IN-20
5319
P- 15

NASA Technical Memorandum 107055
AIAA–95–2397

Evaluation of Rhenium Joining Methods

Brian D. Reed and Sybil H. Morren
Lewis Research Center
Cleveland, Ohio

Prepared for the
31st Joint Propulsion Conference and Exhibit
cosponsored by AIAA, ASME, SAE, and ASEE
San Diego, California, July 10–12, 1995

National Aeronautics and
Space Administration

EVALUATION OF RHENIUM JOINING METHODS

Brian D. Reed and Sybil H. Morren
NASA Lewis Research Center
Cleveland, Ohio

Abstract

Coupons of rhenium-to-C103 flat plate joints, formed by explosive and diffusion bonding, were evaluated in a series of shear tests. Shear testing was conducted on as-received, thermally-cycled (100 cycles, from 21 to 1100 °C), and thermally-aged (3 and 6 hrs at 1100 °C) joint coupons. Shear tests were also conducted on joint coupons with rhenium and/or C103 electron beam welded tabs to simulate the joint's incorporation into a structure. Ultimate shear strength was used as a figure of merit to assess the effects of the thermal treatment and the electron beam welding of tabs on the joint coupons. All of the coupons survived thermal testing intact and without any visible degradation. Two different lots of as-received, explosively-bonded joint coupons had ultimate shear strengths of 281 and 310 MPa and 162 and 223 MPa, respectively. As-received, diffusion-bonded coupons had ultimate shear strengths of 199 and 348 MPa. For the most part, the thermally-treated and rhenium weld tab coupons had shear strengths slightly reduced or within the range of the as-received values. Coupons with C103 weld tabs experienced a significant reduction in shear strength. The degradation of strength appeared to be the result of a poor heat sink provided during the electron beam welding. The C103 base material could not dissipate heat as effectively as rhenium, leading to the formation of a brittle rhenium-niobium intermetallic.

Nomenclature

ASTM	American Society for Testing Materials
Au	gold
C103	niobium-hafnium-titanium alloy
Cu	copper
CVD	chemical vapor deposition
EB	electron beam
EDM	electrical discharge machining
EDS	energy dispersive spectroscopy
Hf	hafnium
Ir	iridium
Ir/Re	iridium-coated rhenium
LOX	liquid oxygen
MMH	monomethylhydrazine
Mo	molybdenum
Nb	niobium
NTO	nitrogen tetroxide
Ni	nickel
N2H4	hydrazine
Pd	palladium
Pt	platinum
Re	rhenium
Rh	rhodium
SS	stainless steel
Ta	tantalum
Ti	titanium

Introduction

A material system composed of a Re substrate and an Ir coating has proven to provide high-temperature (2200 °C), long-life (hours) operation for radiation-cooled rockets operating on Earth storable propellants (ref 1). There is an on-going effort to develop flighttype, Ir/Re engines, particularly at the 440-N thrust level (ref. 2). Complementing this effort is a more fundamentals-oriented radiation-cooled rocket material program, including evaluation of methods for joining Re to dissimilar metals. The focus of this study was the joining of Re to C103.

Ir/Re chambers require joining Re to an injector and a nozzle skirt composed of dissimilar metals. Common injector materials include 304L SS, C103, and Ti. Since Re is a relatively heavy material and its high temperature capability is not needed throughout the nozzle, the Ir/Re chamber can be truncated at a low area ratio and a lighter refractory, such as C103, used for the nozzle skirt. The configuration of injector-to-chamber and the chamber-to-nozzle joints vary depending on the specific engine design. Often the joints are designed not to bear any major mechanical loads, so that the primary requirement for the joint would be to seal against hot combustion gases. In operation of the engine, the joints will be subjected to thermal cycling. The range, number, and duration of the thermal cycles are dependent on the particular application.

EB welding would be an attractive production method for joining Re chambers to injectors and nozzles. Direct EB welding of Re to C103, however, has been found to form brittle joints due to a brittle Re-Nb intermetallic that forms at 2162 °C. The presence of the brittle intermetallic prevents the use of fusion welding methods (melting of material) for joining Re chambers to C103 nozzle skirts. As a result, brazing and nonfusion welding have been investigated for joining Re-to-C103. This paper will survey Re joining technology programs and present an evaluation of two Re-to-C103 joining methods: explosive bonding and diffusion bonding. The joining methods would be used to form a bi-metal joint or transition piece, to which the Re chamber and C103 nozzle could be EB welded. The joint evaluation involved the thermal cycling, thermal aging, welding, and shear testing of flat plate coupons. Test results and posttest metallography will be discussed.

Re to Dissimilar Metals Joining Review

In an Ir/Re engine technology program, Aerojet (ref. 1) investigated different methods of joining Re to 304L SS, Hastelloy B2, and unalloyed Nb. Inertia welding of Re-to-Nb produced a strong joint, but the technique was ineffective for Re-to-304L SS and Re-to-Hastelloy B2 joints. Five braze filler alloys were evaluated for their wetting ability: Palcusil 25, Silcoro 75, Palsil 10, Nioro (82Au-18Ni), and 50Au-50Cu. Good to excellent wetting was found for all the braze alloys on Re, 304L SS, and Hastelloy B2. For Nb, however, Silcoro 75 and 50Au-50Cu was found only to wet marginally well. Palcusil 25 and Nioro were investigated further in lap and ring shear testing. Both of these braze alloys demonstrated strong joints, though Nioro joints tended to be stronger. Nioro was recommended as a brazing alloy for Re-to-304L SS joints, since no intermetallics were indicated in the Au-Re and Ni-Re phase diagrams. Furnace brazing using Nioro was utilized in joining a 304L SS injector, a Pt-10Rh trip ring, and an Ir/Re chamber for a 62-N flighttype engine (ref. 3).

Re-to-Nb joints produced by EB welding were found to be brittle, due to the formation of a brittle intermetallic phase that forms above 2162 °C. This intermetallic phase probably formed during the solidification of the weld and was retained in a metastable condition at room temperature. Re-to-304L SS and Re-to-Hastelloy B2 joints were achieved using a "parent metal braze" technique. Here only the 304L SS and Hastelloy B2 were melted, wetting the Re and solidifying to form the joint.

