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Brazing of High Performance, Passively Cooled, Heat Absorbing Mirrors for Electron Cyclotron Heating Launchers

Mr. Stephan Z. Jurczynski[1], Mr. Robert A. Ellis[1], Dr. Joel C. Hosea[1]
1Princeton Plasma Physics Laboratory, Princeton, NJ, USA

Mr. Howard Grunloh[2] and Dr. John Lohr[2]
[2]General Atomics, San Diego, CA, USA

Abstract

Electron Cyclotron Heating is essential for the operation of high performance plasma fusion experiments. A 6 cm diameter, 1 MW, 110GHz beam is typically guided to a specific location by a steerable mirror. This mirror is subject to design requirements that work against each other. High heat loads, and absence of convective cooling dictate a mirror made from conductive material with a significant heat capacity and mass. These qualities tend to increase electromagnetic forces on the mirrors, complicating the design of the mirror supports.

A successful design compromise has been to make the mirror as a brazed assembly with stainless steel bars inlaid into a copper block. As power levels and pulse lengths increase, the use of higher strength copper alloys has been explored.

Chrome Zirconium Copper, [C18150] has emerged as an attractive candidate for mirror construction. The zirconium, however, causes difficulties in brazing. We have developed a process that overcomes these difficulties, and also includes heat treatment as part of the braze cycle, so that the strength of the copper alloy is partially recovered after the high temperature braze.

This paper describes the design challenges associated with ECH launcher mirrors, the development of a high temperature braze technique for C18150, and the latest mirror design.

Introduction

Electron Cyclotron Heating has emerged as a critical element in advanced magnetically confined fusion experiments[1,2,3], both for plasma heating and, more recently, for stabilizing neoclassical tearing modes using Electron Cyclotron Current Drive (ECCD)[4]. In either ECH or ECCD, a beam, typically ~6cm diameter, is launched into a plasma by reflecting it off a fixed mirror, which may provide some focusing, and then off a steerable mirror. [Figure 1] Typically, between 0.15% and 0.2% of incident power is absorbed by each mirror. The DIII-D ECH system[5], at General Atomics, employs four ECH launchers built by Princeton Plasma Physics Laboratory.

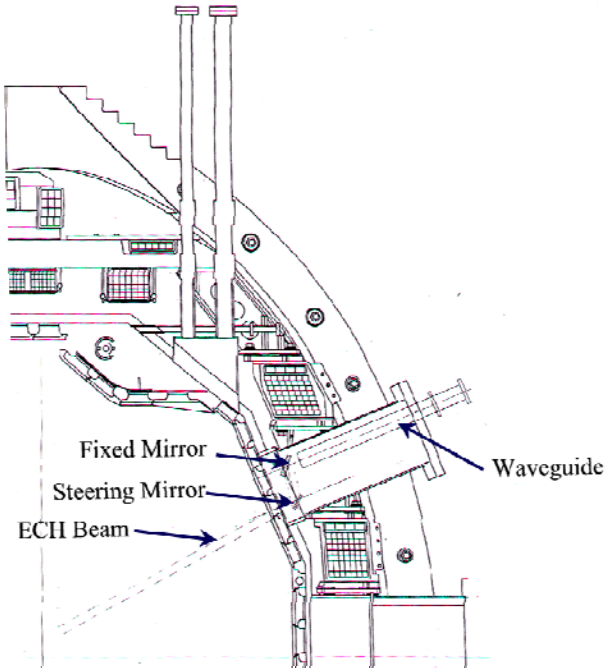


Figure 1. Schematic Launcher Elevation

Many existing heating systems operate at pulse lengths less than ten seconds. For ECH pulse lengths of up to 5 seconds and beam power levels up to ~1MW, it has been acceptable to rely on passive, or inertial, cooling of the mirrors. The DIII-D ECH system has progressed to this level in recent years, and a new system will extend this power and pulse length to consistently operate at 1.5MW for 10 seconds, with pulses every 15 minutes. Passively cooled heat absorbing components in magnetic fusion experiments are subject to two inherently conflicting design requirements –diffusion of the heat load requires a large mass of highly conductive material; the large mass of conductive material results in high induced currents and electromagnetic forces.

