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Stress based forming limit diagram for formability characterization of 6061 aluminum

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Abstract: Two numerical criteria of forming limit diagram (FLD) criterion and ductile fracture criterion (DFC) are presented for FLD prediction of 6061 aluminum. The numerical results are compared with the experimental FLD and also punch's load−displacement curve of experimental samples. Experimental FLD of this study is calculated using hemispherical punch test of Hecker. Experimental FLD is converted to FLSD and imported to the Abaqus software to predict necking of samples. Numerical results for FLSD prediction were compared with experimental FLSD. Results show that ductile fracture criterion has higher accuracy for FLD and FLSD prediction of 6061 aluminum. Comparison of numerical and experimental results for force−displacement curve of punch shows that numerical results have a good agreement with experiment.

Key words: aluminum alloy 6061; forming limit diagram (FLD); forming limit stress diagram (FLSD); ductile fracture criterion; finite element method

1 Introduction

Prediction of the forming limits in sheet metal forming is very important in order to identify the conditions that may lead to necking and fracture. The forming limit curve at necking (FLCN) is used as a criterion for prediction of sheet metal forming limit. It displays in principal strain space (major and minor strains) at the onset of local necking. On the other hand, the forming limit curve at fracture (FLCF) is defined by the combined principal strains up to fracture. Figure 1 indicates the schematic diagrams showing the FLCN and FLCF. Here, α ($=\mathrm{d}\sigma_2/d\sigma_1$) defines stress ratio and ρ ($=\mathrm{d}\varepsilon_2/\mathrm{d}\varepsilon_1$) is the strain ratio. For a given initial strain path, after the onset of strain localization, the material deforms in restricted area and follows an almost plane strain path up to failure [1].

FLD of sheet metals was initially characterized by KEELER and BACKOFEN [2] and GOODWIN [3] and later became industrial practice as well as a topic of research, both theoretically and experimentally. Since then, a lot of researches have been performed for calculation of FLCN and FLCF. Forming limit diagrams at necking and at fracture for AA6111-T4 sheet material were experimentally determined by JAIN et al [4], and surfaces of fractured dome specimens were observed by optical microscopy and by scanning electron microscope (SEM). OZTURK and LEE [5] obtained the limit strains for FLD by substituting stress and strain values obtained from the finite element (FE) simulation of out-of-plane formability test into the ductile fracture criterion.

SAFDARIAN et al [6] used different numerical methods for FLD prediction of tailor welded blanks (TWBs). Their results showed that numerical methods are useful for prediction of left hand side of FLD, but they can not extend in the right hand side of FLD. They also studied the effect of thickness ratio on the level of FLD for St12 TWB with different thickness ratios in another research [7]. Their results showed that FLD's level increases by thickness ratio decreasing of TWB. SAFDARIAN [8] used Marciniak−Kuczynski (M–K) model for necking prediction of IF tailor welded blank. Bending strain was added to the M−K model and a new model was presented which was used as a criterion in the Abaqus software. Python programming language was used to link this model to software.

Although the FLD method is useful tool for the analysis of sheet metal formability in the forming processes, it has been shown to be valid only for cases of

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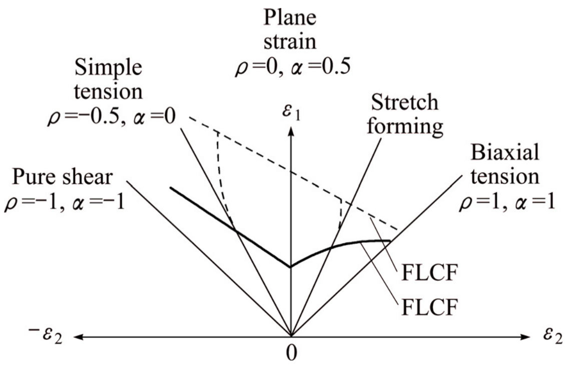

Fig. 1 Schematic diagram showing FLCN and FLCF

proportional loading, where the ratio between the principal stresses remain constant throughout the forming process. In an industrial application, complex work pieces are usually manufactured in multi-step processes, from which the influence of the non-proportional strain history on the FLD can be problematic [9]. Under such conditions, the FLD cannot be successful for formability prediction in the sheet metal forming. Additionally, several authors have used FLSD and proved that a FLD only applies to linear strain ratios [10−12].

