Electromagnetic peening - a novel sheet metal forming method

Chunping Fang, Jingze Zhao, Li Ling, Wenping Wang and Min Wan

February 13, 2020

Electromagnetic peening -a novel sheet metal forming method

Chunping Fang[a], Jinze Zhao[a], Ling Li[a], Wenping Wang[b], Min Wan[b,]

[a]*Aerospace Research Institute of Materials & Processing Technology, East Highland Street, Fengtai District, Beijing 100076,China*
[b] *School of Mechanical Engineering and Automation, Beihang University, No. 37 Xueyuan Road, Haidian District, Beijing 100191,China*

Abstract

A novel high energy rate forming method named electromagnetic peening (EMP) which makes use of stress relaxation to form a sheet part is proposed. To understand the forming mechanism through stress relaxation behavior during the process, a 3D numerical model including electromagnetic field and structural field is established by ANSYS and ABAQUS finite element code based on the principle of loose coupling method. Furthermore, the experiments was conducted on 2524-T3 aluminum alloy sheet to verify the simulation result. It is found that the new process of electromagnetic peening technology is feasible to aluminum alloy sheet parts forming.
Keywords: aluminium alloy sheet, electromagnetic peening, stress relaxation, forming

1. Introduction

To satisfy the requirements of lightweight technology in automotive and aerospace industries, Thibaudeau et al. [1] and Meng et al. [2] reported that aluminium alloys with the excellent inherent properties of low density, high strength, high specific stiffness, and so on, are commonly utilized to manufacture lightweight structural parts to improve the fuel economy and reduce environmental pollution. However, it is widely acknowledged that the aluminium alloy sheet is difficult to be formed to the structural parts due to its poor formability than steel and enormous tooling cost in conventional stamping forming process. Miao et al. [3] demonstrated that shot peening is commonly used as a cold working process in which multiple small particles impact a ductile material and cause localized plastic strains to improve the fatigue life of metallic components and induce the curvature of thin aeronautic aluminium alloy components. However, the application of shot peening is limited owing to the poor surface quality of the workpiece caused by mechanical impact force. Furthermore, Lu et al. [4] presented that the laser peening forming has been emerged as a viable means for the flexible shaping and metal forming because of the advantages of non-contact, tool-free and high efficiency. However, as the large scale components widely used in aircraft and aerospace industrial clusters, Hu et al. [5] reported that it is still of great concern to further improve the formability of convex curvature parts to increase the forming efficiency because the pulse repetition rate of available laser system is still very limited. Therefore, it is necessary to develop other advanced technologies that can effectively form large aluminium alloy structures and enhance the mechanical properties simultaneously.

Kleiner et al. [6] indicated that electromagnetic forming (EMF) technology is a high-speed manufacturing process, which utilizes pulse electromagnetic force to fabricate workpieces made of metals with high electrical conductivity in a very short time. Several studies have demonstrated that the formability of aluminium alloy increases under the high-speed deformation. An investigation by Imbert et al. [7] had demonstrated that the electromagnetically aided forming owns serial advantages

* Corresponding author. Tel.: +86-010-68380659
E-mail address: chunpingfang@foxmail.com

of suppressing damage and increasing forming limits for the AA5754 sheet. Thomas et al. [8] explored the ductility of freely expanding electromagnetically loaded aluminium tubes, and they argued that the ductility of aluminium alloy increases in free forming due to the introduction of the electromagnetic field. Li, et al. [9] described that the formability of 5052 aluminium alloy sheet in the dynamic EMF process is a little higher than that observed in quasi-static tensile tests.

Recently, plenty of research work has been conducted to produce structural parts via introducing the electromagnetic field into the conventional forming processes. Shang, et al [10] developed a new sheet metal forming process named electromagnetic assisted stamping (EMAS) to form a non-symmetric metal panel of Al 6111-T4. Cui et al. [11] described a novel process denoted as electromagnetic incremental forming (EMIF) to form deep shape parts and tube parts combining the principle of electromagnetic forming and single point incremental forming. Dydo et al. [12] developed a new method for surface treatment of the workpiece through pulse electromagnetic force interacting with the working surface to cause indentation and form compressive stress layer. Consequently, the multiple treated surface is strengthened to a certain degree after several discharging times.

