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The Effect of Strain Rate and Temperature on Forming Limit Diagram for DKP-6112 and AZ31 Materials

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Abstract

Forming limit diagrams (FLDs) are used in sheet metal operations widely for predicting blank fracture and forming characteristics of materials. There are three approaches for building forming limit diagrams which are the experimental, theoretical and numerical methods. Experimental method, which includes Nakazima formability test, is generally preferred for determining forming limit diagrams, although it requires complex experimental setup and effort. This study, firstly, compares the experimentally determined FLD results with the numerically obtained ones by using the constitutive models formed through the use of von Mises criteria with isotropic, kinematic and combined hardening models, and Hill48 yield criterion at quasi-static loading and room temperature conditions. The stress-strain relations are obtained by applying the Johnson-Cook phenomenological model for DKP-6112 and AZ31 materials. Then, the constitutive relation that gives closest results to experimental data is chosen to evaluate the effects of the variations of strain rate and temperature values on the FLDs for both materials. Nakazima tests, with 8 different blank specimens, are simulated by using a finite element software to present and compare the numerical forming limit diagrams. For determining the necking time in numerical FLDs maximum strain acceleration strain localization method is used. It is observed that forming limit diagram shifts downwards with strain rate increase and shifts upwards with temperature increase for both materials.

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Keywords: Forming Limit Diagram; Formability; Strain Rate; Temperature

1. Introduction

Forming limit diagram shows the strain values which lead to failure. The diagram is used for estimating the onset of failure due to necking and location of possible failure spots according to different loading histories. Forming limit curves are generally used for tool manufacturing and optimization of stamping tools. However, forming limits of materials are dependent on the strain path and FLDs are not successful to represent the failure behaviour of the materials which have nonlinear strain paths.

For determining forming limit diagram, experimental methods are generally used. Although the most reliable method is experimental, complex experimental set-up and experimental procedure are required as in Nakazima test which is one of the most widely used method. Due to this complexity on experimentation, some theoretical models were introduced on the basis of the classical Swift and Hill instability criteria [1] and Stören and Rice theory [2], and the outputs were compared to the experimental results. In addition to experimental and theoretical methods, forming limit diagrams have been also determined by using the numerical methods. These newly-developed methods were based on the numerical simulation of Nakazima or other formability tests and the simulations are performed by using finite element method. To determine the necking time, ductile damage criteria [3] or strain localization criteria [4] have been used. Maximum strain acceleration, ratio of equivalent plastic strain increment, maximum punch force

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criteria are the methods used for strain localization. Within these maximum strain acceleration criterion [5] is the mostly used one as strain localization method to predict necking time.

This paper aims to develop the numerical forming limit diagrams of DKP-6112 and AZ31 materials to explain the effect of strain rate and temperature. For this purpose, initially, the experimentally determined FLD results are compared with the numerically obtained ones. The constitutive models were formed through the use of von Mises criterion with isotropic, kinematic and combined hardening models and Hill48 [6] yield criterion for quasi-static loading and room temperature conditions. Then, the constitutive relation that gives closest results to experimental data is used to evaluate the effects of the variations of strain rate and temperature values on the FLDs for both materials. The stress-strain relations are obtained by applying the Johnson-Cook phenomenological model [7] for DKP-6112 and AZ31 materials. The finite element simulations of Nakazima tests, with 8 different blank specimens, were conducted for both materials. For most of finite element software, there are several built-in ductile damage models. In this study, maximum strain acceleration method was used to predict necking.

2. Maximum strain acceleration criterion

In this study, in order to determine forming diagram, maximum strain acceleration criterion is used. Maximum strain acceleration criterion is based on the evaluation of second time derivative of major strain with respect to time. In this criterion, the duration of localized thinning is determined by a sudden change in the value of second time derivative of major strain. After maximum strain acceleration is attained, the localized thinning proceeds gradually until the onset of fracture [4]. An example for strain acceleration method is in Figure 1.

