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The effect of laser welding process parameters on the mechanical and microstructural properties of V–4Cr–4Ti structural materials ☆

C.B. Reed *, K. Natesan, Z. Xu, D.L. Smith

Fusion Power Program, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA

Abstract

This paper reports a systematic study which examined the use of a pulsed Nd:YAG laser to weld sheet materials of V–Cr–Ti alloys and to characterize the microstructural and mechanical properties of the resulting joints. Deep penetration, defect-free, and oxygen contamination free welds were achieved under an optimum combination of laser parameters including focal length of lens, pulse energy, pulse repetition rate, beam travel speed, and an innovative shielding gas arrangement. The key for defect-free welds was found to be the stabilization of the keyhole and providing an escape path for the gas trapped in the molten weld pool. Oxygen and nitrogen uptakes were reduced to levels only a few ppm higher than the starting material by design and development of an environmental control box (ECB). Laser-applied post-weld heat treatments showed that five-passes of a diffuse laser beam over the welded region softened the weld material, especially in the root region. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

V–Cr–Ti alloys are among the leading candidate materials for the first wall and other structural material applications in fusion power reactors because of several important advantages including inherently low irradiation-induced activity, good mechanical properties, good compatibility with lithium, high thermal conductivity and good resistance to irradiation-induced swelling and damage [1]. However, weldability of these alloys in general must be demonstrated, and laser welding, specifically, must be developed. Laser welding is considered to be an attractive process for construction of a reactor due to its high penetrating power and potential flexibility.

To address these issues, a systematic study was conducted to examine the use of a pulsed Nd:YAG laser to weld sheet materials of V–Cr–Ti alloys and to characterize the microstructural and mechanical properties of the resulting joints. Vanadium alloy heat #832665, nominal composition V–4 wt% Cr–4 wt% Ti (designated as BL-71) was selected for the study. Bead-on-plane (BOP) welds were produced on 4 mm thick sheets of the alloy using a 1.6 kW pulsed Nd:YAG laser with optical fiber beam delivery. The effects of laser parameters on depth of penetration, oxygen and nitrogen uptake, and microhardness, were determined experimentally. The three main tasks of the study were to:

(a) Determine the optimal parameters for full penetration, defect-free, laser beam welding of 4 mm thick sheets of V–Cr–Ti alloys, and examine the microstructural characteristics of the welded sections, including base metal, heat-affected-region, and core of the weld.

(b) Determine the extent of oxygen uptake from the welding process, its influence on weld joint hardness, and minimize it.

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* Corresponding author. Tel.: +1-630 252 5970; fax: +1-630 252 5287.

E-mail address: cbreed@anl.gov (C.B. Reed).

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(c) Evaluate the influence of different post-welding heat treatments on microstructural characteristics and local hardness profiles.

2. Studies to increase depth of penetration

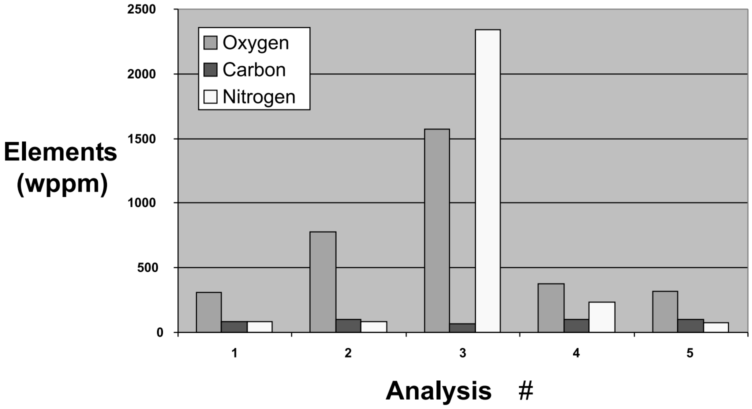
A number of parametric studies [4] were carried out with the objective of producing full penetration, defect-free welds on the 4 mm thick material. As the welding parameters were optimized, it was found that the amount of porosity decreased as the beam travel speed decreased. Porosity-free welds were obtained when the weld depth reached full penetration. The final results [4] seem to show that full penetration provides a path on the bottom side of the sample for the gas trapped in the welding keyhole to escape, thus eliminating porosity.

3. Studies to minimize contamination

Weld purity issues, including oxygen, carbon, and nitrogen uptake during processing [3] were investigated. Uptake of oxygen leads to embrittlement of the alloy and therefore must be avoided. With beam travel speed, lens, and shielding gas flow identical to the conditions which produced the full penetration weld above, two weld specimens, 990223B (23B) and 990223C (23C), were produced and the core of each weld was machined into chips and analyzed for O, C, and N. All specimens in the contamination study were wiped with acetone before and after welding, except specimen 09B (to be discussed later), which was cleaned in a pickling solution after welding. The content of oxygen, nitrogen, and carbon of laser-welded samples was analyzed by the inert gas fusion (IGF) method. Results of those analyses, along with analyses of the base material adjacent to the welds (specimen 23A), are shown in Fig. 1; also shown for comparison purposes, are reference analyses of O, C, and N from the original Heat 823665, from which the 4 mm sheets were produced. It can be seen that specimens 23B and 23C obviously exhibit unacceptably large amounts of oxygen and nitrogen.

