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Yag laser welding of neutron irradiated stainless steels

S. Nishimura [a,*], R. Katsura [a], Y. Saito [b], W. Kono [c], H. Takahashi [b], M. Koshiishi [d], T. Kato [d], K. Asano [e]

[a] Nippon Nuclear Fuel Development Co., Ltd., Higashi, 2163 Narita-cho, Oarai-mati, Ibaraki-ken 311-13, Japan
[b] Nuclear Energy Div., Toshiba Corp., Shinsugita, Isogo-ku, Yokohama 235, Japan
[c] Heavy Apparatus Engineering Laboratory, Toshiba Corp., Toshiba-cho, Fuchu-shi, Tokyo 183, Japan
[d] Hitachi Works, Hitachi Ltd., Hitachi-shi, Ibaraki-ken 317, Japan
[e] Materials Eng. Group, The Tokyo Electric Power Co., Inc., Egasaki-cho, Tsurumi-ku, Yokohama 231, Japan

Abstract

Type 304L stainless steel plates of 8 mm thickness irradiated in a boiling water reactor (BWR) to 1.2×10^{25} n/m^2 ($E > 1.0$ MeV) containing 9 appm helium from transmutation have been successfully welded using a high power Nd–YAG laser under conditions of both continuous wave (CW) and pulse modes. Unirradiated Type 316L stainless steel plate was lap welded to the irradiated Type 304L stainless steel plate under heat inputs ranging from 240 to 540 J/cm. Bead on plate welding was carried out under the same welding conditions as lap welding. Tensile tests of lap welded joints were conducted at room temperature. All joints fractured not in the irradiated materials but in the unirradiated materials and showed good mechanical properties. Based on these results it does not appear that helium affects the mechanical properties of joints. Small grain boundary cracks were observed in HAZ of the weld made by the CW YAG laser with heat inputs of 480 and 540 J/cm and crack length decreased with decreasing heat input.

1. Introduction

Austenitic stainless steel is the main constituent material used in the internal structure of boiling water reactors (BWRs). It contains ^{10}B and Ni. Helium is produced by the transmutation of ^{10}B and two-step decomposition of ^{59}Ni. The presence of grain boundary helium bubbles can cause a substantial loss of ductility in irradiated materials at elevated temperatures [1]. Since the mobility of helium atoms in the austenite matrix is negligibly small within the BWR operating temperature range, BWRs have not incurred the detrimental effects from helium.

However, in the event of needed weld repair of irradiated stainless steel components, the helium effect is an important issue that needs to be addressed. The helium bubbles grow rapidly under the influence of high temperature and tensile stress [2,3]. Since the welding process always produces high temperature and high thermal stress, especially in the heat affected zone (HAZ), the enhanced growth of grain boundary helium bubbles is anticipated during welding which leads to inter-granular cracking.

Recently, the authors studied the TIG weldability of Types 304 and 316L austenitic stainless steels irradiated in a BWR to fluences ranging from 8.5×10^{22} to 1.4×10^{26} n/m^2 ($E > 1.0$ MeV) [4]. The integrity of the weld was better with lower heat input as well as lower helium containing material. These results led to the idea that low heat input welding method such as laser welding should show better weld integrity than TIG welding.

The objective of this study is to investigate the YAG laser weldability of neutron irradiated Type 304L austenitic stainless steel.

2. Experimental

2.1. Material

Rectangular weld plates (30 mm wide × 60 mm long × 8 mm thick) were machined from Type 304L

* Corresponding author. Tel.: +81 29 267 9007; fax: +81 29 266 2589; e-mail: nisimura@nfd.co.jp.

