Comparing High-Temperature Nickel Brazing Filler Metals

Brazing filler metals were tested and compared for their applications in industry and interest to design and industrial engineers

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Environmental concerns have forced automotive manufacturers to design engines with reduced harmful emissions, and aerospace manufacturers are making improvements to heat-transfer systems to keep both engine components and passengers at comfortable temperatures. Nickel brazing is one way in which manufacturers can optimize the costs associated with meeting these requirements.

The automotive and heat-transfer equipment industries demand large production runs for parts and components. New families of brazing filler metals have been developed that offer the properties needed to meet the requirements of the manufacturing processes and the end product specifications, both technically and commercially.

The Ni-P and Ni-Cr-P alloys are used in assembly of parts in nuclear power plants and some defense applications. These alloys led the way to the evolution of the newer Ni-Cr-Si-P alloys being used today to provide the productivity and performance required.

This article provides a comprehensive description and evaluation of the Nicrobraz® Ni-Cr-Si-P filler metal alloys, including their brazing characteristics, corrosion resistance, mechanical strength, and microstructural properties that will be useful to design and other engineers.

Introduction

High-temperature brazing filler metals containing phosphorus as a major melting point depressant have been available for many decades (Ref. 1). Such alloys include AWS BNi 6 (Nicrobraz 10), AWS BNi 7 (Nicrobraz 50), and AWS BNi 12 (Nicrobraz 51) (Ref. 2).

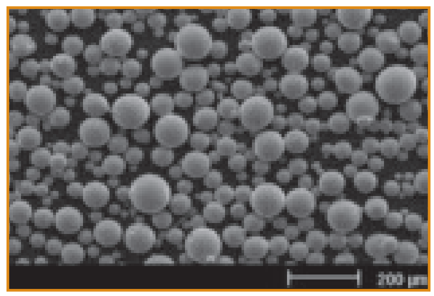

Fig. 1 — Example of Ni-P-Cr-Si alloy brazing filler metal powder.

These brazing filler metals have the advantage of being free flowing even in a soft vacuum or protective atmosphere such as cracked ammonia. The absence of boron is another advantage, especially when brazing thin metal sections sensitive to base metal erosion. The absence of boron gave rise to their use in nuclear power applications.

In recent years, several new brazing filler metals containing phosphorus have been added to this range in which phosphorus and silicon have been used together to provide enhanced corrosion resistance and joint strength combined with improved substrate structural integrity through minimized alloying interactions between the filler and the base materials.

Brazing Filler Metals

The three brazing filler metals and nominal compositions investigated are shown in Table 1.

The powders were manufactured by induction melting and gas atomization, and screened to AMS/AWS 140°F (–106, + 45 µm) particle size distribution. A photo of the powder shown in Fig. 1 illustrates the desired spheroidal morphology.

Table 1 — Ni-P-Cr-Si Brazing Filler Metal Alloy Nominal Chemical Compositions

Brazing Filler Metal	Ni wt%	Cr wt%	Si wt %	P wt %
Nicrobraz® 31	Balance	22.0	6.5	4.5
Nicrobraz® 33	Balance	29.0	6.5	6.0
Nicrobraz® 152	Balance	30.0	4.0	6.0

Table 2 — DTA Analysis from Ni-P-Si Brazing Filler Metal Powders Showing the Solidus and Liquidus Estimations

Brazing Filler Metal	Solidus (heating/ cooling)	Liquidus (heating/ cooling)	Solidus (heating/ cooling)	Liquidus (heating/ cooling)
	°F		°C	
Nicrobraz® 31	1805° / 1783°	1976° / 1972°	985° / 973°	1080° / 1078°
Nicrobraz® 33	1815° / 1779°	1879° / 1862°	991° / 971°	1026° / 1017°
Nicrobraz® 152	1805° / 1792°	1933° / 1944°	985° / 978°	1056° / 1062°

The following tests were carried out:

- Melting range determinations by differential thermal analysis (DTA) (Fig. 3) and cooling curve
- Furnace brazing trials including joint clearance filling performance tests
- Tensile testing of brazed joints
- Corrosion resistance comparison
- Filler metal aggression testing
- Metallographic examination
- Microhardness testing.

