Dynamic Fracture Behaviors of Selected Aluminum Alloys Under Three-point Bending

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Abstract

The dynamic fracture behaviors of the extruded 2024-T4 and 7075-T6 aluminum alloys are investigated by using an instrumented drop tower machine. The specimens are made from a 25 mm diameter extruded circular rod. The dynamic three-point bending tests of each alloy are carried out at different impact velocities. The initiation fracture toughness and average propagation fracture toughness of 2024-T4 and 7075-T6 are determined at different loading rates. The results show that both the initiation toughness and the propagation toughness increase with the loading rate. Further, the difference between the fracture toughness behaviors of 2024-T4 and 7075-T6 is found to be dependent on the variation of fracture mechanism. The comprehensive fractographic investigations of the fracture surfaces clearly demonstrate that the fracture mode of 2024-T4 is predominantly transgranular fracture with high density small-sized dimples, and the fracture mode of 7075-T6 is mainly intergranular fracture with many intermetallic particles in the bottom of voids located in the fracture surface.

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Keywords: Fracture toughness; Three-point bending test; Aluminum alloy; Transgranular fracture; Intergranular fracture

1. Introduction

Aluminum alloys have been the most widely used structural materials in aerospace industry on account of their high stiffness/weight ratio and strength/weight ratio for several decades [1,2]. Two types of alloys, 2000 series (Al−Cu−Mg) and 7000 series (Al−Zn−Mg−Cu) alloys are age-hardened aluminum alloys (artificial aging) with high strength. Many experiments have been conducted to investigate the compressive or tensile stress−strain behavior of aluminum alloy under the static and dynamic loading [3−6]. However, in some applications, the aluminum alloy structures are easily fractured due to impact loading, such as the impact of debris during take-off or landing of a plane. Therefore, it is of major importance to understand and predict the dynamic fracture behaviors of high-strength aluminum alloys for actual engineering application.

A comprehensive characterization of the fracture behaviors of aluminum alloy under quasi-static and dynamic loading has prompted numerous investigations into its fracture behaviors in recent years. Pedersen et al. [7] studied the fracture mechanisms of AA7075-T651 aluminum alloy under various loading conditions, and discussed the influence of stress triaxiality on its fracture behavior through the introduction of a notch in the tensile specimen. Mostafavi et al. [8] made a series of uniaxial, biaxial and triaxial tests for AA2024-T361, and investigated the effect of stress state on the fracture of AA2024-T361. Chen et al. [9] explored the dynamic fracture behavior of extruded aluminum alloy by using an instrumented Charpy test machine and V-notch specimens. It was found that the dissipated energy is practically invariant to specimen orientation and notch direction for the recrystallized alloy. For the extruded alloys, the
dissipated energy is lower when the longitudinal direction of specimen is at a 90° angle to the extrusion direction. Dumont et al. [10] studied the relationship among microstructure, strength and toughness of 7000 series aluminum alloy. They examined the influences of quenching rate and aging treatment on the precipitate microstructure and the associated compromise between yield strength and fracture toughness. Han et al. [11] studied the effects of the pre-stretching and aging on the strength and fracture toughness of 7050 aluminum alloy. The results show that the peak-aged 7050 aluminum alloy possesses a higher strength, but its fracture toughness is poor. Recently, Børvik et al. [12] investigated the quasi-brittle fracture of AA7075-T651 aluminum alloy plate in plate impact test.

In fact, the fracture behaviors of aluminum alloys are different from those of materials processed by rolling, extruding and heat treatment due to their complex and inhomogeneous microstructures [13]. How the microstructure affects the fracture toughness and crack propagation is of special interest [14]. Even though the aforementioned authors studied the fracture behavior of aluminum alloy plate, they did not pay enough attention to the fracture behavior of extruded aluminum alloy rod, especially under impact loading.

The aim of this paper is to study the dynamic fractures of age-hardened 2024-T4 and 7075-T6 aluminum alloys. A series of dynamic three-point bending tests of the notched specimen were carried out by using Instron Ceast 9350-HV drop tower. Specifically, the effects of loading rate (expressed as the time rate of change of the stress intensity factor [15]) on the initiation fracture toughness and propagation fracture toughness were investigated. The metallurgical investigations of fracture surfaces by using optical microscopy (Keyence VHX-E1000) and desk-top scanning electron microscopy (Phenom-World BV Phenom G2 Pro) are presented below.

