Discussion

Reply to comment on “Identification of SAGBO-induced damage zone ahead of crack tip to characterize sustained loading crack growth in alloy 783”

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Received 15 March 2005; received in revised form 13 September 2005; accepted 19 September 2005
Available online 17 October 2005

Abstract

The damage zone, formed during sustained loading by stress accelerated grain boundary oxygen embrittlement, is a localized region ahead of the crack tip. Before the crack growth reaches a steady rate, the existence of the crack growth transient period shows that cracking is likely to occur within the damage zone. This is indeed compatible with the dynamic embrittlement model.

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Keywords: Alloy 783; Oxygen; Transient period; Grain boundary; Diffusion

1. Introduction

McMahon’s comment [1] on using the damage zone model to characterize the sustained loading crack growth of alloy 783 subjected to the heat treatment only giving γ' precipitation may be summarized as follows: (1) The intergranular cracking has already occurred during the incubation period. Since cracking by a so-called dynamic embrittlement mechanism is a kind of percolation phenomenon in which fingers of cracking extend into un-cracked material, the un-cracked ligaments hold the crack faces together, and prevent the detection of cracking from compliance changes. Also, these ligaments would be difficult to detect by the direct current potential drop method. Therefore, McMahon suggests that after the steady sustained loading crack growth or a period of holding, the subsequent fatigue crack indeed propagates in a region in which intergranular cracking has already occurred. This mechanism can reasonably explain the measurement of damage zone size of 200 μm at 650 °C and 100 s holding. (2) The nomenclature SAGBO (stress-assisted grain boundary oxidation) is coined to refer to the formation of bulk oxides in grain boundaries rather than oxygen intergranular penetration. In response to McMahon’s comments, the authors propose the following as clarification.

1.1. Response 1

A damage zone model has been proposed to satisfactorily explain the time-dependent fatigue crack growth and sustained loading crack growth of superalloys 783 and 718 [2,3]. It is believed that the status of material ahead of the crack tip where cracking is to occur plays a predominant role in defining the crack growth rate. In our model, a damage zone refers to the localized region ahead of the crack tip, wherein the material has been weakened and is different from the original bulk material of specimen. Presumably, oxygen in air is thought to be a detrimental element and responsible for weakening grain boundaries at elevated temperature. It should be noted that the damage zone model is mainly employed to characterize the steady stage of crack growth under the time-dependent...
fatigue and sustained loading condition. McMahon’s argument is correct that the intergranular cracking is likely to occur during the incubation period or given a sufficient holding time. Actually, this claim is also observed in the authors’ report as shown in Fig. 1(a) [4], wherein a transient period of crack growth exists before crack growth approaches a steady rate. In Fig. 1(a), the slope of the linear portion of crack growth curve represents the steady crack growth rate, \( \frac{da}{dt} \). The intersection between the steady crack growth line and the horizontal line represents the incubation period, wherein the crack starts to grow stably. The transient period of crack growth is relatively short in Fig. 1(a); however, it is remarkably evident in alloy 783 subjected to a long term isothermal exposure as shown in Fig. 1(b) [5]. The remarkable crack growth transient period indicates that before crack growth reaches a constant rate, cracking already took place. As suggested by the dynamic embrittlement mechanism, it is likely that some fingers of cracking or so-called micro-cracks, appearing during the transition period, can extend into the un-cracked material. These micro-cracks may or may not be detected depending on the resolution of detecting system. Nevertheless, the material status ahead of the crack tip no longer represents the original bulk material of specimen, i.e. a damage zone has been formed. If the sustained period is relatively short, a damage zone can still be formed in the front of the crack tip. This conclusion has been verified in alloy 718 as shown in Fig. 2 [3].

Clearly, the sudden increase in crack length is caused by the fatigue portion, i.e. unloading and loading, in a cycle. The 100 s hold time of sustained loading only contributes a minor part to the total crack growth in one cycle. It takes a certain number of fatigue cycles to reach a constant crack growth rate, and an obvious change in transition cycles is present. As more cycles are applied, the abrupt crack increment by fatigue increases until it reaches a constant value. Meanwhile, the static crack growth, which occurs during 100 s holding, decreases and eventually vanishes. At the steady state, the total crack growth rate is completely equivalent to the abrupt crack increment by fatigue. Therefore, no matter whether cracking occurs during holding, a damage zone ahead of crack tip is always formed. The crack propagates by consecutively cracking the damage zone. It has been examined that the formation and propagation of damage zone is at a speed equivalent to the sustained loading crack growth rate as the steady crack growth is approached [4]. As the holding period is close to the incubation, the unstable crack growth occurs, i.e. the transient period of crack growth appears. This observation is consistent with Pfaendtner and McMahon’s results [5], and the transient period is associated with cracking or the presence of micro-cracks within the damage zone. Further research is necessary to differentiate, in situ, the

![Fig. 1. Sustained loading crack growth at \( K_{\text{max}} = 38.5 \text{ MPa} \sqrt{\text{m}} \) and at 650 °C: (a) alloy 783 subjected to the heat treatment only giving \( \gamma' \) precipitation and (b) alloy 783 subjected to long term isothermal exposure.](image-url)

![Fig. 2. Crack growth behavior of alloy 718 tested by 100 s hold time fatigue cycle at \( K_{\text{max}} = 26.5 \text{ MPa} \sqrt{\text{mm}}, R = 0.05 \), and 650 °C.](image-url)
formation of micro-cracks from the propagation of the main crack. Grain boundary micro-cracks are also expected to exist in the damage zone at the stage of steady crack growth, but they must develop during the transient stage. It is difficult to confirm at this time whether the potential drop technique can detect the formation of those micro-cracks during the transient stage, Fig. 1(b).

1.2. Response 2

The authors agree with McMahon’s opinion that the term SAGBO (stress assisted grain boundary oxidation) refers to the formation bulk oxides in grain boundaries. To be precise, formation of the damage zone in the sustained loading crack growth or time-dependent fatigue crack growth at elevated temperature should be ascribed to stress accelerated grain boundary oxygen (SAGBO) embrittlement. This nomenclature has actually been used in Lyons’s report [6]. Oxygen diffusion ahead of the crack tip under stressed condition essentially governs the cracking process. It has been reported that AlNi-type β precipitates in alloy 783 is beneficial to resisting the stress accelerated grain boundary (SAGBO) embrittlement, since the presence of β precipitates along grain boundaries could prevent the oxygen diffusion and dilute the intergranular oxygen concentration due to its particular oxidation-resistant characteristics [7,8]. In the authors’ report [4], absence of the intergranular NiAl-β precipitates may allow the grain boundaries to act as a dislocation pipe without significant reaction-induced absorption to block the oxygen diffusion. Therefore, the oxygen intergranular diffusion depth, damage zone size and cracking velocity could be enhanced.

2. Conclusion

A damage zone ahead of a crack tip refers to a region in which the material is embrittled due to oxygen penetration and the status of material is different from the bulk material. There may or may not be cracking within the damage zone depending on the period of sustained loading; however, a damage zone is always formed and the crack propagates through the propagation of damage zone. Before attaining a steady crack growth rate, there is a crack growth transient period indicating that cracking occurs during the incubation period. This observation is compatible with the dynamic embrittlement mechanism. The precise term regarding the cause of damage zone formation should be stress accelerated grain boundary oxygen embrittlement.

References