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Caracterização da resistência ao trincamento a quente com base nos trabalhos esssenciais de mecânica da fratura - aplicação aos aços inoxidáveis duplex

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Abstract

Duplex stainless steels (DSS) involve two ductile phases, i.e. ferrite and austenite, with a proportion of each phase around 50%. The main advantage in comparison with other austenitic and ferritic stainless steels is the excellent combination of high strength and corrosion resistance together with good formability and weldability. Unfortunately, DSS present in general a poor hot workability. Standard hot ductility tests like hot tensile or hot torsion tests are always helpful to compare the fracture resistance of two very ductile materials. A new method based on the essential work of fracture (EWF) concept has been used in order to determine the hot cracking resistance. The EWF concept was introduced to address ductile fracture based on the entire load-displacement response up to the complete fracture of a specimen and not from the initiation measurements such as in classical fracture mechanics concepts. The aim of the method consists in separating, based on dimensional considerations, the work performed within the plastic zone from the total work of fracture in order to provide an estimate of the work spent per unit area within the fracture process zone to break the material. This method proved to be very well adapted to high temperature cracking. Two different duplex stainless steels have been characterized by the essential work of fracture method. Examination of the fracture micrographs and profiles match the EWF results. This method turns out to be a discriminating tool for quantifying hot cracking and to generate a physically relevant fracture index to guide the optimization of microstructures towards successful forming operations.

Keywords: Duplex stainless steel, hot cracking resistance, essential work of fracture.

Resumo

Aços inoxidáveis duplex (AID) envolvem duas fases dúcteis, isto é, ferrita e austenita, com uma proporção de cada fase de cerca de 50%. A principal vantagem, em comparação com outros austeníticos e aços inoxidáveis ferríticos, é a excelente combinação de alta resistência mecânica e resistência à corrosão com conformabilidade *e boa soldabilidade. Infelizmente, AID apresentam, em geral, uma deficiente trabalhabilidade a quente. Ensaios-padrão de ductilidade a quente ou ensaios de torção elástica a quente sempre são úteis para comparar a resistência à fratura de dois materiais muito dúcteis. Um novo método baseado no trabalho essencial de mecânica da fratura tem sido usado para determinar a resistência ao trincamento a quente. O conceito da EWF foi introduzido para tratar a fratura dúctil com base na resposta de deslocamento de carga inteira até a fratura completa de um modelo e não a partir das medições de iniciação, como na mecânica da fratura clássica. O objetivo do método consiste em separar, com base em considerações de ordem dimensional, o trabalho realizado dentro da zona de plástica a partir do trabalho total de fratura, a fim de fornecer uma estimativa do trabalho gasto por unidade de área dentro da zona de processo de fratura para quebrar o material. Este método provou ser muito bem adaptado à fratura em alta temperatura. Dois diferentes aços inoxidáveis duplex têm-se caracterizado pelo trabalho essencial do método de fratura. Exame da micrografias de fratura e perfis correspondem aos resultados EWF. Esse método acaba por ser um instrumento de discriminação para quantificar o trincamento a quente e para gerar um índice de fratura fisicamente relevante para orientar a otimização da microestrutura para conformações bem-sucedidas.*

Palavras-chave: *Aço Inoxidável Duplex, hot resistência à quebra, trabalho essencial de fratura.*

