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The use of Acoustic Emission Method to Evaluate Creep-Fatigue Interaction

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Abstract. Acoustic emissions from creep-fatigue crack growth have been examined in 304 stainless steel. Under trapezoidal waveform, acoustic emission signal had different characteristics according to each loading mode. During the tensile creep loading, low counts rate and steady emissions were shown due to the continuous creeping at the crack tip. When the unloading and loading of fatigue cycle, emissions were burst and high counts rate was recoded. This high emission was supporting the fact that the redistribution of stress and strain after stress relaxation of previous creep loading. As the crack grew, total counts were increased due to expansion of plastic zone, however the contribution of each mode to the damage was different according to tensile hold time and maximum load. Experiments with different hold-time and maximum load were shown that the hold time and maximum load were important factors to control the contribution of each mode to the total damage in terms of acoustic emission counts. Overall experimental results indicated that acoustic emission monitoring during creep-fatigue crack growth test was useful to distinguish between the two damage modes and clarify the creep-fatigue interaction in elevated temperature application.

Introduction

Many industrial plants and components operating at high temperature must withstand several deformation modes, which include creep, fatigue or combination of these two. Creep is the time-dependent change in the size or shape of a material due to constant stress or force on that material. Fatigue is a phenomenon leading to fracture when the material is under fluctuating stresses. The combination of creep and fatigue can be considered a general deformation mode, since components generally repeat the startup, operation and shutdown according to their scheduled or unscheduled operation [1]. In this circumference, materials tend to behave in a complex way and synergistically act to cause premature failure.

The nature of this creep-fatigue interaction is that ageing plant under creep loading conditions could show dramatic drop in component life when subjected to cyclic operation. It will have an untoward effect on safety and reliability. Thus, further understanding of material behavior and proper non-destructive evaluation method are necessary to ensure safer operations. One of non-destructive testing methods, acoustic emission technique can be an effective method to evaluate creep-fatigue crack growth. Because the release of strain energy during continuous straining at the crack tip and crack growth are good sources of acoustic emission.

In the present study, acoustic emission was monitored during creep-fatigue crack growth test to evaluate the creep-fatigue interaction at high temperature. As a basic approach to analyze the high temperature damage, acoustic emission response to each loading modes was checked and damage contribution was examined in terms of acoustic emission parameter. In addition, overall acoustic behavior during crack growth was examined.

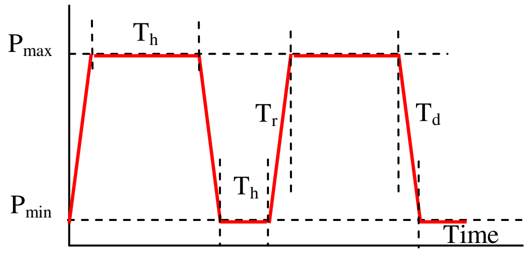


Fig. 1. Trapezoidal waveform

Table 1. Details of loading conditions

Test	Loading	P_{max} [kN]	P_{min} [kN]	T_r [min]	T_h [hr]	T_d [min]	T_h [hr]
#1	Creep-Fatigue	6	0.6	1	5	1	0.1
#2		6	0.6	1	1	1	0.1
#3		8	0.8	1	1	1	0.1
#4	Creep	8	-	1	-	-	-

Experiment

The materials tested was type 304 austenitic stainless steel which has been considered one of the strongest candidate materials for high temperature structural components such as pressure vessels and pipes. Compact tension specimens with thickness B=12.5mm and width W=25mm were used for tests. All the specimens were fatigue pre-cracked at room temperature prior to testing at high temperature. Load controlled creep-fatigue crack growth test with a load ratio, R=0.1 were performed on each loading conditions at 538°C (1000°F) using servo hydraulic machine equipped with electric furnaces for heating the specimens to the test temperature. Trapezoidal loading waveforms as shown in Fig. 1 with a rise/decay time of 1 min and hold time of 0, 1 and 5 hours were employed. Details of loading conditions are summarized in Table 1. The load line displacement was measured by clip gage assembly.

During the creep-fatigue crack growth test, acoustic emission was detected by SPARTAN-AT computerized monitoring system with 150kHz resonant piezoelectric transducer. To acquire the signal from specimen at elevated-temperature, 1m long waveguide of cylindrical shape was welded to the specimen surface. The use of this kind of waveguide is usual in high temperature application [2, 3, 4]. The sensor was attached to the other end of waveguide. The acoustic emission signals through the waveguide were amplified by 40 dB fixed gain pre-amplifier. A band pass filter, with a range of 100–300 kHz was used in the preamplifier. The pre-amplified signals were further amplified by 20dB in main amplifier and analyzed in SPARTAN-AT system. A threshold of 45 dB was selected, which was just above the background noise level which determined by preliminary test.