The parent metal braze technique was utilized by Aerojet in joining a 304L SS adapter piece to a Re chamber for a high performance 440-N flighttype engine (ref. 4). The SS injector was then EB welded to the 304L SS adapter. On the same 440-N engine, joining of the Re chamber to the C103 nozzle skirt was accomplished using the method illustrated in figure 1. A Re/C103, bi-metal ring was formed by the application of CVD Nb over Re and C103 pieces. The Re chamber was then EB welded to the Re side of the bi-metal ring, while the C103 skirt was EB welded to the C103 side.

The 440-N engine was tested for 80 full thermal cycles and over 6 hours on NTO/MMH propellants. The maximum temperature measured nearest to the injector joint (at the SS to SS EB weld) was 169 °C. The nozzle joint maximum temperatures were measured to be 1166 °C and 1013 °C, on the Re and C103 sides of the joint, respectively. The injector and nozzle joints survived testing intact. The nozzle joint failed from the exterior, after testing was over, due to oxygen embrittlement of uncoated C103. This type of failure would not have occurred in ground tests if the nozzle exterior was coated with disilicide or in actual operation in the vacuum of space.

TRW (ref. 5) investigated methods of joining Re-to-C103 in a development program for a LOX/N2H4, 440-N class engine. Direct EB welding of Re-to-C103 resulted in cracking in the weld due to the formation of a brittle intermetallic phase between Re and Nb (as was seen in reference 3). Thin (0.43 cm) Mo, Ti, and Ta shims were evaluated as filler materials to the EB weld. All of the Re-to-C103 welds tried with these filler materials cracked and separated. A Ti filler shim twice the width (0.089 cm) of the others, showed no signs of cracking. However the Ti formed a brittle intermetallic phase with Re resulting in low tensile strength.

Several braze materials were evaluated for furnace brazing of Re-to-C103, including 65Au-35Pd, 50Au-50Pd, and Ti. These three braze joint samples were subjected to thermal aging (4 hours at 1200 °C) and thermal cycling (room temperature to 1200 °C for 20 cycles) tests. The Ti sample showed a small crack at the braze/Re interface, due to the formation of a brittle phase. The 50Au-50Pd sample showed void areas where there was poor flow of braze and shrinkage forming cracks. The 65Au-35Pd sample showed only some small voids and no diffusion of the braze material into Re or C103. Diffusion of Nb and Hf (from the C103 alloy) into the braze was found, however. Based on this investigation, the 65Au-35Pd braze alloy was recommended for furnace brazing Re-to-C103. TRW is investigating alternatives to brazing, including the use of bi-metal joints fabricated by inertia welding (ref. 6).

Brazing has been investigated most extensively as an alternative to EB welding for joining Re chambers to injectors and C103 nozzle skirts. However, there are potential problems that can arise with braze joints. The brazing process often requires a complex design at the interfaces to properly wet the joining area. Braze layers are relatively thin and have limited strength, raising concerns about the joint's ability to survive the severe vibrational environment experienced during launch and under repeated pulsing of the rocket. Furthermore, most braze materials have limited temperature and thermal cycling capabilities.

A bi-metal ring or tube, as illustrated in figure 2, could be used as a separate transition piece rather than directly joining the chamber to the injector or nozzle. The bi-metal piece can be fabricated using a nonfusion (non-melting) bonding process, thereby avoiding the brittle Re-Nb intermetallic seen with EB welding. The Re chamber would then be EB welded to Re side of the bi-metal joint and C103 can be EB welded to the C103 side of the joint. (There are no inherent problems with EB welding a material to itself). This same concept can be used to join Re to other metals. Use of a transition piece allows a great amount of flexibility in the joint design. Plates or tubes of Re and C103 can be joined by the nonfusion bonding process and easily machined into any suitable configuration. This study evaluates the use of explosive bonding and diffusion bonding for creating bi-metal joints.

Bi-Metal Joining Techniques

Explosive Bonding

Explosive bonding is a high pressure welding process that uses controlled explosive detonations to force two pieces together rapidly and at a low contact angle (refs. 7 and 8). The duration of the explosive bonding process is so short that the heat effected zone between the metals is microscopic. The bond line is an abrupt transition from one metal to the other, with virtually no degradation of the metals' mechanical properties. The explosive bond is nearly an ideal composite, that is, it is a metallurgical bond with virtually unaffected base materials. The formation of brittle intermetallics is avoided, since this is essentially an ambient temperature process (the generated heat cools very rapidly).

Diffusion Bonding

In diffusion bonding, temperature and pressure are applied uniformly to a piece to expand it into the other piece (ref. 8). The interdiffusion of the materials make up the joint in solid state. Since heating is uniform, the entire structure will undergo the same metallurgical changes and there will not be a heat-affected zone. The lack of fusion and heat-affected zones give unaffected base materials, producing nearly an ideal composite. Diffusion bonding of Re to Nb and Nb alloys has been performed in technology programs for the SP-100 nuclear reactor (ref. 9).

Re-to-C103 Joint Coupons

The Re plates used in this program were fabricated by powder metallurgy and further consolidated using hot isostatic pressure for a density greater than 98 percent of theoretical. The C103 plates had a composition of 89 percent Nb, 10 percent Hf, and 1 percent Ti.

Two Re-to-C103, explosively-bonded plates, each approximately 5.1 cm by 15.2 cm by 1.11 cm, were received from Northwest Technical Industries. The Re thickness was approximately 0.64 cm, while the C103 was 0.48 cm thick. The two plates represented differences in the parameters used in the explosive bond process and were labeled lot #2090 and lot #2097, respectively. A sleeve-on-sleeve (tube) joint configuration could also be fabricated using explosive bonding, but was not evaluated in this study.

Two Re-to-C103, diffusion-bonded plates, each 5.1 cm by 2.2 cm by 0.80 cm, were received from Advanced Methods and Materials. The Re thickness was approximately 0.32 cm, while the C103 was 0.48-cm thick. Each plate was fabricated using the same process parameters. A sleeve-on-sleeve configured joint, essentially a diffusion-bonded tube with a C103 exterior and a Re interior, was also provided. Visual inspection showed it to be in excellent condition, although a detailed evaluation has not yet been performed.

