Asymptotic approach to the constant velocity of hydrogen delamination growth

A.V. Balueva

School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

Abstract

We consider delamination crack growth controlled by gas diffusion into the crack. If the gas is accumulated inside the delamination, after some incubation period, the crack starts growing under the pressure of the accumulated gas. An important example is given by hydrogen-induced delamination. Hydrogen absorbed by a metal is typically dissolved in the proton form within the lattice. Some of the protons reach the surface of pre-existing or freshly created cracks or delaminations where they recombine with electrons and form molecular hydrogen in the crack cavity. Since the molecular form of hydrogen is thermodynamically more stable, this process leads to accumulation of hydrogen gas inside the delamination crack. Under the excessive hydrogen pressure fracture often takes place even in the absence of any additional external loading. It is especially dangerous if the metal is covered with coating, where because of the dissimilarity of materials, microscopic voids appear more frequently. This leads first to hydrogen precipitation within these coating–metal interface voids and then to their development. This results in the delaminating of the coating. As it is well known, in the absence of aggressive media the cracking resistance of a material is characterized by a unique constant: so that if the stress intensity factor is smaller than this constant, the crack is fixed, and if it is larger, the crack moves in a dynamic regime. But in the presence of aggressive media, particularly hydrogen, the crack development is characterized by a smooth kinetic function $v(K_I)$, which is dependence of the crack velocity on the stress intensity factor, with the lower threshold value of resistance K_{scc} smaller than the static critical stress intensity factor K_{Ic}. As numerically shown in the author's earlier work for the internal crack growth, the crack velocity first increases in accordance with the kinetic function, until reaching some value of v_s, and remains at the same level afterwards. Since, as has been obtained by the author in the previous paper, kinetic equations for internal and delamination cracks are essentially identical, the same conclusion can be derived for the latter. In this paper the stability and asymptotic approach to the constant velocity of delamination growth is proved analytically. If v_s is known, the corresponding value of the stress intensity factor, K_s, is obtained by substituting v_s into the kinetic function $v(K_I)$.
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Keywords: Delamination growth; Asymptotic stationary regime; Hydrogen-induced cracking; Kinetic functions

0. Introduction

Delamination, defined here as the separation of the surface layer from the solid body, is observed in many engineering processes and natural phenomena, ranging from surface buckling of layered composites (e.g., [1–3, 56]) to surface fracturing caused by hydrogen embrittlement in metals (e.g., [4–6]). For example, in the case of pipelines for hydrocarbon transport (e.g., [7,8]), anti-corrosion, polymer coating sometimes results in more frequent appearance of small scale delaminations [9]. In time, these delaminations spread under molecular hydrogen accumulated in a cavity, damaging the coating and allowing the moisture access to the metal; the result being the external corrosive fracture of the pipeline and its premature replacement. Understanding the mechanism of protective coating delamination may improve estimates of the pipeline longevity, thereby creating an essential industrial potential. In this paper, we studied the general case of delamination caused by the hydrogen-induced cracking (HIC).

Despite intensive study the mechanism of hydrogen embrittlement remains poorly understood. Four main

mechanisms have been known in the literature (e.g., [10,11]): (i) formation of hydride phase; (ii) enhanced local plasticity; (iii) grain boundary weakening (decohesive mechanism); (iv) blister and bubble formation. Hydride-induced embrittlement, observed for example in metals such as zirconium and titanium, occurs by the precipitation of brittle hydrides at stress concentration locations, which leads to reduction of the fracture toughness of metals by several orders (e.g., [12]). For applied stress intensity factors larger than the threshold but less than the fracture toughness of the solid solution, crack velocity depends strongly on loading, or on the stress intensity factor (so called a kinetic function $v(K)$ (e.g., [12])).

The enhanced local plasticity mechanism is based on a premise that hydrogen affects the behavior of the dislocations emission at the crack tip area, which enhances the plasticity in front of the crack tip (e.g., [11,13–17]). This type of fracture is typical for low-strength materials.

