GA–A22426

PRODUCTION AND FABRICATION OF VANADIUM ALLOYS FOR THE RADIATIVE DIVERTOR PROGRAM OF DIII–D

— Annual Report Input for 1996

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W.R. JOHNSON, J.P. SMITH, and R.D. STAMBAUGH

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PRODUCTION AND FABRICATION OF VANADIUM ALLOYS FOR THE RADIATIVE DIVERTOR PROGRAM OF DIII–D — ANNUAL REPORT INPUT FOR 1996

W.R. Johnson, J.P. Smith, and R.D. Stambaugh (General Atomics)

SUMMARY

V-4Cr-4Ti alloy has been selected for use in the manufacture of a portion of the DIII–D Radiative Divertor (RD) upgrade. The production of a 1200-kg ingot of V-4Cr-4Ti alloy has been completed at Teledyne Wah Chang of Albany, Oregon (TWCA) to provide ~800-kg of applicable product forms, and two billets have been extruded from the ingot. Chemical compositions of the ingot and both extruded billets were acceptable. Material from these billets will be converted into product forms suitable for components of the DIII–D Radiative Divertor structure. Joining of V-4Cr-4Ti alloy has been identified as the most critical fabrication issue for its use in the RD Program, and research into several joining methods for fabrication of the RD components, including resistance seam, friction, and electron beam welding, is continuing. Preliminary trials have been successful in the joining of V-alloy to itself by electron beam, resistance, and friction welding processes and to Inconel 625 by friction welding.

PROGRESS AND STATUS

1. Introduction

General Atomics (GA), along with the Argonne National Laboratory (ANL) and Oak Ridge National Laboratory (ORNL), has developed and is implementing a plan for the utilization of vanadium alloys in the DIII–D tokamak. This plan will culminate in the fabrication, installation, and operation of a water-cooled vanadium alloy structure in the DIII–D RD upgrade.[1,2] The use of a vanadium alloy will provide a meaningful step towards developing advanced materials for fusion power applications by 1) demonstrating the in-service behavior of a vanadium alloy (V-4Cr-4Ti) in a typical tokamak environment, and 2) developing knowledge and experience on the design, processing, and fabrication of full-scale vanadium alloy components.

The program consists of three phases: first, small vanadium alloy specimens and coupons will be exposed in DIII–D; second, a small vanadium alloy component will be designed, manufactured, and operated in conjunction with the existing DIII–D divertor; and third, the upper private flux baffle of the new double-null, slotted divertor will be designed, fabricated from vanadium alloy product forms, and installed in DIII–D. A major portion of the program is research and development to support fabrication and resolve key issues related to environmental effects. The plan is being carried out in conjunction with GA and the Materials Program of the Department of Energy's Office of Fusion Energy (DOE/OFE). The execution of the plan is a joint effort by GA, the DIII–D Program, and DOE Material Program participants, primarily ANL, ORNL, and Pacific Northwest National Laboratory (PNNL).

2. PHASE 1: Specimen and Coupon Exposures and Analysis

Miniature Charpy V-notch (CVN) impact and tensile specimens of V-4Cr-4Ti alloy were exposed/monitored in DIII–D in positions behind the divertor baffle for ~9 months.[4] GA has collated the environmental data, and ANL has developed and is now implementing an analysis plan for the evaluation of the specimens. A new set of samples, installed during the January 1996 vent, is currently undergoing exposure.

In parallel to these exposures, other V-4Cr-4Ti alloy samples underwent short-term exposures utilizing the DIII–D Divertor Material Exposure System (DiMES). A V-4Cr-4Ti alloy disc, and subsequently CVN specimens, were exposed/monitored during baking and cleaning of DIII–D.[4] GA has collated the environmental data, and ANL has developed and is now implementing an analysis plan to determine the pickup of any impurities in these specimens. Other DiMES exposures are being considered to evaluate the effects of other DIII–D environmental conditions (e.g., discharge cleaning, boronization, etc.).

3. PHASE 2: Small Component Exposure

A second step in the DIII–D Vanadium Plan is to install a small V-4Cr-4Ti alloy component in DIII–D. This component will be manufactured utilizing many of the methods proposed for the Phase 3 water-cooled private flux baffle. The component will be installed, exposed for some period of tokamak operations, and then removed. Samples from the component will be excised, and metallurgical analyses and property measurements will be made on the excised materials. Specific plans have not yet been defined.

