Effect of loading rate on tensile and fracture behavior of AA2050-T84 alloy at high temperature

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Abstract. AA2050-T84 alloy is commonly used in the fabrication of modern commercial aircraft wing parts. Load and temperature variation during aircraft take-off, flight, and landing at different environmental conditions is substantial. Mechanical properties variation of AA2050-T84 alloy at sub-zero and room temperatures are significant and well documented in the literature. In the present work, at a high temperature of 200°C, the effect of load rate variation on tensile and fracture properties of AA2050-T84 alloy are experimentally and numerically studied. The load rates represented in strain rates were applied at 0.01, 0.1, and 1 s⁻¹. Experimental tensile tests exhibited the positive strain rate dependency on the yield and ultimate strength of the alloy. 2D numerical elastic-plastic fracture analysis was carried out using Abaqus 6.14. Similar to tensile results, the fracture parameters dependency on strain rates was witnessed. Overall, higher strain rate causes the increased susceptibility of fracture failure with the increase in yield stress of the material.

Keywords: AA2050-T84 alloy, load rates, tensile properties, J-integral, CTOD.

1. Introduction

Al-Li alloys are extremely popular in aircraft and space applications due to their significant mechanical properties over conventional aluminum alloys [1, 2]. Lithium is one of the lightest (in terms of density) elementary metallic materials make it a primary choice for alloying elements in aluminum [2]. Lithium’s moderate success in aluminum made the Al-Li alloys attractive for lightweight component applications. The significant enhancement of mechanical properties in the Al-Li alloy, such as low density and specific strength, are mainly attributed to lithium addition through advanced processing techniques [2,3]. The high cost of producing the Al-Li alloys restricted the application only to aircraft and space applications.

The restriction of lithium addition below 2% in aluminum and unique manufacturing techniques led to the development of 3rd generation AA2050-T84 alloys [2]. The improved damage tolerance properties of AA2050-T84 alloy over other lightweight composites and conventional aluminum made it suitable for wing spars and ribs fabrication. However, anisotropy, lower damage tolerance at higher load rates, and thermal instability were the primary limitations of the 2nd generation Al-Li alloys [4]. Due to the failure of 2nd generation Al-Li alloys during hard landings and severe operating conditions, some major disasters were made to withdraw the alloys from aerospace applications [3,4].
Tensile and crack behavior of 3rd generation high-strength steels used for lightweight automotive applications showed the low (quasi-static) and high (dynamic) loading rate dependency [5]. It was recommended to consider the load rate dependent data based on application. Similarly, tensile strength and fracture strength at room temperature of concrete material exhibited the load rate dependency [6]. Literature studies reveal that both ductile (steel) and brittle (concrete) material's tensile and fracture performance depended on the low-temperature loading rate. Similarly, yield and ultimate strength of aluminum material at quasi-static strain rates at room and higher temperatures were studied [7]. The study revealed the increase in yield and ultimate strength as strain rate increases at all temperatures considered. The comparison of tensile, compression, and fracture properties of AA2050-T84 alloy at room and sub-zero temperature are available in the literature [8]. The increase in tensile strength and reduction of plane strain fracture toughness (KIC) was reported at sub-zero temperatures [9]. However, these studies limited to microstructural studies of the alloy at room and sub-zero temperatures intended its applicability to space shuttle applications. Temperature and load rate variations in modern operating commercial aircraft wing parts are commonly observed. The behavior of the AA2050-T84 alloy during flight, landing, and take-off is crucial as operating temperature and loading rates on the wing parts varying continuously. As per earlier literature, the steels and aluminum alloys are sensible to load rates and temperature. Moreover, the major limitation of withdrawal of 2nd generation Al-Li alloy was also related to inadequate damage tolerance performance at higher load rates [3,4].

