Application of Electromagnetic Forming as a Light-Weight Manufacturing Method for Large-Scale Sheet Metal Parts

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Abstract

Electromagnetic forming (EMF), due to its advantages of light-equipment, single-side die, improved formability, reduced wrinkling, lower spring-back, and so on, is high potential for shaping large sheet metal parts in aviation and aerospace industries, which are generally relative expensive and difficult to be formed with conventional process. By exploiting the potential benefits of EMF, the required forming cost can be reduced, and the forming quality can be improved. Until now, however, the EMF of large sheet metal is still under-developed, which is highly attributed to the limited forming capability of the present equipment and the lack of a systematic design methodology for the process.

In recently, we developed an EMF process that capable of shaping large sheet metal parts with light-weight equipment, and has successfully applied this process for manufacturing ellipsoid shaped aluminium alloy parts with 1378 mm diameter. To realize the light-weight of the proposed process, two newly–developed devices are highlighted. In this paper, the forming performance of the process are experimentally evaluated for AA5083 and AA2219 sheet workpieces, in terms of die fittability, thickness distribution, and radial material flow distribution. Furthermore, the comparisons of the proposed process with several other related forming processes are conducted to identify the advantages of the proposed process.

Keywords

Metal forming, Electromagnetic forming, Large-scale sheet metal part

1 Introduction

Electromagnetic forming (EMF) is a high velocity forming process that shapes metal workpiece with high pulsed Lorentz force. As suggested by lots of publications (Daehn, 2006; Psyk et al., 2011), compared with conventional quasi-static forming process, this process possesses the advantages of light equipment, single-side die, improved formability, reduced wrinkling, lower spring-back, and so on, making it highly promising for shaping large sheet metal parts in aviation and aerospace industries, which are generally relative expensive and difficult to be formed with conventional quasi-static process. By exploiting its advantages, the forming cost can be reduced, while the forming quality can be improved.

Until now, however, the applications of EMF on large sheet metal forming is still under-developed. According to the literatures (Lai et al., 2014a; Cui et al., 2016), the length-scales of two relative large electromagnetically formed sheet metal parts are limited to 640 mm and 780 mm, respectively. The major EMF processes are focused on delivering plastic deformation for a local workpiece area. One application of this EM-based local deformation process is combined with quasi-static process, and used for providing a local sharp feature on a pre-formed workpiece (J., 1998; Golovashchenko et al., 2011; Imbert and Worswick, 2011; Liu et al., 2011), eliminating spring-back (Iriondo et al., 2006; Iriondo et al., 2011), or altering plastic strain distribution in the conventional stamping (Vohnout et al., 2004; Shang and Daehn, 2011). Another application is working alone and in an incremental mode, in which a series of discharge sequences are consecutively conducted to shape a relative large metal area (Cui et al., 2014; Long et al., 2017). While applying EMF as a local deformation process can effectively utilize some advantages of EMF under a relative low requirement on the equipment, the proposal of EMF as a global deformation process is another important and promising method for broadening the application of EMF.

The technical obstacles that limit the application of EMF as a global deformation process for large sheet metal parts may be divided into two categories. The first one is the limitation on the forming capability of the present equipment, including the short lifetime of the forming coil and the relative low stored energy of the capacitor bank. The second one is the complexity of the highly dynamic and multi-physics nature of EMF, making it difficult to obtain a comprehensive methodology on controlling the high velocity plastic deformation behaviour, thus the final deformation results.

In recently, we developed a new EMF process that can shape large sheet metal parts with light-weight equipment, and has validated its feasibility on manufacturing ellipsoid-shaped AA5083 part with 1378 mm diameter (Lai et al., 2017a). In this paper, the forming performance of the process are further evaluated on AA5083 and AA2219, in terms of die fittability, thickness distribution, and radial displacement distribution. Furthermore, the comparisons of the proposed process with other related processes are also performed to identify the advantage of the proposed process.

