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Evaluation of flow stress and damage index at large plastic strain by simulating tensile test of Al6061 plates with various grain sizes

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A B S T R A C T

This work was focused on evaluation of the more accurate flow stresses and damage indices after onset of necking by simulating tensile tests of Al6061 plates with various grain sizes. By assuming strength coefficient and strain hardening coefficient, load vs. displacement curve was obtained from finite element simulation and then was compared with that obtained from the experimental tensile test. By means of repetition of this procedure, the flow stress curve with the accurate strength coefficient and strain hardening coefficient after onset of necking were determined when the error between load vs. displacement curves obtained from simulation and experiment of tensile test was minimized. Through comparison of the deformed shapes obtained from FE simulation and experiment of tensile test, the reliability of flow stress was verified. Based on the flow stress determined, the damage index of normalized Cockcroft–Latham ductile fracture criterion was evaluated at the displacement where fracture initiates during tensile test. Finally, grain size effect of Al6061 plate on the flow stress and damage index was investigated. It was revealed from this work that the strain hardening exponent and damage index increase when the grain size increases. On the contrary, strength coefficient is not so much different regardless of the grain size.

1. Introduction

Numerical simulation has sustainably contributed to enhance design efficiency of the part and process required in various industrial fields because it has been used as a powerful and efficient tool for visually describing the field variables such as stress, strain, temperature and the complicated deformation behavior. The reliability of such a simulation is strongly dependent on the input data assigned. Especially in metal forming simulation, the flow stress is one of main input data which has a significant effect on the reliability of simulation results.

In recent, important concerns in metal forming simulation are how to estimate the more accurate flow stress and whether the desired deformation can be accomplished without any facture generation of work material. In these points of view, the tensile test is commonly used for determining the flow stress and damage index in order to predict fracture generation of ductile materials [1–6].

However, the flow stress is only valid before the onset of necking because necking during tensile test induces the deformation inhomogeneity and stress triaxiality. Moreover, it is not possible to evaluate the damage index at strain where fracture occurs if the accurate flow stress after onset of necking to fracture is not estimated. For this, many works have been carried out to find the accurate flow stress after onset of necking using theoretical approach or numerical simulation [7–10]. Especially, Joun et al. [8] suggested the methodology to find flow stress after necking to fracture based on engineering stress vs. strain curve by iteratively minimizing the error between tensile loads obtained from simulation and experimental tensile test.

So far, numerous theoretical damage models have been proposed and used in metal forming simulation due to their simplicity of application [11–18]. These models are generally expressed as the following function of Eq. (1) in terms of stress and effective strain which have significant influence on fracture occurrence.

$$\int_0^{\bar{\varepsilon}_f} f(\sigma,\bar{\varepsilon})d\bar{\varepsilon} = C_{\text{crit}} \quad (1)$$

where σ, $\bar{\varepsilon}$, $\bar{\varepsilon}_f$ and C_{crit} denote the stress components, effective strain and effective strain at fracture, critical damage index, in that order.

The critical damage index in Eq. (1) can be evaluated from comparison of the results obtained from simulation and experiment of tensile test. If the damage index predicted from simulation exceeds the critical one it can be regarded as fracture generation in metal forming simulation. Here, it should be noticed in Eq. (1) that

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Nomenclatures

a/b	element size ratio.
C_{crit}	critical damage index.
K	strength coefficient.
K_A	assumed strength coefficient.
N	strain-hardening exponent.
n_A	calculated strain-hardening exponent from K_A.
n_{theo}	theoretical strain-hardening exponent.
ε	strain.
ε_n	strain at necking.
ε_o	pre-strain.
$\bar{\varepsilon}$	effective strain.
$\bar{\varepsilon}_f$	effective strain at fracture.
σ	stress.
σ_n	stress at necking.
σ_p	stress at yield point.
σ_s	stress at steady state.
σ_u	ultimate tensile stress.
σ^*	maximum tensile principle stress.
$\bar{\sigma}$	effective stress.

the accurate stress components at strain where fracture initiates have to be calculated to obtain accurate critical damage index.

