Development of High Temperature Dissimilar Joint Technology for Fission Surface Power Systems

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Abstract

NASA is developing fission surface power (FSP) system technology as a potential option for use on the surface of the moon or Mars. The goal is to design a robust system that takes full advantage of existing materials data bases. One of the key components of the power conversion system is the hot-side Heat Exchanger (HX). One possible design for this heat exchanger requires a joint of the dissimilar metals 316L stainless steel and Inconel 718, which must sustain extended operation at high temperatures. This study compares two joining techniques, brazing and diffusion bonding, in the context of forming the requisite stainless steel to superalloy joint. The microstructures produced by brazing and diffusion bonding, the effect of brazing cycle on the mechanical tensile properties of the alloys, and the strength of several brazed joints will be discussed.

Introduction

The U S. Space Exploration Policy calls for lunar exploration activities to enable sustained human and robotic exploration of Mars and more distant destinations in the solar system. One major concern for every space exploration mission is the amount of power required to sustain life and efficiently operate the communication and scientific equipment. NASA is evaluating a wide range of power technologies that can satisfy anticipated future space mission power requirements. Future generations of power systems for spacecraft and lunar surface systems may require a diverse suite of power options that goes beyond the current capabilities of chemical, radioisotope thermoelectric generator and solar technologies. Recently, NASA has embarked on a Fission Surface Power (FSP) technology project to develop an option that can be used to provide power for human outposts. The FSP system would use nuclear energy converted into electricity through a conversion system similar to terrestrial power plants. Key to the success of this program will be the ability to design a compact and robust system based on existing technologies [1].

This is a system with many diverse materials needs. Stainless steel is the preferred structural material in the reactor section and nickel based superalloys are desired in the power conversion section. One proposed way to reconcile these requirements is to have a dissimilar metals joint in the hot-side Heat Exchanger (HX). For this design, a liquid metal NaK mixture would be flowing on the outside of the 316 L stainless steel manifold while transferring heat to the Inconel 718 convertor heater head containing pressurized helium gas. The anticipated joint temperature is 830 to 870 K (1034 to 1106 ºF). Several brazing filler metals applicable to either stainless steels or superalloys have been reported [2], but no open literature reports have been found describing the integration of both alloy systems. The integrity of the dissimilar metal joint is crucial since it is in the heat transfer path. In this paper, we discuss two joining options for this transition from stainless steel 316 L (SS316L) to Inconel 718 (IN718) to fabricate the HX. Both candidate processes, diffusion bonding and brazing, do not involve any melting of the base metals and could provide an acceptable fabrication bonding process for the HX application.

Experimental Procedure

The first joining approach used a diffusion bonding technique using a hot pressing process. This process was recently applied [3] to identify diffusional interaction issues between various refractory alloys with superalloys, and SS316L with commercial purity titanium. The results of the study successfully aided in the process to downselect superalloys and refractory alloy candidates. Diffusion bonding was demonstrated to be a good primary screening technique to evaluate the diffusional stability of joined dissimilar metals. Also, the process allows the introduction of metal interlayers of different compositions to limit the interdiffusion of elements between alloys.

The second joining approach utilized a brazing process, where two types of brazing materials were heated to temperatures approximately 323 K (122 ºF) above the melting point of the filler material.

The chemistry of the alloys used in this study is listed in Table 1. IN718 is a precipitation-hardenable nickel-chromium alloy containing significant amounts of iron, niobium, and molybdenum along with lesser amounts of aluminum and titanium. It combines corrosion resistance and high strength with outstanding weldability including resistance to postweld cracking. The alloy has excellent creep-rupture strength at temperatures up to 973 K (1292 ºF). IN718 derives its high temperature strength from the precipitation of specific secondary phases (e.g. gamma prime and gamma double-prime) into the metal matrix. The precipitation of these nickel-(aluminum, titanium, and niobium) phases is induced by an age heat treatment in the temperature range of 866 - 1088 K (1099 - 1499 ºF). For this metallurgical reaction to properly take place, the aging constituents (aluminum, titanium, and niobium) must be fully in solution.

SS316L is part of the family of austenitic stainless steels which constitute the largest stainless family in terms of number of alloys and usage. The L designation indicates a lower carbon specification. The main difference between stainless steel type 316 from the basic type 304 is the addition of molybdenum up to a maximum of 3 wt. %, which enhances its corrosive properties.

Hot Press Diffusion Bonding Approach

Joints between the superalloy IN718 and the SS316L were produced by hot pressing small coupons of each material in vacuum for 2 hours at 1000 K (1340 ºF) or 1150 K (1610 ºF) with a pressure of 90 MPa (13 ksi). The 1150 K (1610 ºF) temperature was initially selected to ensure that some solid state bonding would occur, while the 1000 K (1340 ºF) temperature was explored to minimize the formation of undesirable second phases. All samples were surface ground to 600 grit, ultrasonic cleaned in acetone and methanol and air dried. Figure 1 shows an illustration of a dissimilar material stack-up. By stacking the disks, a single hot-press run could form several diffusion couples at once. Thin sheets of Ni and V were explored as possible metal interlayers between the SS316L and the IN718 alloys. Metal interlayers may enhanced the bonding and minimize alloy to alloy diffusion reactions.

