Pop-in Crack Propagation Monitoring for AA2024-T3 Ductile Alloy

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This paper demonstrates the use of temperature change, induced by thermo-mechanical effect, as a means of monitoring the pop-in crack propagation of ductile materials. Center crack tensile (CCT) tests are performed at room temperature using 1/4” thick AA2024-T3 aluminum alloy specimens at different loading speeds. The temperature variation in the vicinity of the crack tip is measured and correlated with the changes in the applied load and fractographs. The results show that the load and temperature curves comprise three distinct regions, corresponding to the initial thermo-elastic stage, a stable cracking extension stage, and an unstable cracking extension stage, respectively. The load and temperature characteristics in each stage are highly distinctive and therefore provide a reliable means of monitoring the state of the crack propagation process.

Keywords: 2024-T3, aluminum alloy, thermo-mechanical, center crack test, pop-in

1. Introduction

The crack propagation behavior of a material is generally assessed by analyzing its stress and strain characteristics under tensile or bending loads. Typical analytical methods include: the KIC method, the J-integral method, the R-curve approach. Crack propagation behavior is sensitive to the thickness of the plate; when the thickness is reduced, many analytical methods will be subject to some limitation. Therefore, alternative methods are required to analyze the fracture behavior of thin plate components. Hence, this study investigates the feasibility of using temperature change induced during crack propagation as a means of monitoring the fracture state of thin, ductile materials.

The temperature variations induced in a specimen, as a result of thermo-mechanical effects during loading at an ambient temperature, are generally neglected since the magnitude of the temperature change is very small (typically from 0.01 to 0.1 K corresponding to the thermo-elastic phenomenon). Kelvin¹ showed that the temperature of a metal drops slightly during tensile loading in the elastic region. Sih et al.²–⁴ and Lee et al.⁵–⁸ showed that the temperature change in a material, subject to adiabatic and reversible thermo-elastic deformation, is given by \( \Delta T = -(\alpha / \rho) C_v T \Delta \sigma_{xx} = -K_m T \Delta \sigma_{xx} \), where \( T \) is the reference temperature, \( \sigma_{xx} \) is the uniaxial elastic stress, \( \alpha \) is the volume thermal expansion coefficient, \( \rho \) is the density, \( C_v \) is the specific heat capacity at a constant volume, and \( K_m \) is the thermo-elastic coefficient of the material. In other words, the magnitude of the deformation induced temperature change \( \Delta T \) is directly proportional to the change in the uniaxial elastic stress \( \Delta \sigma_{xx} \).

The cooling or heating behavior of a metal in the thermo-elastic region is governed by Kelvin’s law, i.e. \( \Delta T/T = -\gamma (\Delta V/V) \), where \( \Delta V \) is the volume change and \( \gamma \) is the Grüneisen parameter, given as \( \gamma = K_f / C_v \), where \( K_f \) is the isothermal modulus of compressibility of the material. However, when the loading increases to the point of plastic deformation, slippage takes place and the dislocation motion along the slip planes generates a significant friction heat. Consequently, the transition from thermo-elastic to thermoplastic deformation generates a notable effect of temperature reversion. This phenomenon has prompted researchers to study the feasibility of monitoring temperature changes within mechanically-loaded materials as a means of detecting crack propagation. Sih et al.⁹ applied the dissipated energy density theory to predict micro-scale temperature variations at the crack tip of AISI 1020 steel compact tension (CT) specimens. The results indicated that a secondary temperature fluctuation was induced close to the crack tip during the cracking process. Beghi et al.⁹ applied uniformly increasing displacements to a fatigue pre-cracked CT SUS 316 stainless steel specimen and demonstrated that the temperature within the specimen fell slightly during the thermo-elastic stage, but increased in the subsequent thermoplastic stage. Lee et al.⁶–⁸,¹⁰ reported similar temperature variation tendency in specimens subjected to tensile loading, cyclic loading and three-point bending (TPB) tests, respectively.