1. Introduction

Duplex stainless steels (DSS) are defined as a family of stainless steels consisting of two phase: δ-ferrite and γ-austenite with a proportion of each phase around 50%. These alloys present an attractive combination of good mechanical properties with excellent corrosion resistance and are suitable for marine and petrochemical applications. However, in the processing of flat products, hot rolling is a critical step: cracking occurs at the edges and sometimes over several centimeters. The poor hot workability of DSS can stem from different factors, such as: the balance of the phases (Iza-Mendia and Gutierrez, 2007), the nature of the interface (Iza-Mendia et al., 1996), distribution, size and shape of the second phase (Pinol-Juez et al., 1996), and possibly also from difference in rheology between ferrite and austenite (Duprez et al., 2002; Hernandez-Castillo et al., 2005). The characterization of the high temperature fracture resistance of metallic materials and the influence of microstructural parameters remain experimental and theoretical challenges. The main difficulty is the definition of a relevant fracture parameter which properly quantifies the controlling fracture phenomena, for example during high temperature forming operations. In some applications, the resistance to damage initiation and growth is the main issue. In that case, the high temperature fracture strain measured on tensile specimens usually provides valuable information. In some other forming applications, the resistance to crack 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. The fracture mechanics concepts are most of the time not valid in such cases due to very high ductility at high temperature and the short crack lengths (Cotterell and Atkins, 1996). The purpose of the present paper is to demonstrate the interest in using the essential work of fracture (EWF) concept as a reliable and discriminating tool for quantifying the high temperature tearing resistance. This method generates also a physically relevant fracture index to guide the optimization of microstructures towards successful forming operations.

2. Materials and methods

Materials

Two different DSSs with composition shown in Table 1 have been investigated in the present work. These steels were supplied by APERAM in the as-cast conditions.

Both as-cast microstructures consist of a ferritic matrix with Widmanstätten lathy austenite (see Figure 1). Microstructure of alloy A is different from the microstructure of alloy B in terms of phase proportion and austenite lath size (Table 2). Both as-cast slabs present a strong microstructural gradient through the thickness (see example in Figure 1C).

	Cr	Ni	Mo	Mn	Si	Cu	C	N
A	21.87	2.94	0.99	2.87	0.35	0.64	0.03	0.19
B	22.77	5.69	3.09	1.76	0.47	0.17	0.03	0.18

Table 1
Chemical composition in wt.% of the duplex stainless steels.

The EWF method

The essential work of fracture concept was introduced by Cotterell and Reddel (Cotterell and Reddel, 1977) as a mean of quantifying the fracture resistance of thin ductile metal sheets. The basic idea is simple (see also (Cotterell

Table 2
Austenite laths size and proportion of phases in the different zones through the slab thickness.

	Alloy A			Alloy B		
	e_γ (μm)	% γ	% δ	e_γ (μm)	% γ	% δ
Slab skin	20	65	35	7	49	51
Columnar zone	45	58	42	23	47	53
Transition zone columnar-equiaxed	45	50	50	24	42	58
Equiaxed zone	38	50	50	21	37	63

