Theoretical Analysis of the Temperature and Strain Rate Effects on the Forming Limit Diagram of AA3104

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ABSTRACT: Forming limit diagram is one of the most applicable methods for prediction of the plastic instability in sheet metal forming in which is very much affected by the influences of strain rate and temperature. In this paper, taking the temperature and strain rate effects into account, the true stress-true strain and forming limit curves of AA3104 aluminum alloy are analytically investigated by considering the Marciniak-Kuczynski method and Johnson-cook model. The obtained theoretical results based on the Ludwik model are validated with the experimental ones. Furthermore, according to the stress-strain curves based on the Ludwik equation, Johnson-Cook coefficients are calculated for sheet metal AA3104. The stress-strain respond and forming limit diagram are produced over a range of strain rates (10^{-5} to 10^{-3} S^{-1}) and temperatures (50-400 ºC). The results show that the stress-strain curve decreases with increasing temperature and increases with increasing strain rate. Also the forming limit diagram increases with increasing temperature and decreases with increasing the strain rate. The results exhibit a positive sensitivity of the temperature on the limit strain due to the thermal softening and the negative strain rate sensitivity on the forming limit diagram AA3104 due to the behavior of crystallographic structure of the material.

1- Introduction

The effect of strain rate on the formability of metal sheets materials which are strain rate dependent behavior, researchers are still studying. Several experimental researches had been carried out to understand the strain rate sensitivity on Forming Limit Diagram (FLD) using Marciniak-Kuckzynski (M-K) model. Employing Johnson-Cook constitutive law, Gerdooei and Dariani [1] analytically investigated the effect of strain rate on FLD and dynamic instability of non-homogeneous Oxygen-Free High Conductivity (OFHC) copper metal sheets under biaxial stretching. Dariani *et al.* [2] experimentally carried out the forming velocity sensitivity on FLD of Al6061-T6 and AISI1045 sheets. Johnson–Cook constitutive model and the Jones–Wilkins–Lee (JWL) model were used to investigate the strain rate effect for metal sheets and the explosive charge, respectively. They concluded that the impact loading has a positive sensitivity on permeability of both Al6061-T6 and AISI1045 sheets.

The positive temperature effect on the formability validate only for sheet metal with low capability of formability at room temperature. The effects of strain rate and temperature on the FLD with YLD96 anisotropic yield surface were theoretically performed by Khan and Baig [3]. A modified Ludwick hardening law was employed to investigate the strain rate and temperature effects of the formability of AA5086 by Chu et al. [4]. Zhang et al. [5] experimentally investigated the effects of strain rate and temperature on the forming limit curves of AA5086 sheets using the modified Voce constitutive model.

In this paper, the effects of temperature and strain rate on FLD of AA3104 are theoretically investigated based on the M-K model and Johnson-Cook hardening low.

2- M-K Model

The Marciniak–Kuczynski method is considered based on initial geometrical inhomogeneity or initial imperfection as a groove which grows continuously by increasing the plastic strains to form finally from a localized neck. Non-linear system of equations can be derived from strain compatibility equation, energy equation and two force equilibrium equations.

$$\frac{d\varepsilon_{nn}^{b}\sigma_{nn}^{b} + d\varepsilon_{tt}^{b}\sigma_{tt}^{b} + 2d\varepsilon_{nt}^{b}\sigma_{nt}^{b}}{d\bar{\varepsilon}^{b}\bar{\sigma}_{Y}^{b}} - 1 = 0 \tag{1}$$

$$\frac{d\varepsilon_{tt}^{b}}{d\varepsilon_{tt}^{a}} - 1 = 0 \tag{2}$$

$$f\frac{\sigma_{nn}^{b}}{\sigma_{nn}^{a}} - 1 = 0 \tag{3}$$

$$f\frac{\sigma_{nt}^{b}}{\sigma_{nt}^{a}} - 1 = 0 \tag{4}$$

3- Yld2011 Yield Function

The Yld2011-18p yield criterion with two linear

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transformations is defined according to [6].

