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

— Semiannual Report Input for 1997

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DISCLAIMER

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PRODUCTION AND FABRICATION OF VANADIUM ALLOYS FOR THE RADIATIVE DIVERTOR PROGRAM OF DIII–D — SEMIANNUAL REPORT INPUT FOR 1997

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

SUMMARY

V-4Cr-4Ti alloy has been selected for use in the manufacture of a portion of the DIII–D Radiative Divertor upgrade. The production of a 1200-kg ingot of V-4Cr-4Ti alloy, and processing into final sheet and rod product forms suitable for components of the DIII–D Radiative Divertor Program (RDP), has been completed by Wah Chang (formerly Teledyne Wah Chang) of Albany, Oregon (WCA). CVN impact tests on sheet material indicate that the material has properties comparable to other previously-processed V-4Cr-4Ti and V-5Cr-5Ti alloys. Joining of V-4Cr-4Ti alloy has been identified as the most critical fabrication issue for its use in the RDP, and research into several joining methods for fabrication of the RDP components, including resistance seam, friction, and electron beam welding, and explosive bonding is being pursued. Preliminary trials have been successful in the joining of V-alloy to itself by resistance, friction, and electron beam welding processes, and to Inconel 625 by friction welding. In addition, an effort to investigate the explosive bonding of V-4Cr-4Ti alloy to Inconel 625, in both tube-to-bar and sheet-to-sheet configurations, has been initiated, and results have been encouraging.

PROGRESS AND STATUS

1. Introduction

General Atomics (GA) has developed a plan for the utilization of vanadium alloys in the DIII–D tokamak. The plan is being implemented with the assistance of the Argonne, Oak Ridge, and Pacific Northwest National Laboratories (ANL, ORNL and PNNL), and will culminate in the operation of a water-cooled vanadium alloy structure in the DIII–D Radiative Divertor (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 currently consists of three phases: first, small vanadium alloy specimens and coupons have been are continuing to be exposed inside the DIII–D vacuum vessel to evaluate the effects of the DIII–D vacuum environment; 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, installed in DIII–D, and operated. In addition, as part of a collaboration between GA and Japan Atomic Energy Research Institute, small vanadium alloy specimens and coupons are being exposed inside the vacuum vessel of the tokamak in Japan to evaluate the effects of the vacuum environment for comparison with data obtained from 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 by GA as part of the DIII-D Program, and with the support of ANL, ORNL, and PNNL, participants in the Materials Program of the Department of Energy's Office of Fusion Energy (DOE/OFE).

2. PHASE 1: Specimen and Coupon Exposures and Analysis

Minature Charpy V-notch (CVN) impact and tensile specimens of V-4Cr-4Ti alloy (ANL 500 kg heat)[3] were exposed/monitored in DIII–D in a position on the vessel wall behind the divertor baffle for ~9 months, experiencing a maximum temperature of ~350°C.[4] CVN tests conducted at ANL at temperatures over the range of –196 to +150°C indicated ductile behavior for all test temperatures, and tensile tests conducted at ambient and elevated temperatures indicated values similar to that for unexposed material.[5] A new set of V-4Cr-4Ti alloy samples, installed during the January 1996 vent, is currently undergoing exposure to provide more data for confirmation and statistical verification.

In parallel to these exposures, additional 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, miniature CVN specimens, were exposed/monitored during bakeout of the DIII–D vacuum vessel (maximum temperature of ~350°C).[4] CVN tests conducted at ANL at temperatures over the range of –196 to +150°C indicated ductile behavior for all temperatures.[5] A surface analysis (for hydrogen) of the V-4Cr-4Ti alloy disc specimen was completed at Sandia National Laboratory in Albuquerque, NM, and evaluation of that data was performed at ANL and reported previously.[5] Other DiMES exposures of V-4Cr-4Ti alloy are being considered to evaluate the effects of other DIII–D environmental conditions (e.g., discharge cleaning, boronization, etc.) In addition, miniature and standard CVN specimens, miniature tensile specimens, standard bend specimens, and small coupons (for O and H analysis) of V-4Cr-4Ti alloy (GA 1200-kg heat) are being exposed/monitored in the Japanese tokamak JFT-2M in a position under the JFT-2M divertor baffle, where they will experience a maximum temperature of ~300°C. These specimens and coupons will be evaluated jointly by JAERI and GA after their removal.

