High Strength Nickel-Palladium-Chromium Brazing Alloys

Filler metals based on nickel-palladium replace gold-based filler metals in critical superalloy brazements

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Introduction

Aircraft engine fabricators have traditionally used brazing processes for joining engine components. Nickel- and gold-based filler metals are primarily used in these applications due to their superior performance at elevated temperatures. Historically, one gold-based alloy, designated by the American Welding Society as BAu-4, has established itself as a dependable filler metal to many fabricators. Although this filler metal is finding less use due to its precious metal content, many critical engine components, especially those made of γ' hardened superalloys, are still brazed with BAu-4. The γ' hardened superalloys (such as Inconel-718*) should not be brazed at temperatures exceeding 1010°C (1850°F), to prevent possible coarsening and dissolution of strengthening phases (γ' or γ''), as well as to inhibit grain growth during brazing operations. The brazing temperature of BAu-4 is below 1010°C (1850°F), and it provides necessary elevated temperature properties. Furthermore, the availability of BAu-4 in flexible foil forms makes it suitable for joining parts of complex shapes.

Prior studies (Refs. 1-3) have indicated that a number of nickel-based filler metals of the AWS BNi family, which are currently available as flexible metallic glass foil form, also provide adequate elevated temperature properties in certain base metals. However, the brazing temperatures of such alloys are higher than 1010°C (1850°F), making these alloys unsuitable for joining γ' hardened superalloys.

Recently, it has been demonstrated that alloys of the Ni-Pd-Cr-Fe-B-Si family containing up to 36 wt% Pd possess solidus and liquidus temperatures comparable to those of BAu-4 (Ref. 4). Hence, the brazing temperature for these compositions are also below 1010°C (1850°F), making them suitable for use as filler metals for joining γ' hardened superalloys. It has also been realized that these alloys can be processed into flexible metallic glass foil form by rapid solidification techniques.

The present study has been structured to investigate the fundamental characteristics of Ni-Pd filler metals in brazing. The mechanical properties, corrosion behavior and microstructural characteristics of joints prepared with these filler metals are compared to BAu-4 brazed joints. Recommendations on optimum alloy composition are derived.

Alloy Development

The objective of alloy development efforts was to produce a filler metal alloy according to the following criteria:

1. Adequate flowability at or below 1010°C (1850°F).
2. Glass forming composition to provide flexible and preformable ribbon.
3. Precious metal content lower than BAu-4.
4. Joint mechanical properties comparable to those of BAu-4 at elevated temperatures (540°-800°C/1004-1472°F).
5. Oxidation and corrosion resistance at elevated temperatures (~600°C/1112°F).
6. Sufficient ductility of brazed joints.

The Ni-B-Si ternary system was selected for preliminary studies. This system has a number of ternary eutectic compositions connected by monovariant melting troughs (Ref. 5). One of the ternary eutectic compositions of this system is $Ni_{77}B_{10}Si_{13}$ (at%) with a liquidus temperature of 1010°C (1850°F). This was confirmed by differential thermal analysis (DTA). However, the brazing temperature of an alloy is usually higher than its melting or, more specifically, liquidus temperature. Hence, the basic Ni-B-Si ternary composition required modification to further depress the melting temperature. A review of binary phase diagrams suggested the selection of Mn or Pd as suitable melting point depressors. The Ni-Pd and Ni-Mn systems exhibit minimum temperatures at 1237°C (2259°F) (45 at% Pd) and 1018°C (1864°F) (62 at% Mn), respectively (Ref. 6). However, Mn was not selected because of its high vapor pressure, which is undesirable for high temperature vacuum brazing applications.

In addition to palladium, chromium was added to provide corrosion and oxidation resistance, and iron to improve the joint strength. The (Ni,Pd,Cr,Fe)-B-Si pseudoternary system was then investigated for eutectic or near-eutectic compositions by means of DTA and metallographic techniques. These compositions are usually castable into amorphous foil form.

A second pseudoternary system consisting of (Ni,Cr,Fe)-Pd-B was also studied.

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By the elimination of silicon, the formation of hard and brittle silicides in the joint is avoided. Furthermore, alloys containing both boron and silicon were characterized by a wide melting range with low solidus temperatures, making them less suitable for high temperature applications.

Experimental Procedures

Material Specifications

Three Ni-Pd alloys and BAu-4 were selected for detailed joint characterization. The nominal chemical compositions of brazing filler metals are given in Table 1. Alloys MBF-1001X and MBF-1002X contain Ni, Pd, Cr, Fe and B. By comparison, alloy MBF-1003X contains silicon, in addition to the above-mentioned elements. The liquidus and solidus temperatures of the filler metals were determined by DTA technique and are listed in Table 2.

The nominal chemical compositions of the base metals Inconel-718 and AISI-316 stainless steel are given in Table 3.

Table 1—Nominal Chemical Compositions of Various Brazing Filler Metals (wt%)

Alloy Designation	Ni	Pd	Cr	Fe	B	Si	Au
MBF-1001X[a]	Bal	35.32	8.63	4.63	2.69	–	–
MBF-1002X[a]	Bal	32.25	8.61	0.93	2.69	–	–
MBF-1003X[a]	Bal	27.12	8.83	0.95	1.84	2.38	–
BAu-4[b]	Bal	–	–	–	–	–	82.0

[a]Foils produced by Metglas Products Department, an Allied Company, Parsippany, N.J.
[b]According to AWS specification A5.8.