The effect of load rates on tensile and fracture performance of the AA2050-T84 alloy at high temperatures is scarcely reported in the literature. In the current work, experimental tensile tests were conducted on AA2050-T84 alloy at 200º C for various strain rates. Further, the tensile stress-strain data at quasi-static strain rates were used to numerically analyze the elastic-plastic fracture behavior using Abaqus 6.14 [10]. Finally, the AA2050-T84 alloy vulnerability to failure at different strain rates will be discussed based on tensile and fracture strain rate dependent performance.

2. Experimental test details

2.1. AA2050-T84 alloy
A two-inch AA2050 alloy rolled plate, heat-treated with T84 condition, is used for specimen extraction. The tensile and fracture test specimens were taken out in the plate's longitudinal (rolling) direction. The chemical composition of AA2050-T84 alloy is given in Table 1.

| Cu  | Mg  | Mn  | Zn  | Fe  | Ti  | Si  | Li  | Zr  | Ag  | Al  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 3.743 | 0.369 | 0.372 | 0.025 | 0.045 | 0.040 | 0.039 | 0.798 | 0.087 | 0.398 | Base |

2.2. Tensile test and specimen details
Tensile specimens prepared as per ASTM E8 / E8M-21 at room temperature [11]. Tensile tests were performed at 200º C using a heat chamber in the universal testing machine (UTM). The mechanical properties such as Young's modulus (E), yield stress (σy), ultimate stress (σu), percentage elongation (% EL), and stress-strain curves were recorded through the extensometer and load-displacement curve. Figure 1 shows the round tensile specimen used in the test.

2.3. Fracture test and specimen details
The fracture toughness (JIC) tests were conducted as per ASTM 1820-20b at 200º C [12]. Figure 2 shows the Compact Tension (C(T)) specimen used for the fracture toughness test. The dimensions of the C(T) specimen are crack length (a), specimen width (W), specimen thickness (B) and specimen height (H) with W = 25.4 mm, a/W = 0.5, B/W = 0.25 and H/W = 1.2 were used. Fatigue pre-cracking
was done at room temperature to emulate the natural crack characteristics at the C(T) specimen crack tip. Compliance technique along with clip gauge measurement at the crack opening was used to record the load-line data.

![Figure 1. Tensile specimen](image1)

**Figure 1.** Tensile specimen

![Figure 2. C(T) Specimen](image2)

**Figure 2.** C(T) Specimen

3. Numerical analysis details

Two-dimensional (2D) numerical fracture analysis was carried out using Abaqus 6.14. The symmetrical 2D C(T) model is shown in figure 3, and the crack tip is surrounded by fine mesh and y-symmetry imposed along the ligament (W-a). The 2D model has been meshed using 8-node biquadratic quadrilateral elements with reduced integration (CPS8R and CPE8R). The state of stress (plane stress or plane strain) had an insignificant effect in 2D numerical analysis.

The meshed model for a/W = 0.5 had around 2500 elements and 7800 nodes. A reference point (RP) was created at the hole center for the effective load application at the hole periphery. The kinematic coupling was established between the reference point and hole surface to replicate the experimental loading pattern. The RP was restricted with boundary conditions $U_x = 0$, $U_y \neq 0$ and $UR = 0$.

The 2D elastic-plastic analysis was carried out at different loading rates with material properties Young's modulus (E), Poisson's ratio ($\nu$), and post-yield behavior data from the stress-strain curve. A typical stress-strain data extracted after the yield point from the stress-strain curve at strain rate $0.01 \text{ s}^{-1}$ is shown in figure 4. The values of J-integral are extracted using the interaction-integral method built-in Abaqus directly. Ahead of the crack tip, user-defined five contours were selected, and the average of the last three contours was used to find J-integral. The detailed procedure to carry out elastic-plastic analysis is discussed in Kodancha et al. [13].
4. Results and discussion

4.1. Experimental tensile test results

Tensile tests were conducted, and test data recorded as specified in the ASTM E8 / E8M-21. The 3-loading rate measured in terms of strain rate 0.01, 0.1, and 1 s\(^{-1}\) were applied at 200\(^0\) C during tensile tests. The extensometer is used to record the change in length, and the computer is integrated with the UTM for load-line data interpretation. A minimum of 3 specimens was tested under UTM at each strain rate, and the average of 3 tensile specimen mechanical properties was used for tabulation. The recorded mechanical properties under these test conditions are shown in Table 2 for different strain rates.

