Metallurgical Characterization of Inconel-625 and Waspaloy Joints Brazed using Five Ag, Cu and Ni-Base Active Braze Alloys

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Abstract

Many industrial components such as heat exchangers and gas turbines are fabricated by joining a number of simpler units into complex structures. This demands development and demonstration of robust joining technology applicable to a wide variety of materials including alloys that can withstand very high temperatures that are encountered in jet engines, furnaces, combustion cans, and other systems. This research characterized brazed joints of two high-temperature nickel-based alloys for microstructure, composition, and hardness. The purpose was to evaluate the effectiveness of selected brazes and joining conditions to form integral joints that could be further characterized prior to pilot-scale testing and evaluation. Inconel-625 and Waspaloy[1] were vacuum brazed using two Ni-base amorphous brazes (MBF[2] -20 and MBF-30), two Ti containing Ag-Cu base brazes (Cusil-ABA and Ticusil), and a Cu-base active braze (Cu-ABA) with brazing temperatures in the range 1108-1348 K. All five brazes formed well-bonded metallurgically-sound joints. MBF-20, MBF-30, Ticusil-ABA and Copper-ABA exhibited substantial diffusion and prominent interaction zones whose thickness increased with increasing braze liquidus temperature.

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[1] *High-performance alloys; also referred to in industry as superalloys. These alloys have exceptional resistance to deformation and corrosion at elevated temperatures usually encountered in gas turbines and marine turbines.*

[2] *MBF stands for metallic glass braze foil. MBF is trademark of Metglas Solutions Inc. The company was bought by Allied-Signal/Honeywell in 1999, and in 2003, by Hitachi Metals Ltd.*

Cusil-ABA with the lowest temperature (1108 K) had the smallest reaction layer whereas MBF-30, with the highest temperature (1348 K) had the thickest reaction layer. The interaction zones in Cusil-ABA and Ticusil joints were enriched in titanium and accompanied by Ti depletion and low hardness within braze matrix. The MBF-30 joints revealed the most prominent and most complex reaction layer of all brazes consisting of at least four different regions identified by their Knoop hardness.

Introduction

Inconel-625[3] is a versatile nickel-based alloy with excellent strength, ductility, and corrosion and oxidation resistance over a wide range of service temperatures, from cryogenic to about 982°C. Applications of Inconel-625 include propeller blades and exhaust ducts, submarine propulsion motors, steam-line bellows, heat-exchanger tubing, wire rope for mooring cables, and plasma confinement equipment in nuclear reactors. Some superalloy components can be formed by a single-step casting process but in many applications these alloys must be joined to themselves and to other materials to create parts. For example, a high pressure turbine nozzle assembly may be structurally supported by a nozzle support assembly formed by brazing a number of individual superalloy members. Brazing process parameters need to be controlled to avoid part cracking that may result from thermal stresses. These stresses develop when structural elements with different dimensions are joined together.

Although many superalloys are weldable[4], they often contain titanium and aluminum, which make the alloys susceptible to heat affected zone cracking during welding [Arafin et al, 2007]. High-temperature brazing with nickel-base filler alloys, containing boron and silicon as melting point depressants, has evolved as an effective alternative to welding to join superalloys. There are, however, a number of key metallurgical issues that must be addressed to realize the full benefit of brazing.
For example, while the addition of boron to the filler metal is effective in depressing the alloy liquidus[5], boron has high grain

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[3] *INCONEL is a trademark of INCO Alloys, Huntington, WV*

[4] *Welding involves melting and fusion of the work-pieces whereas brazing involves melting and spreading of a low-melting point filler metal between work-pieces.*

[5] *The liquidus temperature is the temperature above which an alloy is completely liquid. Likewise, the solidus temperature is the temperature below which an alloy is completely solid. Between its solidus and the liquidus, an alloy is mushy (solid plus liquid). For a pure substance, solidus and liquidus temperatures are identical and equal the melting point of the substance.*

boundary diffusivity at elevated temperatures. This causes boron to diffuse away from the joint before reaching the brazing temperature thus preventing complete braze melting and bond formation. In addition, Ti, Al, Fe and Nb are added to most superalloys including Inconel-625 to strengthen the alloys and enhance their oxidation resistance by forming tenacious metallic oxides. Unfortunately, these non-wettable protective oxides hinder braze spreading and flow, restrict surface coverage, and impair the bond quality. Thus, brazing of superalloys involves issues that require careful metallurgical evaluation of joints brazed using different type of filler metals.