Table 1. Chemical Analysis of Alloys Studied

Wt.%	**Al**	**B**	**C**	**Co**	**Cr**	**Cu**	**Fe**	**Mn**	**Mo**	**Nb**	**Ni**	**Si**	**Ti**	**V**
IN 718	0.6	100ppm	0.04	0.12	18.7	540ppm	19.2	870ppm	2.74	4.49	52.9	470ppm	0.89	660ppm
SS316L		50ppm	0.02	0.08	17.1	0.42	68.1	1.42	1.86	80ppm	10.12	0.66	0.024	0.045

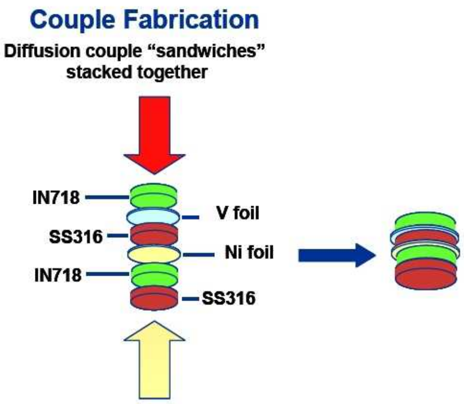

FIGURE 1. Illustration of Hot Pressing Sequence to Produce Multiple, Dissimilar Metal Diffusion Couples.

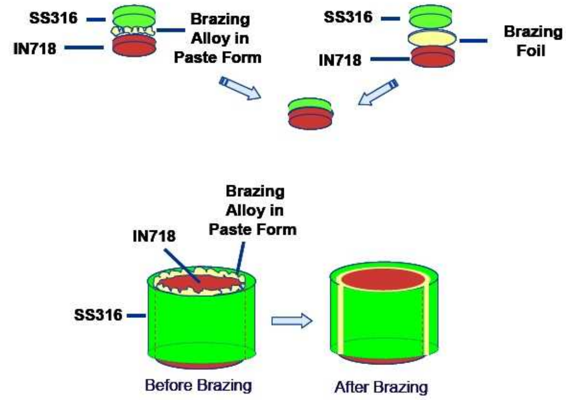

FIGURE 2. Illustration of various Brazing Approaches using Paste and Foil to Evaluate the Process and the Compatibility of various Commercial Braze Alloys with SS316L and IN718 alloys.

Brazing Approach

The brazing approach is another joining process that does not involve any melting of the base metal. The coalescence of the metal surfaces to be joined is generally produced by the distribution of a lower melting point filler metal by capillary attraction to the closely fitted surfaces, by heating to suitable temperatures [4]. Properly designed braze joints can remain structurally intact and hermetically sound under heavy pressures, even when the joint is subjected to shock or vibrational types of loading [5]. The compatibility of several filler materials with the SS316L or IN718 were initially evaluated using an overlapping type joint technique. Figure 2 shows schematic representations of the overlapping brazing process for flat surfaces using either foil or paste, and the capillarity attraction process for tightly fitted SS316L pipe and IN718 solid rod. Based on the projected use temperature, 830 - 870 K (1034 - 1106 ºF), two classes of brazing materials were initially selected, nickel- and gold-based alloys. The nickel-based braze alloys, listed in Table 2, have similar characteristics and elements already present in the bonding alloys. The gold-based alloys listed may be less reactive, but are more expensive. Both brazing systems have similar coefficient of thermal expansion as the substrate alloys. Other critical aspects such as melting point, the ability to wet the surfaces of the materials to form a continuous, sound and strong bond seem to be adequate.

Table 2 – Brazing Materials Evaluated and Post-Bonding Thermal Exposures

Nickel-based Brazes	Composition (wt.%)	Brazing Temperature	Post-Bonding Exposures at 900 K
AMDRY 790	Ni-1.74B-3.22Si	1403 K (2066 ºF)	100, 1000, 3000 h
AMDRY 108	Ni-23Cr-11.5Fe-4.2P-6.4Si	1403 K (2066 ºF)	100, 1000, 3000 h
AMDRY 775	Ni-15.38Cr-3.8B	1403 K (2066 ºF)	100, 1000, 3000 h
Gold-based Brazes			
Nioro	82Au-18Ni	1258 K (1805 ºF) 1273 K (1832 ºF)	100, 1000, 3000 h
Palniro-7	70Au-22Ni-8Pd	1323 K (1922 ºF)	100, 1000, 3000 h

Method for Evaluating Alloy and Brazed Joints Strength

The evaluation of the strength of brazed joints followed the recommended practice from the American Welding Society (AWS), American National Standard C3.2M/C3.2:2008 [6]. Since the two alloys evaluated have different strength, where IN718 is typically much stronger than the SS316L, two sheets of SS316L were used to double-up against a single sheet of IN718 to fabricate multiple double-lap shear specimens. All the faying surfaces were prepared with a 600 grit finish, ultrasonically cleaned with acetone and alcohol. The tension testing of the double-lap shear specimens were performed in accordance with ASTM E 8, Standard Test Methods for Tension Testing of Metallic Materials. All specimens were tested in tension at 830 K (1034 ºF) by Metcut Research Inc. (Cincinnati, OH). The breaking load and location of the failure, whether through the brazed area or in the metal base, were recorded.

