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Crack interaction with incrementally accumulated plastic deformation under nonstationary thermal actions

D.A. Tereshin *

Applied Mechanics, Dynamics and Strength of Machines Department, South-Ural State University, Lenin Avenue 76, Chelyabinsk, Russia

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ABSTRACT

One of the failure modes of ductile structural elements undergoing repeated thermal loading is incremental collapse caused by strain accumulation. Another failure mode typical for such loading is the stable growth of long cracks, with the crack being able to achieve the size of thermal tension zone movement. The impact of general incremental deformation accumulation on cyclic crack growth under repeated thermal actions is studied in this paper. The computational interpretation of the experiment shows that the static damage resulted from overall incremental deformation accumulation exceeds the fatigue one caused by reversed plasticity. This fact proves that under severe thermal ratchetting a crack can be driven mostly by a quasistatic opening produced by the strain accumulated within a body rather than by fatigue.

1. Introduction

There are many practical examples demonstrating crack growth against the background of plastic strain accumulation under thermal actions. For example, the radial thermal crack growth in gas burner flame spreaders is accompanied by a substantial outer diameter increase (Fig. 1a). The strain accumulation over service life leads to a noticeable crack opening. A similar process takes place in slag wool spraying rolls, which are used in slag wool production as shown in Fig. 1b. Such rolls are cooled from the inside by water, and with the start of spraying hot melted slag, severe thermal stresses arise. In both described cases the thermal fields are axisymmetric, and the stress state is uniform in the hoop direction, therefore, multiple cracks grow from the periphery.

Another case is represented by slag carriage vessels being used to transport melted slag from steel plants. In these vessels long cracks develop in the zone where plastic deformation accumulates (Fig. 2). These vessels, initially being conical shells with straight generating line, accumulate strain in their upper part under repeated fillings with melted slag, with crack systems rapidly developing in the same region. These cracks achieve substantial length and opening, so that the tank starts leaking.

2. Theoretical background

Failure modes under thermal load have some peculiarities due to the fact that thermal stresses are self-equilibrated. One of the failure modes of ductile structural elements intrinsic to thermal load is incremental plasticity. Melan's shakedown static theorem states that if there exists a residual stress field being added to the elastic stresses, the total stress yields an admissible stress field at every time moment, then after some initial loading history such residual stress distribution will

* Tel.: +7 951 47 96 325; fax: +7 351-267 93 06.
E-mail addresses: denisat75@gmail.com, tdenis75@mail.ru

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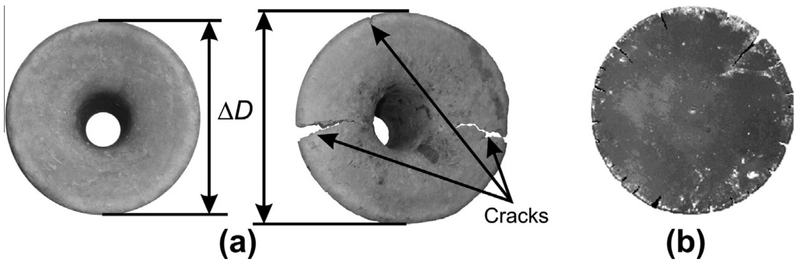

Fig. 1. Crack opening caused by accumulated deformation in a gas burner flame spreader (a) and in a slag spraying roll (b).

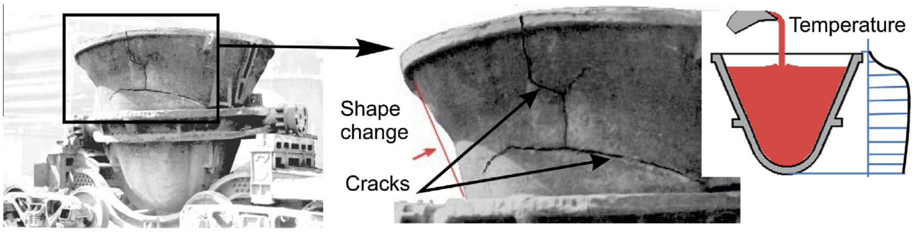

Fig. 2. Cracks in the region of severe deformation accumulation in a slag carriage vessel.

be worked out and plastic deformation will stop. This phenomenon is known as shakedown or elastic shakedown and has been studied in a number of works, with effective numerical methods for shakedown load boundary estimates being developed (e.g. by Gokhfeld and Cherniavsky [1], Maier et al. [2], Ponter and Haofeng [3], and others). However, if there is no such a field, plastic deformation will never stop. During some initial period the deformation process is stabilizing, and afterwards the plastic cycle parameters do not change from cycle to cycle. In many practical cases overall deformation is accumulated over time, and in a stabilized process the deformation is growing by a constant increment over each loading cycle. Such kind of stable cyclic plastic structural response is referred to as incremental plasticity, ratcheting, or incremental collapse – the phenomenon studied by some researchers [1,4], however, in general, being much less studied than elastic shakedown. It is noteworthy, that the main distinction form instant plastic collapse is that plastic flow in incremental collapse occurs in different body parts at different moments of a cycle so that the plastic flow is anisochronal.

Another failure mode typical for thermal loading is the stable growth of long cracks studied by Tereshin [5]. As distinct from mechanical loading this growth is not an unstable dynamic process but the process of anisochronal quasistatic crack growth proceeding along with thermal stress change as it occurs with plastic strain in incremental collapse. In this process a crack tip either follows thermal tension zone, so that the crack can grow to a large extent over one loading cycle, or it grows cyclically over a number of cycles in the opposite direction to the movement of thermal stress field at the moments when the crack tip is located in the tension zone. In both cracking modes the crack grows quasistatically, but the length of the final crack can considerably exceed the thermal tension zone and extend throughout the zone over which the tensile stresses travel. One more mode is fatigue crack growth under cyclic transient thermal actions [6], with the crack extension being also able to achieve the size of the tension zone travel.

The examples given in the introduction demonstrate that both the process of cyclic strain accumulation and the process of crack growth can take place simultaneously and interact with each other. Although the problem of the limit state of cracked structures has been studied in a number of works (in particular, in [7,8]), and there are some studies (e.g. carried out by Habibullah and Ponter [9], Weib et al. [10], and others) concerning cracks in ratchetting in the literature, so far the influence of general ratchetting caused by thermal stresses on cyclic crack growth has never been studied in spite of the fact that severe ratchetting mostly occurs under thermal actions. Thus, the aim of the present study is to estimate the impact of general incremental deformation accumulation on cyclic crack growth under thermal actions.

3. Experimental demonstration

In order to gain insight into the phenomenon, an experimental study and the following computational analysis have been carried out. The experiment technique was similar to the one in the ratchetting experiments [1,4], which simulates the movement of heat carrying liquid in a vessel as it occurs, for instance, with slag carriage vessels.

3.1. Experiment technique

For creating severe thermal conditions a cylindrical thin-walled specimen made of untempered low-alloyed steel containing 0.3% C, 1% Si, 1% Mn, 0.3% Ni, 1% Cr was being passed at constant speed through a circular high frequency inductor for