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Influence of process parameters on hybrid forming of aluminum sheet ①

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[Abstract] The influences of the plastic melt pressure and its distribution from the gate to the end of the mold, and of the friction coefficient between the sheet flange and the mold on forming process of the aluminum sheet have been investigated by Finite Element Method. It was shown that further deformation is mainly concentrated on metal sheet around the root corner of the mold, and that two highly strained zones with the severest thickness reduction are formed when the plastic melt pressure increased from 30 MPa to 50 MPa. The deformation of the sheet flange decreased and biaxial tension in plane of the sheet in the mold increased with increase of the friction coefficient. The non-uniform distribution of the plastic melt pressure had negligible influence on forming process of the sheet.

[Key words] sheet metal forming; injection molding; process parameter; finite element method (FEM); aluminum sheet

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1 INTRODUCTION

Hybrid forming is a new method for manufacturing of metal sheet and plastic combined macro-composite components[1]. Two metal sheets with pretreated surfaces are held together along their edges by clamping operation of the mold for hybrid forming through the injection machine, from nozzle of which the plasticized plastic melt is injected and flows along sprue gate of the mold. The metal sheet is deformed by pressure according to contour of the mold cavity similar to hydroforming[2~5]. The more the plastic melt is injected into, the more sever deformation the metal sheet undergoes, and the bigger the contact areas between the metal sheet and the mold cavity become, and thus the higher pressure of the plastic melt can be built up in the deformed metal sheets. After the injection stage, the plastic melt gets cool and is transferred into solid state gradually, in which it adheres to the surface of the deformed metal sheets directly and thus the macro-composite component combining the two metal sheets with the plastic has been fabricated. Fig. 1 shows the schematic diagram of the hybrid forming. This macro-composite component is composed of the two kinds of parts and the properties are quite different from metal and plastic, and posses a combined quality, such as light density, high stiffness, thermal insulation, and sound and vibration damping[6~10]. In the hybrid forming, the injected plastic melt supplies forces for deformation of the metal sheets and the formed metal sheets act as molding cavity of the plastic melt. It is an interweaving process. Hence the deformation of the metal sheets is very complex. In order to obtain the components with the desired shape and high accuracy, and a good adhesion between the plastic and the metal sheets, it is necessary to determine the process parameters having effects on hybrid forming of the metal sheets. The influences of the plastic melt pressure and its distribution from the gate to end of the mold, and of friction coefficient between the sheet flange and the mold on the hybrid forming process of the aluminum sheet have been investigated by FEM and experiment.

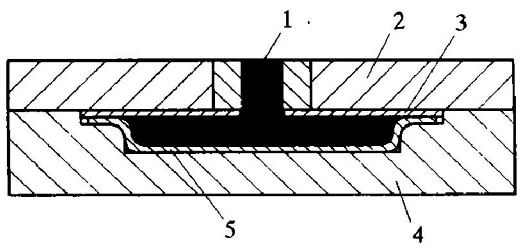

Fig. 1 Schematic of hybrid forming for metal sheets and plastic
1 —Plastic; 2 —Plate;
3 —Unformed aluminum sheet with a hole;
4 —mold; 5 —Formed aluminum sheet

2 FACTORS INFLUCING HYBRID FORMING OF METAL SHEET

In the hybrid forming process, the metal sheet

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forming and the plastic injection molding are integrated into one procedure. The parameters that have effects on pressure of the plastic melt and its distribution, friction action between the metal sheet and the mold, and clamping of the metal sheet will have influences on the forming process and the deformation characteristics of the metal sheet in hybrid forming. These parameters include the plastic materials, the temperature of the plastic melt, the injection pressure, the injection rate, the clamping force of the metal sheet and the friction action between the sheet metal and the mold.

Due to the wide application of polyethylene and polypropylene and their low cost, the high-density polyethylene (HDPE) and polypropylene (PP) were chosen in the experiment. The metal sheets are half-hard commercial pure aluminum sheets with 50 mm in diameter and 1 mm in thickness. During the clamping operation of the mold, the sheet was compressed on its edge by 0.05 mm in thickness.

The main injection parameters determined for HDPE are the injection temperature 200 ℃, the injection pressure 140 MPa and 107 MPa respectively, and for PP the injection temperature 230 ℃ and the injection pressure 116 MPa. The same injection rate of 4.35 cm^3/s is determined for both of the plastic materials. The pressure transducer is used to measure pressure of the plastic melt near the end of the mold. It is shown that the maximum pressures is 49.7 MPa and 35.1 MPa respectively for HDPE and 50.2 MPa for PP, and that the pressure increases to the maximum values rapidly in about 1.2 s. As will be shown in the following section, the maximum pressure has influences on the deformation process of the aluminum sheet in hybrid forming.