Each of the explosively-bonded and diffusion-bonded plates were sectioned (using EDM) into sandwich and "Z" coupon configurations, as shown in figure 3. Figure 4 shows explosively-bonded coupons, while figure 5 shows diffusion-bonded coupons. In each photo, C103 is the darker metal, while Re is the lighter metal. From visual inspections, all of the flat plate coupons evaluated in this study appeared to be in excellent condition, with no obvious defects or deformation at the bond line.

Joint Evaluation Procedure

Test Matrix

The evaluation of the Re-to-C103 joints consisted of a series of thermal, welding, and shear tests, as listed in table I. Thermal cycling was performed to assess the integrity of the joint during an operational cycle. Thermal aging of samples were performed to determine if time at temperature would promote the formation of brittle intermetallics or degradation due to interdiffusion at the joint. EB welding of Re and/or C103 tabs to coupons was performed to determine if welding to the bi-metal joint would have any adverse effects. Nearly all of the coupons were shear tested after being subjected to thermal testing. Ultimate shear strength was used as a figure of merit to compare as-received coupons with thermally cycled and EB welded coupons. Furthermore, shear testing would locate the weakest part of the diffusion zone, which generally will be the region with intermetallics.

Thermal Testing

As-received sandwich coupons of each type were subjected to thermal cycling tests. A total of 100 thermal cycles were performed, from 21 to 1100 °C. The coupons were placed in an evacuated quartz vessel. The vessel was heated in a furnace to 1100 °C (the maximum furnace temperature) and immediately cooled to 21 °C by quenching the vessel in water. From thermocouple measurements on the vessel exterior, the heating and cooling transients typically were 3 and 5 minutes, respectively. After thermal cycling the coupons were machined into the Z-configuration (using EDM) and shear tested.

An explosively-bonded (lot #2090) and diffusion-bonded sandwich coupon were thermally aged in furnace with an inert environment, for 3 hours at 1100 °C. Another diffusion-bonded sandwich coupon was thermally aged for 6 hours at 1100 °C. The diffusion-bonded coupons were EDMed into Z configuration and shear tested.

EB Welding

Sandwich coupons of each type had 2.86 cm by 0.64 cm tabs EB welded to them. The Re weld tabs were 0.32 cm thick, while the C103 tabs were 0.48 cm thick. A set of sandwich coupons had only Re EB welded to the Re side, another set had only C103 EB welded to the C103 side, and a third set of coupons had both, Re EB welded to the Re side and C103 EB welded to the C103 side. The tabs were welded along the length of the coupons, as illustrated in figure 6. The power settings for Re welding was nearly double the C103 settings. Full penetration was achieved on the welds. All three sets of coupons were then subjected to 100 thermal cycles, 21 to 1100 °C. The coupons were then EDMed into Z configuration and shear tested. Additionally, C103 EB welding was done with an explosively-bonded (lot #2090) and a diffusion-bonded coupon. Thermal cycling was not performed on these two coupons. Rather, they were machined into Z's and shear tested directly.

Shear Testing

The Z-configured coupons tested in this study were used to get an order of magnitude estimate of bond strength and results were not traceable to ASTM standards. The shear coupons were pushed against a fixture (as shown in figure 7) in order to reduce bending moments that may have resulted from pulling the coupon. Two tests were conducted with as-received coupons of each set. One test was conducted with coupons from each set that had been thermally cycled and/or had EB welds.

Joint Evaluation Results

Thermal Test Results

All of the explosively-bonded (both lots) and diffusion-bonded coupons survived thermal cycling with no visible signs of degradation of the joint. This was true whether the coupons had EB welded tabs or not. The thermally-aged coupons also showed no apparent defects or degradation after testing.

Shear Test Results

The results of the shear testing are summarized in table II. Ultimate shear strength values are plotted in figure 8 and 9 for the explosively-bonded and diffusion-bonded coupons, respectively.

The as-received, explosively-bonded coupons from lot #2090 had shear strengths of 281 and 310 MPa. Shear strengths of the as-received coupons from lot #2097 were 162 and 223 MPa. In both lots of explosively-bonded joints, thermally-cycled coupons with no welds and with Re weld tabs had shear strengths within 30 percent of the as-received values. The lot #2090 as-received coupons had higher shear strengths compared to the no weld and Re weld coupons, while the lot #2097 as-received coupons had lower values. These results indicated scatter in the data.

Explosively-bonded coupons with either C103 weld tabs or C103 and Re weld tabs had a clear reduction in shear strength compared to the other coupons. Thermally-cycled coupons with C103 weld tabs had shear strengths of 53.8 and 75.8 MPa, for lots #2090 and #2097, respectively. Thermally-cycled coupons with both C103 and Re weld tabs had 24.1 and 26.2 MPa shear strength values, for lots #2090 and #2097, respectively. This large reduction in shear strengths could not be dismissed as data scatter. A lot #2090 coupon with an C103 EB weld, that had not been thermally cycled broke during handling, before the shear test could be conducted.

The as-received diffusion-bonded coupons (tested two months apart from each other) had shear strengths of 199 and 348 MPa. The thermally-cycled coupon with the Re weld tab had a shear strength of 155 MPa, reduced from the as-received coupons. The two thermally-aged coupons had comparable shear strengths to the Re weld coupon. There was little difference between the coupons aged for 3 hours (122 MPa) and 6 hours (134 MPa). The cycled coupons with no welds and with both, C103 and Re weld tabs, had comparable shear strengths (87.6 and 82.7 MPa, respectively). These shear strengths were about 20 percent lower than the Re weld and thermally-aged coupons.

The shear strength of the thermally-cycled coupon with a C103 weld tab was 29.0 MPa, greatly reduced from the other coupons. Another diffusion-bonded coupon had a C103 tab EB welded to it, but was not thermally cycled. This coupon was tested at the same time as the second as-received coupon. The C103 weld coupon had a shear strength of 247 MPa, while the second as-received coupon had a 348 MPa shear strength, as mentioned above. While the C103 weld coupon had a 29 percent reduction of shear strength from the as-received coupon, both coupons had shear strengths above the group that was tested two months earlier. These differences again pointed to the presence of scatter in the data.