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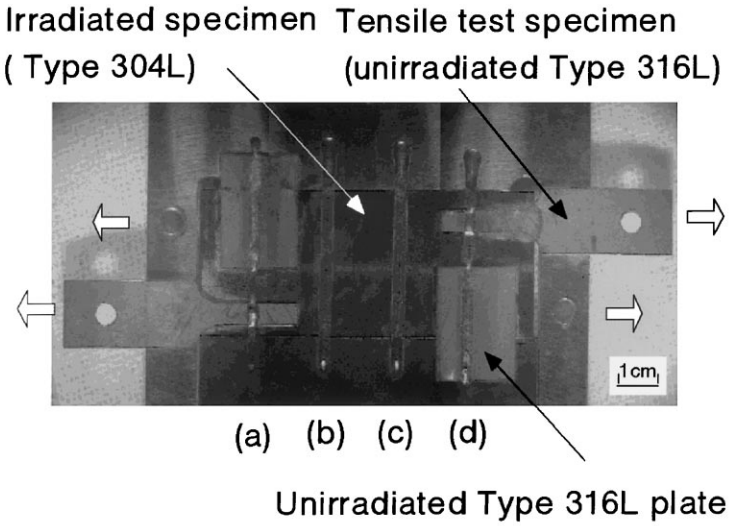

Fig. 1. Example of welded specimen. (a) and (d) are the lap welded joints and (b) and (c) are the bead on plate welds.