4. PHASE 3: Radiative Divertor Program

The design, manufacture, and installation of a V-4Cr-4Ti alloy private flux baffle structure for the upper divertor of the RD program will be performed as the third phase of the vanadium alloy program (Fig. 1). The V-4Cr-4Ti alloy structure will contain two, toroidally-continuous, water-cooled structural panels with inertially-cooled graphite tiles mechanically attached to their surfaces by welded studs. The panels will be water cooled during machine operation, experiencing a maximum temperature of ~60°C. During post-vent clean-up, hot air will replace the water in the coolant channels of the structure, and the structure (along with the DIII–D vessel) will be baked to ~400°C. The panels will be supported from the vacuum vessel by Inconel 718 supports which will provide the required strength for reacting disruption loads and the flexibility for withstanding differential thermal growth during baking. Due to the lower electrical resistivity of the V-4Cr-4Ti alloy as compared to Inconel 625, the toroidal current flow during disruption will be approximately four times larger. The design of the panels and supports will be modified to react the larger loads.[1]

The panels will be made in six segments and fabricated of sandwich construction from two 4.8 mm sheets, each containing a 1.5 mm deep coolant channel milled into its side to provide an internal coolant channel. Resistance seam welding is the primary candidate process being considered for structurally joining the panels edges, with electron beam welding utilized for making a perimeter leak tight seal. Other methods of joining are proposed for different areas of the design. To facilitate installation, bi-metallic V-4Cr-4Ti alloy to Inconel 625 tube-to-tube joints are planned for effecting in-vessel gas-tungsten arc field welds to Inconel 625 water supply tubes.

A. Fabrication of Product Forms for the Radiative Divertor

Processing of the V-4Cr-4Ti alloy by TWCA was initiated in September 1995. Details of this processing up to the vacuum-arc melting of a 1200-kg V-4Cr-4Ti alloy ingot, including processing of the raw vanadium from high purity vanadium oxide, selection of raw vanadium lots, and electron beam melting of two (2) high purity vanadium ingots (a ~900-kg ingot and ~400-kg of another ingot) for the alloy, were presented in a previous report.[4] During February 1996, the two vanadium ingots were

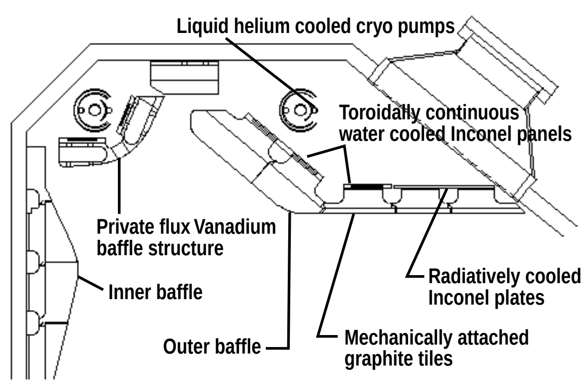


Fig. 1. Location of vanadium structure in radiative divertor.

machined into large chips and consolidated with high purity Cr and Ti (double vacuum-melted Ti), and a 1200-kg V-4Cr-4Ti alloy ingot was produced by double vacuum-arc melting (Fig. 2). The resulting ingot was 34.9 cm in diameter × 210.8 cm in length. Chemical analysis of the ingot (Table 1) at three separate locations (top, middle, and bottom) indicated that the ingot was generally within specification limits for all elements except primarily for Nb, as was expected based on the Nb levels measured on the high purity vanadium ingots used for its production.[4] Based on this analysis, the ingot was accepted for continued processing.

