

Chapter 2

Initiation and Propagation Fracture Toughness of AA7475-T7651 Under Different Loading Conditions



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Abstract Fracture toughness of an engineering material is an essential parameter for the damage and the safety assessment of a structure exposed to different loading conditions in applications like defense, automotive, and aircraft structure. In this article, an effort is made to evaluate the fracture toughness of AA7475-T7351 alloy under different loading rates. Single edge three-point bend experiments are conducted at four different loading rates 1 mm/min, 10 mm/min, 100 mm/min, and 1000 mm/min. Quasi-static experiments are conducted using two different electromechanical universal testing machines (Zwick-Roll/Z-50 and MTS). Quasi-static initiation and propagation fracture toughness are evaluated from the load vs. crack mouth opening displacement (CMOD) diagram. It is observed that the fracture toughness of the material increases with the increase of loading rates. The fracture propagation toughness of the material also shows a positive sensitivity towards the loading rates.

Keywords Fracture toughness · Propagation toughness · TBP specimen · AA7475-T7651

2.1 Introduction

The key factor behind the rapid use of the 7XXX series aluminum alloy in aerospace, defense, and automotive industries over the previous few decades is the high strength to density ratio, high resistance against fatigue crack growth, high fracture toughness, and corrosion resistance [1–3]. These structures are more prone to face different uncertain loads such as blast, crash, and impact. Metallic material's mechanical behavior is sensitive to loading rate and temperature [4, 5]. 7XXX alloy series has a face-centered cubic (FCC) crystal structure. Different metallic solutes are used to form precipitates in the metal matrix to make more superior alloys in terms of strength and ductility [6, 7]. The concept of dynamic fracture toughness plays a vital role in structural analysis and design. As many components of the different structures may fail under the action of impulsive loads (e.g., airplane crashes, the impact of flying objects, projectile impacts, and earthquakes). Different researcher [8–12] used different setup (one bar or tow bar setup) and technique (one-point, two-point strain gauge method and high-speed optical measurement) to study the fracture toughness of a material. Bacon et al. [8] studied the fracture behavior of glass and PMMA on glass and PMMA under different loading rates using a modified Hopkinson pressure bar. The author evaluated the stress intensity factor and established a relationship between the stress intensity factor and applied dynamic load. The effect of inertia was emphasized to evaluate the correct value of the stress intensity factor. It is reported that the stress intensity factor of PMMA is proportional to load point displacement for the first vibration mode. The author also performed a comparison of fracture toughness evaluated from two different techniques (load point displacement and two-point strain measurement). Rubio et al. [9] performed three-point bend experiments to evaluate the dynamic fracture initiation toughness of AA7075-T651 under dynamic load using input load, displacement, and CMOD as input parameters. A high-speed imaging system was used to determine crack mouth displacement of three-point bend specimen. Numerical analysis using ABAQUS was performed to validate the experimental results. Xing et al. [10] used a drop tower mechanism to determine the fracture toughness of two different aluminum alloys, AA2014 and AA7075, under different loading conditions. The author observed a

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constant increase of initiation fracture toughness and propagation toughness for both aluminum alloys with the increase of loading rates. Moreover, it is observed that AA2014 offers higher initiation toughness but AA7075 offers better propagation toughness. The author observed transgranular and intergranular of AA2014 and AA7075 under scanning electron microscope. Singh et al. [11] studied the dynamic fracture behavior of sandwich aluminum and brittle Homolite-100 under dynamic loading conditions on a single notch three-point bend specimen using modified Hopkinson pressure bar. The applied load and the load point displacement were measured by using a two-point strain measurement technique. Two high-speed cameras were used to find crack initiation, delamination, and crack re-initiation velocity of sandwich three-point bend specimen. It was observed that crack initiation, delamination, and crack re-initiation time decrease with the increase of loading rate. The presence of a thin aluminum layer increases the overall fracture toughness of the specimen. Galvez et al. [12] investigate the dynamic fracture toughness of high-strength armor steel using split Hopkinson pressure bar. The author directly placed the cracked specimen between the incident and transmitted bar. The specimen displacement was measured by strain gauges mounted on the bars where fracture initiation time was obtained using fracture gauge pasted on the specimen. The author observed that the fracture toughness of armor steel is insensitive towards loading rate. This article investigates the fracture toughness of AA7474-T7351 aluminum alloy under different loading rates and temperatures.