Lap Shear Tests

Figures 1 and 2 show the dimensions of single lap shear samples made with Inconel-718 and AISI-316 base metals, respectively. Prior to brazing, the mating surfaces of the blanks were roughened by using No. 80 grit emery paper, followed by ultrasonic degreasing in acetone and rinsing in alcohol. All filler metal foils were 0.338 mm (0.0015 in.) thick and served as joint spacers. After fixturing, the edges of the samples were lightly tack welded by gas tungsten arc welding to hold the assemblies together during brazing.

Brazing was performed in a vacuum furnace at a vacuum of about 10^{-4} to 10^{-5} torr. After brazing, the Inconel-718 samples were solution treated in the following manner to achieve optimum strength of the base metal: 980°C (1800°F)/1 hr, air cool to room temperature, 720°C (1325°F)/8 hr, furnace cool to 620°C (1150°F)/8 hr, and finally, air cool to a base metal hardness of Rc 38–42.

Inconel-718 brazements were tensile tested at 538° ± 5°C (1000° ± 10°F). The AISI-316 brazements were tensile tested at room temperature. The breaking loads of the specimens were noted to determine the shear stress.

Table 2—Melting Characteristics and Brazing Temperatures of Various Filler Metals

Designation	Liquidus Temperature, °C (°F)	Solidus Temperature, °C (°F)	Brazing Temperature, °C (°F)
MBF-1001X	996 (1825)	945 (1733)	1010 (1850)
MBF-1002X	993 (1819)	934 (1713)	1010 (1850)
MBF-1003X	985 (1805)	825 (1517)	1010 (1850)
BAu-4	970 (1778)	946 (1735)	1004 (1840)

Ductility Tests

Inconel-718 sheet blanks were brazed together in the shape of a T, as illustrated in Fig. 3. The brazed samples were heat treated to achieve optimum strength, as described above, and then twisted 90 deg, keeping one end fixed. The joints were inspected visually and under a stereo microscope for cracks.

Stress Rupture Tests

Stress rupture tests were conducted using Inconel-718 base metal. The joint configuration was of the butt type. Filler metal foils were placed between the mating surfaces of the Inconel-718 blanks, and the assemblies were lightly tack welded. Brazing was performed in a manner similar to that for the lap shear samples.

After brazing, samples were machined to the dimensions shown in Fig. 4, and all extra filler metal on the joint surface was removed by careful grinding. Prior to testing, all samples were heat treated as described in the lap shear case.

Stress rupture tests were conducted at 538°C ± 5°C (1000°F ± 10°F) and at 816°C ± 5°C (1500°F ± 10°F) under static loading. The times of failure under different static loading were noted.

Microstructure

Brazed specimens were cross-sectioned, mounted and polished for metallographic inspection. All samples were etched in 5 g $FeCl_3$, 50 ml HCl, 100 ml distilled water solution. Joint microstructures were examined by optical and scanning electron microscopy. Elemental distribution was determined by Auger electron spectroscopy.

Corrosion Test

Corrosion properties of MBF-1002X and Inconel-718 were examined at room temperature in 0.1 N KOH solutions with and without 0.1 N KCl. Since glassy filler metal foils devitrify during brazing (Ref. 7), the MBF-1002X foil was heated to a temperature below its solidus to transform its structure from amorphous to crystalline. Strips of these alloys were examined in an electrochemical cell, where they served as the test electrodes. Platinum foil in the cell was used as the counter electrode. Potentials of the test electrodes were determined with respect to a saturated calomel electrode (SCE) situated in a separate compartment, attached by a liquid junction to the cell.

Shortly after immersion of a test electrode into oxygen-saturated solution, a corrosion potential (E_{cor}) was read directly with respect to the SCE. In addition to this direct measurement of E_{cor}, the cathodic component of the corrosion potential was determined by applying various constant current densities (cd) to the test electrode and recording the electrode potential (E) with respect to SCE. Similarly, the anodic component of the corrosion potential was determined by applying a constant E, higher than E_{cor}, to the test electrode and recording cd at a given E. In a final experiment, MBF-1002X and Inconel-718 electrodes were shorted, and the corrosion potential of the coupled electrode was determined.

Table 3—Nominal Chemical Composition of Different Base Metals (wt%)

Alloy Designation	Ni	Cr	Fe	Mo	Si	Others
AISI-316[a]	12.0	17.0	Bal	2.5	1.0	Mn2.0
Inconel-718[b]	Ni+ Co = 52.5	19.0	18.5	3.0	–	Cb + Ti = 5.1

[a]American Iron and Steel Institute (AISI) designation.
[b]Trademark of the International Nickel Co., New York, N.Y.

Results and Discussion

Mechanical Properties

Lap Shear Tests

Results of the lap shear tests at 538°C (1000°F) are given in Table 4. At an overlap of 2t (two times the base metal thickness), most samples failed in the joint. Only the samples brazed with MBF-1001X failed in the base metal. Failure in the base metal indicates a brazed joint stronger than the base metal. In other words, the base metal will fail before the joint. When the overlap distance was increased to 4t (four times the base metal thickness), all brazements made with Ni-Pd based alloys failed in the base metal, indicating, again, joints stronger than the base metal. On the other hand, the BAu-4 brazements, even at an increased overlap of 4t, failed in the joint.

Analyses of the strength data indicate that, in general, joint strengths of Ni-Pd based alloys, especially those of MBF-1001X and MBF-1002X filler metals, are equal to or greater than those of the BAu-4 alloy. However, the filler metal MBF-1003X, which contains both boron and silicon as melting point depressors, exhibited poor joint strength compared to MBF-1001X, MBF-1002X and the BAu-4 alloys.

