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3D FE analysis on the product defects of composites formed by liquid–solid extrusion process

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ABSTRACT

The liquid–solid extrusion process for forming composite products was simulated by the three-dimensional thermo-mechanical finite element method. The mechanism for forming defects was analyzed based on the distribution of temperature and flowage of the work piece. The surface annular cracks occurring at the initial stage was caused by the high deformation temperature together with the axial tensile stress which was caused by uneven axial flow rate. However, the low deformation temperature in the terminal stage led to high resistance of deformation and interfacial strength, resulting in the fracture of fibres during severe deformation. The deformation condition in the middle stage was feasible to obtain composite products that were defect free. The simulation was verified through the comparison of the deforming force between the calculated and the measured one in laboratory conditions. The results indicate that the forming quality depends on the thermal and deformation state of the work piece, which can be controlled by the selection and adjustment of the process parameters.

1. Introduction

The finite element method (FEM) has become one of the most important and effective tools to analyze the thermo-plastic forming process quantificationally. In the past several years, many scholars had studied the effect of the material thermal–mechanical state on the forming quality of products using finite element analysis (FEA). Cavaliere et al. (Cavaliere, 2004a; Cavaliere et al., 2004b) simulated the isothermal forging of metal matrix composite by 3D FEM and the best conditions for this forging process were determined. Pater (2006) established the 3D mechanical model of the cross wedge rolling process and the phenomena limiting forming stability such as the uncontrolled slipping and core necking were forecast by means of the numerical simulation. Zhou et al. (Chanda et al., 2001; Li et al., 2004; Zhou et al., 2004) investigated the isothermal and iso-speed extrusion of aluminium using 3D FE simulation. With the predetermined ram speed profiles, the fluctuations of the maximum work piece temperature were controlled within a range of 10 °C, which would promote the consistency of the extruded product quality. The composite extrusion was simulated by use of a coupled thermo-mechanical simulation with the commercial FE-code (Kleiner and Schikorra, 2006). The process optimization strategies to reduce stresses on the reinforcement and to improve the material flow have been developed by variation of process parameters. In the extrusion of aluminium sections engineering, Halvorsen and Aukrust (2006) studied the mechanisms for buckling and waving utilizing FEM software. By varying the feeder geometry, the billet flow conditions had been altered to avoid the shape variations of product. These cases indicate that the combined FEA and experimental analysis played an important role for forming defect analysis and process optimization in solid plastic forming processes. So far, how-

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ever, few similar works have been done in the semisolid or liquid–solid forming process.

The composite liquid–solid extrusion process is a typical semisolid (or liquid–solid) forming technology in which the liquid metal infiltration and semi-solid extrusion is integrated. The forming process includes several complicated nonlinear problems, such as liquid metal infiltration, solidification under pressure, heat transfer and large plastic deformation. The hybrid approach combines numerical simulation and experimental analysis and is considered to be an effective means in the research of liquid–solid extrusion process (Qi et al., 2002). In general, the vital parameters which influence the stability of the forming process and product quality include the temperature of pouring, preheated temperature of the die, infiltration pressure, pressure-keeping time and extrusion velocity. The research concerning the process of liquid metal infiltration and extrusion in advance had ascertained the scope of these parameters on the whole (Jiang et al., 2004; Qi et al., 2002). Up to now, however, there is hardly any work about forming quality of composite product in the liquid–solid extrusion process. It is well known that the corrosion resistance and mechanical property of extruded products are determined by its superficial and inner forming quality. In order to improve the forming quality and avoid forming defects, therefore, it is important for the researchers to understand the underlying mechanisms for forming defects fully in this forming process.

In the present work, the composite liquid–solid extrusion process experiment was simulated using 3D thermo-mechanical coupled FEM on MSC SuperForm code. The regularities of temperature distribution and material flow in the forming process were analyzed in detail from the simulation results. Meanwhile, the underlying mechanism for forming defects was discussed and revealed according to the analysis of forming defects in experiments. The work provides theoretical guidance for selecting and adjusting process parameters in order to improve the consistency of quality for the extruded composites.