2.2 Material Description

The 7475-T7351 aluminum alloy used in the present study was procured from Falcon Aerospace (USA) in the form of a rolled plate of 12.75 mm thick and T7351 temper. AA7475-T7351 is the purified version of the AA7075 aluminum alloy with higher yield strength, ductility, and fracture toughness. The percentage of the chemical composition obtained from EDX was compared with the manufacturer's data and allowable limits of those compositions in Table 2.1.

2.2.1 Sample Preparation and Specimen Geometry

All samples are obtained by cutting the strip from the large AA7475-T7351 aluminum alloy panels and making the notch using EDM wire cut. Single edge three-point bend specimens are adopted for quasi-static with width $W = 20$ mm, thickness $B = W/2 = 10$ mm, and span length $S = 4W = 80$ mm as shown in Fig. 2.1.

At the middle, a crack of uniform width 1.5 mm and length 7 mm is made; subsequently, a V-notch of length 1.5 mm at 30° angles is created using EDM wire cut. A prefixing flaw (fatigue crack) of length 1.5 is developed using a 100 kN capacity

Table 2.1 Chemical composition of aluminum alloy 7475-T7351

Elements	Al	Zn	Mg	Cu	Fe	Si	Ni	Mn	Cr	Ti	V	Sn	Pb
As per present study EDX W (%)	90.85	5.2203	2.12	1.4216	0.074	0.0506	0.0023	0.005	0.1944	0.0379	0.0097	<0.001	0.0011
As per manufacturer W (%)	89.88	5.9	2.3	1.7	0.07	0.04	0.0029	0.01	0.2	0.03	0.01	0.0012	0.0015
Allowable limit W (%)	88.5–91.5	5.2–6.2	1.9–2.6	1.2–1.9	0.00–0.12	0.00–0.10	–	0.00–0.08	0.18–0.025	0.00–0.06	0.00–0.05	–	–