Pop-in crack extension (PCE) is an interesting mechanical phenomenon observed in many engineering materials. Several researchers¹¹–¹⁵ have reported that when loading a pre-cracked specimen, PCE zones are formed in the more brittle regions of the material. Various explanations have been proposed for the formation of these PCE zones, including: an excessive presence of carbide at the grain boundary in low carbon, high nitrogen steel;¹¹ the presence of martensite bands in medium carbon steels;¹² the absence of grain boundary ferrite;¹³ a segregation effect of Si, Mn, and S;¹⁴ the formation of segregation bands rich in Cr and/or Mn;¹⁵ and so forth. In general, the occurrence of pop-in cracking is highly dependent on the material type, size, geometry, and loading mode of the pre-cracked specimen. Reviewing the literature, it is found that previous studies have focused primarily on the formation of PCE in brittle and/or hard materials such as steel. By contrast, the occurrence of PCE in ductile materials

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such as aluminum alloy has attracted comparatively little attention.

To deal with the issue of PCE in aluminum alloy, the current study conducts center crack tensile (CCT) tests using AA2024-T3 aluminum alloy specimens with a \( \frac{1}{4} \)\( ^{\circ} \) thickness under ambient temperature conditions and loading speeds of 0.005 mm/s, 0.05 mm/s, and 0.5 mm/s, respectively. The temperature variation induced near the crack tip during the crack extension process is monitored continuously throughout the loading process using high precision thermistors and is correlated with the corresponding load variation. Following specimen failure, the fracture surfaces are observed via optical microscopy (OM) and scanning electron microscopy (SEM) in order to identify the major PCE features in the ductile specimens. Finally, the temperature and load variation tendencies are correlated with the surface features of the fractured specimen, in order to verify the feasibility of using the temperature change induced by the thermo-mechanical effect during crack propagation as a means of monitoring the fracture state of ductile materials.

2. Experimental Procedure

The CCT experiments were conducted using AA2024-T3 aluminum alloy supplied in plate form with a thickness of 6.35 mm \((\frac{1}{4}\text{\ ''})\). The tensile properties of the alloy are summarized in Table 1. As shown in Fig. 1, the plates were cut into test specimens with dimensions of 455 mm \times 127 mm. Prior to CCT testing, a starter notch with a length of 28 mm was machined into the center of the specimen using an EDM process to ensure that crack initiation occurred at the desired location. The specimen was then subjected to fatigue loading to form a sharp pre-crack at both ends of the starter notch to give a total length of \( 2a = 38 \text{ mm} \), where \( a \) is the initial crack length. The temperature variation induced during the CCT tests was measured at three separate locations \((T_1, T_2, \text{ and } T_3)\) spaced at intervals of 10 mm and arranged along an imaginary horizontal line extending from the tip of the pre-crack toward the edge of the specimen. The CCT tests were performed in accordance with the ASTM E647 standard\(^{16}\) and were conducted using an MTS 810 servo-hydraulic machine set in displacement control mode. Following the CCT tests, the macro and micro features of the fracture surfaces were observed using OM and SEM techniques.

The CCT tests were conducted under ambient temperature conditions with loading speeds of 0.005 mm/s, 0.05 mm/s, and 0.5 mm/s. The temperature at each of the three measurement points was recorded continuously over the full duration of the test, using highly sensitive thermistors. The variation in the applied load over the loading cycle was also automatically detected via a MTS810 test machine. The thermistors employed to measure the temperature within the specimen had a head dimension of 2.0 mm \times 2.3 mm, and were capable of temperature detection over the range of \(-50 \text{ to } 400\text{°C}\). To enhance the sensitivity and response rate of the temperature detection system, the thermistors were attached to the specimen using thermal conductive paste, and then protected by thermal insulation tape. Following a series of tests, the resolution of the thermal measurement system was determined to be \( \pm 0.012 \text{ K} \). Figure 2 shows the stable response of the measurement system over a period of 60 seconds prior to CCT testing, and confirms its ability to detect even very slight temperature variations.

<table>
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<th>Table 1 Tensile properties of AA2024-T3 alloy.</th>
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\(^{*}\) at 0.2% offset
that the present AA2024-T3 alloy specimens failed as a result of a ductile fracture mechanism. Thus, it could be concluded that the present AA2024-T3 alloy specimens failed as a result of a ductile fracture mechanism.