Experimental Program Results

Melting Characterization and Brazing Temperature Determination

The DTA testing involves heating or

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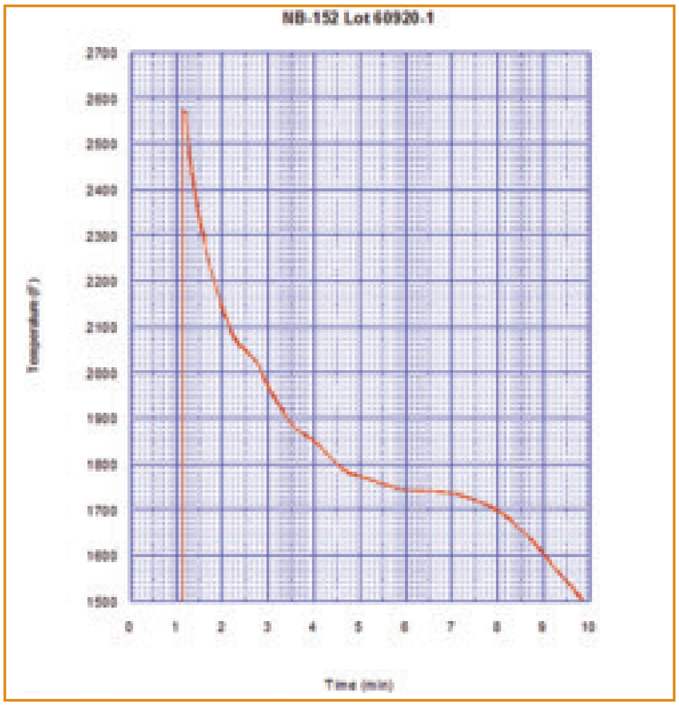


Fig. 2 — Cooling time vs. temperature curve.

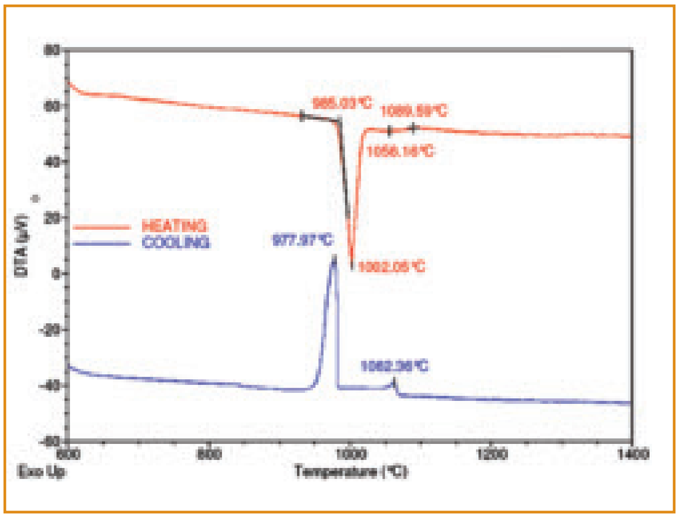


Fig. 3 — Differential microvolts vs. temperature.

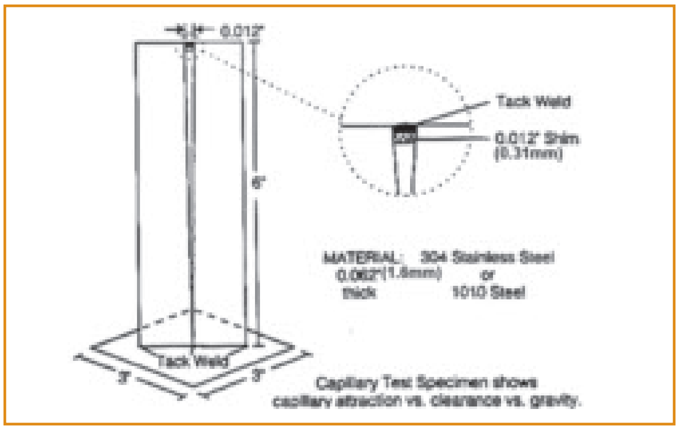


Fig. 4 — Variable clearance test fixture with vertical orientation (R. L. Peaslee).

