Ball Pad Mold Electromagnetic Forming Process for Aluminium Alloy Sheet*

Wen-Ping Wang[1], Xiang-Dong Wu[1], Min Wan[1], Xiao-Wei Chen[1], Wei-Ren Xiong[1]

[1] School of Mechanical Engineering and Automation, BeiHang University, 37 xueyuan road, Beijing, 100191, China

ABSTRACT

In order to meet requirements of lightweight technology in the field of aerospace, the new forming technology for aluminium alloy skin parts and integral panel are brought to more attention. Based on the principle of electromagnetic forming (EMF) and energy distribution, a new electromagnetic forming process using ball as pad mold for aluminium alloy sheet forming was suggested and test apparatus was designed. The new method was verified by the finite element simulation and experimental technology, and all studies were carried out on 2024-T3 aluminium alloy sheet. The results show that the new process of ball pad mold electromagnetic forming is feasible to aluminium alloy sheet parts forming. Rubber cushion thickness and electromagnetic pulse voltage are significant contributors to the curvature radius of the test sample. Based on these observations, application advantages and prospects of this new process were pointed out, and the subsequent research was put forward.

Key words:

Aluminium alloy, Sheet metal, Electromagnetic forming, Ball pad mold

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Corresponding author: Xiang-Dong Wu; xdwu@buaa.edu.cn; Tel.:+86 010-82338613

1 Introduction

In order to meet requirements of lightweight technology in the field of aerospace, large-scale aluminium alloy skin panel is used to lightweight structure parts [1]. The strength, the stealth effect, and other performances of large-scale aluminium alloy skin panel are better than that of the mosaic structure with small skin panels. But forming large-scale skin panel is limited by the size and capacity of manufacturing machine. In the field of aerospace manufacturing, there is perennial interest in seeking adaptive methods for forming large aluminium alloy skin panels.

Electromagnetic forming (EMF) is an impulse or high energy rate forming technology, which uses high-voltage pulse current through an electromagnetic coil or actuator to generate a strong transient magnetic field that induces eddy currents in the nearby conductive workpiece. These eddy currents in turn produce an associated secondary magnetic field around workpiece. This causes the coil and workpiece to repel each other by the electromagnetic force (Lorentz effect) and this force accelerates the workpiece away from the coil. In an EMF process, the material can achieve velocities in the order of 100m/s in less than 0.1 ms [2]. Meanwhile, single side tooling or no tooling can be used because of non-contact loading. In comparison to conventional quasi-static forming processes, the electromagnetic forming process has prominent advantages such as significantly improved formability, slight springback and reduction in residual stresses [3-6]. In addition, the electromagnetic force can be adjusted steplessly according to the technical requirements, that to satisfy the flow characteristics of metal parts. At present, the EMF technology is mainly used in aviation, aerospace, weapon and automobile manufacturing. The researches and applications focus on lightweight structure sheet and tube forming, difficult machining parts forming and hybrid forming [2-9].

However, it has rarely reported about the electromagnetic forming of aircraft skin panel. Only in 1999, Newman et al [10] did some researches about electromagnetic forming of aircraft skin panel, which was supported by Navy SBIR Program IAP Research. They presented a new process named MagneStretch process, in which the EMF process was introduced into stretch forming. The formability trials were performed directly on 7075 aluminum alloy sheet from T6 heat treatment condition. The results show that the MagneStretch process can (1) allow stretch forming of 7075 from T6 condition with little or no springback, (2) eliminate costly pre and post forming heat treating steps in conventional stretch forming process, (3) not alter the microstructure. Compared with the traditional process, the new process method is flexible, short production cycle and greatly reduce costs.

In this paper a new electromagnetic forming process with ball pad mold for aluminum alloy sheet forming is suggested that bases on the principle of electromagnetic forming and energy distribution. In order to determine the feasibility of this ball pad mold electromagnetic forming process, forming process is analyzed firstly by the finite element method, and then experiment apparatus is designed and aluminium sheet forming tests is carried out.

