An experiment and simulation study of the rebound effect in electromagnetic forming process*

Xianlong Liu, Liang Huang, Jianjun Li

State Key Laboratory of Materials Processing and Die & Mould Technology, College of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract

Electromagnetic forming (EMF) has been proved to be a useful method to form the aluminium alloy sheet as it has so many advantages. As a high-speed forming process, it can suppress crack, reduce springback, and improve the formability of material at room temperature. But in the process of EMF, the rebound effect caused by high velocity impact has an important effect on the flatness of the formed part. Then a spring damper system has been added under the female stop block to eliminate this effect. The results of formed shape, thickness distribution and stress and strain state are investigated by comparing with free-forming process. On the other hand, the influence of spring stiffness and damping coefficient is analysed by using of ANSYS loose-coupled method. The results shows that it helps to improve the flatness of formed parts with a spring damper system used. Beside of the changing of formed shape, the difference of stress strain state results in difference of thickness distribution. And crack happened at the bottom is supressed, and this does favour for further processing. Furthermore, the results also shows that low spring stiffness and right damping coefficient are benefit for reducing the rebound effect.

Key words

Electromagnetic metal forming (EMF), Impact, Rebound effect, Spring damper

---

* This work was supported by the National Basic Research Program of China (No. 2011CB012802)

1 Introduction

Electromagnetic metal forming (EMF) has been proved to be a useful method to form the aluminium alloy sheet, it has many advantages such as unnecessity of lubricant, simple designed mold and high production rates in contrast to the conventional sheet metal forming, and it can also suppress crack, reduce springback, and improve the formability of material at room temperature[1].

As a high-speed forming process, the workpiece is accelerated up to 300m/s. The rebound effect caused by high velocity impact between the workpiece and dies has an important effect on the forming precision and quality of the formed part. So far, most attentions have been focused on changing the shape of bottom die to increase the fittability, but there is little research of controlling rebound effect when the die is flat-bottomed. J.Imbert Boyd[2,3] had done conical die experiments, its results showed that the workpiece fitted good with die. Oliveira[4] implemented a simulation for electromagnetic forming with a flat-bottomed die by 3D loose coupling method, the results shows that excessive rebound happens. And an experiment was also carried out, it shows that maximum fraction of cavity fill is less than 50%. D. Risch[5,6] proposed to locally increase the stiffness of the workpiece to handle the rebound effect. In EMF process, the speed of workpiece is high. When it contacts with dies, one part of the kinetic energy is transformed to plastic deformation work, the other part could not dissipate in a short time, and then the rebound effect happens.

The system with a spring damper is added under the female stop block in this paper, the resuls of formed shape, thickness distribution and the stress-strain sate are compared with free forming. The effect of spring stiffness and the damping coefficient on the rebound is also studied by simulation. The results provides a foundation for electromagnetic forming with a die.

2 Research Method

2.1 Experiment Method

The pulse generator for electromagnetic forming is shown in Figure 1 (a). The maximum stored energy is 96kJ with 213 μF capacitance at 30kV. The set up used in experiments is shown in Figure 1 (b).