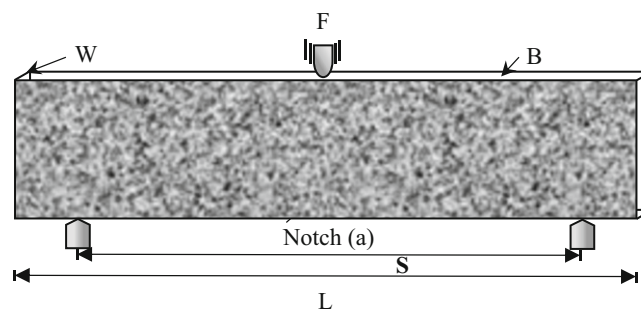


Fig. 2.1 Geometry of TBP specimen

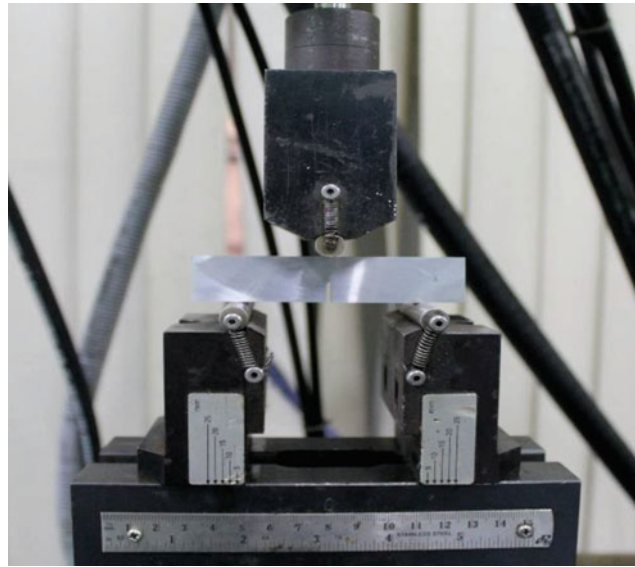


Fig. 2.2 Fatigue crack preparation

MTS machine, as shown in Fig. 2.2. The minimum and maximum loads applied during fatigue crack in the TBP specimen are 200 N and 2000 N, respectively. The mean load and load amplitude are measured 1100 N and 825 N. The loading frequency set at 25 Hz, and the number of cycles needed to obtain the required fatigue crack length was between 41,450 and 44,250.

2.3 Experimental Procedure

The characterization of the material's fracture behavior under a wide range of loading rates using one mechanical testing machine is very impractical because of their limited crosshead velocity range. Thus, based on the magnitude of the loading rate, various devices are used to evaluate fracture toughness. A Zwick-Roll/Z50 electromechanical universal testing machine is used to determine the fracture toughness for loading rate 1–100 mm/min, whereas for loading rate 1000–5000 mm/min a 250 kN capacity MTS machine with hydraulic grip is used.

2.3.1 The Theoretical Aspect of Static Fracture Toughness

All quasi-static three-point bend experiments usually conducted using a clip gauge to measure crack mouth opening displacement (CMOD). The static fracture toughness (K_{Ic}) for the single edge 3-point bend specimen is calculated using

$$K_{Ic} = \frac{3S\sqrt{a}}{2BW^2} Y\left(\frac{a}{W}\right) F \quad (2.1)$$

where a is the total crack length (notch + fatigue crack), B is the thickness, S is span length, L is the specimen length, F is the force applied on the specimen and

$$Y\left(\frac{a}{W}\right) = \frac{1.99 - \left(\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)\left(2.15 - 3.93\frac{a}{W} + 2.7\left(\frac{a}{W}\right)^2\right)}{\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{3/2}} \quad (2.2)$$

Here F can be calculated from the Load vs. CMOD diagram.

2.4 Experiments and Results

A three-point bend specimen with a single edge has been mounted on Zwick/Roll-Z50 and MTS machine as shown in Fig.2.3a to achieve three-point bend loading conditions. In order to quantify the crack mouth opening displacement (CMOD), a clip gauge is attached to the specimen at the mouth of the notch. Two knife-edges are pasted at the mouth of the notch to hold the clip gauge. The applied load on the specimen and corresponding CMOD of the specimen are recorded in the computer attached with the machine. Zwick-Roll/Z-50 is used for loading range between 1 and 100 mm/min, whereas for above 500 mm/min loading rate MTS machine has been used. The specimen before and after the experiment is shown in Fig. 2.3b.

2.5 Results and Discussion

The Load vs. CMOD of AA7475-T7351 aluminum experiments performed at a different loading rate (1–1000 mm/min) are reported in Fig. 2.4. It can be observed that with the increase of loading rate, the specimen required a higher load to deform. The fracture toughness of metal is evaluated corresponding to the maximum load of load vs. CMOD diagram. To evaluate

