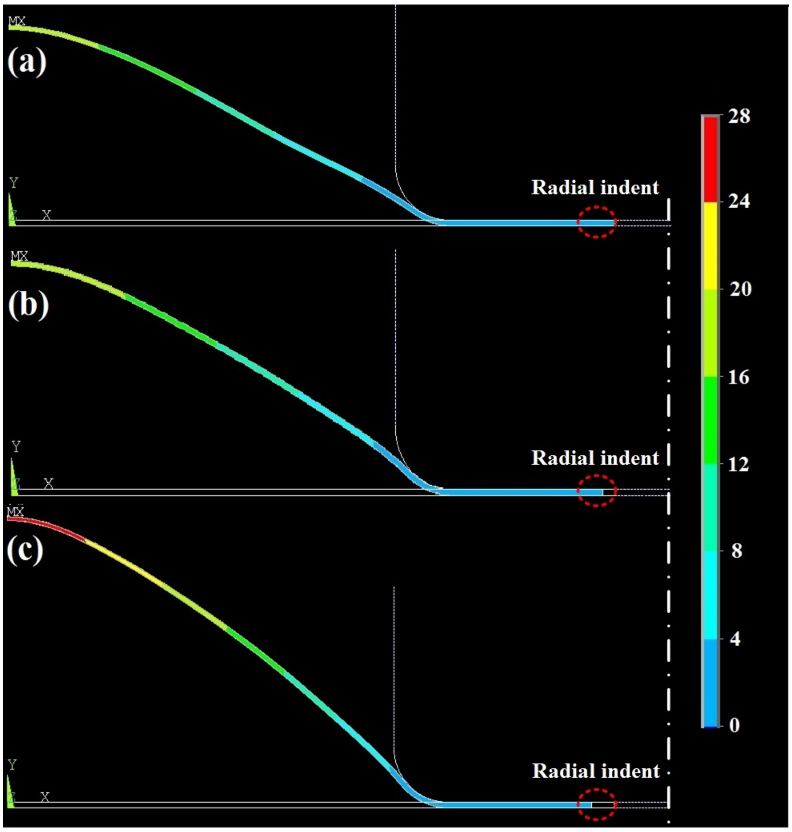

***Figure 2**: Numerical prediction profiles of the deformed workpiece for the three cases: (a) the workpiece end is assumed to be fixed and the simulation is based on a sequential coupling method; (b) the workpiece end is free and the simulation is based on our numerical method; (c) the workpiece end is free and the simulation is based on a loose coupling method.*

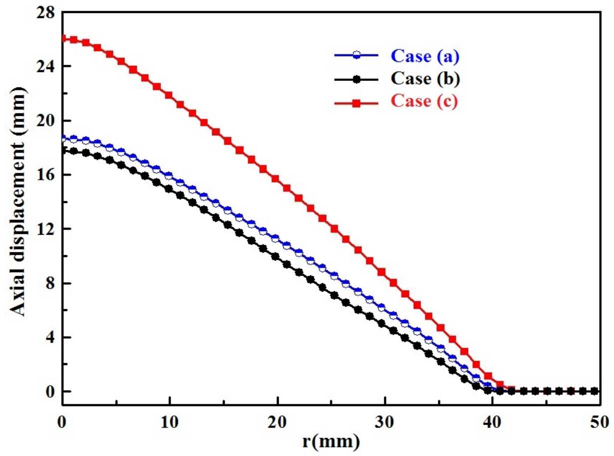

***Figure 3**: Axial displacements of the workpiece at the center for the three cases: (a) the workpiece end is assumed to be fixed and the simulation is based on a sequential coupling method; (b) the workpiece end is free and the simulation is based on our numerical method; (c) the workpiece end is free and the simulation is based on a loose coupling method.*

3 Experimental setup and studies

3.1 Pulsed Power Supply

Three types of pulsed power supply, capacitor banks of 1 MJ/25 kV/3.2 mF, 200 kJ/25 kV/640 μF and 14.4 kJ/30 kV/32 μF, have been developed and built for the Stic-Must-PMF forming system at the WHMFC in China, as shown in Figure 4. These three types of pulsed power supplies can be used singly or in combination to generate short and long pulsed magnetic fields with different tool coils.