The ECH launchers currently in operation on DIII-D have been in service since the installation of the P2001 launcher[6] in 2001. Since then, we have added the P2002 and P2006 launchers. During this time, we have steadily improved the design of the fixed mirrors, while the steerable mirrors originally supplied in 2001 have remained adequate. The new P2012 ECH launcher is expected to operate with the 1.5MW power source, and we therefore implemented new, and

significantly improved, designs for both the fixed and steerable mirrors.

During the design of the new mirrors, both actively cooled, steady-state mirrors and passively cooled mirrors were considered. While it is evident that the passively cooled mirrors, because of their necessarily large temperature excursions, will experience significant thermal fatigue stresses and therefore require periodic replacement, the lower operational and developmental risk made them a good choice for this application. Advances in our ability to analyze electromagnetic forces have enabled us to re-examine the mirror designs, and optimize them for the additional heat loads while minimizing the electromagnetic forces.

The new fixed mirrors for the DIII-D ECH launchers were machined from a solid block of chrome-zirconium-copper alloy, C18150. This material was chosen for its combination of high strength and ability to be age hardened. The steerable mirrors are a brazed assembly. Most joining techniques for this alloy will not perform adequately at high temperatures, or are not suited to this mirror geometry[7]. Special techniques were required in order to obtain successfully a high temperature braze joint using high-strength chromium zirconium copper alloy.

A summary of the mirror design, and a detailed description of the braze process, is presented below.

Steerable Mirror Design

The original steerable mirrors for the DIII-D P2001 ECH launcher were made from a stainless steel block with copper bars inlaid longitudinally and brazed. [Figure 2] The front, reflecting surface of the mirror was copper plated. The heat flux on the mirror surface diffuses through the copper bars rapidly, and then only has to penetrate the stainless steel in the thin direction. Initial thermal analysis indicated that the mirrors would remain two hundred degrees Celsius below the melting point of the gold-nickel eutectic braze alloy, which was chosen for its high melting temperature. In recent years, we had observed signs of thermal fatigue at the mirror surface. In view of the increased power load for the P2012 launcher, we redesigned the mirrors.

Figure 2. Rear surface of P2001 steerable mirrors

The design objectives of the P2012 steerable mirrors[8] were to reduce the temperature excursions, reduce the thermal stresses, and reduce the effect of minor surface damage on mirror performance. These three goals were accomplished by making the new mirrors from a solid block of C18150 copper alloy, and then making a brazed assembly with inlaid stainless steel bars. Again using improved electromagnetic analysis, we were able to make the central area of the mirror from solid copper. Radiation provides adequate cooling for the new mirrors, and the maximum temperature is now roughly 550C – 200C less than on the old design. [Figure 3]

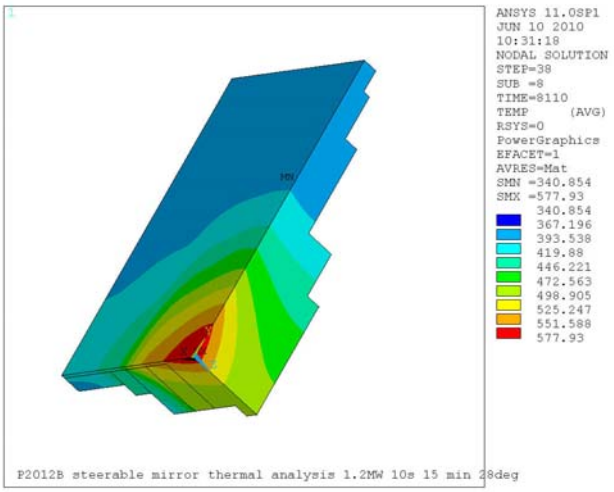


Figure 3. Maximum temperature contours in mirror

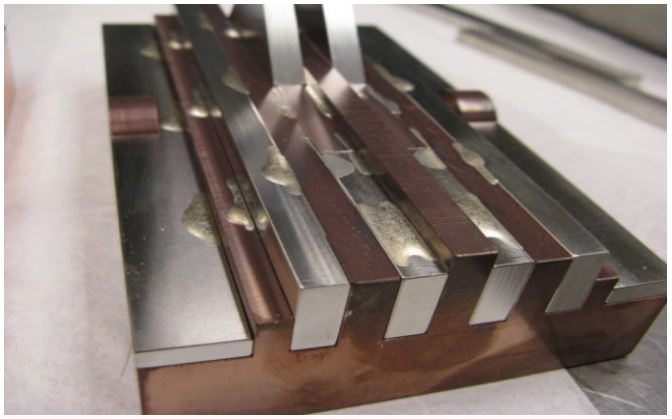


Figure 4. Failed braze of C18150 to 304 stainless steel

Equipment and Procedure

Brazing was conducted using a 2Barr high vacuum furnace which has the capability of partial pressure brazing and gas quenching. Vacuum levels of 5.0e-6 Torr are readily attainable at braze temperature. Partial pressure brazing is accomplished by evacuating to high vacuum levels and back filling with high purity argon to vacuum levels of 350e-3Torr and maintaining these levels during brazing.