Ductility Tests

Results of the ductility tests, conducted at room temperature, are shown in Table 5. None of the joints made with Ni-Pd alloys cracked after twisting the T specimens 90 deg. The brazements made with the BAu-4 alloy, however, did develop cracks in the joint after testing. The T tests demonstrate that the Ni-Pd brazed joints were more ductile compared to that of BAu-4.

Stress Rupture Strength

The results of the stress rupture tests are given in Tables 6 and 7. It is evident from Table 6 that the rupture strengths of all the Ni-Pd based alloys at 538°C (1000°F) are superior to those of BAu-4.

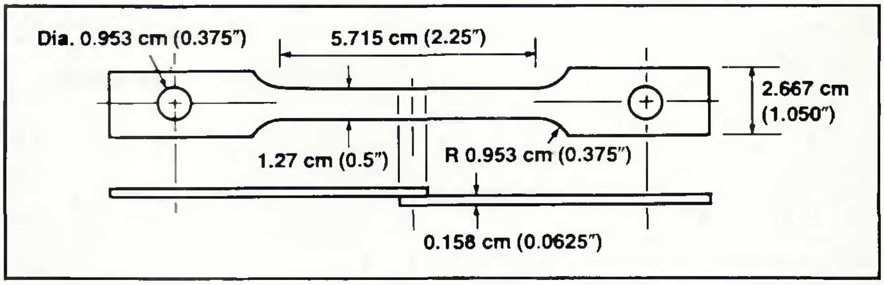

Fig. 1—Finished Inconel-718 single lap shear test specimen

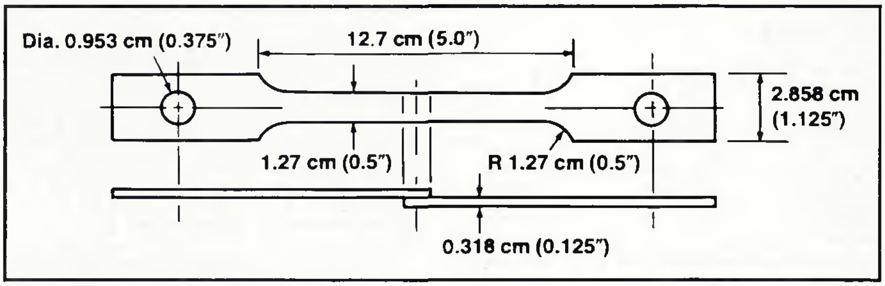

Fig. 2—Finished AISI-316 single lap shear test specimen

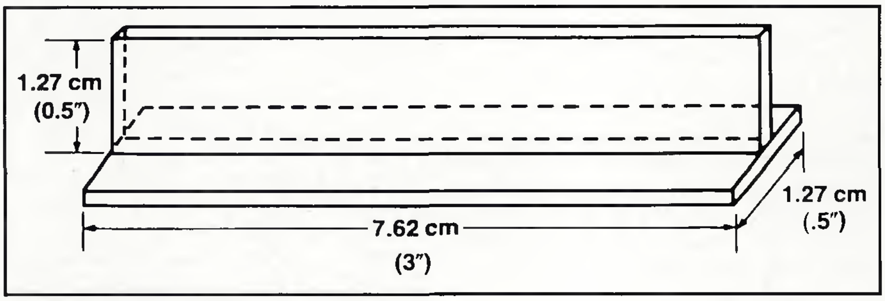

Fig. 3—Ductility test specimen dimensions

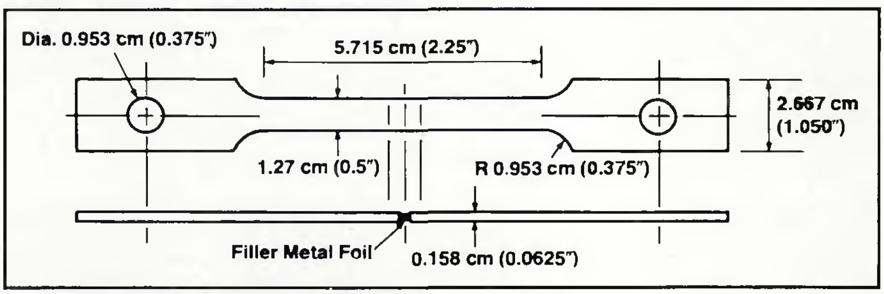

Fig. 4—Finished Inconel-718 stress rupture test specimen

Table 4—Mechanical Properties of Joints Brazed with Various Filler Metals Tested at Elevated Temperature 538°C (1000°F)

Brazing Alloy	Overlap Distance [t = 0.159 cm (0.063 in.)]	Shear Strength MPa (psi)	Tensile Strength MPa (psi)	Comments
BAu-4	2t	337 (48,813)	687 (99,627)	Failed in joint
	4t	222 (32,187)	887 (128,747)	Failed in joint
MBF-1001X	2t	376 (54,560)	752 (109,120)	Failed in base metal
	4t	240 (34,820)	946 (137,280)	Failed in base metal
MBF-1002X	2t	354 (51,280)	700 (102,600)	Failed in joint
	4t	249 (36,160)	997 (144,640)	Failed in base metal
MBF-1003X	2t	270 (39,200)	540 (78,400)	Failed in joint
	4t	221 (32,080)	885 (128,320)	Failed in base metal

Table 5—Results of Ductility Tests

Alloy	Brazement Characteristics	Comments
MBF-1001X	Did not develop cracks	Ductile joint
MBF-1002X	Did not develop cracks	Ductile joint
MBF-1003X	Did not develop cracks	Ductile joint
BAu-4	Developed cracks	Brittle joint

