Experimental and Numerical Investigation of Forming Limit Diagram for AA3105

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Abstract. In this work, forming limit diagram for aluminum alloy 3105 is performed experimentally using out of plane test. In addition, using ductile fracture criteria and finite element simulation, forming limit diagram of aluminum alloy 3105 is performed numerically. Finally, it is shown that the results obtained from numerical prediction are in good agreement with experimental results.

Keywords: Forming Limit Diagram, Experimental and Numerical Prediction, Ductile Fracture Criteria.

INTRODUCTION

Sheet metal formability is generally defined as the ability of metal to deform into desired shape without necking or fracture. Each type of sheet metal can be deformed only to a certain limit that is usually imposed by the onset of localized necking, which eventually leads to the ductile fracture. A well-known method of describing this limit is the forming limit diagram (FLD), which is a graph of the major strain ($\varepsilon_{11}$) at the onset of localized necking for all values of the minor strain ($\varepsilon_{22}$). The diagram can be split into two sides; “left side” and “right side”. At the “right side”, which was first introduced by Keeler and Backofen [1], only positive Major and Minor Strains are plotted. Goodwin [2] completed the FLD by adding the “left side”, with positive Major and negative Minor Strains. Various strain paths can be generated in order to create different combinations of limiting Major and Minor Strains. Usually FLDs are determined by using one of the following two types of test methods:

1) Marciniak in-plane test
2) Nakazima out-of-plane test

In this work, Nakazima (Dome) out-of-plane test is used. Since 1970s, finite element theories have been developed for providing the useful information to the real processes in industries [3, 4]. The FEA usually gives the information of forming process such as the deformed shape, strain and stress distribution, punching load, and the fracture. Recently, several researchers [5–8] have used ductile fracture criteria to determine the limit strains. The limit strains were determined by substituting the values of stress and strain histories calculated by the finite element simulations into the ductile fracture criteria.
CRITERIA FOR DUCTILE FRACTURE

Based on various hypotheses, many criteria for ductile fracture have been proposed empirically as well as theoretically [5, 9]. It is well known that the forming limit of sheet metals depends greatly upon the deformation history. Therefore, the histories of stress and strain may have to be considered in the criteria. The energy or generalized plastic work criterion was first given by Freudenthal [10]:

\[ \int_0^{\bar{\varepsilon}_f} \bar{\sigma} \, d\bar{\varepsilon} = C_1, \quad (1) \]

Cockcroft and Latham [11] proposed a fracture criterion based on “true ductility,” which states that the fracture in a ductile material occurs when the following condition is satisfied:

\[ \int_0^{\bar{\varepsilon}_f} \sigma_{\text{max}} \, d\bar{\varepsilon} = C_2, \quad (2) \]

The Cockcroft and Latham criterion was modified by Brozzo et al. [12] to introduce the effect of hydrostatic stress \( \sigma_h \) in an explicit form and to correlate their experimental results.

\[ \int_0^{\bar{\varepsilon}_f} \frac{2\sigma_{\text{max}}}{3(\sigma_{\text{max}} - \sigma_h)} \, d\bar{\varepsilon} = C_3, \quad (3) \]

In the above equations \( \bar{\varepsilon}_f \) is the equivalent strain at which the fracture occurs, \( \sigma_{\text{max}} \) is the maximum normal stress, \( \sigma_h \) is the hydrostatic stress, \( \bar{\sigma} \) the equivalent stress, \( \bar{\varepsilon} \) the equivalent strain, and \( C_1, C_2 \) and \( C_3 \) are material constants. To determine the material constants, destructive tests have to be operated under at least one or two types of stress conditions. In the present study, the material constants \( C_1 - C_3 \) are determined simply by uniaxial tension. \( C_1 - C_3 \) parameters obtained from this procedure in this work are 23.58, 28.30 and 0.1.

EXPERIMENTAL PROCEDURE

Uniaxial tensile test specimens, 50mm long and 12.5mm wide at zero degree to the rolling direction, prepared from the sheets were pulled to fracture at a cross-head speed of 5mm/min, producing an average strain rate of \( 1 \times 10^{-3} \text{s}^{-1} \) as the specimen...