The average shear stress in the filler metal at failure and the average tensile stress in the base metal at failure were computed using the equation from the AWS standard as shown:

Average shear stress (brazing filler metal) =

$$\text{Breaking load} / (2A \times W) \qquad (1)$$

and,

Average tensile stress (base metal) =

$$\text{Breaking Load} / (W \times T) \qquad (2)$$

Where, A is the brazed joint overlap length, W is the width, and T is the material thickness (all in mm). Control specimens without brazed joints, processed through the brazing and secondary heat treatment cycles, were also tested at 830 K (1034 ºF) to determine the effect of the thermal cycles on the properties of the metals. Figure 3 shows typical brazed double-lap shear and control specimens used in this study. Base metal hardness measurements were performed on all the samples to monitor the effect and reproducibility of the brazing heat treatment process.

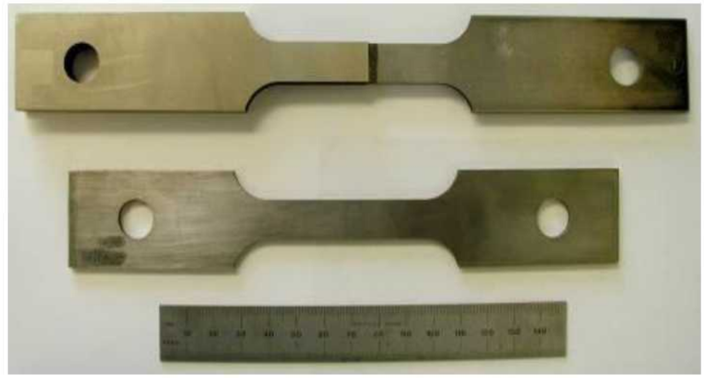

FIGURE 3. Typical Brazed Double-Lap Shear and Control Specimens Used for Testing at 830K.

Results and Discussion

Diffusion Bonded Joint

Observations of the bond produced under various hot pressing conditions were used to guide the selection of the threshold temperature to create a sound bond with minimal reaction zone. Initial bonding experiments indicated that hot pressing at 1150 K (1610 ºF) for 2 hours produced a sound bond line. Table 3 lists the diffusion couples that were formed by diffusion bonding as well as subsequent annealing conditions. Figure 4 shows optical micrographs of as-bonded couples (a) SS316L to IN718, (b) SS316L to 25 μm thick Ni-foil interlayer to IN718, and (c) SS316L to 25 μm thick V-foil interlayer to IN718. Bonding occurred in all three systems; however it is quite evident that the V-foil has reacted and embrittled the interface between the two alloys and resulted in nearly continuous longitudinal cracks. (Fig. 4c).

Table 3. Diffusion Bonded Couples Evaluated Hot Press Bonding Conditions and Post-Bonding Thermal Exposures

Hot Pressing Conditions	Exposure Temp, K	Exposure Time, h
1150 K (877 ºC) for 2 h at 90 MPa		
SS316L/IN718	1000	300, 1000
SS316L/Ni/IN718	1000	300, 1000
SS316L/V/IN718	1000	300, 1000
1000 K (727 ºC) for 7 h at 90 MPa		
SS316L/IN718	1000	300, 1000

The Ni-interlayer appears to accommodate gracefully the bonding of both alloys, although some fine porosity as shown in the Field Emission SEM (FESEM) image (Fig. 5), were observed at the Ni/IN718 interface. Energy dispersive spectrum analyses confirmed the presence of Al_2O_3 particles trapped in the porosity which are believed to be coming from the grinding media used during metallographic sample preparation. Similar porosity with the presence of small Al_2O_3 particles was also detected at the interface formed in the hot pressed SS316L to IN718 couple. A hot isostatic pressing (HIP) process which can provide up to three times the pressure compared to hot pressing, is being investigated, to understand if the porosity is due to the limited hot pressing pressure, or if it was formed by the preferential diffusion of some elemental species present in the alloys which can leave behind Kirkendall porosity.