Table 6—Results of Stress Rupture Tests at 538°C (1000°F)

Alloy	Time of Failure @ 455 kg (1000 lb)
MBF-1001X	Did not fail after 300 hr
MBF-1002X	Did not fail after 300 hr
MBF-1003X	Did not fail after 300 hr
BAu-4	1 hr

Table 7—Results of Stress Rupture Tests at 816°C (1500°F)

Alloy	Time of Failure 228 kg (@500 lb)	455 kg (@1000 lb)
MBF-1001X	60 min	6.0 min
MBF-1002X	138 min	12.0 min
MBF-1003X	0.0 min	0.0 min
BAu-4	0.0 min	0.0 min

All BAu-4 brazements failed within an hour, while brazements made with Ni-Pd alloys did not fail even after 300 hr, when the tests were discontinued.

However, at the higher test temperature of 816°C (1500°F), both MBF1003X and BAu-4 alloys failed immediately after loading. The alloy MBF-1002X exhibited the best rupture strength, followed by the MBF-1001X alloy. It is again interesting to note here that the alloy MBF-1003X contains silicon in addition to boron as a melting point depressor.

Melting Characteristics

Figure 5 illustrates the DTA curves of the Ni-Pd alloys. Alloys MBF-1001X and MBF-1002X, containing only boron, exhibit single melting troughs which are characteristic of near-eutectic alloys. In contrast, the alloy MBF-1003X, which contains silicon in addition to boron, shows two distinct troughs. The low temperature trough is believed to be due to the melting of palladium silicides. The MBF-1003X alloy is also characterized by a wide melting range, having a solidus temperature (825°C/1517°F) much lower compared to MBF-1001X and MBF-1002X (solidus temperatures 945° and 934°C/1733° and 1713°F, respectively). A lower solidus temperature of the braze filler metal is undesirable in applications where brazements are exposed to elevated temperatures, such as aircraft engine components. Based on these equilibrium melting characteristics alone, the addition of silicon with boron was found to be detrimental for the Ni-Pd based alloys.

Structure-Property Correlation

Based on DTA and mechanical properties, addition of silicon to Ni-Pd-Cr-B leads to detrimental effects. The silicon-and-boron-containing MBF-1003X has a wider melting range and is characterized by a lower solidus compared to the boron-containing MBF-1001X and 1002X. Also, mechanical properties of MBF-1003X brazements are comparatively inferior to those of MBF-1001X and MBF-1002X. These phenomena are believed to stem from palladium silicide formation in joints brazed with MBF-1003X. Therefore, it behooves us to examine representative brazed joint microstructures and determine the role of silicon in modifying joint morphology and associated mechanical properties. For this comparison, brazed joints were made using AISI-316 stainless steel base metal. Filler metals used were MBF-1001X and MBF-1003X alloys. Brazing was performed in a vacuum furnace at a vacuum of about 10^{-4} torr for 10 min

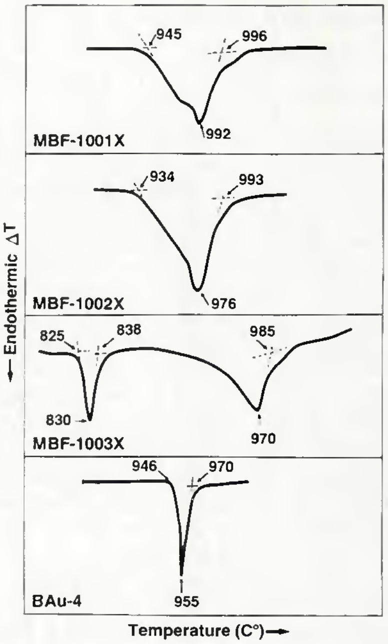

Fig. 5 — Thermograms of various alloys

and for 12 hr, at a temperature of 1010°C (1850°F).

Microstructure of AISI-316/MBF-1001X Joints Brazed for 10 Minutes and for 12 Hours

Figure 6 illustrates AISI-316/MBF-1001X joints brazed for 10 min. A narrow centerline eutectic was observed in the brazed joint (Fig. 6A), a portion of which is further magnified in Fig. 6B. Three distinct phases were identified in the centerline eutectic region by Auger elemental analysis — Fig. 7. These phases, as labelled in Fig. 6B, consist of:

1. Dark particles — found to be rich in Cr and B.

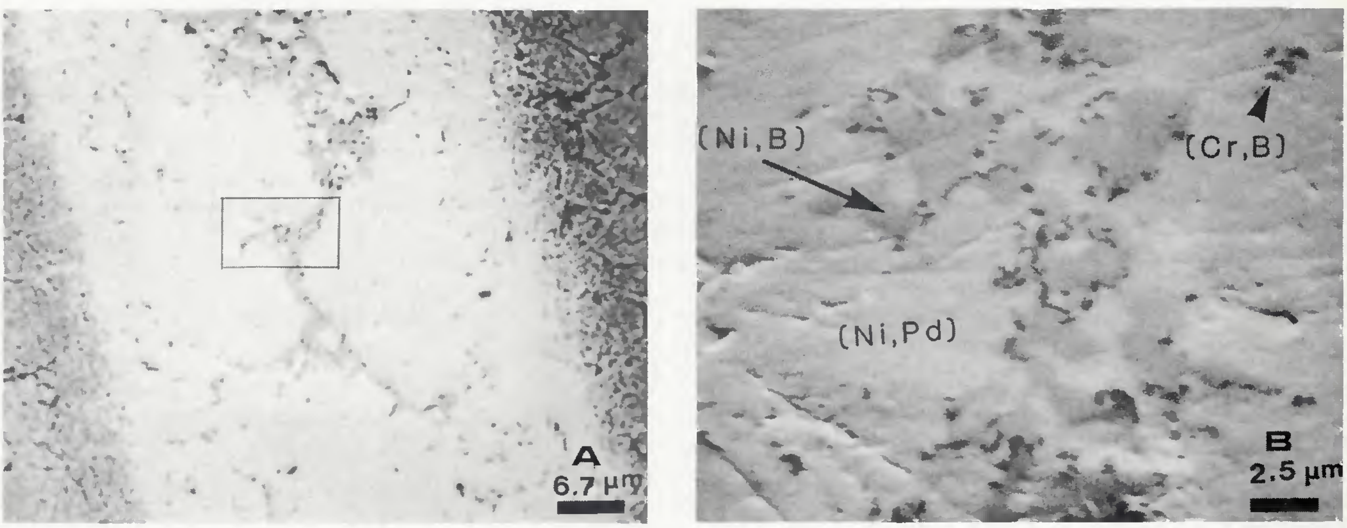

Fig. 6 — Photomicrographs of AISI-316/MBF-1001X joint brazed for 10 min. A portion of the narrow centerline eutectic in A (inside the black box) is shown at a higher magnification in B

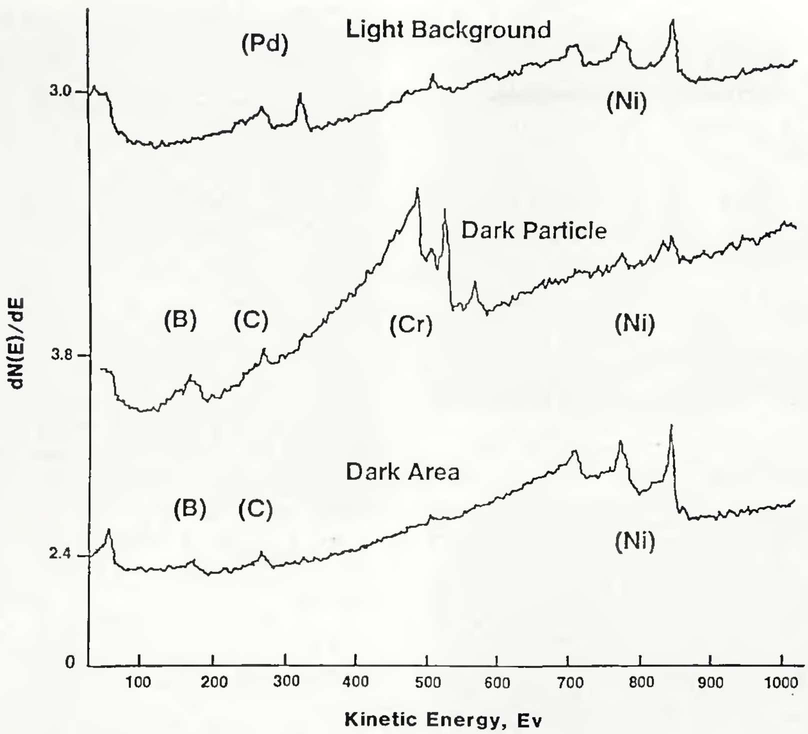

Fig. 7 — Differentiated spectrums of Auger electrons obtained from different phases of AISI-316/MBF-1001X joint brazed for 10 min

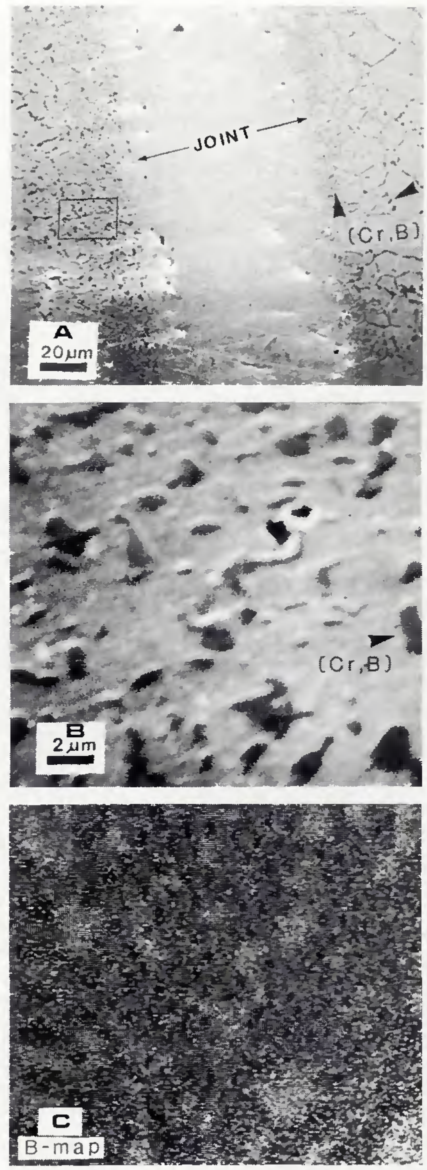

Fig. 8 — Photomicrographs of AISI-316/MBF-1001X joint brazed for 12 hr. A portion of the base metal near the interface in A (inside black box) is shown at a higher magnification in B. C — a photomicrograph of Auger elemental mapping

2. Dark area — found to be rich in Ni and B.
3. Light background — identified to be rich in Ni and B.

The centerline eutectic completely disappeared at an increased brazing time of 12 hr — Fig. 8A. A high concentration of boron was found along the grain boundaries of the braze interface. A typical area of the braze interface was shown at a higher magnification in Fig. 8B. The dark particles along the grain boundaries in Fig. 8B were identified to be rich in Cr and B by Auger mapping — Fig. 8C.