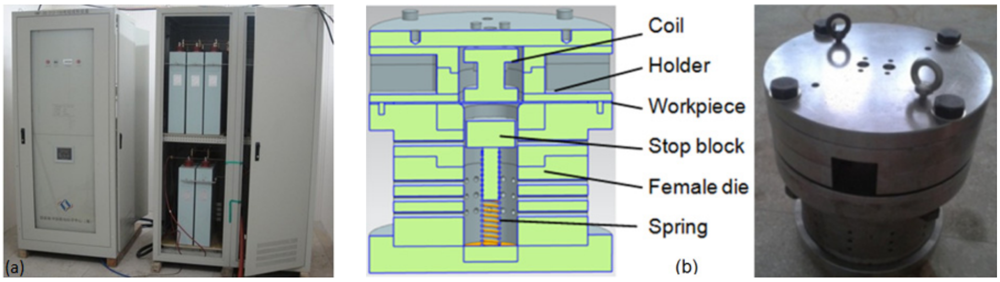

***Figure 1**: Forming equipment (a) electromagnetic pulse generator (b) set up used in the experiments*

The material used in this study is aluminium alloy 5A06 with the diameter 180mm and the thickness 1mm. The coil was made of six layers of copper wire and each layer has three turns, the section of each turn is 3mm wide and 6mm high. The bottom die chosen for this study is 100mm for the diameter, 290mm for the depth, 20mm for the radius. The spring parameters are as follows: shear modulus G is 200GPa; spring wire diameter d is 2.5 mm; spring pitch diameter D_2 is 32mm;number of active coils n is 20;

$$K = \frac{Gd^4}{8D_2^3 n} \tag{1}$$

So the spring stiffness K is 1656N/m which is computed by formula (1).

As shown in Figure 2(a), a spring damper system is added under the workpiece. The spring damper system consists of a nylon block to insulate from the aluminium sheet, a steel block with a guide bar to keep stability of the system and a spring. During the forming process, the workpiece always moves with the system. The schematic diagram of a time in the process is shown in Figure 2(b).

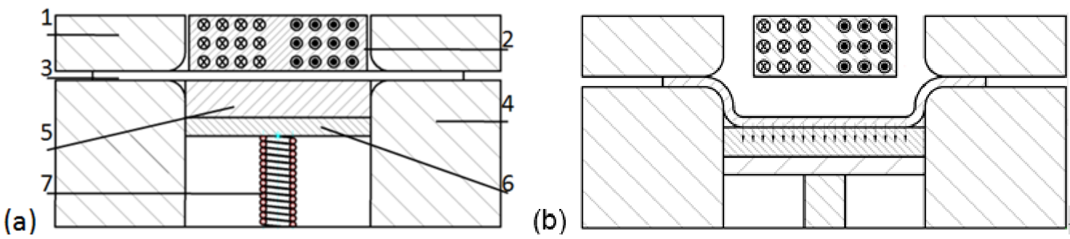

***Figure 2** :The schematic diagram of experiment (a) before the forming (b) in the forming process. Where, 1-holder, 2-coil, 3-workpiece, 4- female die, 5-nylon block, 6-steel block, 7-spring.*

2.2 Finite Element Simulation

In this paper, a axisymmetric model is set up using two-dimensional loose-coupling method. The main thought is to calculate electromagnetic (EM) forces in ANSYS Emag and use it as load to compute structure deformation.

The propagation of the electromagnetic field is defined by quasi-stationary Maxwell equations as follows:

$$\nabla \times H = j \tag{2}$$

$$\mu_a \frac{\partial H}{\partial t} = -\nabla \times E \tag{3}$$

$$j = \sigma(E + \mu_a v \times H) \tag{4}$$

where H is the magnetic field intensity, j is the current density, E is the electric field intensity, σ is the electric conductivity, v is the velocity, μ_a is the magnetic permeability of medium under consideration.

Based on these rules, a two-dimensional finite element model of electromagnetic field is established as shown in Figure 3(a). Magnetic flux parallel conditions is set at x=0, when x=300mm is made as far field by the use of infi110 to insure accuracy. The current curve used as load in the simulation of EM field is depicted as Figure 3(b). Only the first half of the curve is selected to do the computation because of two reasons: 1.the current itself is weakened; 2.with the forming carrying on, the distance between the workpiece and the coil increases, the effect of follow-up current is reduced.

