CONF-871007--33

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BRAZING OF CERAMIC AND GRAPHITE TO METAL IN THE FABRICATION OF ICRF ANTENNA AND FEEDTHROUGH COMPONENTS*

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CONF-871007--33

DE88 001763

Abstract

Fabrication of some of the more critical components of ion cyclotron range of frequencies (ICRF) antenna and feedthrough assemblies has involved the brazing of alumina ceramic and graphite to various metals. Copper end pieces have been successfully brazed to alumina cylinders for use in feedthroughs for TEXTOR and in feedthroughs and capacitors for a Tokamak Fusion Test Reactor (TFTR) antenna. Copper-plated Inconel rods and tubes have been armored with graphite for construction of Faraday shields on antennas for Doublet III-D and TFTR. Details of brazing procedures and test results, including rf performance, mechanical strength, and thermal capabilities, are presented.

Introduction

The rf technology program at the Oak Ridge National Laboratory (ORNL) is actively involved in the development of hardware for heating fusion plasmas with rf waves in the ICRF. Components designed and fabricated at ORNL have been installed on or are planned for present-day fusion experiments throughout the U.S. and EURATOM programs. This hardware includes coaxial rf vacuum feedthroughs that are being used on the TEXTOR tokamak in the Federal Republic of Germany, a compact loop antenna that has been delivered to Doublet III-D, and antennas that are being built for the TFTR, Tore Supra, and the Advanced Toroidal Facility (ATF).

Figure 1 is a cross-sectional view of an ORNL 50-Ω rf feedthrough. A critical component is the cylindrical alumina sealed between the inner and outer conductors. It must have high transparency to rf waves and withstand high rf voltage (up to 100 kV) while maintaining vacuum on one side and insulating gas pressure on the other. Brazed to each end of the insulator are metal rings that seal to the adjacent structure with metal or elastomer O-rings. The braze joints and insulator must be moderately strong to withstand axial and transverse forces.

The first ORNL feedthroughs used a commercially available insulating break assembly consisting of an alumina cylinder with thin Kovar sleeves brazed to the ends. Performance of this feedthrough was limited by the size of the insulator and by the composition and geometry of the sleeves. To improve the performance, a new insulator assembly was developed.

We began our development of an insulator assembly by brazing niobium to alumina. Niobium has fairly good electrical conductivity (~14% that of copper), and its thermal expansion closely matches that of alumina. Relatively thick (6-mm) niobium end pieces were brazed to the flat ends of a 96% alumina cylinder using an active metal type (Ticusil†) brazing alloy foil. Leak-tight assemblies were routinely produced. However, when they were installed into feedthrough assemblies, the slight flexing of the niobium due to uneven clamping pressure frequently cracked the braze joints and caused leaks. Even when successfully installed, the assemblies were susceptible to shock. The problem was more severe with metal seals than with elastomer O-rings. The end pieces were made thinner, and the braze joints were made on the outside of the alumina, but limited success was realized with these modifications. During this time, development of an insulator assembly with copper end pieces was undertaken. The resulting design is used for support and insulation of the variable capacitors and the feedthrough in the compact loop antennas.

Another critical part of a compact loop antenna assembly is the Faraday shield. Figure 2 shows the Faraday shield on a development antenna. This array of tubes must shield the

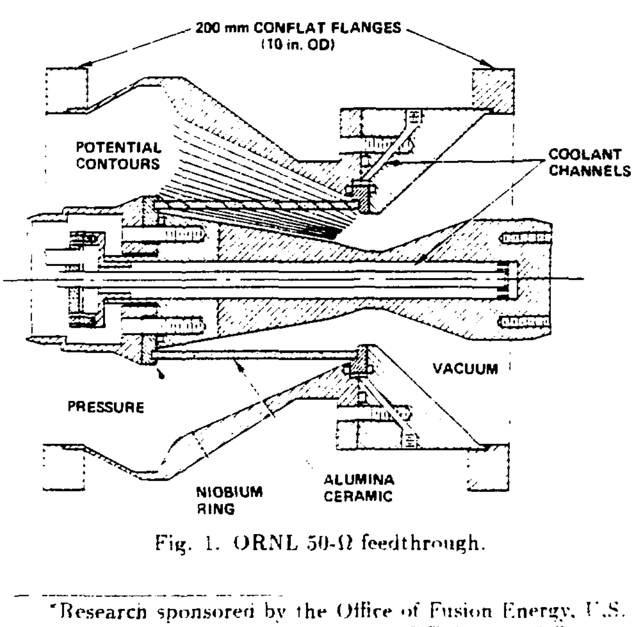

Fig. 1. ORNL 50-Ω feedthrough.