Material behavior

Fig. 2 shows the applied load vs. time and load line displacement vs. time behavior in a creep and creep-fatigue loading respectively. Load line displacements in both cases illustrate the curve, which is very similar to general creep curve and represent an increasing displacement with increase of time. These curves can simply be split up into three main sections according to their behavior. The slop of curve is increases with time in early stage then, reaches steady state in which the slop changes little with time, and finally the slope increases rapidly with time until fracture occurs.

By comparison of two curves, it is apparent that the introducing a unloading and loading of fatigue load leads to the serious decrease in crack growth lifetime and the creep-fatigue interaction at high temperature is detrimental effects on crack growth.

Acoustic emission response under each damage mode

As a basic approach to evaluate the creep-fatigue interaction, real-time monitoring at the fatigue and creep mode were conducted. Fig. 3(a) is a plot representing the load-time profile and its correlation between AE counts. Before startup of unloading of fatigue cycle, the hold time at maximum load has maintained for 1 hour. In this creep period, low and steady AE counts are observed. However, during the decay and rise period of fatigue mode, high emissions counts are shown.

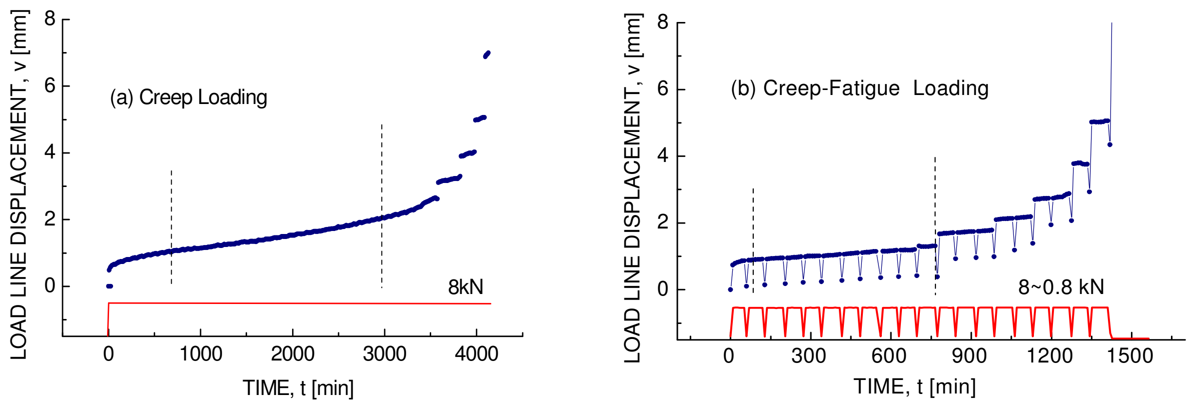


Fig. 2. Variation of load line displacement with time during crack growth test

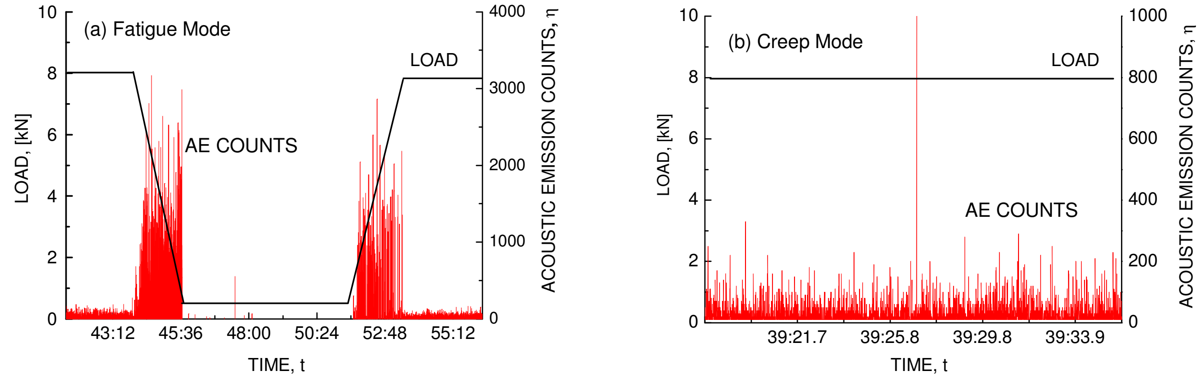


Fig. 3. Acoustic emission response under each loading mode (a) Fatigue mode, (b) Creep mode

When the creep mode is resumed again after fatigue mode, emission counts shows the same trend of previous creep mode. When the creep mode is maintained, AE counts slightly increases with time as shown in the Fig. 3(b). It is considered that the increase in counts was associated with the expansion of creep zone with the help of continuous creeping at the crack tip as shown in Fig. 4(a). This acoustic emission activity generally follows the load profile fairly well with the steady acoustic emission except the fatigue period.