Microstructure of AISI-316/MBF-1003X Joints Brazed for 10 Minutes and for 12 Hours

The 10 min brazed joint exhibited a wide centerline eutectic, as illustrated in Fig. 9A. As this filler metal contains silicon in addition to boron as melting point depressors, the joint morphology was also different compared to that of the MBF-1001X alloy. The volume fraction of the centerline eutectic is much larger and the microstructure is significantly coarser. Two distinct phases, present in the centerline eutectic region (Fig. 9B), were identified by electron probe microanalysis (EPMA) x-ray area scans (Fig. 9C and 9D) as:

1. white area — compounds of Pd and Si
2. dark area — compounds of Ni, Cr and B

In addition, a silicon profile of the 10 min brazement obtained by electron probe microanalysis indicated that almost all the silicon was concentrated in the joint area, as illustrated in Fig. 10.

As described in the previous case, the centerline eutectic disappeared when the brazing was performed for 12 hr — Fig. 11A. Voids in the joint base metal interface were observed, probably due to Kirkendall effect. The distribution of silicon determined by EPMA is shown in Fig. 11B. It was found that, for longer brazing time, silicon did diffuse out of the joint area into the matrix. However, as observed from Fig. 11, most of the silicon was concentrated near the braze interface.

Comparison of Joint Strength

The joint strengths of the boron-containing MBF-1001X alloy and the boron-plus-silicon-containing MBF-1003X alloy were evaluated using single lap shear test specimens, as described previously in the Lap Shear Tests section. The results of the lap shear test are given in Table 8. Analysis of the strength data indicated significant improvement of joint strength after prolonged brazing in the case of MBF-1003X alloy. This is possibly due to diffusion of silicon from the brazed joint, as illustrated in Fig. 11. The MBF-1001X alloy, on the other hand, did not exhibit any noticeable improvement of joint strength after prolonged brazing for 12 hr. In general, however, the MBF-1001X alloy produces much stronger joints compared to the MBF-1003X alloy. These tests demonstrate that addition of silicon in Ni-Pd alloy reduces the joint strength. This deleterious effect appears to stem from a coarse centerline eutectic consisting of palladium silicide particles.

Corrosion Behavior

The primary objective of the corrosion tests was to investigate the possibility of galvanic corrosion at the brazed joint. The nobilities of the braze alloy (MBF-1002X) and the base metal (Inconel-718) in alkaline and chlorinated alkaline solutions were determined and compared. The results of the electrochemical behavior are shown in Figs. 12 and 13. From the intercept of the anodic and cathodic E-i

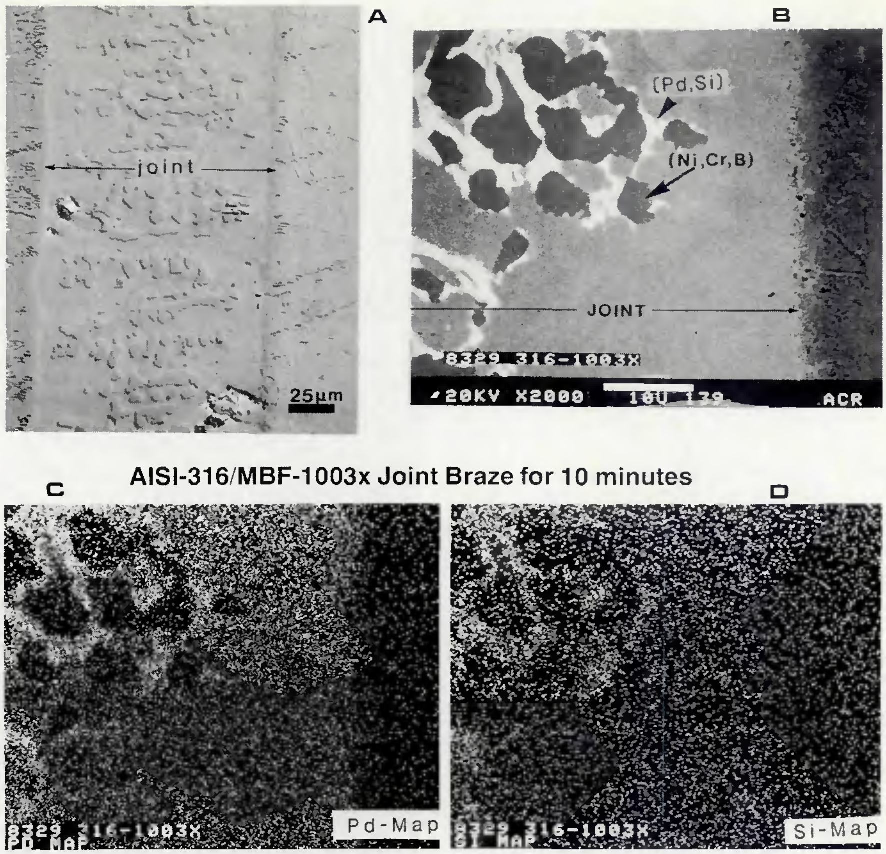

Fig. 9—Photomicrographs of AISI-316/MBF-1003X brazed joints, illustrating presence of palladium silicides in the centerline eutectic region