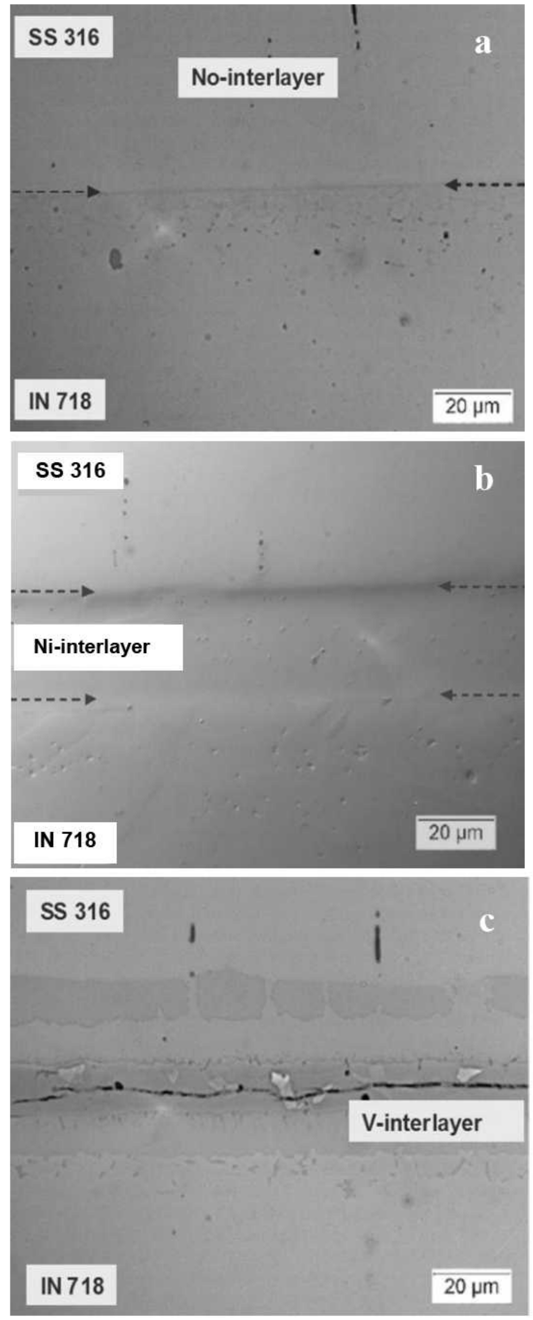

Figure 4. Optical Micrographs of Hot Pressed at 1150 K for 2 hours at 90 MPa Couples: (a) SS316L to IN718, (b) SS316 to Ni-interlayer to IN316, and (c) SS316L to V-interlayer to IN718. Bond Interface Indicated with Arrows.

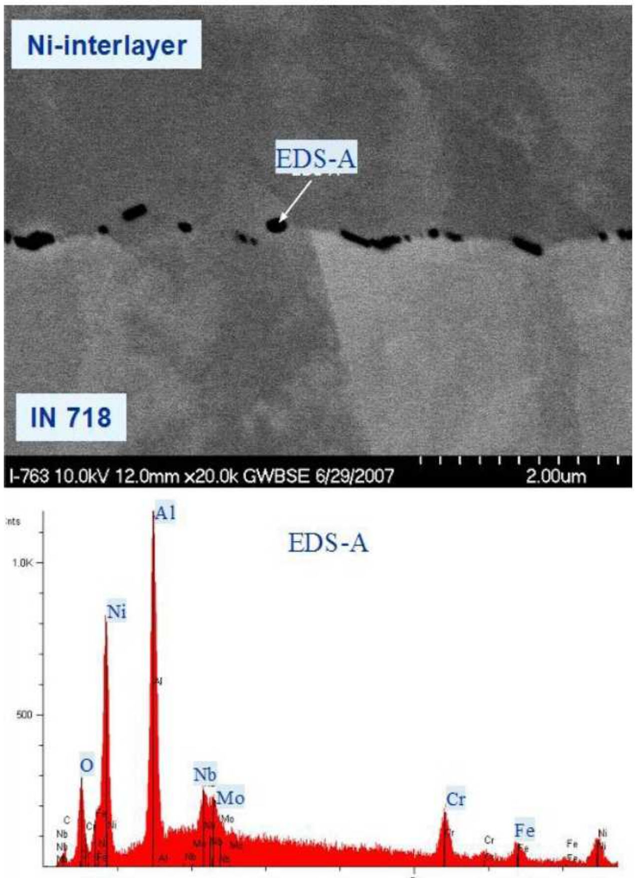

Figure 5. FESEM Image and Energy Dispersive Spectrum Confirming the Presence of Al_2O_3 Particles Trapped in the Fine Pores Formed at the IN718/Ni-Interlayer Interface after Hot Pressing at 1150 K for 2 Hours at 90 MPa.

Brazed Joints

Microstructural Observations

As discussed previously, two classes of commercial brazing materials were evaluated. The chemical compatibility and stability of the braze alloys and the two different base metals were observed after brazing and long term exposures. Figure 6 shows FESEM backscattered images of Nioro brazed SS316L to IN718 after brazing for 5 minutes at 1248 K (1787 ºF) in vacuum at 1.33 x 10^{-3} Pa, and after post-brazing exposures at 900 K (1160 ºF) for 100, 1000 and 3000 hours. Minimal reaction with

