Available online at www.sciencedirect.com

SciVerse ScienceDirect

Acta Materialia 60 (2012) 4646–4660

Acta MATERIALIA

www.elsevier.com/locate/actamat

A macro- and micromechanics investigation of hot cracking in duplex steels

Guilhem Martin [a,*], Sampath Kumar Yerra [b], Yves Bréchet [a], Muriel Véron [a], Jean-Denis Mithieux [c], Béchir Chéhab [c], Laurent Delannay [b], Thomas Pardoen [b]

[a] Laboratoire de Science et Ingéniérie des Matériaux et Procédés, Groupe Physique du Métal, Domaine Universitaire, 1130 Rue de la Piscine, 38402 Saint Martin d'Hères, France

[b] Institute of Mechanics, Materials and Civil Engineering, Université Catholique de Louvain, Place Sainte Barbe 2, B-1348 Louvain-la-Neuve, Belgium

[c] Aperam Research Center, BP 15, 62230 Isbergues, France

Received 19 December 2011; accepted 21 March 2012
Available online 3 May 2012

Abstract

The relationship between microstructure and high temperature ductile tearing in duplex stainless steels has been investigated. Several grades were considered corresponding to different chemical compositions, different volume fractions and morphologies of the ferrite and austenite phases and different oxide inclusion contents. The high temperature cracking resistance has been quantified using both the essential work of fracture (EWF) and the fracture strain. The EWF discriminates the different grades of duplex steels and the different microstructures in terms of hot tearing resistance better than does the fracture strain. Metallographic characterization reveals that damage preferentially nucleates near inclusions at the austenite/ferrite boundary. Voids grow inside the ferrite until they coalesce. Damage develops more rapidly when increasing either the mismatch of rheology between the phases, which was evaluated by micro-scale strain measurements, or the inclusion content. The cracking resistance is related to the plastic work performed in the fracture process zone whereas the fracture strain depends on the damage kinetics. Both processes involve length scales related to the morphology and to the microstructure dimensions. Guidelines for improving the hot cracking resistance of duplex steels are formulated.

Keywords: Duplex stainless steels; Crack propagation; Micromechanics; High temperature deformation; Essential work of fracture

1. Introduction

Duplex stainless steels (DSSs) consist of a two phase microstructure involving δ-ferrite and γ-austenite. An exceptional combination of strength and toughness together with good corrosion resistance under critical working conditions designate DSS as suitable alternatives to conventional austenitic stainless steels. This good structural performance explains their use in a variety of applications, particularly in the petroleum and gas industries, as well as in chemical vessel applications [1].

Unfortunately, the poor hot workability of these alloys makes the industrial processing of flat products particularly critical. Cracking along the edges of the coils during hot rolling is frequently reported [2,3]. As a consequence, additional operations like grinding, discontinuous processing or scraping are often required, increasing the manufacturing costs. The high temperature mechanical behaviour of DSS depends on several phenomena: phase proportions [4], chemical composition [2], impurities [2,5], size and morphology of both phases [6,7], nature of the interphase boundaries [8], softening mechanisms in the constituting phases [9–13], and strain partitioning between ferrite and austenite [3,14]. A fundamental research effort is thus needed in order to unravel the mechanisms at the origin of a reduction in toughness at high temperature. Only the

* Corresponding author. Tel.: +33 (0) 476826707; fax: +33 (0) 476826644.
E-mail addresses: guilhem.martin@simap.grenoble-inp.fr, gui12@hotmail.fr (G. Martin).

1359-6454/$36.00
http://dx.doi.org/10.1016/j.actamat.2012.03.040

use of a multiscale approach can link the cracking resistance to the relevant microstructural characteristics.

One of the main difficulties in hot cracking studies is the definition of a relevant material parameter characterizing the fracture resistance and capturing its sensitivity to the controlling phenomena. In some applications the resistance to damage initiation and growth is the main issue. In such cases the high temperature fracture strain measured on tensile specimens usually provides valuable information. In other applications the resistance to cracking initiation from stress concentration is the main issue. Finally, the tearing resistance, i.e. the resistance to the propagation of a crack, is the key parameter for edge cracking during hot rolling. At high temperatures the classical approach to non-linear fracture mechanics is most of the time not valid, due to extreme ductility and rate sensitivity, especially if the initial cracks are short [15].

