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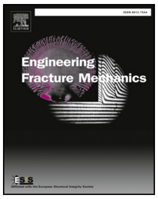

The effect of crack path on tearing resistance of a narrow-gap Alloy 52 dissimilar metal weld

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ABSTRACT

Fracture mechanical testing of welds with strength mismatch can lead to deviation of the crack path from the initial crack growth plane. Current fracture mechanics standards do not give guidance for analyses of the effect of crack path on the tearing resistance. In this study, the effect of crack path on tearing resistance was investigated by fracture mechanical testing and crack path analyses of a narrow-gap Alloy 52 dissimilar metal weld. The results show that tearing resistance of HAZ cracks deviating towards the same zone close to the fusion boundary is larger for cracks initially further from the fusion boundary. The results were obtained for a specific dissimilar metal weld, but the results can also be used to interpret the effect of crack path on tearing resistance in other type of welds.

1. Introduction

Welds are readily used in structures to connect different components efficiently [1]. However, welds are susceptible to crack formation that can lead to sudden catastrophic failures. Weld failure risk can be controlled by manufacturing the weld of different strength than the base material, which is called strength mismatching. The purpose is to direct the cracking into the softer and more ductile regions of the weld joint, thus avoiding sudden failure [2]. Strength mismatch, M_s, is defined as the ratio of the yield strength of the weld metal σ_{WM} to that of the base material σ_{BM} [3].

Strength mismatched weld joints are applied in thermal power plants, e.g., nuclear power plants (NPPs). In NPPs, strength mismatch of weld joints is used between ferritic pressure vessel and austenitic piping steels. This type of weld is known as a dissimilar metal weld (DMW), joining of different materials. The ferritic pressure vessel steel has a higher strength than the austenitic pipe material. A DMW has typically intermediate mechanical properties compared to the two base materials. Otherwise, high residual stresses may form, reducing significantly the performance of the weld. In addition to the weld and the base materials, DMWs consist of heat-affected zones, HAZs, and other narrow microstructural zones forming during welding in the interface region. The mechanical properties of the interface zones differ from those of the adjacent zones or bulk material. The zones in the interface region affect the mechanical behaviour of the weld [4,5]. Even if the DMW is strength mismatched, DMWs can be susceptible to crack formation. To use components with cracks cost efficiently and safely, it is important to determine the severity of the crack with structural integrity assessment methods. The methods are used for obtaining the largest crack size that does not cause catastrophic failure. A part of the assessment process is to determine the lower boundary tearing resistance properties of the material, described with the J-R curves [6].

A problem in J-R curve testing of DMWs and other welds with strength mismatch is that the cracks do not grow along the initial

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Nomenclature

Δa	crack extension
σ_{BM}	base material strength
σ_{WM}	weld metal strength
σ_{zone}	strength of 1 mm thick zone in the interface region
ν	Poisson's ratio
B	thickness
E	elastic modulus
J_{1mm}	J-integral at 1 mm of crack growth
L	length
M	parameter in the blunting line
M_s	strength mismatch
W	width
10 × 10 SE(B)	a single edge-notched bend specimen with a thickness of 10 mm and width of 10 mm
10 × 20 SE(B)	a single edge-notched bend specimen with a thickness of 10 mm and width of 20 mm
CMOD	crack mouth opening displacement
DMW	dissimilar metal weld
HAZ	heat-affected zone
NPP	nuclear power plant
SE(B)	single edge-notched bend

crack growth plane. For example, in Alloy 52 narrow-gap DMWs, HAZ cracks initially further away from the fusion boundary can deviate from the initial crack growth plane to the fusion boundary, the weakest location [7,8]. In the fusion boundary region, the microstructure changes rapidly over only 1 mm and the strength mismatch can be high [9]. Crack deviation affects the shape of the J-R curve and complicates the interpretation of the J-R curves. The J-R curve, in case of crack deviation, describes the measured crack path and not the tearing resistance along the initial crack growth plane [7].

Current fracture mechanics methods are developed for homogeneous materials with straight cracks [10–12]. In case of pop-in, ASTM E1820 recommends that the specimen is examined metallographically to ensure that the crack tip has sampled the region of interest. Other instructions are not given for characterisation of the initiation location or crack path. In BS 7448 [11], guidelines are given for post-test metallography of weld specimens, with the aim to verify that the crack tip is located in the target microstructure. Currently, there are no guidelines for analyses of J-R curves of cracks deviating to another region of the weld.

Manufacturing of the initial crack in the target microstructure, typically the weakest location, can be challenging, because microstructurally small deviations in the crack location may lead to large variations in the tearing resistance. For the majority of the J-R curve testing, the crack can propagate along the weakest region, but the crack may initiate in another microstructure, which affects the measured J-R curve [8]. In these cases, utilisation of the obtained results to characterise a lower boundary value is useful, instead of requiring the crack to initiate and propagate along the weakest location, which may lead to several measurements before the crack is located in the target region and reducing the cost-efficiency of the characterisation procedure.

In previous investigations, crack path deviation has been observed in the interface region of welds [1,7,13,14]. The investigations have focused on identification of the crack deviation, and the shape of J-R curve was observed to vary depending on the crack location respective to the fusion boundary. However, the effect of crack location on J-R curves of cracks deviating from different distances to the weakest zone has not been investigated in detail previously. Additionally, the fracture mechanical characterisation of the DMWs has previously been based on 20 and 14.4 mm wide SE(B) specimens [7,8,15]. The benefit of SE(B) specimens is that less weld metal is consumed compared to C(T) specimens [16]. Use of smaller SE(B) specimens can even further reduce the material consumption, but the smaller ligament size can affect the shape of the J-R curve [17].

In this study, the investigated material is a narrow-gap dissimilar metal weld, plate mock-up, consisting of ferritic pressure vessel steel, 18MND5, and austenitic stainless steel piping, AISI 316L, base materials and Ni-base Alloy 52 weld metal. The weld is strength under-matched respective to the ferritic base material. The effects of the crack path on tearing resistance are investigated through fracture mechanical testing and crack path analyses of cracks deviating from different locations towards the weakest zone close to the fusion boundary in the ferritic steel HAZ. Also the crack growth behaviour of cracks adjacent to the fusion boundary in the weld metal are investigated. Tearing resistance of the DMW is measured with 10 × 20 × 100 mm^3 single edge-notched bend (SE(B)) specimens, but also a smaller specimen size, 10 × 10 × 55 mm^3 SE(B) specimens, is utilized. The specimens are sectioned after the measurement to characterise the crack growth path. The effect of the results on the current fracture mechanics standards for welds is discussed.

2. Materials and methods

2.1. Test material and specimens

A narrow-gap DMW plate mock-up consisting of ferritic low-alloy steel, 18MND5 (similar to SA508), and austenitic stainless steel, AISI 316L, and Ni-base weld metal Alloy 52, was manufactured in MULTIMETAL, a European collaboration project [18]. Table 1

Table 1
Chemical compositions.

Material	C	P	Si	Mn	S	Ni	Cr	Co	Mo	Cu	Fe	V
18MND5	0.2	0.005	0.23	1.29	0.001	0.56	0.2		0.49	0.09		0.002
AISI 316L	0.013	0.016	0.36	1.85	0.001	11.35	17.40		2.43			
Alloy 52	0.023	0.002	0.17	0.24		59.52	28.67	0.002	0.01	0.01	10.08	