2 Experimental setup

2.1 Process principle

Fig. 1 shows the schematic diagram of the proposed process. The advantage of this process is that it can shape large workpiece with a light-weight facility. Herein, the forming equipment for shaping Ø1378 mm workpieces is only with a length-scale about 1840 mm.

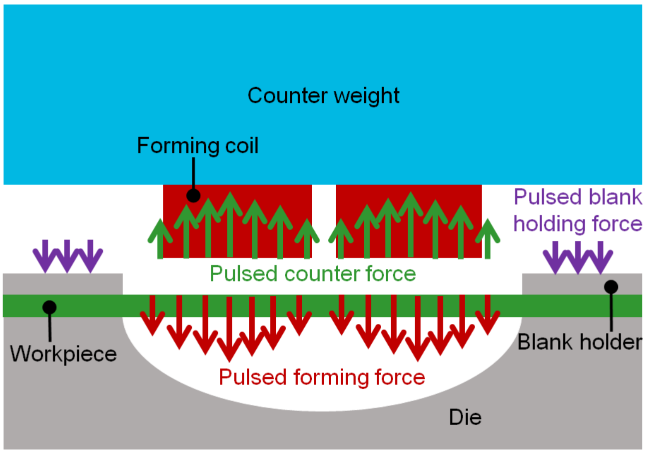

Figure 1 *Schematic diagram of proposed EMF process for shaping large sheet metal parts*

As shown in Fig. 1, the realization of this process consists of four major sub-systems:

- ***Die system*** defines the desired geometry of the sheet metal parts.
- ***Forming coil system*** consists of a forming coil and a capacitor bank to produce high pulsed Lorentz force over global sheet metal area.
- ***Pulsed electromagnetic blank holding system*** is a newly-developed and highlighted blank holding mechanism. It utilizes a pulsed attraction Lorentz force as blank holding force (BHF); the attraction force can be self-balanced, thus no counter force should be restrained.
- ***Inertia confinement system*** is another highlighted device, which utilizes the inertias of the forming coil and a counter weight to confine the upward pulsed Lorentz force acting on the coil. It can effectively simplify the forming equipment that generally complicated and heavy.

2.2 System parameters

2.2.1 Die system

Fig. 2 shows the structure of the die, defining the geometry of the desired metal part, which is an ellipsoid shape with 500 mm long semi-axis and 350 mm short semi-axis. The center of the ellipsoid is 140 mm axially upward offset to the die flange. The die corner radius is 150 mm. To avoid the huge air resistance induced by the high velocity deformation of the workpiece, 25 circular holes were drilled on the die and connected to a vacuum pump to remove the air in die cavity, and vacuum grease was painted at die flange for sealing. The vacuum level of die cavity was monitored by a vacuum gauge, showing the air pressure can be decreased from 0.1 MPa to less than 100 Pa.