$$\bar{\sigma}_Y = \left\{ \frac{1}{\xi} \sum_{i=1}^{3} \sum_{j=1}^{3} \left| S_i' + S_j'' \right|^M \right\}^{1/M} \tag{5}$$

$$\xi = \left(\frac{4}{3}\right)^M + 4\left(\frac{2}{3}\right)^M + 4\left(\frac{1}{3}\right)^M , M \succ 1 \tag{6}$$

4- Johnson–Cook Model

The Johnson–Cook constitutive model incorporating strain rate and temperature functions can be employed [7].

$$\bar{\sigma}_Y = \left(A + B\bar{\varepsilon}^n\right)\left(1 + C \ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right) \tag{7}$$

5- Results and Discussion

Prediction of the stress - strain curve by using J-C model at temperatures 50, 300 and 400 °C and the strain rate of 10^{-5}, 10^{-4} and 10^{-3} s^{-1} for AA3104 are presented in Fig. 1. The positive strain rate sensitivity and the negative temperature sensitivity on the stress-strain response can be concluded at quasi-static conditions.

The influences of temperature and strain rate on the forming limit diagram of AA3104 are showed in Fig.2 using the M-K theory. The results show that by increasing the temperature, the FLD increases and the formability increases. So by increasing the strain rate, the FLD decreases and the formability decreases. The strain limit at in-plane strain condition is illustrated in Table 1. By changing the temperature of 50 to 300 °C, FLD_0 increases more than 50 percent and occurs more than three times with increasing temperature to 400 °C. By increasing the strain rate, in temperature 300 °C, FLD_0 decreases about 28% and decreases almost 11% in temperature 400 °C.

6- Conclusions

The main conclusions of the paper are as follows:
- Increasing of temperature decreases the stress-strain response and increases the forming limit curve of AA3104 aluminum alloy.
- Increasing of strain rate increases the stress-strain response and decreases the forming limit diagram of AA3104 sheet.
- For AA3104 aluminum sheet metal, the maximum strain limit result in up temperature and down strain rate.

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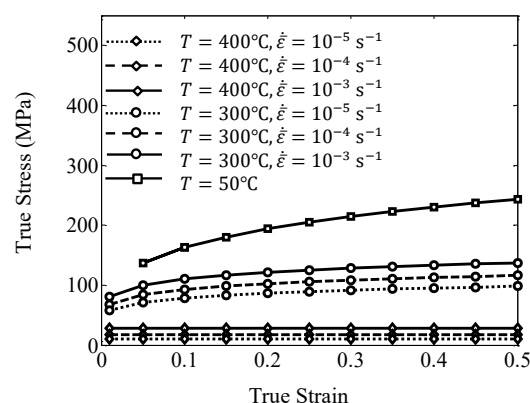
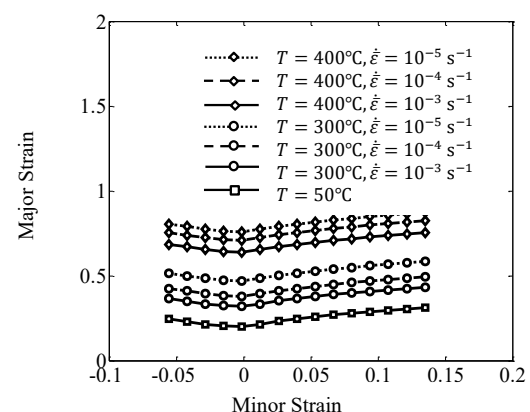**Fig. 1. The effect of temperature and strain rate on stress-strain response of AA3104**

Fig. 2. The effect of temperature and strain rate on FLD of AA3104

Table 1. FLD_0 at different temperature and strain rate

Temperature , °C Strain rate , s^{-1}	50	300	400
10^{-5}	0.214	0.462	0.737
10^{-4}	0.214	0.402	0.707
10^{-3}	0.214	0.334	0.657

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