Optics and Lasers in Engineering 51 (2013) 1272–1277

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

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

Studies on autogenous laser welding of type 304B4 borated stainless steel

Shanmugarajan B.[a,*], Chary J.N.[a], Padmanabham G.[a], Arivazhagan B.[b], Shaju K. Albert[b], Bhaduri A.K.[b]

[a] International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Balapur P.O., Hyderabad 500005, India
[b] Indira Gandhi Centre for Atomic Research, Kalpakkam, India

ARTICLE INFO

Article history:
Received 4 September 2012
Received in revised form
30 April 2013
Accepted 4 May 2013
Available online 28 May 2013

Keywords:
Laser welding
Borated stainless steel
Shielding gas

ABSTRACT

304B4 Borated austenitic stainless steel is widely used in the nuclear industry due to high neutron absorption efficiency. In the present investigation, autogenous bead-on-plate (BoP) laser welding studies were carried out on 3 mm thick 304B4 grade stainless steel using a 3.5 kW slab CO_2 laser. Influence of variables such as laser power, welding speed, shielding gas and laser beam mode on microstructure and mechanical properties were studied. Dye penetrant testing, macrostructural analysis, bead geometry measurements, microhardness survey, and microstructural analysis in both as-weld and post-weld heat treated conditions were carried out. The macrostructural and bead geometry analyses of the welds have shown that the welds were free from cracks in the fusion zone (FZ) and also in the heat affected zone (HAZ) for all the welding parameters studied. The Gaussian mode has given a very narrow weld width compared to donut mode. During welding use of helium and nitrogen has reduced the width of the FZ and HAZ. The as-weld micro hardness was more than double the base metal, and the peak hardness was shifted from the centre to the fusion boundaries with the increase in heat input. The PWHT has reduced the hardness of both the FZ and HAZ. In summary, usable laser welding parameters for welding 3 mm thick 304B4 grade stainless steel have been identified.

1. Introduction

Boron containing austenitic stainless steels known as borated austenitic stainless steels (BASS) has been widely used in the nuclear industry as reactor control materials in the nuclear reactor due to their ability to absorb thermal neutrons [1]. The basic purpose of using shielding is to reduce the intensity of neutron bombardment and hence to control the chain reaction in the nuclear reactor [2]. Other applications of this steel include construction of fuel storage racks, casks for storage of densified and spent fuel [3,4].

Increased thermal neutron absorption cross section of element boron (B) leads to a wide spread use of B-containing materials as thermal-reactor control rods and burnable poisons in nuclear power plants [5]. These steels contain either boron alloyed or dispersed in stainless steel metal matrix. Due to their limited solubility of boron in austenite matrix (solubility limit is around 100 ppm), they form intermetallic compounds rich in Fe, Cr and Ni.

The chemical composition and mechanical properties requirements of borated stainless steels are covered by ASTM specification A887, which includes eight boron levels (types) and two grades per type. For each of the eight types, specification A887 describes two grades A and B, based on mechanical property requirements. The classification of borated stainless steel ranges from 304B1 to 304B7. The typical boron content varies from 0.2 to 2.25% by weight. 304B4 is widely used in the construction of radiation shielding for Intermediate heat exchanger (IHX) applications in Indian prototype fast breeder reactor (PFBR) construction.

In borated austenitic stainless steels due to the formation of intermetallic compounds there will be a reduction in ductility as compared to type 304 austenitic stainless steel. Primarily this alloy is used as simple strap-on neutron shielding materials where structural requirements are very minimal. In earlier days, these alloys were typically bolted/riveted to a structural element to cater to the reactor control requirement. Due to slow and also non-automatic nature of riveting process, welding is introduced in the later stages of fabrication [6]. Also, BASS have been recently accepted by ASME boiler and pressure vessel code and many of the present day conceptual designs require welded fabrication.

The presence of boron content leads to the formation of iron–boron eutectic phase in austenitic stainless steel. The heat of welding can result in the formation of low melting eutectic phase leading to

* Corresponding author. Tel.: +91 4312577241.
E-mail address: bsrajan@bheltry.co.in (S. B.).

0143-8166/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.optlaseng.2013.05.004

liquation cracking in the heat affected zone (HAZ). Also, the boron in the fusion zone will go into solution elevating the hardness values in the fusion zone which will reduce the toughness of this alloy in the as welded condition. The above mentioned welding issues should be given a careful consideration for use of this alloy as a welded structure.

The hot cracking tendency was found to be more pronounced with boron content less than 0.5%. It has been earlier studied that amount of boron more than 0.5% will result in increased content of low melting eutectic phase thereby increase the solidification range of borated stainless steel [5]. With the increase in boron content beyond 0.5%, weldability resembles that of conventional type 304L stainless steel [7,8]. Hence cracks were not observed in the HAZ of weldment. However, use of minimum heat of welding will be beneficial in reducing the liquation cracking in the HAZ due to the reduction in width of the HAZ. Post weld heat treatment (PWHT) at a temperature of 1200 °C have shown to modify the shape of the borides and improve the ductility and toughness of the welds [4].