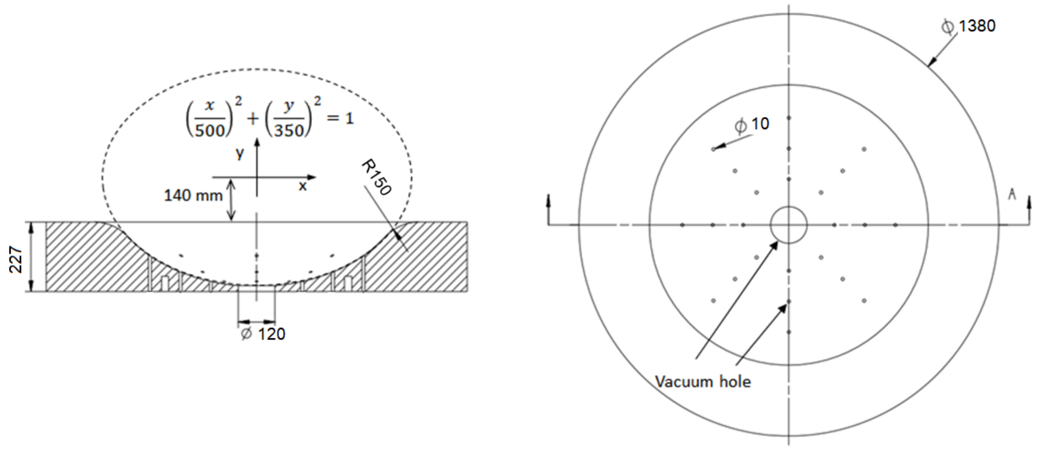

Figure 2 *Die structure*

2.2.2 Forming coil system

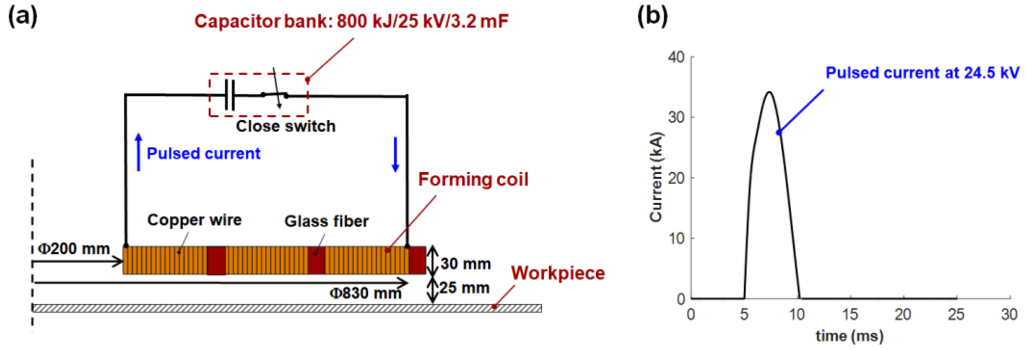

Figure 3 *Forming coil system: (a) system parameters; (b) discharge current at 24.5 kV*

Fig. 3 (a) shows the forming coil system. The coil winding was wounded from copper wire, and had total turn number of 54. The inner and outer diameters of the coil winding were 200 mm and 830 mm. An 800 kJ capacitor bank (2560 μF/25 kV) was to supply sufficient forming energy. A light-triggered thyristor switch was used to control the working timing of the pulsed forming force. Fig. 3 (b) shows the discharge current of the forming coil under 24.5 kV discharge voltage. The result shows a 5 ms pulse width for the current, which is much greater than that in common EMF. This pulse width may be argued for low energy efficiency. In fact, this is not intentionally designed, but a resultant of the large size of the coil winding, the relative great turn number (54 turns), and the relative high capacitance (2.56 ms). In other word, this great pulse width is a side-effect of the large length-scale of the workpiece.

2.2.3 Electromagnetic pulsed blank holding system

The electromagnetic pulsed blank holding system utilizes the pulsed attraction force between two adjacent electromagnetic coils. And the detailed principle and realization of the system may refer to (Lai et al., 2016; Lai et al., 2017a).

Fig. 4 shows the pulsed BHF and the corresponding discharge current generated by this system. The peak value of the BHF is 690 kN, the pulse width of the BHF is longer than 30 ms. In our experiments, the discharge timing of the pulsed BHF leads the pulsed forming force by 5 ms. In this way, during the whole span of the discharge current of the forming coil as shown in Fig. 3, the BHF can be above 500 kN.