Metallography

The fracture surfaces of some of the coupons (indicated in Table I) were examined using EDS analysis. Although the elemental weight concentrations were not determined (the EDS spectra were not compared to standards), the relative concentrations of the elements could be discerned by comparing spectra peaks to the spectra of the Re and C103 base materials.

Cu was detected in all of the explosively-bonded fracture surfaces that were examined. The presence of Cu was probably due to the use of a brass wire in the initial EDMing of the explosively-bonded coupons. The diffusion-bonded coupons were EDMed later in the program using a Mo wire. Neither Mo nor Cu were found in the fracture surfaces of diffusion-bonded coupons.

Spectra close to the base C103 material were found on both fracture surfaces of the as-received, explosively-bonded coupons. There were also small peaks of Re and Cu found on both surfaces. The lack of strong Re peaks indicated that both coupons failed primarily in the C103 or a lightly alloyed version of

C103. For the as-received, diffusion-bonded coupon, strong Re peaks were found on both fracture surfaces. and a Nb peak was found on one of the fracture surfaces, indicating that some interdiffusion had taken place during the bonding process. However the high shear strength of the coupon (348 MPa) suggested that the small amount of interdiffusion did not adversely affect strength.

All of the thermally-cycled coupons that were examined had higher concentrations of Hf than were present in the C103 base material. Undoubtedly the high levels of Hf were due to diffusion from C103 to Re during thermal cycling. There was concern that diffusion of Hf into Re was creating a brittle intermetallic and that was responsible for the degradation of strength seen in the C103 EB welded coupons. However, high levels of Hf were found in fracture surfaces of lot #2090, explosively-bonded coupons with both no weld tabs and with a Re weld tab. These coupons had relatively high shear strengths. No correlation could be found relating the degradation of shear strength and the concentration of Hf.

The degradation of shear strength, then, seemed to be related to the EB welding of C103 tabs. One concern was that the EB welding was somehow softening the C103 base material. The C103 hardnesses on two lot #2090, explosively-bonded coupons were determined. Both coupons had been thermally-cycled, but one had no EB welds, while the other had a C103 weld tab. The Rockwell B hardnesses of the no weld and C103 weld coupons were similar, 77.4 and 74.3, respectively. The Rockwell B hardnesses of the Re were also similar to each other, 106.8 and 104.9, respectively, for the no weld and C103 weld coupons. The similar hardnesses between coupons indicated that EB welding of C103 was not having adverse effects on the base material.

Another concern with EB welding C103 was the possible formation of the known brittle Re-Nb intermetallic phase (between 63 and 76 weight percent Re). Coupons were clamped at one end during the welding, providing for a poor heat sink. Although the Re EB welding involved higher power settings, the Re with its high thermal conductivity was able to dissipate heat better than C103. The C103 EB welding, then, could have raised the temperature at the bond line above 2162 °C at which the brittle intermetallic forms. This would explain why (with one exception) only the coupons with C103 weld tabs had low shear strengths. If this were the explanation, the brittle intermetallic could easily be avoided by simply providing a better heat sink for EB welding and/or a bi-metal joint design with a geometry that would keep the bond line temperature below 2162 °C.

In order to separate the effects of thermal cycling and EB welding, an explosively-bonded (lot #2090) coupon and a diffusion-bonded coupon had C103 tabs EB welded to them, but were not thermally cycled. The explosively-bonded coupon broke during handling before shear testing could be conducted, however it was examined using EDS just as the diffusion-bonded coupon was. The EB welded (C103) side of both coupons had high peaks of Re, along with the expected peaks of Nb. The non-EB welded (Re) side fracture surfaces had lower peaks of Re than seen in the base Re, but significant peaks of Nb. Examination of the EDS spectra of the other coupons with C103 weld tabs showed high peaks of Re and Nb on both fracture surfaces. The lot #2090, explosively-bonded coupons with no weld tabs and Re weld tab also showed high peaks of Re on both fracture surfaces. However the peaks of Nb were less than those seen on the coupons with C103 weld tabs. The common denominator to coupons with low strength would appear to be a spectra containing high peaks of Re and Nb on both fracture surfaces. This would suggest that a Re-Nb intermetallic was responsible for the degradation shear strength.

Concluding Remarks

Explosive bonding and diffusion bonding appear to be viable options for creating bi-metal, Re-to-C103 joints. Re-to-C103 joint coupons, formed by explosive and diffusion bonding, were evaluated in thermal and shear testing. Explosively and diffusion bonded coupons survived 100 thermal cycles from 21 to 1100 °C and thermal aging at 1100 °C for 3 and 6 hours intact and with no visible signs of degradation. As-received coupons of explosively-bonded joints had ultimate shear strengths of 281 and 310 MPa for one lot (#2090) and 162 and 223 MPa for another lot (#2097). As-received coupons of diffusion-bonded joints had ultimate shear strengths of 199 and 348 MPa. The wide range of values indicated scatter in the data. With one exception, the thermally-treated and Re weld tab coupons were slightly reduced or within the range of the as-received values, regardless of whether they were explosively or diffusion bonded.

Coupons with C103 weld tabs, whether alone or with Re tabs, experienced a significant reduction in strength that could not be dismissed as data scatter. This was true with the explosive and diffusion bonded coupons. Examination of EDS spectra on the fracture surfaces of thermally-cycled coupons showed high levels of Hf, regardless of whether the coupon had high or low shear strength. Diffusion of Hf from C103 into Re undoubtedly occurred during thermal cycling, but it could not be correlated with the low strengths of the C103 weld coupons. The low strength was more likely related to the EB welding process itself, where coupons were clamped at one end, providing a poor heat sink. The C103 base material could not dissipate heat as well as Re can. As a result, the temperature at the bond line may have risen above 2162 °C, forming the brittle Re-Nb intermetallic. EDS spectra of the low strength coupons had significant peaks of Re and Nb on both fracture surfaces, which suggested at least some intermetallic of Re and Nb had formed. This problem can be avoided by simply providing a better heat sink during EB welding and/or tailoring the joint design to dissipate heat better in the C103.