3. Observation on temperature and load curves

Figures 5(a)–(c) present the load and temperature variation curves for specimens tested at loading speeds of 0.005, 0.05, and 0.5 mm/s, respectively. As shown, the load variation tendencies of the three specimens were all broadly similar. Namely, the load initially increased linearly (before mark “X” in the figure), and then continued to increase, but at a lower rate (from mark “X” to “Y” in the figure), it fell significantly and finally abruptly to zero as the specimen fractures. Regarding the load at different loading speeds, each had a similar maximum load even when the times required to reach the maximum load differ.

As shown in Figs. 5(a)–(c), the temperature variation tendencies of the three specimens are all broadly similar. In each case, the temperature reduced initially, then increased comparatively slowly, and finally increased extremely rapidly. As seen, each of the temperature curves between marks “X” and “Y” had a significant step-like profile and that the temperature amplitude of the individual step increased as experimental time increased. The time interval of each step increased as time increased. At the final stage (after mark “Y”), the temperature curves showed sharp fluctuation features until the end of the experiment. The maximum temperature dropped in each experimental case around the mark “X”; the higher loading speed led to lower temperature.

3.3 Crack propagation behaviors in ductile material

In this experiment, the aluminum alloy (AA2024-T3) with a thickness of 1/4 inch was used. Under the fixed condition, the temperature and load behaviors presented in Fig. 5, and the macro- and micro-fractographies in Figs. 3 and 4 suggest that:

(1) The crack propagation process in the current AA2024-T3 CCT specimens is a ductile fracture process (according to the dimple-like feature.)

(2) The crack propagation is comprised of three major stages (according to the temperature development during the test), namely: an initial thermo-elastic (TME) stage (labeled as “I” in Fig. 5), then a stable crack extension (SCE) stage (labeled as “II” in Fig. 5), and an unstable crack extension (UCE) stage (labeled as “III” in Fig. 5).

3.3.1 Thermo-elastic stage (TME)

This stage extended from the start of the loading to mark “X” (refer to Fig. 5), corresponding to the position of the maximum temperature drop. In this stage, the temperature reduced monotonically and quasi-linearly over time as the load increased. In other words, this stage corresponded to the thermo-elastic cooling stage; significantly, the original pre-crack did not start to propagate. During this stage, the material only experienced an elastic deformation in the status of tension stress. According to Kelvin’s Law, while the volume difference increased in the elastic region (subjected to a tensile force), it experienced a temperature drop.

Why did the temperature drop during elastic expansion? It may be that the atoms in the material at certain temperatures are always vibrating in different modes around their equilibrium positions; while the lattices are elastically expanded due to tension stress. The system volume was increased due to the equilibrium distance among atoms being increased, however, the atoms did not move such a large distance from their previous equilibrium positions to neighboring equilibrium positions (namely, the dislocation did not occur). In such a status, the atomic density in this system volume is relatively decreased (the size of atomic is the same; however,
According to the theory of thermodynamics, the temperature of matter was related to the average kinetic energy of the atoms\(^\text{17}\). This was the extrinsic effect of collision among atoms and the system boundaries. If the probability of collision was higher, the energy transfer rate across the boundary was higher; hence the temperature would be higher as well. Therefore, while the material was subjected to a tensile force to slightly increase its volume and it still maintained inside the elastic range. In a considered system where the atomic density was decreased, the probability of collision among atoms and boundaries was thereby reduced. The temperature would be lower than the previous one, indicating a temperature drop. On the other hand, if the material in the elastic range was subjected to a compression force, the system volume was slightly reduced, and hence the atomic density was relatively higher than its previous state. In this smaller volume, the probability of collision among atoms and system boundaries would be higher, and therefore, the temperature would increase.
3.3.2 Stable crack extension (SCE) stage

This stage extended from mark “X” to mark “Y”, corresponding to the interval at which the temperature profile started to rise stepwise and become highly unstable. During this stage, the load increased continuously (albeit more slowly) and exhibited small ripple-like fluctuations. Compared to the TME stage, the temperature began to increase during this SCE stage, and showed a distinct step-like characteristic. It was observed that the amplitudes of the individual steps increased over time with longer time intervals. After correlating the load and temperature curves, as shown in Fig. 5, it could be concluded that this stage of the crack development process corresponds to a period of stable pop-in crack growth.