Because of cooling of the mold, temperature of the plastic melt decreases and eventually a thin solid layer is formed on the surface of the aluminum sheet, while the viscosity of the plastic melt increases. This will cause non-uniform distribution of the plastic melt pressure in the deformed sheet[11]. Hence it is necessary to make it clear that the influence of this non-uniform distribution of the plastic melt pressure on the deformation process of the aluminum sheet. The non-uniform plastic melt pressure is determined to be 50~35 MPa from center of the mold to the end of the mold with linear distribution.

In addition to the above factors, the deformation process of the metal sheet is affected by the condition of contact and friction between the metal sheet and the mold. Four cases of friction coefficients of 0.02, 0.05, 0.10 and 0.15 are assumed for the finite element simulation of the hybrid forming process. The plastic melt pressure of 50 MPa and the same other conditions are prerequisite in the four cases of different friction coefficients.

3 FINITE ELEMENT ANALYSIS ON ALUMINUM SHEET FORMING

Due to the finite deformation with large plastic strain of the metal sheet in hybrid forming, the updated elastic-plastic Lagrange finite element formulation is used to simulate the forming process of the aluminum sheet on the commercial non-linear MARC[12] finite element code. The forming is treated as an axisymmetrical deformation, so just one half of the metal sheet need to be analyzed. 4 × 65 2-D 4-nodes isoparametric quadrilateral axisymmetric solid elements (i.e. MARC element type 10) with four Gaussian integration points are used to mesh the half aluminum sheet with 65 elements along the radial direction and 4 elements through the thickness for describing of the bending effects. The plates and cavity of the mold are assumed to be rigid.

Characteristic parameters of the aluminum sheet are the elastic modulus 70 GPa, Poisson's ratio 0.33, the initial yield stress 70 MPa, and the tensile strength 100 MPa. The sheet material is treated as an elastic-plastic body with isotropic hardening, and the Von Mises yield condition is adopted. Temperature effects of the plastic melt on mechanical properties of the aluminum sheet are neglected because the contact time between them is only about 1.2 s during which the pressure of the plastic melt reaches its maximum value.

The friction between the sheet and the mold is simulated using the shear stress friction model taking influence of the relative sliding velocity into account adopted by Kobayashi et al[12, 13].

3.1 Effects of maximum pressure of plastic melt

Fig. 2 shows the deformed meshes at the maximum pressures of the plastic melt of 15, 35 and 50 MPa, respectively. It can be seen that the aluminum sheet being deformed can be divided into three different regions: the flange region including the mold entry region (taken as region Ⅰ), the mold bottom contact region (taken as region Ⅱ) and the mold root corner region (taken as region Ⅲ). Fig. 3 presents distribution of the maximum principal plastic strain ε_{max}, the minimum principal plastic strain ε_{min}, the circumferential plastic strain ε_{33} and the equivalent plastic strain ε_e in the mid-plane of the formed aluminum sheet at different maximum pressure of the plastic melt. As for region Ⅰ, ε_{min} remains almost no change during the whole forming. This is due to thickening of the flange is constrained by clamping of the mold. While ε_{max} increases and ε_{min} increases negatively, as a result, ε_e increases. However, it should be noted that there is almost no further plastic deformation in region Ⅰ when pressure of the plastic melt increases from about 30MPa to 50MPa. As in region II, it is obvious that the thickness reduction of the aluminum sheet in the forming process takes place in deformation of stretch forming due to the positive circumferential plastic strain. As pressure of the plastic melt increases, the contact area between the aluminum sheet and bottom of the mold increases, and plastic deformation of region II increases slowly. When the maximum pressure of the plastic melt has reached, the plastic deformation in region III increases rapidly, which results in decrease of the radius of the formed sheet around root corner of the mold. Two highly strained zones, one between region III and region I and the other one between re-

