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Effect of Notch on Dynamic Tensile Properties in 6061 Aluminum Alloy

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Abstract

The dynamic tensile properties of 6061 aluminum alloy are investigated using notched cylindrical tensile specimens with different notch radii. Tensile tests were carried out with strain rates from 7.2×10^{-4} to 2.5×10^{3} s^{-1}. No effect of stress triaxiality on strain rate sensitivity is observed, whereas fracture mode of the specimens changes with an increase in stress triaxiality. Furthermore, plastic constraint decreases with increasing strain rate. Numerical simulations of dynamic tensile tests for the notched specimen reveal that the behavior results from reflecting stress waves at a notch root.

1. Introduction

Al-Mg-Si series alloys are widely used in the transportation and building industries. For safety against fracture under impact loading conditions, it is important to study the deformation behavior and mechanical properties under high strain rate conditions. The strain rate sensitivity and dynamic fracture behavior have been reported for uniaxial compression tests [1] and for uniaxial tension tests [2] using the split Hopkinson bar technique. However, most of components in engineering structures have various geometries differing from the uniaxial condition. The stress triaxiality strongly influences the fracture behavior, especially when ductile fracture occurs by void coalescence mechanisms. Generally, increasing the stress triaxiality was found to result in increasing strength levels and decreasing fracture strains [3-5]. It is important to know fracture behaviors and mechanical properties as a function of stress triaxiality at high strain rates. However, there are few reports considering that condition [6]. Thus, under the dynamic loading condition, the notch effect on dynamic tensile properties has to be taken into consideration.

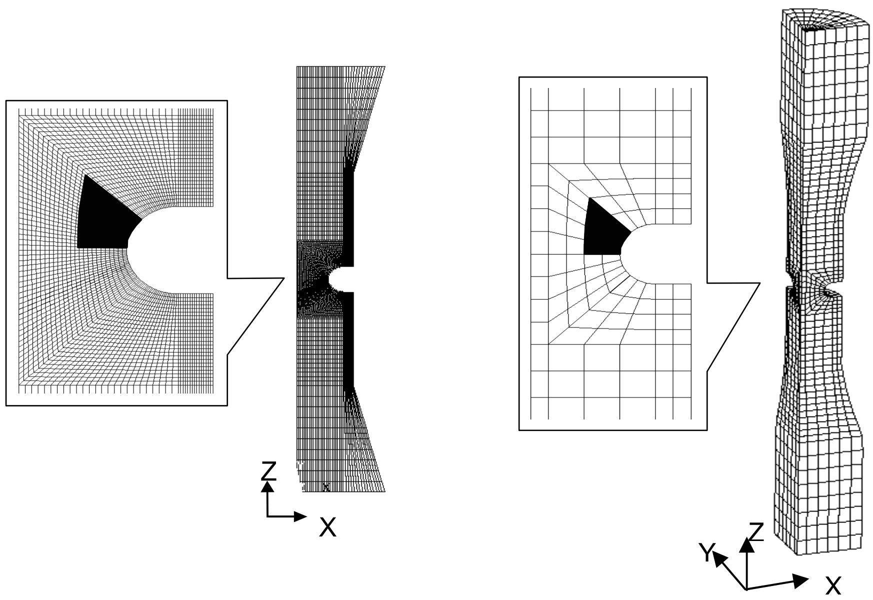
In this study, tensile tests were conducted on notched specimens of a 6061 aluminum alloy with various notch radii for a wide range of strain rates. Finite element modeling (FEM) was carried out to study stress states and stress wave propagations in the notched specimen.

2. Experimental Procedure

The material used in this study is a commercial age-hardening 6061 aluminum alloy, with the chemical composition of Al-0.73Si-0.20Fe-0.25Cu-0.11Mn-1.00Mg-0.05Cr-0.06Zn-0.02 Ti, in mass%. A solution treatment was carried out at 813 K for 10.8 ks, followed by water quenching and an aging treatment at 443 K for 28.8 ks. Cylindrical tensile specimens were machined from the as-received bars with the tensile axis parallel to the extrusion direction.