Acknowlegdements

The author would like to express his deep appreciation to Douglas Wolf of the Surface Science Laboratory at the University of Dayton for conducting the thermal and shear testing and the EDS analyses in this study.

References

1. Wooten, J.R. and Lansaw, P.T.: High Temperature, Oxidation-Resistant Thruster Research, Final Report, Contract NAS3-24643, CR-185233, February 1990.

2. Schoenman, L: 4000 °F Materials for Low Thrust Rocket Engines, AIAA Paper 93-2406, June 1993.

3. Jassowski, D.M. and Gage, M.L.: Advanced Small Rocket Chambers, Option 1 Final Report, Contract NAS3-25646, CR-191014, August 1992.

4. Jassowski, D.M.: Advanced Small Rocket Chambers, Option 3 Final Report, Contract NAS3-25646, CR-195435, November 1994.

5. Chazen, M.L., etc. al.: Space Storable Rocket Technology Program, Option 1 Final Report, Contract NAS3-26246, CR-191171, August 1993.

6. Chazen, M.L., etc. al: Space Storable Rocket Technology Program, Option 2 Final Report, Contract NAS3-26246, to be published.

7. Brasher, D.: Explosive Welding: Principles and Potentials, Outlook, Volume 15, Number 2, 2nd Quarter 1994, pp. 2 & 6.

8. Messler, Jr., R.W.: Joining of Advanced Materials, ISBN 0-7506-9008-9, published by Butterworth-Heinemann, 1993.

9. Horak, J.A. and Kangilaski, M.: Effects of Irradiation on the Tensile Properties of Rhenium, Oak Ridge National Laboratory Report ORNL/TM-12360, April 1993.

Table I: Matrix for Re-to-C103 Joint Evaluation

Coupon	Explosive Bond Lot #2090	Explosive Bond Lot # 2097	Diffusion Bond
As-Received	2[a]	2[a]	2[a]
Thermally-Cycled[b]	1[a]	1	1
Re Tab EB Welded to Re Side and Thermally-Cycled[b]	1[a]	1	1
C103 Tab EB Welded to C103 Side and Thermally-Cycled[b]	1[a]	1	1[a]
Re Tab EB Welded to Re Side and C103 Tab EB Welded to C103 Side and Thermally-Cycled[b]	1[a]	1[a]	1
C103 Tab EB Welded to C103 Side	1[c]	-	1[a]
Thermally-Aged, 3 hrs @ 1100 °C	1[d]	-	1
Thermally-Aged, 6 hrs @ 1100 °C	-	-	1

Notes

a. Fracture surfaces of the coupon were examined by EDS analysis

b. 100 cycles, from 21 to 1100 °C

c. Sample broke before shear testing could be conducted

d. Coupon not shear tested

Table II: Shear Testing Results

Joining Technique	Thermal Treatment	EB Weld Tab	Ultimate Shear Strength (MPa)
Explosive Bond, Lot #2090	None	None	310
	None	None	281
	Cycled	None	219
	Cycled	Re	212
	Cycled	C103	53.8
	Cycled	Re & C103	24.1
	None	C103	Coupon Broke During Handling
Explosive Bond, Lot # 2097	None	None	223
	None	None	162
	Cycled	None	246
	Cycled	Re	231
	Cycled	C103	75.8
	Cycled	Re & C103	26.2
Diffusion Bond	None	None	199
	None	None	348
	Cycled	None	87.6
	Cycled	Re	155
	Cycled	C103	29.0
	Cycled	Re & C103	82.7
	None	C103	247
	3 hrs @ 1100 °C	None	122
	6 hrs @ 1100 °C	None	134

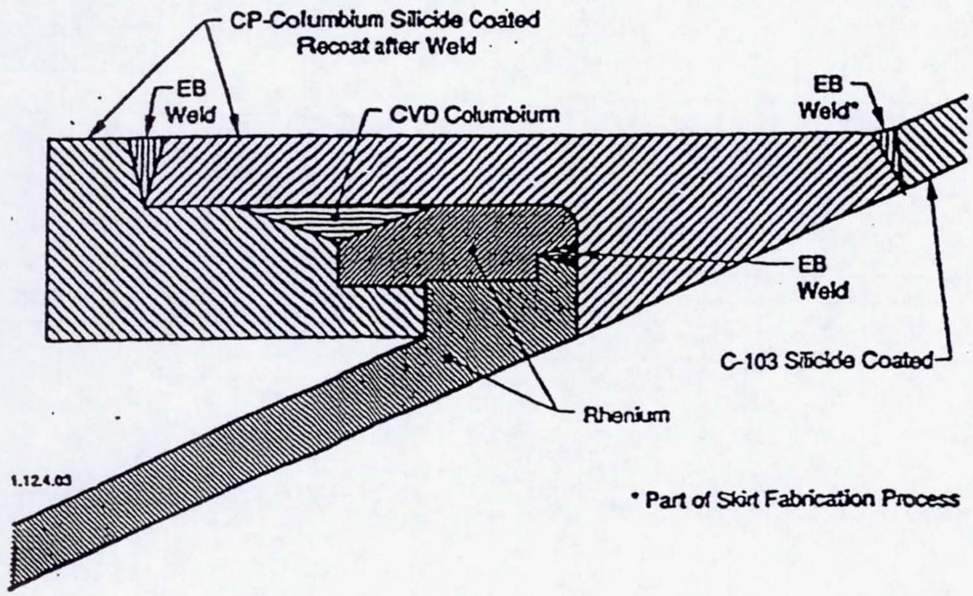
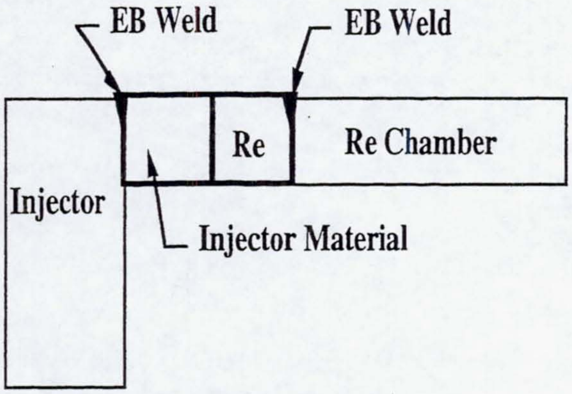
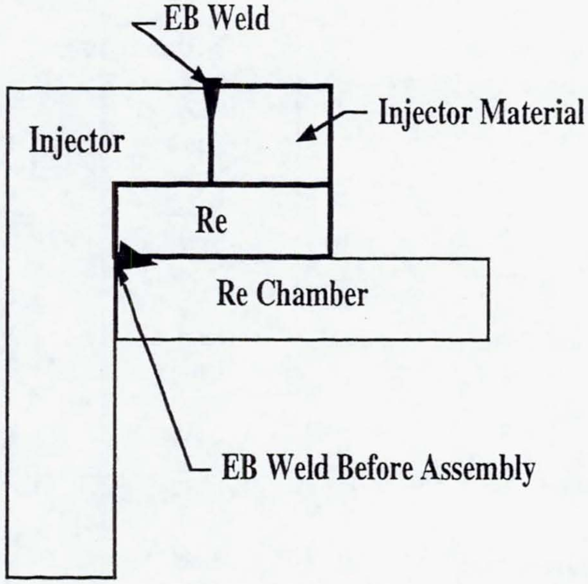