It is highlighted from above literature review that the conventional EMF is far from producing the large aeronautic aluminium alloy components with characteristics of large scale and small curvature due to the limitations of coil dimension and tooling cost. Therefore, it is vital to develop a novel electromagnetic forming technology to accommodate the fabrication of large size sheet metal products and further explore the unique influential mechanism of process parameters on the deformation behaviour of the material. In this research, a methodology based on the inherent advantages of electromagnetic forming, shot peening, and incremental forming was proposed to form the sheet metal products.

2. Material and processing

2.1. Material

The aeronautical aluminum alloy 2524-T3 sheet was used in the experiment and simulation. To validate the developed EMP, the samples with length of 400 mm, width of 150 mm, and thickness of 1.6 mm were adopted in the finite element (FE) simulation. To achieve the mechanical properties of 2524-T3 alloy with thickness of 1.6 mm, the uniaxial tensile test at room temperature was conducted. The basic mechanical properties of the used material are shown in Table 1 and Fig. 1.

Table 1. Mechanical properties of 2524-T3 alloy

Yield stress σs (MPa)	Tensile strength σb (MPa)	Elongation δ (%)	Poisson's ratio μ	Elasticity modulus E (GPa)
320	440	18	0.33	70

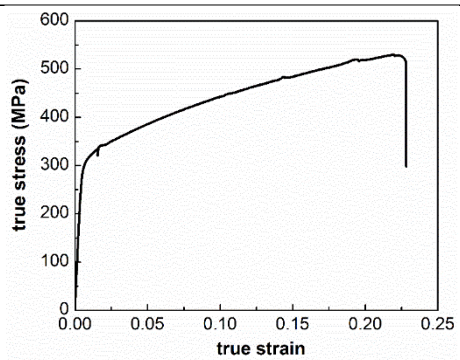

Fig. 1. Quasi-static true stress- strain curve of 2524-T3.

2.2. *EMP process*

Fig. 2 illustrates the principle of the developed EMP process. The forming system is made up of high voltage power, capacitor, working coil, fixture device, cables, sheet metal, resin plate, rubber cushion, multi-point die and control system. In EMP, the electrical energy is stored in a bank of capacitors. When the switch is closed, by suddenly discharging all the stored energy, an instantaneous discharge current runs through a working coil, which produces an intense transient magnetic field around it. According to Faraday's law of electromagnetic induction, when the metal workpiece is placed in a magnetic field, eddy currents are induced on the sheet surface due to the skin effect and the repulsive force occurs between the coil and the sheet. This electromagnetic force is applied to launch the sheet at very high speed and to obtain the local deformation. A resin plate is fixed between working coil and blank to prevent a spark generation between coil and the workpiece. The plastic indentation can be induced on the surface of workpiece owing to the action of multi-point die if the electromagnetic force is great enough. Therefore, a rubber cushion is placed between the sheet metal and the multi-point die. After discharging at one position, the local deformation and stress concentration generate. Sequentially the working coil moves to another special position and the sheet deforms in some cycles of charging and discharging. Finally, once the constraint of sheet metal is removed, the local deformation accumulates and the sheet forms into a final shape after springback because of the stress and strain concentration releasing. Compared with the conventional sheet metal processes such as shot peen forming, the sheet can be formed at a very high speed in a very short time.

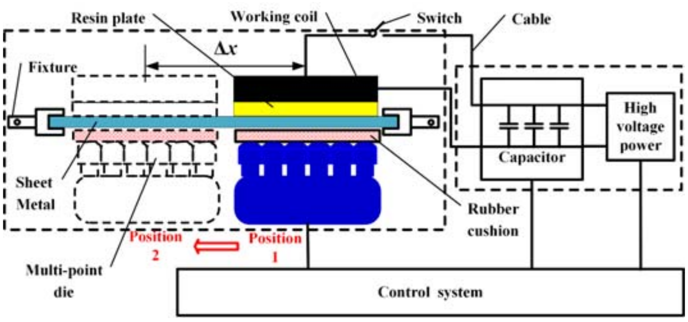

Fig. 2. Schematic illustration of EMP process.

3. Simulation and experiment

3.1. *Numerical simulation*

Fig.3 (a) shows the schematic illustration of FE simulation. The distance between the adjacent spiral coil centres was set to 30 mm. The positions marked as position1, 2 and 3 in Fig.3 (a) are denoted as discharge regions. The sheet is fixed position and the coil is moved to realize the relative movement of the sheet, which leads to the accumulative deformation in different regions of the sheet.