As a feature of fatigue mode, high AE activity is shown in Fig. 3(a), even the load level is lower than that of creep mode. This suggests that fatigue play a important role in creep dominant loading condition. Generally, the crack tip region experiences very high stress and strain concentrations. From the previous research of Tomkins and Wareing, the distribution of stress and strain at the crack tip is readjusted by the relaxation during hold time and can enlarge the amount of crack-tip sliding during subsequent fatigue cycle [5]. The high acoustic emission during fatigue mode was attributed to this specific phenomenon that occur in creep-fatigue interaction.

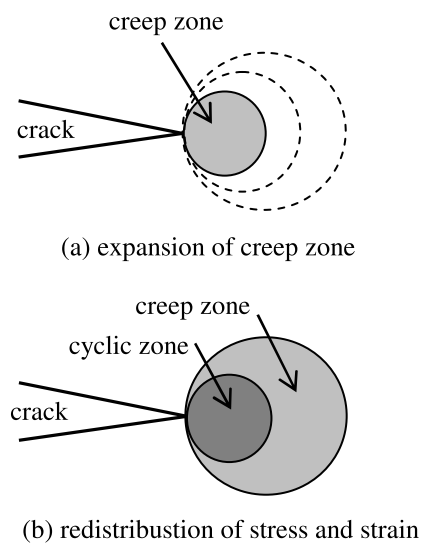
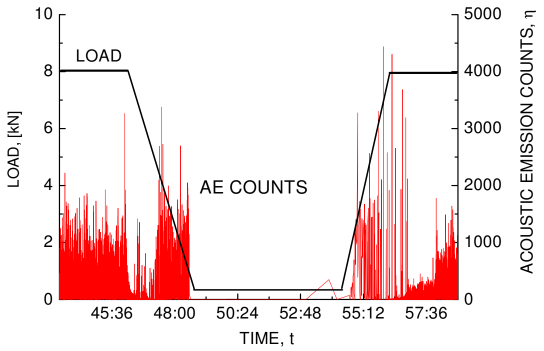
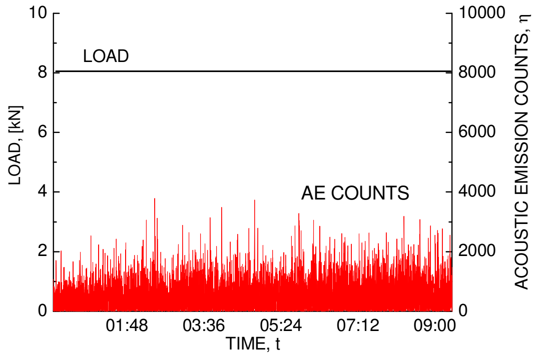


Fig. 4. Schematic representation of creep and cyclic zone at the crack tip [1]

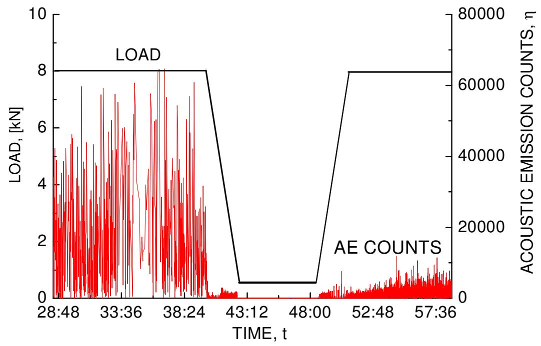
Above acoustic emission responses characterized the each loading mode and corresponding damage at the crack tip. This comes from the fact that emission counts are based on the crack tip state and reflect the crack tip state very well.