2. Materials

Two different age-hardened aluminum alloys, 2024-T4 temper and 7075-T6 temper, are investigated in this research. The alloys are provided as extruded rods with 25 mm in diameter produced by Aluminium Company of America (ALCOA). Their chemical compositions are listed in Table 1. The polished and etched microstructures of 2024-T4 and 7075-T6 aluminum alloys are shown in Fig. 1(a) and (b), which are the tri-planar optical micrographs of the extruded rods along the three orthogonal directions, respectively. For 2024-T4, many coherent CuMgAl2 precipitate phases and Al—Cu—Mn dispersions in the grain interiors are presented, as shown in Fig. 1(a). The coarse recrystallized grains with elongated irregular shape along the extrusion direction are observed in the longitudinal section, while the nearly equiaxed and evenly distributed grains are observed in the transverse section. For 7075-T6, seen from Fig. 1(b), many hardening phase η’ (coherent MgZn2) in the grain interiors and precipitates η (noncoherent MgZn2) at the grain boundaries are elongated along the extrusion direction, too. The precipitate-free zones adjacent to the grain boundaries are formed, as shown in Fig. 1(a) and (b). These zones are softer than the matrix so that the trend towards the formation of strain localization appears during deformation.

### Table 1

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Cu</th>
<th>Mg</th>
<th>Zn</th>
<th>Fe</th>
<th>Mn</th>
<th>Cr</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T4</td>
<td>3.8</td>
<td>1.2</td>
<td>0.2</td>
<td>0.38</td>
<td>0.28</td>
<td>0.1</td>
<td>0.38</td>
</tr>
<tr>
<td>7075-T6</td>
<td>2.0</td>
<td>2.33</td>
<td>5.52</td>
<td>0.38</td>
<td>0.28</td>
<td>0.25</td>
<td>0.20</td>
</tr>
</tbody>
</table>

![Fig. 1. Tri-planar optical micrographs of the microstructures of 2024-T4 and 7075-T6.](image)

![Fig. 2. Engineering stress—engineering strain curves of 2024-T4 at different strain rates.](image)
grain boundary precipitates depends on the cooling condition at the solid solution temperature [10,14].

The tensile properties of the two alloys at a wide range of strain rates have been investigated [16]. The tensile tests of the two alloys at low strain rate were performed on a standard tensile test machine. A split-Hopkinson tension bar (SHPT) was used for the tensile test at high strain rate. The typical engineering stress—engineering strain curves of 2024-T4 and 7075-T6 aluminum alloys at four different strain rates are shown in Figs. 2 and 3, respectively. By comparing Figs. 2 and 3, it is observed that the yield stress of 7075-T6 alloy is higher than that of 2024-T4 alloy. However, 2024-T4 alloy exhibits a moderate strain hardening rate and a strain-rate sensitivity, while 7075-T6 alloy exhibits an insignificant strain hardening rate and a strain-rate sensitivity. Their fracture properties could be strongly affected by strain hardening rate and yield stress [10].

3. Dynamic three-point bending test

The extruded aluminum alloy rods are machined into rectangular specimens with 15 mm in width, 7.5 mm in thickness and 75 mm in length for the dynamic fracture test. The direction of length is consistent with the direction of extrusion deformation. An edge notch with 0.25 mm in width and 4 mm in depth is made at the center of the specimen by using a wire electrical discharge machine. Subsequently, the specimens are fatigued in a three-point bending configuration in order to develop a sharp fatigue crack extending from the end of notch. The length of the fatigue crack is typically about 1 mm, resulting in a total initial crack length, \( a \approx 5 \) mm, such that \( a/W \approx 0.33 \).

A dynamic three-point bending test set-up is shown in Fig. 4, which consists of a drop tower for impact loading, a notched specimen and two anvils. The 5.08 kg drop tower is equipped with an instrumented hemispherical tup. The specimen is placed on two anvils which have a span of 60 mm between them. The impact load profile of specimen is measured by using a dynamic force measurement transducer with the frequency response of 8 kHz. The initial impact velocity is measured by an electro-optical device. For each test, the load signals are recorded as a function of time. Then the displacement, \( x_{dis} \), of drop tower can be estimated using Newton’s second law by successive integration of load signal

\[
x_{dis}(t) = \int_0^t \left( v_0 - \frac{1}{m} \int_0^t F(\tau) \, d\tau \right) \, d\tau
\]

where \( v_0 \) is the measured initial impact velocity, \( m \) is the mass of drop tower (\( m = 5.08 \) kg), and \( F(\tau) \) is the impact load measured at the tup. Finally, the absorbed energy can be calculated by successive integration of force—displacement curve.