The purpose of the study was to compare and contrast the microstructure, composition and microhardness of two vacuum-brazed nickel-base superalloys, Inconel-625 and Waspaloy. These alloys were joined using five different commercial braze alloys. : two Ni-base amorphous brazes, two Ti containing Ag-base brazes, and a Cu-base active braze. The research had the dual objectives: (i) investigate how the process of brazing modifies the composition of a given braze and the metallurgical structure of the braze and the substrate in the vicinity of the joint via diffusion and reactions and, (ii) evaluate how different braze alloys modulate the metallurgical structure, composition and hardness in and around superalloy joints. An evaluation of the basic metallurgical characteristics of Inconel 625 and Waspaloy joined using multiple Ag, Cu and Ni-base braze alloys should permit screening of potentially promising systems for a detailed future investigation.

Both Inconel-625 and Waspaloy retain high strength to elevated temperatures (870-980°C). They are used use under extreme heat and pressure environments such as those in gas turbines, combustors, and turbocharger rotors. Inconel-625 is an oxidation and corrosion-resistant austenitic Ni-based superalloy. Waspaloy is an age-hardenable, nickel-based superalloy with excellent strength properties. Generally, welding Ni-base superalloys is difficult due to cracking and microstructural segregation of alloying elements in the heat affected zone. Brazing such alloys works better than welding. Certain welding techniques can, however, be used with superalloys. Additionally, diffusion bonding [Ahmad et al, 2008], diffusion brazing [Ojo et al, 2004; Laux et al, 2010], transient liquid phase bonding [Egbewande et al, 2008; Ojo et al, 2004], and liquid infiltration

[Zhuang and Eagar, 1997] can also be used. Brazing is attractive to join superalloys because of its relative simplicity and cost-effectiveness.

Experimental Procedure

Inconel-625 and Waspaloy from Inco Specialty Metals were vacuum brazed to themselves using five active braze alloys with brazing temperatures in the range 1108-1348 K. These braze alloys were: Cusil-ABA, Ticusil, Cu-ABA, MBF-20 and MBF-30. The braze alloys Cusil-ABA, Ticusil and Cu-ABA were obtained from Morgan Advanced Ceramics, Inc., and MBF-20 and MBF-30 were obtained from Honeywell Corp. The compositions of Inconel 625 and Waspaloy are shown in Table 1. The composition and selected properties of the brazes are shown in Table 2. The joints created and characterized in the study, and the joining temperatures are shown in Table 3.

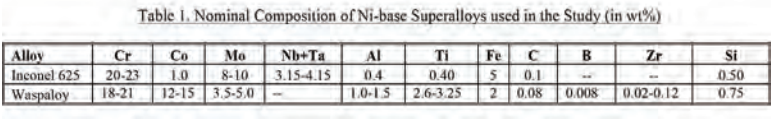

Table 1. Nominal Composition of Ni-base Superalloys used in the Study (in wt%)

Alloy	Cr	Co	Mo	Nb+Ta	Al	Ti	Fe	C	B	Zr	Si
Inconel 625	20-23	1.0	8-10	3.15-4.15	0.4	0.40	5	0.1	--	--	0.50
Waspaloy	18-21	12-15	3.5-5.0	--	1.0-1.5	2.6-3.25	2	0.08	0.008	0.02-0.12	0.75

The Inconel-625 substrates were cut into 2.54 cm x 1.25 cm pieces using a ceramic blade on a high-speed precision saw. The substrates and braze foils were ultrasonically cleaned in acetone for 15 minutes. Braze foils listed in Table 2 were sandwiched between the substrates, and a load of 150 g was applied normal to the joint during brazing. The assembly was heated in a furnace to the brazing temperature under high vacuum[6] (~10^{-6} torr), isothermally held for 5 min. at the brazing temperature, and furnace-cooled to room temperature. The brazed joints were mounted in epoxy and prepared for metallurgical examination, using grinding and polishing on a Buehler automatic polishing machine. The polished joints were examined using optical microscopy (OM), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS), and subjected to the Knoop microhardness test under 200 g load and a loading time of 10 seconds. Multiple hardness scans were accessed across representative regions of joined samples, and average values were reported.