2 The principle of ball pad mold EMF

In the process of electromagnetic forming, the plastic indentation can be produced on the surface of workpiece as shot peening if the electromagnetic pressure is great enough. In the literatures [11,12], James S. Shaw and James. R. Dydo et al applied for two patents about Balanced Electromagnetic Peening and Electromagnetic Pulse Surface Treatment base on the characteristic of electromagnetic. However, it is difficult to treat the workpiece surface only by the electromagnetic pulse force. EMF is a kind of high speed and high strain rate forming process. According to impact dynamics, the certain plastic indentation and compressive residual stress layer with certain thickness can be produced on the workpiece surface, only when the impulse pressure acts on the workpiece surface achieve and exceed the dynamic yield strength of the material. Because the dynamic yield strength is greater than the static yield strength, Electromagnetic Peening or electromagnetic Pulse Surface Treatment requirement for EMF equipment is extremely high and it is difficult for present equipment to meet it, the energy efficiency is only 10-20 percent, the highest energy efficiency is not over 40 percent [3,13]. Therefore, in order to implement the effect as above patents show, the electromagnetic pulse force per unit area need to be increased. There are two approaches to achieve this goal: firstly, the energy and energy efficiency of electromagnetic forming equipment should be improved, at the same time, the contact area between coil and workpiece also should be reduced; secondly, according to the principle of energy distribution, force area on the sheet metal should be decreased by altering the tooling structure.

Based on the existing 20kJ electromagnetic forming equipment, considering tooling structure, a new method of ball pad mold electromagnetic forming process is put forward. The basic idea is described as follows: First, a certain amount of balls are mounted and arranged as a die cushion, so a series of micro mold cavity can be formed in the gap of adjacent spheres. Then a sheet metal specimen is placed on the ball pad mold. When the transient pulse magnetic force applies the specimen, the force per unit area of the specimen is greatly increased because of application of ball pad mold. So, both upper and lower sheet surface will produce plastic deformation indentations in the interaction of the magnetic pressure and the ball support force, and hardening and forming of the specimen will be realized

On the basis of the above proposed idea, the forming experimental system was set up. Fig.1 shows a schematic diagram of test apparatus for aluminium sheet specimen. The apparatus is composed of four parts that includes a control system, an electromagnetic pulse power source, a ball pad mold and a working coil. During the experiment, the specimen is fixed on the ball pad mold. The discharge voltage of capacitor bank is adjusted through the control system of electromagnetic pulse power. The high-speed switch is triggered to deliver a high-frequency current pulse to the working coil. The conductive sheet metal is exposed to an intense transient magnetic field. The resulting Lorentz force pushes the sheet metal away from the coil. At the same time, the sheet metal withstands the supporting force of the ball pad mold. Different degree of surface plastic indentation occurs under the two force fields in the top and bottom sheet. After unloading , specimen will show certain plastic deformation.

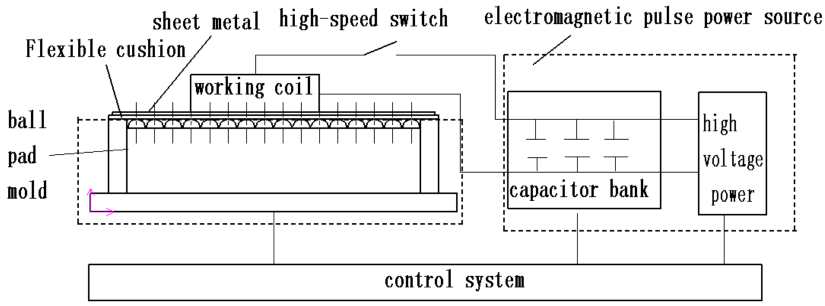


Figure 1 *schematic diagram of test apparatus*

3 Finite element analysis

Numerical modeling of the ball pad mold electromagnetic forming process requires the analysis of the discharge circuit, electromagnetic field and structural field (mechanical problem). The laws of current density distribution of the working coil can be got in the discharge current analysis. In the process of electromagnetic field analysis, the current density is loaded as the magnetic field excitation conditions that can be obtained by the above analysis, then the laws of induced eddy currents and magnetic pulse force distribution of the specimen can be obtained. Finally, the specimen deformation behavior can be gained in the structural field analysis. In the whole process of numerical analysis, the analysis of discharge circuit and electromagnetic field are carried out by finite element software ANSYS/EMAG. The mechanical problem is developed with the commercial finite element code ABAQUS/Explicit.

