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Experimental investigation of creep crack growth behavior in nickel base superally by constant displacement loading method at elevated temperature

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ABSTRACT

Creep crack growth (CCG) experiments were performed with compact tension (CT) specimens of a nickel base superalloy, FGH97, to investigate CCG rates and fracture behavior in the service temperature range from 600 °C to 750 °C. The constant displacement loading method (CDLM) was proposed and adopted since the constant force loading method (CFLM) are costly and time-consuming. Stress intensity factor (K) was employed to correlate the CCG rates (da/dt) for this creep-brittle superalloy and the general form of the K solution for a constant displacement loaded CT specimen was obtained based on finite element simulation. The test results indicate that the CCG rates increase with increasing temperature at a given K value. A unified formula containing temperature parameter was proposed to describe the CCG rates in the second stage of crack growth within this temperature range. A validating test in FGH97 via the CFLM was also carried out at 650 °C. Agreements in the test results indicate the feasibility of the CDLM.

1. Introduction

For components serving in high-temperature environment, cracks that initiate from the intrinsic defects, i.e., cavities, inclusions and damage from the manufacturing process will propagate under the combined effect of elevated temperature and cyclic or sustained static loading in service [1,2]. The governing factor of crack growth varies under elevated temperature condition. When the loading frequency is not too low, e.g. , 0.05–20 Hz, crack growth may be governed by fatigue damage [3–5]. However, creep effect is the dominated one in the case of sustained static load [6–9]. In addition, the combined effect of creep and fatigue and their interaction should be considered when the loading frequency is low enough or a holding time is imposed at the maximum load [10–12]. Whether the creep effect or the combined effect is predominant, it is a primary aspect for the structural integrity assessment of such components to evaluate the creep crack growth (CCG) rate reliably based on the distinct investigation of CCG behavior.

A number of theoretical and experimental investigations have been carried out. Most of the theoretical works on CCG were focused on the analysis of crack tip stress and strain fields in creeping body based on various creep constitutive models [13–15], then the regimes of creep deformation behavior were clearly understood. A significant development was the identification of crack tip parameters which were suitable for characterizing the CCG rates [16–18]. CCGR models thus were proposed, and then CCG life predication of high-temperature components [19,20] was performed using different CCG models. However, the applicability of the choice of crack tip parameters and the proposition of models for CCGRs should be verified by experiments.

Lots of the experimental studies were focused on the CCGR measurement in different materials and the correlation between the CCGR with different controlling parameters. Floreen [21] investigated CCG behavior of several superalloys in the temperature range of 500–750 °C and concluded that CCGRs were proportional to an exponential power of stress intensity factor (SIF, K). Saxena [22] investigated CCG behavior of several materials in power plant applications and then adopted the controlling parameters C^*, $C(t)$ and C_t to characterize the CCGRs. CCG behavior of materials, such as 316 stainless steel, Co-Mo-V steel, P92 steel [23–27], was also investigated by experiments and parameter C^* or C_t was employed to correlate CCGR. However, for several solid solution strengthened alloys and γ' strengthened alloys, K and J^*-integral parameters were appropriate to correlate the CCGR [2]. The test results of another several nickel-base superalloys, such as IN718, HAYNES 230 and SC16, etc., also showed that the SIF was suitable for characterizing CCGR [28–31].

Most of the aforementioned CCR experiments were carried out according to the standard test method proposed by ASTM

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Nomenclature

a	crack length, initial crack length
A,m	material parameters determined by creep crack growth test data
B,W	specimen thickness, specimen width
da/dt	creep crack growth rate
G	shear modulus
μ	Poisson's ratio
K	stress intensity factor
u	load-line displacement
T	temperature