The diameter of the ingot was machined to 32.1 cm and the ingot was sectioned into two (2) ~85 cm pieces. Each section was encapsulated in a stainless steel can fabricated from rolled and seam-welded ~4.8 mm thick sheet. Each can was evacuated (to $\sim 2 \times 10^{-4}$ Torr), and seal welded. The canned ingot sections were shipped to CSM Inc. in Coldwater, Michigan for extrusion into billets (sheet bar). On 1 May, the canned sections were extruded into rectangular billets, ~11.4 cm × ~24.1 cm in cross-section, after heating for several hours in a slightly reducing, gas-fired furnace to a temperature of ~1140°C. Extrusion of the first ingot section (Section A) went as planned, resulting in a ~274 cm long billet which appeared to have an intact can and no observable cracks, tears, etc. During the extrusion of the second ingot section (Section B), however, the extrusion stalled about halfway through the die, yielding only a partial rectangular billet, ~126 cm long, which appeared to have a ~19 cm long crack near the nose end of the billet. This cracked material was later removed by sectioning from the remainder of the billet. Subsequent to the extrusion, the two billets were shipped back to TWCA and sampled for chemical analysis at each end. The stainless steel cans were removed from the billets by rough grinding, the ends of the billets were sectioned to remove any cracks, and the billets were then finely ground/pickled to final sheet bar dimensions (10.4 cm × 23.4 cm × 245.1 cm and 107.4 cm, respectively). The sheet bar materials were then vacuum annealed in preparation for longitudinal rolling into 4.7 cm thick plate. Further processing is currently on hold until the chemical analysis of the two extruded billet materials is completed and accepted.

Fig. 2. This V-4Cr-4Ti ingot (the largest of its type ever made) will be formed into plate and rod for use in GA's DIII–D divertor modification.

TABLE 1
CHEMICAL COMPOSITION GOALS AND CHEMISTRY FOR V-4Cr-4Ti ALLOY
(Heat ID #832864)

	Content, parts/million by weight (ppm)[a]			
Element	**Specification for Alloyed Vanadium Ingot**	**Alloyed Vanadium Ingot (Top of Ingot)**	**Alloyed Vanadium Ingot (Middle of Ingot)**	**Alloyed Vanadium Ingot (Bottom of Ingot)**
Cr	4 ± 0.5 wt. %	3.9	3.8	3.6
Ti	4 ± 0.5 wt. %	3.9	3.6	3.8
Si	400–1000	270	270	280
H	<10	<3	<3	<3
O	<400	380	370	440
N	<200	150	120	120
C	<200	35	29	46
Al	<200	190	200	190
Fe	<300	220	260	205
Cu	<50	<50	<50	<50
Mo	<50[b]	<50	<50	<50
Nb	<20[b]	140	91	87
Cl	<3	<3	<3	<3
Ga	<10	<1	<1	<1
Ca	<1[b]	4	3	4
Na	<1[b]	<2	<2	<2
K	<1[b]	2	2	2
Mg	<1[b]	1	<1	1
P	<30	<30	<30	<30
S	<30	<10	<10	<10
B	<5	<5	<5	<5
Ag	<1	<1	<1	<1
V	balance	balance	balance	balance

[a]Unless otherwise specified in weight %
[b]Desired values – <5 ppm Mo, <1 ppm Nb, <1 ppm total Ca+Na+K+Mg.

B. Manufacturing Technology Development

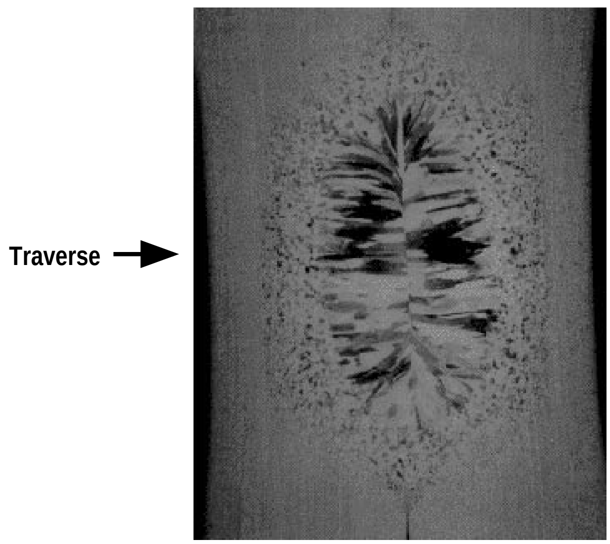
As manufacturing development is a major focus of this project a significant amount of research and development is being performed in this area. The RD structure will require many metal/metal joints, and joining development is therefore a key area of study. GA is using corporate IR&D funds to complement welding efforts at ANL and ORNL, investigating several different joining processes which are attractive for fabrication of RD components including resistance seam, friction, and electron beam welding. The scope of the GA joining development efforts has been limited by the availability of material, some of which has been purchased from TWCA (V-5Cr-5Ti; Heat ID #932394) and some of which has been supplied by ANL (V-5Cr-5Ti alloy; Heat ID #832394 and V-4Cr-4Ti alloy; Heat ID #832665[3]).