| Strain rate, s\(^{-1}\) | Young's modulus (E), GPa | Yield stress (σ\(_{yt}\)), MPa | Ultimate stress (σ\(_{ut}\)), MPa | % elongation |
|-------------------------|--------------------------|-------------------------------|-------------------------------|-------------|
| 0.01                    | 68.322                   | 463                           | 535.356                       | 9.503       |
| 0.1                     | 63.942                   | 490                           | 540.32                        | 8.688       |
| 1                       | 61.706                   | 490                           | 542.297                       | 8.340       |

Figure 3. C(T) meshed model with Boundary conditions

Figure 4. Stress-Strain curve at strain rate 0.01 s\(^{-1}\)
Generally, steels exhibit positive strain rate dependency on tensile properties. At 200°C, positive strain rate sensitivity was observed in the AA2050-T84 alloy tensile strength (yield and ultimate stress). An increase in loading rate increases the yield and maximum tensile strength of the alloy. Similarly, positive loading rate dependency was reported for pure aluminum alloy at various temperatures under high-pressure torsion loading tests [7]. An increase of yield stress of 5.8% and ultimate stress of 1% was observed between strain rate 0.01 and 0.1 s\(^{-1}\), respectively. Ultimate stress is less affected compared to other mechanical properties for quasi-static strain rates. However, Young's modulus and % elongation decreased with the increase in strain rates. A decrease of 7% in Young's modulus and 8.7% in % elongation was noticed between the strain rates 0.01 and 0.1 s\(^{-1}\), respectively. Overall, the strain rate effect on tensile properties is less between the range 0.1 and 1 s\(^{-1}\).

Microstructural changes (defect movement) in the AA2050-T84 alloy are probably sensitive to strain rates.

4.2. Experimental fracture test results
ASTM 1820-20b was used to find the fracture toughness of AA2050-T84 alloy C(T) specimen under quasi-static loads. According to the standard, the considered quasi-static load rates of 0.01, 0.1, and 1 s\(^{-1}\) will provide a single toughness value. The pre-cracked C(T) specimen was tested under Mode-I loading at the strain rate of 0.01 s\(^{-1}\). A typical C(T) specimen mounted on UTM (without heat chamber) for fracture toughness test is shown in figure 5. A minimum of 3 valid fracture toughness tests was conducted at 200°C to obtain the elastic-plastic fracture toughness, \(J_{IC}\). The fracture test ensued the load-line displacement curve, which further processed to find the \(J_{IC}\) value of 22.155 N/mm. The cost restriction of specimen fabrication and difficulty in conduction of valid \(J_{IC}\) tests motivated us to adopt numerical fracture analysis for other strain rates.

4.3. Numerical elastic-plastic fracture results
The linear elastic fracture toughness, \(K_I\) was independent of strain rate for all numerical 2D linear fracture analyses. The inability to account for the tensile property variation in the linear fracture analysis encouraged to adopt elastic-plastic fracture analysis. The current elastic-plastic fracture analysis procedure to calculate J-integral is validated with the earlier work [13].

The 2D symmetric model with meshing, material properties, boundary conditions, and loading is discussed in earlier work [13,14]. The load ratio (\(P_{max}/P_{applied}\)) varied between 0.1 to 1, with a maximum load (\(P_{max}\)) of 10 kN for all strain rates. The J-integral variation concerning load applied for different strain rates at 200°C is shown in figure 6. The positive strain rate dependency of J-integral is observed in numerical elastic-plastic fracture analysis. The 7% increase in J-integral is noticed for all
load ratios between the strain rate 0.01 to 0.1 s$^{-1}$. Similarly, a 3.5% increase in J-integral is seen between 0.1 to 1 s$^{-1}$. The nature of variation of J-integral is identical for all considered strain rates.