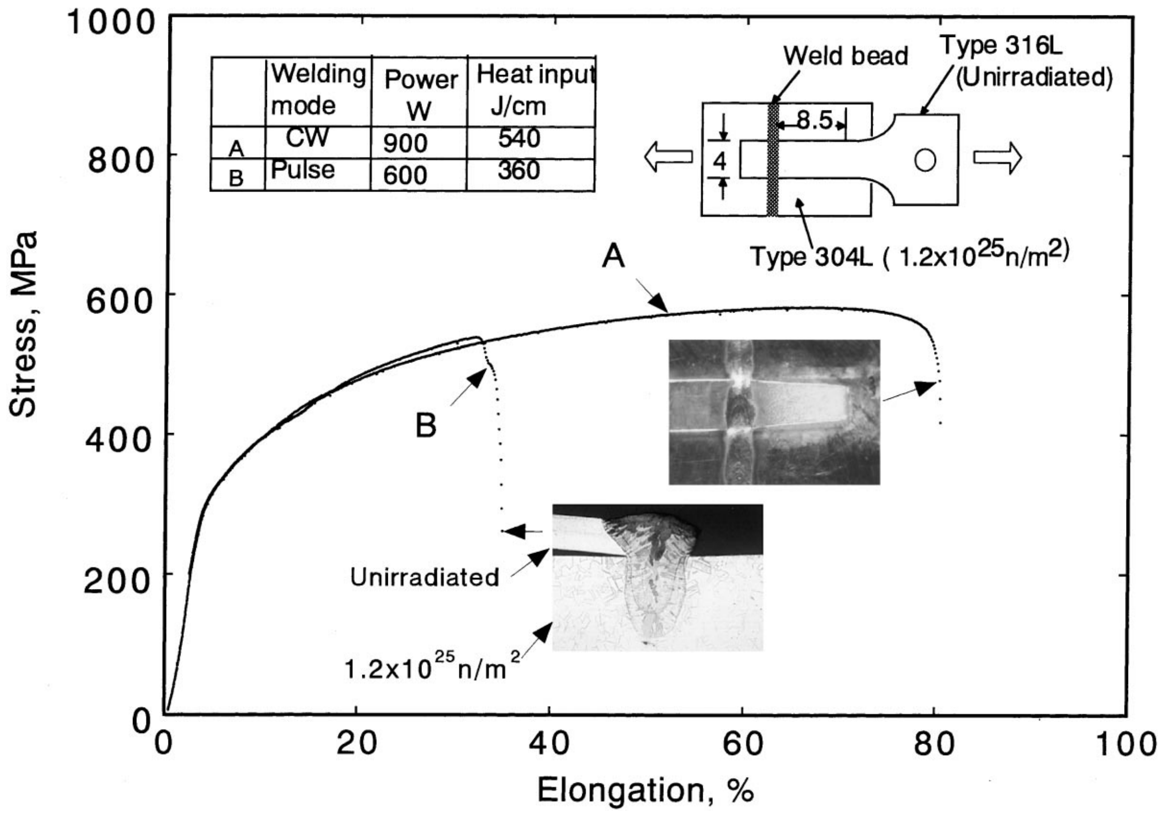

Fig. 2. Example of stress-elongation curves in lap welded joints. A and B are the stress-elongation curves of the joints obtained by CW YAG laser welding with the power of 900 W and pulse YAG laser welding with the power of 600 W. Photographs show the specimens after tensile test. Fracture occurred in unirradiated material.

Table 1
Tensile test results of lap welded joints

Welding conditions			Tensile strength	Uniform elongation	Failure position
Welding mode	Power W	Heat input J/cm	MPa	%	
CW	700	420	546	28.2	Near weld bead of unirr. material
	800	480	531	21.2	Ibid.
	900	540	608	65.9	Base metal of unirr. material
Pulse	400	240	587	47.0	Near weld bead of unirr. material
	500	300	613	49.4	Ibid.
	600	360	562	28.2	Ibid.

stainless steel irradiated in a BWR to 1.2×10^{25} n/m^2 (E > 1.0 MeV). Type 304L stainless steel has the following composition in wt%: 0.01 C, 0.66 Si, 0.88 Mn, 0.018 P, 0.003 S, 10.12 Ni, 18.23 Cr, 0.01 Co, 0.04 N, balance Fe. The specimen surface was mechanically finished to control the surface roughness so that constant welding conditions could be obtained.

Helium content of the material was estimated by interpolation of the data obtained from the same type samples irradiated in a BWR resulting in 9 appm helium [4].

2.2. Welding

Maximum output of the Nd–YAG laser oscillator was 1.4 kW. The laser beam from the oscillator was passed into a quartz optical fiber (0.6 mm core diameter) through an input coupler for a 70 m distance transmission before delivering the laser beam onto the material surface. Focusing optics was equipped with shield box for N_2 gas shielding of the specimen.

Nd–YAG laser welding was performed for conditions of both continuous wave (CW) and pulse modes. CW and pulse YAG laser welding were performed for the specimens lapped with 0.5 mm thick unirradiated Type 316L stainless plates and tensile specimens on the irradiated Type 304L stainless plate without filler wire for average power of 700–900 W for the CW mode and average power of 400–600 W for the pulse mode with the 1 m/min welding speed. Pulse frequency was 40 Hz. For tensile specimen, welding was performed normal to the tensile direction. Bead on plate welding was also carried out under the same welding conditions as lap welding. Fig. 1 is an example of welded specimen. Heat input of

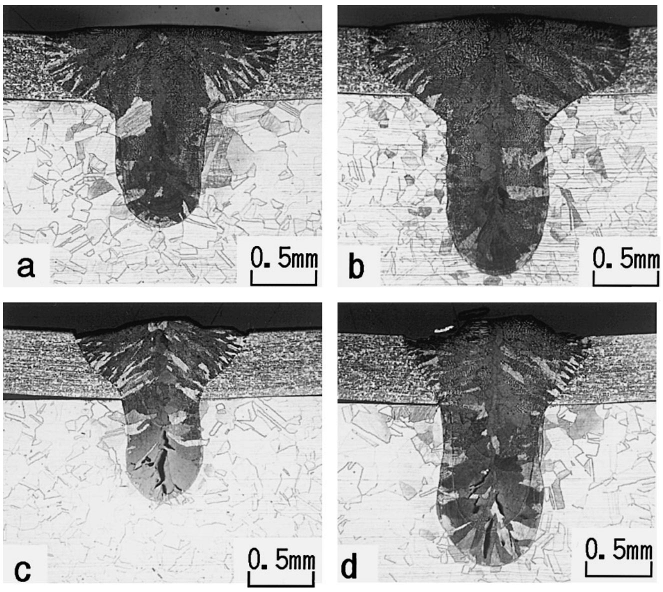

Fig. 3. Transverse section of lap welded joints. (a) and (b) are the macroscopic aspects of the CW YAG laser welds with welding powers of 700 and 900 W, i.e., heat inputs were 420 and 480 J/cm, respectively. (c) and (d) are the macroscopic aspects of the pulse YAG laser welds with welding powers of 400 and 600 W, i.e., heat inputs were 240 and 360 J/cm, respectively.