Resistance Welding Studies

Resistance seam welding is planned for structurally joining two sheets of vanadium alloy together to make the water-cooled panels for the RD program. However, based on experience with Inconel 625, it is not expected to provide a vacuum-tight weld, and therefore, another process will be used to make the seal weld.

As reported previously,[4] 3.8 mm thick sheet material of V-4Cr-4Ti alloy was obtained from ANL and initial resistance spot weld trials were performed in air. No weld nuggets were achieved on 3.8 mm sheet, although some diffusion bonding was obtained, indicating that the material had reached 80% to 90% of its melting point. These diffusion-bonded samples demonstrated considerable strength (up to 135 MPa) in crude shear tests. Additional trials were performed with similar V-4Cr-4Ti alloy sheet material using weld parameters adjusted upward by an amount estimated to produce melting between the facing surfaces of the sheet samples based on the observed diffusion bonding in previous trials. These trials were successful, yielding weld nuggets ~7 mm in diameter, and microhardness values in the weld and heat-affected zoneds (HAZs) only ~10% greater than that of the parent metal (Fig. 3).

Additional spot weld trials have recently been performed using material similar in thickness to that to be used for the RD water-cooled panels (4.8 mm). For these trials, 6.35 mm thick V-5Cr-5Ti alloy sheet material was supplied by ANL, and this material was cold rolled by ORNL to the required thickness and annealed. Power settings for this thickness were increased (and varied) over that used for the thinner material, using as a starting point, current versus thickness data obtained from the literature for carbon steel, which was found to have similar strength and resistivity to V-4Cr-4Ti and V-5Cr-5Ti alloys. These weld trials were also successful, producing weld nuggets with diameters which correlated with the average power per unit time in the welding cycle, varying from ~3.8 to ~12 mm in diameter. Although all of the weld nuggets generally contained single, small, centrally-located pores, welds ~10 mm in diameter demonstrated considerable strength (~685 MPa based on the nugget diameter measured on a companion sample welded using the same weld parameters) in simple single spot lap shear tests. Although the central pores in these welds do not appear to substantially degrade the strength of the weld joints, several additional spot weld trials using increased electrode (forge) pressures at the end of the weld cycle are



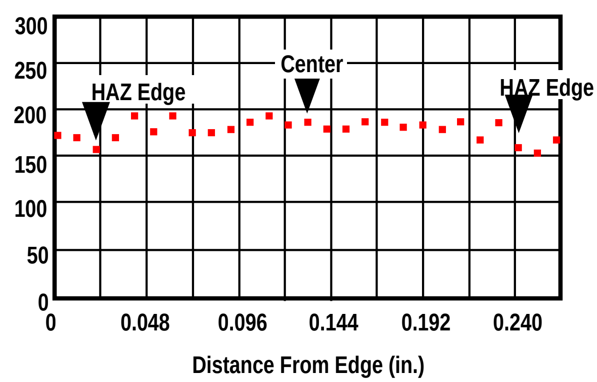


Fig. 3. Resistance spot weld of 3.8 mm thick V-Cr-4Ti alloy sheets with microhardness profile across the weld nugget.

being planned in an attempt to eliminate or minimize them. These trials will then be followed by seam welding trials.

Friction Welding Studies

Two types of friction welding trials are in progress. Inertia (shop) and portable friction welding have been selected as candidate processes for joining vanadium alloy to itself, and inertia welding has been selected for creating a bi-metallic joint between vanadium alloy and Inconel 625. The first inertia weld trials of vanadium alloy (V-5Cr-5Ti alloy) to itself were successful in air. Metallography showed complete bonding with no indications of porosity or cracking, and microhardness measurements showed only slight increases in hardness in the weld and HAZs (Fig. 4). In the photomicrograph shown in Fig. 4, the weld interface maintained a fine grain structure, with little or no grain growth, and a very minimal HAZ. Tensile and torsion tests at room temperature resulted in failures in the parent metal away from the joint and HAZs.