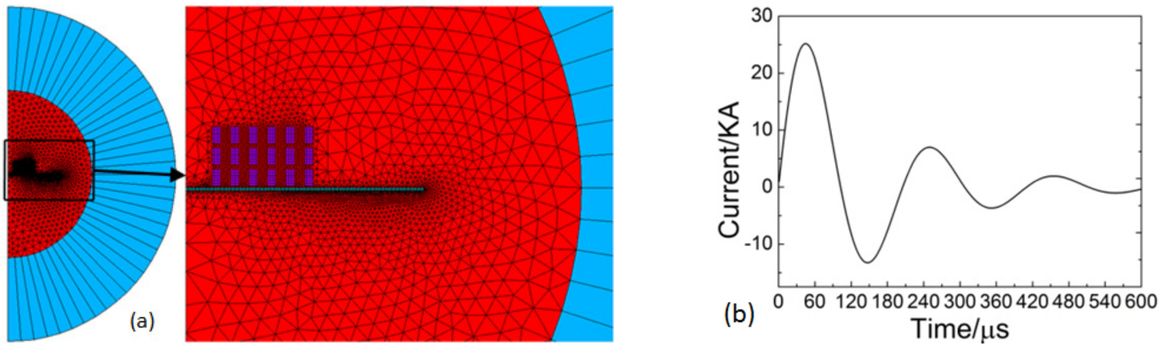

***Figure** 3 :Electromagnetic field analysis (a) electromagnetic fieldmodel (b) current curve used in the simulation*

Dynamic elastic-plastic deformation of solids can be defined by the following equations:

$$\rho \frac{d}{dt} \int_V v dV = \int_S \sigma \cdot ds + \int_V f dV \tag{5}$$

In this paper, an extra pressure is given by the spring damper system, so the formula changes as：

$$\rho \frac{d}{dt} \int_V v dV = \int_S \sigma \cdot ds + \int_V f dV + p ds \tag{6}$$

where σ is the stress tensor, ρ is the density; f is electromagnetic force calculated from maxwell equations, p is the pressure provided by the spring damper system.

The finite element model of structural field is shown as Figure 4(a), the coil, blank holder and the female die are set as rigid body. Property of spring is simulated by setting spring stiffness and damping coefficient parameters of Combin14, and the friction factor is set as 0.1. The true stress-strain curve of 5A06 aluminium alloy as shown in Figure 4(b) is getted by quasi-static tensile tests. As to the high speed quality of EMF, Cowper-Symonds multiplier is introduced to considered the effect of strain rate. The constitutive equation is based on over stress strengthening model, as shown in formula (7):

$$\sigma = \sigma_0 (1 + (\frac{\dot{\varepsilon}}{C})^m) \tag{7}$$

where, to aluminium, C=6500 s-1,m=0.25, σ_0 is the flow stress of the quasi-static tensile curve.

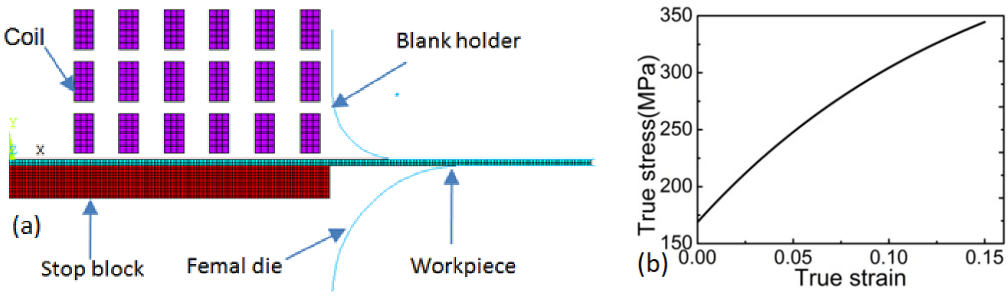

***Figure 4** : Structual field analysis (a) structual field model (b) true stress-strain curve of 5A06*

3 Results and Discussions

3.1 Comparison between free forming and forming with spring damper system

In the following, experiment and simulation are done with the spring damper system used as described in the before paragraph. Free-forming process is also fulfilled to make a contrast.

3.1.1 The difference of shape

It is the free-forming process when the cavity is empty. An experiment is implemented with the charging voltage set as 8kV. As is depicted in Figure 5, the simulation results on the right column are in agreement with experimental results on the left column. The deformed part is always conical without a die even when the discharged voltage is changed. As to this reason, when a second forming is needed to be accomplished, a complicated coil conformed with formed shape must to be made and the cost is increased.