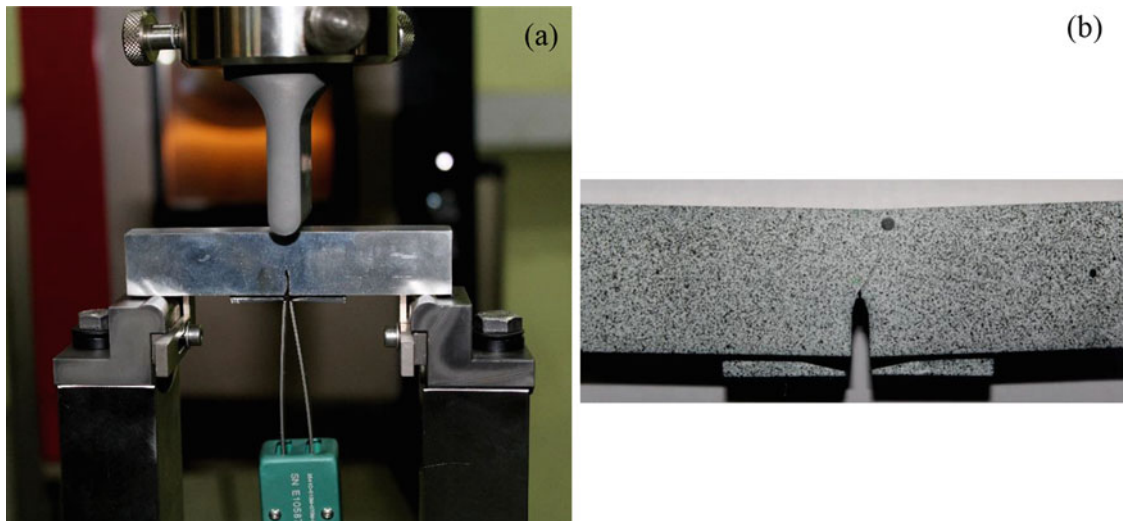


Fig. 2.3 (a) TBP specimen fixing in UTM (b) TBP specimen after experiment

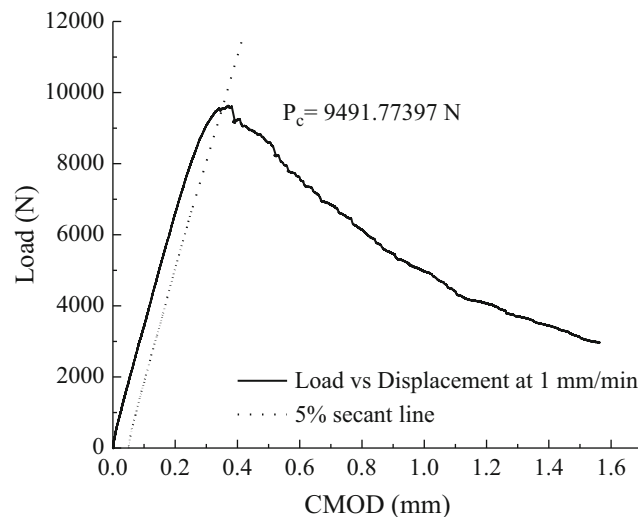
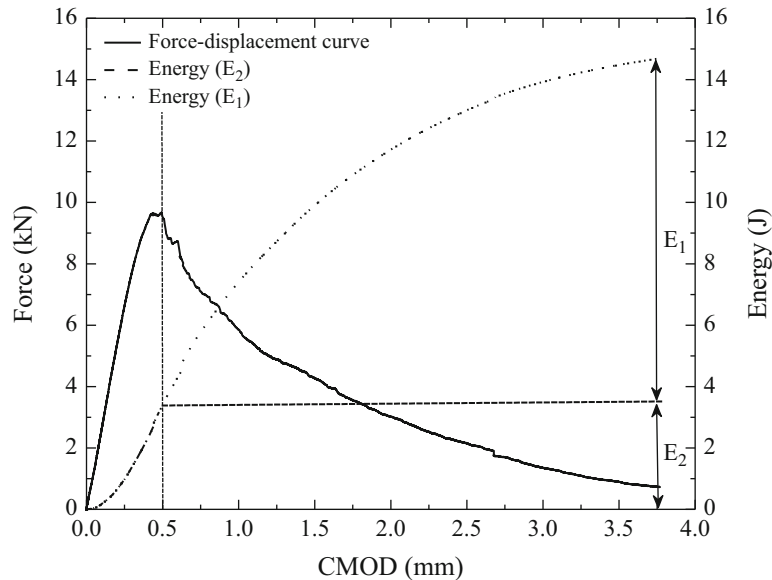


Fig. 2.4 Load vs. CMOD diagram

Table 2.2 Fracture toughness under different loading rates

Loading rate (mm/min)	1	10	100	1000
Fracture toughness ($\text{MPa m}^{1/2}$)	55.51946	56.01403	57.60076	58.92683

**Fig. 2.5** Force and energy absorbed by the TBP specimen vs. CMOD effect of loading rate

fracture toughness, a 5% secant line is drawn parallel to the elastic region of the load-CMOD diagram. The critical load (P_c) is identified as the overlapping point between the load-CMOD diagram and the 5% secant line.