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. Fabrication of this component is planned for the end of 1997, but a specific design for the component has 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 RDP will be performed as the third phase of the vanadium alloy program. Details of the structural design of the toroidally-continuous, water-cooled and radiatively-cooled structural panels which make up the V-4Cr-4Ti alloy private flux baffle were presented in a previous report.[4]

The water-cooled panels for the V-4Cr-4Ti alloy baffle will be fabricated of sandwich construction from two 4.8 mm sheets, each containing a wide 1.5 mm deep slot milled into its face to provide an internal coolant channel. Resistance seam welding is the primary candidate process being considered for structurally joining the panel edges, with electron beam welding proposed for making a leak-tight perimeter seal. Other methods of joining are proposed for different areas of the design such as the graphite armor tile attachment studs and cooling water inlet and outlet manifolds. To facilitate installation, V-4Cr-4Ti alloy/Inconel 625 joints are planned to provide a bi-metallic tube nipple. This component will be used to transition V-alloy water-cooled panels to Inconel 625 tubes which provide a cooling water supply.

A. Fabrication of Product Forms for the Radiative Divertor

Processing of the V-4Cr-4Ti alloy by WCA was initiated in September 1995, and the finished sheet and rod product forms were completed and received by GA from WCA in October 1996. Complete details of the processing, including melting of the 1200-kg ingot, extrusion into billets, warm rolling of the billets into sheet bar material, warm processing (rolling and swageing) of sheet bar material into 4.8 mm thick sheet and 11 mm diameter rod product forms, and chemical analysis of various processed forms, were presented in previous reports.[4,6,7] CVN tests were conducted at ANL on miniature specimens excised from sheet material to characterize the fracture behavior of the heat. Tests conducted at temperatures over the range of –196 to +25°C indicated ductile behavior for all temperatures. The GA heat exhibited a ductile/brittle transition (DBTT) temperature below -196C and an upper shelf energy of ~10 J. The DBTT of the GA heat was similar to that obtained for previously-processed V-4Cr-4Ti and V-5Cr-5Ti alloy heats whereas the upper shelf energy was slightly lower than for the other alloys (~12–16 J).[8] Support will be continued by ANL and ORNL in the development of basic engineering design properties for these product forms.

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 private 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, electron beam welding, and most recently, explosive bonding. Until just recently, i.e., prior to the receipt of the sheet and product forms from the GA heat, the scope of the GA joining development efforts had been limited by the availability of material, some of which has been purchased from WCA (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]). In addition, where required thicknesses of material were unavailable for weld trials, ORNL performed warm and/or cold rolling of available materials to the required thicknesses.

<u>Resistance Welding Studies</u>

Resistance seam welding studies in air have been completed to develop the method for structurally joining sheets of vanadium alloy together to make the water-cooled panels for the RDP.

As reported previously,[4,6,7] spot weld trials were initially performed on 4.8 mm thick V-5Cr-5Ti alloy and V-4Cr-4Ti alloy sheet materials utilizing variations in power input (welding current and dwell time) and electrode pressure, producing diffusion bonds at low power levels and weld nuggets with minimal porosity at higher power levels. Both diffusion-bonded and fully-welded materials had similar strengths (~380 Mpa) in simple spot weld lap shear tests, well above that specified by American Welding Society standards for material of this strength level.

Resistance seam (overlapping spots) welds were then performed on similar 4.8 mm V-4Cr-4Ti alloy sheet using copper alloy wheel electrodes and a variety of power settings, and electrode (wheel) pressures, wheel diameters, and wheel radii. Although full melting (i.e., nugget formation) could not be achieved at the faying surfaces of the coupon samples without some melting of the copper electrodes and surface cracking, leak-tight seam diffusion bonds (~5 to 10 mm in width) were obtained which exhibited room-temperature lap shear test strengths comparable to that achieved for similar spot-welded (and spot-bonded) material.

In addition to the resistance welding studies, preliminary tests were completed at PNNL to study the potential for stress corrosion cracking of vanadium alloy resistance welds in DIII–D cooling water. PNNL performed several crack growth tests on specimens of V-4Cr-4Ti alloy (ANL 500 kg heat[3]) in DIII–D cooling water at a stress intensity of 30 Mpa- $\sqrt{m}$, a factor of ten times the calculated value based on stress analysis. No measurable crack growth, confirmed by SEM analysis of fracture surfaces obtained after the specimens were rapidly broken in tension, was observed during either test (32 and 60 days). [9]

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 as one method for creating a bi-metallic joint between vanadium alloy and Inconel 625. Initial rod-to-rod inertia weld trials of vanadium alloy (V-5Cr-5Ti alloy) bonded to itself, and to Inconel 625, were successful in air, without any protective environment. Metallography showed complete bonding with no indications of porosity or cracking, and mechanical tests at room temperature resulted in failures in material well away from the joint and HAZs, at stress levels greater than the strength of the V-alloy.