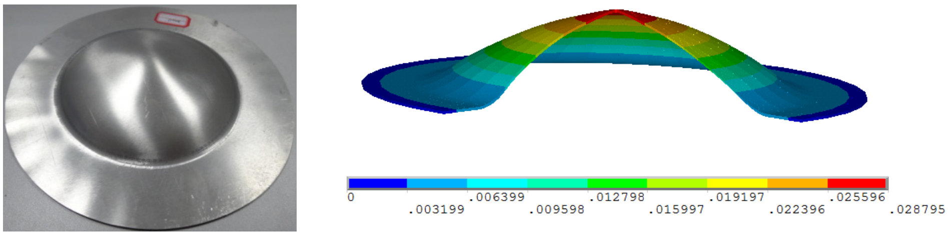

***Figure 5** :Experimental results and the simulation results for the free-forming process*

By using of spring damper system, with the same voltage as free forming process, an study is carried out. The experimental and simulation results are shown as Figure 6. A rather flat bottomed part is formed with the spring damper system applied, and this will do favor to moving down the coil. Multi steps forming would be introduced in the future paragraph based on getting flatted bottom at each step, and this is devoted to solving the difficult problem of forming deep drawing parts by EMF. However, there is a small pit in the center of deformed part which is not predicted by simulation. And there are two reasons caused this problem: firstly, the air resistance is not consider in the simulation; secondly, the EM forces provided by the coil is small in the middle places.

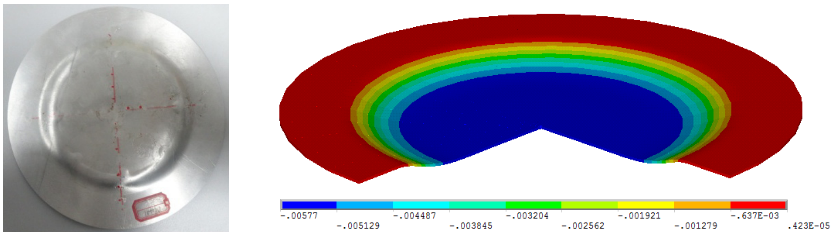

***Figure 6** :Experimental results and the simulation results for the forming with spring damper system*

3.1.2 The difference of thickness distribution

By use of sonic thickness sensor, the thickness of deformed parts are measured by choosing four symmetrical paths to get a mean value. The thickness distribution results of free forming and forming with spring damper system with the discharged voltage 8KV is shown in Figure 7(a),(b).

In the free forming, the distribution of thickness is inhomogeneous as shown in Figure 7(a). The thickness is lower close to the center of the part, and it is higher away from the center. The thinnest place is located at the centerline of the workpiece, where the thickness is 0.89mm. When discharged voltage, the crack damage will happen on the top as shown in Figure 8(a). Even though the deformed parts in deep drawing must not to be flat-bottomed, the sheet metal in free forming is main under stretching state locally. If a second voltage is applied, then thickness in local places is thicken again, and this is an obstacle for further processing.

When forming with the spring damper system, the thickness distribution as shown in

Figure 7(b) is more uniform than that without it. The thickness reduction at different points of the bottom is nearly the same, with flange area growing a little thicker. The thinnest area is the connection of stop block and the die radius, the reason will be discussed in the following segment.

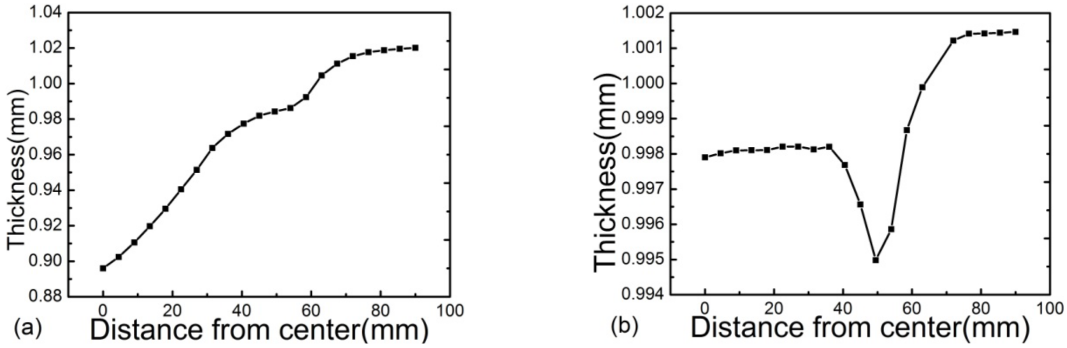

Figure 7 *:Distribution of thickness of discharged voltage 8KV (a) free forming (b) with spring damper system applied*

