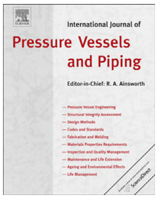
International Journal of Pressure Vessels and Piping 157 (2017) 43–50

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

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



An evaluation of multipass narrow gap laser welding as a candidate process for the manufacture of nuclear pressure vessels

J.C. Feng [a], [b], *, D.W. Rathod [a], M.J. Roy [a], J.A. Francis [a], W. Guo [a], N.M. Irvine [c], A.N. Vasileiou [a], Y.L. Sun [a], M.C. Smith [a], L. Li [a]

[a] School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, UK
[b] Shanghai Rui Rong Laser Welding Technology Co. Ltd., Shanghai 201306, China
[c] Dalton Nuclear Institute, The University of Manchester, Manchester M13 9PL, UK

ARTICLE INFO

Article history:
Received 28 April 2017
Received in revised form
24 August 2017
Accepted 25 August 2017
Available online 14 September 2017

Keywords:
Conduction mode welding
Magnetic beam deflection
Narrow-groove weld
Post-weld heat treatment
Single-sided weld
Welding productivity

ABSTRACT

Nuclear pressure vessels are currently fabricated using arc welding processes. Recently, considerable effort has been directed at the development of electron beam welding as an alternative fabrication technique owing to the substantial productivity gains it would offer. However, little attention has been directed at laser-based techniques. In this work we evaluate the potential for applying multipass narrow-gap laser welding (NGLW) to the fabrication of nuclear pressure vessels, based on the characterization of a 30 mm thick weld in SA508 steel. Although still a multipass process, the number of passes is reduced in comparison to an arc weld of the same thickness, and the deposition of successive passes provides a degree of tempering to previously deposited weld metal in a way that the electron beam welding process does not. Principal engineering challenges for the implementation of multipass NGLW include the achievement of appropriate joint fit-up, and the shielding of a molten pool at the base of a deep and narrow weld groove.

1. Introduction

Historically, the welding of primary reactor components has been implemented by the exclusive use of arc welding processes. However, in recent years some attention has focused on the development of electron beam welding as a high productivity alternative to arc welding [1]. Electron beam welding offers the potential to complete steel welds in thicknesses exceeding 100 mm in a single weld pass, whereas the number of passes required with an arc welding process will be in the order of 100. In contrast, very little attention has been directed at laser welding owing primarily to the fact that single pass welds are not possible in such thick materials. Nevertheless, laser welding offers some advantages over electron beam welding, in that electron beam welding is prone to deflection of the beam if there is any residual magnetism within the steel, whereas laser welding is not. Furthermore, electron beam welding involves the generation of X-rays, whereas this is not the case for laser welding.

The purpose of this work is to evaluate the feasibility of using a multipass narrow-gap laser welding (NGLW) process to manufacture welds in a reactor-pressure-vessel steel. SA508 Grade 3 Class 1 steel was used as the test case owing to its widespread use in reactor pressure vessels (RPVs) and steam generators in nuclear fission power plants [2–4]. The application of laser welding to this steel was recently reported [5]. However, that work involved a single pass weld in relatively thin material (6 mm) and no attention was given to the development of residual stresses, which are known to affect the long term integrity of primary nuclear components [6]. In this work we evaluate the application of multipass NGLW to 30 mm thick SA508 Grade 3 Class 1 steel, focusing on cross-weld tensile properties, pass-to pass tempering effects, levels of residual stress, and the extent to which stresses are relieved by post-weld heat treatment (PWHT).

2. Experimental methodology

2.1. Materials

SA508 Grade 3 Class 1 steel typically has a yield strength in the order of 450 MPa, an ultimate tensile strength in the vicinity of

---

* Corresponding author. Building 2, 1500 Cenglin Road, Pudong New Area, Shanghai 201306, China.

E-mail addresses: fengjc@rr-laser.cn, fjc2002@sina.com (J.C. Feng).

http://dx.doi.org/10.1016/j.ijpvp.2017.08.004
0308-0161/© 2017 Published by Elsevier Ltd.

600 MPa, and it exhibits an elongation in excess of 20% [4]. In this study, two SA508 plates with dimensions of 300 mm × 159 mm × 30 mm were prepared for welding. The length of the groove was approximately 160 mm, which left segments of material intact at either end of the plate for the purpose of providing a degree of self-restraint in order to mitigate weld distortion. The filler wire that was used during welding had a diameter of 1.2 mm. The chemical compositions for the base material and the filler wire are given in Table 1.

2.2. Welding

The details of the weld groove geometry and general set-up are shown in Fig. 1. The weld was completed by first making an autogenous root pass, which was followed by eight filling passes, as might be applied for a butt joint configuration in the 1G welding position. Shielding was provided by argon gas flowing at a rate of 8 l/min. Owing to the self-restraint associated with the ligaments of material at either end of the groove, the specimens needed only light clamping during welding to prevent them from moving. A preheat/interpass temperature between 110 and 125 °C was maintained.