The fracture surfaces, as shown in Fig. 3, contain two features, namely a discrete growth of cracks in the PCE zone initiating at the tip of the original pre-crack, and an obvious necking effect, as a result of plastic deformation along the borders of the fracture surface. The plastic strain energy continuously released during necking induced a continuous temperature rise within the deformed specimen. Meanwhile, surface energy was released as the atomic bonds in the PCE zone break intermittently as new pop-in cracks were initiated. The combined effects of these two events, together with the heat transfer between the specimen and the environment, resulted in the step-like effect observed in the temperature profiles in the SCE stage. As shown in Fig. 5, the amplitude of the temperature fluctuations increased as the loading speed was increased. In general, the local peaks in the temperature profiles coincided with the pop-in bands located between the individual pop-in lines in the PCE zone. At a higher loading speed, the number of temperature peaks associated with each pop-in band was easily identified via naked eye or by low magnification microscopy. However, at a lower loading speed, the correlation between the pop-in bands and the temperature peaks could still be observed, but was less easy to determine.

Why did the pop-in crack occur in this thickness of an aluminum alloy CCT specimen? This heat treatable AA2024-T3 alloy was prepared through the processes of solid solution, cold work, and then natural aging. Hence, there existed many second phase precipitations and dispersed in different sizes, shapes, and locations. These precipitates would strengthen the material because the movement of dislocation was controlled by these precipitates. The dislocation may cut the precipitation particles, pass roundabout the precipitations, or pile-up at the front of these precipitation particles. Considering the specimen thickness of 1/4", in such geometry constraints, the possible dispersion of those precipitations interacted with the dislocations. While the specimen was subjected to a tensile force and beyond the elastic region, the dislocation continues the complex behavior of cutting the precipitation particles, passing roundabout the particles, or piling-up at the particles. What determined the correct scenario while time is passing? That should be the instantaneous equilibrium balance of energy and forces while dislocation interacted with those precipitation particles under the thickness constraint. It could be concluded that the dislocation movement would be easy to change due to lower resistance at the beginning and then a little more difficult, due to the dislocation needed to cut or pass roundabout the precipitations, and finally difficult to move due to the gradual dislocation pile-up around the precipitations. In the final stage, the dislocation motion in the pile-up structure (the dislocation is trapped) was suppressed temporally; however, at the same time the stress increased continuously, and at the end reached a critical stress to destroy the pile-up structure. Hence, the local stress was released and began the first step to repeat the cycle. This situation corresponded to the pop-in extension phenomena.

Kuo et al. performed CCT tests using the same alloy (AA2024-T3) and the same test conditions as those applied in this study, but with specimens of different thicknesses, namely 1/8" and 3/16". In contrast to the results of this study, the fractographs showed no evidence of pop-in events. Furthermore, the measured temperature profiles remained...
stable over time and reduced monotonously with an increasing load. In other words, the crack deformation behavior was confined entirely to the TME stage. Kuo et al.20 also performed CCT tests using specimens of the same alloy (AA2024) and thickness as those used in the present study, but thermally treated using a different tempering process (i.e. T81 rather than T3). Again, the results obtained for the AA2024-T81 specimen were quite different from those reported in this study for AA2024-T3 aluminum alloy. Specifically, the fractographs contained no pop-in features and the three temperature profiles had a smooth appearance and reduced quasi-linearly with an increasing load. Comparing the results presented in Refs. 19 and 20, it was clear that the pop-in characteristics of AA2024 CCT test specimens depend on their heat treatment properties (regarding the microstructure parameter) and thickness (regarding the geometry parameter).