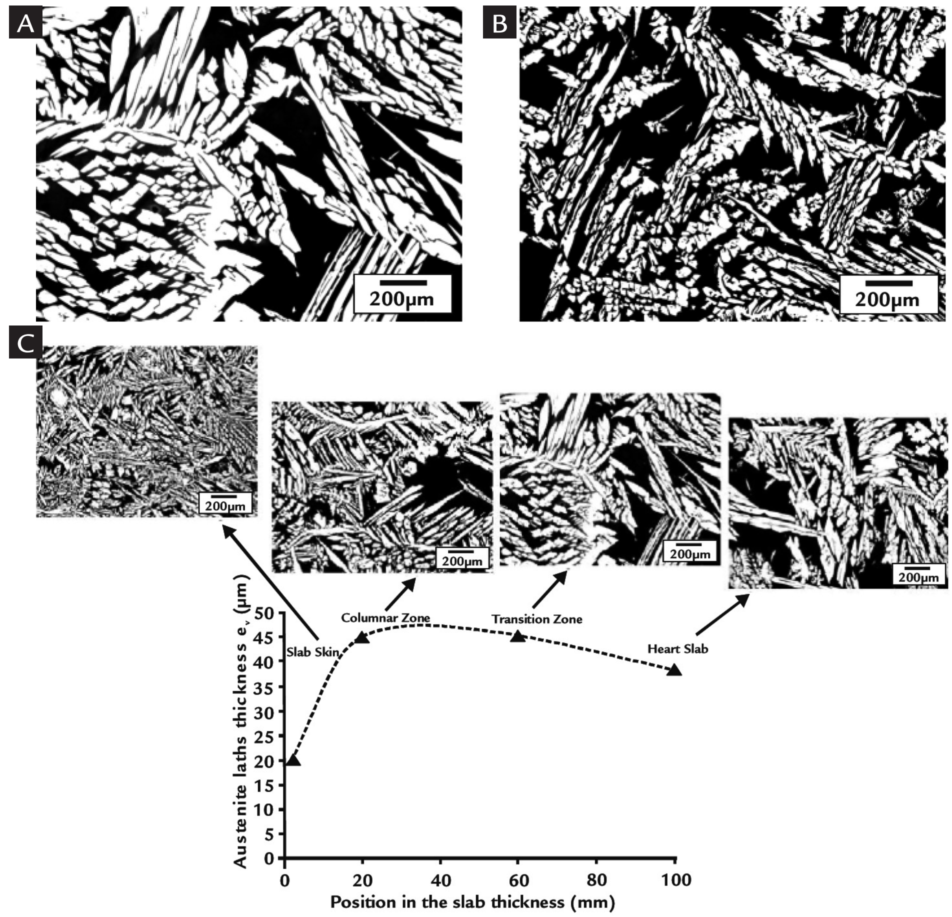

Figure 1.
Microstructure of the as-cast materials in the columnar zone.
(A) Alloy A.
(B) Alloy B.
(C) Microstructural gradient in the as-cast slab thickness of alloy A. Ferrite in black, austenite in white.

et al., 2003; Pardoen et al., 2004)): it consists in separating, based on dimensional considerations, the work dissipated within the plastic zone from the total work of fracture in order to provide an estimate of the work spent per unit area within the fracture process zone (FPZ) to break the material (Broberg, 1975). If the ligament of a sheet specimen is, as shown in Figure 2, completely yielded before initiation, and the plastic zone is confined to the ligament, then the plastic work dissipated for the complete fracture is proportional to the plastic volume at initiation and the work in the FPZ is proportional to the fracture area. That is, the plastic work and the EWF scale differently with samples dimensions. For thin sheets, the double edge notch tension (DENT) geometry (Figure 2A) is particularly well suited owing to the symmetry and advantage of no buckling problems. The area of the plastic zone and the plastic work dissipated to completely break the specimen are proportional to the square of the ligament length, l_0^2. The work performed in the FPZ is proportional to l_0. The total work of fracture, W_f, can be written as the sum of the essential work, W_e, and the plastic work, W_p:

$$W_f = W_e + W_p = t_0 l_0 w_e + \alpha t_0 l_0^2 w_p \tag{1}$$

where w_e is the specific essential work of fracture (work per unit area), w_p is an average plastic work density, t_0 is the initial sheet thickness and α is a shape factor (π/4 for a circular plastic zone). Normalizing the previous equation, the specific work of fracture, $w_f = W_f/t_0 l_0$ is given by:

$$w_f = w_e + l_0 \alpha w_p \tag{2}$$

Thus if several DENT specimens with different ligament lengths, l_0 are tested, the specific essential work of fracture is the constant term in the linear regression, i.e. the work obtained by extrapolating to a zero ligament length the linear evolution of the specific work of fracture against ligament length (Figure 2B). The specific work of fracture was calculated from the areas under the load-displacement curves.

For the measurements of the EWF, DENT specimens with dimensions corresponding to the validity of the method (Cotterell et al., 2003; Pardoen et al., 2004) and with various ligament lengths (15,17,25,35,37 and 39 mm) were machined in the as-cast slab of each DSS with the ligament located in the columnar zone. The specimens were tested at 1200°C and 1050°C under uniaxial tension at a strain rate of 10 mm/s and using a Gleeble-3500 machine. The Gleeble-3500 thermo-mechanical simulator is equipped with a direct resistance heating system and a hydraulic mechanical device. The temperature is measured by a computer-controlled thermocouple. The thermocouple controlling the temperature was welded next to the tip of the notch in order to provide a homogeneous zone of temperature throughout the ligament. This choice was made by Chehab et al. (Chehab et al., 2006), who showed that locating the thermocouple in the centre of the ligament was leading to strong temperature gradient between the middle of the ligament and the end of the notch.