The welding system consisted of an IPG fiber laser with a maximum power of 16 kW, and a wire feeder. The beam parameter product for the laser was 10 mm mrad. A defocused laser beam was used, with a spot diameter of 6 mm at the beam/material interaction point. The laser power values for the root pass and for the filling passes were 4.5 and 7 kW, respectively. The welding speeds for the root pass and for the filling passes were 300 and 240 mm/min, respectively, while the average wire feed rate for the filling passes was 5 m/min.

In initial welding trials, the feasibility of employing a higher laser power for the root pass was explored. The authors had hoped to fuse a greater proportion of the joint thickness in the root pass, through careful design of the weld groove in conjunction with employing the laser in "keyhole" mode. This would have enhanced overall productivity through a reduction in the number of filling passes that would have been required to fill the joint. While it was possible to achieve an autogenous root bead with a thickness (or depth) in the order of 10 mm, the authors found that root beads with high depth-to-width ratios were particularly prone to cracking upon cooling after welding. Thus, the welding parameters employed for the root pass in this work were selected on the basis that they produced root beads that were less likely to crack.

In both the root and the filling passes, a defocussed laser beam was used in conjunction with a welding speed that would be considered to be relatively low for laser welding. The authors found that the use of a focused beam led to insufficient heating of the groove walls and, consequently, significant levels of lack of fusion. The use of narrower weld grooves was also considered, but this would not have enabled the beam to reach the base of the groove without also impinging on the groove walls in other locations. As a result, the combination of a defocussed beam in conjunction with a modest travel speed was found to be the most effective method for avoiding lack of side-wall fusion, which is a defect that cannot be tolerated in critical nuclear welds.

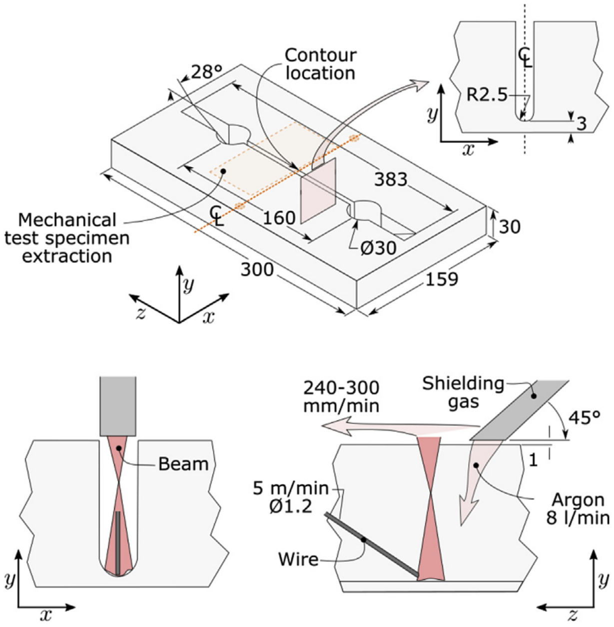


Fig. 1. Configuration of test plates and welding set-up.

2.3. Post-weld heat treatment (PWHT)

After welding, one of the welds was subjected to a PWHT operation, while the other was preserved in the as-welded (AW) condition. The PWHT procedure did not place restrictions on the heating and cooling rates below 300 °C, but the heating and cooling rates were restricted to a maximum of 20 °C per hour between 300 and 607 °C, and the hold took place at a temperature of 607 ± 13 °C for a duration of 2 h. The stringent limits on heating and cooling rates at temperatures above 300 °C were applied to ensure that the heat treatment practice was consistent with a heat treatment that would be applied to a real component, for which the generation of internal stresses during heat treatment would be an important consideration, owing to the much larger wall thicknesses that would be applicable.

2.4. Metallography and hardness measurements

The specimen in the as-welded (AW) condition and the specimen in the PWHT condition were prepared for the extraction of macrographs, and for destructive residual stress measurements. The macrograph sections were etched using a solution of 5 ml nitric acid and 95 ml ethanol. Microstructural examination was carried out using a KEYENCE VHX-500F optical microscope. The variation in microhardness across the joints was measured using a Vickers microhardness machine (Durascan™) with a load of 0.5 kg and a dwell period of 15 s. The nominal distances between indentations were 0.45–0.65 mm in the transverse (x) direction within the fusion zone, and 0.3 mm in the heat-affected zone (HAZ). In the through-thickness (y) direction, the nominal distance between indentations was 0.5–0.55 mm across all regions.

Table 1
Chemical compositions for SA508 Gr. 3 Cl. 1 steel and filler wire (wt.-%).

	C	Si	Mn	Ni	Cr	Mo	V	Al	Cu	Co	Fe
SA508	0.16	0.27	1.43	0.77	0.23	0.52	0.003	0.02	0.04	0.004	Bal.
Filler	0.10	0.20	1.47	0.88	0.03	0.25	0.003	0.003	0.075	–	Bal.