4. Experimental results and discussions

4.1. Calculation of initiation fracture toughness

In all experiments, the load forces are recorded up to the complete fractures of specimens. The representative load—time graph is shown in Fig. 5, with impact velocity of 2.44 m/s. It can be seen from Fig. 5 that the load—time curve of 2024-T4 is almost linear up to a peak point where an abrupt crack growth takes place with a sudden drop in load,
indicating that the dynamic fracture of 2024-T4 is brittle. However, the load–time curve of 7075-T6 displays an initial linearity and noticeable successive oscillations with nonlinear characteristic, and the decrease in load after passing the peak load is slow, indicating that the dynamic fracture of 7075-T6 is ductile. It is worthwhile to note that the initial slopes of the load–time curves of 2024-T4 and 7075-T6 are the same, which may be attributed to the same initiation flexural stiffness of the specimens.

For the quasi-static three-point bend specimen, the plane strain stress intensity factor (SIF) of Mode I fracture can be calculated from the expression given as [17]

$$K_d^I = \frac{3P(t)}{2(1+\frac{c}{r})^{1/2}W^{2}} \left[ 1.99 - \frac{a}{\pi} \left( 1 - \frac{a}{W} \right) \right] \times \left\{ 2.15 - 3.93 \left( \frac{a}{W} \right) + 2.7 \left( \frac{a}{W} \right)^2 \right\}$$

(2)

where $P(t)$ is the load force history. The loading rate, $K^I_d$, is calculated using a least squares fit to the linear portion of the loading curve; and the initiation fracture toughness.

$K^I_{dI}$ is taken as a point where a line has a slope of 0.95$K^I_d$ intersected $K^I_d$–time curve. Here, it should be recognized that the validity of using a static expression, such as Eq. (2), to determinate the dynamic stress intensity factors by simply replacing the static force with the impact force may be questionable unless the certain conditions are satisfied. Obviously, if the loading duration is long enough to neglect the wave propagation effect and the specimen is in the state of dynamic-equilibrium, the quasi-static equation is acceptable. In other words, if a characteristic time $t_0 (t_0 = l/c_l$, where $l$ is expressed as the characteristic length of specimen) is introduced to describe the propagation of wave in specimen, and $c_l (c_l = \sqrt{E/\rho})$ is the characteristic speed of wave in specimen, the specimen can be considered to be in the state of dynamic equilibrium once the loading duration is several times longer than $t_0$. In our experiment, the characteristic time $t_0$ is about 15 s. It can be seen from Fig. 5 that the loading duration is obviously long enough to attain the dynamic equilibrium. Therefore, according to Eq. (2), the variation of $K^I_d$ with time and the loading rate $K^I_d$ at impact velocity of 2.44 m/s for 2024-T4 and 7075-T6 are calculated and shown in Fig. 6, respectively.
In Fig. 6, there is a region of approximate linear variation of $K^d_{II}$ with time. The slope of this region is determined from a least squares fit, and is shown as a dashed line in Fig. 6. The values of $K^d_{II}$ for 2024-T4 and 7075-T6 are indicated on the experimental curve at a point of intersection with the dotted line having a slope of $0.95K^d_{II}$ for the values of 48 MPa m$^{1/2}$ and 32 MPa m$^{1/2}$, respectively. $K^d_{II}$ of 2024-T4 is higher than that of 7075-T6, which indicates that 2024-T4 has better crack initiation tolerance. The overall difference between the fracture behaviors of 2024-T4 and 7075-T6 may be attributed to the different mechanisms of crack nucleation and growth, which is discussed in Section 6.

4.2. Calculation of propagation fracture toughness

Initiation fracture toughness is commonly called as fracture toughness. However, a propagation fracture toughness is used to characterize the resistance to a propagating crack of dynamic fracture. The propagation fracture toughness is directly related to the energy dissipation in failure process. An energetic method is used to calculate the propagation fracture toughness.