3.3.3 Unstable crack extension stage (UCE)
This stage extended from point “Y” to the point of final fracture. The load curve retained its ripple-like characteristic and is gradually reduced until the point of specimen fracture, at which point it dropped abruptly to zero. By contrast, the temperature profiles increased rapidly and it was observed that both the amplitude and the frequency of the individual step-like features increased and became highly irregular. As a result, the strain energy is released more rapidly, causing the temperature to increase at a rate approximately twice that observed in the SCE stage. When the crack grew to a certain critical length, the effective area was insufficient to sustain the load, and thus specimen fracture occurred. At the moment of fracture, the sudden release of surface energy caused by the breaking of the atomic bonds resulted in a dramatic rise of approximately 5 K in temperature.

With a microstructure examination, the features of the fracture surface suggested that the crack propagation mode changed from stable crack growth to unstable crack growth. What would happen in the dislocation when the propagation mode changes? As in the SCE stage, the dislocation would interact with the precipitation particles in certain scenarios. The dislocation in the UCE stage performed a similar process; however, when the tensile test continued for some time, the specimen was subjected to the tensile stress, and the continuous plastic deformation would gradually change the configuration of dislocation, grain orientation, as well as the precipitation particles. At an early stage, the dislocation could overcome the obstacle and move continuously. At a later stage, the dislocation, grain boundary, and precipitation particles were all kinked together and found it difficult to relax. The dislocation in their original slip plane would be difficult to move and, at the same time, the stress accumulated continuously. Therefore, the dislocation would start to move in other complex slip systems, and consequently, released the accumulated stress so that a load decrease would occur.

3.4 Effect of loading speed on temperature variation
As shown in Fig. 5, the basic temperature tendency remained unchanged as the loading speed increased from 0.005 to 0.5 mm/s. However, slight differences could be observed in the detailed features of the three crack development stages in the different specimens. For instance, at a lower loading speed, the time required for the temperature to fall to its lowest point was delayed and the magnitude of the maximum temperature drop was not as great as that observed at the higher loading speeds. This result was expected since at a lower loading speed the relative contribution of the heat transferred to the specimen from the environment was increased, which slowed the rate of temperature reduction induced by thermo-elastic cooling. Therefore, the time required to reach the maximum temperature drop was prolonged, which in turn, allowed the specimen to absorb more heat from the environment, and therefore, limited the magnitude of the maximum temperature drop.

As the loading speed reduced, the time duration from “X” to “Y” increased. Consequently, the number of pop-in lines increased and the interval between them reduced accordingly. As shown in Fig. 5, the step-like features in the temperature profiles of the specimen tested at the lowest loading speed had a greater frequency, but lower amplitude than those in the profiles of the higher loading speed specimens.

4. Crack Propagation Monitoring for Ductile Aluminum Alloy
In general, when examining fractographs of specimens containing a PCE zone, a monotonically reduced pattern of the pop-in band width indicates that crack propagation is arrested; whereas a monotonically increasing pop-in band width implies that the crack development process would go to the UCE stage if the load is not removed.21 In this study, the fractographic evidence showed that significant pop-in line features were formed in the SCE stage. Furthermore, both the baseline temperature and the amplitude of the fluctuations in the temperature profile increased. However, in the UCE stage, no additional pop-in features were observed and the temperature increased rapidly with large, irregular fluctuations. In general, the results presented in Fig. 5 suggested that monitoring the temperature around the pre-crack tip enables the current state of the crack propagation process to be assessed. Specifically, a gradual rise in the baseline temperature, accompanied by temperature fluctuations of increasing amplitude but reducing frequency, provided an early indication of the imminent onset of the final, potentially catastrophic, UCE stage and therefore, provided a trigger highlighting the requirement to take appropriate preventative measures to suppress further crack extension.