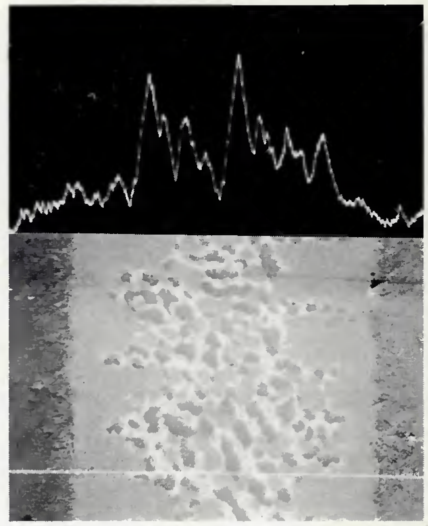

Fig. 10—Silicon profile of AISI-316/MBF-1003X 10 min brazement, illustrating concentration of silicon in the joint area

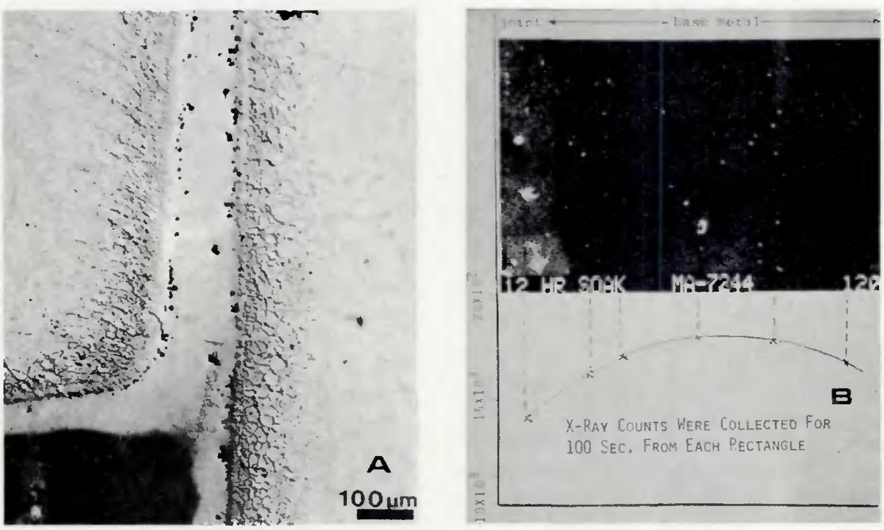

Fig. 11—AISI-316/MBF-1003X joint brazed for 12 hr, illustrating dispersion of centerline eutectic and distribution of silicon

Table 8—Joint Strength for Short and Long Brazing Cycles

Alloy	Brazing Time	Shear Strength MPa (psi)	Tensile Strength MPa (psi)	Area of Failure
MBF-1001X	10 min	200 (29,104)	400 (58,208)	Joint
MBF-1001X	12 hr	215 (31,200)	430 (62,400)	Joint
MBF-1003X	10 min	142 (20,600)	284 (41,200)	Joint
MBF-1003X	12 hr	186 (27,000)	372 (54,000)	Joint

lines, E_{cor} in chlorinated solutions was −0.24 and −0.16 V versus SCE for Inconel-718 and MBF-1002X alloys, respectively. In the solutions without KCl, the potentials at both MBF-1002X and Inconel-718 electrodes were close to −0.2 V versus SCE.

The cathodic components at all electrodes were oxygen reduction and exhibited characteristic linear Tafel relationships (Ref. 8). The anodic component at the early stages of corrosion was the formation of anodic oxide or hydroxide films over the MBF-1002X and Inconel-718 electrodes. From the intercepts of the anodic and cathodic components of E_{cor} of individual electrodes, corrosion current densities (i_{cor}) were determined. The corrosion current densities of both electrodes were found to be about 10^{-7} A/cm^2 in solutions either with or without the presence of Cl^- ions.

It is evident from these experiments that the MBF-1002X alloy, though having different Tafel slopes (*i.e.*, dE/dlogi are different than those of Inconel-718), has corrosion potentials close to the E_{cor} of Inconel-718. Corrosion current densities at MBF-1002X and Inconel-718 are nearly equal in both solutions. From these data, it can be concluded that in alkaline solutions MBF-1002X is well matched to Inconel-718. Slight differences in E_{cor} between Inconel-718 and MBF-1002X may not be significant. When shorted, as in a brazed system, the Inconel-718/MBF-1002X couple shows a common corrosion potential of about −0.2 V versus SCE—Fig. 12. This potential does not change significantly with time for about 20 hr (the end of the experiment). These experiments with coupled electrodes also showed that the MBF-1002X/Inconel-718 brazed system behaves well in alkaline solutions.

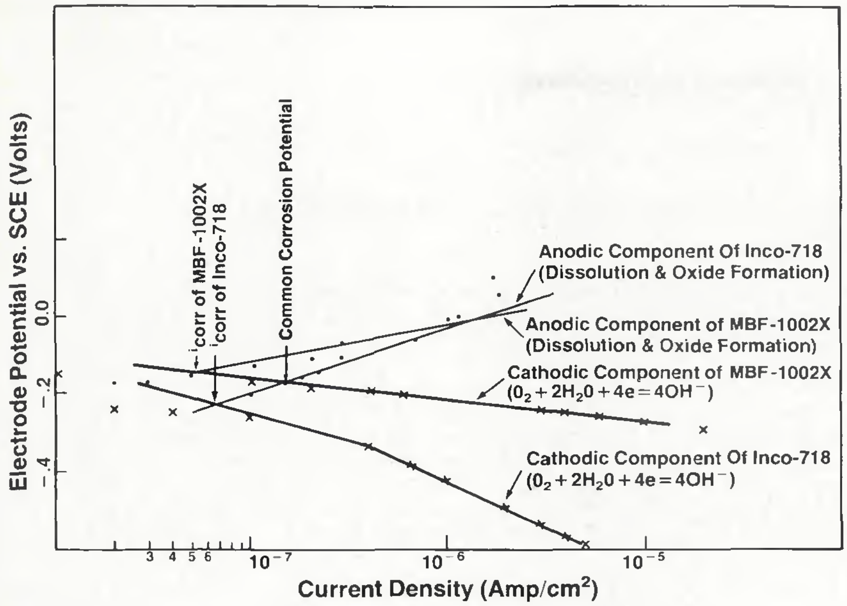

Fig. 12 — Corrosion behavior of MBF-1002X brazing alloy and Inconel-718 base metal in chlorinated 0.1N KOH solution