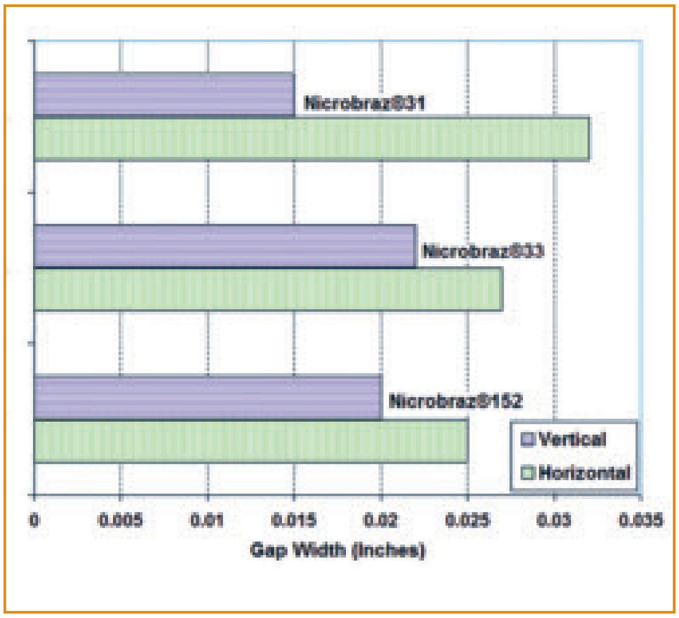


Fig. 5 — Maximum gap filling performance of Ni-P-Cr-Si brazing filler metal powders.

cooling the test sample and a known reference sample under identical conditions while recording any temperature difference between the sample and the reference. Differential temperature rises that occur during the thermal cycle between the tests and reference samples allow determination of the solidus and liquidus temperatures.

In the case of the Ni-P-Cr-Si alloys, DTA testing and direct cooling curve plots produced solidus and liquidus temperature estimates for each alloy. These values are presented in Table 2, while Fig. 2 shows examples of test data for a specific lot of Nicrobraz 152.

The solidus temperatures on heating and cooling for Nicrobraz 31 and 152 are nearly identical. Nicrobraz 33 requires a slightly higher temperature before the onset of liquation. Nicrobraz 31 has the highest liquidus temperature on heating and cooling followed by 152 and 33, respectively. A similar relationship also exists for alloy melting range with Nicrobraz 31 demonstrating the broadest range followed by 152 and 33, respectively.

While the solidus temperature is considered the minimum temperature for liquid-solid diffusion interactions to occur, the liquidus represents the point at which good capillary flow can take place with

Table 3 — Recommended Brazing Temperature for the Ni-P-Cr-Si Brazing Filler Metal Powders

Alloy	Recommended brazing range	
	°F	°C
Nicrobraz® 31	2000 - 2200	1093 - 1204
Nicrobraz® 33	1950 - 2150	1066 – 1177
Nicrobraz® 152	1950 - 2100	1066 - 1149

Table 4 — Filler Metal Spreading Ratios

Filler Metal	Spreading Ratio
Nicrobraz® 31	29%
Nicrobraz® 33	41%
Nicrobraz® 152	53%

Table 5 — Dilution Depth over an Extended Period at Brazing Temperature for 1 h as a Function of BFM Type and Substrate Material

Filler Metal Nicrobraz®	Base Metal	Dilution Zone Depth (inches)	Dilution Zone Depth (mm)
LM	316L SS	0.0037	0.094
LM	Nitronic 60	0.0028	0.07
LM	Inconel 625	0.0048	0.12
31	316L SS	<0.001	<0.025
31	Nitronic 60	<0.001	<0.025
31	Inconel 625	0.0078	0.198
33	316L SS	0.0014	0.036
33	Nitronic 60	0.0028	0.07
33	Inconel 625	0.006	0.15
152	316L SS	0.0012	0.03
152	Nitronic 60	<0.001	<0.025
152	Inconel 625	0.08	2.00

wide solidus/liquidus ranges often indicating the ability to fill larger joint clearances.

Once the solidus and liquidus were ascertained, a recommended brazing temperature was determined based on these values. The recommended brazing temperature for the range of Ni-P-Cr-Si brazing filler metal powders is shown in Table 3.

Recommended brazing temperatures and furnace cycles are predicted based on the combination of heating and cooling tests above and visual examination of brazed T-specimens (Ref. 3).

It should be noted that there is no specific temperature for brazing. Each combination of parts assembly and brazing filler metal is unique and will have a brazing "window" bounded by time, temperature, atmosphere, and fixturing conditions.

Joint Clearance Filling Characteristics

The filling characteristics of these brazing filler metals were investigated using a test piece with a varying joint clearance shown in Fig. 4. The samples were brazed at a temperature of 2050°F (1121°C). The filling characteristics for each alloy were measured and the results are shown in Fig. 5.

For experiments with the Ni-Cr-Si-P alloys, the fixture required a larger shim which set the maximum joint clearance to approximately 0.040 in. (~1 mm).