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[6] *Conventional brazing requires use of fluxes that contain toxic and corrosive chemicals (e.g., hydrogen fluoride, potassium bifluoride, potassium fluoride). These fluxes release fumes and gases (HF and BF3) that cause irritation of eye and respiratory system, and sclerosis of the bone. Vacuum brazing permits extremely clean, high-strength, flux-free braze joints to form without release of toxic or corrosive effluents. Work-piece heats up uniformly under vacuum (less residual stress), and heat-treating could be combined with brazing in a single furnace cycle.*

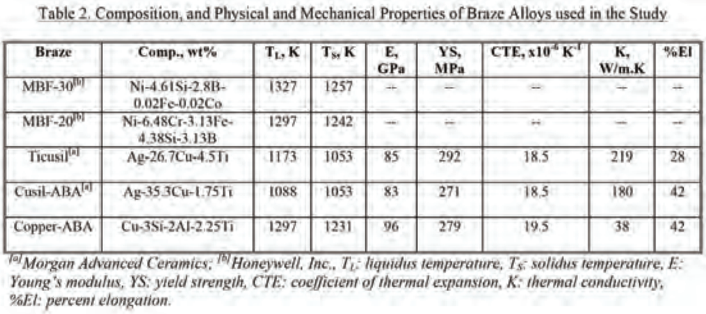

Table 2. Composition, and Physical and Mechanical Properties of Braze Alloys used in the Study

Braze	Comp., wt%	T_L, K	T_S, K	E, GPa	YS, MPa	CTE, x10^{-6} K^{-1}	K, W/m.K	%El
MBF-30[b]	Ni-4.61Si-2.8B-0.02Fe-0.02Co	1327	1257	--	--	--	--	--
MBF-20[b]	Ni-6.48Cr-3.13Fe-4.38Si-3.13B	1297	1242	--	--	--	--	--
Ticusil[a]	Ag-26.7Cu-4.5Ti	1173	1053	85	292	18.5	219	28
Cusil-ABA[a]	Ag-35.3Cu-1.75Ti	1088	1053	83	271	18.5	180	42
Copper-ABA	Cu-3Si-2Al-2.25Ti	1297	1231	96	279	19.5	38	42

[a] Morgan Advanced Ceramics; [b] Honeywell, Inc., T_L: liquidus temperature, T_S: solidus temperature, E: Young's modulus, YS: yield strength, CTE: coefficient of thermal expansion, K: thermal conductivity, %El: percent elongation.

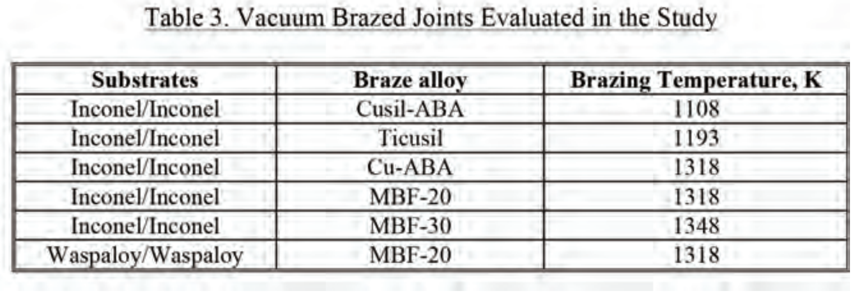

Table 3. Vacuum Brazed Joints Evaluated in the Study

Substrates	Braze alloy	Brazing Temperature, K
Inconel/Inconel	Cusil-ABA	1108
Inconel/Inconel	Ticusil	1193
Inconel/Inconel	Cu-ABA	1318
Inconel/Inconel	MBF-20	1318
Inconel/Inconel	MBF-30	1348
Waspaloy/Waspaloy	MBF-20	1318

Results and Discussion

Figure 1 shows a montage of low-magnification photomicrographs of a complete joint between two bonded Inconel 625 substrates together with the solidified braze layer and the interaction zone that formed during high-temperature brazing from inter-diffusion of alloying elements. The microstructure, composition and representative microhardness of the joints evaluated in the study are displayed in Figs. 2 through 7 and discussed below.