According to reference [14], the discharge loop and electromagnetic field of the ball pad mold electromagnetic forming was analyzed. Based on above analysis results, the finite element model of the structural field were established by ABAQUS/Explicit code as Fig.2 shows. In the model, the aluminium sheet and rubber pad are modeled as deformable parts, while the ball pad die and coil clamp are considered to be planar rigid. The ball diameter is 30 mm. The material tested is 2024-T3 aluminium alloy sheet. The sheet size is 480 × 120 × 1.8 mm. Ball pad mold and coil clamp are fixed during the forming process. Electromagnetic pulse force area under the coil clamp is 225 × 120 mm^2. Fig. 3 shows electromagnetic pulse amplitude curve, the peak pressure is 50MPa.

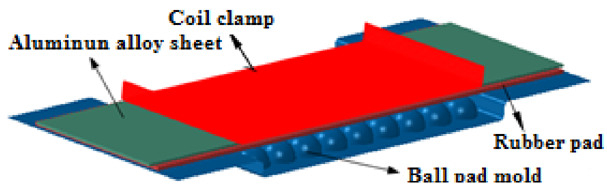


Figure 2 *Finite element model of structural analysis of ball pad mold EMF*

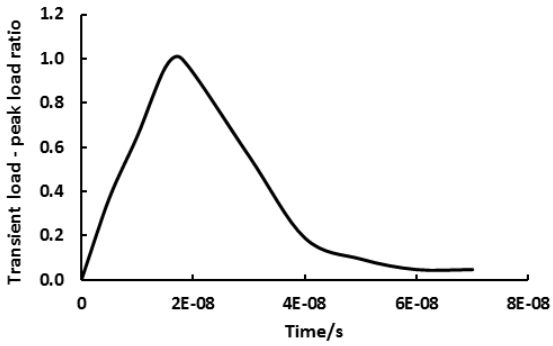


Figure 3 *Electromagnetic pulse force amplitude curve*

When the rubber cushion is not used between sheet metal and ball pad mold in the process of electromagnetic forming, the simulation results of sheet deformation is shown in Fig. 4. This is because the sheet metal comes into contact with the ball pad mold directly and the diameter of the ball is large, then the sheet pressed into the gap of the adjacent balls under the action of electromagnetic pulse force, finally the wave-shaped specimen is easily observed from the graph.

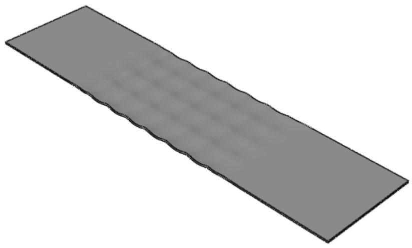


Figure 4 *the morphology without rubber cushion*

In order to improve the surface condition of the forming specimen, a rubber cushion is placed between the sheet metal and ball pad mold. When the strong transient electromagnetic pulse force acts on the blank, the indentations and wave-shape will be avoided due to the rubber cushion buffer action. Fig. 5 shows the finite element analysis result of sheet deformation. It is seen that the sheet has been formed to a certain curvature part, and there are no obvious indentations on the sheet surface.