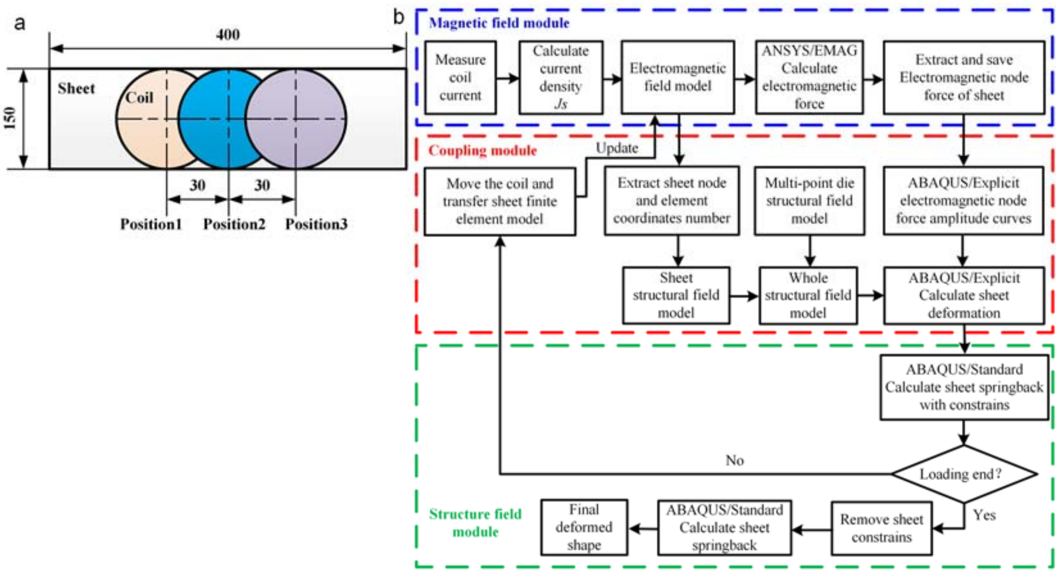

Fig.3. Simulation strategy: (a) schematic illustration of FE simulation, (b) FE analysis flowchart of EMP process.

The numerical simulation of EMP is a multiple field coupling problem which involves the electric field, magnetic field and structure field. Therefore, the loose coupling method is established to analyse the electromagnetic peening forming process. Fig. 3(b) shows the FE analysis scheme for the EMP process. The whole simulation process can be divided into three modules including the magnetic field, the structure field and the coupling module. The FEM software ANSYS and ABAQUS were utilized to analyse the electromagnetic force and calculate the structural field deformation respectively. The used working coil was characterized with flat spiral geometry, as shown in Fig. 4. The geometric parameters of the coil are listed in Table 2.

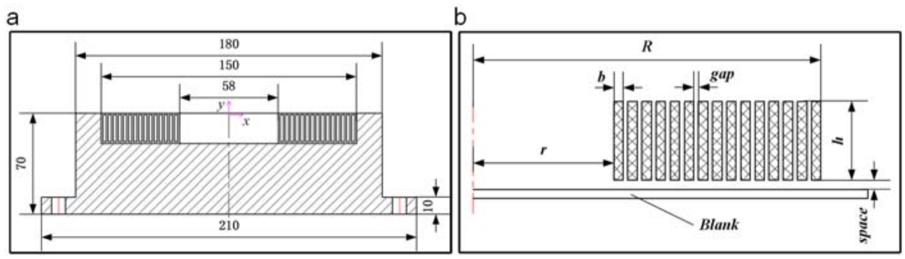

Fig. 4. Structure of the flat spiral coil: (a) coil configuration, (b) cross-section

Table 2. Parameters of the working coil

Parameters	Value
Coil effective inner radius *r* (mm)	30
Coil outside radius *R* (mm)	74.2
Cross-sectional height *h* (mm)	15.5
Cross-sectional width *b* (mm)	2.2
Cross-sectional area *a* (mm2)	2.2 × 15.5
Coil turns *n* (mm)	15
Gap between turns *gap* (mm)	0.8
Space between coil and blank *space* (mm)	10

