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Forming defects in aluminum alloy hot stamping of side-door impact beam

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Abstract: The forming defects, including thinning, rupture, wrinkling and springback, usually arising in producing a side-door impact beam, were investigated by trial and numerical simulation. A temperature-related constitutive model specific to the temperature range from 350 °C to 500 °C was established and used for the numerical simulation. The trial and numerical simulation were conducted to clarify the quantitative characteristics of forming defects and to analyze the effects of process parameters on the forming defects. Results show that the rupture situation is ameliorated and the springback is eliminated in the aluminum alloy hot stamping. The wrinkling severity decreases with increasing blank holder force (BHF), but the BHF greater than 15 kN causes the rupture at the deepest drawing position of workpiece. The forming defects are avoided with lubricant in the feasible ranges of process parameters: the BHF of 3 to 5 kN and the stamping speed of 50 to 200 mm/s.

Key words: aluminum alloy; hot stamping; forming defects; numerical simulation; blank holder force

1 Introduction

In the upcoming years, one of the most important challenges to automotive industry is to meet the demand of reducing fuel consumption with a concurrent improvement for the safety performance of automobile. This requirement is satisfied mainly by using light-mass materials such as advanced high-strength steels, aluminum alloys, magnesium alloys and composites to produce auto-body components. Some novel or improved manufacturing processes are introduced for forming these new-fashioned materials.

In order to overcome the major problems in producing aluminum alloy panel components such as springback, poor formability and microstructure variation, a novel process HFQ was proposed by LIN et al [1−3] in recent years. Solution heat treatment (SHT), hot forming, cold die quenching and artificial aging are successively connected in this process. There are three main steps in this process as schematically shown in Fig. 1.

1) SHT: A sheet blank is soaked at an elevated temperature for a sufficient period, which fully dissolves alloying elements into solid aluminum and gives one single phase.

2) Hot forming and die quenching: The hot blank is transferred to a cold die set where it is quickly formed and held within the dies until quenched to room temperature, which leaves the alloying elements in the unstable solid solution known as “super saturated solid solution”.

3) Artificial aging: Age-hardening is the final stage to improve the properties of heat treatable aluminum alloys. The alloying elements come out of the solid solution to form strengthening particles with appropriate aging time and temperature.

Since HFQ process is proposed, a few researchers have paid attention on it and used finite element (FE) method to investigate the forming defects and the effects of process parameters. Finite element method has become a powerful tool in predicting and preventing the undesirable forming defects of material forming processes. Only few works focusing on the numerical simulation of aluminum alloy hot stamping have been reported in the literatures [4−6] as yet, whereas some investigations focusing on the numerical simulation of boron steel hot stamping have been published. XING et al [7] established a material model of boron steel, and used the finite element code ABAQUS to carry out the

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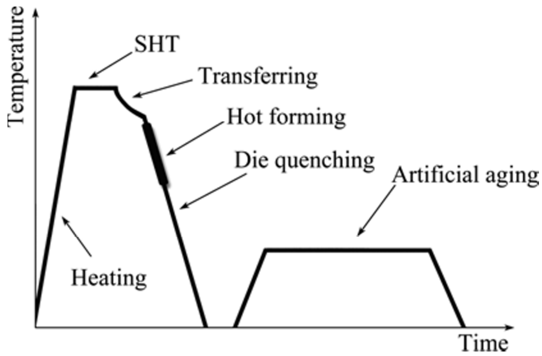

Fig. 1 Schematic diagram showing temperature history of HFQ process

numerical simulation of boron steel hot stamping process for a bending part. SHAPIRO [8] applied the finite element code LS-DYNA in solving the Numisheet 2008 benchmark problem that is relevant to the hot stamping of a B-pillar component. MOHAMED et al [2] established a set of damage-coupled viscoplastic constitutive equations for predicting the material damage in hot sheet forming and implemented the equations in the ABAQUS software through the user-defined subroutine VUMAT for the numerical simulation of aluminum alloy hot stamping.

The warm forming of aluminum alloy was also proposed and developed in the last few decades, and recent results [9−11] show that the formability of aluminum alloy is increased in an elevated temperature range. In addition, the nature of some aluminum alloys under the warm forming condition was investigated and reported [12−14]. The warm forming can improve the formability significantly, but the benefits from raising the temperature of tools and blank would be limited compared with the additional complexity of heating the tools and blank. Superplastic forming has also been used to form aluminum closure panels for recent decades [15]. The primary advantage of superplastic forming is to manufacture large and complex shapes from materials with low formability. However, the main obstacle for the further application of superplastic forming is low productivity due to the relatively slow cycle time [16]. In addition, most of the materials employed in superplastic forming demand a special preprocessing to get a fine- or ultrafine-grained microstructure [17]. The material formed at high temperature in HFQ process makes it possible to achieve a higher level of ductility compared to that at moderate temperature in warming forming, which implies that more complex components can be formed by using HFQ process. The springback of components is eliminated because stress release takes place when the material is held within the die set, which improves the geometrical accuracy of components.

HFQ process is applied to producing a side-door impact beam of car in this work. The forming defects arising in the actual production are investigated by using FE analyses and stamping trials. The constitutive model of AA6111 under HFQ condition, the geometric model and thermal aspects of numerical simulation are presented. The characteristics of forming defects are analyzed and discussed.

2 Numerical simulation of aluminum alloy hot stamping

2.1 Material constitutive model

Flow stress represents the size of the yield function during deformation, and is usually influenced by not only strain but also strain rate and temperature. The behavior of the metals undergoing plastic deformation at high temperatures and different strain rates should be modeled according to the physical behavior of the material [18]. An adapted constitutive equation for describing the material behavior under the hot stamping condition, depending on temperature and strain rate, is selected to apply in the numerical simulations.

ABEDRABBO et al [19] applied an equation of the flow stress including the strain rate sensitivity to performing the coupled thermo-mechanical finite element analyses. Temperature effect is considered and included in this flow equation described by Eq. (1), which is used in the following simulations.

$$\bar{\sigma}(\bar{\varepsilon}_{\mathrm{p}}, \dot{\varepsilon}, T) = K(T)(\bar{\varepsilon}_{\mathrm{p}} + \varepsilon_0)^{n(T)} \left(\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_{\mathrm{sr0}}}\right)^{m(T)} \tag{1}$$

where $K(T)$ represents strength coefficient, $n(T)$ is the temperature dependent strain hardening coefficient and $m(T)$ is the temperature dependent strain rate sensitivity coefficient. $\bar{\varepsilon}_{\mathrm{p}}$ denotes the effective plastic strain and $\dot{\bar{\varepsilon}}$ denotes the effective strain rate. ε_0 is a constant representing the elastic strain to yield and $\dot{\varepsilon}_{\mathrm{sr0}}$ is a strain rate normalization factor whose value depends on the time units used in FE simulation. These material constants and coefficients are estimated according to the stress−strain curves obtained from the hot compression test on a Gleeble−1500 thermal-mechanical testing system.

The symbols in Fig. 2(a) show the hot compression results for AA6111 aluminium alloy deformed at four different strain rates (0.01, 0.1, 1 and 10 s^{-1}) and deformation temperature of 400 °C. The flow stress increases as the strain rate goes up, which indicates a noticeable viscoplastic nature of materials at high temperature. The symbols in Fig. 2(b) show the hot compression results for AA6111 aluminium alloy deformed at four different deformation temperatures (350, 400, 450 and 500 °C) and a strain rate of 1 s^{-1}. The flow stress decreases with the increasing temperature.