Fig. 1 A montage of optical photomicrographs of a complete Inconel/Ticusil/Inconel joint showing the Inconel 625 substrates, the solidified braze layer, and Inconel-braze interaction zone

Figures 2 and 3 show the Inconel joints made using the two Ag-base active braze alloys, Cusil-ABA (Fig. 2) and Ticusil (Fig. 3). The braze region (Figs. 2(a) & (b)) shows the characteristic two-phase eutectic structure (Fig. 2a & b) of the solidified alloy. In joints made using Cusil-ABA, the braze/Inconel interaction zone was too thin to conduct micro-indentation test directly onto the interaction layer.

The Cusil-ABA interlayer has the lowest hardness (87 HK[7]) among the four brazes. However, in both Cusil-ABA and Ticusil joints, the Inconel matrix farther from the joint has slightly higher average hardness (335 HK) than the Inconel matrix in joints made using the two Ni-base metallic glass braze alloys (Figs. 4-6) discussed later. The high hardness of Inconel-625 is known to result from carbides of the type MC and M6C (rich in Ni, Nb, and Mo) as well as carbides of the type M23C6, which is a chromium-rich carbide.

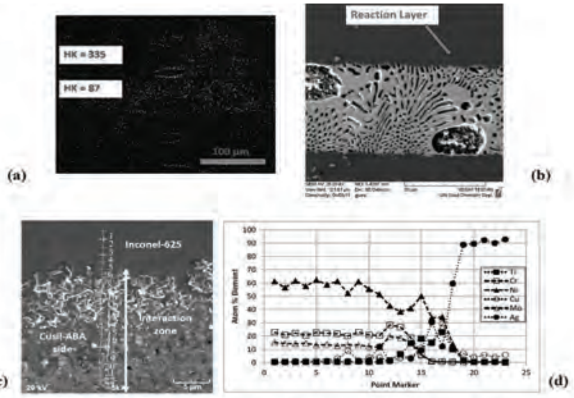

Fig. 2 An Inconel/Inconel joint made using Cusil-ABA braze: (a) overall view showing the average Knoop hardness, (b) SEM image of the joint showing the two-phase eutectic structure of Cusil-ABA, (c) a higher mag SEM view of the interaction zone/Inconel interface, and (d) relative atomic percentages of elements at point markers in (c) based on energy dispersive spectroscopy (EDS).

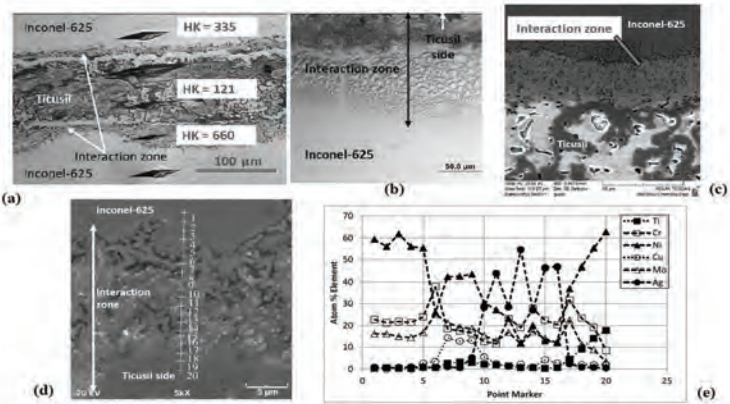

Fig. 3 An Inconel/Inconel joint made using Ticusil braze: (a) overall view showing average hardness of different regions, (b) interaction zone/Inconel-625 interface, (c) & (d) higher magnification secondary electron SEM images of the interaction zone, and (e) atomic percentages of elements at point markers in (d) from energy dispersive spectroscopy (EDS).

The energy dispersive spectroscopy (EDS) results for the Cusil-ABA joints (Figs. 2c & d) revealed Ti enrichment inside the interaction zone (point markers 13 through 18) where a

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[7] *HK denotes Knoop hardness.*

peak concentration of 18 atom % titanium was attained. The EDS results also show Ti depletion within the braze region where the titanium concentration drops to near-zero values and causes the braze hardness to drop to low (87 HK) values. The Cr and Mo concentrations drop precipitously to near-zero value within the interaction zone indicating sluggish diffusion of these solutes at the brazing temperature.