A horizontal fixture was also prepared so that the capillary filler metal flow could be studied when oriented perpendicular to the gravity force component.

Under each test orientation, the setup was constructed so there was zero clearance at the base of the V-joint.

The results show that the Ni-P-Cr-Si alloys were able to fill joint clearances far in excess of 0.01 in. (0.25 mm), and the effect of gravity on joint orientation can be seen. Nicrobraz 33 had superior joint clearance-filling properties in both vertical and horizontal configurations compared to 152.

Nicrobraz 31 is better than the other filler metals in the horizontal setup but did not perform as well in the vertical orientation due to a lower ability to flow under capillary action against gravity compared to the filler metals with higher phosphorus contents.

Wettability

Spreading ratios may be used as an indication of wettability (Ref. 4). A spreading test was performed by applying 0.2 g of filler metal near the center of a 3- × 3-in. (76.2- × 76.2-mm) 316L stainless steel coupon, and heating in a vacuum furnace to 2050°F (1121°C) at 10^{-3} to 10^{-4} torr. The spreading ratio was calculated as the percentage of a 4 in.^{2} (101.6 mm^2) area covered by the filler metal. Comparison data are shown in Table 4.

This test, as performed, is qualitative and indicates relative differences between how these filler metals wet stainless steel under given furnace atmosphere conditions. The filler metals with higher chromium and phosphorus contents (152 and 33) were shown to cover the greatest surface area, respectively. This suggests that the variation in silicon content has minimal influence on brazing filler metal wettability in the presence of a 316L stainless steel substrate.

Filler Metal Aggression Tests

Filler metal aggression tests were carried out on a number of substrate materials where dilution depth was used to provide an indication of base metal erosion potential. Nicrobraz LM was included within the test regime in addition to the three representative boron-free filler metal powders. The test coupon design is presented in Fig. 6, and the results are outlined in Table 5 and Fig. 7.

Compared to Nitronic® 60 and 316L stainless steel, Inconel® 625 was clearly more susceptible to filler metal erosion — Fig. 7. Nicrobraz 152 attained significant dilution (0.08 in. (2 mm)) or more than ten

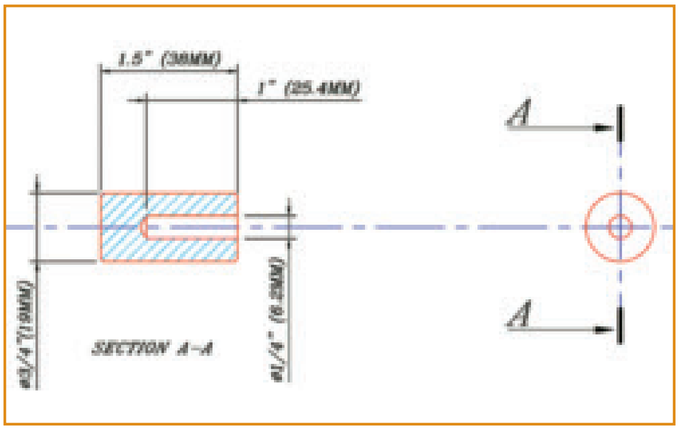


Fig. 6. General arrangement of the aggression test coupon.

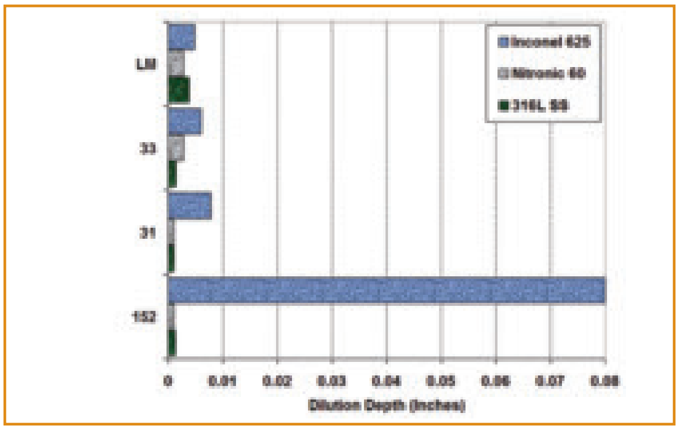
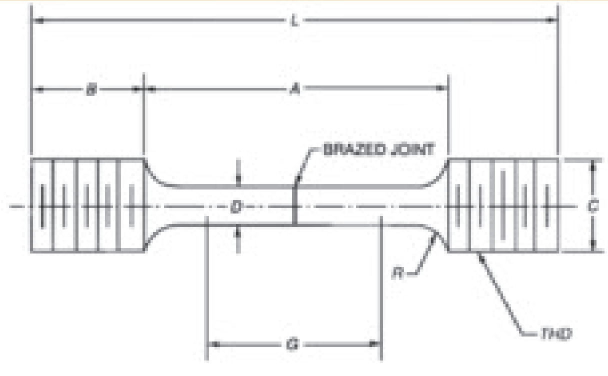


Fig. 7 — BFM dilution depth of representative Ni-P-Cr-Si brazing filler metals and substrate materials.