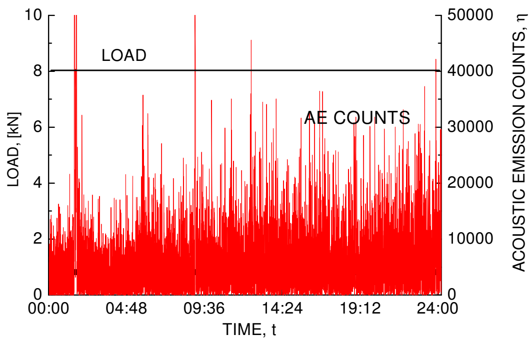
(a) Fatigue mode/ Intermediate region



(b) Creep mode/ Intermediate region



(c) Fatigue mode/ Near-fracture region



(d) Creep mode/ Near-fracture region

Fig. 5. Acoustic emission response in the intermediate and near-fracture region

Damage contribution in terms of acoustic emission

In order to clarify the effects of cyclic load, acoustic emission under every fatigue mode was observed. Fig. 5(a)~(d) show the acoustic emission response which correspond to intermediate region (t/t_f=0.5) and near-fracture region (t/t_f = 0.9) respectively. Counts in each loading mode shows different quantity compared with Fig. 4, which correspond to early region (t/t_f = 0.1). The quantity of emission counts under each loading mode increases as the crack grew. However, the increase of counts under creep become more dominates than counts under fatigue mode. This implies that the contribution of time-dependent process in terms of acoustic emission parameter increased with crack growth by the expenses of cycle-dependent process.

In order to represent cyclic effects on constant creep loading, *the ratio of counts* (r_c) was introduced as follows:

$$r_c = \frac{\eta_c}{\eta_f} \tag{1}$$

Where, η_c and η_f are the counts generated in creep and fatigue period respectively. However, a practical limit exists to the comparison of count itself, since the quantity of counts does not express the exact degree of damage at the crack tip and counts generated under creep mode is too prevalent.

So, *ratio of counts rate* (r_{rc}) was introduced instead of *ratio of counts* (r) for qualitative evaluation. In addition *the contribution factor* (Φ) was also introduced as follows:

$$r_{cr} = \frac{\eta_c / t_c}{\eta_f / (t_r + t_d)} \tag{2}$$

$$\phi_c = \frac{\eta_c / t_c}{(\eta_c / t) + (\eta_f / (t_r + t_d))} \quad (3)$$

Fig. 6 is plot of each contribution factors with *the life fraction* (t/t_f) in the test with different hold time and maximum tensile load. The data for the entire test with hold time express the increasing of creep contribution factor as the life ratio increases. In other words, crack growth under creep-fatigue conditions in 304 stainless steel transits from cycle-dependent to time-dependent in its contribution degree. These results are also reported in literature. Sadananda summarized that the creep contribution to crack growth rate increases with stress intensity and hold time at the peak load [6, 7].

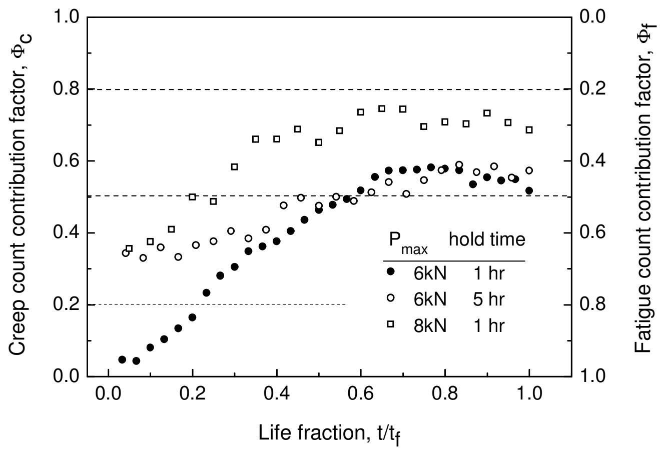


Fig. 6. Creep and Fatigue constribution in terms of acoustic emission counts during crack

The effects of maximum load and hold time is also displayed in Fig. 6. For test result with maximum load of 8kN, time dependent contribution is larger than cycle-dependent contribution compared with result of under 6kN. Generally, crack growth under cyclic load depends on the magnitude of differences of load (ΔP), however creep crack growth depends on maximum load (P_{max}), since creep is more sensitive to the magnitude of stress [7]. Therefore, the increase of creep contribution with increase of maximum load explained by this point. The influence of hold time was adequately explained by increase of creep contribution factor over the whole range of life fraction by comparison of results with 1 hour and 5 hours. From the results, monitoring of acoustic emission from startup to shutdown period and comparison of emission counts will help to understand the contribution of each damage mode and life fraction qualitatively.