A custom-designed environmental control box (ECB) capable of purging with high-purity argon (99.995%) was integrated with the Nd:YAG laser to improve the quality of the welding atmosphere by minimizing oxygen and nitrogen uptake. Fig. 2 schematically shows the setup of the laser system with the ECB. The high-purity argon was purged into the box from both sides and the flow rate was well controlled such that a slow flow of argon out from the slit on the top of the box could be formed, providing a good welding atmosphere to minimize the impurity uptake during welding. A shielding disk just above the slit enhanced the shielding effect and also provided a guiding surface for the lens protection gas.

Fig. 1 shows that the welds produced in the ECB with nearly optimal shielding gas (12B and 12C) have the lowest oxygen content. Welds using the ECB but with a less than optimal gas shielding arrangement (09A and



Analysis #	Specimen #	Welding Conditions	Lens	Beam travel speed (cm/s)	Sample form
1	Heat 832665	Reference Heat Analysis	-	-	-
2	23A	Base material	-	-	Chips
3	23B&23C	No ECB	76mm	1	Chips
4	09A&09B	ECB, Non-optimal gas flow	127mm	0.6, 0.5	Bar
5	12B&12C	ECB+ Optimal gas flow	127mm	0.4, 0.25	Bar

Fig. 1. Chemical analysis results of laser-welded V–Cr–Ti alloy samples.

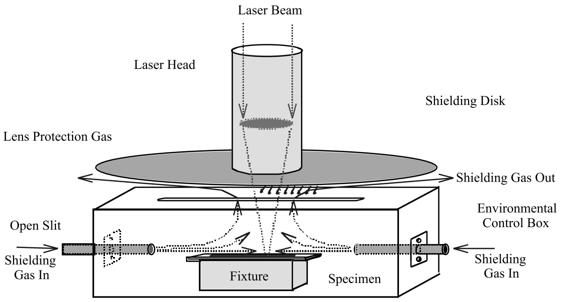


Fig. 2. Setup of the ECB for the laser-welding system.

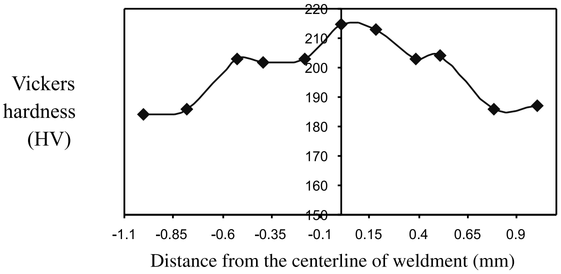


Fig. 3. Microhardness profile for oxygen-uptake-free weldment 12D (equivalent to 12C) at half-width of weldment.

09B) have higher oxygen content compared to those with nearly optimal shielding. Specimen 09B was cleaned in a pickling solution after welding. The welds obtained without using the ECB have the highest oxygen content. The O, N, and C contents of welds produced using the ECB with near-optimal shielding gas are es-