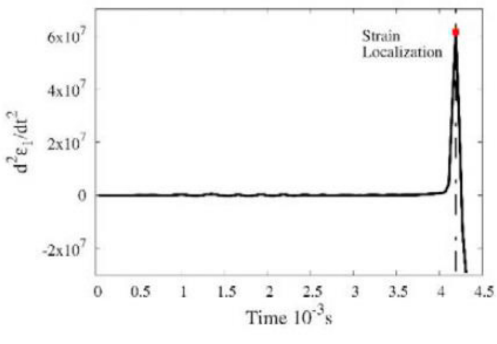

Fig. 1. Prediction of failure time by strain acceleration criteria [8]

In this study, to apply the maximum strain acceleration criterion, the variation of plastic equivalent strain with respect to time is recorded for the most critical element according to finite element analysis results. Then, the second derivative of strain is taken by using forward difference method with four points. In Figure 2 the change of strain acceleration with respect to time is presented for quasi-static case using 50 mm, 75 mm and 125 mm-width blank specimens of DKP-6112 steel. For all three specimens, there is a global maximum of strain acceleration and after that point necking is assumed to start.

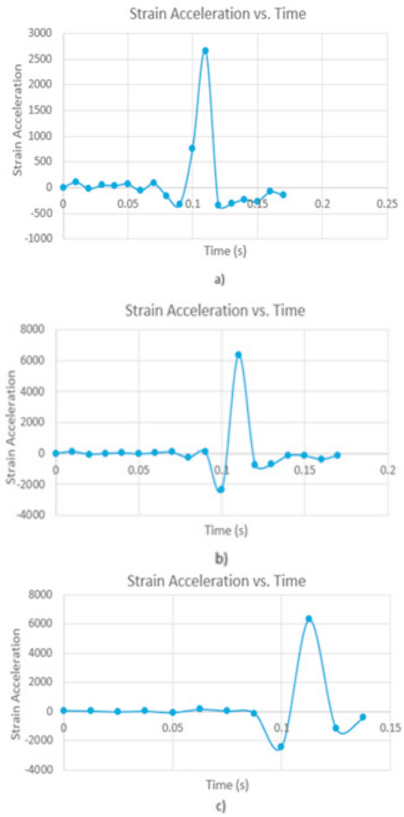

Fig. 2. Strain acceleration vs. time for a) 50 mm b) 75 mm c) 125 mm-width DKP6112 specimens for quasi-static case

3. Constitutive models

In constitutive modelling, von Mises and Hill48 yield criteria are used as yield criterion, isotropic [9], kinematic [9] and combined hardening [9] are used as hardening model and Johnson-Cook phenomenological model is used for explaining stress-strain behavior for different strain rate and temperature conditions.

3.1. Von Mises Yield Criterion[9]

Von-Mises yield criterion [9] is one of the oldest and mostly used yield criterion in plasticity applications. The criterion assumes that plastic yielding will occur only when the second invariant J_2' of the deviatoric stress tensor reaches a critical value κ^2 as given below:

$$J_2' - K^2 = 0 \tag{1}$$

In terms stress components, the criterion can be written as:

$$(\sigma_{xx}-\sigma_{yy})^2+(\sigma_{yy}-\sigma_{zz})^2+(\sigma_{zz}-\sigma_{xx})^2+\sigma_{xy}^2+\sigma_{yz}^2 +\sigma_{xz}^2 = K^2 \tag{2}$$

3.2. Hill 48 Yield Criterion[6]

Hill48 yield criterion [6] is one of the mostly used yield criterion for orthotropic materials. This criterion assumes that hydrostatic stress has no effect on yielding and Bauschinger effect is not considered. The yield function can be written as based on stress components:

$$2f(\sigma_{ij}) = F(\sigma_{yy} - \sigma_{zz})^2 + G(\sigma_{zz} - \sigma_{xx})^2 + H(\sigma_{xx} - \sigma_{yy})^2 + 2L\sigma_{yz}^2 + 2M\sigma_{xz}^2 + 2N\sigma_{xy}^2 - 1 = 0 \quad (3)$$

where F, G, H, L, M and N are material constants describing the state of anisotropic behavior. In order to determine the constants F, G and H, the tensile yield strength values for three principal directions of anisotropy must be measured.