Joint depth and clearances dictated the use of two braze programs, starting with an initial high vacuum run which

disassociated oxides and acted as a cleanup and braze run filling 95% of joints. The second run was performed using partial pressure which completed joint fill up; age hardening was incorporated into this run as part of the cooling down sequence.

The aging sequence for C18150 requires a solution anneal temperature of 950C, held for 60 minutes, and furnace cooling to 475C with a three hour hold at that temperature.

Program 1: ramp at 5C/min to 500C soak for 20 min, ramp at 10C/min to 945C soak for 45min, ramp at 6C/min to 980C soak for 15 min, ramp at 10 C/min to 800C, heat off, furnace cool to ambient.

Program 2: ramp at 5C/min to 500C soak for 20 min, backfill to 350e-3Torr, ramp to 945C soak for 45min, ramp at 6C/min to 980C soak for 15 min, heat off, furnace cool to 475C, heat on, soak for 180 min, heat off, evacuate to high vacuum, furnace cool to ambient.

The braze alloy used was a gold-nickel eutectic 955C melt (Au 82% Ni 18%), preforms included 0.003"sheet, 0.040"dia wire and 325 mesh powder mixed with a nitrocellulose binder and applied as a paste. During first runs at high vacuum all three preforms were applied. During secondary runs at partial pressure powder paste was applied to complete fill up.

Preparation for brazing entailed ultrasonic cleaning of all components, fit up, and preplacement of braze. Areas under inserts had 0.003" sheet preplaced, areas at tops and sides where right angles were formed had 0.040"dia by 5/8" long wire preplaced, then all faying surfaces were covered with powder paste. This added additional braze but more importantly promoted braze flow into the structure at the interface. Figure5.

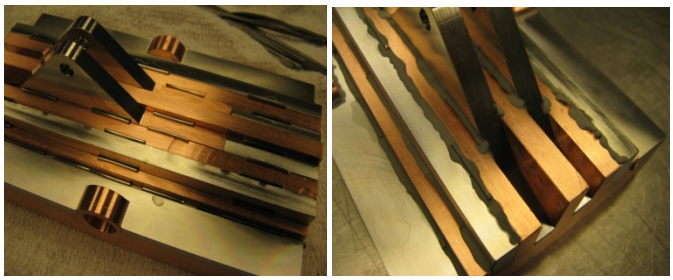


Figure 5. Braze placement

Discussion

Our initial attempts at brazing C18150 at 980C failed. Furnace vacuum levels during brazing were at or below 5.0e-6 Torr. Referring to figure 4, discoloration of the copper alloy was evident, along with limited flow of the braze alloy confined to the stainless steel. We decided to plate the C18150 billet with an electroless low phosphate nickel to a thickness of 0.0005"-0.0010", with the thought that we would be sealing the copper alloy and essentially brazing stainless steel to nickel. Oxygen free copper inserts were used in place of the C18150 inserts at the center of the assembly. Braze material was preplaced as before, and Program 1 was run, successfully. Proper wetting and flow were evident, and a second furnace run with additional braze alloy filled the joints completely. Figures 6a, 6b.

