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Eddy current induced dynamic deformation behaviors of aluminum alloy during EMF: Modeling and quantitative characterization

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ABSTRACT

Unveiling the quantitative influence of the induced eddy current in electromagnetic forming (EMF) is of great significance to realize the precision control of the forming process. To this end, a semi-phenomenological model for predicting the current-carrying dynamic deformation behaviors of aluminum alloy is established by introducing a rate-dependent electroplasticity (EP) model and an elastic thermal expansion model into the high-strain-rate constitutive model. In the modeling process, the electroplastic energy density (EPED), which is a function of prestrain and current density, is defined as the dominant factor of EP-induced stress drop and its threshold value is determined. Moreover, a rate-dependent factor is formulated to consider the effect of wide-range strain rate variation on EP-induced stress drop. Applied to uniaxial-stress EMF process, the present model exhibits preferable prediction accuracy by comparing the predicted results of analytical calculation with experimental ones. The present model captures the characteristic stress responses of EMFed samples, i.e. monotonic strain hardening followed by long-range flow softening. It is found that the peak stress and EP softening ratio both increase with EPED, which can be attributed to the combined influences of increased current density, electric resistivity and acceleration on the competition between strain rate hardening and EP induced softening.

1. Introduction

Electromagnetic forming (EMF) is a high-energy-rate sheet metal forming technique in which material deforms at high strain rates under time-varying eddy current field (Psyk et al., 2011). From the work by Balanethiram et al. (1994), EMF is proved to possess the potential to break through the conventional forming limit of materials. As a result, EMF has gained more and more attentions in the manufacture of hard-to-deform components. For example, Oliveira et al. (2005) investigated free-forming and two configurations of cavity fill operations of AA5754 and AA5182 aluminum alloy sheets in EMF.

With increasing demands of large-scale and large height-to-diameter ratio thin-walled components in aeronautic and astronautic fields, investigators continuously improve the EMF technique by further augmenting the discharging energy and utilizing hybrid processes. Luo et al. (2014) designed a novel multi-layer flat spiral coil to realize hole flanging for large and thick sheets. Lai et al. (2015) united multi-layer driving coil and side driving coil to form large-scale deep drawing part with large drawing ratio. Moreover, a uniform pressure coil was designed by Thibaudeau and Kinsey (2015) with increased forming efficiency and repeatability. For hybrid EMF processes, Cui et al. (2016a) combined stretch forming and EMF for manufacturing large-size and thin-walled ellipsoidal parts. Cui et al. (2016b) and Fang et al. (2016) proposed a new technique called incremental electromagnetic-assisted stamping (IEMAS) with radial magnetic pressure, by which the forming depth could be increased by 31%. The increase of discharging energy leads to the higher induced eddy current in the metal blank during EMF, e.g. peak current magnitude of 80 kA reported by Cao et al. (2014) and around 280 kA reported by Thibaudeau and Kinsey (2015). Hence, the sheet metal undergoes a current-carrying dynamic deformation during EMF, in which the influence of high-density current becomes non-ignorable.

Early studies by Troitskii (1969) and Conrad and Sprecher (1989) have shown that the flow stress of metallic materials can be reduced by high-density current charging during plastic deformation, which is defined as electroplasticity (EP) effect. Moreover, the intensity of the EP effect was proved to be positively correlated with the electric current density by Conrad (2002) and Kopanev (1991). Recently, Roh et al.

