International Journal of Pressure Vessels and Piping 159 (2018) 28–34

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

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

Welding residual stresses in a strip of a pipe

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ABSTRACT

Residual stress was measured through the thickness of a strip sample of a girth welded pipe. The motivation behind this measurement was to investigate whether the segment test, commonly used in validation of Engineering Critical Assessment results, is representative of full girth welds in terms of the welding residual stress. A major rationale was to try to understand how much residual stress will be relieved due to the removal of the strip sample from the pipe. The reported results in this paper are based on aJoint Industry Project (JIP) led by DNV GL on the treatment of residual stress on pipes undergoing high plastic deformation. The paper presents measured residual stresses data in the hoop and axial direction of the pipe. In the current study, the measured residual stresses in the segment sample are found to be similar to those at similar full girth welds but showed more compressive stresses in the weld cap, more tensile stresses in the weld root, and a similar profile through the thickness. This re-distribution of residual stress can be attributed to the release of the "far field" bending stresses when the pipe was sectioned into the strip in both the hoop and axial directions.

1. Introduction

Welding is a well-established joining technique. When assessing the structural integrity of a welded pipe, all sources of loading which may increase the risk of failure should be considered. Loads can be categorized as primary or secondary. Primary loads are those that contribute to plastic collapse, as opposed to the secondary loads which do not. Stresses due to the mechanical loading such as pressure, applied force, self-weight, or long-range structural constraint is categorized as primary loads [1]. Stresses due to temperature variation or welding residual stress are often classified as secondary [2].

In the offshore industry, pipelines could experience displacement-controlled loading during pipe installation or operation. Depending on the installation process, the pipeline can experience different levels of primary load. One method of pipeline installation is reeling which causes high plastic strains (due to bending cycles) in pipelines. For reeled pipes, fatigue and fracture assessments, referred to as Engineering Critical Assessment (ECA) should be carried out to ensure their structural integrity [3–5]. BS7910 [6] is the most common procedure for ECA and has been adopted by DNVGL-OS-F101 [3] and DNVGL-RP-F108 [4] for determining maximum allowable flaw sizes in girth welds. Other applicable ECA codes are R6 [2], API 579–1/ASME FFS-1 [7], API 1104 [8]. Automated software for desk top ECA calculations, such as CRACKWISE [9], are widely used in the offshore industry. Material's fracture toughness, tensile properties, primary and secondary loads are the main inputs for ECA calculations.

One of the reasons for engineering component failure in the early days was lack of adequate material fracture toughness which can be temperature dependent. Nowadays, conventional pipes produced by leading manufacturers typically demonstrate robusttoughness and hence ductile fracture is more likely than brittle fracture in the steel pipes. If fracture toughness testing is not possible and the nominal applied strain exceeds 0.4%, full-scale testing or pipe segment testing is recommended by DNV-RP-F108 [4]. The main purpose of segment testing is to prove that the fatigue and fracture limit state is qualified and demonstrates that the maximum allowable flaw sizes determined by ECA calculation, are conservative.

Segment specimen is taken as a strip specimenfrom a pipe, containing a representative girth weld of a pipeline. Based on the geometry of the segmentspecimen, a notch is fabricated at the relevant position of a segmentspecimen. The height of the notch should represent the maximum allowable height assessed for the relevant notch length for the pipeline. Segment validation testing was originally developed for validating of ECA results with uniaxial plastic strain and not bi-axial stresses. Segment testing is not suited for evaluation of situations where pipelines subjected to plastic strain combined with significant internal pressure [4].

The reported results in this paper are based on a Joint Industry Project (JIP) led by DNV GL [10]. The JIP idea was originated from the requirement to understand the influence of welding residual stress on the girth weld integrity of subsea pipelines when undergoing high plastic deformation such as the reeling process during installation of

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https://doi.org/10.1016/j.ijpvp.2017.11.007
Received 16 August 2017; Received in revised form 6 November 2017; Accepted 13 November 2017

Nomenclature

API579-1/ASME FFS-1	American Society of Mechanical Engineers procedure for the integrity assessment of structures containing defects
BM	Base (parent) material
BS7910	British Standard: Guide to methods for assessing the acceptability of flaws in metallic structures
CHD/iCHD	[Incremental] Centre hole drilling for surface residual stress measurement
DHD/iDHD	[Incremental]Deep hole drilling method for through thickness residual stress measurement
DNV GL	Det Norske Veritas Germanischer Lloyd
ECA	Engineering Critical Assessment
GSFCAW	Gas Shielded Flux Cored Arc Welding
JIP	Joint Industry project
OD	Outer pipe Diameter
PGMAW	Pulsed Gas Metal Arc Welding
R6	A procedure for the integrity assessment of structures containing defects
WCL	Weld Centre Line
WM	Weld Metal
WT or th	Wall Thickness

pipelines [10]. The following steps were taken in this JIP:

- Preparing and welding typical offshore seamless pipes, in a similar practice done in the offshore industry
- Small-scale and full-scale reeling tests at DNV GL's laboratory in Høvik, Norway
- Surface and through-thickness measurements in as-welded condition and after full scale reeling tests on full girth welds and a strip of a pipe
- Detailed Finite Element Analysis (FEA) of full-scale reeling simulation
- Comparisons between FEA and measurements to understand redistribution of residual stresses at different circumferential clock positions

In this paper a brief overview of relevant residual stress measurement data available in the literature for girth welds are given in section 2. The material properties and the welding procedure are included in section 3. Section 4 describes how much “far field” bending residual stresses will be relieved because of cutting off a strip sample from a seamless pipe. Section 5 presents the through thickness residual stress measurements data, and section 6 concludes the current research work.

2. Girth weld residual stress measurement data- an overview

Through thickness residual stress measurement data available in the literature for Ferritic girth welds is rather limited, especially those applicable to offshore industry. This contrasts with the abundance of literature documenting measurement data for austenitic steels. Transverse and longitudinal components of residual stress are usually reported in the open literature. As defects most commonly appear in a radial-hoop plane of a pipe girth weld, it is the transverse component (axial of the pipe direction) of residual stress that is of most concern in ECA. Stacey's [11] review of residual stress showed that the transverse residual stress of girth welds is a function of heat input and radius/thickness. Law [12] and [13] measured residual stress using slitting and neutron diffraction techniques on electric resistance (seam) welded pipe made from X70 grade steel. Leggatt [14] measured girth weld residual stress on an X65 pipe with an OD of 610 mm and WT of 15.5 mm. Through-thickness stress results by the layering method showed that the transverse residual stress was compressive at the OD and almost zero at the inner surface. Hayashi et al. [15] measured residual stresses in a V-groove, manually welded pipe using neutron diffraction, X-ray diffraction, and a strain gauge method. Chauhan and Feng have published results of their numerical and experimental investigations into the effect of hydrotest on X60 pipes [16]. Silva and Pereira [17] carried out residual stress measurement on the external surface of manually welded butt joints using X-ray diffraction. Dasgupta [18] studied residual stress in X60 pipes that included a 42″ diameter pipe with a WT of 32.4 mm. Michaleris has gathered residual stress distributions for multi-pass welds [19]. EWI has carried out several studies examining girth weld residual stress in the 1970s and 1980s [20–22]. TWI [23] and [24]and Subsea 7 [25,26] reported their investigation on girth welds residual stresses which included numerical and experimental studies. Battelle Memorial Institute has carried out a number of research projects in the field of residual stress. Most of the relevant findings of their projects related to girth welds have been published by Dong and his co-authors [27–30]. One of the findings of their research projects [27–31] is characterising through-thickness transverse residual stress distributions in pipe girth welds as:

Table 1
Summary of Tensile test results at 20 °C.

Sample ID	Material	Yield, Mpa		UTS, Mpa	Elongation (%)
		Rp0.2	Rt0.5		
WM, 1 o'clock	WM	553	554	672	–
WM, 5 o'clock	WM	561	562	679	–
WM, 10 o'clock	WM	573	574	675	–
BM, as-received	BM	449	451	525	25.0
BM, pre-tensioned 2.5%	BM	475	478	530	23.6
BM, pre-compressed 2.5%	BM	388	408	526	25.6

- Global bending
- Local bending
- Self-equilibrating

It was argued that pipe thickness and pipe radius to thickness ratio are the two most important parameters that govern the transition from one type to another [27–30].

The literature survey indicates that the scatter in girth welds measurement data is quite high. Itis common to use various upper bound residual stress profiles, recommended by R6, BS 7910, API 579–1/ASME FFS-1, guidelines in ECA. The upper bound residual stress profile recommended by various codes is one of the simplest and often leads to the most conservative ECA results. BS7910 presents decomposed components of upper bound residual stresses. More complex residual stress profiles originated from FEA are suggested [32], although limited measurement data is available to justify their validity for common pipe sizes and materials used in the offshore industry. The R6 code suggests three levels for classifying as-welded residual stresses, of which Level 3 proposes residual profiles based on FEA simulations validated against experimental measurements, and hence it is expected to lead to the most realistic assessment results. However, the R6 Level 3 approach requires detailed knowledge of the welding process and a comprehensive program of residual stress measurements on mock-ups.

3. Material and welding

In the DNV GL led JIP, a few seamless pipes with nominal OD of 323.9 mm, nominal WT of 24.3 mm and length of 11.5 m were supplied