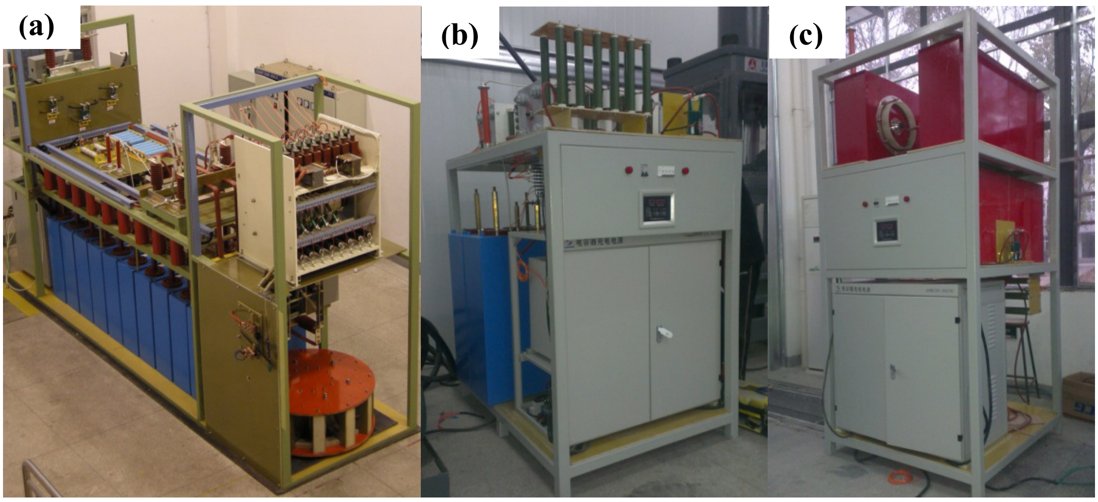

***Figure 4**: Three types of capacitor bank power supply system: (a) 1 MJ/25 kV/3.2 mF, (b) 200 kJ/25 kV/640 μF, (c) 14.4 kJ/30 kV/32 μF.*

3.2 Tool Coil

Several tool coils have been designed and fabricated by introducing the nondestructive pulsed high field magnet technology to suit the requirements of high strength and long life performances, as shown in Figure 5. These coils have been used for different experimental studies of EMF system, such as electromagnetic ring expansion, electromagnetic flanging, electromagnetic sheet bulging and electromagnetic hardening.

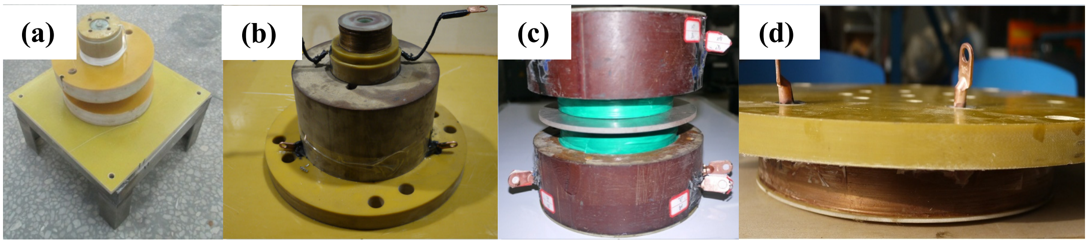

***Figure 5**: Tool coils for different electromagnetic applications: (a)* ring expansion, *(b) two-stage sheet bulging, (c) hardening, (d) flanging.*

3.3 Multi-stage Timing Control System

A three-stage timing control system has been designed and implemented in Figure 6 for controlling the on-and-off of the tool coils to adjust the magnetic field distribution, which is an important part of the Stic-Must-PMF forming technology. The system has following properties: (i) it can be controlled independently or in combination; (ii) it has a high stability due to electrical-optical isolation between the control room and the local control units. (iii) it can provide a triggering time at microsecond level and multi-channel high-speed data acquisition (sample rate > 1 MS/s) for the requirements of high precision control.