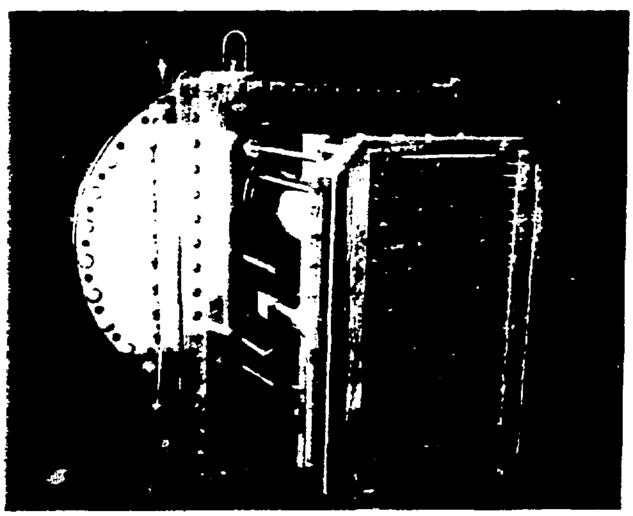

Fig. 2. Graphite Faraday shield on development antenna.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

†Ticusil, a silver copper brazing alloy containing 4.5% titanium, is a product of WESGO Division, GTE Products Corp.

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radiating element from the plasma that it heats. The Faraday shield must be highly transparent to rf waves; it must also withstand the erosion and heat from plasma particles that bombard it without contaminating the plasma. The Faraday shield elements are made of copper-plated Inconel alloy with graphite brazed to the side facing the plasma. For short-pulse (~5-s) applications, active cooling usually is not required, but for long-pulse (tens of seconds to continuous-wave (cw)) operation, coolant must flow through the elements.

Copper-to-Alumina Insulator Development

Design Considerations

Copper is an excellent choice of material for this application because of its high electrical and thermal conductivities. The drawback, however, is the large difference in the thermal expansions of copper and alumina (~1% at 850°C). This problem was addressed by making the braze joints along tapered surfaces on the outside ends of the alumina. The parts are allowed to settle together, maintaining close contact at the tapered surfaces as the copper pieces expand more than the alumina during heating to brazing temperature. Then, during cooldown, the contracting copper is restrained by the alumina and yields. The yield strength of copper is low (~7×10^3 N/cm^2) compared to the compressive strength of alumina (~2×10^5 N/cm^2). In addition, the copper is machined with thin cross sections to further weaken its total yield strength (see Fig. 3).

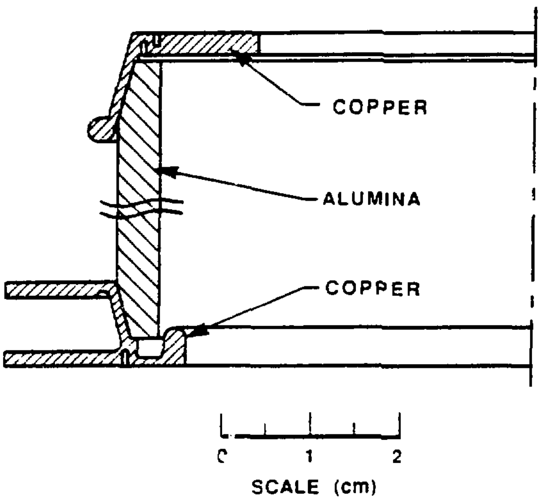

Fig. 3. Cross section of the ends of the insulator.

