Effect of the Duration of Electromagnetic Pulse Force on the Rebound Suppression in V-Bending Experiment [*]

WeiRen Xiong[1], WenPing Wang[1], Min Wan[1],Long Pan[1]

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

Abstract

Electromagnetic Forming (EMF) is one of the high speed forming technologies. The spatial distribution and temporal evolution of electromagnetic body force and the constraint imposed by the die on the sheet metal, are key factors which influence the dynamic deformation behaviour of sheet metal. The great force induced by the collision at high speed of the sheet and the die causes the rebound of the sheet off the die. The rebound has a significant influence on the final shape of the part. On the basis of the comparison of time relationship between the displacement of the sheet metal and the amplitude of electromagnetic force, the study about the rebound phenomenon in an electromagnetic V-bending experiment and its numerical simulation model is carried out in this paper. Collision promotes deformation process, resulting in a drastic change of sheet geometry in which a new distribution of electromagnetic force helps the part to fit the die. The attenuation of force caused by distance increase is comparatively weak when forming into a shallow die, so that the electromagnetic force maintains enough intensity which can effectively suppress the rebound and help to calibrate the V-Shape of the part. Increasing the duration of coil current pulse helps to suppress rebound effect of sheet metal when forming into a shallow die.

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Corresponding author: Wen-Ping Wang; wwp_2003@163.com; Tel.:+86 010-82338613

Keywords

Electromagnetic forming, Aluminium alloy, V-bend, Rebound, Duration

1 Introduction

The application of aluminium alloys is under the restriction of low formability at room temperature, though the advantages of high strength-to-weight ratio, corrosion resistance and weldability [1]. Electromagnetic forming (EMF) is one of the high speed forming technologies, and can improve the formability without the costly expense and time period of thermal treatment. Electromagnetic forming (EMF) has been applied in the aerospace and automotive industries [2].

The finite element method is an important approach to study the instantaneous process of dynamic deformation behaviour of the sheet metal. The sequential coupling strategy and loose coupling strategy are two major strategies used in numerical model of EMF. Comparing the sequential coupling strategy with the loose coupling strategy, the latter does not consider the influence of structure deformation on the electromagnetic calculation. G. Bartels indicates that the deviations between the two strategies increase with time and also draws the conclusion that the loose coupling strategy can only be used as a good approximation for relatively fast deformation processes and small displacement through the numerical simulation of tube forming [3]. With the advantages of lower calculation cost and faster speed, the loose coupling strategy is wildly adopted in the research despite losing some accuracy.

In the loose coupling strategy, the nodal electromagnetic force which has been calculated without the deformation of a work-piece in the electromagnetic field is directly transferred into the work-piece in structure field as input load [2].

The spatial distribution and temporal evolution of electromagnetic body force and the constraint imposed by the die on the sheet metal, are major factors which influence the dynamic deformation behaviour of sheet metal.

The electromagnetic force decays with increasing distance between the coil and sheet during deformation, so the electromagnetic force in loose coupling is usually overestimated, resulting in a more violent collision. The undesirable violent impact often causes the rebound phenomenon preventing us from gaining the target shape of the parts. For this reason, J.Imbert takes a quarter circle of the sinusoid coil current to calculate the electromagnetic force [4]. D.A.Oliveira takes the time period between a quarter and a half of the sinusoid coil current pulse [5]. X.-h.Cui takes half of the sinusoid coil current pulse for his calculation. By neglecting a portion of the time for electromagnetic (EM) calculation, the overestimated force is compensated in structure field [6]. X.Cui investigates the influence of the number of pulse on deformation in a flat sheet free-bulging by comparing the loose coupling with the sequential coupling strategy [7].

J.Imbert reports that the predicted rebound is higher than the experimental result, and attributes the reasons to the energy excessively transmitted, the lower flow stress than actual material, and the extra pulses [4]. D.Risch adopts a spring-dashpot system representing the die’s physical behaviour to draw the conclusion that the optimum combination of stiffness and damping coefficient exists [8] and also introduces the geometrical stiffness of the desired work-piece geometry to investigate the rebound effect [9].

