Less damage accumulation of aluminum alloy sheet during electromagnetic forming based on Gurson-Tvergaard-Needleman model

W Liu1,2*, H Zhou1, Z Meng3, J Li1 and S Huang1
1 School of Materials Science and Engineering, Wuhan University of Technology, Wuhan, China
2 State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha, China
3 School of Automotive Engineering, Wuhan University of Technology, Wuhan, China
* E-mail: weiliu@whut.edu.cn

Abstract. The formability of aluminum alloy sheet is usually improved during electromagnetic forming (EMF). Here, the ductility enhancement mechanism was investigated on the basis of Gurson-Tvergaard-Needleman (GTN) model. The parameters of GTN models under quasi-static tension and EMF conditions were respectively determined by inverse identification. For AA2024-O aluminum alloy sheet under quasi-static tension, the initial void volume fraction is identified as 0.006, the critical void volume fraction where voids begin to aggregate is 0.075, the void volume fraction of nucleating particles is 0.131 and the mean nucleation strain is 0.44. With the similar initial void volume fraction, the other parameters under EMF condition are determined as 0.045, 0.055 and 0.58. The evolution curve of void volume fraction with strain were compared under EMF condition and quasi-static tension. The results show that the total growth of void volume fraction is less under EMF condition than that under quasi-static tension. A box part with inclined flange was preliminary achieved by electromagnetic forming process. The GTN model was finally verified by comparing the numerical and experimental results.

1. Introduction

Electromagnetic forming (EMF) is a high speed forming process by using Lorentz force to make workpiece deform. When an impulse current runs along the coil, an eddy current is induced in the adjacent conductive workpiece, and the Lorentz force is consequently generated between the coil and workpiece. The forming speed of material can exceed $10^2$ m/s and the strain rate can reach up to several $10^3$ s$^{-1}$. Compared with that during the quasi-static forming processes at room temperature, the formability of aluminum alloy sheet can be effectively improved during EMF [1-3]. However, it is still needed to investigate the ductility enhancement mechanism of aluminum alloy sheet during EMF.
The ductile damage behavior of metals is summarized as nucleation, growth and coalescence of micro voids [4]. The ductile damage accumulation in sheet metal forming process will not only relate to the formability, but also affect the mechanical properties in service [5]. Gurson-Tvergaard-Needleman (GTN) model is one of the widely-used damage model [6-9] to predict the ductile fracture of sheet metal in numerical simulation. It uses void volume fraction to represent the damage degree of sheet metals. Imbert et al [10] compared the electromagnetic bulging processes of AA5754 aluminum alloy sheet without and with concave die by experiment and numerical simulation. The GTN model with the same parameters under quasi-static condition was used to numerically investigate the damage behavior of aluminum alloy sheet. The higher formability of EMF was attributed to the increased hydrostatic pressure and the decreased void volume fraction by the interaction between aluminum alloy sheet and concave die. Feng et al [11] used the GTN model to numerically predict the fracture behavior of 5052-O aluminum alloy sheet under high speed electromagnetic impaction. The parameters of GTN model were determined via scanning electron microscopy after EMF experiment. Zeng et al [12] investigated the influences of discharge voltage, impact distance and pre-strain level on the damage evolution of aluminum alloy sheet during EMF with uniform pressure actuator. The numerical simulation with GTN model showed that the damage accumulation was reduced by the high impact pressure between the die and sheet.

In order to inspect the ductile damage behavior of aluminum alloy sheet during EMF by numerical simulation with GTN model, the parameters should be determined at high strain rate. At present, there are three methods to determine the parameters of GTN model: metallographic analysis [13], representative volume element (RVE) [14] and inverse identification [15, 16]. Metallographic analysis is used to determine the damage parameters by observing the metallographic phase of tensile samples at different stages of tensile test. RVE is a method to obtain nucleation-related parameters through finite element analysis of a single cell. The inverse identification is performed by updating the material parameter in numerical simulation to minimize the discrepancy between the numerical and experimental results. Due to the advantages of global accuracy and good convenience, the inverse identification method is commonly adopted to determine the parameters of GTN model.

The GTN model parameters of AA2024-O aluminum alloy sheet were respectively identified with the quasi-static tensile test and electromagnetic hole flanging (EMHF) test. The damage evolution curves were compared under the quasi-static and EMF conditions to inspect the ductile damage behavior of aluminum alloy sheet during EMF. At last, an EMF experiment of a box part with inclined flange was carried out. The GTN model was used for numerical simulation, and it was validated by comparing with the experimental results.

2. Parameter identification of GTN model

2.1. GTN model

The GTN model is expressed as following:

$$\varphi = \left( \frac{\sigma_M}{\sigma_Y} \right)^2 + 2q_1 f^* \cosh \left( \frac{3q_2 \sigma_H}{2\sigma_Y} \right) - 1 - \left( q_1 f^* \right)^2 = 0$$ (1)
where $\sigma_M$ is the von Mises equivalent stress, $\sigma_Y$ is the yield stress, $\sigma_H$ is the hydrostatic stress, $q_1$, $q_2$ are the correction coefficients (the values are usually defined as $q_1 = 1.5$ and $q_2 = 1$), and $f^*$ is the equivalent void volume fraction. The overall rate of the void volume fraction in the GTN model is derived by the rate of the void volume fraction caused by the growth of existing voids and caused by void nucleation.

