ARTICLE IN PRESS

Engineering Fracture Mechanics xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Brittle fracture analysis of Dissimilar Metal Welds

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ARTICLE INFO

Article history:
Received 18 March 2014
Received in revised form 4 July 2014
Accepted 10 July 2014
Available online xxxx

Keywords:
Dissimilar Metal Weld
Brittle Fracture
Narrow gap weld
Ni base alloy
Threshold stress
Cleavage
Heat Affected Zone
Experimental testing
Finite Elements analyses
Plasticity
Loss of constraint

ABSTRACT

This paper deals with a fracture mechanics analysis of a narrow-gap Dissimilar Metal Weld (DMW) in the brittle fracture domain. The considered case is a Ni base alloy weld joint between a ferritic component and an austenitic pipe and the aim of the present study is to show that in the same loading conditions, the weld joint is less sensitive to the brittle fracture than the nearby ferritic part of the component.

The bases of the proposed qualitative study rely on a stress-based criterion model, using a threshold stress (σ_{th}) below which the cleavage cannot occur. From that criterion, brittle fracture risk is evaluated, then compared between two positions of a postulated crack: one in the Heat Affected Zone (HAZ) of the ferritic material, the other in Base Metal (BM) far from the weld joint.

For the experimental part of this comparison, one mock-up containing a DMW is used. From this mock-up, a large number of specimens of various types and with various crack locations was tested at low temperature. In parallel to that extensive experimental program, Finite Element Analysis has been done. The main result of that F.E.A. is that, due to the mismatch between the different materials, the brittle fracture risk is lower in the HAZ because of the stress relaxation with plasticity in the weld material and loss of constraint in the cracked section.

This paper presents firstly a survey of DMW integrity evaluation, then the criterion used for the comparison, the experimental work and the F.E.A. made to show qualitatively the highest risk of brittle fracture of the homogeneous ferritic material compared to the DMW one.

1. Introduction

Large ferritic components such as Reactor Pressure Vessel or Steam Generators are important parts in terms of safety in nuclear plants. For that purpose, brittle fracture occurrence has to be excluded for all situations possibly encountered during the service life. Thus, in the frame of Defense In Depth (DID), it has to be demonstrated that, in every conditions and considering a conventional defect in the weakest and most loaded areas, the ferritic components could not undergo brittle fracture.

Dissimilar Metal Welds (DMW) connecting large components to piping systems are to be considered in those DID analyses. However, this type of weld joint is complex, in particular when considering the objective to define the temperature

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http://dx.doi.org/10.1016/j.engfracmech.2014.07.005
0013-7944/

Please cite this article in press as: Blouin A et al. Brittle fracture analysis of Dissimilar Metal Welds. Engng Fract Mech (2014), http://dx.doi.org/10.1016/j.engfracmech.2014.07.005

Nomenclature

a, W	crack length and CT/SENT specimen width
B, B_{net}	CT/SENT thickness and net thickness
BM	Base Metal
BWR	Boiling Water Reactor
CT	Compact Tension
DID	Defense In Depth
DMW	Dissimilar Metal Weld
EDX	Energy-Dispersive X-ray spectroscopy
F.E.A.	Finite Element Analysis
HAZ	Heat Affected Zone
σ_{11}	principal stress
J, J_c	Rice's contour integral, toughness at fracture instability
G	energy release rate
ΔK	variation of elastic stress intensity factor
K_J	elastic plastic stress intensity factor
NT	Notched Tensile
P_R	cumulative probability of failure
PWR	Pressurized Water Reactor
SENT	Single Edge Notch Tension
V_0, V_{th}	elementary and threshold volume
WWER	Water Water Energy Reactor
σ_{th}, σ_y	threshold and yield stresses
σ_{u_AE}, m_{AE}	BEREMIN parameters
ΔS, S_0	specimens section variation and initial section

below which there is no risk of brittle fracture. In that condition, demonstrating that these welds are less sensitive to brittle fracture than the ferritic components is then a more appropriate approach: this is the one adopted in Blouin's PhD [1] and summarized in this article.

In this work, one mock-up representing an actual narrow gap DMW of the EPR™ reactor is considered. It is composed of a ferritic 18MND5 (A533) pipe, an austenitic 316L stainless steel one and a Nickel base alloy 52 weld. For this DMW, the fracture resistance of the weld joint, and in particular the Heat Affected Zone (HAZ) which may encounter a brittle to ductile transition, is characterized at low temperature (because of their micro-structures, the austenitic Base Metal and the Nickel base alloy weld metal cannot undergo brittle fracture).

From that mock-up, fracture mechanics specimens were prepared and tested at a temperature where only cleavage can occur. From those tests and using a criterion able to predict the probability of brittle fracture occurrence, the brittle fracture risk is evaluated for two separated configurations: the first one corresponds to a crack in the HAZ (close to the interface between Nickel base alloy and ferritic BM) whereas the second one corresponds to a crack in ferritic BM (far from the weld joint). The possibility of fracture of each case, considering the same applied mechanical loading, is compared.

The objective of the paper is to constitute mechanical arguments showing that the HAZ is less sensitive to brittle fracture than the ferritic BM, which means that an analysis of the BM is envelop of the DMW joint configuration.

2. State of the art on fracture of DMW

DMW and in particular weld joints between austenitic stainless steels and low alloy ferritic steels are a necessity within Pressurized Water Reactors (PWR) designs where heavy sections ferritic components are connected to austenitic piping of the main coolant line. Those include the connections of the Reactor Pressure Vessel, Steam Generators and the Pressurizer (safe end welds).

In terms of integrity assessment, the DMW are complex areas where only limited number or codified rules are available. The following difficulties are encountered:

- Within the DMW joint, there are several regions of materials that have substantially different properties. These are strongly depending on the welding procedure, weld joint geometry, parent and consumable materials.
- There are difficulties to accurately characterize local mechanical behaviors of the different materials constituting the DMW and moreover no widely accepted material testing standards for fracture resistance evaluation.

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