The third mechanism, grain boundary weakening or hydrogen embrittlement, is observed conversely for high-strength steels (e.g., [10,18,19]), and results in lowering K_{Ic} (e.g., [20]). On a molecular level, hydrogen ions diffuse between the grain boundaries of the steel, where hydrogen ions recombine into molecular hydrogen (H_2), taking up more space and weakening the bonds between the grains, reducing cohesive strength (e.g., [20–22]). The formation of molecular hydrogen can cause sudden metal failure due to cracking when the metal is subjected to tensile stress. Usually, before catastrophic stage, this type of failure has a period where no damage is observed, called incubation.

The formation of hydrogen blisters or internal hydrogen-induced cracks (HIC) at pre-existing cracks or at sites of nonmetallic inclusions, is typical for low-strength materials [23–26]. Internal cracks and blisters are formed when atomic hydrogen diffuses into the metal and accumulates as gaseous hydrogen at the planar defects [27,28]. The pressure of gaseous hydrogen inside the trapping sites causes separation of the metal–defect interface, forming a cavity which grows in the same plane parallel to the pipeline (e.g., [23,29]). If the cavity is formed near the surface of the pipe, the gas pressure plastically deforms the material between the crack and the free surface of the pipe, forming a blister or delamination of the external surface of the metal. If the crack remains in the half-thickness, it is called a delamination or internal crack (e.g., [23]). No external stress is usually required to examine this type of cracking.

As it follows from the above review, once inside the material, hydrogen can affect the mechanical performance of material in several ways. Two main effects are observed: accumulating hydrogen ahead of the crack tip, which reduces cohesive strength or K_{Ic}, and trapping molecular hydrogen inside cracks (hydrogen-induced cracking, or HIC), which creates the internal pressure.

A limited number of models have been developed to evaluate HIC and hydrogen delaminations initiation and velocities, which is vitally important for estimating

durability of pipelines. Numerical models for hydrogen-assisted cracking have been developed for example in Refs. [12, 24], based on finite element method. Only few models have been created to estimate the propagation and incubation time of HIC and hydrogen delaminations by relatively simple analytical equations. Goldstein et al. [30] developed a model for internal crack growth considering toughness to be a constant. Gonzales et al. [23] proposed a model of a disk crack growth in the middle thickness of the metal. The K_{Ic} was considered to be a constant that does not depend on processes at the crack tip. Using one-dimensional approximation for hydrogen diffusion, Gonzales et al. [23] obtained a closed-form solution for the crack growth rate, which agreed with the experimental results corresponding to the initial stages of the crack growth (according to his result the crack is growing exponentially). A common feature of HIC in pipes, as observed and reviewed by Ref. [23], is that the fractures propagate in the direction parallel to the pipe wall.

Near-surface penny-shaped crack growing parallel to the wall of the plate, or delaminating of the external surface, is considered in this paper. The driving force for the near-surface cracks is the internal pressure of accumulated hydrogen in the cavity. All mechanisms of lowering the strength at the crack tip are incorporated in the kinetic function: the crack velocity is believed to depend on the stress intensity factor, K_I, and, therefore, on the energy release rate, G (e.g., [31–34]), and the actual kinetic functions, $v(K_I)$, are used (e.g., [4,35–37]). As numerically shown by Refs. [38, 40] for internal crack growth, crack velocity first increases in accordance with the kinetic dependence, until reaching some value of v_s, and remains at the same level afterwards. Since, how it was obtained in the previous paper of Ref. [39], kinetic equations for internal [30] and delamination cracks (this paper) are essentially identical, the same conclusion can be assumed for the latter. In this paper, the asymptotic approach to the constant velocity by the delamination is proved analytically. This slow kinetic growth of HIC at constant speed is observed in many experiments (e.g., [23–25,28]).

1. Main equation for the delamination growth

Let a half-space $z < 0$ (e.g., a substrate of the base metal), saturated uniformly by gas (e.g., hydrogen) with concentration c_0, be covered by a thin infinite layer of thickness h. Suppose a circular delamination of the initial radius, a_0, appears in the interface, $z = 0$, at the moment of $t = 0$ (Fig. 1).

Once the gas is sufficiently accumulated in the delamination, and the critical condition is achieved on the crack front, the delamination begins growing and its radius increases to $a > a_0$ (Fig. 1). The growth can be analyzed in the framework of fracture mechanics so that the material resistance to the crack development is described by the fracture toughness, K_{Ic}, or the critical energy release rate, G_c.