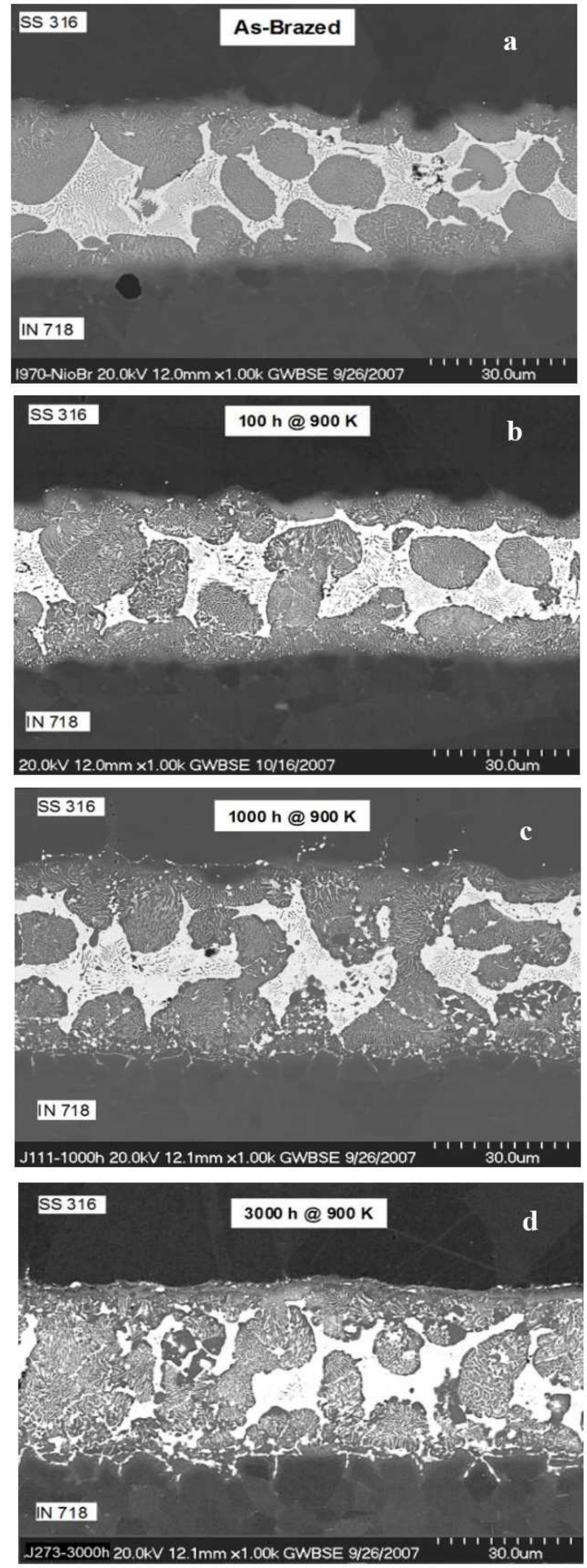

Figure 6. FESEM BSE Images of Nioro Brazed SS316L to IN718 in the (a) as-Brazed Condition, and after Long Term Exposures at 900 K after (b) 100, (c) 1000 h, (d) 3000 Hours.

either alloys and the filler material, or change in the brazed microstructure was observed.

In general, a good bond was accomplished with or without Ni-plating. Figure 7 shows a micrograph of nickel-plated brazed SS316L to IN718 with Nioro after a 3000 h exposure at 900 K (1160 ºF). Ni-enriched areas were observed at either side of the braze joint. Occasionally small regions with discontinuous porosity were detected in the metallographic cross sections. Figure 8 presents elemental maps which show the distribution of the various elements present in the IN718 and SS316L alloys and in the brazed zone after brazing with Nioro, and a short anneal heat treatment at 900 K (1160 ºF) in argon for 1000 hours. Diffusion processes can change the composition of the braze joint and also the chemical and physical properties of the boundary interface between the joined alloys and the filler metal. From the maps, it is clear that gold has not diffused into either alloy. Some Ni/Au enriched strings associated with grain boundaries are observed at the SS316/Braze interface, although ~ 10 wt.% of Ni is already present in the SS316 base composition. Some indication of Fe presence is observed in the center of the braze, at the same location where Ni-enriched pockets are visible. Both alloys have comparable amounts of Cr, but no indication of Cr diffusion into the brazed joint was detected.

Figure 9 shows that the Ni-based brazing filler metals listed in Table 2 have the ability of to wet and spread to both SS316L and IN718 alloys, characteristics required to form a continuous, sound and strong bond. FESEM observations and EDS analyses of the various phases formed with the Ni-brazes have revealed some degree of reaction near the interface and along the base metal grain boundaries. Brazing with AMDRY 775 (AM775) resulted in the apparent segregation of Cr at grain boundaries near the SS316L / braze interface, while Nb and Mo enrichment occurred at the grain boundaries near the IN718 / braze interface.

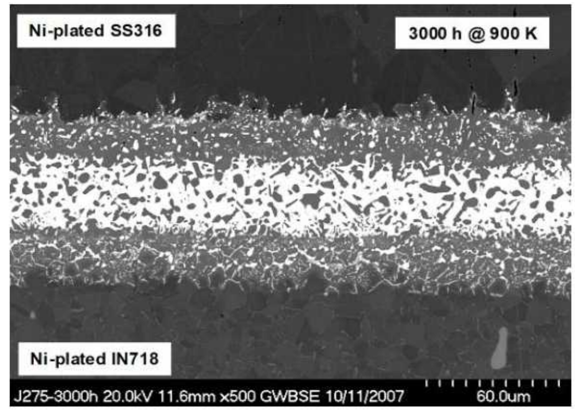

Figure 7. FESEM BSE Image of Ni-plated SS316L and IN718 plates brazed with Nioro after a 3000 Hours Exposure at 900 K.