Brazing Procedure

Figure 4 shows the parts of an insulator assembly and a fixture for holding them in alignment during brazing. The 96% alumina cylinder is 9.5 cm in diameter and 11.7 cm long. It has a 0.5-cm-thick wall and 15° by 5-mm tapered ends. The corresponding 15° tapered surfaces on the copper pieces are machined with a smaller diameter than the alumina; the amount of difference is equal to the thermal expansion difference between copper and alumina. A narrow step machined at the bottom of each tapered surface provides a stop for the ends of the alumina.

The brazing fixture consists of a stainless steel bottom flange with a spindle welded at the center and a heavy top flange with a center hole that slides onto the spindle. Both flanges have steps that fit the inside diameters of the copper end pieces.

The alumina and brazing alloy are cleaned before brazing with an ammonia-type cleaner and ethyl alcohol. The copper

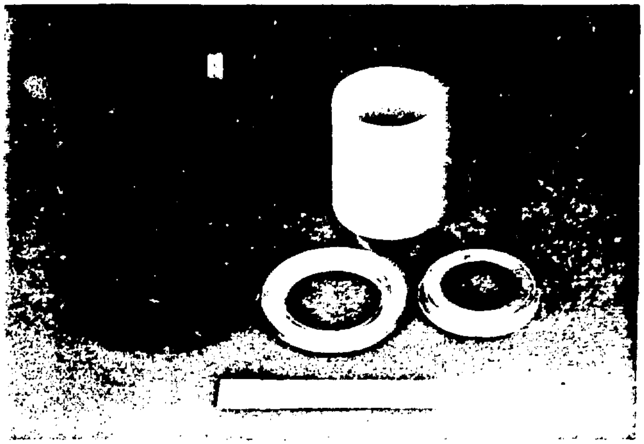

Fig. 4. Insulator parts and brazing fixture.

parts are degreased and chemically etched in a "bright dip" solution.

The alumina and copper pieces, with strips of 0.125-mm-thick Ticusil brazing alloy positioned in the tapered interfaces, are stacked together on the brazing fixture as shown in Fig. 5. This assembly is placed in a vacuum furnace, heated to 850°C, held at this temperature for 20 min, and allowed to cool in vacuum to 50°C.

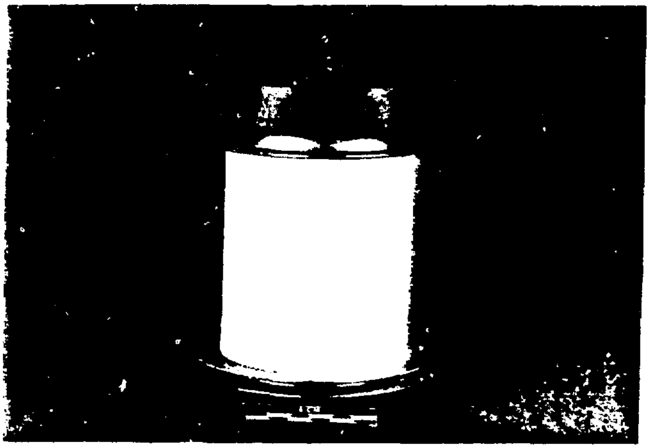

Fig. 5. Insulator parts on fixture for brazing.

Brazing Results

Figure 6 shows a brazed insulator assembly. The insulator area between the copper ends should be free of braze material. Figure 7 shows an area where braze material has migrated up the insulator away from the end pieces. This degrades performance; the material must be removed by careful grinding if optimum performance is to be obtained.

Leak tightness is the main requirement of the brazed assembly. Insufficient dimensional accuracy, which caused too much braze joint clearance, was the usual reason for leaks.