Round notches of different notch radius (r = 6, 2, 1.5, 1 and 0.5 mm) were machined in the center of gage length. It is known that the stress triaxiality can be varied in a controlled manner by changing the notch radius [7]. Tensile tests were carried out with strain rates between 7.2×10^{-4} and 2.5×10^{3} s^{-1}. Static tensile tests (7.2×10^{-4} s^{-1}) were conducted using an Instron testing machine. The intermediate strain rate tensile tests (10^{1} - 10^{3} s^{-1}) were conducted using a servo-hydraulic impact testing machine. The dynamic tests (1.5×10^{3} - 2.5×10^{3} s^{-1}) were conducted using the split Hopkinson bar technique. Fracture surfaces were observed with a scanning electron microscope.

In order to estimate stress states in the notched region, numerical simulations were carried out. The finite element models for static and dynamic loading conditions are shown in Figure 1. The specimen with a notch radius of 0.5 mm was analyzed in the present study. The static and the dynamic numerical simulations were conducted using commercial package programs: ANSYS version 6.1 and LS-DYNA, respectively. Poisson's ratio of 0.35, the yield stress of 68.3 GPa and subsequent strain hardening curve which had been measured in a uniaxial tensile test under static loading condition were used as input data. Loading velocity was 30 m/s in the dynamic analysis. Strain rate effects for the 6061 aluminum alloy were considered using the Cowper-Symonds constitutive relation.



(a) (b)

Figure 1: Finite element models for the static (a) and dynamic (b) tensile tests.

3. Results and Discussion

The stress–strain curves obtained at different notch radii under the static and dynamic loading condition are shown in Figure 2. It is easily seen that 0.2% offset stress and ultimate tensile strength increase with decreasing notch radii, i.e., with increasing stress triaxiality. Similar tendency is seen under the dynamic loading condition (10^{3} s^{-1}). The observed tendency results from plastic constraint at notch region. Less strain rate sensitivity in the stresses is obtained up to the strain rate of approximately 10^{3} s^{-1}. Ogawa [2] has studied the mechanical properties of 6061 aluminum alloy and indicated that the rapid strain rate dependence on stresses was observed over strain rate of 10^{3} s^{-1}.

Fracture strain calculated using the initial and final minimum root diameters is shown as a function of notch radius in Figure 3.

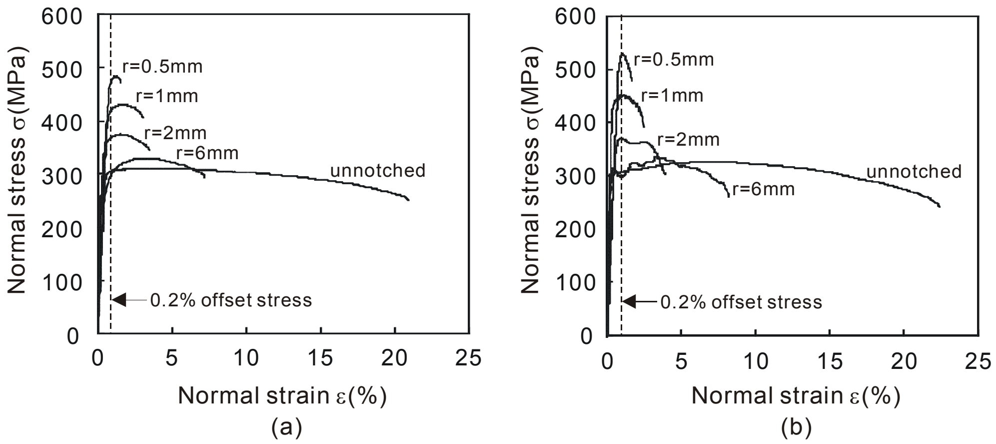


Figure 2: Stress–strain curves of the 6061 aluminum alloy at different notch radii under static (a) and dynamic condition (b).

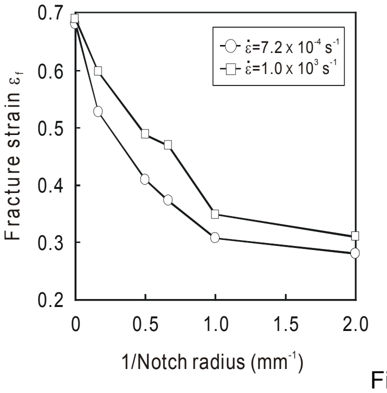


Figure 3: Variation of fracture strain on notch radius at different strain rates.