3.3. Johnson-Cook Phenomenological Model[7]

One of the mostly used model that explains strain rate and temperature effect on stress values is Johnson-Cook model. It is a phenomenological constitutive model. The model is applicable for the range of strain rate values 10^{-3} s^{-1} and 10^3 s^{-1} [7]. There are different parts that takes strain hardening, strain rate and temperature effects into account as given below:

$$\sigma = (A + B\varepsilon^n)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)\right] \quad (4)$$

where A, B and n are the strain hardening constants, C is the material constant that describes the strain rate characteristic, the reference strain rate value which is generally used as 1 in typical application of Johnson-Cook model, T is the operating temperature, T_m is the melting temperature of the material. T_r represents the room temperature and m is a material constant for temperature-dependent part.

4. Numerical Verification of the Constitutive Models

To verify the results obtained for different constitutive models that are formed by using von Mises criterion with isotropic, kinematic and combined hardening and Hill48 criterion a number of simulations were performed according to material data of DKP-6112 [9] and AZ31[10] materials. In the simulations, the finite element models of the Nakazima test specimens were used.

4.1. DKP-6112 Material

The experimental [11] and numerical results are compared in Figure 3 for DKP-6112 material for quasi-static loading at room temperature. From the comparison of experimental and numerical results, it can be observed that Hill48 yield criterion gives the closest results to experimental finding. All of the other models predicted FLD for DKP-6112 quite well except kinematic hardening model when $\varepsilon_1 > 0$. For $\varepsilon_1 < 0$, isotropic Von-Mises model resulted in higher minor strain values whereas combined hardening model predicted lower values than the experiments. Kinematic hardening model's results deviated considerably. Hill48 has a good prediction in this region also.

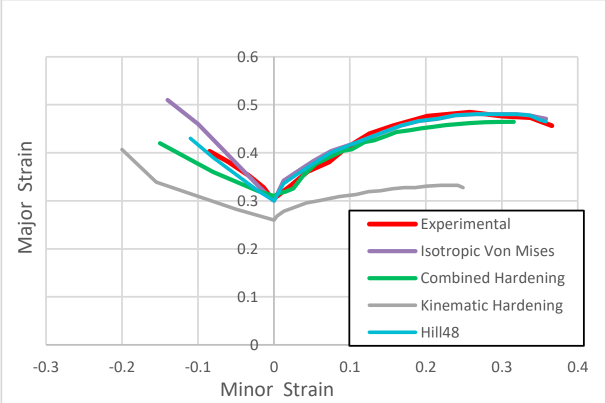

Fig. 3. Experimental and numerical forming limit diagram of DKP-6112 for quasi-static case and room temperature

4.2. AZ31 Material

For AZ31 material, the results of numerical model were compared with experimental results at 150°C for quasi-static case. Comparison of experimental [12] and numerical results are given in Figure 4. Similar to the case with DKP-6112 numerical simulations give close estimates to the experimental results for AZ31 material. Hill48 is the yield criterion that has closest results to the experimental findings. Isotropic and combined hardening models give higher values for the region $\varepsilon_1 > 0$ and lower values for $\varepsilon_1 < 0$ compared to experiments. Results for kinematic hardening model deviates significantly from experimental data in both regions.