Figure 1: Re-to-C103 Nozzle Joint for Flight-Type, 440 N Engine (ref. 4)

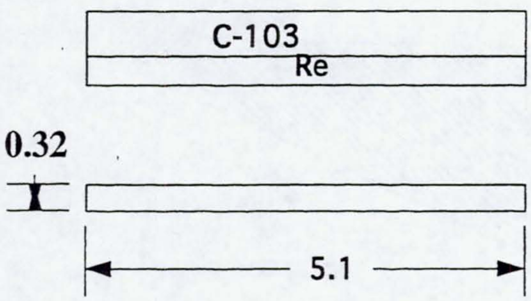


Bi-Metal Ring (in Bold)

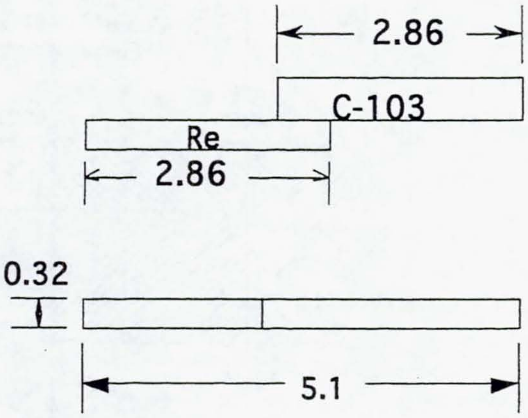


Bi-Metal Tube (in Bold)