The absorbed energy, $W_1$, at maximum force, the absorbed energy, $W_2$, after passing the maximum force and the total absorbed energy, $W = W_1 + W_2$, can be calculated by successive integration of the force–displacement curve during impact, as shown in Fig. 7. In fact, new crack surfaces are created by part of the total absorbed energy. Here, $W_2$ is assumed to represent the dissipated energy during crack propagation [9]. The average propagation fracture energy per unit area is defined as $G_c = W_2/A_c$, where $A_c$ (10 mm $\times$ 7.5 mm) is the area of the crack surfaces created. At

![Fig. 10. Force–displacement curves at different impact velocities for 2024-T4.](image1)

![Fig. 11. Force–displacement curves at different impact velocities for 2024-T4.](image2)

![Fig. 12. Initiation and average propagation toughnesses at different loading rates.](image3)

![Fig. 13. 3D optical micrographs of fracture surfaces from three-point bending tests.](image4)
the plane strain state, the average dynamic propagation fracture toughness is expressed as [18]

$$K_{IC}^{dp} = \sqrt{GcE/(1-\nu^2)}$$  \hspace{1cm} (3)

where $E$ and $\nu$ are Young’s modulus and Poisson’s ratio of specimen, respectively, and $K_{IC}^{dp}$ is the dynamic propagation fracture toughness. The dynamic propagation fracture toughnesses of 2024-T4 and 7075-T6 are determined as 35 MPa m$^{1/2}$ and 85 MPa m$^{1/2}$, respectively, according to Eq. (3) and the calculated $W_2$ in Fig. 7.

4.3. Effect of loading rate

The loading rate is an important factor which influences the fracture toughness of material. In our experiment, the impact velocity of the drop tower is varied from 2 m/s to 4 m/s to adjust the loading rate. Figs. 8 and 9 show the dynamic SIF—time curves of 2024-T4 and 7075-T6 at the different impact velocities, respectively. As shown in Figs. 8 and 9, the experiments were achieved at four different loading rates, and the corresponding initiation fracture toughnesses of 2024-T4 and 7075-T6 were determined. Figs. 10 and 11 show the displacement—load force curves of 2024-T4 and 7075-T6 at the different impact velocities, respectively. The approach described in Section 5.2 is used to calculate the propagation fracture toughness. Fig. 12 shows that both the initiation and propagation fracture toughnesses almost increase linearly with the loading rate. It can be seen from Fig. 12 that 2024-T4 has better crack initiation tolerance, while 7075-T6 has better crack growth tolerance. The differences may be attributed to the effect of microstructure on the fracture behaviors of two selected 2000 and 7000 series aluminum alloys, which is discussed in detail in the next section.

5. Fractography

A comprehensive fractographic investigation of the fracture surface is carried out by using Keyence VHX-1000E optical digital microscope with low magnification and Phenom G2 Pro scanning electron microscope with high magnification. The overall 3D fracture surface feature is observed by

![Optical micrograph of crack tip region of 2024-T4](image1)

![Optical micrograph of crack tip region of 7075-T6](image2)

![Backscattered electron micrographs of fracture surfaces of 2024-T4 specimen](image3)

Fig. 14. Optical micrograph of crack tip region of 2024-T4.

Fig. 15. Optical micrograph of crack tip region of 7075-T6.

Fig. 16. Backscattered electron micrographs of fracture surfaces of 2024-T4 specimen.
Keyence VHX-1000E, while more details are observed by Phenom G2 Pro, revealing how the microstructure affects the fracture mechanisms.

5.1. Optical microscopy

The 3D optical micrographs of the fracture surface were obtained by using the feature of depth composition of Keyence VHX-1000E in the three-point bending tests of 2024-T4 and 7075-T6, as shown in Fig. 13(a) and (b). It can be seen from Fig. 13 that the fracture surface consists of two regions. One is in the center of fracture zone of specimen characterized by typical tensile fracture, and another is in the boundary of fracture zone characterized by typical shear fracture, which is at a 45° angle with respect to the main fracture surface. The shear fracture is caused by the larger shear stress on the central axis of bending specimen. The fracture surface of 7075-T6 is rougher than that of 2024-T4, which implies that more energy is absorbed in the process of crack propagation.

