Modeling hydrogen attack effect on creep fracture toughness

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Abstract

The effect of high temperature hydrogen attack on creep crack growth rates in steels is studied by modeling the interaction between creep deformation and gaseous pressures generated by hydrogen and methane. The equilibrium methane pressure as a function of hydrogen pressure, temperature and carbide types for carbon steels and Cr–Mo steels is calculated. This gaseous driving force is incorporated into a micromechanics model for void growth along grain boundaries of a creeping solid. Growth and coalescence of voids along grain boundaries is modeled by a microporous strip of cell elements, referred to as the fracture process zone. The cell elements are governed by a nonlinear viscous constitutive relation for a voided material. Two rate sensitivities as well as two types of grain boundaries are considered in this computational study. Simulations of creep crack growth accelerated by gaseous pressures are performed under conditions of small-scale and extensive creep. The computed crack growth rates at elevated temperatures are able to reproduce the trends of experimental results.

1. Introduction

Plain carbon steels and Cr–Mo steels are susceptible to high temperature hydrogen attack (HA) which can result in component fracture. This is a costly engineering problem for the petrochemical industry. At elevated temperatures, hydrogen can diffuse into steels and react with carbides to form methane gas which accumulates at microcavities and grain boundaries. Owing to their large size, the methane molecules are unable to diffuse away and this generates high internal pressure. Depending on the reactivity of different carbide types, methane pressure can be one to two orders of magnitude higher than hydrogen pressure. Driven by gaseous pressure and applied stress, voids nucleate at grain boundaries and grow by creep of the adjacent grains as well as by grain boundary diffusion. The growing voids coalesce to form intergranular microcracks which link up to form a macrocrack and eventually intergranular fracture occurs (Shewmon, 1976).

Industry standards for safe operation temperature and hydrogen pressure under HA condition are prescribed by Nelson curves (Nelson, 1977). These curves are empirically based on past service experience. In order to develop a more fundamental understanding of HA corrosion, several attempts have been made to improve on Nelson curves by utilizing insights gained through micromechanistic models. Sundararajan and Shewmon (1981) have presented a detailed model for the kinetics of growth of methane bubbles along grain boundaries. Their work has incorporated the interaction between HA and macroscopic stresses. Shih and Johnson (1982) have applied a void growth model for hydrogen attack of plain carbon structural steels. van der Giessen and co-workers (van der Giessen et al., 1993; van der Burg et al., 1996; van der Burg and van der Giessen, 1996, 1997) have developed a creep cavity growth model, which has been used to analyze damage and cavitation due to hydrogen attack where the grain boundary voids are internally pressurized. However in real practice, the prediction of the crack growth rate under the applied loading in HA remains an interesting research topic. While many experiments have been carried out and experimental data accumulated (Shewmon and Xue, 1991; Chen and Shewmon, 1995; Shewmon and Anderson, 1998), numerical analyses of HA on creep fracture toughness have yet to be performed. This paper aims to address this and provides a bridge to experimental observations.

The effect of high-pressure hydrogen on creep crack growth rates has been measured experimentally by Shewmon and Xue (1991) for a low-carbon steel and Chen and Shewmon (1995) for 2.25 Cr–Mo steel. It is experimentally observed that cracks propagate by the growth and coalescence of densely populated methane bubbles on the grain boundaries. In this respect high gaseous pressure, together with elevated temperatures near the Nelson curve, markedly increases crack growth rates. For example, crack growth rate in a low-carbon steel increases steadily with the hydrogen pressure in the range of 3 to 21 MPa. By contrast, 2.25 Cr–Mo steel can sustain higher levels of stress intensity factor due to higher creep resistance. These are discussed in a review article (Shewmon and Anderson, 1998). More recent experimental studies address...