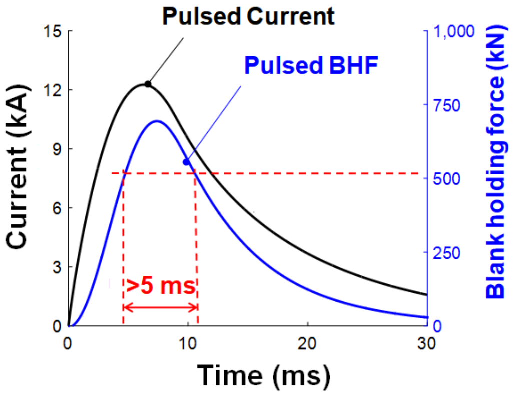

***Figure 4** Pulsed BHF and corresponding discharge current*

2.2.4 Inertia confinement system

The inertia confinement system utilizes the inertias of the forming coil and a counter weight to confine the upward pulsed counter force acting on the forming coil. This mechanism has been mentioned in some early publications, such as (Daehn, 2006; Mamutov et al., 2015), and has been intentionally or unintentionally used for other high velocity forming processes. Herein, we emphasized its applications on large sheet metal forming. As suggested by our previous work (Lai et al., 2017a), five tons counter weight can effectively confine the axial upward motion of the forming coil; this counter weight was used in this paper as well. More information may refer to (Lai et al., 2017a).

2.3 Experimental conditions

To evaluate the performance of the process, two experiments were conducted, in which two different aluminium alloys−AA5083-O and AA2219-O were shaped. Table 1 lists their material properties. Table 2 lists the experimental conditions. In two experiments, the workpieces have same initial diameter 1378 mm and same nominal thickness 4 mm.

According to measurement, the exact thicknesses of AA5083 and AA2219 are 3.945 mm and 3.918 mm, respectively. The discharge voltage of the BHF system was maintained to 25 kV. The discharge timing of BHF coil leaded that of forming coil by 5 ms. Different discharge voltages of the forming coil were set for two workpieces, which was 24.5 kV for AA5083, and 20 kV for AA2219. This decision was made by considering their different material properties, as listed in Table 1. However, these two discharge voltages should not be regarded as optimized ones.

Material	**Electric conductivity**	**Stress-strain curve: $\sigma=K\epsilon^n$**	
		K	***n***
AA5083	1.6807×10^7 S/m	546.15 MPa	0.2932
AA2219	2.4475×10^7 S/m	256.05 MPa	0.2194

Table 1: *Material properties of workpiece*

Exp	**Material**	**Diameter**	**Thickness**	**Forming voltage**	**BHF voltage**	**Discharge timing**
1	5083-O	1378 mm	4 mm (nominal)	24.5 kV	25 kV	BHF leads by 5 ms.
2	2219-O			20 kV		

Table 2: *Experimental conditions*

3 Result and discussion

Fig. 5 shows the photographs of two formed workpieces. The result shows that both AA5083 and AA2219 workpieces were successfully shaped into dome shapes that close to the desired ones. There is one Ø120 mm bump at sheet center, which is induced by high velocity impact with the vacuum hole at die bottom.