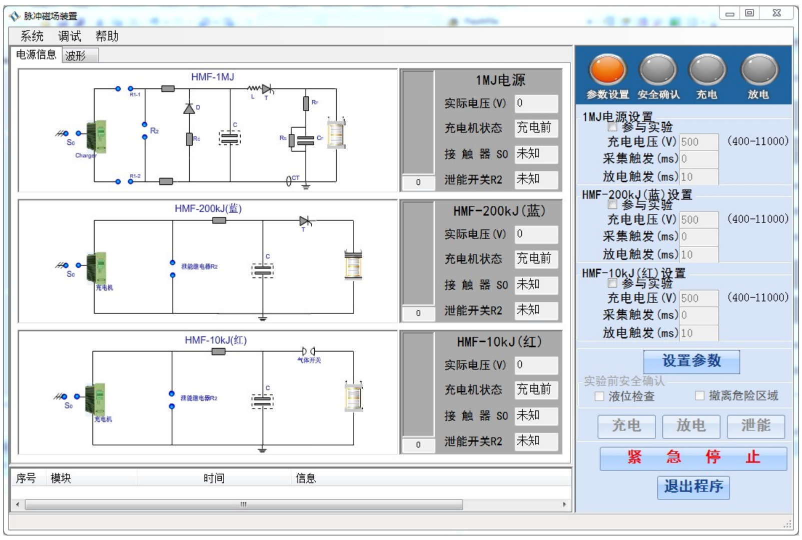

***Figure 6**: Interface of the three-stage timing control system.*

3.4 Experimental Study of a Large-Scale Sheet Forming

The experimental studies mainly focused on the tube EMF system, few of which touch upon the application of metal sheet [1], especially for the large-scale sheet workpiece. An important reason resulting in such phenomena is a strong pulsed electromagnetic force cannot be arbitrarily enlarged to form large parts due to the limitation of the strength of the coil [2]. Recently, the electromagnetic flanging of a large-scale aluminum alloy sheet (AA5083-O), whose outer diameter, bore diameter, sheet thickness are 640 mm, 180 mm and 5 mm, respectively, was investigated at the WHMFC. The quasi-static stress-strain curve of the material is shown in Figure 7. The Hollomon's hardening equation $\sigma = K\varepsilon^n$ (K and the n are 0.5352 GPa and 0.27316, respectively) was adopted to fit the stress-strain relationship of AA5083-O and used to calculate the deformation behavior of the sheet, which didn't consider the high strain-rate effect on the mechanical properties of the workpiece.

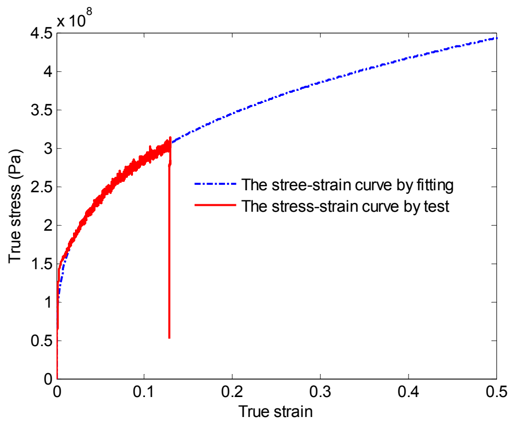

Figure 7: *The quasi-static stress-strain curve of AA5083-O.*

To generate enough electromagnetic force, the discharging energy should be large enough. Thus a bank of capacitor with the maximum energy of 200 kJ was equipped. To make sure the coil's lifetime, the non-destructive pulsed high field magnet technology, where internal reinforcement is inserted between the conductor layers, was used to fabricate the coil. The structural strength of the coil was assessed by numerical calculation of the stress distribution of the coil by FEA. To assess the forming capacity of the EMF system, both the simulation and experimental study of the electromagnetic flange of a large-scale aluminium alloy sheet in the case of 155 kJ have been done.

3.4.1 Coil Design

The design of the coil firstly is the electromagnetic design and secondly is the structural strength design. According to the electromagnetic design, the inner diameter (100 mm), the outer diameter (132 mm), the height (25 mm) and the turns (10 layers in radial direction, each layer has 5 turns in axial direction) of the coil were determined. And for the structural strength design, the reinforcement mode was determined: the conductor was copper wire (4 mm X 2 mm) and each layer was reinforced by Zylon fiber. To assess the structural strength, the stress distribution in the mid-plane of the coil at the coil current's peak value time was calculated by FEM. As shown in Figure 8, the maximum von Mises stress is about 0.8 GPa in the Zylon, which is only one fifth of the ultimate tensile strength of Zylon and confirms that the coil is able to bear the huge Lorentz force.

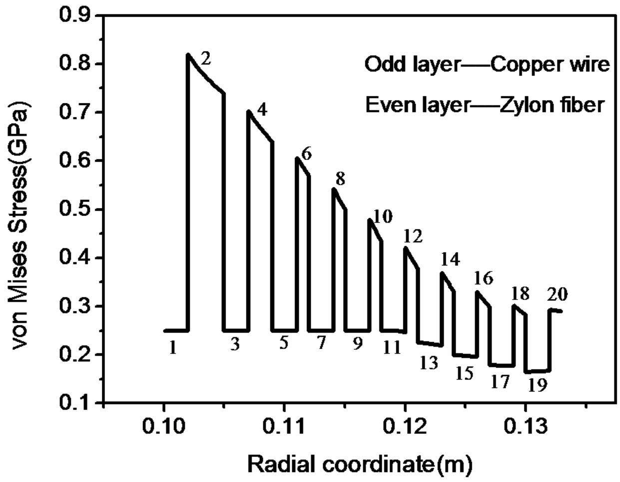

Figure 8: *The von Mises stress of the mid-plane of the coil [8].*

3.4.2 Simulation and Experimental Results

Both the simulation and experimental study of the electromagnetic flange of a large-scale aluminium alloy sheet in the case of 155 kJ were done. Figure 9 shows the main dimensions of the experimental equipment. And Figure 10 shows the setup of the experiment. Figure 11 shows the displacements of the inner bore. The maximum axial and radial displacements are 87 mm and 27 mm, respectively, while the axial displacement by experiment was 90 mm, the relative error was 3%. It can be seen that the agreement between the simulation and experiment results is satisfactory and the EMF system has the capacity to form the large-scale workpiece.