Description	Dimensions mm	Dimensions in
G = Gauge length	25.0 ± 0.10	1.000 ± 0.005
D = Diameter	6.4 ± 0.12	0.250 ± 0.005
A = Length of reduced section	32	1.25
L = Overall length, approx.	76	3.0
C = Diameter of end section	13	0.50
THD = UNF Series threads	13	0.5 × 20
B = Length of end section	16	0.625
R = Radius	6	0.250

Fig. 8 — General arrangement of the butt-brazed specimen as per Ref. 5.

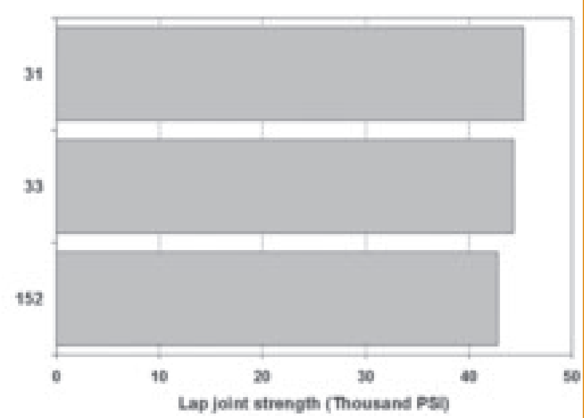


Fig. 10 — The lap-joint tensile performance of Ni-P-Cr-Si brazing filler metal powders.

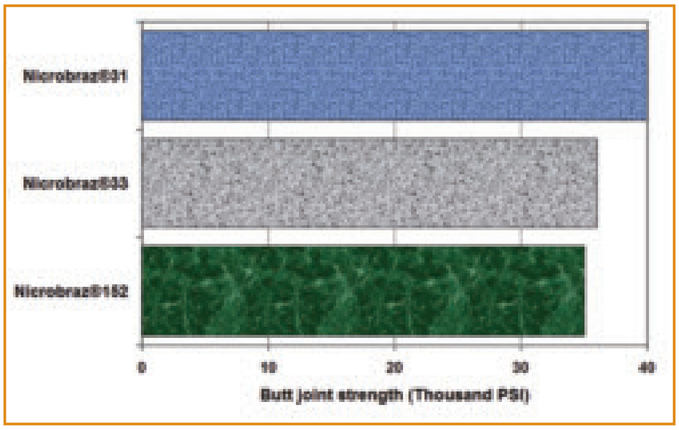


Fig. 9 — The butt-joint tensile performance of Ni-P-Cr-Si brazing filler metal powders.

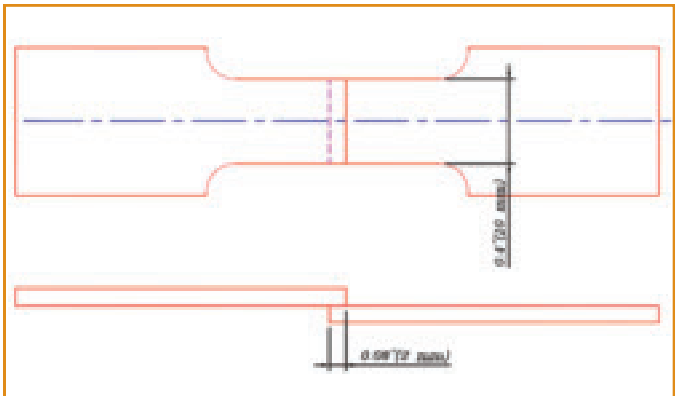


Fig. 11 — General arrangement of the lap-joint tensile specimen (Ref. 6).

times that achieved by 31, which produced the second-highest result of 0.0078 in. (0.198 mm). Nicrobraz LM produced the lowest dilution level for Inconel 625.

Brazing filler metal aggression tests carried out on Nitronic 60 and 316L using Nicrobraz LM showed the highest comparative dilution levels within this test regime with Nicrobraz 31 demonstrating the lowest erosion potential.