The parameters to be determined in GTN model include: the initial void volume fraction $f_0$, the void volume fraction $f_N$ of nucleating particles, the critical void volume fraction $f_c$ where voids begin to aggregate, the failure void volume fraction $f_F$, the mean nucleation strain $\varepsilon_N$, and the standard deviation $\sigma_N$ of the normal distribution of $\varepsilon_N$ (the value is usually defined as $\sigma_N = 0.1$). Here, GTN model is used to characterize the ductile damage evolution of the fully annealed AA2024-O aluminum alloy sheet with the initial thickness of 1mm. The failure of material is not considered. The parameters $f_0$, $f_N$, $f_c$ and $\varepsilon_N$ of GTN model are determined by inverse identification under quasi-static tension and EMF conditions.

2.2. Inverse identification of GTN parameters under quasi-static tension

The quasi-static tensile specimen was shown in Figure 1(a). The longitudinal direction of the specimen is consistent with the rolling direction of the sheet. Unlike the parallel section of standardized uniaxial tensile specimen, a large circular arc with a radius of 500 mm was designed to ensure that the localization occurred in the central region of the specimen, as shown in Figure 1(b). The quasi-static tensile test was carried out at room temperature and nominal strain rate of $0.001 \text{ s}^{-1}$ to obtain the experimental force and elongation curve of 2024-O aluminum alloy sheet. The tests were repeated with three times to show a good agreement.

The 3D finite element model with the same geometry and constrains as the quasi-static tensile test was presented in Figure 2. The part was meshed with shell elements in software LS-Dyna. The element size was refined to be 0.5mm to guarantee the numerical accuracy of deformation in the central area. The fully fixed constraint was adopted at the left end and the displacement was applied at the right end. The simulated force and elongation curve was derived by the reaction force at the left end and the distance increment $\Delta L$ between the point A and B.

![Figure 1](image-url)  
Figure 1. Quasi-static tensile specimen: (a) Geometry, (b) Fracture.
Figure 2. Finite element model of quasi-static tensile test.

The inverse identification can be summarized as numerical optimization problem of minimizing the discrepancy between the simulated and experimental results by updating the parameters of GTN model. Here, the successive response surface method (SRSM) was used to match the experimental and simulated curves of force and elongation for the parameter optimization. The identified parameters of GTN model were shown in Table 1. Finally, the simulated curve showed a good agreement with the experimental one, as shown in Figure 3.

Figure 3. Experimental and simulated curves of quasi-static tensile test.

2.3. Inverse identification of GTN parameters under EMF condition

The principle of EMHF experiment was shown in Figure 4(a). It consists of charging circuit and discharging circuit. In this experiment, the capacitance and voltage were chosen to be 550μF and 3.25kV respectively. The capacitor tank C was previously charged by a power supply of high voltage U0. When the discharging circuit was turn on, a transient electrical current flowed along the coil. Then, a transient magnetic field was generated around the coil and an eddy current was induced in the conductive sheet. Consequently, the Lorentz forces occurred between the coil and sheet. The sheet undergone elastoplastic deformation at high speed. A circular drawbead was used to prevent the outer margin from flowing into die. The experimental setup was shown in Figure 4(b). The die and base were made of steel. A flat spiral coil with winding number of 12 was used in the experiment, as shown in Figure 4(c). The interval between adjacent turns was 1.6 mm. The cross-section of each turn was rectangle of 2.5mm×10mm. The coil was made of copper by electrical discharge machining. It was fixed in polytetrafluoroethylene (PTFE) with epoxy to guarantee the strength and insulation. The
distance between the coil and sheet was 2 mm. The outer and inner diameter of specimen were 180mm and 60mm, as shown in Figure 5(a). After EMHF, the displacement along Z direction and the thickness at the marked points of F, G, H, M and N along a generatrix were measured with accuracy of 0.01mm and 0.001mm, as shown in Figure 5(b). The height of workpiece reached 24.77mm, and the minimum thickness at the top was 0.840mm.

The numerical simulation of EMHF experiment was performed by sequential coupling of electromagnetic and mechanical fields. The electromagnetic field in air was calculated by boundary element method. It avoided the meshes of air and reduced the computation cost. The die, coil and base were defined to be rigid and fixed. The sheet and coil were discretized with hexahedral elements to accomplish the calculation of electrical currents, as shown in Figure 6. The aluminum alloy sheet was characterized by isotropic elasticity, Johnson-Cook (J-C) hardening model and GTN model. The elastic modulus and Poisson ratio were 68GPa and 0.33, respectively. The J-C model was defined as

\[
\sigma = (74\text{MPa} + 362\text{MPa} \times \varepsilon_p^{0.51})\left(1 + 0.0073 \times \ln\left(\dot{\varepsilon}/\dot{\varepsilon}_0\right)\right) \quad \text{with} \quad \dot{\varepsilon}_0 = 10^{-3} \text{s}^{-1}
\]

A surface-to-surface contact with the friction coefficient of 0.2 was applied between the sheet and other components.
The parameters of GTN model under EMF condition were inversely identified by minimizing the discrepancy between experimental and simulated displacements along Z direction of workpiece. The simulated displacements showed a good agreement with experimental ones, as shown in Figure 7(a). The simulated and experimental thicknesses were compared to validate the accuracy of parameters. The numerical thicknesses almost matched with the experimental ones, as shown in Figure 7(b).