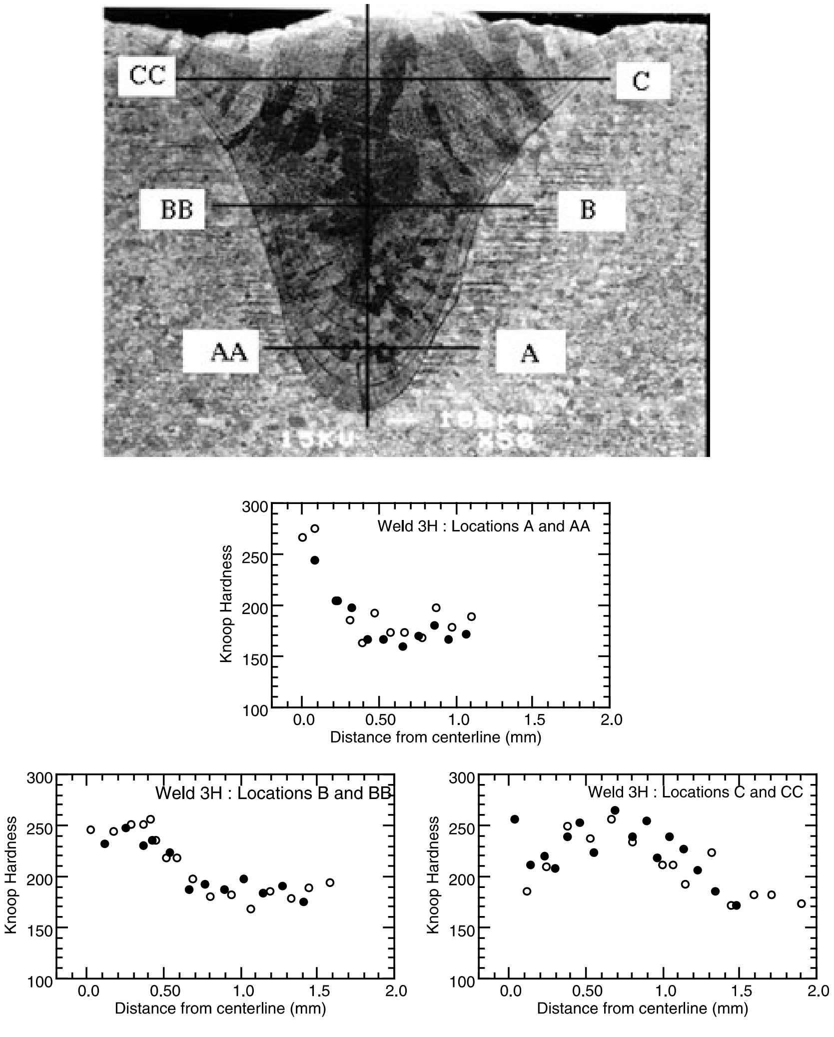


Fig. 4. Hardness profiles at elevations indicated in photomicrograph for laser-welded V–4Cr–4Ti specimen, in as-welded condition. Open and closed symbols represent hardness values measured on either side of the weld centerline.

sentially the same as the values reported as the reference analysis for the starting material. Oxygen analyses obtained from the chip samples (23B & 23C) apparently include additional contamination. Subsequent specimens were not milled into chips prior to chemical analysis, but rather submitted as small bars. By design and development of this ECB method, oxygen and nitrogen uptake were reduced to levels only a few ppm higher than the base metal.

A microhardness profile across the width of weldment 12D (equivalent to 12C) is presented in Fig. 3. This profile shows only a slight increase in hardness in the weld metal, in comparison to the adjacent base metal. This finding is consistent with the low oxygen content found in the sister weldment 12C.

4. Effect of post-weld heat treatment on weldment hardness

For the post-weld heat treatment study, seven different welds were made under identical welding conditions but were subsequently given different post-weld heat treatments [2,4]. Weld depth in these specimens was $\approx$1.2 mm and hardness profiles generally showed a substantial increase (from an initial Vickers hardness value of 170–180, up to 240–280) in the center of the weld; this value stayed high across almost the entire weld zone, see Fig. 4. Post-weld heat treatments were applied as follows: (a) no treatment (as-welded condition), (b) 1 and 5 passes with a 1.3 kW defocused beam ($\approx$4 mm in diameter, compared to a 3 mm weld width), (c) 1 and 5 passes with the same beam at $\approx$50% of the 1.3 kW level, and (d) 1 and 5 passes with the same beam at $\approx$25% of the 1.3 kW level. Weld cross-sections were examined by scanning electron microscopy (SEM). In addition, Knoop hardness measurements were made at three different elevations across the width of the weld, starting at the weld centerline, through the heat-affected zone, and into base metal, e.g., see Fig. 4.

The effect of one pass of post-weld heat treatment with a defocused laser beam was to soften the material in the weld zone; this was indicated by a monotonic decrease in hardness from the weld centerline to the base metal. Even the peak hardness value was somewhat lower and the peak was confined to the region close to the centerline. The impact of such a decrease on the mechanical properties of the weld can be substantial and will probably be beneficial. The effect of five passes of post-weld heat treatment with a defocused laser beam was to soften the material in the weld zone, especially at the root region of weld. A somewhat erratic hardness variation in the weld region of the five-pass, full-power specimen at elevations B and C indicate that grain growth may have occurred in the upper portions of the weld as a result of the multiple passes. The effort directed at developing an acceptable post-welding heat treatment showed that five passes of diffuse laser beam over the welded region softened the weld material, especially in the root region of the weld.

5. Summary and conclusions

A systematic study was conducted to examine the use of a pulsed Nd:YAG laser to weld sheet materials of V–Cr–Ti alloys and to characterize the microstructural and mechanical properties of the resulting joints. Deep penetration and defect-free welds were achieved under an optimal combination of laser parameters including focal length of lens, pulse energy, pulse repetition rate, beam travel speed, and shielding gas arrangement. The key for defect-free welds was found to be the stabilization of the keyhole and providing an escape path for the gas trapped in the weld. An innovative method was developed to obtain deep penetration and contamination free welds. Oxygen and nitrogen uptake were reduced to levels only a few ppm higher than the base metal, by design and development of an ECB. The effort directed at developing an acceptable post-welding heat treatment showed that five-passes of diffuse laser beam energy over the welded region softened the weld material, especially in the root region of the weld.

Acknowledgements

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