Therefore, in this work, the tensile test in conjunction with finite element simulation and experiment was carried out to estimate more accurate flow stress of Al6061 plate after onset of necking and critical damage index at onset of fracture. For this, the flow stress curve after onset of necking was assumed to be expressed in the form of power law which can be defined by strength coefficient and strain-hardening exponent. Using the flow stress obtained from the minimization in error between load vs. displacement curves obtained from FE simulation and experiment of tensile test, the critical damage index of normalized Cockcroft–Latham ductile fracture criterion was evaluated at the displacement where fracture begins. Finally, the effect of grain size of Al6061 plate on the changes in strength coefficient, strain hardening exponent and damage index was investigated.

2. Tensile test

Plastic deformation instability takes place just after peak load in tensile test as shown in Fig. 1. This kind of unstable deformation is associated with diffusion necking formed in tensile specimen and leads to flow localization followed by ultimate ductile fracture. In this work, estimation of flow stress from onset of the necking to fracture and damage index at fracture are done by coupling of FE simulation and experiments of tensile test.

Tensile specimens of aluminum alloy Al6061 were prepared to have the dimension with gauge length of 50.0 mm, width of 12.5 mm and thickness of 8.15 mm and were cut off in the directions of 0°, 45° and 90° against the rolling direction as shown in Fig. 2. In addition, the tensile specimens were annealed at the temperature conditions of 350, 370, 390 and 410 °C for 3 h and were cooled within the furnace for 12 h in order to investigate the effect of grain size of Al6061 plate on the flow stress and damage index. The microstructures and grains size distributions of plane parallel to rolling direction were depicted at each annealing condition in Fig. 3. Initial grain size of as-received Al6060-T6 plate is 18.4 μm and orientation of microstructures arranged to the rolling direction can be observed. It can be observed in this figure that the average grain size increases with increase of annealing temperature.

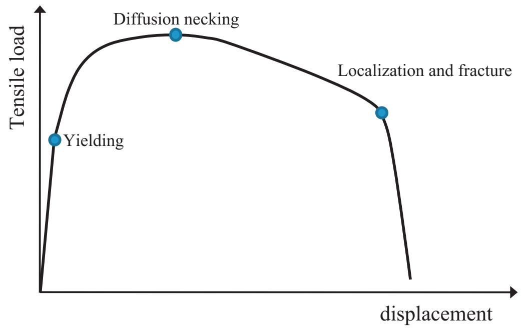

Fig. 1. Schematic diagram of load vs. displacement curve in tensile test.

The specimens were strained with testing speed of 1.5 mm/min at room temperature. Fig. 4 shows the measured load vs. displacement and flow stress curves of Al6061 plate with grain size of 19.4 μm (annealed at 350 °C) according to the orientations of 0°, 45° and 90°, respectively. In this figure, the load vs. displacement curve was described until complete fracture. On the other hand, the flow stress curves were shown just before onset of necking. The load vs. displacement curves in Fig. 4(a) are slight different after the displacement where necking occurs due to the geometrical imperfection of the tensile specimen. Anisotropy was neglected in this work in order to focus the evaluation of flow stress and damage index at large plastic strain. It can be also observed that the flow stress is valid only at the small range of strain of about 0.11 and thus accurate flow stress after onset of necking should be estimated for obtaining the accurate damage index at fracture.

Fig. 5 shows the measured load vs. displacement and flow stresses curves according to the grain sizes. As depicted, the peak load decreases with increasing grain size. On the contrary, displacement until necking or until fracture increases. Likewise, the stress decreases with increasing grain size and the strain at necking increases.

3. Estimation of flow stress

In order to evaluate the flow stress in the range of large plastic strain, FE simulations in conjunction with experimental results of tensile test were carried out. Commercial metal forming simulation program Deform-3D was used [19]. Fig. 6 illustrates the 1/4 model of the tensile specimen, boundary conditions applied and the type of mesh used in simulation of tensile test. All dimensions are the same as those of the specimen used in experimental tensile

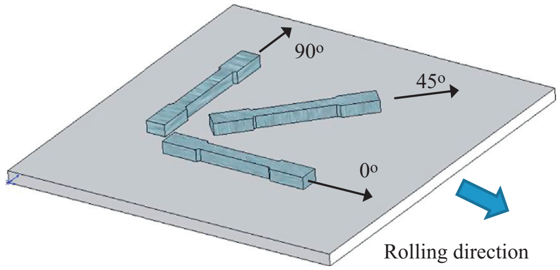

Fig. 2. Preparation of rectangular tensile specimen according to the orientation against rolling direction.