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Journal of Materials Processing Technology 115 (2001) 326–332

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Activated diffusion brazed repair for IN738 hot section components of gas turbines

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Received 26 August 1999

Abstract

The wide-clearance activated diffusion brazing (ADB) techniques with various brazing alloys, namely DF4B and Nicrobraz 150 were applied to restore worn areas of IN738 components. In this study, the microstructure of an ADB joint and the results of thermal cyclic tests as well as tensile tests within the temperature range of from 25 to 980°C were investigated and discussed. The results of the tensile tests showed that ADB specimens brazed by 40 wt.% DF4B at 1190°C exhibited 85% tensile strength of the IN738 base materials at room temperature and retained the same strength as that of the base material at 980°C. However, the ductility of the ADB specimens with both brazing alloys was reduced. The results of cyclic-oxidation tests showed that ADB specimens with Nicrobraz 150 as the brazing alloy decayed after 150 cycles. However, the ADB specimens with DF4B had no obvious weight change until 205 cycles.

Keywords: Activated diffusion brazing; Cyclic oxidation; Nicrobraz 150; DF4B

1. Introduction

1.1. Background

Nickel-base precipitation hardening superalloys are used extensively in hot section components of land-based gas turbines and aircraft engines. To increase the value and extend the service life has resulted in greater interest in the repair of such components as those that have been damaged after long-term service. Unfortunately, fusion weld repairs are limited on those components, specifically those exhibiting precipitation hardening reaction involving titanium and/or aluminum [1–4], because gamma-prime phase (Ni_3Al, Ti) are highly susceptible to hot cracking or post-weld heat treatment (PWHT). Activated diffusion brazing (ADB) has the potential of making these repairs more feasible to eliminate the defects resulting from weld repair [5–9].

However, it must be demonstrated that the reliability of the ADB-repaired part is acceptable. A primary cause for rejection of such components is cracking due to tensile stresses created by non-even temperature distribution during service. These components are required to survive in a highly oxidizing environment. Brazing these cracks differs from conventional brazing:

1. The damaged surface of the base metal is more difficult and inconvenient to clean, and removing its surface materials by a mechanical method will increase the width of the joint gap.
2. The joint is loaded in tension rather than in shear.
3. The environmental damage is minimized by surface coatings. Nevertheless, during the running of the engine, the coating became cracked and the repaired zone of the base metal was exposed to the highly oxidizing environment.

1.2. The wide gap of ADB process

In the wide gap of the ADB process, to accommodate the gap to eliminate the formation of brittle intermetallic compounds, adding the third element is necessary in the brazing process. This is called an additive metal. To ensure that the added metal will function effectively, two demands must be fulfilled [10], these being as follows:

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0924-0136/01/$ – see front matter
PII: S0924-0136(01)00831-7

1. The brazed alloy metalloids have to act as a sink. This is associated with either solid-state diffusion of the metalloids or by partial solution of the additive metal in the liquefied brazes alloy.
2. The additive metal should act as a sponge which absorbs the liquefied brazes alloy by capillary force.

In the literature [5,11], the characteristics of a structure with nickel-base braze alloys have been reported, but limited to simple alloy systems of braze alloys and additive metals. Binary or even ternary diagrams can provide only limited information about the microstructural development in these alloy. Most of the data available in the literature has been obtained by experimental observations. Another work [10] studied the mechanical properties of wide gap brazing using nickel-base braze alloy on carbon steel specimens and reported excellent strength.

The present investigation studied the microstructural characteristics, and examined the mechanical properties and cyclic oxidation, of wide gap ADB joints using different brazing alloys mixed with the additive metal as a filler metal in IN738 plate. IN738 is a cast precipitation hardening nickel-base superalloy used for land-based turbine blades and nozzle vanes.

2. Experimental method

2.1. Materials and experimental procedure

Both the base metal and additive metal used in this study are IN738 nickel-base precipitation hardening superalloy. The brazing alloys are nickel-base Nicrobraz 150 and DF4B prepared by inert gas atomization. The nominal compositions of the base metal and the braze alloys are given in Table 1.

Table 1
Nominal compositions of the IN738 base materials and the brazing alloys used in this study (IN738 is a registered trademark of the International Nickel Co. Ltd.)

Element (wt.%)	IN738[a]	Nicrobraz 150[b]	DF4B[c]
Cr	16.0	15.0	14.0
Co	8.4	–	10.0
Al	3.4	–	3.5
Ti	3.4	–	–
W	2.7	–	–
Mo	1.7	–	–
Ta	1.7	–	–
Nb	0.8	–	–
B	0.01	3.5	2.7
C	0.1	0.1	NA[d]
Zr	0.03	–	–
Y	–	–	0.02
Ni	Balance	Balance	Balance

[a] IN738LC powder of the additive metal is produced from Praxair NI-284-1 powder.
[b] Nicrobraz 150 is produced by Wall Colmonoy Ltd.
[c] DF4B is produced by Sulzer Metco (US) Inc.
[d] Not available.

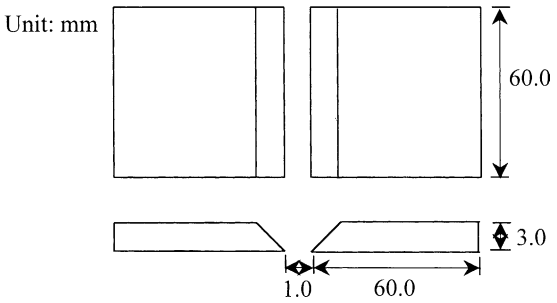


Fig. 1. Specimen geometry for the ADB (dimensions in millimeter).