In this paper, we conducted a V-bending experiment and established the corresponding numerical model with the loose coupling strategy. The rebound phenomenon observed in V-bending numerical model is obviously higher than that in experimental result. Through studying the time relationship of the displacement of sheet and the amplitude of electromagnetic force in sheet, the effect of the pulse duration on rebound suppression can still be revealed. In addition, the effect of the update of distribution of force on the part's final shape was also analyzed. A better understanding of these factors will help to gain a desirable shape of the part.

The experimental procedure and the numerical simulation are introduced in section 2 and section 3 respectively, then the rebound suppression effect is analyzed in section 4, and the conclusion is given in section 5.

2 Experiment

Bend is one of the typical deformation modes in sheet metal forming. In order to gain insights into the local bend deformation behaviour of aluminium sheet metal in electromagnetic forming process, an electromagnetic V-bend experiment is conducted.

2.1 Sample

Sample of 2024-T3 aluminium alloy of 1.8 mm thick is considered in this experiment with the plane dimension of 100 mm × 40 mm. Basic mechanical properties and physical properties of 2024-T3 are shown in table 1.

Table 1: *The mechanical and physical properties of 2024-T3*

Parameter	Value	Parameter	Value	Parameter	Value
Density ($kg \cdot m^{-3}$)	2.68×10^{3}	Tensile Strength (MPa)	483	Resistivity ($\Omega \cdot m$)	5.82×10^{-8}
Elasticity Modulus (GPa)	73.1	Yield Strength (MPa)	345	Heat Conductivity (W/(m·K))	121
Poisson's Ratio	0.33	Elongation (%)	18%	specific heat (J/(g·K))	0.875

2.2 Tool and Die

It is well known that flat spiral coil is commonly used in study. Here an enhanced four-layer flat spiral coil, which provides greater forming force than the single-layer coil, is used in experiment. The geometric and electrical parameters are shown in table 2.

The die used in experiment is shown in Figure 1, and the experimental set-up of the experiment is shown in Figure 2.

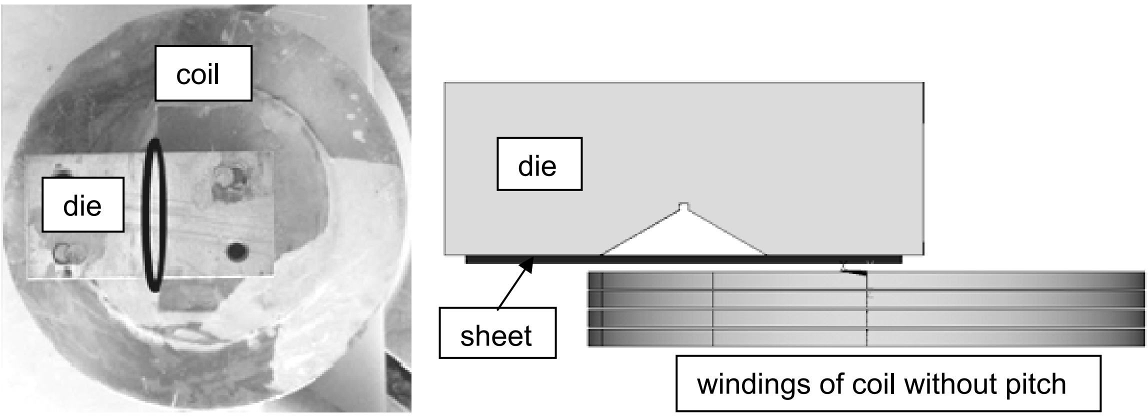
Table 2: *Geometric and electrical parameters of the coil*

Parameter	Value	Parameter	Value
Resistance (Ω)	0.001	Number of Turns	16
Inductance (H)	2×10^{-6}	Gap between Turns (mm)	0.8
Cross-sectional Area (mm^2)	2×4	Gap between Layers(mm)	0.4
Number of Layers	4		

Figure 1*: The die*

2.3 Experiment Set-up and Method

The coil is placed at the bottom, and the sheet is pressed by the die with its cavity facing the upper surface of the coil. The set-up of experiment is shown in top view in figure 2 (a) and side view in figure 2 (b). The charging voltage of capacitor is set at 18 kV. And the formed part is shown in figure 3.