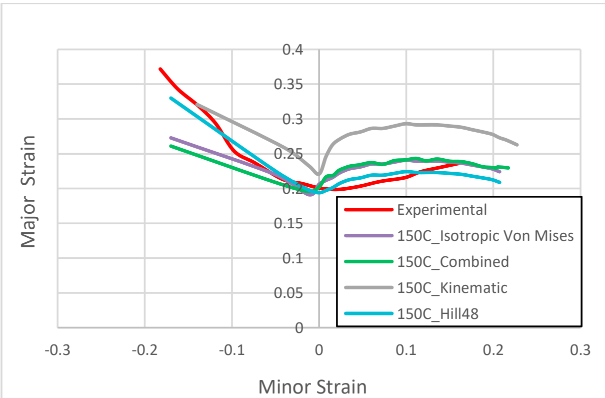

Fig. 4. Experimental and numerical forming limit diagram of AZ31 for quasi-static case and 150°C temperature

5. Results for Different Strain Rate and Temperature

The comparison of the results obtained for different constitutive models that are formed by using von Mises criterion with isotropic, kinematic and combined hardening and

Hill48 criterion with the experimental results showed that Hill48 criterion estimates the FLDs better for DKP-6112 and AZ31 materials. Hence, for higher strain rate and temperature values the simulations were carried out and presented by using the Hill48 criterion with Johnson-Cook model. To observe the effect of strain rate and temperature on FLDs, the limiting values were obtained for the punch speed of 200 mm/s at 25 ^oC and 150 ^oC, and compared with the values calculated for the quasi static case at the same temperatures.

5.1. DKP-6112 Material

For DKP 6112 material, the outputs of numerical FLDs are compared in Figure 5. It is observed that forming limit curves shifted downwards and the duration for necking reduced with the punch velocity increase. As the temperature increased, forming limit curve shifted upwards and the required necking time also increased. It can be commented that with punch velocity increase blank is more prone to fracture in relatively lower strain values.

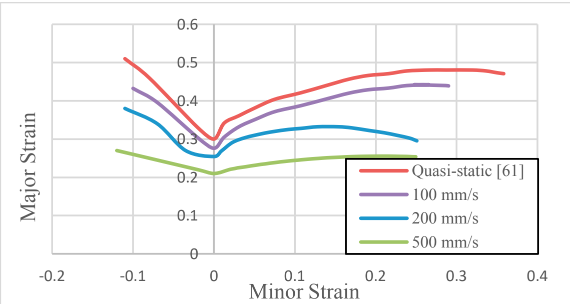

Fig. 5. Comparison of numerical forming limit diagram of DKP-6112 material for different punch velocity values in room temperature

5.2. AZ31 Material

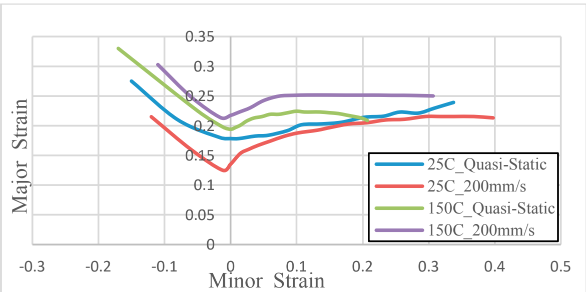

Fig. 6. Comparison of numerical forming limit diagram of AZ31 material for different punch velocities and temperatures

According to results obtained for AZ31 material, it is observed that with the increase of punch velocity, forming limit curve shifted downwards and with the increase of temperature, forming limit curve shifted upwards and also the required necking time increased (Figure 6). It can be generally deduced that increasing punch velocity makes the blank being more prone to fracture and fracture requires greater punch forces. Increasing temperature decreases the possibility of fracture and it requires lower punch forces, however it has undesired effect on minimum thicknesses.

4. Conclusions

In this paper forming limit diagrams has been developed numerically by using finite element analysis to explain the effect of strain rate and temperature on fracture. Numerical results for quasi-static case were compared with experimental results and close results were obtained. The major conclusions of this study as follows:

- Numerical forming limit diagrams by simulating Nakazima test give close results to experimental results.
- For building numerical forming limit diagrams, Hill48 yield criterion with Johnson-Cook phenomenological model is the most suitable combination in the finite element analysis compared to models obtained by von Mises yield criterion with isotropic, kinematic and combined hardening.
- Forming limit curves shift downwards with increasing strain rate and causing the blank is more prone to fracture.
- Forming limit shifts shift upwards with increasing temperature.

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