Damage investigation of boron steel at hot stamping conditions

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Abstract

The uniaxial tension tests of 1500 MPa boron steel at strain rates of 0.01-5.0 s\textsuperscript{-1} and temperatures of 550-850 °C were performed. Considering the difference between the deformation necking cross section and the centre measuring section of specimen, a correction method of measuring strain and temperature at necking cross section are developed. For the method, the deformation of necking cross section was obtained which approximate for the trapezoidal change law near the necking zone. The stress strain curves are corrected based on the correction method of the strain and by considering temperature correction. A set of unified constitutive equations has been developed and calibrated. Correlation between the corrected and predicted true stress data from the constitutive equation is presented. The correlation coefficient is 0.969, and the absolute average relative error is 3.73% in the range of allowable experimental conditions.

Keywords: Boron steel; Visco-plastic damage constitutive model; Boron steel; Correction method; Fracture

1. Introduction

The hot stamping technology is one of the most successful in producing complex components with superior mechanical properties (Åkerström, 2006). Boron steel after hot stamping is a typical ultra-high strength steel. Hardening and fracture of complex parts effect on thermoforming properties needs further study. Unified visco-
plastic damage constitutive equations are required to model the interactive effects between the dislocation density and damage evolution, which would analyze the forming law and forming defects during hot stamping process.

Mohamed et al. (2012) established the unified visco-plastic constitutive equations of AA6082 alloy during hot stamping process. However, the effect on true stress of temperature rise and strain to failure was out of consideration; Luan et al. (2014) also brought in correction method for temperature rise in studying the constant temperature deformation process of AZ31 magnesium alloy. Deformation heat effect and necking played an important role in the analysis of experimental results, so it is necessary to improve on experimental technology.

In the aspect of hardening, Mohamed et al. (2012) found constitutive model based on the dislocation density evolution of AA6082 alloy during hot stamping process. Then, in the another aspect of ductile fracture, Li et al. (2011) concluded damage evolution model of boron steel and Al alloy based on continuum damage mechanics during hot stamping. Lin et al. (2005) summed up damage evolution mechanism, damage modeling and its calibration during several kinds of deformation conditions such as creep and superplastic forming. Thus, in view of the hardening and fracture, this paper will make a further step in the study of boron steel during hot stamping by correcting damage factor based on the above model.

In this paper, nearly isothermal tensile test of B1500HS had been carried out at different temperature and different strain rates. True stress strain curves had been obtained by using a corrected method on temperature and necking during the process. Then, unified visco-plastic damage constitutive equations based on dislocation density incorporated with corrected damage factor and optimized material constant was established.

2. Experimental set-up

2.1. Material and equipment

The material used in this study was boron steel B1500HS provided by the project sponsor IMRA Europe. All specimens used for the experiment were machined from the same batch of as-delivered, 1.6mm thick, boron steel sheet. Nearly isothermal tensile tests for quenched samples were conducted using a Gleeble 3800 thermal simulator investigate the effect of processing parameters on the thermo-mechanical characteristics of the material.

2.2. Experimental program

Uniaxial tensile tests have been performed to determine the thermo-mechanical characteristics of B1500HS within the strain rate range of 0.01–5 s\(^{-1}\) and deformation temperature range of (550-850 °C). The selective strain rate range is sufficient to cover the strain rates range experience in industrial practice and so is the selective temperature.

The heating process is divided into two steps: the first step is to heat the test pieces to 730 °C using a heating rate of 8 °C; the second step is to 900 °C with a heating rate of 3°C. The second step ensured full austenite transformation in the steel. This particular heating route is used to simulate the industrial process (A. Barcellona et al, 2009). After heating, test-pieces were cooled to testing temperatures at a cooling rate of 50 °C/s, which is similar to that experienced in transporting the blank to the press, in the industrial process (Cai et al, 2011).

3. Techniques for improvement of experimental results

3.1. Strain correction at necking stage

When failure does not occur at the specimen center section where the dilatometer is clamped, the strain obtained from dilatometer measurement cannot accurately present the deformation behavior of specimen after onset of necking. Therefore, a method has been defined to correct measured strain data to represent that at the necking position. Fig. 1(a) schematically shows the longitudinal area of interest between the center section and failure section of a tensioned specimen. At the time just before onset of necking (at the peak load), the area has a rectangular shape (light grey). The specimen width and the distance between center section and failure section are
When localized deformation takes place, the shape of the area deviates from rectangular, and in this method, it is simplified as a trapezium: the trapezium drawn in dashed lines represents an instantaneous shape during necking, where the widths of center section and failure section are $W_{ci}$ and $W_{fi}$, respectively, and the distance between center section and failure section is $l_i$; the trapezium in dark grey represents the final shape of the area when the specimen fails, where the corresponding dimensions are $W_{cn}$, $W_{fn}$, and $l_n$. The angle $\alpha$ represents the deviation of specimen edge from its original direction. It equals zero in the beginning, and for a constant strain rate, it is assumed to increase proportionally with time during necking.