ARRIEUX [13] presented the method of FLSD determination which used the information obtained from total deformation paths for the crack initiating area, by using the Nakazima FLD tests. STOUGHTON [14] used stress-based forming limit diagram for forming limit investigation of both proportional loading and non-proportional loading. Forming limit stresses can also be obtained from numerical results of forming tests in the finite element method (FEM). In the FEM, the numerically calculated stresses can be evaluated incrementally in the necking area while approaching the FLD-failure criterion. UTHAISANGSUK et al [15] used FEM simulation of Nakazima tests to determine the forming limit stress diagram. When the strains from the crack-critical elements in the simulation reach the forming limit curve (FLD criterion), the maximum stresses on these elements are evaluated. FANG et al [16] studied FLD and FLSD of aluminum alloy 1060 under linear and nonlinear strain paths. In this study, influences of the material's yield criteria on FLSD are also discussed by comparison of the Hill's 48, Hill's 79 and Hosford non-quadratic criterion.

In the present work, different numerical approaches are used to predict the FLD and FLSD of aluminum alloy 6061. These methods contained: forming limit diagram (FLD) criterion, ductile fracture criterion (DFC) and forming limit stress diagram (FLSD).

Experimental tests of FLD are done based on the Nakazima FLD test to characterize forming behavior of 6061 aluminum sheet. Numerical results for FLD, FLSD and punch's load−displacement prediction are compared with experimental results of present research. Numerical results have a good agreement with experimental results.

2 Methodologies

2.1 Experimental materials and properties

Because of the high specific strength, aluminum alloy 6061 has many applications in different industries like automotive and aerospace industries and can help the reduction of fuel consumption. Sheet of aluminum alloy 6061 with thickness of 1 mm was used for formability characterization in the present study. The chemical composition of this alloy is shown in Table 1. Figure 2 shows engineering stress−strain curve of aluminum alloy 6061. Mechanical properties of this aluminum are shown in Table 2. These mechanical properties are yield stress (YS), ultimate tensile strength (UTS), work hardening exponent (n), work hardening coefficient (K) and elongation which were evaluated by standard tensile testing of ASTM-E8 specification at 2 mm/min cross-head speed [17]. Hollomon's equation ($\sigma=K\varepsilon^n$) was used to model the plastic behavior of sheet material. The R^2 value in Table 2 shows curvature fitting of stress−strain curves related to 6061 aluminum sheet.

The standard seven different strain paths (25 mm × 175 mm to 175 mm × 175 mm) were cut from a 6061

Table 1 Chemical composition of aluminum alloy 6061

Mg	Si	Fe	Mn	Cr	Zn	Cu	Ti	Al
0.9	0.62	0.33	0.06	0.17	0.02	0.28	0.02	Bal.

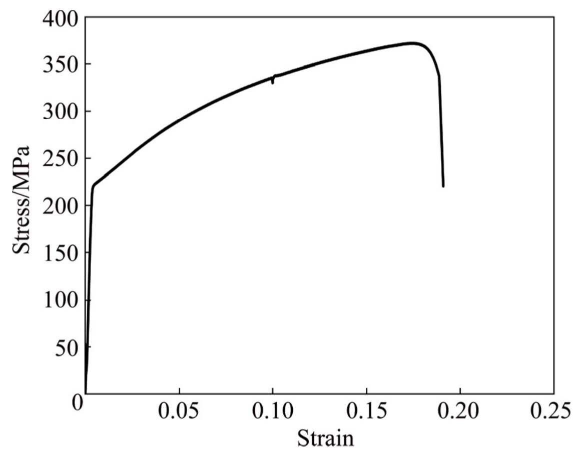

Fig. 2 Tensile test results of 6061 aluminum sheet

Table 2 Mechanical properties of aluminum alloy 6061 from tensile test

Sheet	YS/ MPa	UTS/ MPa	Elongation/ %	n	K/ MPa	R^2
AA6061	217.5	372.56	17.5	0.1829	511.9	0.984