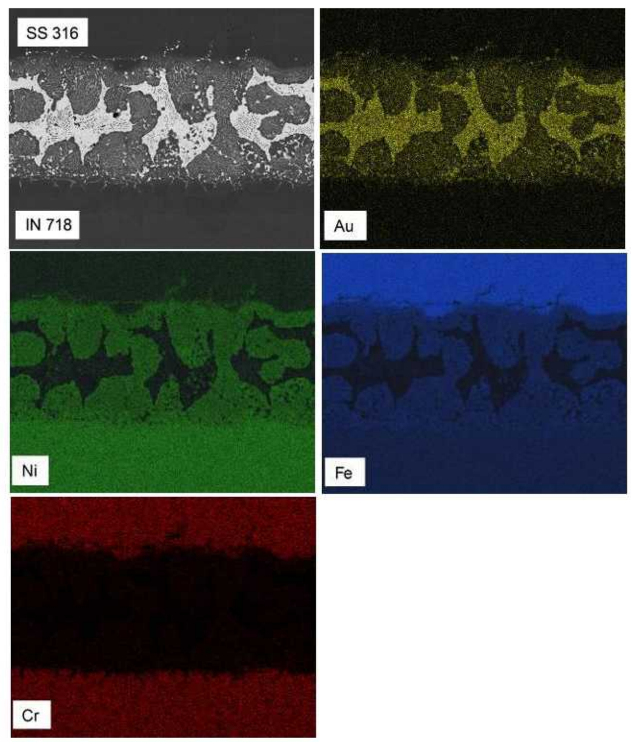

Figure 8. FESEM BSE image of Nioro brazed SS316L to IN718 after long term exposure at 900 K for 1000 hours with energy dispersive spectroscopy elemental maps for Au, Ni, Fe, and Cr.

Chromium segregated in the center of the braze as part of a eutectic formation.

Brazing with AMDRY 790 (AM790) revealed a similar enrichment of Cr at SS316L / braze interface and Nb at IN718 / braze interface. Well defined

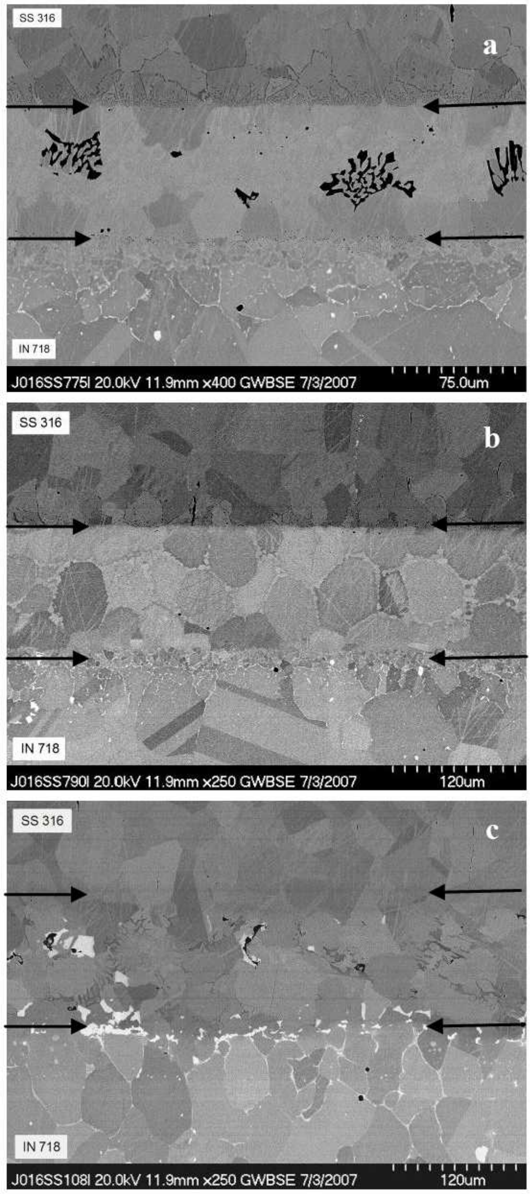

Figure 9. FESEM Images Showing Approximate Location of the Original Interfaces, Features of the Brazing Bonds and Reaction near the Bond Interfaces after the Brazing Process using (a) AM775, (b) AM790, and (c) AM108 Brazes.

grains, with grain boundaries enriched in Ni and depleted in Si, can be clearly visualized inside the brazed section. Brazing with AMDRY 108 (AM108) resulted in a complex microstructure due to the presence of the higher numbers of elements initially available in the AM108 braze. No clear indication of Cr-enrichment was detected in the SS316 side; however possible enrichment of Nb or Mo occurred at the interface. Further clarification, if needed, would require other techniques, since the P-Kα, Nb-Lα, and Mo-Lα x-ray peaks overlap.

Mechanical Properties

The mechanical performance of a brazed joint is determined by the integration of the braze filler metal, the base metal, the geometry of the brazement, and the brazing procedure [6]. First the response of the base metal to the perspective braze-cycle thermal exposures was investigated since the base metals properties, especially for the IN718, are very sensitive to the thermal cycle process parameters. Tensile testing close to the target temperature of 830 K (1034 ºF) resulted in a significant drop in the ultimate and yield strength, and considerable increase in the elongation for IN718 after the simulated brazing exposures. No significant changes were observed in the ultimate strength or elongation for the SS316, but a slight drop (~10%) in the yield strength was noticed. Figure 10 summarizes the effects of various thermal cycles. Again, the goal was to understand the ramifications of the brazing thermal cycle on the mechanical properties. Therefore sample strengths are compared in the starting condition, after a brazing-like heat treatment without the presence of braze alloy, after a brazing-like heat treatment with the presence of braze alloy, as well as the braze-like heat treatment followed by an aging step. The appropriate starting condition was solution anneal + aging for the IN718 and as-received for the SS316L. The representative brazing cycle was a Nioro-type brazing at 1248 K (1787 ºF). The strengths of the stainless steel were largely unchanged but it appeared that the superalloy was adversely affected by the representative braze thermal cycle. It was found that the tensile strength of the solution anneal + aged IN718 can be recovered with a secondary aging heat treatment after a Nioro-type brazing cycle.

