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Original Research Article

Damage characterization of aluminum 2024 thin sheet for different stress triaxialities

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ABSTRACT

Due to its attractive mechanical properties, aluminum 2024 is widely used in aircraft manufacturing industries, especially as fiber metal laminates, such as GLARE. In the present work, a series of experiments for different stress triaxialities are used to study the ductile damage of Al 2024 considering continuum damage mechanics (CDM). Stress triaxiality is produced using notched specimens. The main objective of the present study is to predict the local equivalent plastic strain to fracture and introducing a relation which describes the effect of stress triaxiality factor (TF) on it in the medium range of stress triaxiality. Hence, a nonlinear damage model is utilized for Al 2024 and its parameters are determined by an experimental/numerical/optimization procedure using tensile test on plain specimens. The experiments showed that for large notch specimens (Al-NL) and medium notch samples (Al-NM) fracture started from the center of the notch root of the specimens, whereas for small notched specimens (Al-NS) the failure initiated from the notch root surface. Finite element simulations are performed using the presented nonlinear damage model and are compared with the experimental data. Results show that the proposed damage model can predict the damage evolution for different stress triaxialities.

1. Introduction

Prediction of ductile fractures and damage evolution of metals in engineering structures is an important subject in the automotive, aerospace, marine and military industries [1–5]. Aluminum alloys, for example 2024, due to its excellent mechanical properties and high fatigue resistance, have wide application in manufacturing the fuselage of aircrafts in form of fiber metal laminates, such as GLARE [6–10]. Although aluminum 2024 used in aerospace structures is a high strength alloy, it is recognized as a ductile material [11]. In numerous experimental investigations, it has been reported that the material fracture strain varies with loading conditions or stress states [12–14]. Xue and Wierzbicki [15] presented a calibration procedure for aluminum alloy 2024-T351 using the damage plasticity theory consisting of a full three dimensional damage evolution law. Bao and Wierzbicki [16] carried out a

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Table 1 – Chemical composition of Al 2024 alloy.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Impurities total	Al
Quantity (%)	0.1	0.26	3.8	0.5	1.3	0.01	0.08	0.02	0.08	Base

series of experiments including upsetting, shear and tensile tests on 2024-T351 aluminum alloy providing clues to fracture ductility for a wide range of stress triaxiality factor (*TF*) defined as follows:

$$TF = \frac{\sigma_H}{\sigma_{eq}} \quad (1)$$

with

$$\sigma_H = \frac{1}{3}(\sigma_I + \sigma_{II} + \sigma_{III}) \quad (2)$$

$$\sigma_{eq} = \sqrt{\frac{(\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2}{2}} \quad (3)$$

where σ_{eq} is the equivalent von-Mises stress and σ_H is the hydrostatic stress. In addition, σ_I, σ_{II} and σ_{III} are the principal value of the stress tensor. Based on the experimental and numerical results, they found a relation between the equivalent strain to fracture versus TF. Bonora et al. [17] validated a model formulation based on CDM against ductile damage evolution, experimentally measured in A533B low alloy steel under various stress triaxiality conditions. They reported transferability of damage parameters definition and potential of the damage model to predict the ductile failure in structures and components under multi-axial loadings. Driemeier et al. [18] discussed experimental procedures, visual observations and test results to investigate the combined effects of effective stress, TF and Lode parameter on material response and failure behavior of aluminum alloys. They argued that the experimental data can be used to propose and verify constitutive models and failure criteria depending on both TF and independent Lode parameter. How to correctly calculate the local values of TF in tensile deformed Al 6xxx sheet alloys samples was investigated by Bacha et al. [19]. Furthermore, they numerically studied the ductility of sheet samples by a damage mechanics cell model based on finite element method (FEM). They concluded that the predicted average ductility values exhibited a good agreement with the experimental results. Li et al. [20] studied the ductile fracture characteristics of Chinese Q460 high strength structural steel under quasi-static condition by mechanical tests on four types of notched specimens. Also, they investigated the influence of stress state on the material fracture mechanism. It was found that the results could be used to calibrate a series of micromechanical fracture models for Q460 steel. Stefanik et al. [21] determined a critical values of the normalized Cocroft–Latham criterion for different values of temperature and strain rates using the comparative method for the uniaxial tensile test of notched specimens. Yue and Zheng [22] performed a finite element analysis to study the void enlargement in a smooth and notched tensile bar made of 40 Cr steel alloy. The dependence of the void growth parameter on the local TF and local effective plastic strain near the crack tip of ductile materials have been investigated by Wang et al. [23]. Kossakowski [24,25] analyzed the load-bearing capacity of S235JR steel elements subjected to complex stress states, taking into account the effect of microstructural damage.

As stated above, numerous studies on the ductile fracture of aluminum 2024 under different TFs can be found in the literature. However, nonlinear CDM models in the failure mechanism have not been widely considered. In the present work, ductile fracture of aluminum 2024 sheet is investigated based on Bonora [26] nonlinear damage model. The optimized damage parameters are determined based on experimental results and iterative FE simulation. Meanwhile, numerical simulations are conducted to obtain desired values of TF and failure strain in the center of the notch root for all specimens. The ability of the damage model is simulated by finite element method and results are validated by experiment for each notch radius.

2. Material and experiment

In the present study, Al 2024 sheet with average thickness of 0.84 mm is used for tensile tests. Chemical composition and the percentage of each element in used aluminum alloy are given in Table 1. To study the notch effect on damage behavior of specimens, three notch radii are used to investigate the effect of TF on failure strain. Furthermore, a plain specimen (unnotched) is prepared to obtain the mechanical properties of Al 2024 (e.g. Young modulus, Poisson's ratio and the true stress–strain plastic flow curve). For each notch radius and also for the plain specimen, three specimens are prepared to study the tests repeatability. Thus twelve samples are prepared in total. Fig. 1 shows the geometry of unnotched and notched specimens employed in this work. For each specimen a code was assigned as shown in Table 2.

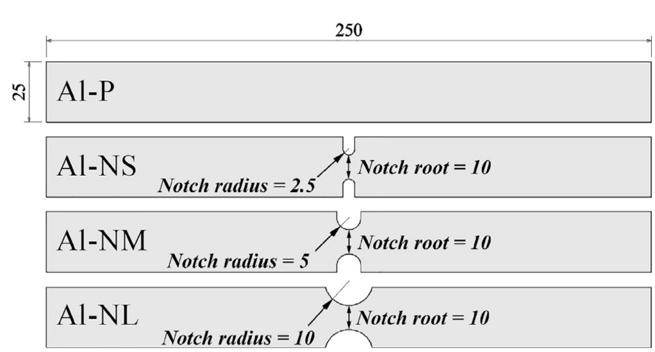

Fig. 1 – Geometry of plane and notched specimens (dimensions are in mm).