Mechanical Tests

Two tests of mechanical strength were made on an insulator assembly mounted in a feedthrough. In the first test, the feedthrough was held horizontally by securing the outer conductor to a stationary support. A fixture was attached to the center conductor end, and a transverse static force equivalent to 40 kg was applied. This produced a moment of force

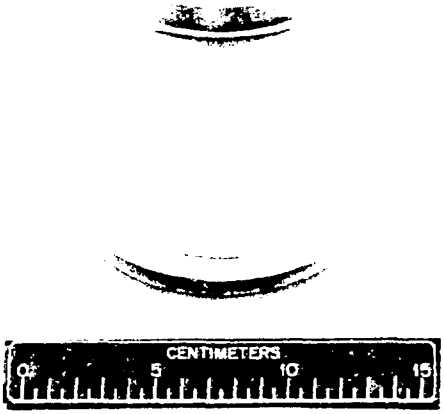

Fig. 6. Brazed insulator assembly

Fig. 7. Braze material on insulator

[illegible] kg m at the outer conductor end of the insulator. In the second test, with the feedthrough under vacuum and in a vertical position, an axial force equivalent to 920 kg was applied to the center conductor, putting the insulator in compression. The insulator assembly withstood both of these tests and remained leak tight.

RF Performance

The voltage limits of a 50 Ω feedthrough have been measured on a test stand at 25 MHz. With 2 atm of [illegible] on the pressure side, the voltage limits were [illegible] kV for [illegible] ms pulse, 80 kV for a 5-s pulse, and 75 kV [illegible]. [illegible] of these feedthroughs are in service [illegible] and have been operating at 40 kV and a power [illegible] s pulses.

Faraday Shield Elements

Fabrication

The [illegible] which graphite [illegible] brazed [illegible] and [illegible] have been [illegible] strength and [illegible] of [illegible]. [illegible] 0.05 mm of [illegible] before brazing [illegible]. The graphite (POCO AXF-5Q) [illegible] of [illegible] beveled ends. The internal radius of the [illegible] outside diameter of the tubes (see Fig. 8).

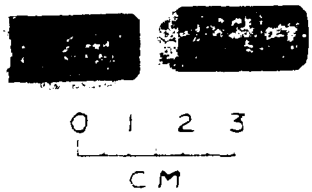

Fig. 8. Graphite shells

A grooved graphite plate is used to position the graphite shells and tubes for brazing. Shells are placed in the grooves with their convex sides down. With wires setting the desired spacings, the shells are secured to the graphite plate with brazing cement (see Fig. 9). Lengths of 0.075-mm-thick Incusil brazing alloy are preformed to the outside diameter of each tube. Then the tubes are positioned in the graphite shells, with the preformed alloy between tube and shell. A flat graphite plate is placed on top of the tubes (see Fig. 10). This assembly, with 31 kg of mass added, is heated to 850°C in a vacuum furnace, held at this temperature for 30 min, and cooled in vacuum.

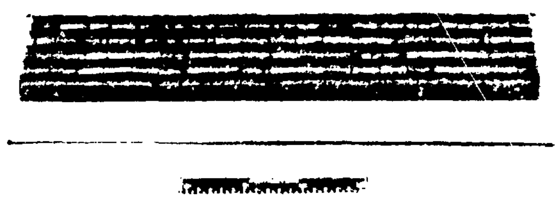

Fig. 9. Graphite shells cemented to plate

Fig. 10. [illegible]

Brazing Results

Although there is an appreciable difference in the thermal expansions of graphite and Inconel [illegible], the strength and flexibility of thin graphite and the ductility of the brazing alloy made it possible to make satisfactory braze joints. Some brazed tubes are shown in Fig. 11. Figure 12 shows the external braze fillet between the graphite and the Inconel. Figure 13 is a photomicrograph of the cross section of a brazed tube and shows a satisfactory braze joint. There is a small (~0.07 mm) amount of diffusion of braze material into the graphite. Results like those shown in Figs. 11–13 can be expected when good fit and intimate contact between graphite and tube are maintained during brazing. Figure 14 shows what can happen when close contact is not maintained. Other problems included excess braze material flowing into graphite end spaces and cracked graphite shells. Close (~0.02 mm) dimensional tolerances on all parts, including holding fixtures, are essential in obtaining optimum brazing results. Maintaining these tolerances has been very difficult.