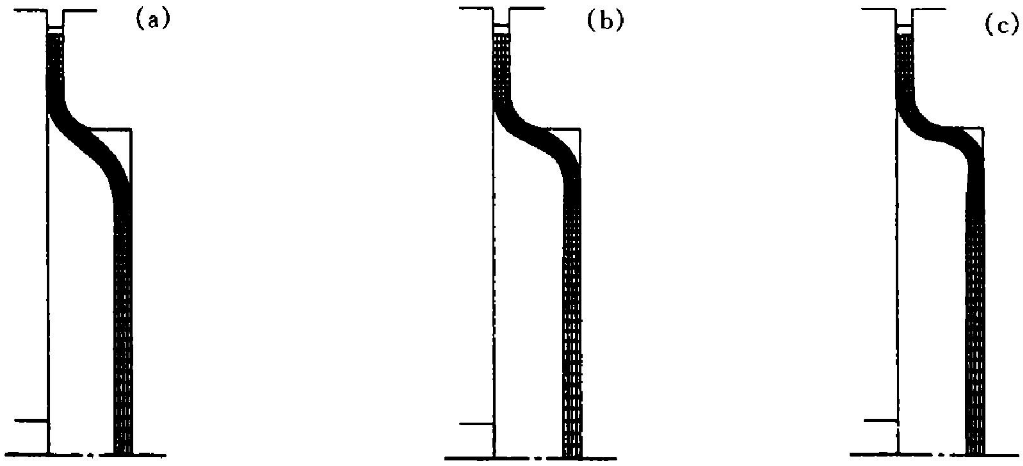

Fig. 2 Deformed meshes at different maximum pressures of plastic melt
(a) —15MPa; (b) —35MPa; (c) —50MPa