3.1.3 The difference of stress and strain state

As shown in top column of Figure 8(a), when the discharged voltage is increased to 10.5KV in free forming process, a bulging crack on the top of deformed part will be happen. The stress and strain state of workpiece is presented at the bottom column of Figure 8(a), it is bi-axial tensile strains state at the crack region. When a spring damper system is added under the workpiece, there will be a fiction provided by the stop block, and the stress and strain state has been changed as shown in Figure 8(b). Radial stress σ_1 and hoop stress σ_3 are tensile stress, σ_2 is stress through thickness is compressive stress. Based on volume conservation law, the condition of $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$ is satisfied, and the strain through thickness is $\varepsilon_2 = -(\varepsilon_1 + \varepsilon_3)$. When the faction force is small, the radial strain and hoop strain are all tensile strain, so ε_1, ε_3 >0. In contrast with free forming, the tensile stress of σ_1 and σ_3 is reduced by the faction force provided by stop block, then tensile strain ε_1 and ε_3 are cut down. Because of this, the strain through thickness is reduced, that is to say the thinning of the workpiece is reduced. When the faction force is big enough, hoop strain ε_3 may low than zero, there will be fewer thinning after the forming.

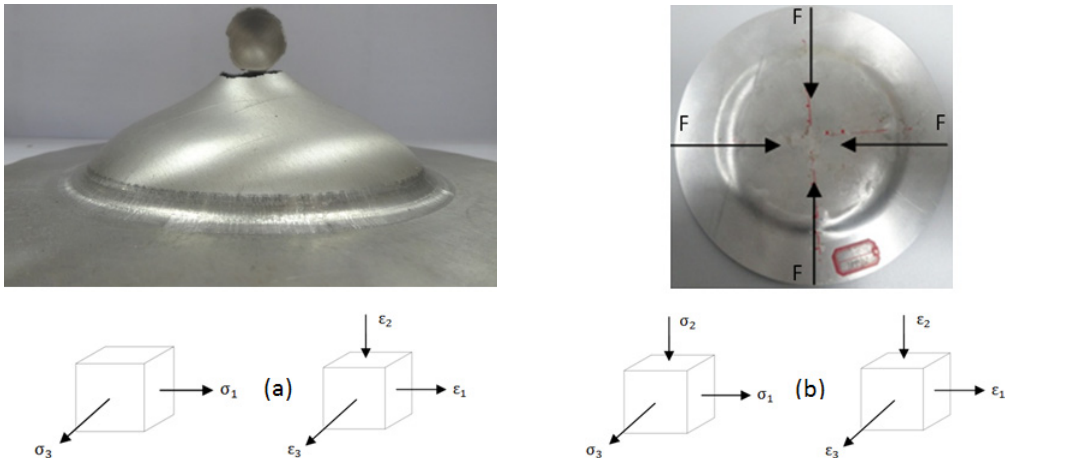

***Figure 8** : Formed part and its stress strain state (a) free forming (b) forming with spring damper system*

To make a better understanding of relation between strain and time, simulation of free forming and forming with spring system are implemented to make an comparison. With the discharged voltage set as 8KV in both conditions, the strain-time curve of middle point of the workpiece are shown as Figure 9 (a), (b). By contrast of the simulation results of two forming state, the stain history of free forming is a typical plane stress state. There are tensile strains in two directions, and compressive strain in one direction. But when the spring damper system is used, the strain state is changed. There are compressive strains in two directions, and tensile strain in one direction. As to the friction force provided by the stop block during the forming process, the hoop strain changes to compressive strains, this would be helpful to cutting down the thinning of the workpiece and good for subsequent process.