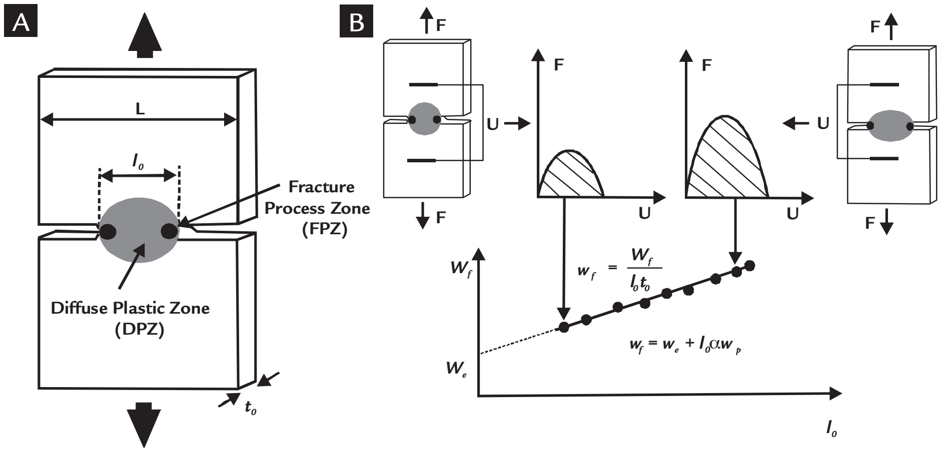

Figure 2
(A) DENT geometry showing the diffuse plastic zone as well as the localized necking zone in front of the crack tips.
(B) Experimental determination of the essential work of fracture.

Material characterization

DENT specimens were polished following the longitudinal direction. The fracture surface of broken samples was observed by a scanning electron microscopy (SEM).

3. Results

The total specific work of fracture, wf, was calculated from the areas under the load-displacement curves (see examples in Figure 3) and plotted as a function of the ligament length l_0.

The results, shown in Figure 4, follow, as expected by the theory (Equation (2)), a linear relationship for both alloys at different temperatures. Dispersion of the results can be explained by the strong heterogeneity of the as-cast slabs. The essential works of fracture are summed up in Table 3. At 1050°C, alloy A is two times less resistant to ductile tearing than alloy B. When increasing temperature to 1200°C, both alloys A and B become more ductile and the difference in term of essential work of fracture decreases. The work performed in the plastic zone is similar for both alloys at 1050°C as well as at 1200°C (see Table 3).

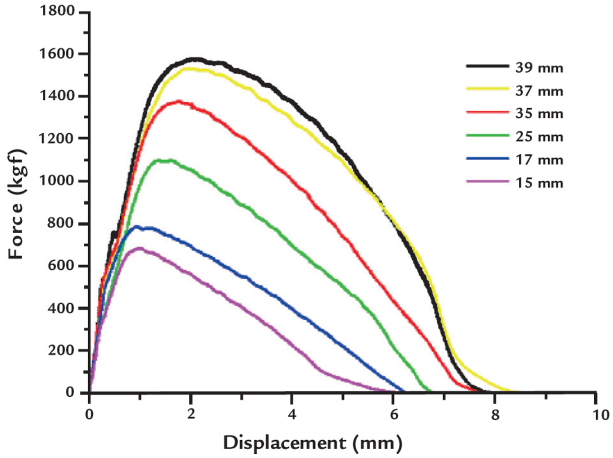

Figure 3
Typical load-displacement curves of alloy B at 1050°C.

		w_e (kJ/m²)	αw_p (kJ/m³)
1050°C	A	140	9.5
	B	320	9.3
1200°C	A	117	5.8
	B	143	6.1

Table 3
Results of the EWF method applied to alloys A and B at 1050°C and 1200°C.