This study examined AA2024-T3 aluminum alloy with a thickness of 1/4 inch in the conditions of a pre-cracked CCT test, and presented the monitoring method based on the temperature development, as shown in Fig. 6. Using a logarithm scale, the possible yielding time and the beginning of the UCE stage could be well fitted as the following empirical power law equation with good R² values.

$$T = a \ast v^n,$$  

where T is the time (sec), and v is the loading speed (mm/s), and a, n the coefficients that were determined by the experimental data.
In this study, under certain loading speeds, the specimen starts to yield \( (T_y) \) following the empirical eq. (2), while the beginning of the unstable crack extension \( (T_u) \) follows the empirical eq. (3):

\[
T_y = 5.8341 \times v^{-0.8288}, \quad R^2 = 0.9971 \tag{2}
\]

\[
T_u = 11.452 \times v^{-0.8962}, \quad R^2 = 0.9824 \tag{3}
\]

According to these empirical equations, if the specimen has a thickness of \( 1/4'' \) and is under a specified constant loading speed, this study could predict when the yielding and the beginning of UCE would occur. The crack propagation behavior obviously depended on the microstructure features and the shape of the specimen. This paper presents a method based on the temperature development profile as a means to deal with this issue.

As described above, the pop-in crack propagation occurred in many engineering materials. Especially, in previous literature, many studies focused on brittle materials, and there were scanty studies focusing on the ductile material. This study examined the pop-in crack propagation in aluminum alloy, and found that the pop-in crack propagation would be affected by the thickness, microstructure feature (e.g. precipitates), and loading condition. The engineering significance of the monitoring of pop-in crack propagation includes the following:

1. The occurrence and disappearance of the pop-in crack propagation in materials signify the change of the dislocation slipping mode. Before the occurrence of the pop-in, there is an elastic deformation and the continuous temperature drop clearly defines the region. If the material is used in this region, the crack would not extend and would remain in a safe operating condition. Once the pop-in occurred, the crack extended and its development depended on the loading speed, thickness, and microstructure. Hence, it is suggested obtaining the data as depicted in Fig. 6 for the specified thickness, material, and loading condition at the beginning, since the pop-in depends on these parameters and it is not a general phenomenon. When Fig. 6 was constructed for providing parameters (thickness, loading speed, material), the crack behavior of this ductile material could be predicted. During the operation, if the pop-in crack disappears, the operation should be stopped to prevent future material rupture.

2. The pop-in crack propagation in ductile material is not a general phenomenon. It is believed that the microstructure (e.g. precipitates, lattice structure, and slippage system), the geometry, and the loading condition will affect the occurrence of the pop-in. Therefore, developing a parameter map for the pop-in crack of the ductile material would be interesting future work.

5. Conclusion

This study conducted CCT tests using \( 1/4'' \) thickness AA2024-T3 aluminum alloy specimens at room temperature and specified loading speeds. The changes of temperature and load were recorded, and micro- and macro-fractographs were examined. The temperature curves showed three different features while the macro-fractographs showed pop-in extension in certain areas. Micro-fractographs examination revealed the dimple-like feature, hence, the fracture was identified as a ductile fracture. From the experimental data and applying the dislocation theory, the following can be concluded:

Pop-in cracking exists in ductile materials in a particular condition which is affected by the size and shape as well as the microstructure of the specimen. Using the temperature changes due to the thermo-mechanical effects, the crack propagation can be easily identified in three stages: (1) thermo-elastic stage where the temperature will initially drop until yielding occurs; the temperature drop is related to the reduction of the kinetic energy and the probability of collision of the atoms in the considered system volume; (2) stable crack extension stage where the macro-fractiontography shows the typical pop-in features and the increasing temperature curve presents a step-like feature; it was concluded that the step-like feature is due to the complex effects of dislocation interactive with the precipitation particles in a constrained size and shape (the thickness is \( 1/4'' \)); (3) unstable crack extension stage where the temperature has a higher rate of increase and a higher temperature fluctuation, compared to the SCE stage; the change in the temperature trend correlates to the change of the slip mode of the dislocation. In this final stage, most dislocations perhaps cannot slip on their original slip system because the dislocation is kinked. They need more energy to overcome the kinking, and develop another slip system to adapt to the instantaneous stress state.

These three stages can very clearly be identified by examining the temperature curve; therefore, this study proposed a monitoring method based on the feature of a temperature curve to predict the crack propagation.

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