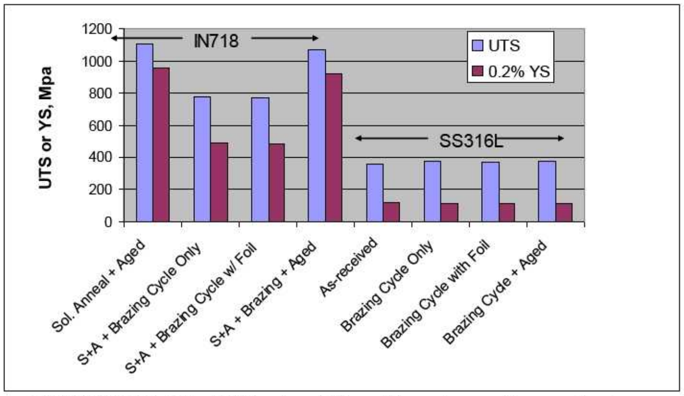

FIGURE 10. Effect of the Brazing, Anneal, Age Thermal Cycles, and Contact with Braze Material on the Mechanical Properties of IN718 and SS316L at 830K.

After determining appropriate brazed and post-brazed thermal treatments, the tensile strength of the brazed joints were evaluated with double-lap shear specimens. As recommended by the standard method, various overlaps were explored as well as various types of brazes. Figure 11 shows typical cross sections of double lap specimens with 1.5 and 9 mm overlaps. In most cases the brazing material completely filled the gap between the plates. Figure 12a shows a plot of the average shear stress, calculated with equation 1, and the average tensile stress in the base metal, calculated with equation 2, at 830 K with Nioro as a brazing filler metal, as function of overlap distance. Typically as the overlap is increased, the failure shifts from failure in the braze joint to failure in the base metal. In other words, joints made with an overlap greater than this transition value will behave as being stronger than the materials being joined. In the case of the Nioro braze, the overlaps studied were not sufficient to reach this transition value. Failures occurred in the filler material independently if the material was or not exposed to a post-aging heat treatment. However, as shown in Figure 12b, where the average shear stress and tensile stress obtained for a Palniro-7 braze are plotted, the 9 mm overlap resulted in the shift of failure from the brazed joint to the SS316 base metal; the filled symbols represent failure through the base metal.

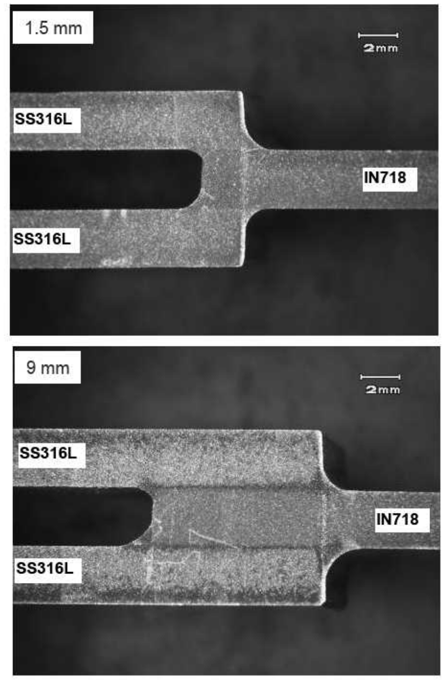

Figure 11. Cross Sections of SS316L/ IN718 Double-lap Shear Specimens Brazed with Nioro with (a) 1.5 and (b) 9 mm Overlaps.

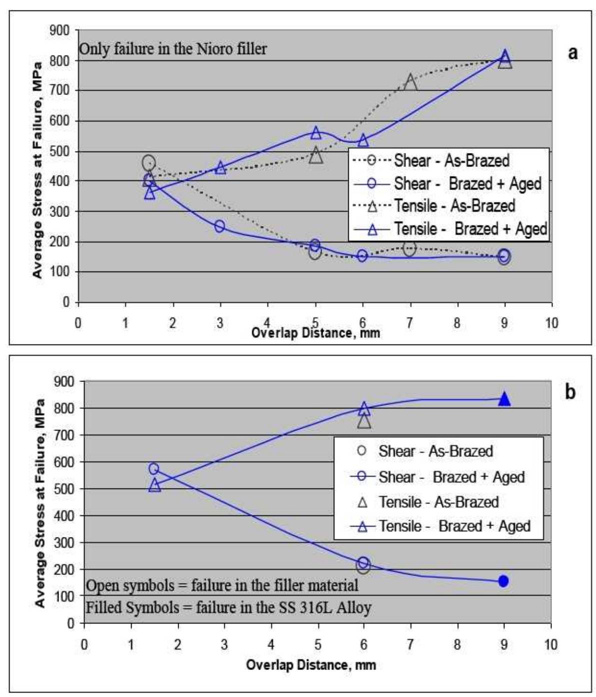

Figure 12. Average Shear Stress and Tensile Stress as a Function of Overlap Distance with (a) Nioro: Failure Occurred only in the Brazing Filler Metal, and (b) Palniro-7: Failure Transition from Filler to SS316L Base Metal at the 9 mm Overlap.