The identified parameters of GTN model were compared with the similar initial void volume fraction in Table 1. Considering that the deformation path at the edge of EMHF specimen is nearly the same with that at the central zone of quasi-static tensile specimen, the curves of void volume fraction (VVF) and strain at the two zones were compared to inspect the ductile damage evolution, as shown in Figure 8. The VVF increased with the deformation under the both conditions. However, the VVF increased significantly after the effective plastic strain of about 20% under quasi-static tension, while it increased slowly under EMF condition. With the deformation becoming larger, the induced current and Lorentz forces decreased quickly. The EMF deformation continued to increase by inertia effect, so the inertia effect was assumed to result in slow growth of VVF.

| Parameters          | $f_0$ | $f_c$ | $f_N$ | $\varepsilon_N$ |
|---------------------|-------|-------|-------|-----------------|
| Quasi-static tension| 0.006 | 0.075 | 0.131 | 0.44            |
| EMHF                | 0.006 | 0.045 | 0.055 | 0.58            |
3. Application for EMF of a box part with inclined flange

A box part with inclined flange was shown in Figure 9(a). The maximum and minimum heights were 32mm and 17mm respectively. Due to the complex geometry, it is difficult to be deformed by the traditional forming methods such as deep drawing. Because of the high formability of aluminum alloy sheet during EMF, an EMF process with flat rectangular coil was applied for the box part, as shown in Figure 9(b). The coil was positioned at horizontal plane, and the sheet was placed at inclined plane. Where the sheet was closer to the coil, the Lorentz forces were larger and the deformed depth was larger. When the sheet contacted to the bottom of die, the rubber at the bottom absorbed the residual energy of sheet to form the flat bottom. The experimental setup was shown in Figure 10(a). The blank holder was installed on the hydraulic machine to press the flange of specimen with pressure of about 20MPa in order to avoid wrinkles. The flat rectangular coil was shown in Figure 10(b). The overall size of the coil is 110mm×96mm×10mm and the interval between adjacent turns was 3 mm. The capacitance and voltage were chosen to be 550μF and 6.5kV here. The specimens were shown in Figure 11. The principal strains were measured by a grid analysis software after deformation.

(a)

Figure 9. Box part with inclined flange: (a) Geometry (b) EMF principle.
Figure 10. EMF experimental setup: (a) Die and tools, (b) Coil.

Figure 11. Specimens with inclined flange: (a) Before deformation, (b) After deformation.

The numerical model of EMF for the box part with inclined flange was shown in Figure 12. The GTN model was used for the AA2024 aluminum alloy sheet. The simulation results were shown in Figure 13. The thickness reduction of the box part was shown in Figure 13(a). The maximum and minimum thickness reductions were 7.79% and -10.02%. The distribution of VVF was shown in Figure 13(b). The maximum value of 0.0072 appeared at the maximum depth.

Figure 12. Numerical model of box part with inclined flange.
In order to verify the GTN model, the results of experiment and simulation were compared along the symmetric section in Figure 11(b). The height, thickness, principal strains of specimen were compared with the numerical results respectively, as shown in Figure 14. The profile of the part was close to the simulated one, although the experimental height was slightly larger than the simulated value at the smaller depth, as shown in Figure 14(a). The maximum and minimum thicknesses were 1.090mm and 0.926mm, as shown in Figure 14(b). The first and second principal strains of numerical simulation were basically consistent with those of experimental part, as shown in Figure 14(c) and 14(d). The results showed that the parameters of GTN model is accurate for numerical simulation.

**Figure 13.** Numerical results: (a) Thickness reduction, (b) Void volume fraction.

**Figure 14.** Comparisons of EMF experiment and simulation: (a) Height, (b) Thickness, (c) First principal strain, (d) Second principal strain.
4. Conclusion
The inverse identification of GTN model were performed under the quasi-static tension and EMF conditions for AA2024-O aluminum alloy sheet. With the similar initial void volume fraction, the other parameters are different under both conditions. The curve of void volume fraction and strain increased more significantly under quasi-static tension when compared with that under EMF condition. Therefore, the less damage accumulation was revealed for AA2024-O aluminum alloy sheet during EMF. It can be attributed to an important aspect of the ductile enhancement mechanism for EMF. The numerical simulation with GTN model was performed for EMF of a box part with inclined flange. The accuracy of GTN model was verified by comparing the simulation and experimental results.

5. References
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Acknowledgments
The work is financially supported by National Natural Science Foundation of China (grant number 52005374) and by open research fund of State Key Laboratory of High Performance Complex Manufacturing, Central South University (grant number Kfkt2021-04).