The 3D electromagnetic FE model of EMP is illustrated in Fig.5 (a). The model consists of coil, air, far air and sheet. The regions of the air, coil and sheet are meshed with SOLID97 elements. The far air is meshed with INFIN111 element to simulate the infinite boundary conditions. The main regional properties in 3D electromagnetic model are given in Table 3. In electromagnetic field analysis, boundary conditions can be built as follows:

(1) In the global Cartesian coordinate system, the far air flag is set to the external surface to define the infinite boundary condition.
(2) The coordinate system of working coil from Cartesian coordinate is transferred to the local cylindrical one, and then the current density is inflicted on the discharge coil.

The measured coil current under 5500 V voltage is used as the excitation source for numerical analysis of electromagnetic field. Since the first current pulse is largest and most significant for the electromagnetic forming process mentioned by Mamalis et al. [13], only a part of coil current waveform from 0 to 200 μs was homogeneously divided into ten portions to calculate the electromagnetic force.

Table 3. Properties of the electromagnetic FE model

Region	Sheet	Coil	Fair	Far fair
Relative permeability	1	1	1	1
Electrical resistivity (Ω·m)	2.78e-8	1.72e-8	——	——

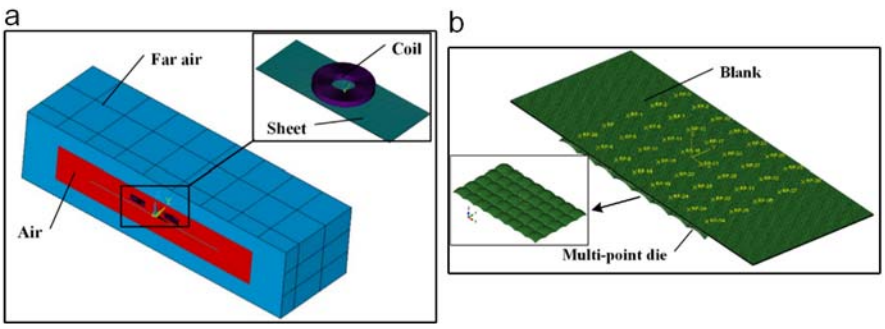

Fig. 5. Finite element model of EMP process: (a) 3D electromagnetic mode, (b) structural field model

In the structural field model, the sheet model was created by node and element information transferred from the electromagnetic field model. Besides, only the top profile of the multi-point die was built as discrete rigid body Fig.5 (b) shows the structural field model of the multi-point die.

3.2. Experimental procedure

The EMP experiments were performed on an electromagnetic forming machine which consists of two main modules, i.e., electromagnetic generator and control system, as shown in Fig. 6 (a). In addition, the detailed parameters of the machine are listed in Table 4.

Table 4. Main parameters of electromagnetic forming machine

Parameters	value
Capacitance (μF)	250
Maximum stored energy (kJ)	50
Minimum breakdown voltage (kV)	3
Nominal voltage (kV)	20