2. Formulation of the coupled thermo-mechanical FE model

In the rigid-viscoplastic FEM, the basic equations to be satisfied are the equilibrium equation, the incompressibility condition and the constitutive relationship. When applying the Lagrange multiplier method, the exact velocity field in the body should satisfy the variational equation in the form (Kobayashi et al., 1989):

$$\delta\pi = \int_V \delta E(\dot{\varepsilon}_{ij})\delta\dot{\varepsilon}_{ij}\ dV + \int_V \lambda\delta\dot{\varepsilon}_v\ dV + \int_V \delta\lambda\dot{\varepsilon}_v\ dV - \int_{S_F} F_i\delta u_i\ dS = 0 \tag{1}$$

When Eq. (1) is discretized using the finite element method, the following expressions can be obtained

$$\delta\pi = \delta\pi(\{U\},\{\lambda\}) = \sum_e \delta\pi^e(\{u\}^e,\{\lambda\}^e) = 0 \tag{2}$$

where $\{U\}$ is the vector of the ensemble of nodal velocity and $\{\lambda\}$ is the vector of Lagrange multipliers.

Eq. (2) can be converted into the following form

$$\delta\pi = \frac{\partial\pi}{\partial\{U\}}\delta\{U\} + \frac{\partial\pi}{\partial\{\lambda\}}\delta\{\lambda\} = 0 \tag{3}$$

Due to the arbitrariness of $\delta\{U\}$ and $\delta\{\lambda\}$, the following nonlinear difference equation set with regard to $\{U\}$ and $\{\lambda\}$ must be satisfied

$$\begin{aligned} &\frac{\partial\pi}{\partial\{U\}} = 0 \\ &\frac{\partial\pi}{\partial\{\lambda\}} = 0 \end{aligned} \tag{4}$$

To solve Eq. (4) with the Newton–Raphson method, the following iterative formulas were used

$$\begin{aligned} &\left\{\frac{\partial^2\pi}{\partial\{U\}\partial(\{U\})^T}\right\}_{n-1}\cdot\{\Delta U\}_n = -\left\{\frac{\partial\pi}{\partial\{U\}}\right\}_{n-1} \\ &\left\{\frac{\partial^2\pi}{\partial\{\lambda\}\partial(\{U\})^T}\right\}_{n-1}\cdot\{\Delta U\}_n = -\left\{\frac{\partial\pi}{\partial\{\lambda\}}\right\}_{n-1} \end{aligned} \tag{5}$$

Eq. (5) can be expressed by the following form

$$\begin{aligned} &([K]_p + [K]_F)\cdot\{\Delta U\} + [Q]\{\lambda\} = \{F\}_p + \{F\} \\ &[Q]^T\cdot\{\Delta U\} = \{F\}_\lambda \end{aligned} \tag{6}$$

where

$$[K]_p + [K]_F = \sum_e \frac{\partial^2[\int_{V^e} E(\dot{\varepsilon}_{ij})\ dV]}{\partial\{u\}^e\partial(\{u\}^e)^T} + \sum_e \frac{\partial^2[-\int_{S_F^e} F_i u_i\ dS]}{\partial\{u\}^e\partial(\{u\}^e)^T},$$

$$[Q]^T = \sum_e \int_{V^e} [C]^T dV,\quad [C]^T = (1,1,1,0,0,0),$$

$$\{F\}_p + \{F\} = -\sum_e \int_{V^e} \partial E(\dot{\varepsilon}_{ij})\frac{\partial\dot{\varepsilon}_{ij}}{\partial\{u\}^e}\ dV + \sum_e \int_{S_F^e} F_i\frac{\partial u_i}{\partial\{u\}^e}\ dS,$$

$$\{F\}_\lambda = \sum_e \int_{V^e} \{C\}^T\{u\}^e\ dV.$$

According to the law of conservation of energy, the basic equation for the 3D heat transfer problem for a liquid–solid extrusion process can be expressed by (Chanda et al., 1999):

$$\frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\dot{q}_V}{\rho c} - \frac{\partial T}{\partial t} = 0 \tag{7}$$

where T, λ, ρ and c is the temperature, thermal conductivity, density and specific heat of the work piece respectively. $\dot{q}_V$ is the intensity of internal heat source.

The initial and boundary conditions can be defined by the following equations respectively:

$$T(x,y,z,t=0) = T_0(x,y,z) \tag{8}$$

$$\lambda\left(\frac{\partial T}{\partial n}\right)_\Gamma + h(T - T_m) - q_0 = 0 \tag{9}$$