In Inconel joints made using Ticusil (Fig. 3), a prominent interaction zone of high (660 HK) hardness developed. The high hardness was caused by the diffusion of titanium atoms toward the interaction zone which is confirmed from the Ti enrichment noted in Figs. 3d & e (point markers 17-20). However, even with a partial loss of Ti, the Ticusil braze retains higher hardness (121 HK) than Cusil-ABA (87 HK). This was because of a higher initial titanium concentration (4.5 wt%) in Ticusil than in Cusil-ABA (1.75 wt%). Precipitation of secondary phases in the interaction zone is revealed in Figs. 3(b-d). The EDS scans across the Ticusil joints also show that regions of high Mo and Cr concentrations correspond to low Ti concentration regions and vice versa. It appears that the microstructure of the Ticusil/Inconel interface consisted of an interaction zone[8] extending from the brazed region into the Inconel substrate along the Inconel's grain boundaries. The interaction zone was much harder than the braze region or Inconel substrate. In contrast to the Ticusil-ABA braze, the Cusil-ABA braze formed a very thin interaction zone, which is barely visible under an optical microscope. Compared to Ticusil, the smaller concentration (1.75 wt%) of the reactive titanium and lower liquidus temperature (1088 K) of Cusil-ABA were responsible for the thinner interaction zone in Cusil-ABA joints.

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[8] *Research on phase analysis of the interaction zone was not attempted within the constraints of the project*

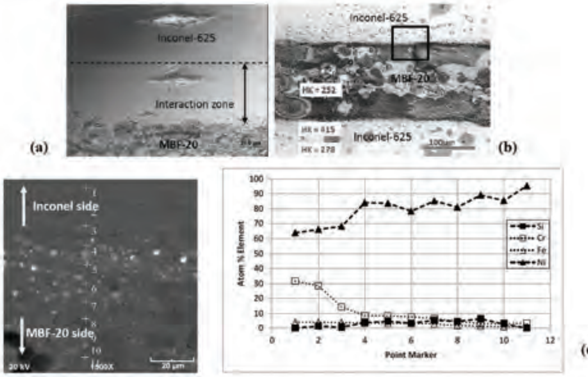

Fig. 4 An Inconel/Inconel joint made using MBF-20 amorphous braze filler: (a) Inconel/braze interface showing interaction zone, (b) average Knoop hardness values in braze, interface, and Inconel matrix, (c) SEM image of the interaction zone, and (d) relative atomic percentages of Si, Cr, Fe and Ni at point markers in (c).

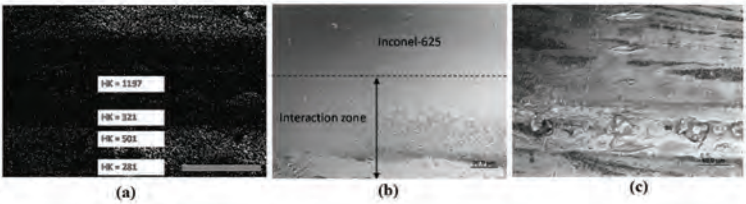

Fig. 5 An Inconel/Inconel joint made using MBF-30 amorphous braze filler: (a) overall view with average Knoop hardness of different regions, (b) Inconel/braze interface showing the Ni grain structure revealed by secondary phase precipitation at grain boundaries near the interface, and (c) overall view showing hardness indentation marks.

Although the brazing time (5 min.) was relatively short, Cu and Ag from Ticusil diffused along the Inconel grain boundaries to measureable distances forming a prominent interaction layer at the interface (Figs. 3(b-d)). This observation is consistent with the strong chemical affinity between Ag and Ni and between Cu and Ni that aided elemental diffusion along Inconel grain boundaries and facilitated bond formation upon solidification. Diffusion occurred in the solid state during heating to the brazing temperature and during cooling at the conclusion of brazing. Because excessive diffusion and solute segregation of the low melting point metals Ag and Cu may deteriorate the elevated temperature properties of Inconel-625, it is necessary to optimize the brazing temperature and time to develop a strong interfacial bond without causing degradation of the mechanical properties of the joined Inconel substrates. Such an optimization was not attempted in the present study.