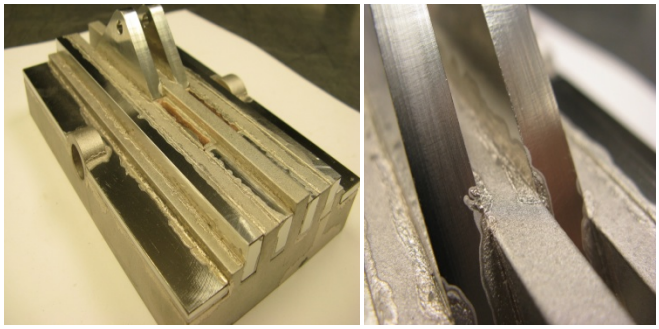


Figure 6a. Plated copper billet showing successful braze. Proper wetting and flow, additional braze volume necessary

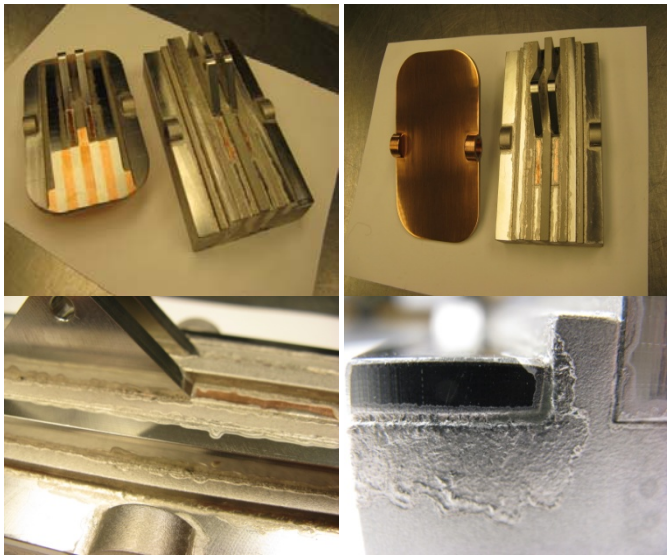


Figure 6b. mirror assemblies brazed using Program 2 with additional braze and heat treatment, also showing completed mirror. Top images.

Examination and Testing

A production mirror was sectioned, and micrographs were made of the braze joints. Sections from one of the failed mirrors were also examined, to verify the lack of wetting. Braze flow tests, hardness tests and tensile tests were performed on coupons in order to more fully understand the effects of the nickel plating, solution annealing and age hardening.

Micrographic Examination

Sections were cut from both successful and failed braze assemblies as shown in fig. 7, below. Some sections were etched, as in fig. 8, in order to show braze flow and copper grain structure. Others were polished and evaluated under a scanning electron microscope.

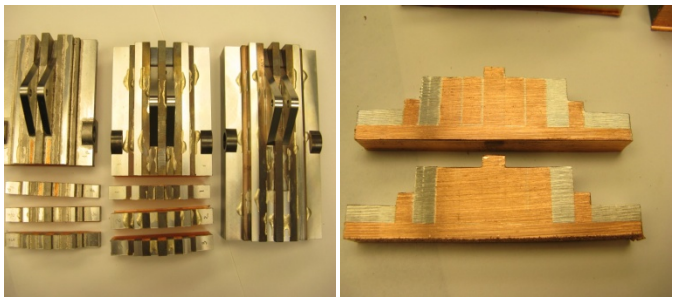


Figure 7. Sectioning of brazed mirror assemblies

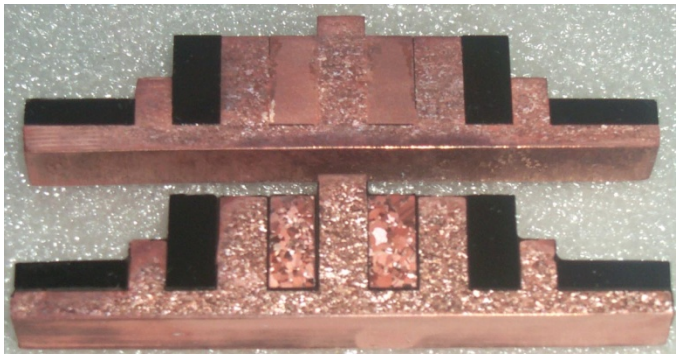


Figure 8. Acid-etched micrographs of mirror sections. Failed braze, top.

The bottom micrograph in fig. 8 shows successful brazing. Stainless steel and the braze alloy are both dark. The fine grain structure of the C18150 block is evident, as well as the coarser grain of the C10100 inserts. Complete flow and wetting is evident in the bottom section, as compared to the top section.

Figure 9, below, shows polished sections prepared for SEM micrographs. A section with a failed braze is on the left; at right is a successful braze.

