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MATERIALS TESTS AND ANALYSES OF FARADAY SHIELD TUBES FOR ICRF ANTENNAS

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ABSTRACT

The ion cyclotron resonant frequency (ICRF) antennas for heating fusion plasmas require careful analysis of the materials selected for the design and the successful fabrication of high integrity braze bonds. Graphite tiles are brazed to Inconel 625 Faraday shield tubes to protect the antenna from the plasma. The bond between the graphite and Inconel tube is difficult to achieve due to the different coefficients of thermal expansion. A 2-D stress analysis showed the graphite could be bonded to Inconel with a Ag-Cu-Ti braze alloy without cracking the graphite. Brazing procedures and nondestructive examination methods have been developed for these joints. This paper presents the results of our joining development and proof testing.

INTRODUCTION

The radio frequency (rf) development group at ORNL is designing, fabricating, and testing antennas to supply large amounts of auxiliary heating power to fusion-grade plasmas in the Toroidal Fusion Test Reactor (TFTR) and Tore Supra. Each antenna consists of a pair of resonant double loops in a single, movable housing designed to fit through a horizontal midplane port. Each loop is designed to launch up to 2 MW of power for a total of 4 MW per port. A single Faraday shield structure protects the loops which are mounted side by side on TFTR and Tore Supra (see Fig. 1). The Faraday shield consists of two tiers of actively cooled Inconel alloy tubes. The front tier is covered with semicircular graphite sleeves to minimize the introduction of high-Z impurities into the plasma from the Faraday shield.[1,2] Successful operation of the antenna requires the making of high integrity bonds between the Inconel tubes and graphite tiles by brazing.

FARADAY SHIELD TUBES

Materials

The front row tubes of the TFTR and Tore Supra rf antenna Faraday shields are 9.5 mm diam and 440 to 480 mm long. They are made from Inconel 625 alloy. This alloy was chosen for its high tensile and fatigue strength that is derived from additions of molybdenum and niobium to a nickel-chromium matrix. These tubes, which are copper plated for improved electrical conductivity, are protected from the plasma heating flux by brazing a graphite tile to the front side. POCO AXF-5Q graphite was chosen for this application because it is a very fine-grained, isotropic material with suitable strength and thermal expansion properties. The fine-grained graphite was important to the brazing operation since it reduces the wicking of the molten braze alloy into graphite. Brazing tests with other grades of graphite had resulted in nearly all the braze material being wicked into the graphite, leaving none at the joint area. The braze for this application was Ticusil, an active metal braze alloy containing silver-copper-titanium produced by GTE WESGO. It has a brazing temperature of nominally 845°C. The differences in thermal expansion properties of the Inconel 625 and the graphite tile cause residual stresses in the brazed tiles to occur as it is cooled to ambient temperature from the brazing temperature. The magnitude of these stresses are of concern because of the relatively low tensile strength of the graphite tile.

2-D Stress Analysis

The residual stress state in the tube-to-tile braze joints was obtained by utilizing a 2-D finite element model analysis with the MSC/NASTRAN code. A nonlinear analysis technique was utilized to obtain residual stress states in the two materials as shown in Fig. 2. The results indicate that the stresses in the POCO graphite are well below the failure criteria. The results shown are for one-half of a brazed tube which contains a perfect braze with no unbonded areas. Studies are continuing to estimate the change in stresses when defects are present in the braze joints.

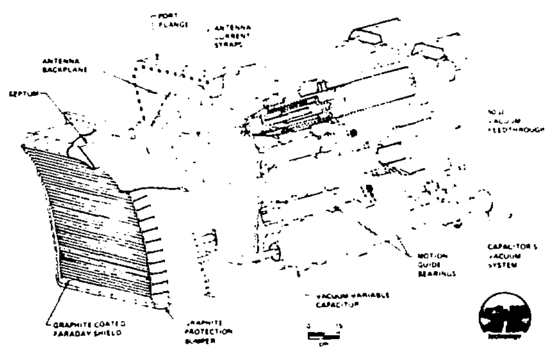

Fig. 1 The antenna for TFTR.

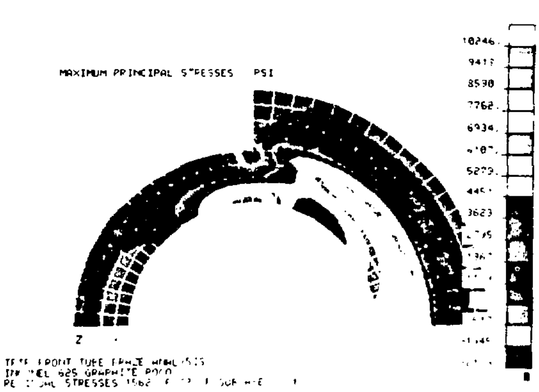

Fig. 2 Residual stress state in Faraday shield tube resulting from brazing graphite tile.

During normal operation of the rf antenna, the tubes will be subjected to plasma and rf heating. These heating fluxes will produce temperature gradients in the graphite and Inconel material, and these gradients will induce additional stresses into the materials. The final state of stress will consist of a combination of the residual stresses from the brazing process and the stresses produced by the heating fluxes. The MSC/NASTRAN 2-D model was used to predict the temperature gradients and the subsequent stresses from the heating conditions and the combined stresses for the two sources. Examination of the combined maximum and minimum principal stresses indicate they are within allowable limits.

Brazing Procedure

Brazing tests were performed for joining the graphite tile to the copper-plated Inconel tubes. Initial results were inconsistent for the bond area between the two components. Detailed analyses of the test brazes revealed that several problem areas had contributed to the variability of the bonds and to the presence of large voids in the braze.