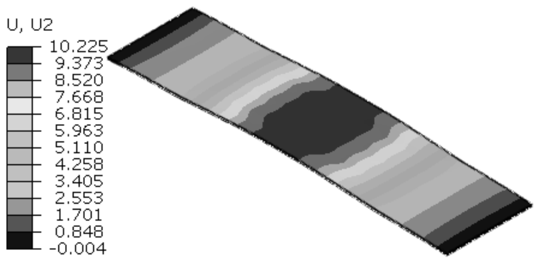


Figure 5 *the morphology with rubber cushion*

4 Ball pad mold EMF experiment

From the above finite element analysis, it can be seen that the new process of the ball pad mold EMF is feasible for forming a certain curvature part of the 2024-T3 aluminum alloy sheet. Consequently, test fixture of the ball pad mold EMF is designed and manufactured. The structure of the ball pad mold is depicted as Fig. 6(a). The cross-section area of a ball is 30 × 30 mm^2, and the balls array is 6 × 8 mm. A flat circular spiral coil (Fig. 6(b)) is adopted as electromagnetic coil. The specification for the coil is presented in Table 1. The maximum energy storage of the EMF equipment in the experiment is 20kJ. The specimens are the 2024-T3 aluminium alloy with the thickness of 1.8 mm and the plane size of 482 × 120 mm. The discharge voltage levels used range from 1800 V to 2800 V. The capacitance is set to 2400 μF.

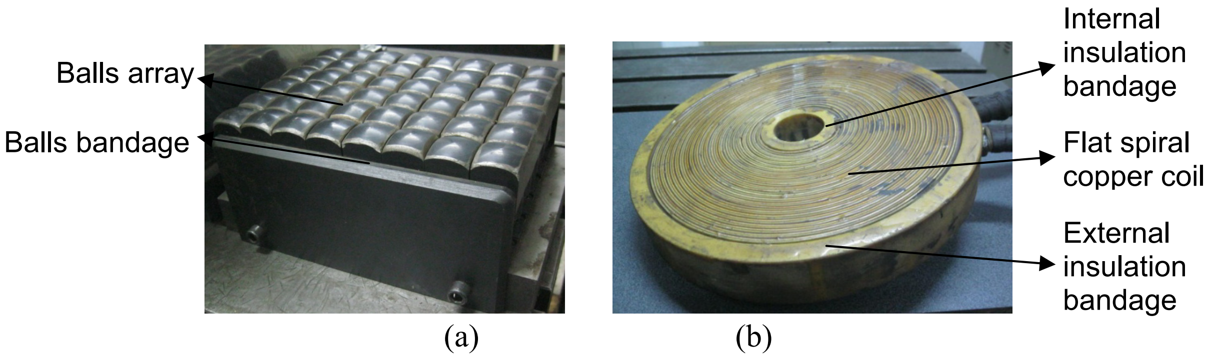


Figure 6 *Ball pad mold (a) and Electromagnetic coil (b)*

Table.1 Electromagnetic coil specifications(*mm*)

Number of windings	Internal radius	External radius	Thickness	The effective internal radius	The effective external radius	Copper wire section
23	20	140	40	30	125	1.7×6.3

5 Results and Analysis

Firstly, the discharge voltage is set to 1800 V and 2000 V, and a sample is placed on the ball pad mold directly in the EMF test. The results show that there are obvious dents in the sample and a significant wave-shaped morphology specimen without certain curvature shape is obtained as shown in Fig. 7, which is agree with the result of the finite element analysis in Fig. 4.

Secondly, the thickness of 1.5 mm or 3 mm flexible rubble cushion is placed between the specimen and ball pan mold. Considering the existing electromagnetic forming equipment capacity, ensure adequate electromagnetic pulse force to act on the whole blank, the specimen is struck sequentially 8 times at the same discharge voltage. Each action position is transformed by adjusting relative positions between the electromagnetic coil and the sample. Fig. 8 shows the relative positions between the edge of electromagnetic coil and the sheet. An interval of 25 mm is allowed between the adjacent position. The effect of deformed samples is shown in Fig. 9.