Joint Tensile Strength

The three brazing filler metals were used to make brazed butt joint test specimens in accordance with AWS C3.2M/C3.2: 2008, *Standard Method for Evaluating the Strength of Brazed Joints* (Ref. 5). The general specimen design is shown in Fig. 8.

The samples were then subjected to uniaxial tensile testing. The results are shown in Fig. 9.

The uniaxial tensile test results show that the alloys produce joints with excellent tensile strength with UTS values in excess of 35,000 lb/in.^{2} (241 MPa). Nicrobraz 31 and 33 achieved superior tensile strengths compared to Nicrobraz 152.

Further work carried out on brazed lap joint specimens in accordance with JIS Z 3192 demonstrated that under tensile loading, these alloys exhibited strengths in the order of 42,800 to 45,200 lb/in.^{2} (295 to 312 MPa) — Fig. 10. Nicrobraz 31 and 33 achieved superior tensile strengths than 152. The general lap-joint specimen design is shown in Fig. 11 (Ref. 6).

Corrosion Resistance

Three 316L stainless steel T-piece joints were subsequently brazed with the alloys under consideration and immersed in a solution of 2.5% H_2SO_4 + 0.5% HNO_3 for 240 h (~10 days). The solution was analyzed to determine the pickup of silicon and phosphorus ions lost from the brazed joints due to corrosion of the joint. This allowed a ranking to be developed based on the dissolution of Si and P ions into the corrosive media during the test.

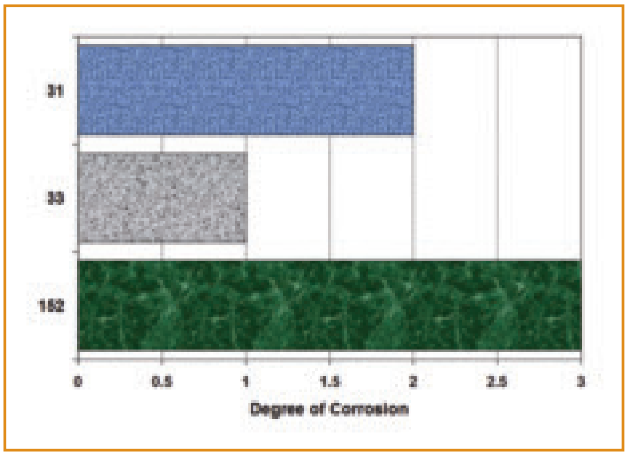


Fig. 12 — Ni-P-Cr-Si brazing filler metal corrosion performance.

The results, charted in Fig. 12, show Nicrobraz 33 had three times greater resistance to acidic media attack than 152, attributed to its relatively high chromium and silicon contents (Ref. 7).

Metallographic Examination

Sections were cut from the brazed T-pieces for metallographic examination. A cross section of a Nicrobraz 31 joint is shown in Fig. 13.

Energy-dispersive X-ray (EDX) spot chemical microanalysis was performed on the "dark" and "light" regions within the lathe-like structure. This lathe-like structure represented the ductile Cr-Ni-rich matrix phase containing the harder Cr-Ni-P-rich phases. The results of EDX chemical microanalysis are shown in Fig. 14.

Although the Ni-Cr-P-Si filler metals are able to fill joint clearances by capillary action far in excess of 0.01 in. (0.25 mm), filling relatively large joint clearances often requires a prolonged hold time at maximum brazing temperature, which can promote further precipitation and growth of hard centerline phases.

Most brazing filler metals exhibit non-congruent melting characteristics, whereby liquid and solid phases coexist between the solidus and liquidus temperatures. It is always desirable to make a braze joint that has a minimal degree of continuous hard intermetallic centerline phases that reduce strength and ductility (Ref. 8). Figures 15 and 16 show braze fillet micrographs from Nicrobraz 152 and 33 horizontal variable clearance tests at joint clearances of 0.003 and 0.002 in. (~0.075 and ~0.05 mm), respectively. The degree of discontinuous centerline phases found within each fillet is shown to be comparable.

The micrographs presented in Figs. 17 and 18 show horizontal clearance test fillets with joint widths in excess of 0.009 in. (~0.23 mm). The results show that Nicrobraz 33 filled larger joint clearances while maintaining lower levels of continuous hard centerline phases than the 152 test.