The first of these was the design of the joint and the accurate control of the joint tolerances. Consistent braze bond results require that very accurate joint clearances be present to permit the flow of the braze alloy by capillary action. Due to the differences in coefficients of expansion between POCO AXF-5Q graphite and Inconel 625, the proper joint clearances must be obtained at the brazing temperature, not at room temperature. The graphite semicircular tiles' inside diameters were machined to match the outside diameters of the tubes at 845°C, the brazing temperature. Additionally, it was found that the standard drawn tubing outside diameter was not accurate enough to provide consistent braze results. It was necessary to machine the tube to a consistent diameter (± 0.0125 mm) prior to copper plating and then control the thickness of the plating. Control of the graphite tile inside diameter tolerances was equally important. Finally, it was necessary to design braze fixtures which accurately aligned each of the 18 to 20 tiles required for each tube. These fixtures were fabricated from graphite, Inconel, and TZM to match the expansion of the tiles during heat-up to the braze temperature.

The second problem area identified in the test braze experiments was variability in achieving the brazing temperature. Control of the vacuum furnace temperature was inadequate to produce consistent results. It is essential to know the temperature at the braze joint. Thermocouples were placed inside the Faraday shield tubes during brazing to assure accurate attainment of the 845°C brazing temperature at the joint. This temperature control combined with the proper joint dimensions produced braze bonds as shown in the photomicrograph in Fig. 3.

A third problem area which affected the yield of acceptable tubes was control of the vacuum furnace gas pressure. The graphite was cleaned and baked to 1000°C for 2 h prior to brazing. Exposure to air occurred during assembly of the parts on the brazing fixture. When the tubes were raised directly to brazing temperature after pumpout, the rejection rate of tubes based on a criterion of 80% bonding for the worst tile was about 33%. After instituting a bakeout in situ at 650°C for 30 min followed by an overnight pumpout, the rejection rate was reduced to less than 10%.

Nondestructive Examination

Two NDE techniques were developed to inspect the braze joints in the Faraday shield tubes. These were infrared thermography and radiography. Both techniques were used for determining the integrity of the bonds. Infrared thermography was used to screen the brazed tubes for unbonded areas between the graphite and Inconel. Heating for this thermal analysis was obtained by resistance heating the Inconel tube with a pulse of 700 A, ac, for approximately 0.2 s. The graphite tiles were photographed with an AGA Model 680 infrared camera at 0.2 s from the initiation of the current pulse. Analysis of the photographs revealed any unbonded areas in the braze joints or laminar cracks in the graphite as areas of

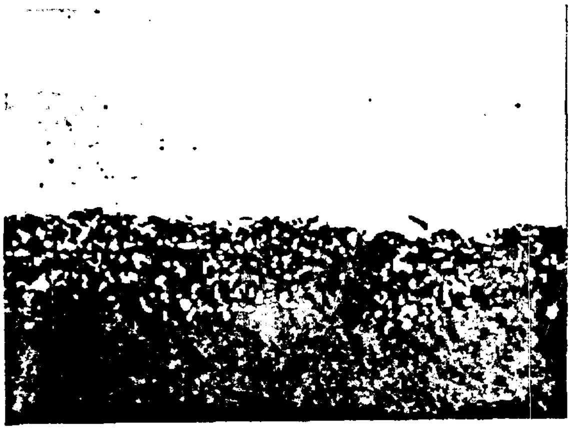

Fig. 3 Braze bond between POCO AXF-5Q graphite and copper-plated Inconel 625.

lower temperature than the bonded regions. The practical flaw size detection with this equipment is estimated to be 3 mm diam. The theoretical flaw size detection was calculated to be 1.5 mm diam.

Radiography was used to determine more quantitative information about the unbonded flaw sizes present in the braze joints. A series of tangential radiographic exposures were made through the brazes joints at approximately 30° rotations of the tube. Close examination of the film allowed for actual measurements to be made of unbonded regions. Each of the tiles on each Faraday shield tube were examined. If unacceptable bonds were detected the tube was discarded. Our goal was to achieve at least 90% total bond area for the graphite tiles with no tile having less than 80% bonded area to insure satisfactory performance of the Faraday shield. We met this requirement by averaging 94% bond area per tube.

Proof Testing

After radiographic and infrared inspection, some tube samples were tested by exposing the graphite tiles to a neutral beam. The tests fell into two categories: disruption tests where high thermal loads were imposed for very short pulses (45 J/cm^2 in 20 ms), and normal operational tests with lower loads for long pulses. The tubes sustained 10,000 disruption shots with no damage. Other disruption tests with the energy flux increased fourfold (192 J/cm^2) showed that a partially bonded tile could sustain the heat flux. The long pulse tests were first performed with 1,000 shots at 140 W/cm^2 for 2 s in both a restrained condition (ends of tubes welded in a frame) and an unrestrained state. This is more than the design heat flux for TFTR or Tore Supra. Then a sample was subjected to 10,000 shots at 350 W/cm^2 for 2 s with no damage. The thermal testing results showed that braze bonded graphite can sustain substantially more heat flux than specified by the designs.

SUMMARY

Reliability of the graphite-to-Inconel tube braze bonds in the Faraday shield of the ICRF antennas is critical if it is to survive in the plasma edge environment with heating from both the plasma and rf sources. Joining of graphite to Inconel by brazing is difficult due to the mismatch of properties and coefficients of expansion. A 2-D stress analysis showed that POCO AXF-5Q graphite tiles can be brazed to Inconel 625 tubing without cracking the graphite. Accurate control of braze joint tolerances at the brazing temperature and attention to all details of the brazing operation were necessary to obtain joints of high integrity for this application. Infrared thermography and radiographic NDE techniques were developed to inspect the braze bonds for any defects that could be present. Bonding between the graphite and the tubes has averaged 94% of the total area per tube for a Faraday shield.

ACKNOWLEDGMENTS

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