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Multiscale 3D characterization of discontinuities in underwater wet welds

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ABSTRACT

Underwater wet welding is performed in direct contact with other, with high cooling rates and gas metal reactions that lead to the formation of pores, cracks and inclusions in the weld metal. These discontinuities appear in a wide range of sizes, shapes and orientations, and require 3D techniques for complete characterization. Lab scale X-ray MicroCT was used to analyze pores and cracks, while synchrotron MicroCT and FIB/SEM were used to characterize inclusions. Specific image analysis sequences were developed to deal with different types of noise, segment the discontinuities, eliminate spurious features, and measure 3D parameters. The relevant objects were rendered in 3D, confirming the expected size and orientation characteristics. Whenever possible, results from different scales and techniques were compared.

1. Introduction

The repair of offshore structures used for oil production and transportation many times requires the use of underwater wet welds (UWW). Welding is performed in direct contact with water, leading to severe cooling rates and gas–metal reactions [1,2]. These, in turn, give rise to the formation of discontinuities in the weld metal (WM) that adversely affects mechanical properties.

High hardness microstructures in the heat-affected zone (HAZ) or WM in the presence of high amounts of hydrogen absorbed by the molten pool may lead to the formation of micro-cracks (hydrogen cracks) [3,4]. The cracks in the weld metal form mostly transversal to the welding axis because the highest tensile residual stresses are oriented parallel to the welding axis [5]. Hydrogen can also induce the formation of elongated pores in the WM, which are oriented in the solidification direction [6]. Pore number and size increase with the welding depth, as the partial pressure of hydrogen increases with water pressure.

With increasing pressure the oxygen content in the weld metal tends to reach its solubility limit and reacts with deoxidizer elements in steel, leading to the formation of spherical oxide inclusions [7].

These 3 kinds of discontinuity – pores, cracks and inclusions – show a wide range of sizes (from nm to tens of microns), shapes (elongated, platelet, spherical), orientation (aligned, no aligned) and spatial distribution [8,9]. The potential and limitations of 3D image acquisition, processing and analysis of these discontinuities in underwater wet welds are explored in this article.

Lab scale X-ray MicroCT was used to analyze pores and cracks while synchrotron MicroCT and FIB/SEM were used in the characterization of inclusions. Specific 3D image processing and analysis routines were developed for each kind of discontinuity, employing free software.

2. Experimental

2.1. Wet welding and test samples

The welding for this work was done at the welding laboratory of the Universidade Federal de Minas Gerais (UFMG) using a LINCON ELETRIC, POWER WAVE 450 as the electronic source. Rutile coated electrodes with a low carbon steel wire core possessing a diameter of 3.25 mm and a length of 35 mm were used under different conditions. For shallow underwater welds, a gravitational welding device was used and to simulate greater depths. This device was inserted into a hyperbaric welding simulator. The test samples used in this study are shown in Table 1.

The two main parameters used to prepare these samples were the type of electrode coating (rutile) and the welding depth. The rutile coating increases the susceptibility to cracking due to diffusible hydrogen that can reach concentrations of about 90 ml/100 g. The variation of the weld depth and the hydrogen dissolved in the weld metal leads to a variation in porosity [10]. Table 1 shows the technique used related to the analyzed defects.

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Table 1
Samples, discontinuities and experimental techniques applied.

Sample	Code	Depth of weld (m)	Defect	Shape of sample	Dimensions (mm)	Technique
1	3W1	10	Pores	Cylinder	3.5 × 5 (D × H)	MicroCT
2	5W1	20	Pores	Cylinder	3 × 5 (D × H)	MicroCT
3	5W1	20	Pores	Cylinder	4 × 5 (D × H)	MicroCT
4	1N1	0.5	Cracks	Prism	4 × 4 × 10	MicroCT Bench
5	1W1	0.5	Inclusions	Cylinder	0.25 × 0.5 (D × H)	Synchrotron MicroCT
6	1W1	0.5	Inclusions	Sheet	[a]	FIB–SEM

[a] Volume observed 30 × 14 × 9 μm.

Table 2
Acquisition conditions for MicroCT.