Acoustic emission behavior during crack growth

Fig. 7 shows the acoustic emission counts (η) behavior with the life fraction. The relationship is characterized a bilinear relation between counts and time. In early stage of crack growth, the counts increase with time, however counts are constant with time after intermediate life fraction. Both results of test with and without hold time represent similar counts behavior. Because the creep-fatigue crack growth test was performed under creep dominant condition and most of emission counts were generated under creep loading condition. So, the creep-fatigue interaction effects are not presented in these figures.

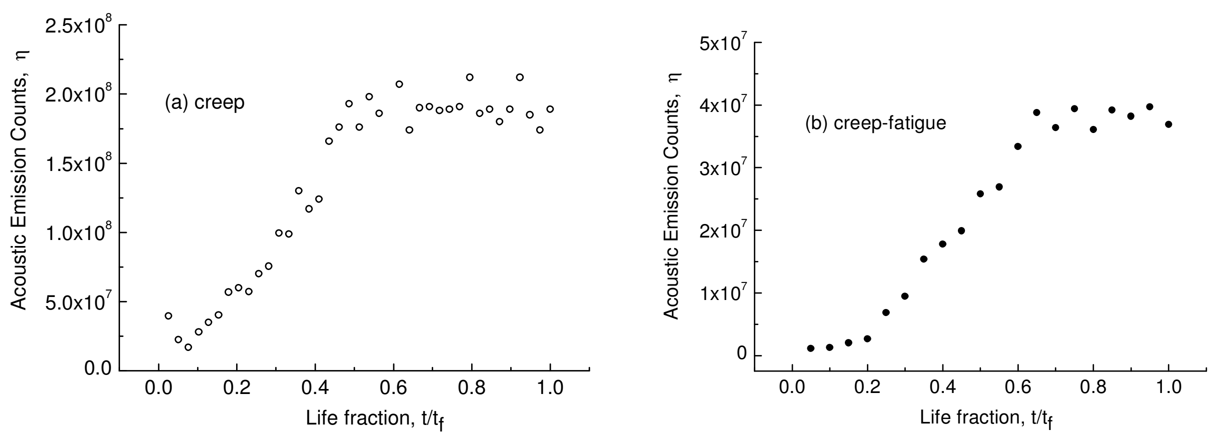


Fig. 7. Counts generated during (a) creep and (b) creep-fatigue test

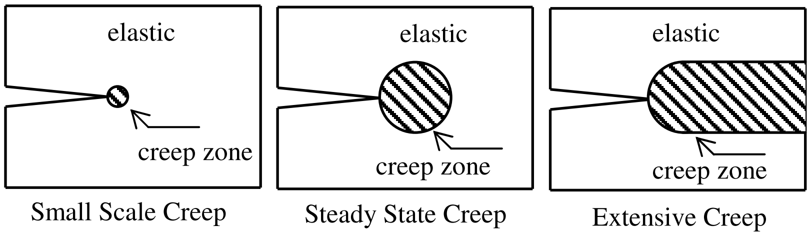


Fig. 8. Development of creep condition with crack growth

Fig. 8 schematically shows the regimes of small-scale creep, the steady state creep and the extensive creep [1]. Under small-scale creep, the creep zone is small in comparison to the crack length and pertinent dimensions of the body. As the crack grow, the small scale creep condition transit to steady state creep and to extensive creep condition. The small scale creep and steady state creep conditions are transient conditions characterized by the crack tip stresses, which vary with time as the stress redistributes with the un-cracked ligament. It is considered that the reason of increase in counts early life fraction region in Fig. 7 is associated with this creep zone expansion. On the other hand, extensive creep condition is a steady-state condition because the crack tip stress remains constant with time. Therefore, the constant emission region in Fig. 7 is attributed to this phenomenon.

From the curves in Fig. 7, it is possible to provide a hint for life estimation strategy by monitoring of cracked body under creep or creep-fatigue loading conditions. The exhaustion of acoustic emission source by crack growth and development of creep condition indicates impending of fracture with a decrease of counts.

Summary

The acoustic emission response has been examined during creep-fatigue crack growth test in 304 stainless steel at 538°C. The basic acoustic emission response to each loading mode was checked. Under trapezoidal wave loading form, low and steady AE counts are observed in the creep mode due to continuous creeping at the crack tip. In the fatigue mode, high emissions counts were shown due to redistribution of crack tip stress and strain by the relaxation during hold time. As the crack grew, creep contribution is increased in terms of acoustic emission, so transition of cycle-dependent to time-dependent trend was shown. Overall acoustic behavior during crack growth was characterized as a bilinear relation between counts and life fraction. This is attributed to development of creep condition which small scale creep condition to extensive creep condition.

Acknowledgement

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