$$\varepsilon_f = -2 \ln \left( \frac{W_f}{W_0} \right),$$

(1)

where $W_0$ is the initial width of specimen. The calculation of $W_f$ is given in detail as follows:

$$W_f = W_{ci} - 2 \left\{ \frac{l_i}{n} \left( \frac{S_0}{S_n} \right) + \frac{i}{n} (l_i - \frac{l_i}{n} \frac{S_0}{S_n}) \right\} \tan \left\{ \frac{i}{n} \left( \arctan \left( \frac{W_{cn} - W_{fn}}{2l_n} \right) \right) \right\},$$

(2)

where $W_{ci}$ is obtained from dilatometer measurement, $n$ is the total number of time intervals for the necking stage in data acquisition, $i$ represents an instantaneous time interval. $S_0$ and $S_n$ correspond to the strokes (data from Gleeble data acquisition) at the onset of necking and failure, respectively. The value of $l_i$ can be manually measured from the fractured specimen. $W_{cn}$ is read from dilatometer measurement, $W_{fn}$ are manually measured from the fractured specimen.

Fig. 1(b) shows the true stress-true strain curve before correction and after correction which was carried out at temperature 700°C and strain rate 1 s$^{-1}$. From the figure, we can notice that the true stress and the true strain were anastomotic before and after correction when necking had not occurred, yet the true stress strain after correction were apparently larger than that before correction when necking had taken place.

### 3.2. Temperature correction

The temperature was measured and controlled by thermocouple and computer, but the response time of thermocouple is often a limited factor. When the strain rate is high enough, it cannot control the instantaneous temperature change to a constant temperature, so the deformation process is not completely isothermal (Li et al., 2002). Fig. 2(a) shows the measured temperature changes during the tensile tests at preset temperatures of 700 °C and 800°C and strain rates range of 0.01 to 5 s$^{-1}$. It can be seen that at strain rate of 0.0 1s$^{-1}$, the temperature change is about 2 °C; however, at a strain rate of 5 s$^{-1}$, the maximum temperature rise is 25°C. Thus, the flow stress at high strain rates must be corrected. The changes of stress caused by temperature rise can be calculated by the following equation (Luan et al., 2014).
\[
\Delta \sigma = \left[ \frac{\partial \sigma}{\partial (1/T)} \right] \left( \frac{1}{T_n + \Delta T} - \frac{1}{T_n} \right),
\]

where \( \sigma \) is the flow stress (MPa), \( T_n \) is the preset temperature (°C) and \( \Delta T \) is the difference between the specimen temperature measured by the thermocouples and \( T_n \) (°C).

Fig. 2. (a) Temperature rise \( \Delta T \) of hot stamping for boron steel at pre-set temperature of 700°C and 800°C and (b) True stress-true strain curves before (lines) and after corrections (symbols) tested at different temperatures and at strain rates of (a) 1s\(^{-1}\).

Fig. 2(b) shows the comparisons of the flow curves of B1500HS boron steel with temperature corrected and non-corrected. It can be seen that the thermal effect on flow stress becomes larger at lower temperatures.

### 4. Determination of constitutive model

#### 4.1. Modeling of damage

Under a hot forming condition when the temperature is normally half \( T_m \) above, and strain rates are higher than 1s\(^{-1}\), plasticity induced damage may occur around inclusions and hard particles. The grain boundary diffusion at high temperatures which facilitates grain rotation and grain boundary sliding tend to be inhibited, due to the high strain rates (J. Lin et al, 2005). The damage dominating in hot forming conditions can be schematically illustrated, as shown in Fig. 3.

A new damage model suitable for hot deformation comprehensively considered equivalent stress, strain rate and damage was established based on damage mechanism, high temperature creep damage model and the existing damage model proposed by scholars, which highlighted the importance of strain rate on damage(J. Lin et al, 2005).

\[
\dot{D} = \beta_d \frac{\sigma \varepsilon^\gamma_3}{(1-D)^{\varepsilon_2}},
\]

where \( \dot{D} \) is the damage evolution rate, \( \beta_d \) is a material constant to represent the temperature effects on damage evolution \( d_2 \) and \( \gamma_3 \) are material constants. The temperature dependent parameter \( \beta_d \) can be given as:

\[
\beta_d = \beta_0 \cdot \exp \left( \frac{Q_d}{RT} \right),
\]
where $Q_0$ is a material constant related to the activation energy of damage.