(a) (b)

Figure 2*: The experiment set-up. (a) The top view, (b) The side view.*

***Figure 3**: Forming result of part after EMF*

3 Numerical Analysis

3.1 Simulation Method

In this paper, the loose coupling strategy is chosen as a numerical simulation approach to perform the analysis. An electromagnetic field simulation is firstly conducted with the actually measured pulse current as excitation source to solve the nodal electromagnetic force in the sheet in electromagnetic field, and then the electromagnetic force is directly input into the structure field as driving load that form the sheet. The measured coil current used for simulation is presented in figure 4, and the coupling approach is illustrated in figure 5. Only the first pulse of coil current is applied in the simulation.

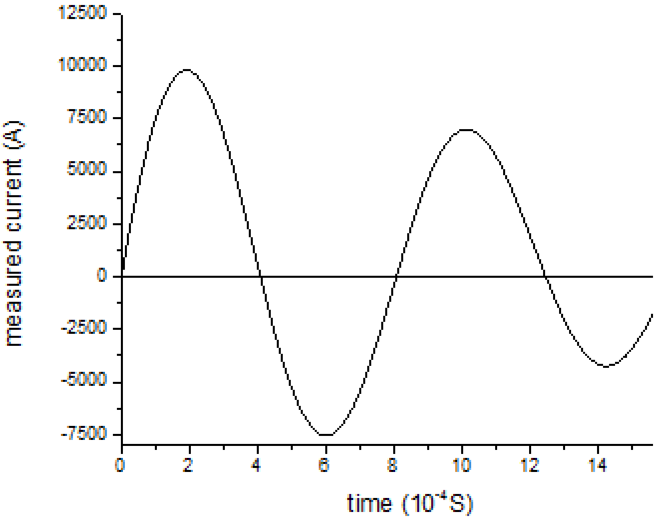


***Figure 4**: Measured coil current*

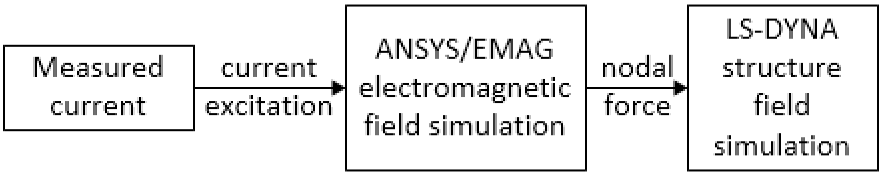


***Figure 5**: Flowchart of the loose coupling strategy*

3.2 Material Model

Equation (1) expresses the rate-dependent constructive model, Cowper-Symonds model, which is applied with the rate-dependent parameters C=6500 s^{-1} and P=4 [10]. σ_y is the dynamic flow stress at plastic strain rate $\dot{\varepsilon}$, σ_{ys} is the quasi-static flow stress. For the value of σ_{ys}, refer to [11].

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{p}}\right]\sigma_{ys} \tag{1}$$

4 Rebound Effect Suppression

Without considering the decay of electromagnetic force with increasing distance between the coil and the sheet in deformation stage, the electromagnetic force in the sheet is always overestimated. In order to compensate the over-input energy, the electromagnetic force is removed at 1.3×10^{-4} second when the sheet has not reached its deepest position in the die cavity, then the sheet continue to move into the inner die cavity in initial state with velocity field at this moment. Then, the sheet decelerate, rebound and stop at the position in figure 6. The kinematic energy stored in the sheet at this moment is high enough to push the sheet off the die, though part of the energy has been dissipated in collision.