Figures 19 and 20 show microhardness test results for various sized Nicrobraz 152 and 33 braze fillets comprising varying networks of intermetallic hard phases. The nonintermetallic zones within each of the representative brazed fillets (Figs. 20, 21) demonstrate microhardness values of 156 and 105 DPH_{100g}, respectively. The intermetallic centerline regions are considerably harder in comparison, with 152 producing the highest reading of 288 DPH_{100g}.

Discussion and Conclusions

A test program has shown that Nicrobraz Alloys 33 and 31 outperform 152 in terms of joint clearance fill capacity, joint strength, and corrosion resistance.

Variable joint clearance capillary flow testing established that the joint clearance filling performance of 33 surpassed that for 152 in both vertical and horizontal configurations. Nicrobraz 31 appeared to excel in the horizontal position but demonstrated the poorest vertical flow characteristics. Under vertical orientation, the higher phosphorous content in Alloys 33 and 152 may have been responsible for promoting a freer-flowing alloy whose capillary action is less affected by gravitational force.

The free-flowing influence through higher phosphorus content was further reinforced by the wettability characteristics, which exhibited spreading ratios ranging from 29% (Alloy 31) to 53% (Alloy 152).

Filler metal aggression testing established that with the exception of Inconel® 625, each of the representative boron-free filler metals showed lower base metal erosion potential compared to Nicrobraz LM with Nicrobraz 31 demonstrating the best

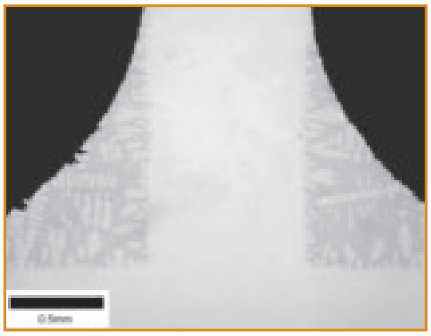


Fig. 13 — Metallographic cross section of a brazed Alloy 31 T-piece.

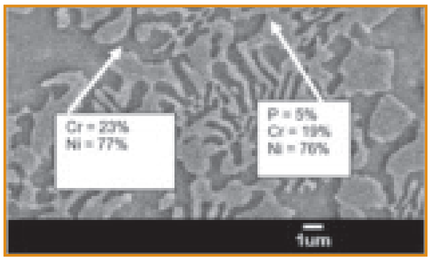


Fig. 14 — Electron micrograph of lathe structure in Alloy 31 brazed joint detailing local chemical microanalysis.

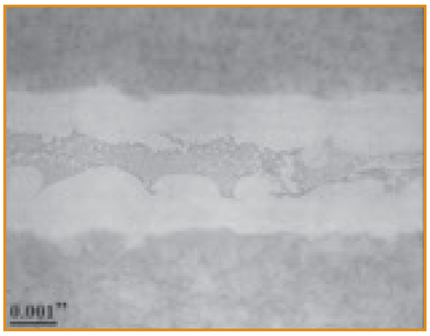


Fig. 15 — Alloy 152 section from horizontal variable clearance test showing brazed joint of approximately 0.003 in. (~0.075mm).

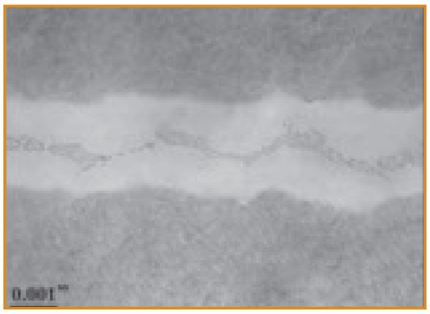


Fig. 16 — Alloy 33 section from horizontal variable clearance test showing brazed joint of approximately 0.002 in. (~0.05mm).

overall performance.

Careful consideration of joint designs and the type of testing performed is always required in brazing applications. Many assemblies to be brazed are designed with lap joints rather than butt joints. The relationships between filler metal shear strength and joint design are illustrated in more detail in the *Brazing Handbook*, 5th edition (Ref. 9). Joint designs can generally be made with sufficient load-carrying area to ensure that the assembly will be functional.

Butt-joint uniaxial tensile strength testing carried out as part of this investigation is a relevant method of establishing comparative results for the three representative Nicrobraz alloys in which 31 obtained the highest tensile strength ~40,000 lb/in.^{2} (276 MPa), followed by 33 (36,000 lb/in.^{2} (248 MPa)), and 152 (35,000 lb/in.^{2} (241 MPa)).