Equipment	ASU			Xradia MicroXCT 200		Synchrotron APS
Conditions	Samples (pores)			Sample 4 (cracks)		Sample 5 (inclusions)
	1	2	3	Low res	High res	
Voltage (kV)	150	140	150	150	150	–
Power (W)	4.5	3.8	4.5	10	10	–
Exposure time (s)	40	60	40	4	15	0.3
Total time (h)	9.45	12	8.5	3.3	14.5	0.33
N° of projections	721	721	721	2000	3000	1441
Pixel size (μm)	3.8	3.2	4.0	4.3	2.17	0.74

2.2. MicroCT, FIB–SEM and complementary techniques

The MicroCT process for the acquisition of the projections was conducted in three different types of equipment: a lab scale MicroCT custom built at Arizona State University (ASU — USA) [8,9] — used for pore analysis; a synchrotron tomography line of the Advanced Photon Source (APS — USA) — used for inclusion analysis; and a MicroXCT 200 system from XRadia (California — USA) — used for crack analysis. The acquisition of images using the FIB–SEM process was carried out at the Microscopy Laboratory (Labmi) of the National Institute of Metrology (INMETRO — Brazil) with the *Dual Beam* Nova NanoLab 600 model, manufactured by FEI. Tables 2 and 3 list the various acquisition conditions of the MicroCT and FIB–SEM techniques for each sample, respectively.

Optical microscopy (OM) and scanning electron microscopy (SEM) were also used to validate inclusion analysis results. A Zeiss AxioImager M2m (Digital Microscopy Laboratory — LMD, PUC—Rio) was used for the optical microscopy and for electron microscopy a JSM — JEOL 6510LV (Electron Microscopy Laboratory — LME, PUC—Rio) was used.

2.3. 3D reconstruction, image processing and analysis

All projections acquired by the MicroCT process were processed using a reconstruction algorithm in order to generate images of each layer. A MatLab implementation of the FDK (Feldkamp–Davis–Kress) filtered back-projection algorithm was applied to the images produced at ASU and Chicago APS. The images obtained with the XRadia equipment were reconstructed with proprietary software from the manufacturer. The images generated by FIB–SEM correspond to "real" images (not projections); however, they required an alignment step before processing.

FIJI/ImageJ was the main software used for the processing of all images. Both the 2D functions that act on the stack layers and the 3D functions that act on the reconstructed sample volume were used. A typical sequence involving the steps of pre-processing, segmentation, post-processing, measurements and 3D image rendering was followed.

Table 3
Acquisition conditions for FIB–SEM.

Conditions	Sample 6 (inclusions)
x–y pixel size (nm)	4.85
z spacing (nm)	46
Beam Dwell time (s)	3×10^{-7}
Magnification	30,000×
Voltage (kV)	2
Resolution (pixel)	2048 × 1768
Current (nA)	0.84
Number of images	196
Total acquisition time (h)	~5

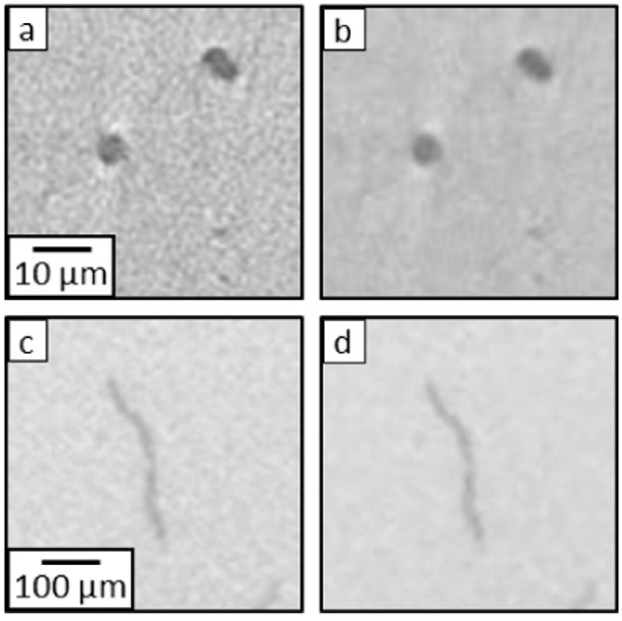

Fig. 1. Noise filtering. (a) and (c): Original images; (b) image filtered with sigma; (d) image filtered with 2D anisotropic diffusion filter.