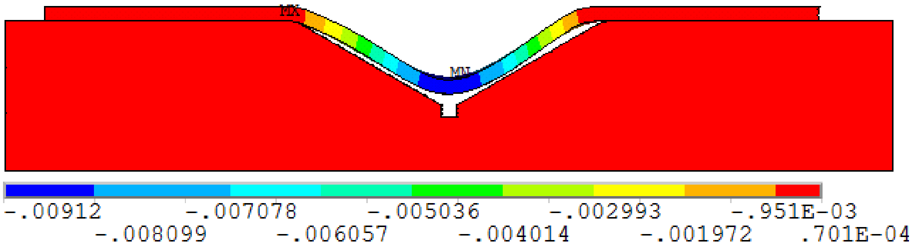


***Figure 6**: The final shape of the part at the condition of relasiing electromagnetic force at 1.3×10^{-4} second*

However, the fact that the sheet in experiment keeps contact with the die reveals that the intensity of the electromagnetic force is strong enough to efficiently suppress the rebound. In reality, after the time of 1.3×10^{-4} second, the sheet still undergoes the electromagnetic force. Figure 7 shows the final shape of the part under a whole current pulse excitation. The gaps between the part and die at both left side wall and right side wall of the part are obviously more significant than those in figure 3 and in figure 6. The gap at left side is caused by rebound. The compartive bigger gap at the right die radius is mainly caused by asymmetric electromagnetic force towards left at the right side of the sheet. The duration of force in figrure 7 is apparently longer than that in figure 6.

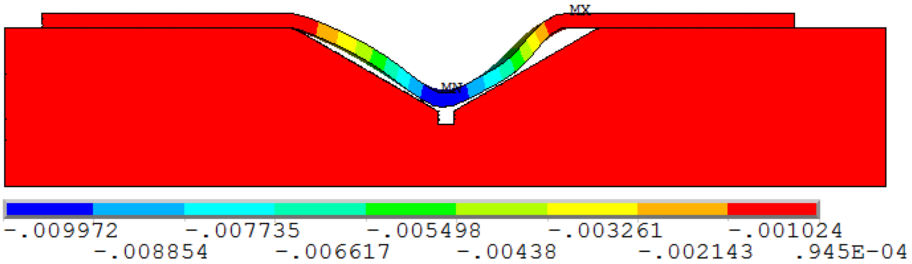


***Figure 7**: Final shape of the part under a whole current pulse excitation*

Figure 8 shows the time relationship between several different normalized physics quantities. *J* is the current in the coil, *Uz* is the displacement of the sheet towards –Z direction, *Fz1* and *Fz2* is the nodal electromagnetic force corresponding to the elements in position “1” and “2” as shown in figure 9. We are primarily concerned with the temporal evolution of absolute value. For ease of comparison, the maximum value of *J* is normalized to 3, the maximum value of *Uz* is normalized to 2, the maximum value of *Fz1* and *Fz2* is normalized to 2. The sheet reaches its deepest position in its deformation history at the time of 1.5×10^{-4} second when the displacement tracking process is stopped. It can be observed from the graph that the width of force pulse is narrower than that of current pulse.