Figure 7 *Specimen after forming*

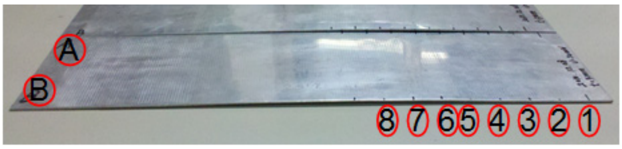
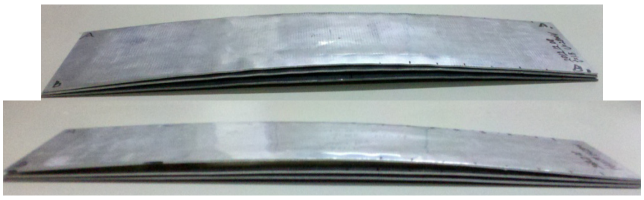


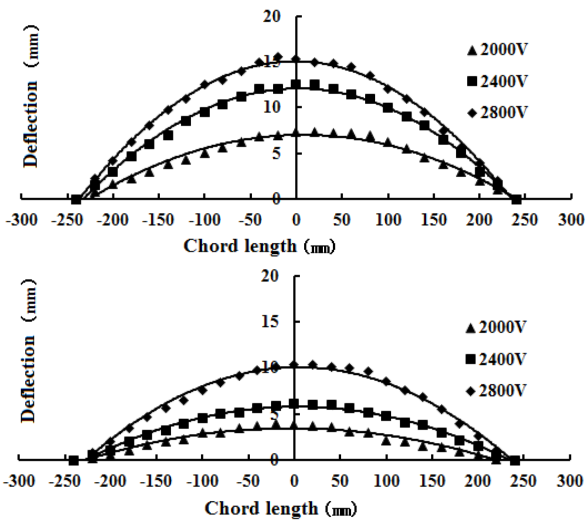
Figure 8 *Relative positions in order*



(a) 1.5 mm thickness of the rubber pad (b) 3 mm thickness of the rubber pad

Figure 9 *Specimens after the ball pad mold EMF*

The specimen deformation deflection of A and B sides (Fig. 8) is measured, and both sides of deflection is almost the same, the maximum difference is no more than 0.5 mm. The result shows that the sample has good deformation uniformity in the ball pad mold electromagnetic pulse forming process. The measured deflection curve is presented for 1.5 mm and 3 mm thickness of the rubber pad in Fig. 10. It can be seen from the chart that forming deflection increased with the discharge voltage increasing, whereas reduced with the thickness of rubber pad increasing.



(a) 1.5 mm thickness of the rubber pad (b) 3.0 mm thickness of the rubber pad

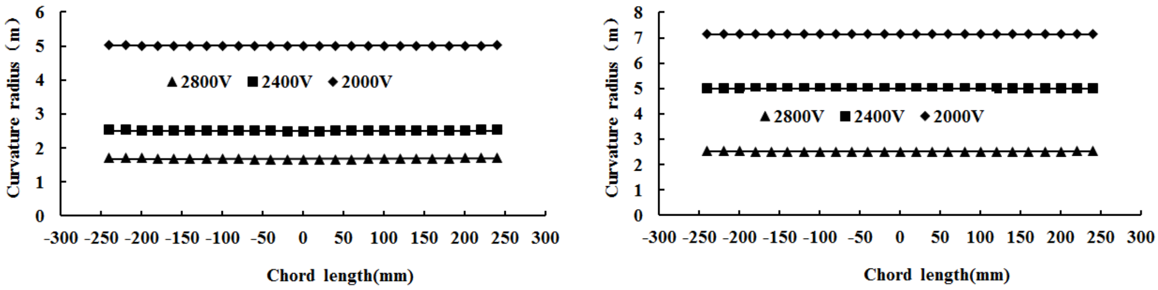
Figure 10 *Deflection curve under the different thickness of rubber pad*

Curvature is the ratio of the change in the angle of a tangent that moves over a given arc to the length of the arc. While radius of the curvature is the absolute value of the reciprocal of the curvature of a curve at a given point and it can be used to describe the bending degree somewhere in the curve. The formula of the radius of the curvature is

$$\rho = \frac{\sqrt{(1+y'^2)^3}}{y''} \tag{1}$$

In the formula, y' is the first order derivative of *x* of the curve on *y*, y'' is the second order derivative of *x* on *y*. In this paper, *y* is the specimen bending deflection and *x* is the specimen chord length.