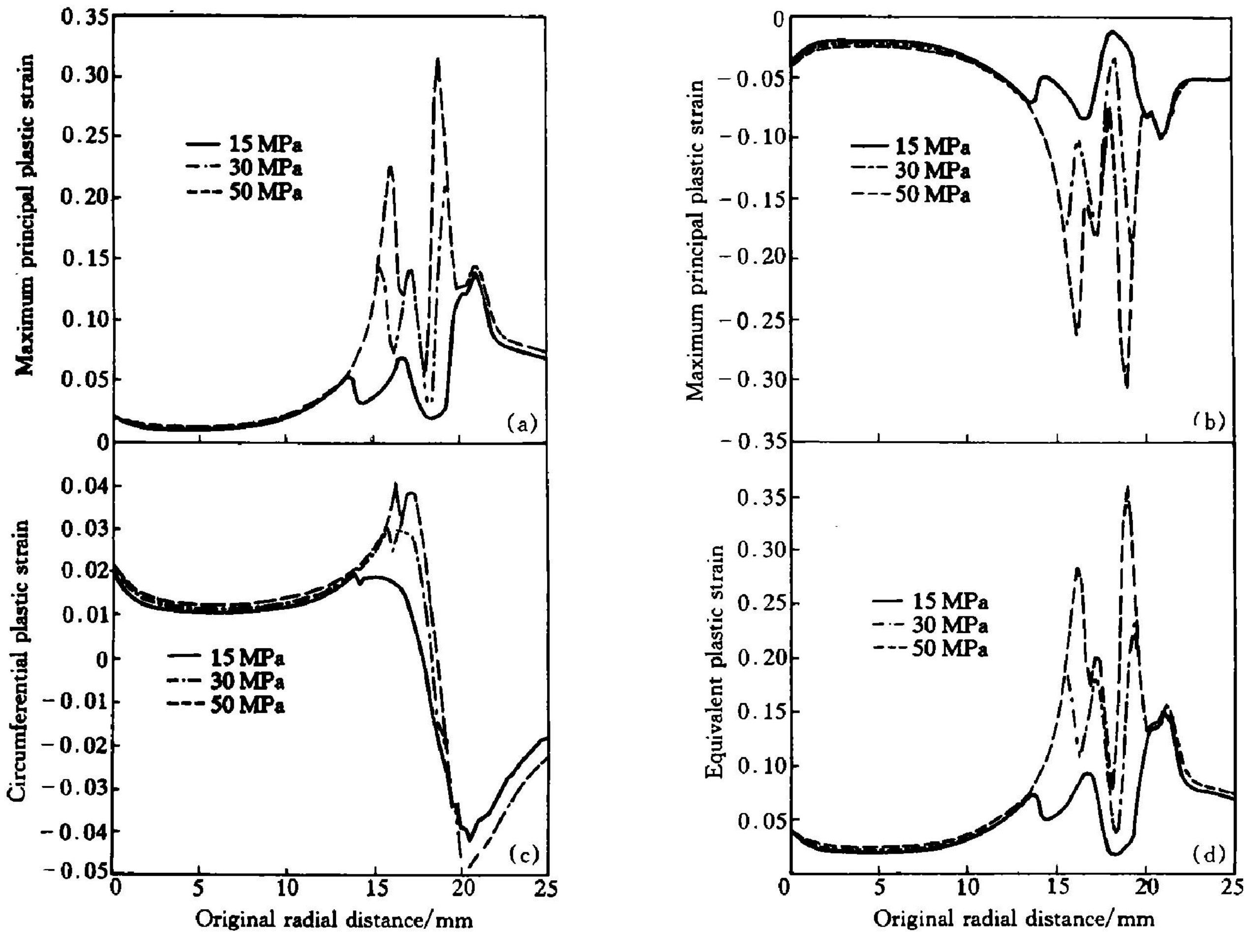

Fig. 3 Distribution of maximum principal plastic strain ε_{max}(a), minimum principal plastic strain ε_{min}(b), circumferential plastic strain ε_{33}(c) and equivalent plastic strain ε_{e}(d) in mid-plane of formed aluminum sheet

gion III and region II, have developed. Fig. 4 shows thickness distribution of the formed aluminum sheet by FEM simulation and by experiment (the values in bracket) at 50 MPa of the plastic melt pressure. It can be seen that the simulated results agree with the experimental ones.

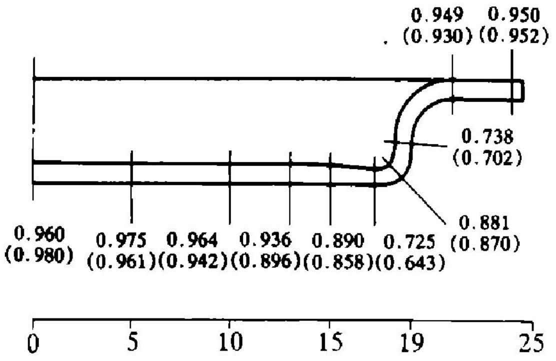

Fig. 4 Thickness distribution of formed aluminum sheet by FEM simulation and by experiment (values in bracket, unit: mm)

3.2 Effects of pressure distribution of plastic melt

Fig. 5 shows the distribution of the equivalent plastic strain ε_e and the circumferential plastic strain ε_{33} in the mid-plane of the formed aluminum sheet at the pressure distribution of 50~ 35 MPa and 35~ 35 MPa from center of the mold to the end of the mold with linear distribution. It can be seen that the non-uniform distribution of the plastic melt pressure caused by viscosity of the plastic melt just results in very small difference of plastic deformation of the aluminum sheet in region II. The same result is shown also at the pressure distribution of 60~ 50 MPa and 50~ 50 MPa from center of the mold to the end of the mold with linear distribution. The agreement of thickness of the formed aluminum sheet by FEM simulation at the maximum pressure of 50 MPa and 35 MPa (both are with uniform pressure distribution) with those obtained by the experiment also demonstrates that the non-uniform distribution of the plastic melt pressure has negligible influence on the plastic deformation of the aluminum sheet in hybrid forming.

3.3 Effects of friction coefficient between flange and mold

Fig. 6 shows evolution of draw-in of outer edge of the flange of aluminum sheet with pressure of the plastic melt during hybrid forming under different friction coefficients between the flange and the mold. It can be seen that the draw-in increases with decrease of the friction coefficient. Fig. 7 shows the circumferential plastic strain ε_{33} in mid-plane of aluminum sheet at different friction coefficients. It can be seen that ε_{33} in region I increases negatively and that ε_{33} in region II decreases as friction coefficient decreases.

4 CONCLUSIONS

1) The updated elastic-plastic Lagrange finite element formulation has been used to simulate the deformation process of aluminum sheet in hybrid forming. The simulated results agree with the experiment.