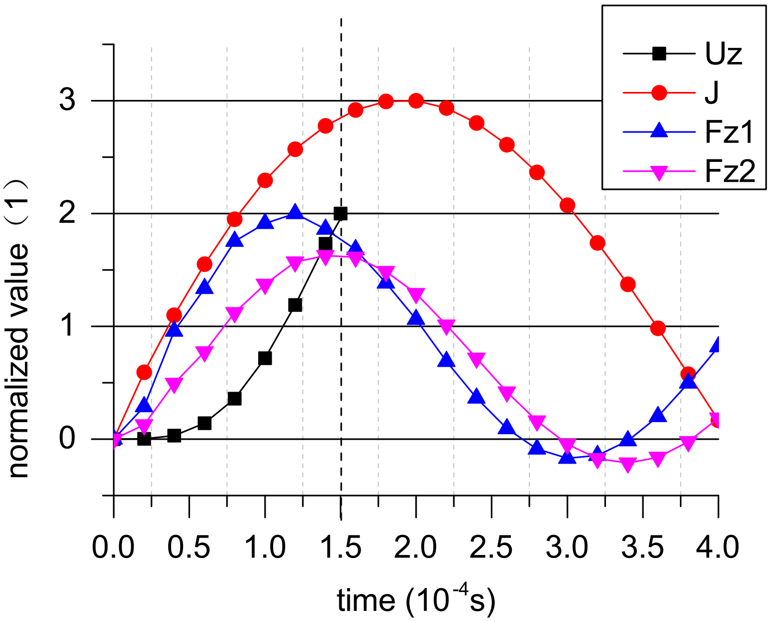


***Figure 8**: The graph of displacement, current and the electromagnetic force versus time*

In flat sheet free-bulging process, due to unlimited motion of the sheet and longer period of time for deformation, the increased distance between sheet and die causes a significant attenuation rate of force. However, in this article, the distance of the sheet from the coil is limited by the shallow die, wherein the attenuation of force is relatively weaker. Meanwhile, as shown in figure 8, the electromagnetic forces, *Fz1* and *Fz2*, reach their peaks ahead of coil current. When the sheet reaches the deepest position, the forces maintain enough intensity nearby their own peaks.

The distance dependent decaying curve of electromagnetic force versus time has already been analysed by [7]. Figure 10 shows the schematic curve of sequential coupling electromagnetic force. Its amplitude is relatively lower compared to the electromagnetic force in a loose coupling simulation. The abscissa is time and the ordinate axis is the amplitude of normalized force. The sheet reaches its maximum depth at the time *t1*, then rebounds away from the die until time *t2* when the sheet fit the die for a second time.

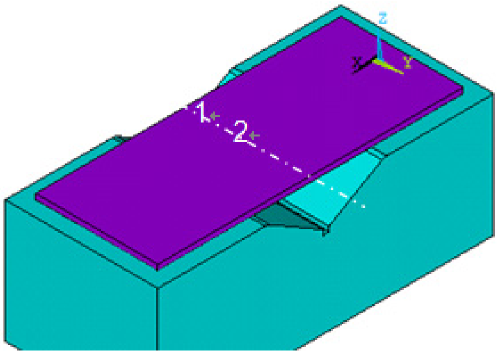


Figure 9. Positions of *Fz1* and *Fz2*

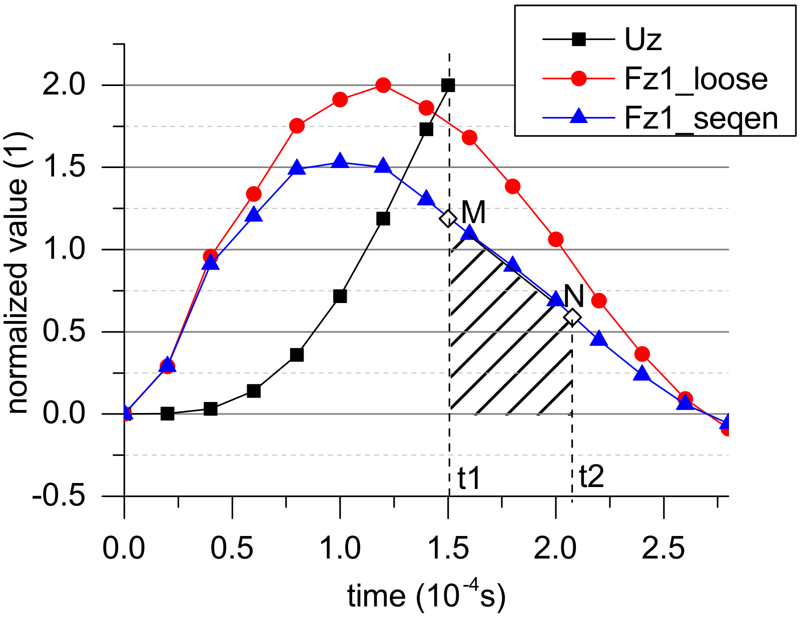


Figure 10: *The electromagnetic force in loose coupling strategy and the schematic one in sequential coupling strategy*