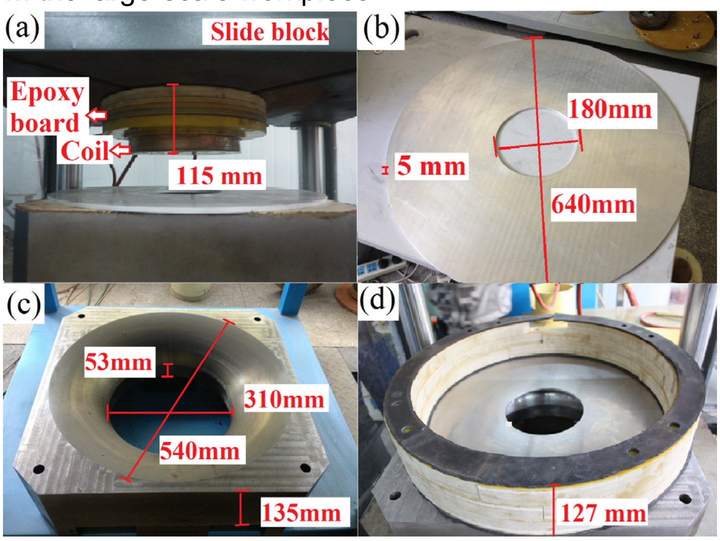

Figure 9: *(a) The coil and several epoxy boards were fixed on the slide block; (b) the workpiece; (c) the die; (d) the blank holder [8].*

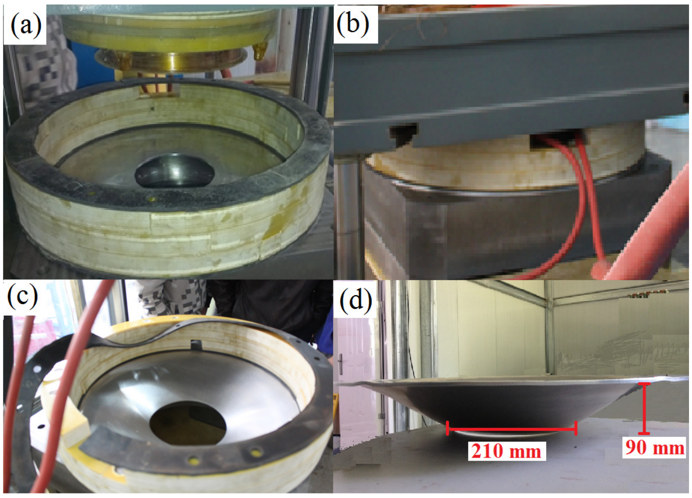

***Figure 10**: The experiment setup: (a) before the slide block was moved down; (b) the slide block was moved down; (c) after the discharge; (d) the formed workpiece [8].*

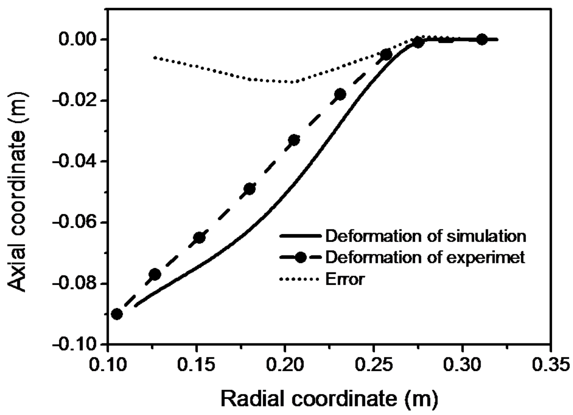

***Figure 11:** The comparison of the simulation and the experiment deformation profiles [8].*

4 Conclusion

A strong and well-designed space-time distribution of electromagnetic force could lead to the forming and manufacturing of sheet and tube parts and components with controlled materials properties. However, there are great challenges in developing such new forming and manufacturing technology. In the project, we need to solve a key scientific problem: the rules of space-time distribution of the strong space-time-controlled multi-stage pulsed magnetic field and control of the force field in forming. For this, an effective numerical simulation method has been developed, which can be used to predict the dynamic behavior of the workpiece in a single coil system or multi-stage coil system (although the numerical studies presented in the paper is just for a single coil system). Meanwhile, three types of pulsed power supply, tool coils and three-stage timing control system have been designed and implemented for the future researches of the Stic-Must-PMF forming system.

In particular, a two-stage forming coil system has been developed for axisymmetric deep drawing in our lab recently. More numerical and experimental results are still on going and will be reported later.

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