Recently, the essential work of fracture method has been successfully applied to characterize the high temperature tearing resistance of ferritic stainless steel [16]. The EWF concept has been widely used over the last 35 years to quantify the fracture resistance of ductile metallic materials sheets (brass, bronze, zinc alloys, aluminium alloys and steels) [17–22] or polymer thin sheets or layers [23–26]. The EWF represents the work per unit area spent in the fracture process zone. It is computed over the complete duration of ligament cracking (see Fig. 1). This work represents the energy spent locally at the crack tip due to damage and necking. Using micromechanics arguments it can be related to the physical mechanisms of failure and to the microstructure. This is essential in the context of the present study. The major advantages of the EWF method are that it does not require any monitoring of crack propagation and that it can be used in circumstances where non-linear fracture mechanics concepts, such as the J integral, cannot be applied. Nevertheless, application of the EWF method at temperatures above ambient is not common. It has been used at intermediate temperatures (100–300 °C) on polymers [27,28] inside a furnace. Applying the EWF concept is an experimental challenge for higher temperatures (>1000 °C). In addition to the difficulties of controlling the microstructures at high temperature in materials affected by phase transformations, carrying out the test in a homogeneous temperature furnace requires special care [16].

The objective of the present work is to address the high temperature fracture resistance of DSSs using the EWF concept. Using further characterizations and models we aim to establish the link between such fracture energy, the microstructure and the failure mechanisms in order to guide materials optimization. The EWF is expected to be sensitive to the alloy composition and to the microstructural parameters, such as the γ phase morphology or the inclusion content. As a preliminary task, model microstructures with different γ morphologies (equiaxed (E) or Widmanstätten (W)) were generated while controlling the phase proportion and the size of the γ phase. For that purpose, three different duplex steels were investigated, D1, D1bis and D2, with different inclusion contents. The materials in the as-cast conditions were also tested for comparison. Different parameters characterizing the high temperature fracture resistance have been measured and assessed: (i) the equivalent fracture strain ($\varepsilon^{eq}_{fracture}$); (ii) a mean damage nucleation strain ($\varepsilon^{eq}_{damage}$); and (iii) the tearing resistance determined by the EWF (w_e). These tests have been supplemented by in-depth analysis of the microstructure and damage mechanisms.

The outline of the paper is as follows. The materials and the experimental procedures are described in Section 2. Section 3 presents the experimental results, which are discussed in depth in Section 4. The discussion addresses the influence of the microstructural parameters on the high

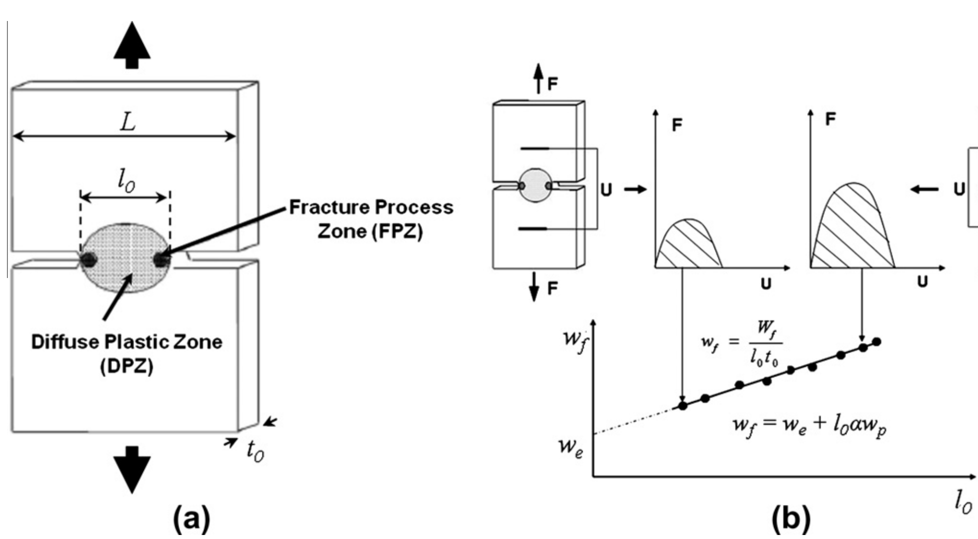

Fig. 1. (a) DENT geometry showing the diffuse plastic zone as well as the localized necking zone in front of the crack tips. (b) Diagram illustrating the method to determine the specific essential work of fracture.