The fracture toughness calculated corresponding to critical load (P_c) and Eq. (2.1) under different loading rates reported in Table 2.2.

2.5.1 Calculation of Propagation Fracture Toughness

Fracture initiation toughness is usually referred to as fracture toughness, physically explained as the resistance against crack initiation in a material. However, the propagation toughness is expressed as the resistance against a propagating crack under a specific loading condition. The propagation toughness of a material is directly linked with energy absorbed during the failure process. So, a purely energy-based method is used to determine the propagation fracture toughness.

The energy absorption by a material during failure may be divided into two parts; energy absorbed corresponding to maximum force, E_1 , and E_2 , after passing the maximum load. The total energy absorbed during the failure process is expressed as $E = E_1 + E_2$. All these energies E_1 , E_2 , and E can be evaluated by successive integration of the load-CMOD curve during the failure process, as described in Fig. 2.5. Here it is assumed that the E_1 is the amount of energy required to initiate the crack and E_2 is energy used to propagate the crack [13]. Under plane strain condition, the average propagation fracture toughness is expressed as [14]:

$$K_{Ic}^P = \sqrt{G_C Y / (1 - \nu^2)} \quad (2.3)$$

where $G_C = \frac{E_2}{A_c}$, Y is the Young's modulus, ν is the Poisson's ratio and A is the fracture area.

2.5.2 Effect of Loading Rate

The loading rate have significant influence on the initiation and propagation toughness of a material. In this study, the experiments are performed at 1 mm/min, 10 mm/min, 100 mm/min, and 1000 mm/min, respectively. The effect of loading rate on the load-CMOD is shown in Fig. 2.6.

The initiation fracture toughness of AA7475-T7351 aluminum alloy at different loading rates is plotted on the log scale as shown in Fig. 2.7a. The propagation toughness of AA7475-T7351 aluminum at particular displacements is plotted on the log scale in Fig. 2.7b. It can be observed that the fracture initiation and propagation toughness of AA7475-T7351 significantly depend upon the loading rates.