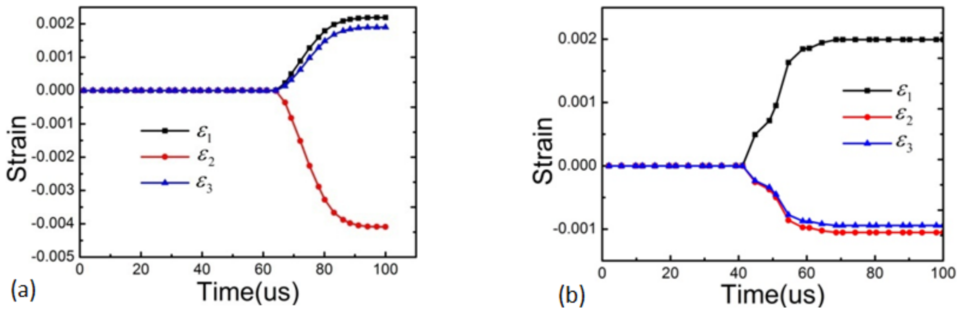

***Figure 9** : The strain-time curve of middle point (a) free forming (b) forming with spring damper system*

3.2 Effect of spring stiffness and damping coefficient on the rebound with spring damper system

The degree of deformation and forming efficiency is low when the discharged voltage is comparable low. When it is contacted with the die, one part of the kinetic energy is transformed to plastic deformation work, the other part could not dissipate in a short time, then the rebound effect happens. The effect of spring stiffness and damping coefficient on the rebound with spring damper system adopted is studied by simulation. The parameters of the spring stiffness K have been varied starting from 1e3 N/m to 1e5 N/m, and damping coefficient c have been varied starting from 10 Ns/M to 10000 Ns/M. And the results is shown in figure10, figure12, figure13.

Figure 10(a)-(d), Figure 11(a)-(d), Figure 12(a)-(d) shows that the higher the damping coefficient the better the workpiece fittability when the spring stiffness are the same. But the forming depth is smaller at the same time. On the contrary, when the damping coefficient is lower, though the forming depth is deeper, but the fittability becomes worse. So there is an optimal damping coefficient that not only good for getting higher forming depth but also benefit for obtaining flat bottomed workpiece.

As shown in Figure 10(a)-12(a), Figure 10(b)-12(b), Figure 10(c)-12(c), Figure 10(d)-12(d), the rebound effect is worse and the fittability decreases as the spring stiffness increases. On the other hand, the forming depth is smaller when the spring stiffness is bigger. But, the workpiece could move down with the die easier with lower spring stiffness. With lower spring stiffness, the bottom flatness of formed parts is improved, and the forming depth is also .

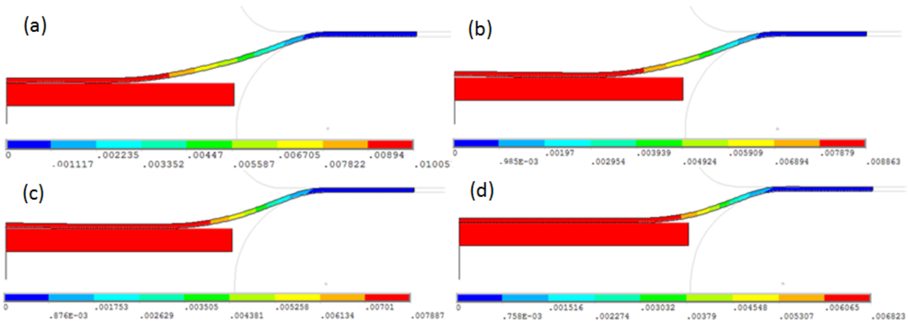

Figure 10 :*Displacement at different damping coefficient with the same spring stiffness 1e3 (a) 10Ns/M (b) 100Ns/M (c) 1000Ns/M (d) 10000Ns/M*