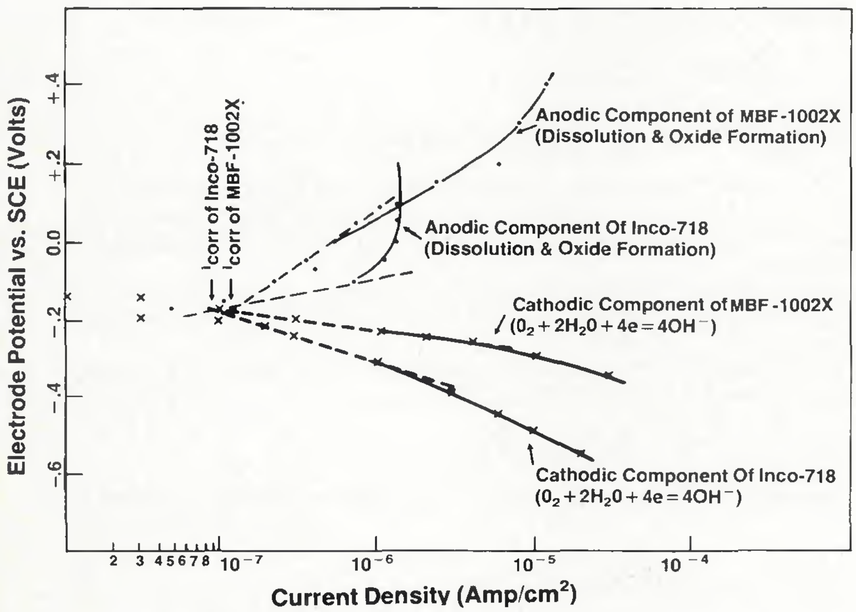

Fig. 13 — Corrosion behavior of MBF-1002X brazing alloy and Inconel-718 base metal in 0.1 KOH solution

Conclusions

Nickel-palladium based filler metals in a flexible metallic glass foil form have been developed primarily as replacements for gold-based filler metals, such as AWS BAu-4 (82Au-18Ni wt%). Like BAu-4, the brazing temperatures of the Ni-Pd alloys are below 1010°C (1850°F), rendering them suitable for joining critical aircraft engine components made with γ' hardened superalloys, such as Inconel-718.

Elevated temperature mechanical properties of Inconel-718 joints brazed with these Ni-Pd based compositions have been compared with those of gold-based BAu-4 alloy. The joint shear strengths of these Ni-Pd alloys at 538°C (1000°F) have been found to be equal or superior to those of BAu-4 filler metal. In addition, Ni-Pd alloy brazements exhibited superior stress rupture behavior at 538° and 816°C (1000° and 1500°F) compared to those brazed with BAu-4 filler metal. The room temperature joint ductility of the Ni-Pd based compositions have been found to be comparable to that of BAu-4 alloy.

Effects of boron and silicon, the primary melting point depressors in Ni-Pd alloys, have also been studied. The presence of silicon in combination with boron in Ni-Pd alloys has been found to be detrimental, since it lowered the solidus temperature, thereby increasing the melting range. Also, the joint strength is reduced due to the formation of palladium silicides in the brazed joint.

The corrosion studies indicate that both MBF-1002X and Inconel-718 alloys have very similar corrosion characteristics. The corrosion current density of both materials is about 10^{-7} A/cm^2. The corrosion potentials in 0.1 N KOH solutions are close to −0.20 V versus SCE. From these data and the behavior of the MBF-1002X/Inconel-718 coupled sample, it can be concluded the Ni-Pd based MBF-1002X alloy is well matched to Inconel-718 base metal.

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WRC Bulletin 301
January 1985

A Parametric Three-Dimensional Finite Element Study of 45 Degree Lateral Connections
By P. P. Raju

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Publication of this report was sponsored by the Task Group on Laterals that reported to the Subcommittee on Reinforced Openings and External Loadings and the Subcommittee on Piping Pumps and Valves of the Pressure Vessel Research Committee of the Welding Research Council.

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April 1985

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WRC Bulletin 305
June 1985

This bulletin contains three summary reports prepared by the Japan Pressure Vessel Research Council (JPVRC) Subcommittee on Hydrogen Embrittlement:

1) "Hydrogen Attack Limit of 2¼ Cr-1 Mo Steel," by Task Group I;

2) "Embrittlement of Pressure Vessel Steels in High Temperature, High Pressure Hydrogen Environment," by Task Group II; and

3) "Hydrogen Embrittlement of Bond Structure Between Stainless Steel Overlay and Base Metal," by Task Group III.

The three Task Group reports were translated and summarized for publication by JPVRC and have been reviewed and edited by the U.S. PVRC Subcommittee on Hydrogen Effects for publication in this bulletin.

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