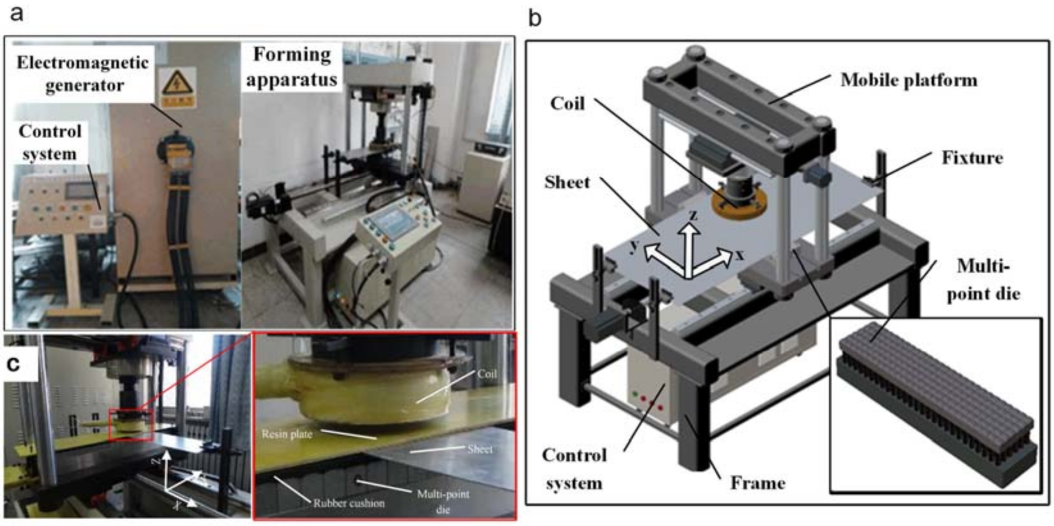

Fig. 6. Experimental equipment: (a) real forming apparatus, (b) schematic diagram of forming apparatus, (c) experimental method of EMP

Fig.6 (b) shows the schematic diagram forming apparatus of EMP. It is mainly composed of frame, mobile platform, fixture, coil, control system, multi-point die, etc. More specifically, the multi-point die is made up of 6 × 27 units with radius of 35 mm ball head which can be adjusted flexibly according to the requirements of forming. In addition, the coil used is made up of 15 turns copper wire and inserted into a glass epoxy board to make coil wire insulate with each other as well as improve coil strength.

Fig.6 (c) illustrates the experimental methodology of EMP process. For the convenience of description, relative assembly relationship among coil, resin plate, rubber cushion, blank and multi-point die is magnified. Moreover, the coordinate system is marked in the figure, namely, the longitudinal, transverse and through-thickness direction of sheet metal defines x, y and z direction, respectively. To be specific, the sheet metal is held on a plane by clamping device before experiment, at the same time the working coil is fixed in the mobile platform by bolts. A thickness of 10 mm resin plate is settled between working coil and sheet. In addition, a certain thickness of rubber cushion is adopted and placed between sheet and multi-point die according to the requirement of experiment. Once the coil discharges in one position, the sheet keeps stationary, meanwhile, the mobile platform moves along x and y directions until the coil arrives at the target location by adjusting the control system, then discharges again, and by this analogy, until the end of the experiment.

4. Result and discussion

In the EMP process, the sheet deforms under the action of electromagnetic force and impact of multi-point die. Fig. 7 (a) shows the distribution of Mises stress along x direction on sheet at the time of 100 μs. It is found that the sheet metal deformation area can be divided into two parts: (1) region 1: deformation coated on the top ball head of multi-point die; (2) region 2: deformation in the cavity between the two adjacent ball heads, as shown in Fig. 7 (b). Furthermore, Fig. 7 (b) describes the local deformation and stress-state information of a micro-unit, where ρ, R represents the neutral surface radius of deformation in region 1 and region 2, respectively. According to simulation result shown in Fig.7 (a), it is clear that the deformation region is in tension outside neutral layer and compression in inner zone. Therefore, the stress state is in accordance with typical bending deformation characteristics.

It is acknowledged that smaller the radius of curvature before springback is, smaller the radius of curvature after springback will be in bending deformation. When electromagnetic force increases, the deformation in region 1 is limited due to contact with ball head of the multi-point die, but deformation in region 2 continually increases until radius of curvature in region 2 is smaller than region 1.Thus, the radius of curvature in region 2 is smaller than region 1 after springback. Consequently, the sheet deformation accumulate into a final shape due to the stress relaxation behaviour in a macroscopic fashion. Fig.7 (c) shows the distribution of equivalent plastic strain.