Similar work using brazed lap-joint specimens showed even higher tensile strengths (42,800 to 45,200 lb/in.^{2} (295 to 312 MPa)) than those achieved using the butt-joint design. The order of tensile strength performance was the same for each joint configuration.

The lathe-like structure produced after brazing a 316L stainless steel T-piece using Alloy 31 comprised hard Cr-Ni-P-rich phases within a more ductile Ni-Cr matrix. Nicrobraz 31 being the lowest phosphorus-containing alloy of the group would have greater ductility resulting in its enhanced ultimate tensile strength properties.

Microstructural examination of horizontal variable joint clearance samples revealed that under wider joint clearance conditions (0.009 to 0.011 in. (0.23 to 0.27 mm)), Nicrobraz 33 produced braze fillets with fewer brittle intermetallic centerline phases compared to 152.

Microhardness testing established that the continuous centerline fillet produced using Nicrobraz 152 is hard and brittle in contrast to the softer semicontinuous network formed with 33. It is also important to note that the Nicrobraz 33 braze fillet is almost double the width of that observed for 152.

Corrosion performance characteristics of brazing filler metals are extremely important in many applications including automotive, aerospace, and nuclear power generation. Following immersion trials within an oxidizing sulfuric plus nitric containing media, Nicrobraz 33 demonstrated the highest resistance to corrosion, followed by 31 and 152, respectively.

Chromium as a major alloying element in nickel alloys is well known for its ability to provide improved resistance to oxidizing media and attack by hot sulfur-bearing gases (Ref. 10). Although the chromium content of Nicrobraz 33 and 152 is similar, the corrosion results clearly demonstrate that a small increase in silicon content (~2.5%) greatly enhances the oxidation resistance of the representative Ni-P-Cr-Si alloys.

Nicrobraz 33 and 31 demonstrated enhanced brazing properties and characteristics in comparison to 152, and for many applications would make good alternatives for many phosphorus-containing boron-free brazing filler metals.♦

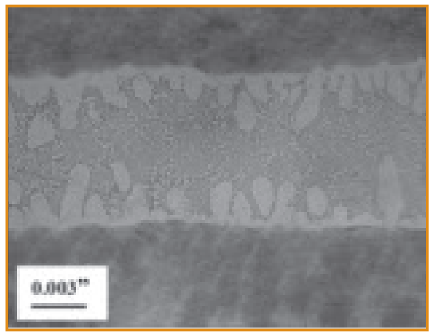


Fig. 17 — Alloy 152 section from horizontal variable clearance test showing brazed joint of approximately 0.009 in. (~0.23mm).

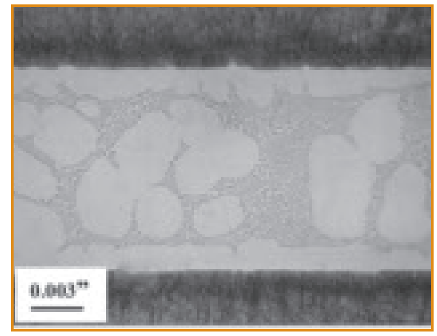


Fig. 18 — Alloy 33 section from horizontal variable clearance test showing brazed joint of approximately 0.011" (~0.28mm).

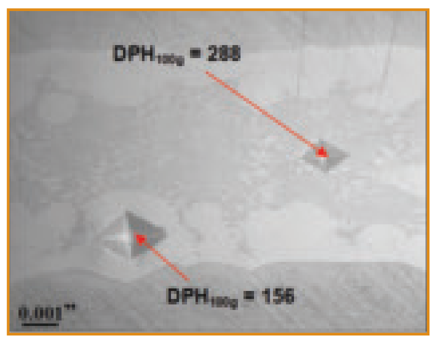


Fig. 19 — Alloy 152 section from horizontal variable clearance test showing microhardness indents within a brazed joint of approximately 0.006 in. (~0.15mm).

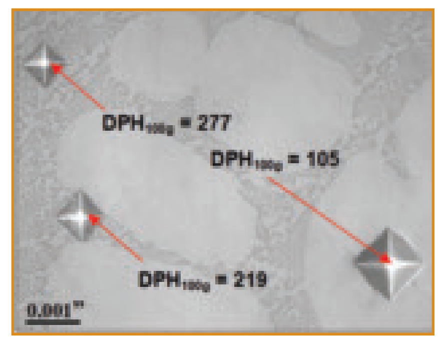


Fig. 20 — Alloy 33 section from horizontal variable clearance test showing microhardness indents within a magnified area of a 0.011 in. (~0.28mm) brazed joint.

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