welded bead was calculated as $0.6 \times A$ (W) (J/cm), where A is a laser power for welding speed of 1 m/min and laser absorption ratio of the material was assumed to be 100%.

3. Results and discussion

3.1. Tensile tests of lap welded joints

Dye penetration tests were carried out subsequent to the welding and no crack indications were recognized for any welded joints.

Tensile tests of lap welded joints were conducted at room temperature. Specimen thickness, width and gage length of unirradiated materials (Type 316L) were 0.5, 4 and 8.5 mm, respectively. Strain rate was 5.9%/min. Fig. 2 plots examples of stress-elongation curves. Curves A and B are the results for joints made by CW YAG laser with power of 900 W and pulse YAG laser with power of 600 W. Heat inputs were 540 and 360 J/cm, respectively. Neutron fluence of irradiated materials (Type 304L) were 1.2×10^{25} n/m^2 ($E > 1.0$ MeV). Tensile test results are listed in Table 1. All specimens failed near weld bead or in base metal of unirradiated materials in a ductile manner and failure or cracking in the weld metal or HAZ of irradiated materials were not found. This facts indicate that helium did not affect the mechanical properties of lap welded joints. Tensile strength of all specimens exceeded the standard value of Type 316L (480 MPa for Japanese Industrial Standard), thus fulfilled the standard requirement of the welded joint. Uniform elongation of all joints resulted in between 21.1% and 65.9% which seemed to be large enough to be applied in actual use.

3.2. Metallography of lap welds

Fig. 3(a)–(d) are the macroscopic metallographs of the cross-section in the welds obtained by the CW YAG