It can be seen that the fracture strain decreases as notch radii decrease at both the strain rates. The results show the fracture strain slowly decreases at the smaller notch radius ($r^{-1} > 1$), although the fracture strain significantly decreases at larger notch radius ($r^{-1} \leq 1$). Similar behavior has also been reported by Mourad [6]. Furthermore, Figure 3 shows the same tendency and increasing fracture strain with increasing strain rate at all notch radii under the dynamic loading condition. It is indicated that strain rate effect on the fracture strain is more clear than that on the stresses. The strain rate dependence of fracture strain at various notch radii is shown in Figure 4. At all the notch radii, it is shown that the fracture strain increases with increasing strain rate, especially over strain rate of 10^3 s^{-1}.

The increasing stress triaxiality leads to a change in the macroscopic fracture mode. Macroscopically, the unnotched specimens exhibited shear fracture and all the notched specimens exhibited cup and cone fracture. Chen and Li [3] reported a similar change of macroscopic fracture mode during increasing stress triaxiality in static loading condition. Furthermore, a shear lip region decreases with decreasing notch radius. No strain rate effect on fracture mode is confirmed. Otsuka *et al.* [4] showed that dimple size distributed in center of fracture surface increases with decreasing notch radius. Thus, these results indicate that the change in macroscopic and microscopic fracture mode has no effect on strain rate dependence of the stresses and fracture strain.

The variations of plastic constraint factor are shown as a function of strain rate in Figure 5. The plastic constraint factor [8] is defined as:

$$\lambda = \sigma_z/\sigma_y \, , \qquad (1)$$

where the parameter, σ_z/σ_y, is the ratio of 0.2% offset stresses between a notched specimen and an unnotched specimen.

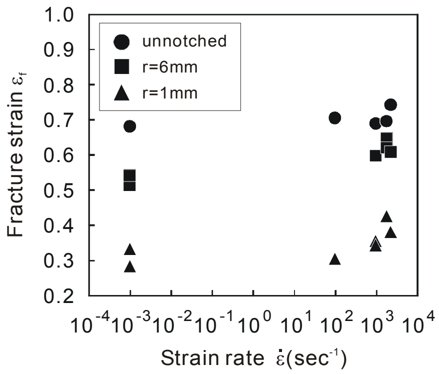


Figure 4: Strain rate dependence of fracture strain at various notch radii.

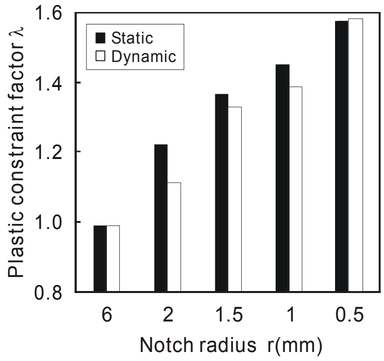


Figure 5: Effects of strain rate on plastic constraint factor at various notch radii.

Figure 5 shows that the plastic constraint factor decreases with increasing strain rate. This behavior indicates that the stress triaxiality is modified under high strain rates. Thus, it is predicted that the stress states of dynamic loading condition may differ from that of the static loading condition.

In order to obtain local stress states in the notched region under the static and dynamic loading conditions, FEM was carried out. The stress states at loading time of 3 μs under the dynamic loading condition are shown in Figure 6. From these results, it can be seen that within the region of the dashed line, high σ_z and low σ_x are seen in Figure 6 (a) and (b), respectively. It is estimated that this behavior results from reflection of stress waves at the notch root. Along the specimen axis the stress waves propagating from the top of the specimen are being propagated downwards.

However, the stress waves propagating towards the notch root are reflected at the notch root. Note that compressive waves generated by the reflection of tensile waves at the free end are observed. Since the generated compressive waves are propagating in the x-axis direction, σ_x decreases and σ_z increases in regions near the notch root, as shown in Figure 6. Variations of mean stress triaxiality of the notched region shown in Figure 1 with time under the static and dynamic conditions in the numerical simulation are shown in Figure 7. Although the mean stress triaxiality in the static condition monotonously increases with time, significant oscillation in the dynamic condition is confirmed due to the compressive waves generated by the reflection at the notch root. Variations of mean stress triaxiality with loading condition averaged at three regions, which are from 0 to A, from A to B and B to C in Figure 7, are shown in Figure 8. The results show that the averaged mean stress triaxiality decreases with increasing strain rate in all regions.

