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Pressure rate controlled unified constitutive equations based on microstructure evolution for warm hydroforming

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ABSTRACT

A viscoplastic model considering the influence of microscopic evolution and macroscopic deformation has been developed to represent the deformation behavior of material in warm sheet hydroforming process. Based on a hydroforming environment, a set of rate dependent constitutive equations, which is constructed by using the pressure rate, the evolution of dislocation density and kinematic isotropic hardening, has been proposed to predict stress–strain response of material. The non-linear Chaboche's isotropic hardening criterion is also modified to characterize the instantaneous state of hardening considering microstructure evolution. Different from traditional sheet plastic forming process, the rate of fluid pressure variation is a significant factor that can determine the forming speed. Therefore, the pressure rate is applied to be one factor that can influence the deformation of material in warm hydroforming. The hydraulic bulge experiments on aluminum alloy at warm temperature indicated that the deformation behavior of material is sensitive to pressure rate. The genetic algorithm optimization technique was used to determine the optimum values of a set of free material constants associated with the proposed constitutive model. The computed data has been in a good agreement with the test data on the basis of the optimized material constants.

1. Introduction

During metal forming process such as sheet hydroforming, the plastic deformation behavior of metals has a great association with microstructure evolution and some external conditions, such as temperature and liquid pressure. As temperatures rise, there are significant differences on the microscopic mechanical properties of material [1]. It is clear that the macroscopic differences are caused by microstructure changes which include recrystallisation, grain growth, dislocation evolution, and so on. A number of efforts had been focused on the constitutive modeling for metals and alloys in high temperature deformation [2–4]. However, these models are not enough to reflect the complicated and non-linear relationship between flow stress, microstructure and processing parameters. Accordingly, it is vital to develop an accurate and complicated model to predict material properties and represent the dynamic microstructure changes. Many researchers have recognized the need to combine macrostructure deformation with microstructure evolution through establishing constitutive models based on microstructure changing mechanism [5–8]. Zhou and Dunne [9] developed multi-axial constitutive equations for superplastic behavior of titanium alloys. In their study, the equations were combined with A-F kinematic hardening rules and base on deformation mechanism, which includes diffusion creep, grain boundary sliding and dislocation climb. Subsequently, Dunne [10] developed the equations which coupled with grain growth to investigate the influence of microstructure evolution on superplastic stress–strain behavior and inhomogeneity of deformation. Lin [11] developed a set of constitutive equations based on stress relaxation, creep and age hardening, and then used them to predict springback of aluminum alloy. However, there are few works to establish constitutive models describing the relationship between microstructure and plastic deformation in warm hydroforming with consideration of pressure rate.

In order to analyze and study the deformation behavior of the materials, the testing methodologies, such as tensile, compression test and torsion, were commonly used to obtain flow curve. Due to mechanical response of most of materials being sensitive to the rate and temperature, different strain rates and temperatures can be used to preferably test the material mechanical properties while specimens are loaded. However, each test method has its own specific field of application. With the development of sheet hydroforming technology, the hydraulic bulge test has caused the extensive concerns. Koç [12] performed a hydraulic bulge test at elevated temperature and obtained proper data to determine the flow curve. The changing rate of fluid pressure as the driving force

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of the forming process of warm hydroforming should be used as standardized parameter to test mechanical properties. Lang et al. [13] found that the thickness distribution was greatly influenced by the pressure variation in sheet hydroforming test. Hence, the pressure rate is proposed to directly control the deformation of the bulge process and further have an influence on the change of strain.

The plastic deformation of aluminum alloy in warm sheet hydroforming is strongly related to temperature and microstructure evolution. It may be also affected by the changing rate of fluid pressure on account of the specificity of hydroforming process. In recent years, traditional constitutive model for warm sheet metal hydroforming cannot effectively show its specialty on some influence factors such as the changing rate of fluid pressure, microstructure evolution and temperature. In the present paper, it is proposed that deformation is directly related to the effect of pressure rate on sheet hydroforming process. The 7xxx series aluminum alloys have a combination of attractive comprehensive properties, such as low density, high strength, ductility, high fracture toughness and resistance to fatigue [14,15]. These advantages make them widely used as structural materials in aerospace applications. The 7075 aluminum alloy plate, in O temper condition, has been utilized extensively due to their higher formability in comparison to the other temper conditions [16]. In the present work, the 7075-O aluminum alloy was used as testing material. It can not only validate the model, but also represent the deformation behavior of 7075 aluminum alloy. Based on these points, a set of unified and viscoplastic constitutive equations are established with pressure rate, hardening and dislocation evolution. For convenience of calculation, discretization scheme of the equations is obtained by using the fourth-order Runge–Kutta method. Furthermore, the Optimization technology is applied to determine the material constants of this model. With the application of the GA (genetic algorithm), an automatic computational procedure can be easily used to determine the material constants. Comparing with the experimental data, the computational data which is obtained by the proposed model can effectively reflect mechanical properties of AA7075-O aluminum alloy.