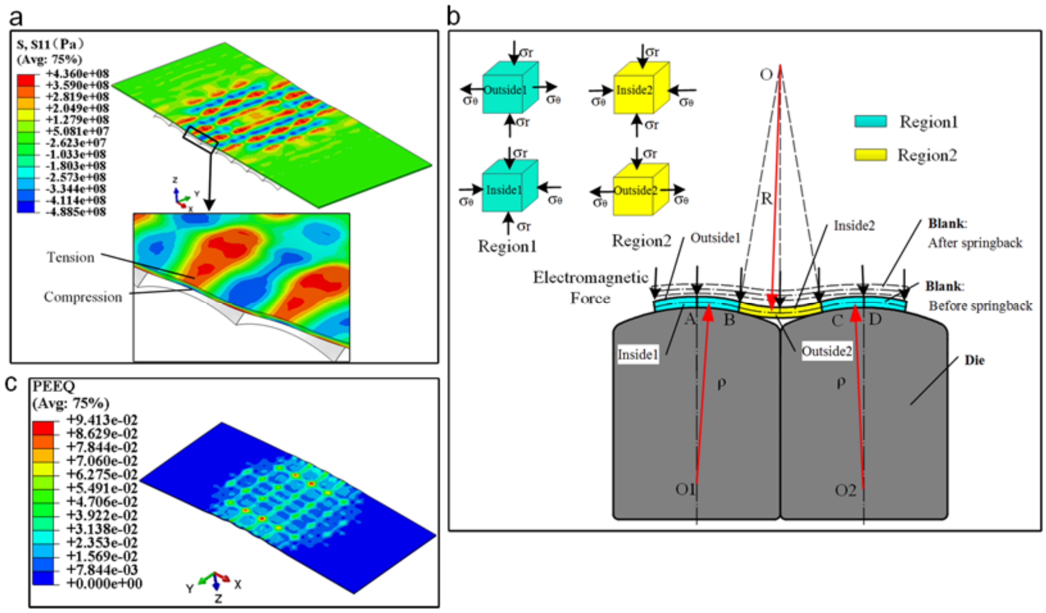

Fig.7. Simulation result: (a) distribution of Mises stress along x direction at 100μs, (b) local deformation and stress-state of cubic element, (c) distribution of equivalent plastic strain after springback

To assess the validity of the FE model, a small-size part forming experiment was confronted with FE simulation. The size of the experimental sheet is 400 mm×150 mm×1.6 mm, thickness of the resin plate is 10 mm, discharging voltage of the working coil is 5500 V, and incremental interval of coil moving is 30 mm (Δx in Fig. 2). The experiments were carried out according to the methodology shown in Fig.8 (a) under two different circumstances: (a) without rubber cushion, (b) with a thickness of 8 mm rubber cushion. Fig. 8 (a) (b) shows the experimental results of the final shape, where Δh and D represents the maximum pit height and the maximum defamation value, respectively. It is clearly found that the maximum pit height of the sheet formed without rubber cushion is higher than the sheet formed with a thickness of 8 mm rubber cushion. Thus, it can be proved that the rubber cushion has obvious inhibitory effect on pit defect. This may come from the fact that the impact action between the sheet and multi-point die will be dispersed and reduced significantly due to the buffering action of rubber cushion. Therefore, it can be conclude that this method will ensure a workpiece with good surface quality if the rubber cushion is thick enough.

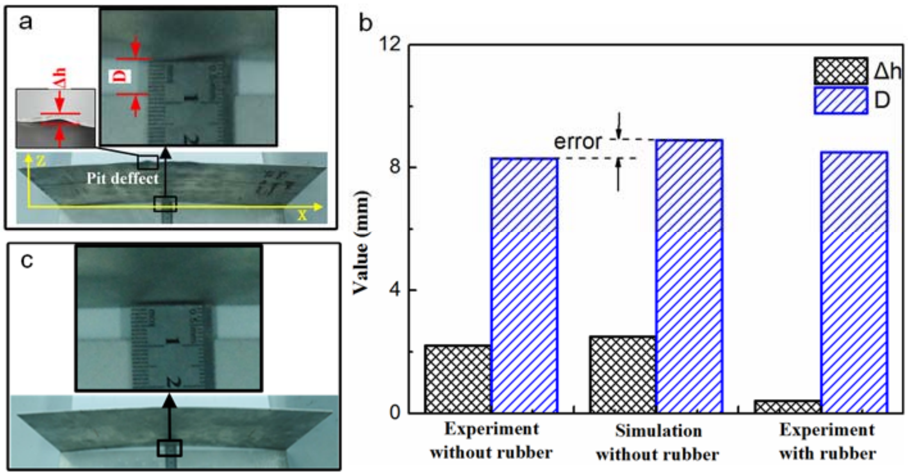

Fig. 8. Experiment and simulation results: (a) without rubber cushion, (b) with rubber cushion, (c) deformation

In addition, it is revealed that the maximum deformation value of experiment without rubber is almost same with the result of experiment with rubber. On the other hand, the deformation value of simulation is a little bit larger than the result without rubber cushion. But the biggest gap exists in experimental result and simulation one is about 0.6 mm. In consideration of the sheet size and deformation value for experiments are 400 mm×150 mm×1.6 mm and 8.3 mm, the simulation error is very small, as shown in Fig.8(c). Therefore, it can be concluded that the experimental result is in great agreement with the simulation one.