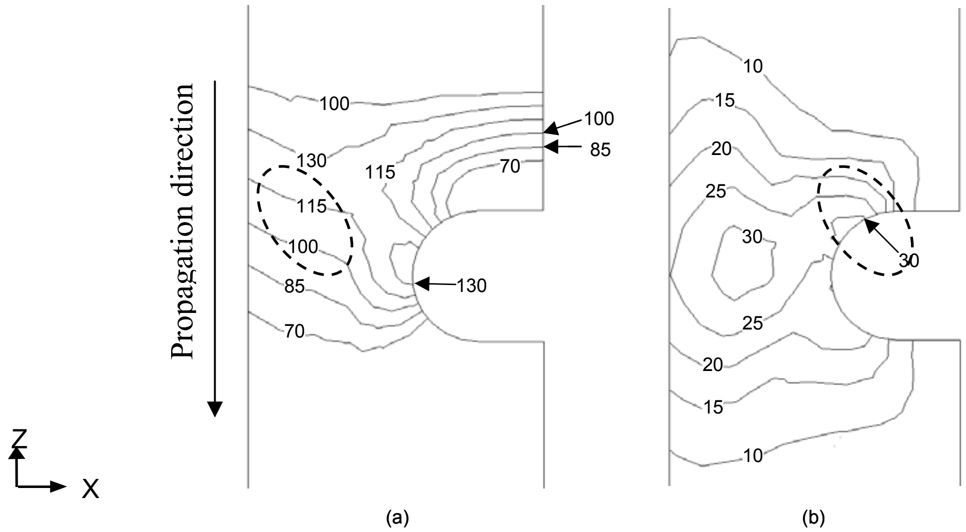


Figure 6: Distributions of (a) σ_z and (b) σ_x at loading time of 3 μs under the dynamic loading condition.

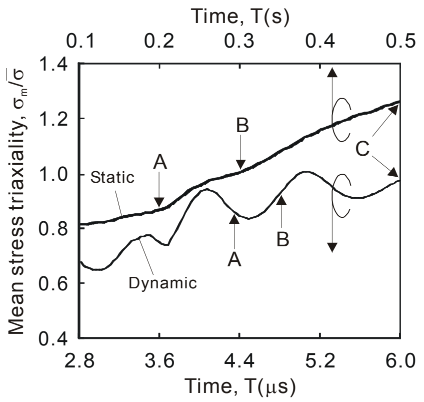


Figure 7: Variations of mean stress triaxiality with time under the static and dynamic loading conditions for notch radius of 0.5mm; A is a proportional limit, B is a 0.2% offset stress and C is a 1.0% offset stress.

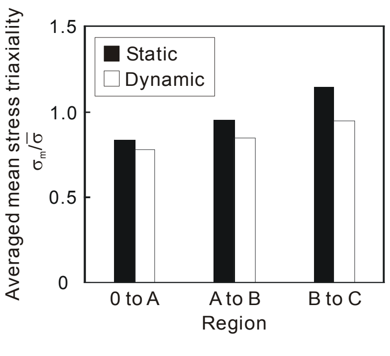


Figure 8: The averaged mean stress triaxiality in the regions indicated in Figure 7 under the static and dynamic loading conditions.

4. Conclusion

The strain rate dependence of the 6061 aluminum alloy was examined for various notch radii. For all the selected notch radii, fracture strain is found to increase with increasing strain rate, especially when the strain rate is above 10^3 s^{-1}. While increasing stress triaxiality leads to a change in the fracture mode from share to cup and cone, no influence of this behavior on strain rate sensitivity of fracture strain is observed. Furthermore, the plastic constraint factor, σ_z/σ_y, reduces with increasing strain rate. The numerical simulation results indicate that the stress triaxiality decreases with increasing strain rate. This behavior results from the compressive stress waves generated by the reflection of stress waves at the notch root.

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