Amorphous Ni-base brazing foils MBF-20 and MBF-30 (Table 2) have been developed using rapid solidification technology [Rabinkin, 2004] and used to join alloys including Inconel [Rabinkin, 2004; Wu, 2000; Miyazawa and Ariga, 1992]. The Inconel joints made using MBF-20 (Fig. 4) show a distinct interaction zone (Figs. 4a & b) of higher average hardness (Knoop hardness: 415 HK) than either the braze region (252 HK) or the Inconel matrix (278 HK). The EDS results (Fig. 4 c & d) across the interaction zone/Inconel boundary showed the presence of small (6-7 atom %) concentrations of Si and Fe in the interaction zone; the high Fe concentration regions overlap the low Si regions. Silicon and boron were added as melting point depressants to the amorphous filler metal. The chromium content continuously decreased from 30 atom % on the Inconel side (point markers 1 & 2, Figs. 4c & d) to about 4-8 atom % in the interaction zone (point markers 4-10). The Ni content increased gradually from 62 atom % (point marker 1) in Inconel to nearly 95 atom % (point marker 11) in the interaction zone. The element boron could not be detected in the interaction zone using the EDS; however, it is known [Grushko and Weiss, 1984] that appreciably faster diffusion of boron compared to that of Cr and Si could lead to large penetration distances of boron and formation of hard and brittle boride phases (e.g., Ni3B and CrB2 [Jalilian et al, 2006; Pouranvari, 2009]) especially after long brazing times and at high temperatures. The relatively short (5 min.) brazing times used in the present study may have limited the boron diffusion to near-interface regions where possible formation of hard boride phases could have led to higher hardness. Absence of any observable changes in the microhardness of the Inconel substrate far from the interface region was consistent with the presumed lack of long-range diffusion of boron during brazing.

An Inconel 625 joint made using MBF-30 amorphous braze is shown in Fig. 5. Of all brazes examined in the study, MBF-30 led to the most prominent and most complex reaction layer consisting of at least four different regions identified by their Knoop hardness values. The hardness of the braze region averaged 1197 HK and was the highest value observed. The region closest to MBF-30 had a hardness of 321 HK whereas the hardness farther out toward the Inconel boundary was 501 HK.

The Inconel matrix far from the joint had a hardness of 281 HK similar to the value (278 HK) for MBF-20 (Fig. 4). The formation and distribution of brittle borides of Cr and Ni are responsible for the increase of micro-hardness. Solute diffusion and segregation along the matrix grain boundaries, together with the precipitation of secondary phases (e.g., carbide and boride), are seen to have decorated the Inconel grain boundaries that are visible in the un-etched sample of Fig. 5b.

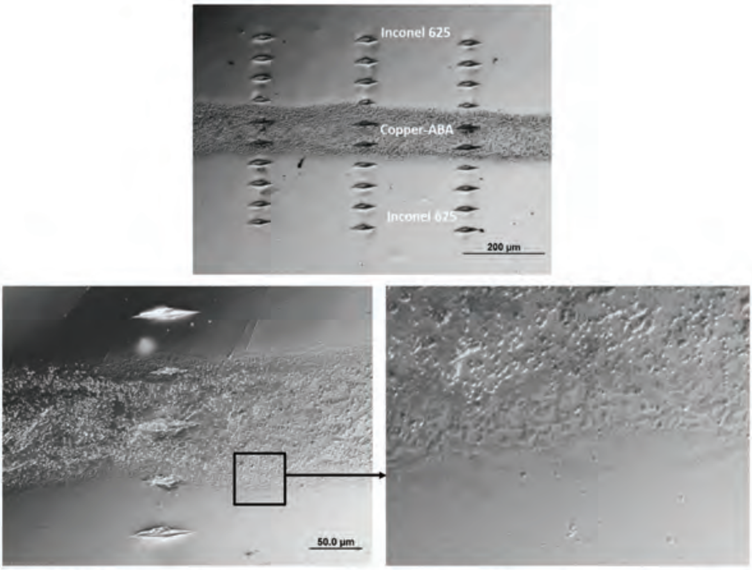

Fig. 6 (a)-(c) An Inconel/Inconel joint brazed using Copper-ABA braze showing a defect-free interaction zone and hardness indentation marks across the joint.