The functional relation between the specimen deflection (*y*) and the specimen chord length (*x*) is created by curve fitting. Then the radius of specimen curvature is calculated by the above formula. The radius versus chord length is depicted in Fig. 11.



(a) 1.5 mm thickness of the rubber pad (b) 3.0 mm thickness of the rubber pad

Figure 11 *Curvature radius under the different thickness of rubber pad*

As we can see from the Fig. 11, the radius of curvature of the specimen surface is relatively uniform. Also, the relation curve between the curvature radius and the discharge voltage is obtained by averaging the radius of curvature at each point under different discharge voltages as Fig.12 shows. Obviously, radius curvature decreases with the increase of discharge voltage and increases with the increase of the rubber pad thickness. The rubber cushion thickness and discharge voltage are both important factors that influence the curvature radius of specimen. Meanwhile, the curvature is small in the range of 10^{-3} mm^{-1} to 10^{-4} mm^{-1}. So, the ball pad mold EMF process has potential to form the large integral aluminium alloy skin panels with small curvature and large length-to-width ratio.

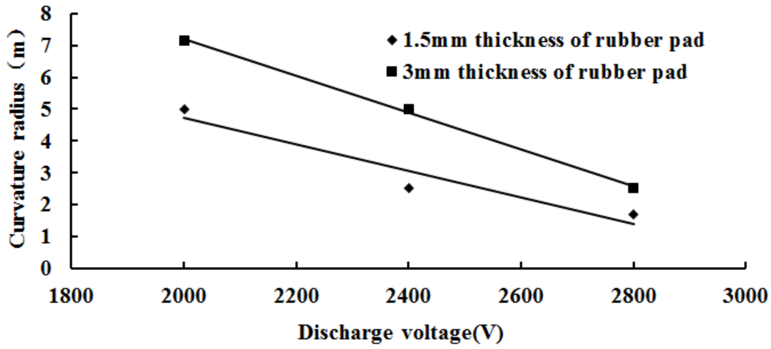


Figure 12 *Relationship between curvature radius and discharge voltage*

It can be observed from the experiment deformation results that the specimen deformation is maximum at the 2800 V discharge voltage, and the maximum thickness variation is only 0.004 mm for 1.5 mm rubber cushion and 0.002 mm for 3mm rubber cushion separately. Hence, the thickness variation of the specimen is negligible when a certain curvature sheet metal was formed using the ball pad mold EMF.

In follow-up studies, the forming mechanism of the ball pad mold EMF will be deeply analyzed. The sheet metal dynamic deformation behavior and inertial stress variation rules under the action of strong transient electromagnetic force will be revealed by the comprehensive application of plastic dynamics, electromagnetics theory, experiments and multi-physics coupling finite element analysis. Multi-step forming path of the single curvature and complicated curvature integral skin panels will be designed by optimization method and will be carried out by the ball pad mold EMF experiments. These researches will lay a solid foundation for the future application of the ball pad mold EMF process in the integral aluminum skin panels forming.

6 Conclusions

The method of the ball pad mold EMF process is presented. For certain diameter balls, the rubber cushion thickness and discharge voltage are the important factors that influence the workpiece curvature.

Because large repulsive electromagnetic forces can accelerate the workpiece to high velocities and make the workpiece have high inertia forces, the new ball pad mold EMF process allows forming directly from the T condition aluminium alloy eliminating the need of conventional process for the pre and post heat treating steps .

Because of using the simple structure, strong versatility ball pad mold device, ball pad mold EMF process requires smaller energy EMF equipment than the general EMF process. Therefore, ball pad mold EMF process can reduce costs, save energy, as well as improve the life of electromagnetic coil.

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