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Nomenclature

e_0 and e_n The nominal and real electric energy density
E_n The real electric energy
I, J, t_p and T The intensity, density, pulse width and period of the electric current
A_0, l_0 and V_n The initial section area, the length and the volume of the specimen gauge section
v_M The crossbeam velocity in mechanical test
ρ_e The electric resistivity
$\Delta\sigma_d$, $\Delta\sigma_p$ and $\Delta\sigma_E$ The overall electroplasticity (EP) induced stress drop and its plastic and elastic components
$\Delta\sigma_{pinch}$ and $\Delta\sigma_{TE}$ The pinch stress and the thermal expansion stress
E, G, and υ_P Young's modulus, shear modulus and Poisson ratio
$\mu_r$and μ_0 Magnetic permeability factor and the magnetic permeability in vacuum
α_{TE} The coefficient of linear expansion
c_p The heat capacity
ρ The mass density
σ_{fi} the flow stress upper bound before the ith electric current pulse
T_{min-i}, T_{max-i}, T_{room} and ΔT The transient temperature before and after the ith pulse, the room temperature and the temperature rise
$\Omega(e_n, \varepsilon_p)$ and Ω_C Electroplastic energy density and its critical value
n_{PL} The power-law hardening exponent
ε_p and $\dot{\varepsilon}_p$ the plastic strain and strain rate
$\dot{\varepsilon}_{p-EP}$, $\dot{\varepsilon}_{p-0}$, $\dot{\varepsilon}_{EP-0}$, $\dot{\varepsilon}_0$ The plastic strain rate with and without EP effect, The datum strain rate in thermal activation theory with and without EP effect
$\dot{\varepsilon}_{r-max}$ and $\dot{\varepsilon}_{r-min}$ The maximal and minimal reference strain rates
$F(\dot{\varepsilon}_p)$ The rate dependent factor for describing the effect of strain rate on EP
$\dot{\varepsilon}_{0EP-D}/\dot{\varepsilon}_{0D}$ and $\dot{\varepsilon}_{0EP-QS}/\dot{\varepsilon}_{0QS}$ The ratio of datum strain rate with EP effect to the one without EP effect in dynamic regimes and in quasi-static regimes, respectively
ρ_{mEP-D}/ρ_{mD} and ρ_{mEP-QS}/ρ_{mQS} The ratio of mobile dislocation density with EP effect to the one without EP effect in dynamic regimes and in quasi-static regimes, respectively
$d\varepsilon_r^t$, $d\varepsilon_r^e$, $d\varepsilon_r^p$ and $d\varepsilon_r^{TE}$ The total, elastic, plastic and thermal expansion radial strain increments of the ring specimen
$\dot{\varepsilon}_r^t$, $\dot{\varepsilon}_r^e$, $\dot{\varepsilon}_r^p$ and $\dot{\varepsilon}_r^{TE}$ The total, elastic, plastic and thermal expansion radial strain rates of the ring specimen
σ^* and σ_{ew} Thermal activation stress and electric wind force
ΔH_{EP}^*, ΔH^*, V_{EP}^*, V^* and ΔS^* The thermal activation enthalpy with and without electric pulse, activation volumes with and without electric pulse, and the thermal activation entropy
d_l, $l^*$and υ^* The average free path, the spacing and the vibration frequency of the dislocations
ρ_m, ρ_f and Θ The density of mobile and forest dislocations and the mobile fraction
$\boldsymbol{S}$ The deviatoric stress tensor
$\hat{\varepsilon}$ The deviatoric strain tensor
$\boldsymbol{\varepsilon_{el}}$, $\boldsymbol{\varepsilon_p}$ and $\boldsymbol{\varepsilon_r}$ The elstatic, the plastic and the radial strain tensor
$\bar{\varepsilon}_p$, $\bar{\varepsilon}_r$ The effective plastic strain and the radial strain
$\sigma_s(\varepsilon_p, \dot{\varepsilon}_p, T, \boldsymbol{\psi})$, σ_D, σ_{QS} and σ_{EMRE} The yield stress, the dynamic yield stress, the quasi-static yield stress and the yield stress in electromagnetic ring expansion (EMRE)
$F^*(\varepsilon_p, \dot{\varepsilon}_p, T, \boldsymbol{\psi})$ The high strain rate yield function
D_{mp}^i and D_{exp}^i The model predicted and experimentally obtained ultimate diameters of the 2 × 2 rings
ξ The EP softening ratio,viz. $\sigma_D - \sigma_{EMRE}/\sigma_D$
I_C and I_r The circuit current and the ring current in EMRE
R_r, R_C, R_L and R The resistance of the ring specimen, coil, line and the overall resistance in the circuit
L_r, L_C, L_L and L The self-inductance of the ring specimen, coil, line and the overall self-inductance in the circuit
M The mutual inductance between the ring specimen and the coil
U_{max}, C The maximal discharging voltage and the capacitance of the capacitor
v_r and $\ddot{r}$ The velocity and acceleration of the ring specimen
δ The skin depth
ω The angular frequency of induced current
b_z, b_r and b The axial, the radial and the overall intensity coefficient of magnetic field
r_{eq} The equivalent radius of the ring section
m Mass of the ring specimen
T_r The trasient temperature of the ring specimen
σ_θ, σ_r and σ_t The circumferential, radial and thickness stress of the ring specimen
ε_θ, ε_r and ε_t The circumferential, radial and thickness strain of the ring specimen
K_J, K_Ω, β, γ Constants

(2014) used a newly defined parameter, electric energy density, to reflect the intensity of the EP effect. By actively applying current to the metal blank during or after plastic deformation, EP effect is successfully utilized in electrically-assisted manufacture to reduce forming load (Salandro et al., 2010; Nguyen-Tran et al., 2015), enhance material plasticity (Li et al., 2012) and ameliorate microstructure (Xie et al., 2015; Sánchez Egea et al., 2016). Moreover, in recent decade, a renewed understanding of EP effect by Satapathy and Landen (2006) and Landen et al. (2007) indicates that high-density electric current leads to flow softening of metals during plastic deformation, even in high strain rate regimes and under short current durations.

However, the effect of eddy current on the deformation behaviors of metals has been not yet considered in current numerical simulation of EMF, which may result in an under-prediction of the forming depth within the current-acting zone. In order to realize the precision prediction of the EMF processes, quantitatively characterizing the effect of electric parameters (e.g. current density, charging time) on the stress responses of sheet metals becomes a hinge issue. However, the real-time measurement of deformation information in EMF process is still challenging in present state-of-art due to the high forming velocity and the time-varying electromagnetic field, which makes the quantification of the effect of eddy current a tough task.

Provided with the superiorities of simple loading mode and convenience in velocity and current measurement, electromagnetic ring expansion (EMRE), as a uniaxial stress EMF process, has become an important method to quantitatively investigate the current-carrying dynamic deformation behaviors in EMF (Grady and Benson, 1983). Earlier investigations by Niordson (1965) focused on the enhanced plasticity with a description of multiple necking and fragmentations. In the works of Altynova et al. (1996) and Hu and Daehn (1996) the enhanced plasticity/ductility of metals was attributed to the inertial effect on the necking and fracture behavior. In the more recent work by Zhang and Ravi-Chandar (2006, 2008), diffuse necking strain in EMRE was predicted to be around the Considère strain and the steady state deformation of EMRE was believed to be responsible for the enhanced plasticity. In addition, Altynova et al. (1996) pointed out that the temperature rise and microstructure change caused by combined action of high-density current and wide-range strain rate variation might result in the change of the deformation behaviors of materials in EMRE.

With the aid of advanced experimental technologies, researchers