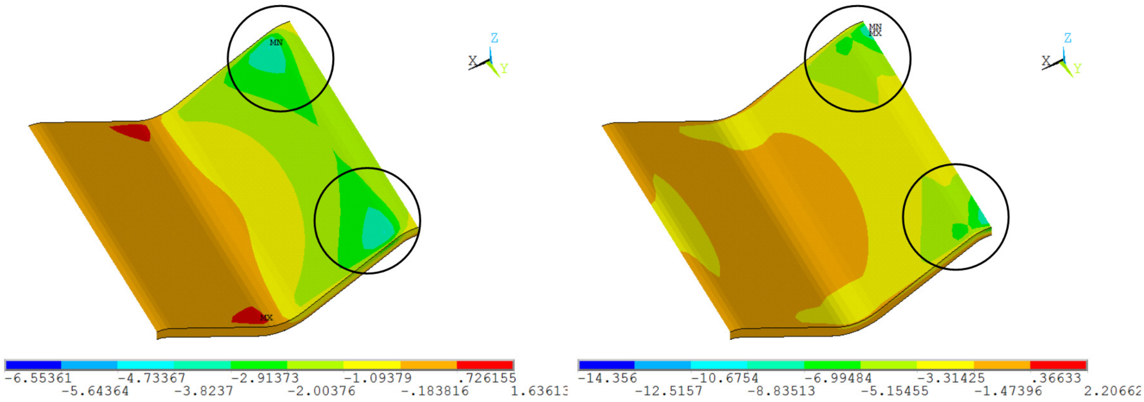
Assuming that the rest of kinematic energy has been dissipated in the second collision, the force from *t1* to *t2* plays the role of preventing the sheet from bouncing back away from the inner surface of the die. The area of the shaded portion in figure 10 is the impulse applied to the sheet by force within the time period between *t1* and *t2*.

The distribution of electromagnetic force also influences the forming result. X. Cui investigated the effect of the second current pulse on deformation in free bulging experiment and concluded that the width of current pulse plays a role on the accuracy of the predication by comparing a loose coupling strategy with a sequential coupling strategy [7]. And, the fact that the electromagnetic force is mainly perpendicular to the curved surface of the sheet geometry is presented in [12, 13]. The following equation defines the electromagnetic force.

$$\boldsymbol{F}=\boldsymbol{J}\times\boldsymbol{B} \tag{2}$$

Where, ***F*** is electromagnetic force, ***J*** is current, ***B*** is flux intensity.

The geometric meaning of the equation (2) expresses that ***F*** is normal to the plane of ***J*** and ***B***. Since that the induced eddy current can only flow in the sheet geometrical surface, there is always a component of the force normal to the surface of the sheet. Figure 11 shows the contour graph of components of electromagnetic force in the deformation region in another numerical model where the sheet has gotten the V-shape. These two components all push the sheet to the die. The circles show the region with maximum amplitude of force along X and Z direction in figure 11 (a) and figure 11 (b) respectively. And the force in the circles help to reduce the gaps at right die radius as shown in figure 7 and figure 3 by preventing the right part of sheet from moving toward the cavity of die. That is, the new direction of electromagnetic force after deformation helps to press the sheet toward the sidewall of the V-shape die. So, this is a calibration-like process. However, the accuracy of prediction of the loose coupling strategy is limited in the prediction of forming process with die for its insufficient in updating the distribution of force.



（a）　　　　(b)

Figure 11*: (a) X component of electromagnetic force and (b) Z component of electromagnetic force*

5 Conclusion

Our analysis shows that, the bigger electromagnetic force pulse width extends the time period of acting force. So, a more accurate part can be manufactured through supressing the rebound effect by means of widening the width of electromagnetic pulse when forming into a shallow die wherein a weaker attenuation of electromagnetic force exists as a result of the small distance between the sheet and the coil. The new distribution of force helps to push the sheet to the die, therefore helps to maintain the V-shape of the part. In addition, the sequential coupling strategy that can update the amplitude and distribution of force is needed to conduct a more accurate prediction.

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