In earlier studies on electron beam welding of BASS; it was observed that there was improvement in toughness in the as-weld condition because of the refined microstructure [6]. Hence it has been construed that use of laser power beam process for welding of 304B4 stainless steel can be beneficial in reducing the size of the HAZ thereby reducing the liquation cracking tendency of 304B4 weldment. There is no literary information on the laser welding of 304B4. Hence, in the present work, laser welding studies were carried out on 3 mm thick 304B4 grade using a high beam quality DC035 slab CO_2 laser. The parameters chosen for the studies were laser power, welding speed, laser beam mode and shielding gas. Various shielding gases used are Argon, Helium and Nitrogen. Shielding gas was chosen as one of the parameters to study the effect of shielding gas on improving the penetration and reduce the partially melted heat affected zone (PMHAZ) apart from the heat input and laser beam mode. The resultant welds were characterised using metallography, microhardness survey and microstructural analysis in both as welded condition and PWHT condition and the results are reported.

2. Experimental procedure

2.1. Welding

Bead-on-plate (BOP) welding trails were carried out using laser power source on 3 mm thick 04B4 stainless steel sheets. The chemistry of the base material is presented in Table 1.

In the present study the following process variables are studied; Laser power, welding speed, laser beam mode and shielding gas (argon, helium and nitrogen). Welding trials were conducted by focussing the laser beam using a 300 mm focal mirror to achieve the laser spot size of 180 μm and 360 μm in Gaussian and donut modes respectively. The focal plane of the laser was positioned at the surface of the sheets during all the trials. The shielding gas is also used as a plasma suppression gas that was supplied through a 5 mm diameter nozzle in the trailing mode configuration at a gauge pressure of 1 bar. The nozzle standoff distance was maintained constant at 4.5 mm throughout the experiments. The laser power and welding speed combinations

Table 1
Composition of base metal (wt%).

C	Si	Mn	P	S	Cr	Ni	B	Fe
0.06	0.92	1.84	0.029	0.005	18.20	9.18	0.97	Bal

Table 2
Welding parameters.

Laser power (kW)	Welding speeds (m/min)	Beam mode
2	4, 3, 2, 1	Gauss
2.5	5, 4, 3, 2, 1	
3	7, 6, 5, 4, 3, 2, 1	
3.5	8, 7, 6, 5, 4, 3, 2	
3.5	3, 2	Donut

along with the laser beam mode used for experimentation are given in Table 2. The parameters were chosen to achieve keyhole mode of welding. The experimental matrix as indicated in Table 2 was followed for all the shielding gases experimented. i.e Argon, Helium and Nitrogen.

The welds were subjected to dye penetrant testing according to ASTM E1417-05 practice to check for any open surface defects. Subsequently, the welds were cut transversely, mounted and polished using Buehler make automatic polishing machine following the standard metallographic procedure. Two specimens were taken for each parameter to investigate the consistency. The polished specimens were etched using aqua regia solution (1 part of conc. HNO_3 and 3 part of conc. HCL). The macrostructural analyses were performed using an Olympus make stereo microscope at a magnification of 25X. The bead geometry measurements were taken using the image analysis software integrated with the optical microscope. Selected weld specimens were subjected to post weld heat treatment (PWHT) at a temperature of 1200 °C for 4 h. Microhardness survey and microstructural analyses were performed for selected specimens in both as-weld and PWHT condition. Microhardness measurements were carried out across the weld using UHL automatic microhardness tester at a load of 200 g with dwell time of 15 s and inter indent spacing of 150 μm. Microstructural analyses were performed using optical microscope at a magnification of 200X–1000X.

3. Results and discussions

3.1. Macrostructure observation of welds

Dye penetration examination revealed that surface of welds is free from any defects such as porosity, hot cracks which are open to the surface. Macrostructures of the welds are given in Fig. 1. The macrostructures show that the welds are free from any internal defects such as cracks, porosities, etc. for the wide range of heat input and shielding gas combinations that has been experimented. The 304B4 alloy used in the present investigation has boron content of above 0.5% which, is considered to be the threshold value to avoid hot cracking. The high amount of boron ($>0.5\%$) will result in increased content of low melting eutectic phases which in turn will increase the solidification range.

This increase in solidification range will produce crack healing effect where in the cracks are refilled by the low melting phases. Hence, no hot cracking tendency was exhibited by any of the welds. The welds were also free from any PMHAZ as observed from the macrostructural examination. Due to the concentrated nature of the heat source coupled with the use of shielding gas, the cooling rates associated with laser beam are generally >1000 °C/s. Also, since the conductivity of SS 304B4 is less, the cooling rates experienced in the fusion zone will be much higher than the rate of heat conduction. Hence, the peak temperatures in the HAZ would not have reached the threshold value required for melting of eutectics or the time for which a particular zone experienced the melting temperature of eutectics would have been extremely less. These two factors could have suppressed