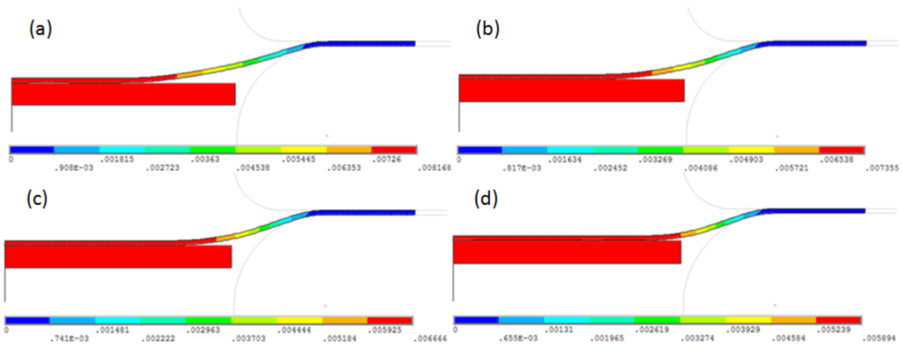

Figure 11 :*Displacement at different damping coefficient with the same spring stiffness 1e4 (a) 10Ns/M (b) 100Ns/M (c) 1000Ns/M (d) 10000Ns/M*

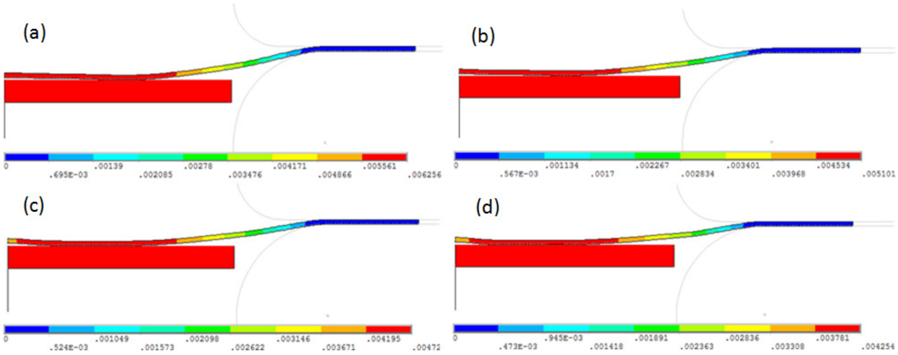

Figure 12 *:Displacement at different damping coefficient with the same spring stiffness 1e5 (a) 10Ns/M (b) 100Ns/M (c) 1000Ns/M (d) 10000Ns/M*

4 Conclusions

1. With a spring damper system added under the female stop block, the flatness of formed parts is improved.
2. Compared with free forming, difference of the stress strain-sate leads to the difference of thickness distribution, and the crack at the bottom is supressed.
3. The simulation results show that low spring stiffness and appropriate damping coefficient is beneficial to control the rebound effect when spring damper system is adopted.

References

[1] *Psyk, V.; Risch, D.; Kinsey, B. L.; et al.:* Electromagnetic forming—A review[J]. Journal of Materials Processing Technology, 2011, 211(5): 787-829.

[2] *Golovashchenko, S.; Imbert, J. M.; Worswick, M. J.:* Contributing Factors to the Increased Formability Observed in Electromagnetically Formed Aluminum Alloy Sheet[J]. 2006.

[3] *Boyd, J. M. S. I.:* Increased formability and the effects of the tool/sheet interaction in electromagnetic forming of aluminum alloy sheet[D]. University of Waterloo, 2005.

[4] *Oliveira, D. A.; Worswick, M. J.; Finn, M.; et al.:* Electromagnetic forming of aluminum alloy sheet: free-form and cavity fill experiments and model[J]. Journal of Materials Processing Technology, 2005, 170(1): 350-362.

[5] *Risch, D.; Brosius, A.; Kleiner, M.:* Influence of the workpiece stiffness on the electromagnetic sheet metal forming process into dies[J]. Journal of materials engineering and performance, 2007, 16(3): 327-330.