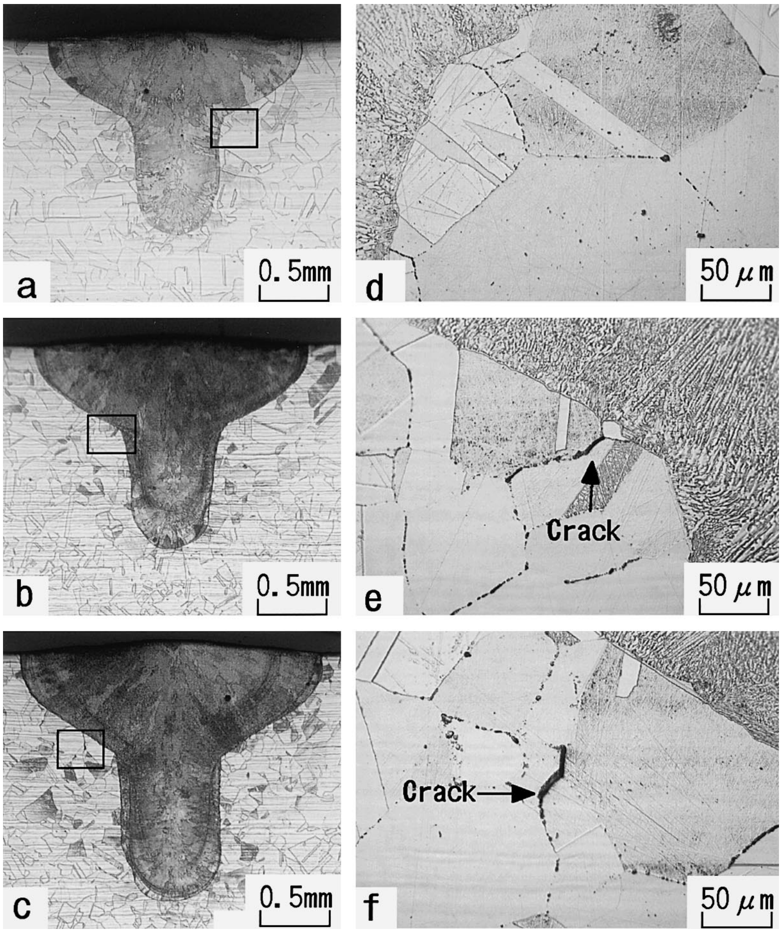

Fig. 4. Transverse section of CW YAG laser welds. (a)–(c) show macroscopic aspects when the welding powers were 700, 800 and 900 W, i.e., heat inputs were 420, 480 and 540 J/cm, respectively. (d)–(f) are their respective magnifications.

laser with power of 700 and 900 W and pulse YAG laser with power of 400 and 600 W, respectively. Penetration width and depth increased with increasing heat input. For CW YAG laser welds, no blow holes or cracks were observed, but for pulse YAG laser welds cracks appeared in the weld metal of irradiated materials. This cracking may have occurred during solidification of the weld metal. Microscopic observations of the welds were conducted and no helium-induced cracking in HAZ was recognized for any welded joints.

3.3. Metallography of bead on plate welds

Figs. 4 and 5 show metallographic sections through stringer beads in CW and pulse mode YAG laser welded plates containing 9 appm He, respectively. In these figures, (a)–(c) show macroscopic aspects of welds and (d)–(f) are their respective magnifications. Cross-sectional shape was typically a wine-cup shape and penetration depth and width increased with increasing welding power.

Bead on plate tungsten inert gas (TIG) welding of the same materials as in this study, with the same specimen dimensions and irradiated in a BWR up to 1.4×10^{25} n/m ^{2} ($E > 1.0$ MeV), has been made and dye penetration tests and metallurgical examination of welds were conducted [4]. In this case, when the heat input was higher than 10.8 kJ/cm, cracks running parallel to the welding direction were detected in the HAZ by the dye penetration test. Cross-sectional metallographic examination of the welds revealed that for the 7.0 kJ/cm heat input, many pores were found in the weld metal and obvious cracking appeared in the HAZ. These pores and cracking were considered to be formed due to the migration of helium atoms held in solution in the metal matrix before welding. Conversely, from Figs. 4 and 5, it was clear that there were no pores or blow holes in the CW and pulse YAG laser weld metals. And for the pulse