Figure 5 presents the fracture surfaces of specimens of alloy A and alloy B at 1050 and 1200°C. The fracture profile of alloy B is predominantly flat along the whole ligament at 1050°C (Figure 5A). A classical ductile profile with dimples is observed at the micro-scale. The phenomenon responsible for cracking initiation is the growth and coalescence of voids ahead the blunted crack tip. The crack propagates under a constant thickness reduction, with steady-state geometry of the FPZ (Figure 5B). The fracture profile of alloy A is very irregular and shows only a few ductile dimples (Figure 5A). The propagation occurs with varying thickness reduction. Fracture profiles of both alloys A and B are flat along the whole ligament at 1200°C (Figure 5C and 5D). However, the fracture profile of alloy B seems to be a little bit more regular than the fracture profile of the alloy A. Examination of the fracture micrographs and profiles match very well with the EWF results.

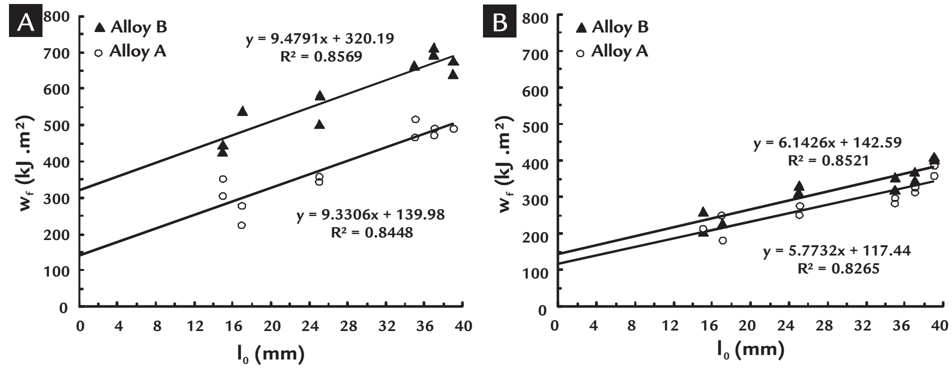

Figure 4
Variation of the specific work of fracture versus ligament length for separation of the essential work of fracture.
A) T=1050°C.
B) T=1200°C.

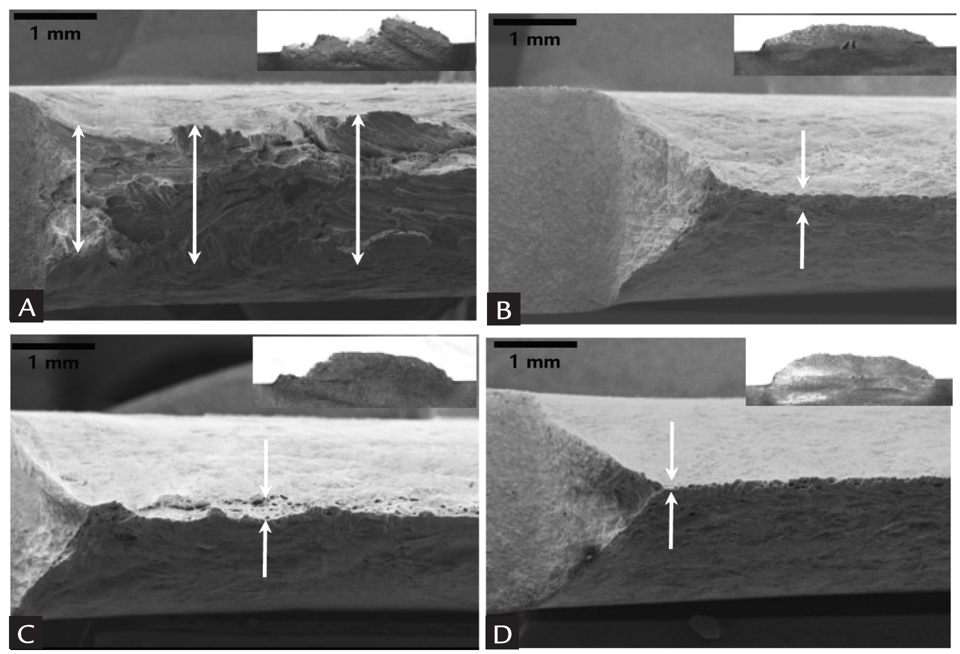

Figure 5
Fracture micrographs and profiles of the broken DENT (l_0=17mm).
A) Alloy A 1050°C.
B) Alloy B 1050°C.
C) Alloy A 1200°C.
D) Alloy B 1200°C.