4.2. Unified visco-plastic damage constitutive equations based on dislocation density

Unified constitutive equations for visco-plasticity damage have been developed for many metal materials (Lin et al., 2002). This work intends to develop a set of unified visco-plastic damage constitutive equations to model the evolution of recovery, dislocation density, hardening and damage to rationalize their inter-relationships and effects on visco-plastic flow of materials. The mechanism-based unified visco-plastic damage constitutive equations for hot stamping may take the form:

$$
\dot{\varepsilon}^p = \dot{\varepsilon}^p \left( \frac{\sigma}{1 - D - H - k} \right)^n \frac{1}{(1 - D)^{\gamma}} \dot{\varepsilon}^{\gamma} = \begin{cases} 
1, & \text{when } \sigma > 0 \\
-1, & \text{when } \sigma < 0
\end{cases},
$$

$$
\dot{\rho} = A \cdot (1 - \rho) \left| \dot{\varepsilon}^{\gamma} \right| - C \cdot \rho^{\gamma},
$$

$$
H = B \rho^{0.4},
$$

$$
\dot{D} = \beta_{\rho} \cdot \frac{\dot{\varepsilon}^{\gamma}}{(1 - D)^{\gamma}},
$$

$$
\sigma = E \cdot (1 - D) \cdot (\varepsilon' - \varepsilon^p).
$$

Relevant temperature dependent constants are given by:

$$
k = k_0 \exp \left( \frac{Q}{RT} \right),
K = K_0 \exp \left( \frac{Q}{RT} \right),
n = n_0 \exp \left( \frac{Q}{RT} \right),
C = C_0 \exp \left( - \frac{Q_{\sigma}}{RT} \right),
B = B_0 \exp \left( \frac{Q_{\sigma}}{RT} \right),
E = E_0 \exp \left( \frac{Q_{\sigma}}{RT} \right),
$$

$$
\beta = \beta_0 \exp \left( \frac{Q_{\beta}}{RT} \right),
$$

(7)

where $T$ is the absolute temperature, $Q$ is the activation energy and $R$ is the gas constant.

4.3. Determination of the equations via optimization

The equation sets have 20 material constants that must be determined: $k_0, K_0, n_0, C_0, B_0, E_0, \beta_0, Q, Q_{\sigma}, Q_C, Q_E, Q_{\beta}, \gamma_0, \gamma, A, d_2, Q_0, N_q, A_0$. They are determined by fitting theoretical and experimental stress strain curves for different strain rates and deformation temperatures. The values of the material constants were determined by the optimization techniques (Li et al., 2002). Computed values of the material constants are listed in Table 1.

4.4. Verification for the constitutive model

The constants in Table 2 were used to make the model predictions (curves) for stress versus strain shown in Fig.4(a), which demonstrate a good agreement between the model predictions and corrected experimental results (symbols) for B1500HS at different strain rates at a deformation temperature of 700 °C. In order to explore the model calibration, the predicted true stress is plotted against the corrected ones in Fig. 4(b). The correlation coefficient $R_c$ for the predicted constitutive model is 0.969, which means that a good correlation between the predicted and corrected data has been achieved. The average relative error between the calculated and the predicted
values is 3.73%, which indicates that the predicted model can give an accurate estimate of the hardening and fracture for B1500HS boron steel.

| $Q_c$ (J/mol) | $Q_t$ (J/mol) | $Q_d$ (J/mol) | $k_0$ (MPa) | $B_0$ (MPa) | $C_0$ (-) | $K_0$ (MPa) | $n_0$ (-) | $\beta_0$ (-) | $E_0$ (MPa) |
|----------------|----------------|----------------|-------------|-------------|---------|-------------|---------|-------------|-------------|
| 8400           | 99900          | 10650          | 12.4        | 80          | 13000   | 30          | 0.0068   | 1.09e-4     | 1100        |

| $Q_0$ (s$^{-1}$) | $N_0$ (-) | $\gamma_0$ (-) | $A_0$ (-) | $\gamma_0$ (-) | $\beta_0$ (-) | $Q_d$ (J/mol) | $Q_t$ (J/mol) | $d_0$ (-) |
|------------------|-----------|----------------|--------|----------------|-------------|-------------|-------------|---------|
| 0.01             | 0.5       | 0.1            | 3.666 | 1.54           | 16.3        | 0.1         | 50000      | 17500   | 0.9178   |

5. Conclusion

The flow stress was corrected by taking temperature rise and necking into consideration. It is verified that experimental accuracy has been improved by promoting experimental techniques. A set of unified visco-plastic damage constitutive equations were formulated to predict the hardening and damage of B1500HS boron steel accurately. The correlation coefficient is 0.969, and the absolute average relative error is 3.73% in the range of allowable experimental conditions.

Acknowledgements

The authors thank IMRA Europe S.A.S.U.K. Research Centre for financial support.

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