Engineering Fracture Mechanics 99 (2013) 239–250

Contents lists available at SciVerse ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

# Loss of constraint during fracture toughness testing of duplex stainless steels

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ARTICLE INFO

*Article history:*
Received 2 December 2011
Received in revised form 10 September 2012
Accepted 8 January 2013

*Keywords:*
Duplex stainless steel
Fracture toughness
Delamination
Splits
Pop-in
Normalization
Master curve

ABSTRACT

Delamination of the fracture surfaces, so called splits, is an important phenomenon that occurs at sub-zero temperature for hot-rolled duplex stainless steels during impact and fracture toughness testing. To evaluate how the splits influence the fracture toughness, sub-zero temperature fracture toughness testing of 50, 30 and 10 mm thick plates of hot rolled 2205 duplex stainless steel was performed. The results show that the splits cause loss of constraint along the crack front. This can be observed as local difference in crack growth in the specimen. The initiation fracture toughness is not influenced by the specimen thickness. Furthermore, due to the delamination the material exhibits a stable fracture process despite the presence of cleavage fracture. This is interfering with the master curve method so for evaluating the fracture toughness at sub-zero temperatures an assessment of the fracture resistance curve is instead suggested. For assessing the brittle crack behaviour at sub-zero temperatures it is proposed to use the split initiation as a “failure” criteria. The splits are also the cause of the pop-in behaviour observed for the duplex stainless steels. The susceptibility for pop-in is influenced by the microstructure.



## 1. Introduction

Reported fracture toughness values for duplex stainless steels (DSSs) demonstrate high toughness at low temperatures [1–5]. A common feature is secondary cracks, so called splits, which are delamination of the material growing normal to the plane of the fatigue crack. They are often seen after fracture toughness and impact testing when tested through-thickness along the rolling direction (T–L) [1–6]. Their size, numbers and proximity to the fatigue crack increase with decreasing temperature [7]. It has been proposed that splits affect the scatter in fracture toughness measurements [3].

The splits are assumed to occur in the ferritic phase or at austenite/ferrite phase boundaries and the orientation of the splits is governed by the orientation of the fracture plane in relation to the microstructure. A T–L specimen will have splits parallel to the crack growth direction while a T–S specimen will have splits perpendicular to the crack growth direction.

Delamination of the fracture surface during fracture toughness testing has been observed for a range of materials and the mechanism has been explained by the existence of weak planes in the material which delaminate under testing due to the through-thickness stress [8]. The explanations for these weak planes have either been the interaction of different crystallographic orientations or banding of weaker phases. Two examples of the former case is the splits in a ferritic stainless steel which was found to be due to texture banding from the rolling procedure [9] and the splits found in a pipeline steel where rolling at low finishing temperature resulted in a texture that promoted cleavage fracture parallel to the plane of rolling [10].

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0013-7944/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engfracmech.2013.01.002

**Nomenclature**

| | |
|---|---|
| $A_p$ | plastic work |
| $b_0$ | initial ligament length |
| $B_0$ | plate thickness in Fig. 3 or specimen thickness in Eq. (4) |
| $B_{1T}$ | reference thickness |
| $B_N$ | net thickness of the specimen |
| $C_1$ | coefficient from the power law regression of the $J{-}\Delta a$ data |
| $C_2$ | coefficient from the power law regression of the $J{-}\Delta a$ data |
| $E$ | Young's modulus |
| $J_e$ | elastic component of the $J$-integral |
| $J_{Ic}$ | initiation fracture toughness |
| $J_{pl}$ | plastic component of the $J$-integral |
| $J_Q$ | tentative initiation fracture toughness |
| $K$ | stress intensity factor |
| $K_{Jc(0)}$ | measured fracture toughness at the point of instability |
| $K_{Jc(1T)}$ | size adjusted fracture toughness |
| $K_{min}$ | threshold value for cleavage fracture |
| $m$ | constraint parameter, function of crack depth and strain hardening exponent |
| $M$ | non-dimensional deformation limit |
| $T_0$ | reference temperature |
| $\delta$ | crack-tip opening displacement (CTOD) |
| $\Delta a$ | crack extension |
| $\eta$ | dimensionless parameter |
| $\upsilon$ | Poisson's ratio |
| $\sigma_{ys}$ | yield strength at the test temperature |
| $\sigma_Y$ | effective yield strength at the test temperature |
| CMOD | Crack Mouth Opening Displacement |
| DSS | duplex stainless steels |
| LOM | light optical microscope |
| SEM | Scanning Electron Microscope |

In the case of banding of weaker phases there is an example of another pipeline steel where the thermomechanically process caused thin layers of martensitic or bainitic grains to occur through the thickness parallel to the rolling direction [11].

In the work by Nilsson [6] the impact toughness of 50 mm and 12 mm plates of 2205 duplex stainless steel were tested from room temperature down to liquid nitrogen temperature for all the major orientations in Fig. 1. The conclusions were that the specimens are toughest when the notch is oriented in the normal plane (L–S, T–S and 45-S) followed by the case when the notch is oriented perpendicular to the normal plane (L–T, T–L and 45–45). The lowest toughness is reached when the notch is oriented parallel to the normal plane (S–L, S–T and S-45) which is the same plane as for the splits. It is interesting to note that the 12 mm plate has higher toughness than the 50 mm plate in all orientations except for the last-mentioned where the 12 mm plate transition region has moved to higher temperature and lower upper-shelf energy compared to the 50 mm plate. A texture characterisation showed that the ferrite in the 12 mm plate had strong texture while the ferrite in the 50 mm plate was more prone to exhibit random texture. However, no unambiguous effect of the crystallographic orientation could be related to anisotropy of the impact toughness [6].

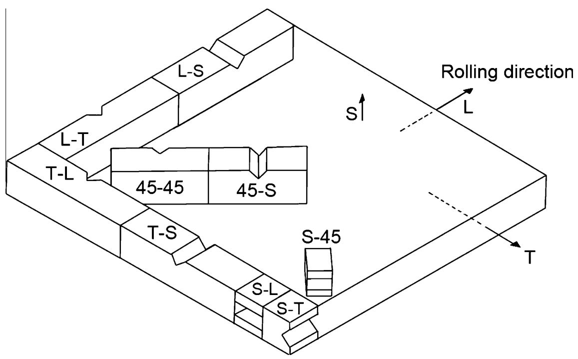


**Fig. 1.** Schematic drawing of specimen orientations. L is the rolling direction, T is the transversal direction and S is the through-thickness direction.