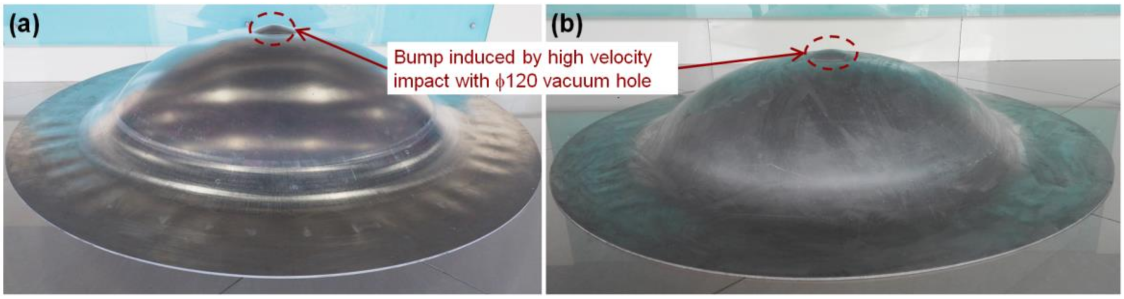

Figure 5 *Photographs of two formed workpieces: (a) AA5083; (b) AA2219*

Fig. 6 shows the detailed deformation results, in terms of die fittability, thickness reduction, and radial displacement distribution. Fig. 6 (a) shows the distributions of fitting gaps along one radial path, obtained by 3D scanner. The results indicate that, for AA5083 and AA2219, the maximum fitting gaps can be limited to about 4.2 mm and 3.5 mm. The major gaps are concentrated at region with radial coordinate less than 300 mm, which may be attributed to the smaller geometric stiffness of this area. Fig. 6 (b) shows the distributions of thickness reductions along radial direction, which are the mean measured data of four radial paths. The results indicate that, apart from the severe thickness reduction at sheet center about 17.4% and 17.3%, respectively, attributed to the severe stretching during the high velocity impact with the vacuum hole at die bottom, the thickness reductions of other region can be limited to 8.9% and 5.4%, respectively. Fig. 6 (c) shows the distributions of the radial displacement along radial direction, which are the mean measured value of four radial paths. The results indicate a substantial radial inward material flow over the region with radial coordinate greater than 300 mm, indicating a dominant deformation mode of drawing.

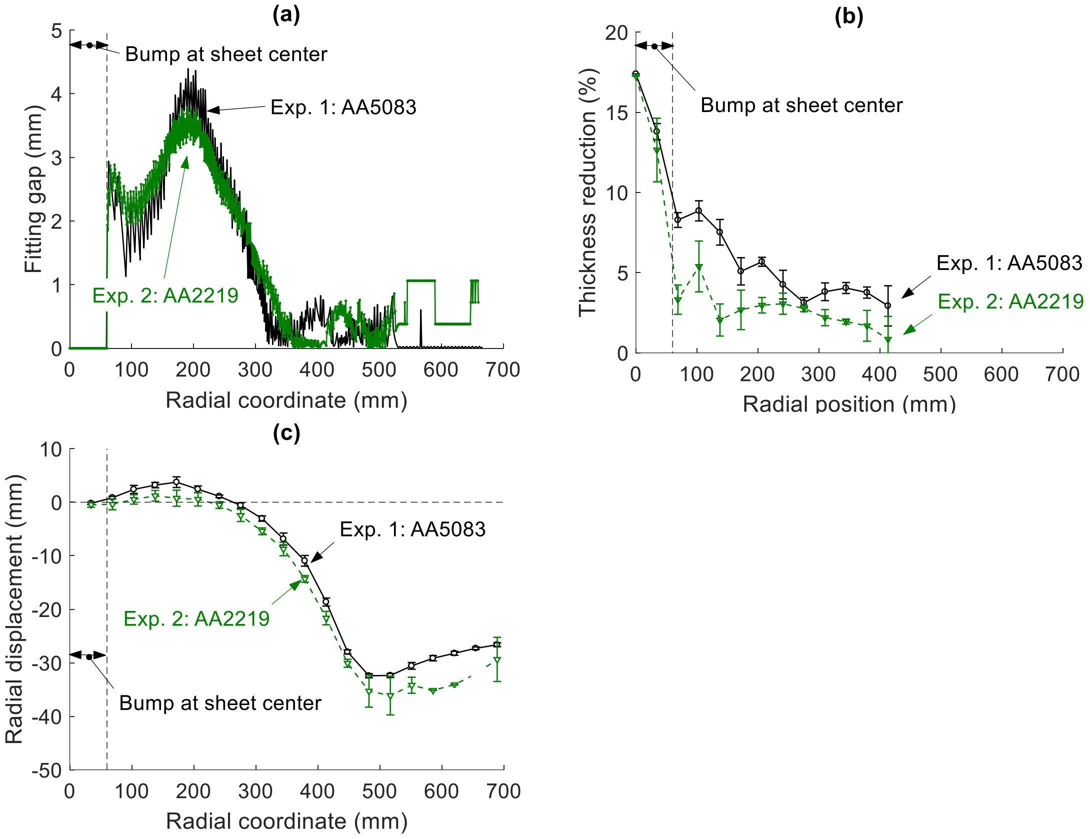

Figure 6 *Deformation results: (a) die fitting gap distribution; (b) thickness reduction distribution; (c) radial displacement distribution*