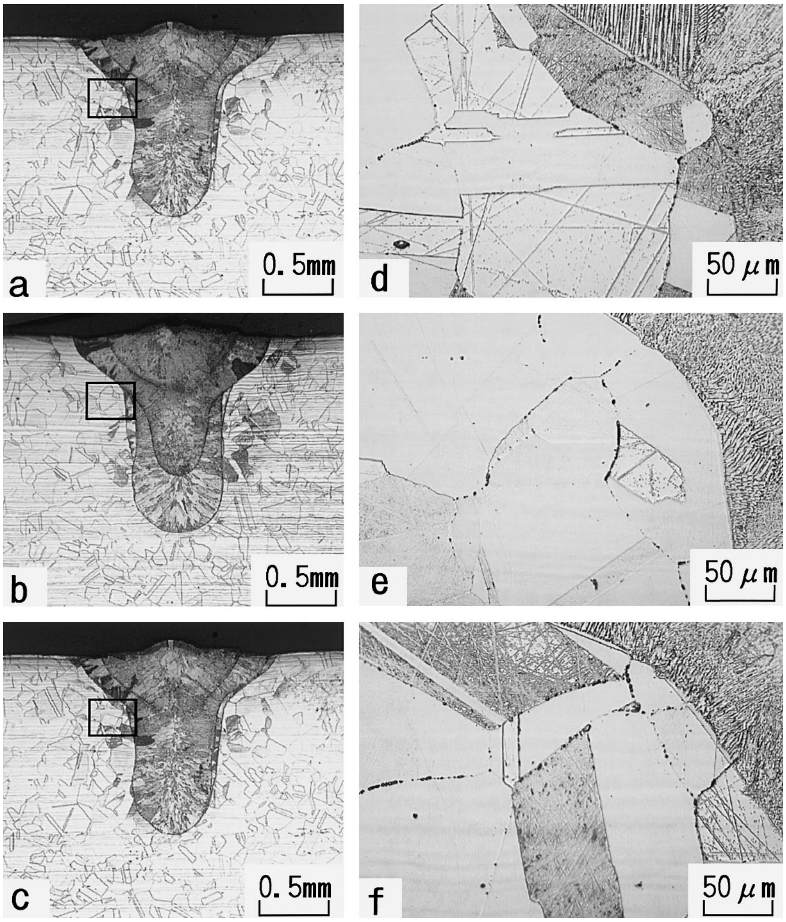

Fig. 5. Transverse section of pulse YAG laser welds. (a)–(c) show macroscopic aspects when the welding powers were 400, 500 and 600 W, i.e., heat inputs were 240, 300 and 360 J/cm, respectively. (d)–(f) are their respective magnifications.

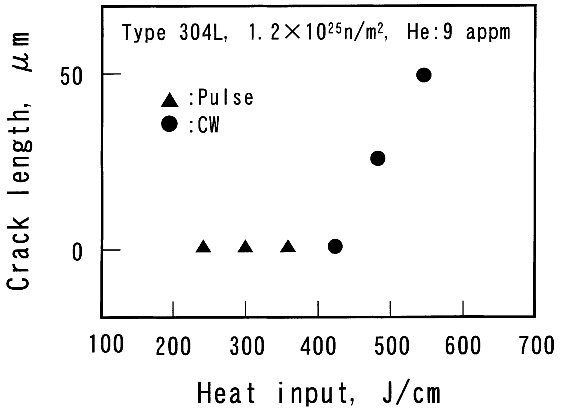

Fig. 6. Heat input vs. crack length of CW and pulse YAG laser welds.

YAG laser weld, no cracking was observed in HAZ (Fig. 5(d)–(f)). Cracking was detected in the CW YAG laser weld for powers of 800 and 900 W (Fig. 4(e) and (f), heat inputs were 480 and 540 J/cm, respectively), but these cracks were very small comparing with those observed in the TIG welded HAZ for 7.0 kJ/cm heat input [4]. Consequently, low heat input suppresses the initiation and growth of pores in weld metal and cracking in HAZ. Fig. 6 is the heat input dependence of the crack length in HAZ. Crack length decreased with decreasing heat input and below 420 J/cm heat input, helium-induced cracking was not observed.

4. Summary

1. Tensile tests of lap welded joints made by CW and YAG laser with heat inputs ranging from 240 to 540 J/cm resulted fracture occurring not in the irradiated material but in the unirradiated material. Helium was found not to affect the mechanical properties of joints and strength of all joints met standard property requirements.
2. No surface defects or cracks were detected for any bead on plate or lap welded specimens made by CW and pulse YAG laser with heat inputs in the range of 240–540 J/cm.
3. For lap welded specimens, no blow holes or cracks were recognized in the weld metal, except for the specimens made by pulse YAG laser. Helium-induced grain boundary cracking was not detected in any lap welded specimens.
4. No blow holes or cracks were observed in weld metal of any bead on plate welded specimens. Small grain boundary cracks however were observed in the HAZ of bead on plate welded specimens made by CW YAG laser with heat inputs of 480 and 540 J/cm. Crack length decreased with decreasing heat input, thus helium-induced grain boundary cracking was suppressed by lowering the heat input.

These results suggest that the YAG laser welding is one of the promising method for weld repair of neutron irradiated core internals.

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