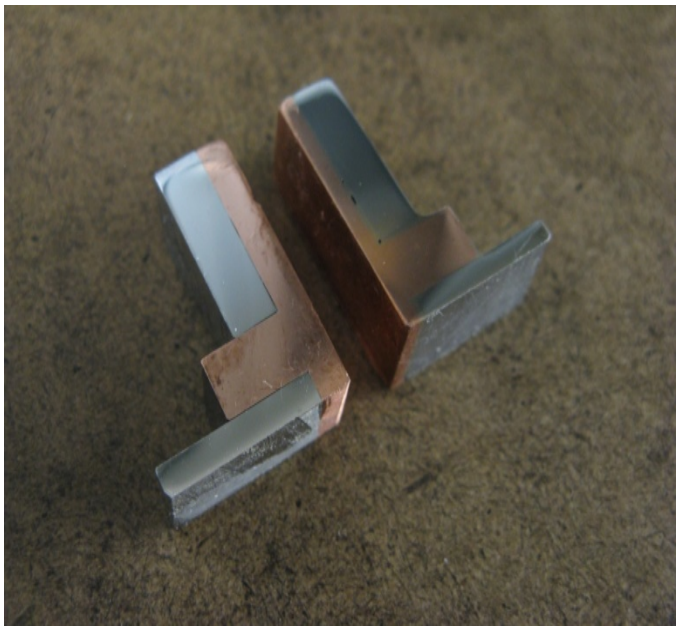


Figure 9. Sections prepared for ESEM micrographs. Failed braze, left

Figure 10a, below, shows a micrograph of a section of a failed braze. The preplaced braze foil is shown clearly adhering to the stainless steel, with a void between it and the C18150.

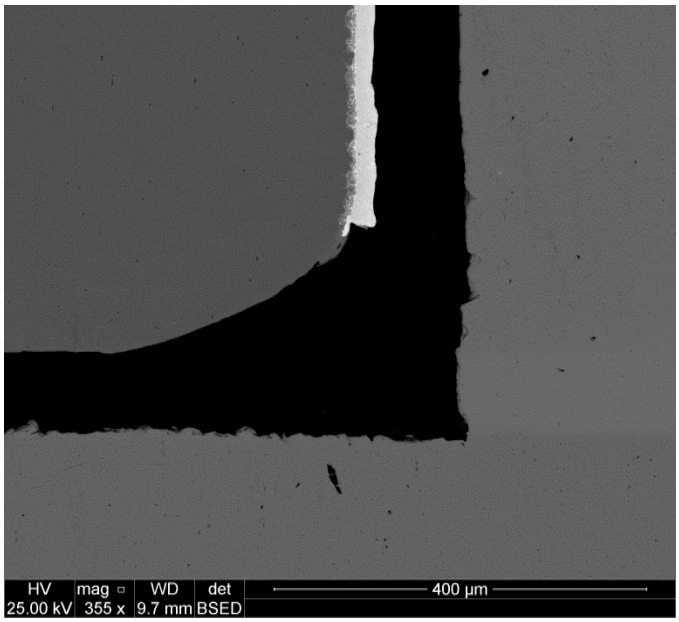


Figure 10a. SEM micrograph of failed braze.

Figure 10b, below, is another failed braze showing an area where preplaced braze sheet adhered to the stainless steel but did not interact with the C18150 at the boundary.

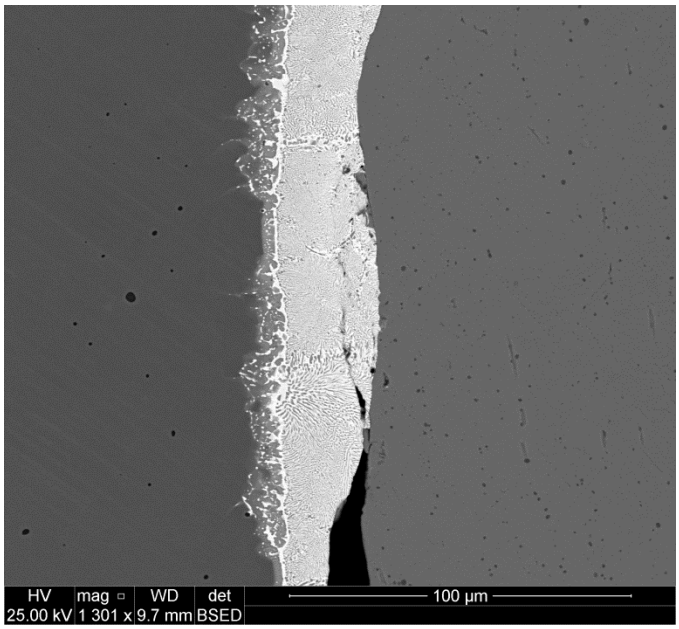


Figure 10b. SEM micrograph of another area of failed braze.