4. Discussion

Discussion focuses on two points: (1) on the use of the EWF method to characterize high temperature ductile tearing; (2) on factors which determine the difference of hot tearing resistance between alloy A and alloy B.

The EWF method is a discriminating tool to quantify hot cracking. The application of the EWF concept at high temperature presents several advantages:

- The EWF method quantifies the resistance of the material to the propagation of a crack which is not true in usual hot ductility measurements (tensile or shear tests).
- At high temperature, the conditions of validity of the method will almost always be fulfilled owing to the high ductility.
- The method does not require any crack detection systems which are complex to implement at high temperature.
- A significant temperature gradient was observed when moving from the ligament centre to the head of the specimens. This gradient helps for confining the plastic deformation in the ligament while the rest of the sample remains purely elastic. For instance, local plastic yielding is avoided at the gripping system, making the overall load-displacement results sufficiently accurate for data reduction (no need for a local extensometer to be used).

In the as-cast condition, the two different alloys show differences in terms of phase proportion and mean austenite laths thickness. Iza-Mendia et al. (Iza-Mendia and Gutierrez, 2007) have reviewed results concerning hot ductility of duplex stainless steels as a function of the ferrite volume fraction. These results showed that the ductility of a duplex microstructure is significantly lower than that of pure ferrite and is slightly lower than that of pure austenite. Alloy B contains more ferrite than alloy A and it can partly explain the difference of ductility between the two alloys. The mean lath size can also account for the poor hot workability of alloy A. Indeed, as the voids nucleate at the interface δ/γ, the Widmanstätten austenite forms a favourable path to crack propagation. Longer are the laths, longer is the path to crack propagation. The rheological difference between ferrite of alloy A and ferrite of alloy B can also affect the difference of hot cracking resistance. Determination of the micro scale strain distribution in both alloys is under investigation.

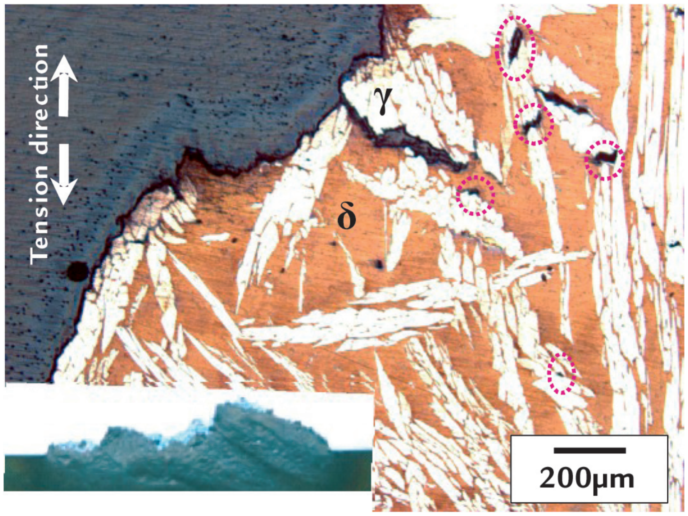

Figure 6
Longitudinal cutting of a DENT specimen: nucleation of voids at the interface δ/γ.

5. Conclusion

This investigation demonstrates the effectiveness of the essential work of fracture method for quantifying the hot damage tearing resistance of metallic materials. It opens the path for many other applications in which, up to know, the lack of robust hot cracking resistance characterization is a limitation for the metallurgist when optimizing materials and high temperature forming operations.

6. Aknowledgments

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