The drawing deformation mode, shown in Fig. 6 (c), is greatly responsible for the die fitting and thickness reduction results in Fig. 6 (a) and (b). This argument can be supported by the experimental and numerical works in (Lai et al., 2014b; Lai et al., 2015; Lai et al., 2017b), where a radial inward Lorentz force was introduced to enhance the draw-in of the flange region in EMF process. These works found that the enhanced draw-in can effectively change the thickness distribution and the deformed profile of the workpiece.

It is also of interest to analyse the differences on the two experimental results, which are resultant of the different material properties and the different discharge voltages. It is found that, for AA2219 workpiece, the maximum fitting gap is about 0.7 mm smaller than that of AA5083, and the maximum thickness reduction is about 3.5% smaller. The greater radial inward material flow of AA2219, shown in Fig. 6 (c), may be a key reason for these differences. However, due to the limited number of the experimental data and the lack of knowledge about the dynamic forming process, it is hard to say that the greater drawing will be always benefit for better die fittability and thickness distribution. And as suggested in (Risch et al., 2004), the complicated workpiece-die interaction also plays an key role on the final deformation results.

4 Comparison with other processes

When shaping large sheet metal parts with conventional process, a heavy forming tool is generally required, resulting in a high investment on the forming tools. The proposed process highlights the advantage of EMF on light weight equipment. The highlighted inertia confinement system and the pulsed electromagnetic blank holding system eliminate the heavy frame-work structure necessary for hydraulic or mechanical press. In addition, these two systems are suitable for other high velocity forming processes as well, which may advance the development of whole spectrum of high velocity forming processes.

Compared with other EMF processes, where the major applications are focused on generating local plastic deformation, the proposed process emphasises the application on delivering global plastic deformation. This may remarkably broaden the applications of EMF technology. And the potential advantages of EMF may be better exploited. For instance, the advantage on reducing wrinkling, which is of great significance in shaping thin-walled sheet metal parts, may be effectively utilized in this global forming process.

Furthermore, compared to lots of other high velocity forming processes where the stretching is the dominant deformation mode, the proposed process highlights the drawing deformation. And as suggested in (Lai et al., 2014b; Lai et al., 2015; Lai et al., 2017b), in EMF process, an active control on the drawing can effectively alter the thickness distribution and the deformation profile of the workpiece, thus may enable the manufacturing of much more complicated parts.

5 Conclusions

In this paper, the performance of a new EMF process is evaluated by shaping two Ø1378 mm AA5083 and AA2219 workpieces. According the experimental results, the following major conclusions can be drawn:

- The process can limit the maximum fitting gap within 3.5 mm, and limit the maximum thickness reduction (over die-impact workpiece region) within 5.4%, showing a relative well forming quality.
- The drawing deformation mode and the workpiece-die interaction are two dominant mechanisms on influencing the aforementioned forming results.
- The proposed process can provide much lighter and cheaper equipment for shaping large sheet metal parts, when compared with conventional quasi-static process, thus providing a promising alternative for the production of large sheet metal parts.

- As two key devices for the realization of the light-weight of the proposed process, the electromagnetic pulsed blank holding system and the inertia confinement system are suitable for other high velocity forming processes, which may advance the development of whole spectrum of high velocity forming process.
- Compared with the dominant stretching mode in general high velocity forming, the highlighted drawing deformation mode in proposed process provides a much more flexible and effective control on the deformation behavior. An active control of the combination of drawing and stretching deformation may enable the manufacturing of much more complicated metal parts.

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