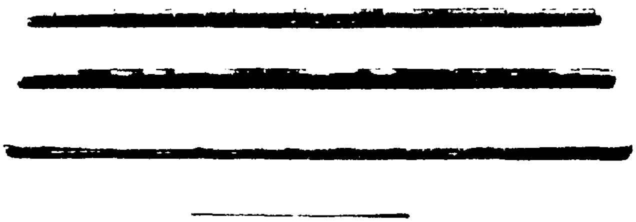

Fig. 11. Brazed tubes.

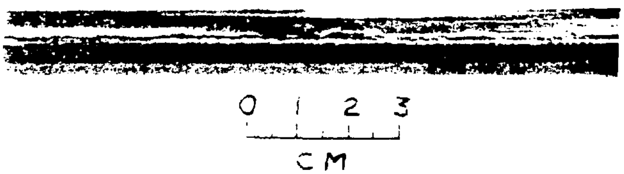

Fig. 12. Braze fillet.

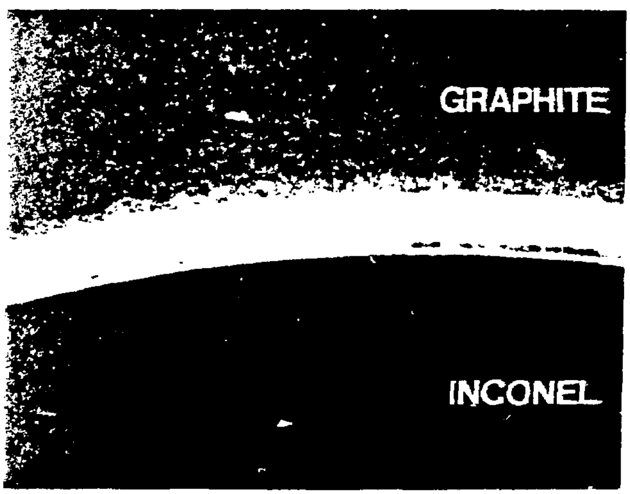

Fig. 13. Photomicrograph (60×) of braze joint between graphite and copper plated Inconel.

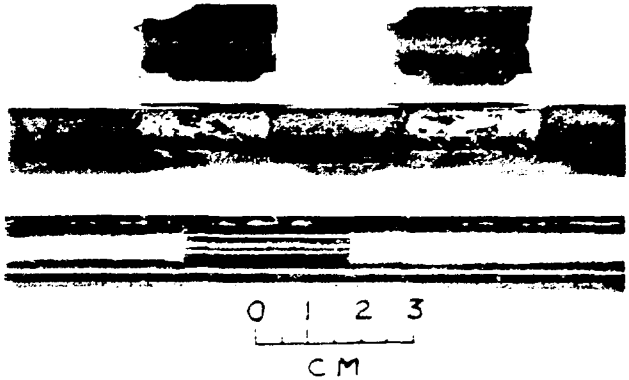

Fig. 14. Results of poor contact during brazing

Thermal Tests

Tests were made on sample graphite armored Inconel tubes to determine their ability to withstand the heat flux of energetic particles. One tube was restrained at the ends so that it could not expand freely; another was unrestrained. Both were cooled with water flowing at 20 cm^3/s. Each sample was exposed to a 25-keV hydrogen particle beam at an average power level of 140 W/cm^2 (peak level of 200 W/cm^2). Each sample received 1000 1-s beam pulses at a 10-s repetition rate. Both tubes withstood these tests with no visible effects.

Mechanical Tests

Tests were performed to determine the effect, if any, of the brazing alloy on the mechanical strength of the Inconel. Brazed and unbrazed tubes were tensile tested to determine their yield strengths. No appreciable difference in strength was found. Also, photomicrographs of the brazed tubes showed no significant diffusion.

Conclusion

Insulator assemblies constructed of copper brazed to 96% alumina with Ticusil alloy have been produced for use in rf feedthroughs and antennas. Mechanical strength is adequate, and rf performance is good.

Faraday shield elements constructed of Inconel and graphite brazed with Ticusil have been satisfactorily produced when close tolerances of the parts were maintained.

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