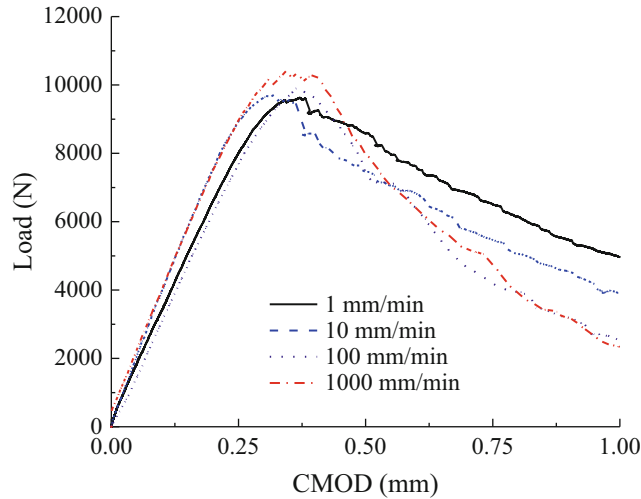


Fig. 2.6 Load vs. CMOD under different rate of loading

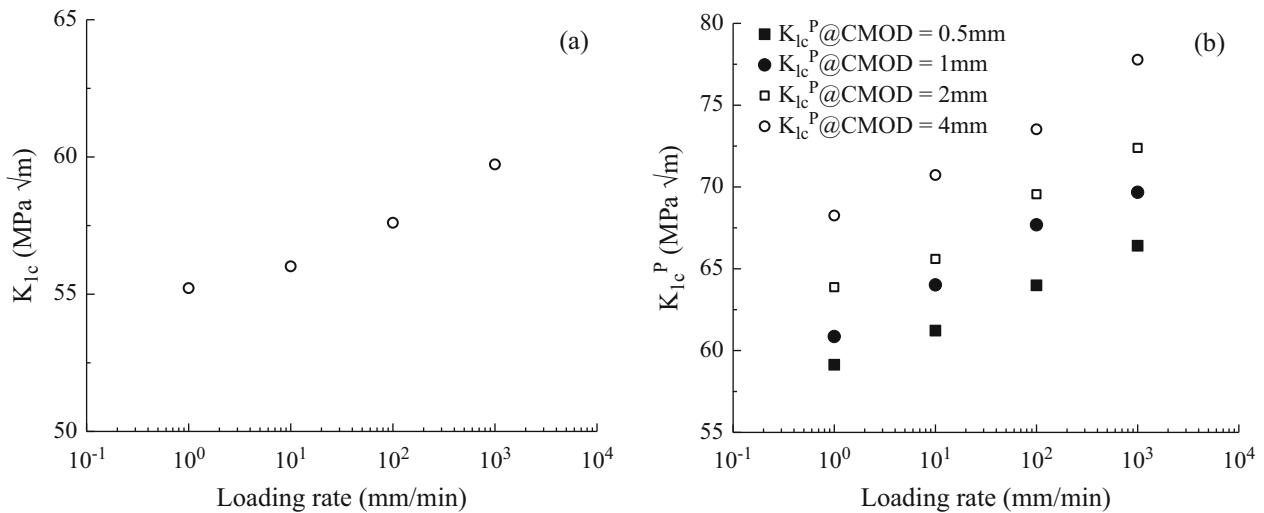


Fig. 2.7 (a) Initiation fracture toughness at different loading rates (b) Propagation fracture toughness at particular displacement under different loading rates

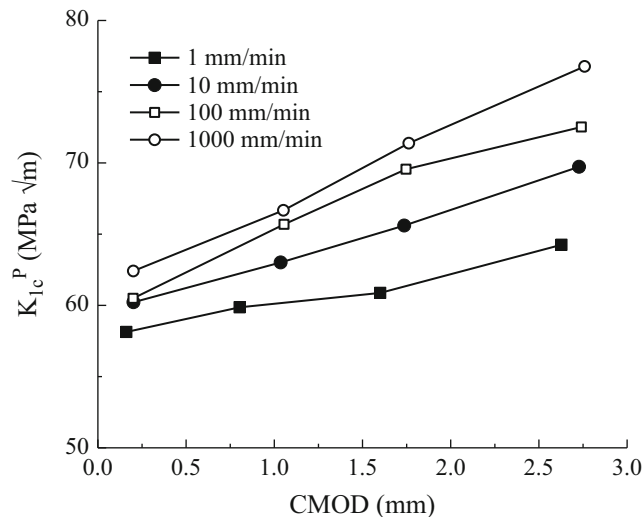


Fig. 2.8 Effect of displacement on the propagation toughness

2.5.3 Effect of Displacement on the Propagation Toughness

The effect of accumulated strain or successive displacement has an important influence on the propagation toughness. The propagation fracture toughness at a particular displacement is plotted under different loading rates in Fig. 2.8. So, it's clear that the propagation toughness of material is largely dependent upon the accumulated displacement.

2.6 Conclusion

A single edge notched three-point bend specimen is used to investigate the fracture behavior of AA7475-T7351 aluminum alloy under quasi-static loading conditions. The initiation fracture toughness is evaluated at different loading rates. The average propagation fracture toughness of AA7475-T7351 aluminum alloy is also evaluated. The initiation and propagation fracture toughness are evaluated as a function of loading rates. It is observed that loading rate has a significant effect on initiation and propagation toughness and AA7475-T7351 aluminum alloy shows positive loading rate sensitivity towards loading rate.

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