2. Deformation mechanisms at warm temperature

2.1. Evolution of dislocation density

The physical mechanism giving rise to the plastic deformation is predominantly dislocation nucleation and glide. For the sake of understanding the deformation behavior in the warm hydroforming process, the strain hardening of the material should take into account of the dislocation density evolution. The dislocation exists in the crystal as a kind of crystallographic defects and has a great influence on the mechanical characteristic of crystal grains. The changes of dislocation structure and dislocation density are the driving force for microstructure evolution such as recrystallisation and grain growth. The flow stress is also associated with the change of dislocation structure according to dislocation mechanism. In addition, its values are equal to plastic resistance that impedes the dislocation motion.

In the plastic deformation process, the accumulation and annihilation of dislocation density cause both work-hardening and dynamic softening. The deformation caused by warm hydroforming is a competing progress of work-hardening and dynamic softening. At the beginning of deformation, the growth of dislocation density contributes to the increase of the work hardening effect, and then work hardening exceeds dynamic softening. As the deformation progresses, the dynamic softening such as dynamic recovery occurs, which can decrease the effect of work hardening and reaches the balance. In this case, the accumulation and annihilation of dislocation density also reach equilibrium, therefore making steady state deformation possible. In the present study, the model proposed by Kocks and Mecking [17] is used to describe the process. They reported that the flow stress is decided by single structure parameter (dislocation density). Taking account of work-hardening and dynamic softening, the rate of dislocation density is composed of two parts [17]:

$$\frac{d\rho}{d\varepsilon} = m_1\sqrt{\rho} - k_2\rho \tag{1}$$

Here, the first term in equation expresses the increase of dislocation density due to working-hard and the second one represents its decreasing because of dynamic recovery. The average dislocation density is expressed as ρ. It is defined as the total length of dislocation per unit volume and the unit is $m/m^3 = m^{-2}$ .Where m_1 is the material coefficient; k_2 represents a function of temperature and stain, which is written as [18]:

$$k_2 = k_{20}\frac{\dot{\varepsilon}_0^*}{\dot{\bar{\varepsilon}}}e^{\frac{Q}{R_r(T+273)}} \tag{2}$$

In which, k_{20} is a proportional coefficient; $\dot{\varepsilon}_0^*$ is the reference strain rate; Q denotes activation energy; R_r is the molar gas constant, which has a value of 8.314 J mol^{-1} K^{-1}; T is Celsius temperature. The coefficient m_2 is defined as:

$$m_2 = k_{20}\dot{\varepsilon}_0^* \tag{3}$$

Apply Eq. (2) to Eq. (1), and then the expression for the evolution of the dislocation density can be expressed by [19]:

$$\dot{\rho} = m_1\sqrt{\rho}\dot{\bar{\varepsilon}}^{\mathrm{p}} - m_2 e^{-\frac{Q}{R_r(T+273)}}\rho \tag{4}$$

2.2. Hardening rule

After the material reaches its elastic limit, the effective stress meets the initial yield surface at $\sigma = k$. As the loading continues, hardening can be manifested in one of two forms (or both): isotropic and kinematic hardening. In isotropic hardening, the yield surface expands with plastic deformation. Contrarily, the yield surface translates in stress space rather than expanding.

A common form of non-linear isotropic hardening R is developed by Chaboche [20] in the following form:

$$\dot{R} = B(U - R)\dot{\bar{\varepsilon}}^p \tag{5}$$

In which, B and U are material constants. The constant B determines the rate of hardening, and U is the saturated value of isotropic deformation resistance stress R. In order to describe dynamic recovery of viscoplasticity, another term is added into Eq. (5) and the equation is modified as [21]:

$$\dot{R} = \dot{B}(U - R)\dot{\bar{\varepsilon}}^p - aR \tag{6}$$

In which, a is a material constant which reflects the rate of dynamic recovery. This equation enables the amount of dislocation density consumed by dynamic recovery to represent the decreasing of isotropic hardening in macroscopic mechanical properties.

In addition to describing the material's hardening response, Lin and Dean [22] proposed that the strain hardening rate of material plastic deformation has a linear relationship with the rate of dislocation density evolution, which is obtained as

$$\dot{R} = H\dot{\rho} \tag{7}$$

In fact, the development of the macrostructure strain hardening resulted from deforming history and microstructure dislocation motion. Taking account of this fact, it is assumed that both deforming history and microstructure dislocation motion have contributed to macrostructure hardening. In the general case, hardening during the deformation is significantly correlated with