As reported previously,[4,6,7] inertia weld trials were performed to fabricate bi-metallic V-5Cr-5Ti alloy/Inconel 625 joints in a butt joint configuration which could be machined into a bi-metallic tube nipple, a component which could be joined to a V-alloy water-cooled panel (via a controlled shop weld, e.g., electron beam welding) and subsequently to an Inconel 625 cooling water tube (via a field tungsten-inert gas weld). After initial unsuccessful attempts, followed by a joint configuration change, joints were produced which were vacuum leak tight to DIII–D standards and exhibited strengths >~720 MPa in room-temperature tensile pull tests, with failures occurring in a ductile (tearing) mode in the V-alloy away from the joint.

As previously reported,[6,7] portable friction welding trials of vanadium alloy rod to plate were also performed to develop methods of *in-situ* replacement of studs on water-cooled panels. After several partially-successful trials, in which substantial bonding was achieved, but with attendant large hardness increases at the weld interface and thick heat-affected zones (HAZs), additional trials were performed using shorter welding times to reduce heat input, and ram pressures and rotational speeds were selected to be similar to that used for the successful inertia weld trials.

These trials yielded several samples which were bonded over ~100% of the contacting areas, possessed no observable porosity, and exhibited a joint strength comparable to that of the V-4Cr-4Ti alloy. An additional set of ~40 trials, utilizing threaded studs similar to that to be used for fabricating the RD structure, is currently in progress.

Electron Beam Welding Studies

Preliminary electron beam welding trials on 6.35 mm V-5Cr-5Ti alloy sheet have been completed, and were reported previously.[6]

Explosive Bonding Studies

Explosive bonding is being investigated as an alternate method for producing a dissimilar metal joint between V-4Cr-4Ti alloy and Inconel 625 for application as a tube nipple/connector to transition a V-4Cr-4Ti alloy water-cooled RD panel to an Inconel 625 water supply tube. A lap joint for this tube-to-tube configuration may be more preferable for this application compared to the butt joint configuration developed by inertia welding because of its enhanced mechanical strength and potential for a longer (up to ~10 times) leak path between the cooling water inside the tube and the external vacuum environment of DIII–D.

As reported previously, [7] a preliminary explosive bonding trial of a V-4Cr-4Ti alloy tube (~150 mm long × 22.1 mm o.d. × 2 mm wall) to an Inconel 625 round bar was performed. This trial was partially successful, producing a vacuum leak tight joint with no porosity only over about 1/2 of the length of the sample. Another bonding trial is being planned in which additional explosive material will be placed on the outer surface of the V-4Cr-4Ti alloy tube in order to bond the entire length of the sample. For this trial, 22 mm O.D. × 2 mm wall V-4Cr-4Ti alloy tubing is currently being fabricated (by cold drawing) from a section of 47 mm thick V-4Cr-4Ti alloy sheet bar longitudinally rolled from extruded billet material.

Another method being pursued for developing a V-4Cr-4Ti alloy/Inconel 625 tube nipple/connector involves the forming of explosively-bonded V-4Cr-4Ti alloy/Inconel 625 sheet material into a tubular shape by a deep drawing process. As part of this investigation, a preliminary explosive bonding trial of a V-4Cr-4Ti alloy sheet (380 mm × 125 mm × 2 mm thickness) to an Inconel 625 sheet (1.25 mm thickness) was performed. Ultrasonic testing of the explosively-bonded composite sheet showed no indications of debonding between the two materials, and metallography of samples excised from a number of locations in the sheet revealed no evidence of porosity at the bond line between the V-4Cr-4Ti alloy and the Inconel 625. Plans are currently underway to perform shear tests on strips excised and machined from the explosively-bonded sheet. In addition, another explosive bonding trial has recently been performed using larger pieces of sheet material (~360 mm × ~230 mm) in order to provide a sufficient amount of material for deep drawing studies. Evaluation of this bonding trial is currently in progress.

CONCLUSIONS

A program for utilizing vanadium alloys in DIII–D has been developed to assist the deployment of low activation alloys for fusion applications, and production of material for this program has been completed. A 1200-kg V-4Cr-4Ti alloy ingot of acceptable chemical composition has been melted, extruded into rectangular billets, and processed into sheet and rod product forms. CVN impact properties of the finished alloy are comparable to those of previously-processed V-4Cr-4Ti and V-5Cr-5Ti alloys. Preliminary successes have been achieved in developing similar and dissimilar metal welds in vanadium alloy by resistance, inertia, portable friction, and electron beam welding, and explosive bonding methods.

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