In order to further investigate the crack front propagation process, the specimens are bended at very small impact velocity such that the pre-crack is extended at a short distance, but does not lead to a catastrophic failure. The region around the crack tip of the specimen is cut out, and its plane normal to the plane of crack propagation is polished. The optical micrographs of crack tip regions in 2024-T4 and 7075-T6 aluminum alloys are shown in Figs. 14 and 15, respectively. For 2024-T4 from Fig. 14, the slender crack propagates mainly through matrices containing the fine the fracture mode is predominantly transgranular and the crack path occasionally follows the grain boundary. For 7075-T6 (Fig. 15), two interesting observations are obtained. First, a mixed fracture mode consisting of intergranular and transgranular facets is observed. The grain boundary precipitate density of 7075-T6 is higher than that of 2024-T4. This promotes an intergranular ductile fracture, which is a prominent fracture mode in high strength metallurgical state (e.g., T6-treated material). Second, many voids nucleated at grain boundary precipitates are observed. Through voids growth and linking each other, the macro-voids and macro-cracks are formed, which is associated with the higher fracture energy absorbed by 7075-T6, as shown in Fig. 7.

5.2. Scanning electron microscopy

The microstructure of aluminum alloy, including grain boundaries, grain boundary precipitates, precipitation free zones, and coarse intermetallic particles, is important to investigate the fracture behavior. The effect of microstructure on the fracture mechanism was further investigated by using the scanning electron microscope. All microscopic examinations are done on the fracture surface in the middle of the specimen thickness. The typical backscattered electron micrographs [low magnification (2000×) and high magnification (10,000×)] of fracture surfaces of 2024-T4 and 7075-T6 specimens are shown in Figs. 16 and 17(a) and (b), respectively, revealing the dimple structures and the distribution of particles on fracture surfaces. Two classes of dimples are observed, namely the large-sized dimples caused by the coarse intermetallic particles or the grain boundary precipitates, and the high density small-sized dimples nucleated in the grain interiors. It is easily observed from Figs. 16 and 17 that the characteristic feature of fracture surface of 2024-T4 is markedly different from that of 7075-T6. The fracture surfaces of 2024-T4 are decorated with few small intermetallic particles and high density small-sized dimples. It indicates that the crack growth is mainly transgranular by forming the voids around fine but densely distributed dispersoid particles, and seldom intergranular along the grain boundaries or precipitation free zones, as shown in Fig. 16(a) and (b). This can be also seen from the optical micrographs in Fig. 14. However, for 7075-T6, the primary intermetallic particles in the bottom of void are presented on the fracture surface (Fig. 17(a)), and an area with high density dimples is seldom observed from Fig. 17(b). It indicates that the crack growth is mainly intergranular along the grain boundaries or precipitate free zones. Since these particle zones are softer than the matrix and are prone to strain localization during deformation, many voids are easily
nucleated at the locations of these particles. This may be used to explain why 7075-T6 has higher yield stress but lower initiation fracture toughness compared with 2024-T4. The initiation fracture toughness is strongly dependent on the fracture mode. The observed fractographs reveal that the initiation fracture toughness of 7075-T6 with intergranular fracture is lower than that of 2024-T4 with transgranular fracture.

6. Conclusions

A notched specimen was used to investigate the dynamic fracture behaviors of the extruded 2024-T4 and 7075-T6 aluminum alloys under three-point bending. The initiation dynamic fracture toughness was determined at different loading rates in terms of the time rate of change of the stress intensity factor. In addition, the average propagation fracture toughness was calculated by using an energetic method. The initiation and average propagation fracture toughnesses of 2024-T4 and 7075-T6 are dependent on loading rate. For selected typical 2000 and 7000 series aluminum alloys, 2024-T4 has better crack initiation tolerance, whereas 7075-T6 has better crack growth tolerance, which are associated with their different fracture modes. The comprehensive investigation of fracture surfaces was carried out by using the optical digital microscopy and the scanning electron microscopy. The fracture mode of 2024-T4 is predominantly transgranular fracture with high density small-sized dimples. However, the fracture mode of 7075-T6 is mainly intergranular fracture with many intermetallic particles in the bottom of void located in the fracture surface.

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