The figure 6 also comprised the experimentally obtained $J_{IC}$ value for strain rate 0.01 s$^{-1}$. The load taken to attain this $J_{IC}$ at different strain rates are diverse. A load of 8651, 8361.48, and 8216.12 N is needed in strain rates of 0.01, 0.1, and 1 s$^{-1}$ to accomplish the experimental $J_{IC}$, respectively. It can also be noticed that as the strain rate increases, a lesser load is required to attain the experimentally obtained $J_{IC}$. Similarly, Crack Mouth Opening Displacement (CMOD) is also measured at different strain rates, and its variation is shown in figure 7. The nature of variation of CMOD for all strain rates is linear and sensitive to strain rate variation. CMOD corresponding to experimental $J_{IC}$ can be attained for a lesser load at higher strain rates, as also witnessed for $J_{IC}$.

![Figure 6. J-integral vs Load at 200°C](image1)

![Figure 7. CMOD vs Load at 200°C](image2)

Another important fracture parameter used in the elastic-plastic analysis is Crack Tip Opening Displacement (CTOD or $\delta$). The critical value of CTOD at fracture of the standard specimen is denoted as $\delta_{IC}$. The CTOD can be obtained from the J-CTOD relationship mentioned in the ASTM 1820-20b and is shown in equation (1). In equation (1), $m$ is a constraint parameter and depends on crack length, specimen width, yield, and ultimate stress. The details of calculating $m$ are given in ASTM 1820-20b. $\sigma_Y$ is the effective yield strength and is defined as the average of ultimate and yield stress of the material. At strain rate, 0.01 s$^{-1}$, the $\delta_{IC}$ corresponding to experimental $J_{IC}$ is 0.025 mm (calculated from equation 1). The calculated CTOD at different strain rates from the corresponding J-integral values of load ratios is shown in figure 8. CTOD is also positive strain rate sensitive, and at higher load rates, lesser load is needed to attain $\delta_{IC}$. The 2D numerical fracture results showed the positive strain rate variation in AA2050-T84 alloy at 200°C.

$$\delta = \frac{J}{m\sigma_Y} \tag{1}$$

Typically, steels exhibit decreased plane strain fracture toughness ($K_{IC}$) as the load rate increases beyond the quasi-static range [15]. The Higher strain rate causes the increased susceptibility of fracture failure with the increase in yield stress of the material. An increase in yield strength associated with high loading rates elevates the crack tip stresses, leading to critical conditions in the crack tip region at lower levels of remote applied load [16,17]. If AA 2050–T84 alloy possesses lower fracture toughness ($K_{IC}$ or $J_{IC}$) as strain rate increases, the designer must be careful in using positive strain rate dependency of the alloy. Overall, the positive strain rate sensitivity towards the yield stress and elastic-
plastic fracture parameters will be helpful in an improved understanding of the crack behavior of the aircraft wing components at high temperatures.

5. Conclusions
In the present work, the tensile and fracture behavior of AA2050-T84 alloy at quasi-static load rates was studied at 200°C. The tensile tests revealed the positive strain rate sensitivity towards the yield and ultimate strength of the AA2050-T84 alloy. Similarly, numerically obtained fracture toughness results suggested that at higher strain rates the susceptibility of fracture failure is high. At high temperature, the sensitivity of the strain rate is significant towards tensile and fracture behavior of the alloy compared to room temperature suggested in the literature. The following conclusions can be drawn based on the current work.

- Positive strain rate sensitivity towards yield and ultimate strength of the AA2050-T84 alloy at high temperature is witnessed. However, the decrease in % elongation suggests the possible brittle nature of the alloy at high strain rates.
- 2D numerical linear fracture analysis could not account for the strain rate dependency and shows the limitations of elastic analysis.
- Crack driving forces in elastic-plastic fracture analysis showed positive strain rate dependency, making the AA2050-T84 alloy vulnerable to early failure at high strain rates.

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