2) The aluminum sheet being deformed can be divided into three different regions, i. e. the flange region including the mold entry region (region I), the mold bottom contact region (region II) and the mold root corner region (region III). When the maximum pressure of the plastic melt increases, plastic deformation of the sheet increases. However, deformation of the sheet is mainly concentrated on region III, and two highly strained zones, one between region III

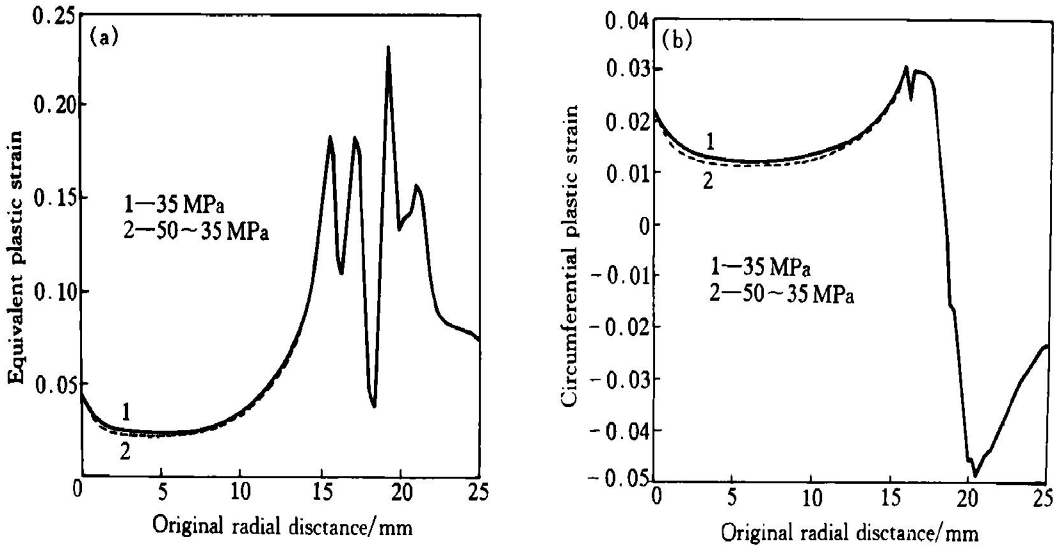

Fig. 5 Distribution of equivalent plastic strain ε_e(a) and circumferential plastic strain ε_{33}(b) in mid-plane of formed sheet at pressure distribution of 50~ 35 MPa and 35~ 35 MPa

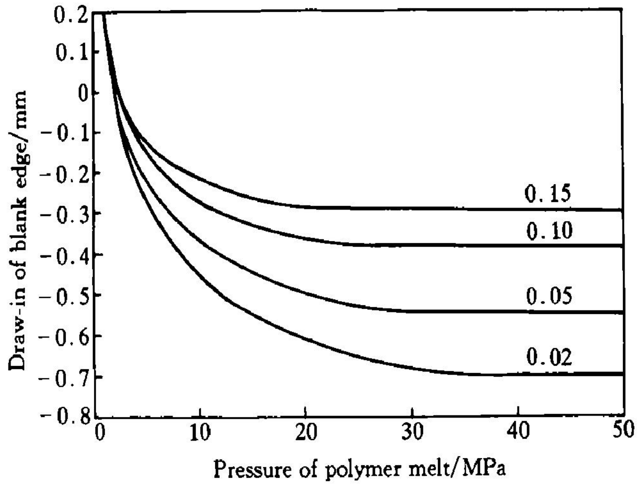

Fig. 6 Influence of friction coefficient on draw-in of blank edge

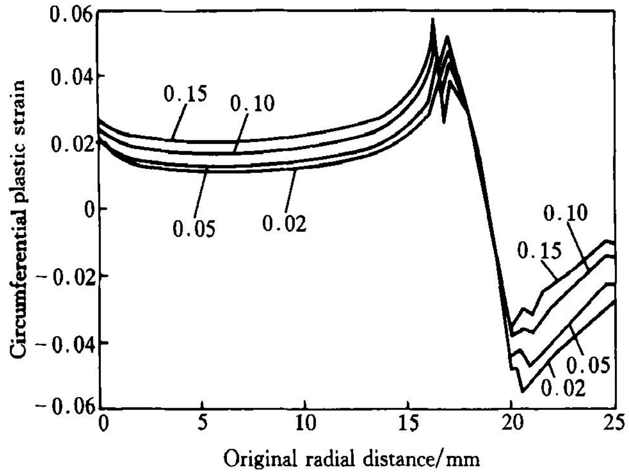

Fig. 7 Influence of friction coefficient on circumferential plastic strain ε_{33}

and region I and the other one between region III and region II, have developed when pressure of the plastic melt exceeds 30 MPa.

3) Non-uniform distribution of the plastic melt pressure has almost no influence on the plastic deformation of the aluminum sheet in hybrid forming.

4) Bi-axial stretching in plane of the sheet in the mold increases with increasing friction coefficient.

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