In fig. 11, below, we see an ESEM micrograph of the corresponding location in a successfully brazed assembly. Nickel and iron islands that can be seen in the braze, and a nickel boundary between the stainless steel and the braze alloy, indicate not just a good bond, but that some of the nickel plating from the C18150 has migrated into and across the braze alloy and attached to the stainless steel.

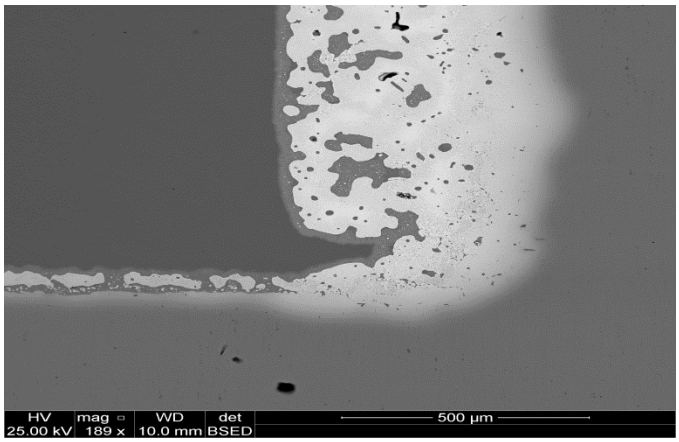


Figure 11. SEM micrograph of successful braze.

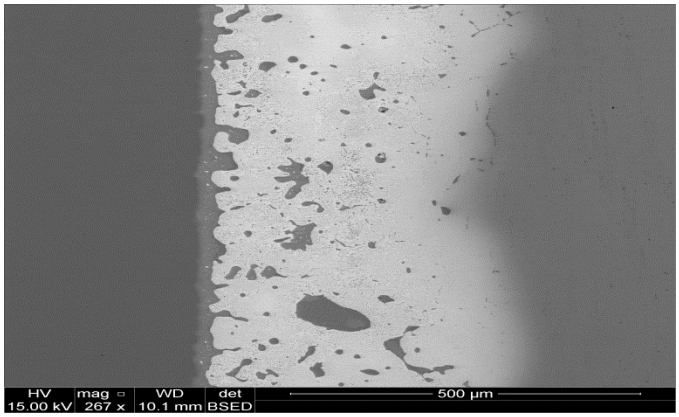


Figure 12. SEM micrograph of another area of successful braze.

Hardness Tests

C18150 coupons were placed in the furnace with the components being brazed. These coupons were taken from the plate from which the mirror was cut. Rockwell B hardness of the as-received material, material that was solution annealed during Program 1, and material aged after Program 2 was compared. The as-received material had a HRB value of 83. After solution annealing [Program 1] it had dropped to HRB 68, but after the age hardening during Program 2 it recovered to HRB 75.

Flow Tests

Plated and unplated C18150 coupons were set on stainless steel bars, as shown in figure 13, with a 2.75 inch longitudinal gap varying from 0.000" to 0.0300". Identical volumes of braze alloy were placed at the closed end, and the flow along the gap was observed. Braze alloy migrated 0.300” on the unplated sample, while on the plated sample it migrated 1.700”.

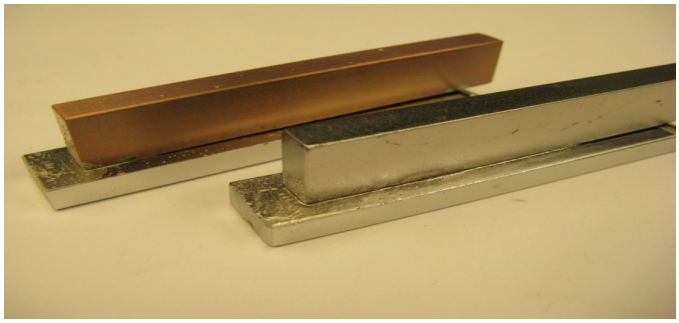


Figure 13. Flow tests, stainless steel to unplated and plated C18150.