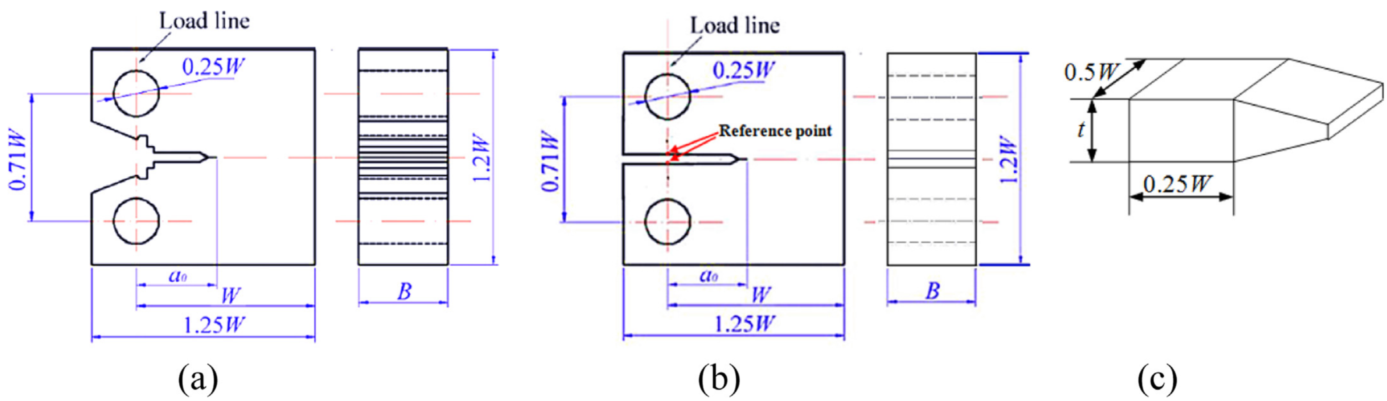

Fig. 1. The geometry of C(T) specimen and wedge.

E1457–13 [32], in which CCG tests should be conducted in creep test rigs with dead-weight or servo-machines loading, then the specimens were heated by an electric resistance or radiation furnace and the direct current potential drop method or travelling microscope was used to measure the crack size. Test method with compact tension (CT) specimens using constant force loading method (CFLM) was described in detail in the test standard [32]. ASTM recommends that parameter C^* or C_t is suitable when materials (in ref [22–27]) show creep-ductile feature, whereas the SIF K is used when materials (in Ref [2,21,28–31]) show creep-brittle behavior. The differences in CCG behavior and fracture mechanism between creep ductile and brittle materials were also distinguished in ref [33–35]. For the determination of the parameters C^*, C_t and K, ASTM E1457–13 presented the particular expression for CT specimen under force loading condition. In addition, numerical approaches based on fracture mechanics were also employed to obtain the solution of these parameters for complex configurations and boundary conditions [36–38].

Although the CFLM recommended by ASTM in the test standard [32] are widely used in the past years, it must be admit that complex testing apparatus are needed to work together and only one specimen can be tested during the testing, which results in extreme consumption in time and costs. Constant displacement loading method (CDLM) is also recommended by the standard test method [32] for extremely creep-brittle materials, but the test results must be compared with those from tests performed by CFLM and verified. Furthermore, the tests by CDLM also should be carried out in creep test rigs.

A modified CDLM was used in this study to investigate the CCG behavior of a nickel base powder metallurgy superalloy, FGH97, which is a creep-brittle material [39], in the service temperature range from 600 °C to 750 °C for comparison, the CFLM test is also performed at 650 °C according to ASTM E1457–13. In the modified CDLM, a wedge, instead of a loading machine, is used to provide an evaluable crack tip stress field of specimen. During the CCG testing, no mechanical machine is needed and several specimens are tested simultaneously, which leads to great savings of testing time and cost. Furthermore, the modified CDLM is just suitable for creep-brittle materials since CDLM can be used only in creep-brittle materials as mentioned in ASTM E1457–13.

2. CDLM for CCG test

For CCG testing, regardless of the adopted loading mode, it is actually that the stress field around crack tip can be formed that is the origin of the driving force for crack propagation. The driving force in CDLM is established by imposing a predesigned crack tip open displacement. Refer to the experience to determine the threshold SIF for stress corrosion cracking ($K_{I\ SSC}$) [40,41], a wedge is employed to insert in the initial notch to introduce a stress field around the crack tip.

2.1. Specimens

In the proposed CDLM, similar specimen type, i.e., a compact tension (CT) specimen, is used as that in the CFLM, which is recommended by ASTM E1457-13 [32]. The only difference is the simplification in the shape of the initial notch, which is designed for the convenience of inserting the wedge to introduce a crack tip open displacement. The geometries of the standard and simplified CT specimens, employed in CFLM and CDLM respectively, and the wedge are given in Fig. 1(a), (b) and (c). The load-line displacement, which decides the crack tip open displacement, is mainly determined by the thickness of the wedge. Wedges with different thicknesses, denoted t in Fig. 1(c), were selected to obtain various initial SIFs. In order to avoid the mismatch in thermal expansion between the specimen and the wedge that could influence the stress filed at the crack tip, the wedge was made of the same material with the specimen.

2.2. Procedure and equipment

Step 1. Pre-cracking the specimens

The following step involves pre-cracking the specimen at room temperature, which is precisely the same as that in any crack growth rate test. Usually, constant-amplitude loading cycles in sine waveform are adopted in this step, and the pre-crack length is no longer than 0.55 W. The final SIF for the pre-cracking step should be less than 70% of the estimated initial SIF for the displacement loading stage. To determine the load-line displacement, the distance between the two reference points shown in Fig. 1