An Inconel joint made using Copper-ABA braze is shown in Figure Fig. 6 (a-c). The joint was defect-free and exhibited a distinct interaction zone. A detailed chemical and metallurgical characterization of the joint using the SEM and EDS was not attempted. The dark phase with round morphology in the braze matrix had been reported [Arafin et al, 2007] to be a Cu phase rich in Si and Ti. The HK in the center of the Cu-ABA braze is 673 HK whereas the reported HK of as-received Cu-ABA per the supplier is 112 kgf.mm-2 (1100 MPa). This hardness increase following brazing is believed to result from the inter-diffusion of alloying elements. The HK of the prominent interaction zone (Fig. 6c) was even greater as evidenced by the smaller size of the indentation (Fig. 6b). Figure 7 shows a Waspaloy/Waspaloy joint vacuum brazed using MBF-20 braze. The joint was sound and defect-free, and exhibited smaller hardness indentation marks within the braze than Waspaloy.

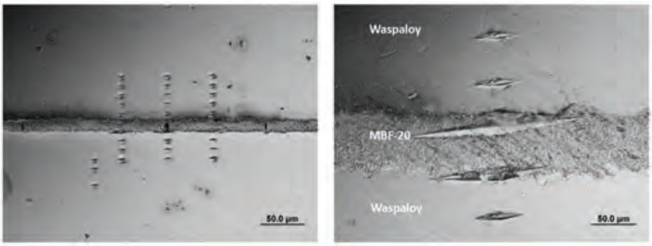

Fig. 7 (a)-(c) An Waspaloy/Waspaloy joint vacuum brazed using MBF-20 braze showing (a) overall view and (b) Knoop indentation marks in braze and waspaloy regions.

Four of the five brazes examined, MBF-20, MBF-30, Ticusil-ABA and Copper-ABA, exhibited substantial diffusion of alloying elements along the braze/Inconel interface, as reflected in the formation of prominent reaction layers. The thickness of the reaction layers showed a correlation with the braze liquidus temperature, which was consistent with enhanced diffusion at elevated temperatures. Cusil-ABA with the lowest liquidus temperature had the smallest reaction layer of all braze alloys whereas MBF-30 with the highest liquidus temperature had the thickest reaction layer. Both very thin and very thick reaction layers are deleterious to bond quality; thin layers provide insufficient bond strength whereas thick layers form excessive brittle reaction products that weaken the joint. An optimum reaction layer thickness can be empirically established for complex multicomponent alloy systems such as those examined here, and related to the joint strength and toughness characteristics.

Conclusion

The purpose of the study was to evaluate the effectiveness of several high-temperature commercial brazes to form metallurgically-sound joints in two industrial nickel-base superalloys. Although the study did not focus on a specific product such as propeller blades, exhaust ducts or combustion cans where such alloys are currently used, the research outcomes offered insights into engineering development of a simple and environment-friendly flux-less joining technology applicable to such components.

The research characterized vacuum brazed joints of Inconel-625 and Waspaloy for microstructure, composition, and hardness. The joints were made using five different commercial braze alloys with brazing temperatures of 1108-1348 K: two Ni-base amorphous brazes, two Ti containing Ag-base brazes, and a Cu-base active braze. All five brazes formed metallurgically sound joints. Four of the five brazes examined, MBF-20, MBF-30, Ticusil-ABA and Copper-ABA, exhibited substantial inter-diffusion and prominent interaction zones. The thickness of the interaction zones showed a correlation with the braze liquidus temperature due to faster diffusion at elevated temperatures. Cusil-ABA with the lowest temperature (1108 K) had the smallest interaction zone whereas MBF-30, with the highest temperature (1348 K) had the thickest interaction zone. The interaction zones in Cusil-ABA and Ticusil joints were enriched in titanium and accompanied by Ti depletion (and low hardness) within the braze. Even with partial loss of Ti in the interaction zone, the Ticusil braze retained higher hardness (121 HK) than Cusil-ABA (87 HK). The MBF-30 joints revealed the most prominent and most complex reaction layer of all brazes consisting of at least four different regions identified by their Knoop hardness.

As excessive diffusion and segregation may degrade joint properties, it is necessary to optimize the joining conditions (e.g., temperature and time) to develop a strong interfacial bond without deteriorating the joint- and substrate properties. Such an optimization was not attempted in the present study, and it represents an area for future study. The optimized joining conditions and the most promising braze alloys identified by further study could then be subjected to pilot-scale testing and evaluation.

In summary, the research provided an understanding about (i) how brazing process modifies the braze composition because of chemical interactions with the substrate, and (ii) the metallurgical structure and hardness of the braze and the substrate in the vicinity of the joint. The study offered an opportunity for in-depth research and exploration of an important manufacturing technology.

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