5. Conclusion

In this research, a forming method defined as electromagnetic peening by applying magnetic pulse load locally on the sheet to form sheet part was developed according to the principle of electromagnetic forming and incremental forming. Based on the numerical and experimental studies on EMP of 2524-T3 aluminium alloy sheet, the main conclusions can be drawn as following:

(1) The EMP process combined with the multi-point die is feasible to produce the large size part with small curvature by making use of applying the electromagnetic force on the local region of sheet metal incrementally.

(2) The rubber cushion between coil and sheet has great effect on suppressing the concave and improving surface quality but has almost no influence on the maximum deformation height.

Acknowledgements

The authors would like to express their sincere appreciation for the financial support of the National Basic Research Program of China (973 Program, Grant No. 2011CB012804).

References

[1] Thibaudeau E., Kinsey B.L. Analytical design and experimental validation of uniform pressure actuator for electromagnetic forming and welding. *J. Mater. Process. Technol.* 2015, 215, 251-263.

[2] Meng, B., Wan, M., Yuan, S., Xu, X.D., Liu, J., Huang, Z.B. Influence of cavity pressure on hydrodynamic deep drawing of aluminium alloy rectangular box with wide flange. *Int. J. Mech. Sci.*, 2013, 77, 217-26.

[3] Miao, H.Y., Demers, D., Larose, S., Perron C., Lévesque, M. Experimental study of shot peening and stress peen forming. *J. Mater. Process. Technol.*, 2010,210, 2089-2102.

[4] Lu, J.Z., Luo, K.Y., Yang D.K., Cheng X.N. Hu J.L. Dai, F.Z., Qi, H., Zhang L., Zhong J.S., Wang Q.W., Zhang Y.K. Effects

of laser peening on stress corrosion cracking (SCC) of ANSI 304 austenitic stainless steel. *Corrosion Sc.*, 2012, 60, 145-152.

[5] Hu, Y.X., Li, Z., Yu, X.C., Yao, Z.Q. Effect of elastic prestress on the laser peen forming of aluminium alloy 2024-T351 Experiments and eigenstrain-based modelling. *J. Mater. Process. Technol.*, 2015,221, 214-224.

[6] Kleiner, M., Beerwald, C., Homberg, W. Analysis of process parameters and forming mechanisms within the electromagnetic forming process. *CIRP Ann.—Manuf. Technol.*, 2005, 54, 225-228.

[7] Imbert, J.M., Winkler, S.L., Worswick, M.J., Oliveira, D.A., Golovashchenko, S. The effect of tool–sheet interaction on damage evolution in electromagnetic forming of aluminium alloy sheet. *J. Eng. Mater. Technol.*, 2005,127, 145–153.

[8] Thomas, J.D., Seth, M., Daehn, G.S., Bradleyc, J.R., Triantafyllidisa, N. Forming limits for electromagnetically expanded aluminium alloy tubes, Theory and experiment. *Acta Mater.* , 2007, 55, 2863-2873.

[9] Li, C.F., Liu, D.H., Yu, H.P., Ji Z.bo. Research on formability of 5052 aluminium alloy sheet in a quasi-static–dynamic tensile process. *Int. J. Mach. Tool Manuf.,* 2009, 49, 117-124.

[10] Shang, J., Daehn, G. Electromagnetically assisted sheet metal stamping. *J. Mater. Process. Technol.*, 2011, 211, 868-874.

[11] Cui, X.H., Mo, J.H., Li, J.J., Zhao, J., Zhu, Y., Huang, L., Li, Z.W., Zhong, K. Electromagnetic incremental forming (EMIF), a novel aluminium alloy sheet and tube forming technology. *J. Mater. Process. Technol.*, 2014,214, 409–427.

[12] Dydo, J.R., Yushanov, S. P. System and method for electromagnetic pulse surface treatment, *U.S. Patent No. 7,378,622.* , 2008.

[13] Mamalis, A.G., Manolakos, D.E., Kladas, A.G., Koumoutsos A.K. Electromagnetic forming and powder processing, trends and developments. *Appl. Mech. Rev.*, 2004.57, 299-324.