As reported previously,[4] inertia welding trials in air continued with the successful joining of Inconel 625 rod to V-5Cr-5Ti alloy rod. Metallography showed complete bonding with no porosity or cracking, and tensile pull tests performed at room temperature yielded joint strengths greater than ~760 MPa, i.e., near that of the Inconel 625. Inertia weld trials were then performed to fabricate bi-metallic joints using a tube-to-tube configuration. These trials, although encouraging, were not completely successful, producing joints which were not leak tight during helium leak checking and with variable strengths in room-temperature tensile tests (~70–380 MPa). Metallography of a sample showed substantial bonding at the joint interface, but with noticeable porosity. Plastic deformation (buckling) of the tubular portion of the Inconel 625 part in a radially-inward direction (Fig. 5), caused by 1) an inadequate wall thickness (for the applied ram load), and 2) a lack of lateral support from the mating V-5Cr-5Ti alloy part near the inner surface of the Inconel 625 part, which reduced the loading (and also frictional heating) at the joint interface, are postulated as the reasons for the observed results. Additional trials, using a new configuration to alleviate this problem, are currently in progress.

Preliminary portable friction welding trials of vanadium alloy rod to plate have been performed, GA to develop methods of *in-situ* replace-ment of studs on water-cooled panels. Initial trials achieved substantial bonding, but the hardness of the weld interface increased significantly over that of the parent metal. In addition, a large amount of grain growth occurred at the interface and substantial HAZs were developed (Fig. 6). It was noted during the trials that the temperature of the weld interface was significantly higher than that observed in the inertia weld process, and the time to create the weld was considerably onger. It is believed that both of these factors resulted in the observed grain growth, large HAZs, and

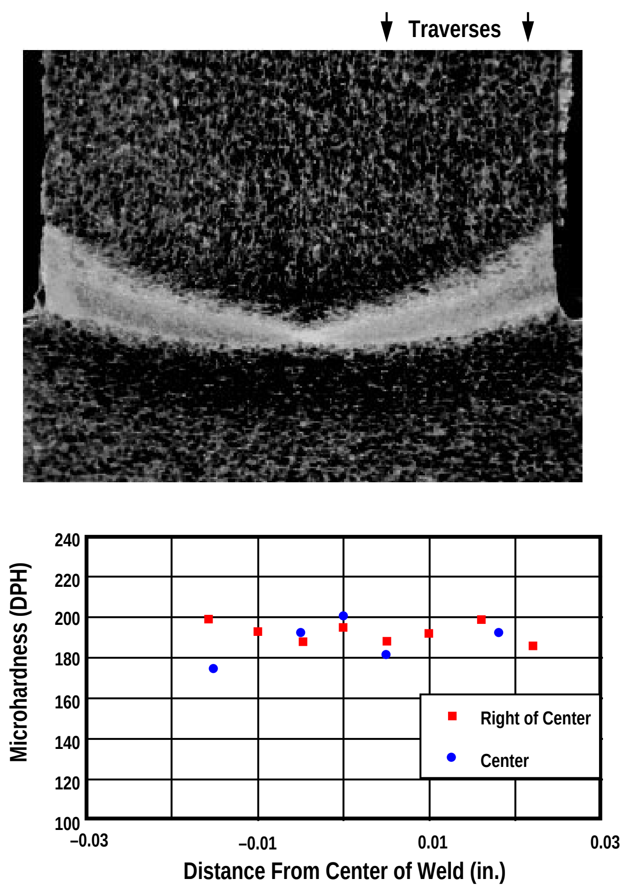


Fig. 4. Etched cross-section of V-5Cr-5Ti alloy inertia weld trial sample showing location of weld joint and microhardness measurements.