Figure 2: Examples of Bi-Metal Joint Configurations



Sandwich Configuration



"Z" (Shear) Configuration

Dimensions in centimeters

Figure 3: Joint Coupon Configurations

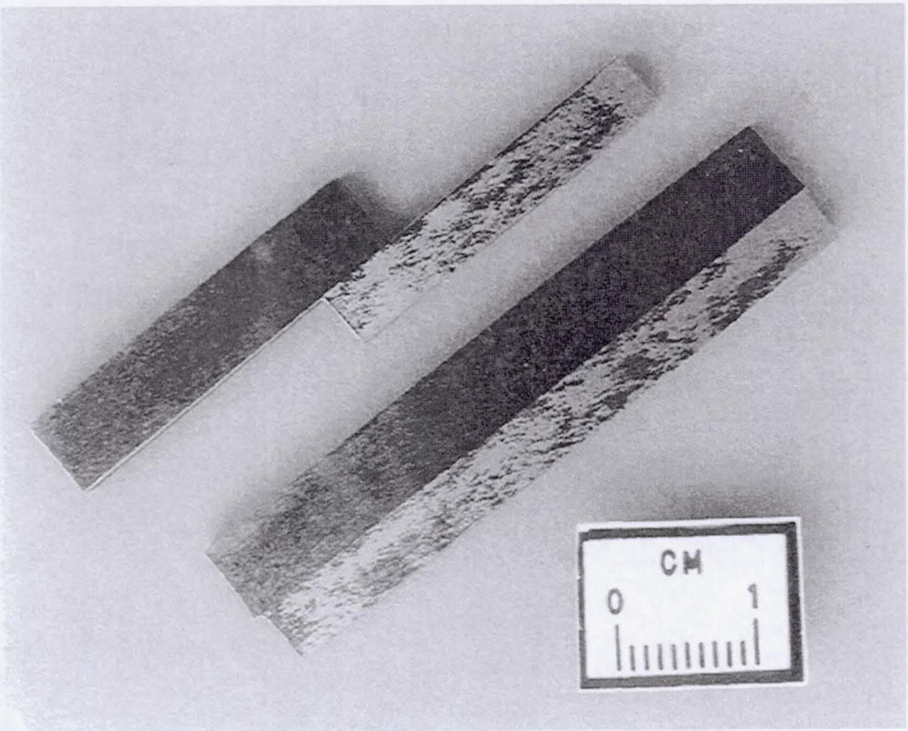


Figure 4: Explosively-Bonded Joint Coupons

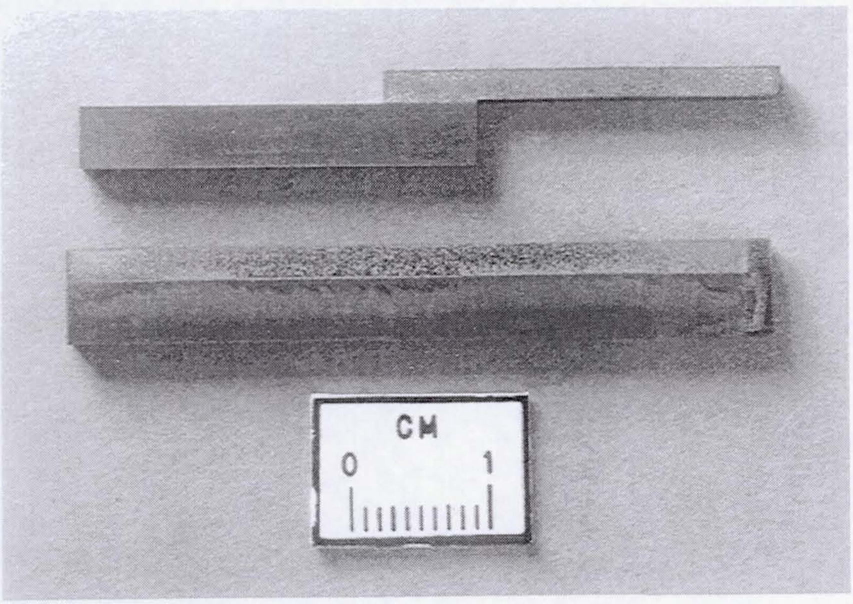


Figure 5: Diffusion-Bonded Joint Coupons

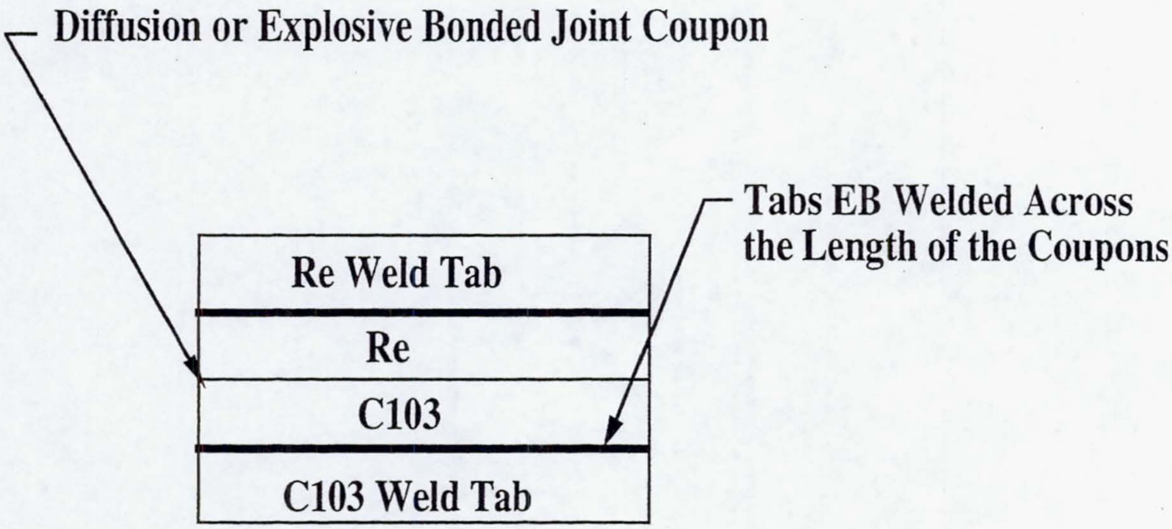


Figure 6: EB Welding of Tabs to Coupons

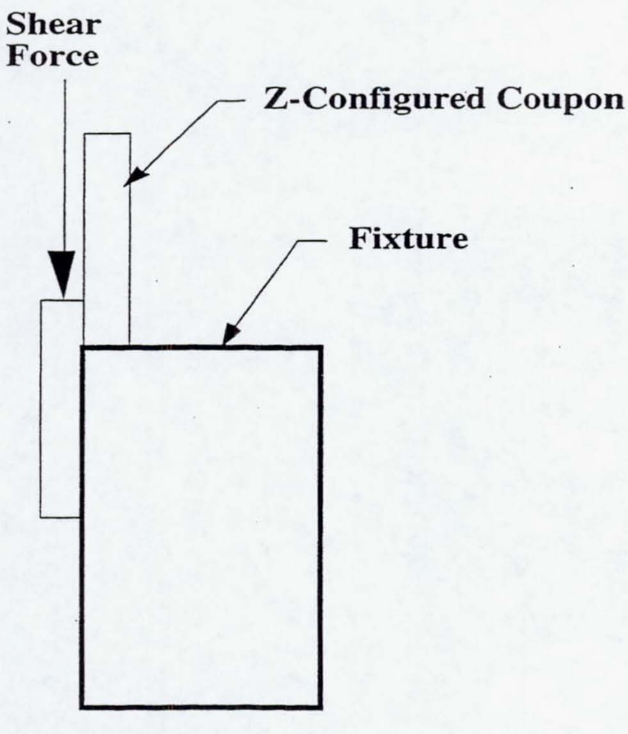


Figure 7: Shear Testing of Coupons

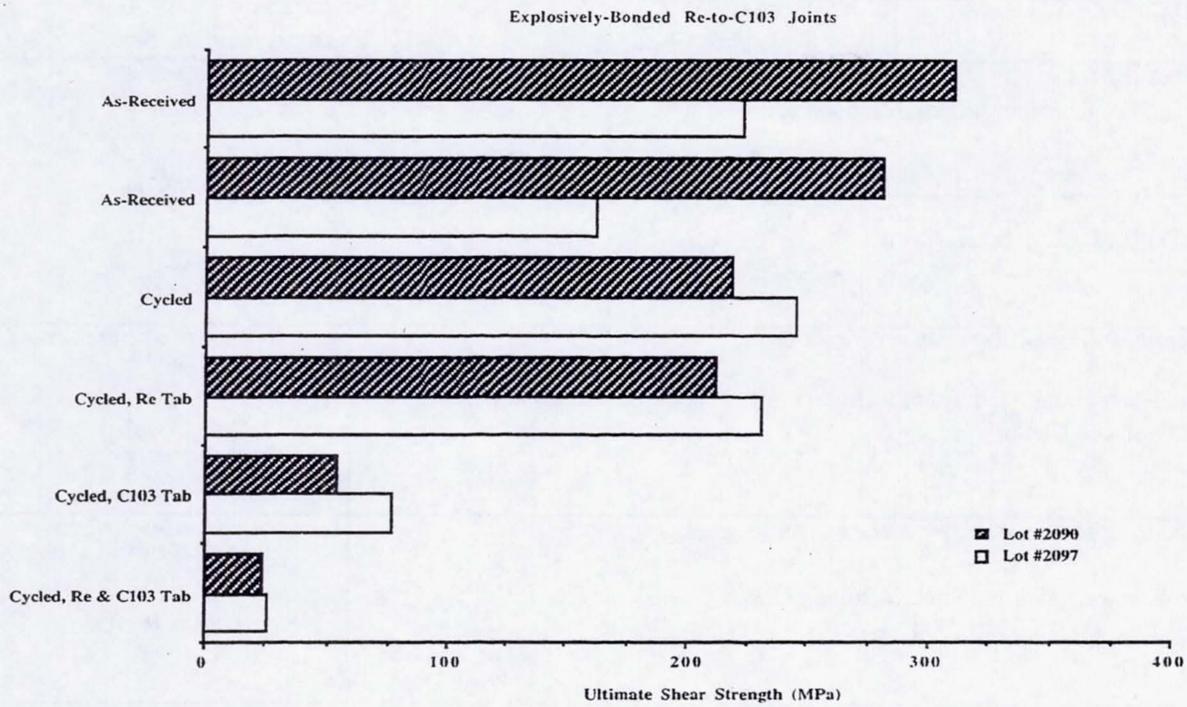


Figure 8: Ultimate Shear Strength for Explosively-Bonded Coupons

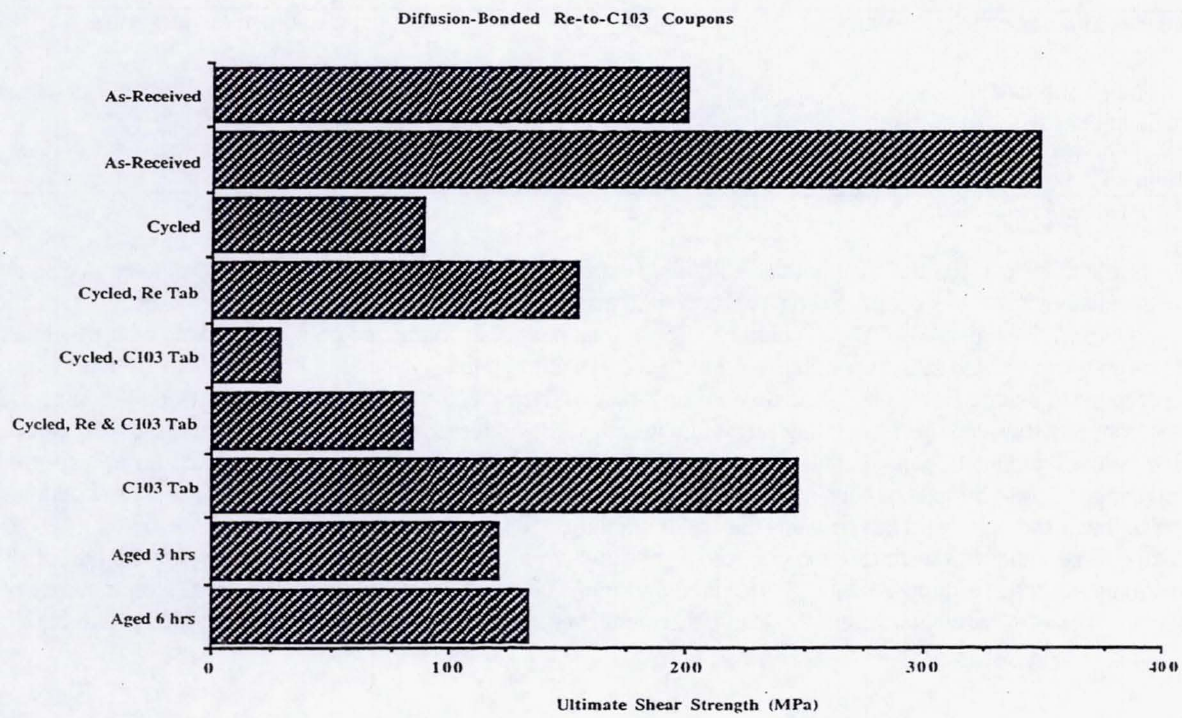


Figure 9: Ultimate Shear Strength for Diffusion-Bonded Coupons

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1995

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Evaluation of Rhenium Joining Methods

5. FUNDING NUMBERS
WU–232–02–03

6. AUTHOR(S)
Brian D. Reed and Sybil H. Morren

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–9903

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–107055

11. SUPPLEMENTARY NOTES
Prepared for the 31st Joint Propulsion Conference and Exhibit, cosponsored by AIAA, ASME, SAE, and ASEE, San Diego, California, July 10–12, 1995. Responsible person, Brian D. Reed, organization code 5330, (216) 977–7489.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 20