Shear Testing

Preliminary shear tests have been performed. Test specimens were prepared in a double lap configuration so that the shear strength of the bond could be evaluated. Shown in fig. 14, the specimens had a center section made from plated C18150, one end 304 stainless steel, and the other end plated C18150. Eight specimens were brazed, and of these, four were age hardened. These were pulled to destruction and, failure loads were evaluated.

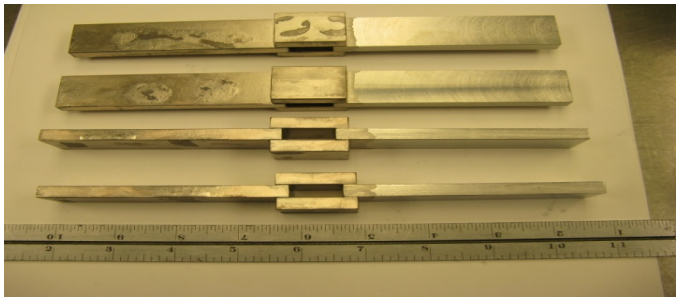
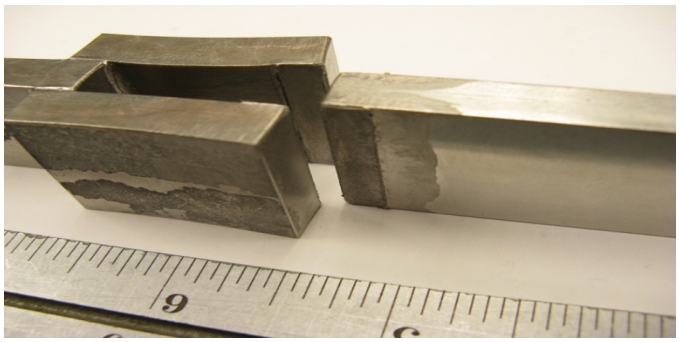


Figure 14. Shear test specimens.

The specimens typically failed at the copper/stainless steel interface, and at an apparent shear stress of roughly 12,000 psi. Visual inspection of the specimens after testing indicates that the actual shear stress is significantly higher than this value. The geometry of the specimens necessarily imparts a significant tensile stress across the braze joint, and a tensile failure across the bond is initiated before the shear strength limit is reached. Further testing and evaluation is required to determine the limiting shear strength of this braze system.


Typical failure of shear specimen at stainless steel interface.

Conclusions

We have successfully brazed C18150 alloy to stainless steel at high temperature in vacuum, using nickel plating of the copper alloy to prevent its oxidation. Metallographic examination revealed a complete bond. Hardness tests at different steps of the process indicate that much of the original strength of the copper alloy can be recovered by age hardening.

Acknowledgments

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References

[1] Prater, R. et al, “Applications of electron cyclotron waves in the DIII-d Tokamak,” in AIP conference proceedings 1187, pp. 491-494

[2] Bae, Y. S. et al, “ECH pre-ionization and assisted startup in the fully superconducting KSTAR tokamak using second harmonic,” Nuclear Fusion, Volume 49, Issue 2 (2009)

[3] Wagner, D. et al, “Recent Upgrades and Extensions of the ASDEX Upgrade ECRH System,” in Journal of Infrared, Millimeter and Terahertz Waves, 32:274-282 (2011)

[4] Volpe, F. A. G. et al, “Advanced techniques for neoclassical tearing mode control in DIII-D,” in Physics of Plasmas Vol 13 (2006), Number 5, p. 055501

[5] Lohr, J. et al, “The electron cyclotron resonant heating system on the DIII-D tokamak,” in Fusion Science and Technology Volume 48 Number 2 (2005) pp. 1226 – 1237

[6] Ellis, R. et al, “Design of the P2001 ECH launcher for DIII-D,” in Proceedings – Symposium on Fusion Engineering (2002) pp. 133-136

[7] Tsuchiya, K. and H. Kawamura, “Mechanical properties of Cu-Cr-Zr alloy and SS316 joints fabricated by friction welding method,” in Journal of Nuclear Materials (1996) pp. 913-917

[8] Ellis, R. et al, “Design of High Performance Passively Cooled Mirrors for ECH Launchers,” in Proceedings – Symposium on Fusion Engineering (2011)

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Princeton Plasma Physics Laboratory
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