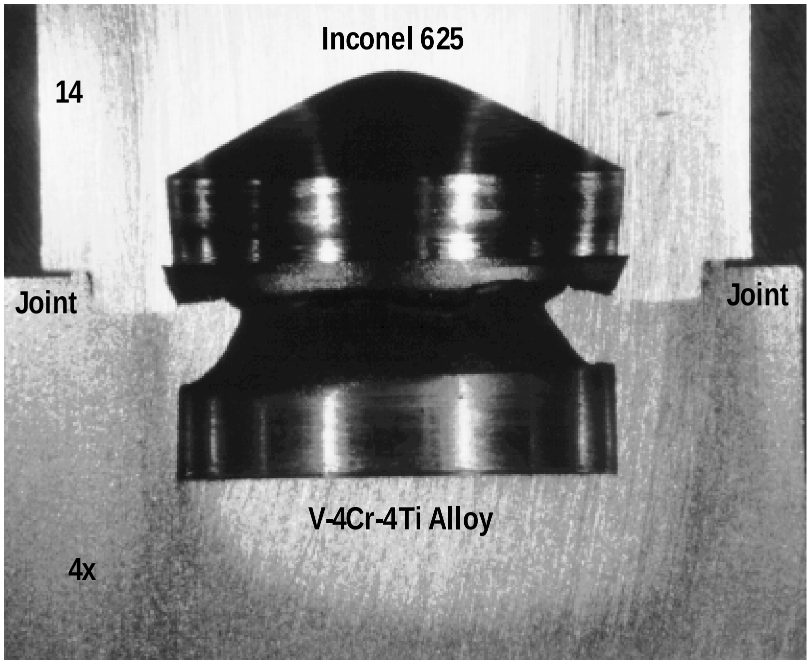


Fig. 5. Ground cross section of inertia-welded V-4Cr-4Ti alloy (bottom)/Inconel 625 (top) joint in simulated tube-tube configuration. Note: indentation and inward plastic flow of original V-alloy surface and inward flow (buckling) of tubular Inconel 625 lip.

increase in weld interface hardness. Additional trials are in progress using weld parameters to minimize these effects.

<u>Electron Beam Welding Studies</u>

Preliminary electron beam welding trials have also been performed at GA to complement the work being performed at ORNL. Initial weld parameters were obtained from ORNL personnel and weld penetration tests were performed using 6.35 mm thick V-5Cr-5Ti alloy plate acquired from ANL to establish specific weld parameters for creating a lap weld of two 3.85 mm thick vanadium alloy sheet materials (V-5Cr-5Ti alloy to V-4Cr-4Ti alloy). A lap weld of the materials was created and verified by metallography to be free of cracks. Microhardness measurements showed less than ~10% increase in hardness across the weld and HAZs, and room-temperature tensile tests performed on flat reduced-section specimens failed in the parent metal well away from the weld joints and HAZs at values greater than the parent metal strength.

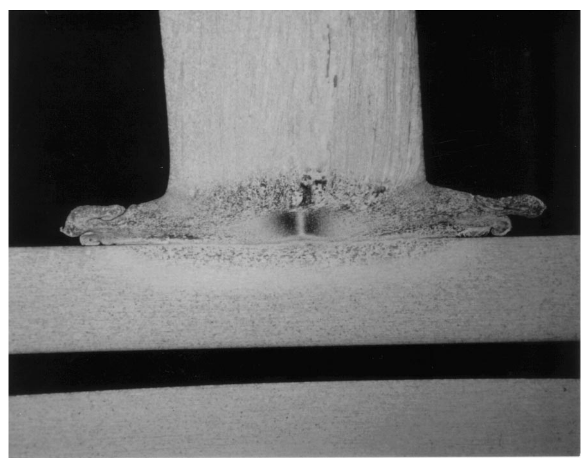


Fig. 6. Etched cross-section of V-5Cr-5Ti alloy portable friction weld trial sample showing location of weld joint.

CONCLUSIONS

A program for utilizing vanadium alloys in DIII–D has been developed to progress the development of low activation alloys for fusion, and production of material for this program has started. Two vanadium ingots have been electron beam melted, consolidated with high purity Cr and Ti, and double vacuum-arc melted to produce a 1200-kg V-4Cr-4Ti alloy ingot of acceptable chemical composition. The alloy ingot has been extruded into rectangular billets and machined into sheet bar for further processing into sheet and rod product forms. Preliminary successes have been achieved in developing similar and dissimilar metal welds in vanadium alloy by resistance, inertia, portable friction, and electron beam welding methods.

ACKNOWLEDGMENTS

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