This publication is available from the NASA Center for Aerospace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Coupons of rhenium-to-C103 flat plate joints, formed by explosive and diffusion bonding, were evaluated in a series of shear tests. Shear testing was conducted on as-received, thermally-cycled (100 cycles, from 21 to 1100 °C), and thermally-aged (3 and 6 hrs at 1100 °C) joint coupons. Shear tests were also conducted on joint coupons with rhenium and/or C103 electron beam welded tabs to simulate the joint's incorporation into a structure. Ultimate shear strength was used as a figure of merit to assess the effects of the thermal treatment and the electron beam welding of tabs on the joint coupons. All of the coupons survived thermal testing intact and without any visible degradation. Two different lots of as-received, explosively-bonded joint coupons had ultimate shear strengths of 281 and 310 MPa and162 and 223 MPa, respectively. As-received, diffusion-bonded coupons had ultimate shear strengths of 199 and 348 MPa. For the most part, the thermally-treated and rhenium weld tab coupons had shear strengths slightly reduced or within the range of the as-received values. Coupons with C103 weld tabs experienced a significant reduction in shear strength. The degradation of strength appeared to be the result of a poor heat sink provided during the electron beam welding. The C103 base material could not dissipate heat as effectively as rhenium, leading to the formation of a brittle rhenium-niobium intermetallic.

14. SUBJECT TERMS
Joining; Bonding; Welding; Rhenium; Radiation-cooled rockets

15. NUMBER OF PAGES
15

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18