Figure 13 contrasts the two modes of failures observed with the same 9 mm overlap, through the SS316L base metal brazed with Palniro 7 (Fig. 13a), and through the Nioro filler material (Fig. 13b). The average tensile stress at failure and the average shear stress at failure are plotted in Figure 14 as a function of braze materials and overlap distances. The double-lap specimens brazed with Palniro 7 show consistently higher tensile stress values than the Nioro or the Ni-based brazes.

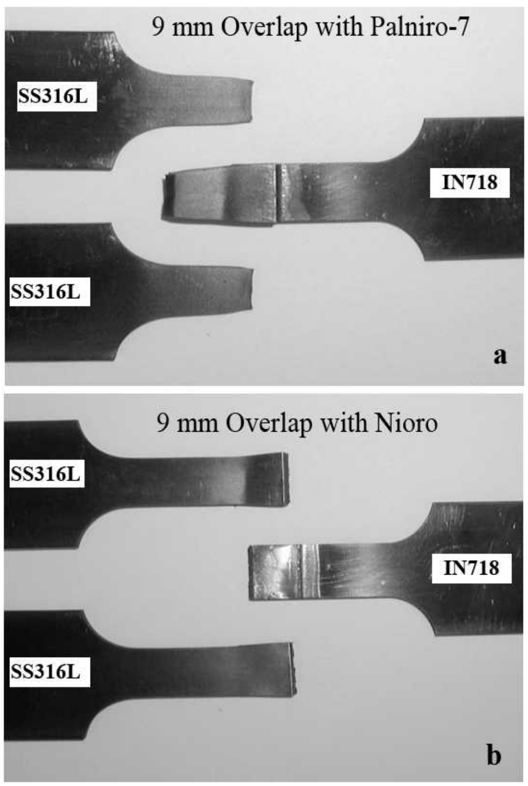

Figure 13. Different Types of Failures with same 9 mm Overlap (a) Failure in the Base Metal with Palniro-7 (SS316L), and (b) Failure in the Nioro Brazing Filler Metal.

Conclusions

In order to ensure a metallurgically sound joint that would survive extended use at approximately 830 K (1034 ºF), diffusion bonding and brazing of SS316L and IN718 were studied. The joining of two dissimilar metals required an evaluation of the

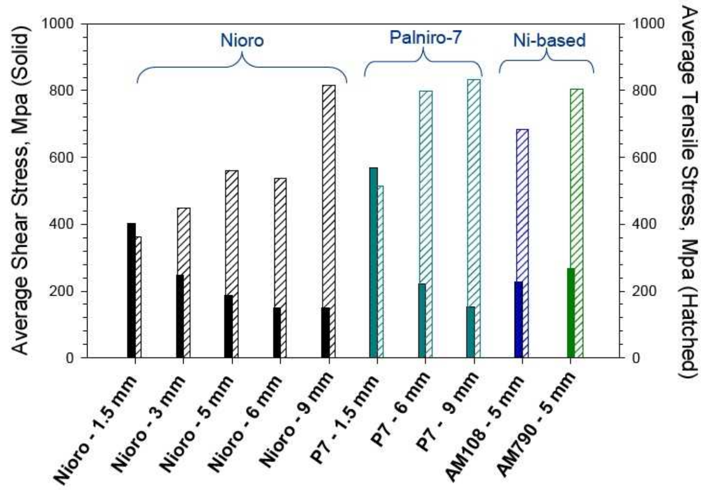

Figure 14. Average Shear and Tensile Stress at Failure as a Function of Braze Materials and Overlap Distances. All Brazed Specimens Were Aged before Testing.

effect of the pressing parameters or the brazing cycles and post-joining heat treatments on the microstructures and mechanical properties of both alloys. Hot press diffusion bonding trials showed that bonding occurred with and without a pure nickel interlayer. Fine porosity was detected at the new interfaces, but may be reduced or eliminated with higher pressures and optimized bonding parameters. Microstructural observations indicated that gold-based brazes resulted in minimal reaction with either base metals. The chemical reaction was observed to be more extensive with any of the Ni-based brazes studied. Double-lap shear tensile specimens were successfully fabricated and tested at 830 K (1034 ºF). For a specific overlap, the average tensile strength observed from the brazed double-lap shear specimens for Palniro 7 and the Ni-base brazes are higher compared to the Nioro braze; however, the higher brazing temperatures required for Palniro 7 and any of the Ni-brazes may impact negatively on the properties of both base metals. The Inconel 718, which is extensively used in the aerospace industry, required only an aging heat treatment, after a typical Nioro brazing cycle, to regain most of its strength. The stainless steel 316L alloy, not affected from secondary phase precipitation or dissolution, maintained its ultimate tensile strength after a typical Nioro brazing cycle, however its yield strength was more sensitive to the thermal exposures. Based on the lowest impact on the base metal strength and the minimal chemical interaction, Nioro is the leading braze candidate to join the two dissimilar metals for the HX application.

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