Brazing mixtures were prepared from different weight percentages of the brazing alloys and the additive metals, 30/70, 40/60, and 50/50, respectively. The mixtures were thoroughly mixed in a three-dimensional mixer for 2 h. A schematic diagram of the specimens for the wide gap ADB joint is shown in Fig. 1. The faying surface of the IN738 base metal was electroplated with a nickel layer of 0.03 mm thickness.

Brazing was conducted in a vacuum of approximately 4×10^{-5} Torr. A typical thermal cycle of the ADB is shown in Fig. 2.

2.2. Microstructural examination

Microstructural observations were made on cross-sectional samples using an optical microscope (OM), scanning electron microscope (SEM), and electron probe X-ray microanalyzer (EPMA). The samples were prepared by electrolytic etching at 6 V in a solution consisting of 10 ml H_3PO_4, 40 ml H_2SO_4, and 40 ml HNO_3.

SEM examination was conducted using a Hictach 2100 system operated at an accelerating voltage of 20 kV. EPMA was conducted using a Joel JXA-8800M microscope operated at an accelerating voltage of 15 kV, and a specimen current of 1.0×10^{-7} A was used to detect boron and carbon.

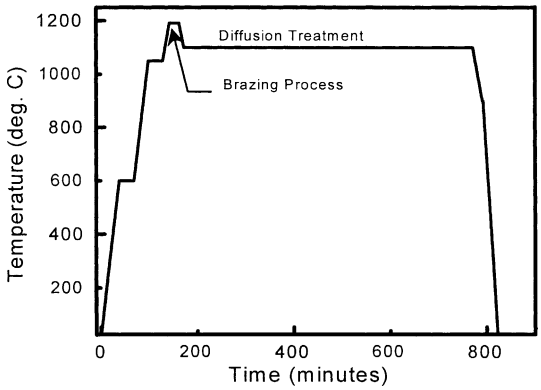


Fig. 2. Schematic illustration of the thermal cycle used in the present investigation.

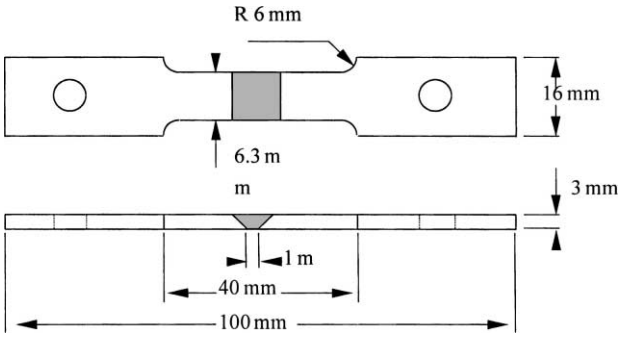


Fig. 3. Schematic diagram of the ADB tensile specimens.

2.3. Evaluation of mechanical property and cyclic oxidation

The tensile tests were performed at room temperature, 760°C, and 980°C with a strain rate 0.04 mm/s; a schematic diagram of the specimens machined from the ADB samples according to ASTM E8M being shown in Fig. 3.

Cyclic-oxidation tests were conducted at 980°C, and involved moving the sample in and out of a horizontal furnace. Each cyclic test consisted of oxidation for 1 h in the furnace followed by 5 min outside the furnace with fan cooling to room temperature, the weight change of the ADB sample, being measured. The experimental apparatus, shown schematically in Fig. 4, consisted of a furnace and a cooling fan.

3. Results and discussion

3.1. Microstructural examination

The mechanical properties and oxidation resistance of the zones repaired using the ADB process are determined strongly by their microstructural and chemical composition.

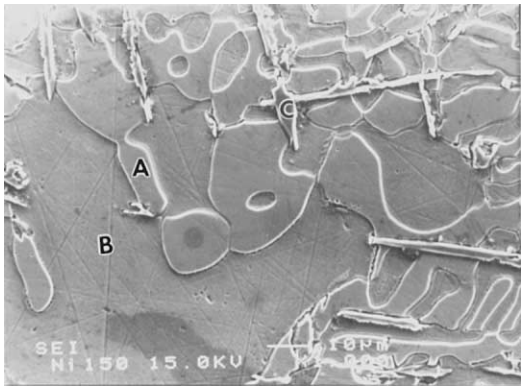


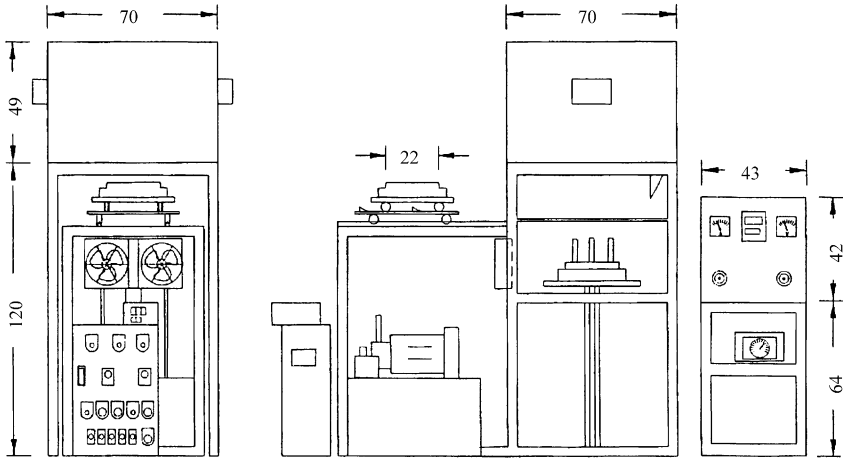
Fig. 5. Microstructure (SEM) of a brazed joint produced by pure Nicrobraz 150. The nickel boride phase is shown by marker A; the γ-phase by marker B; the chromium boride phase by marker C.

3.2. Nicrobraz 150

Fig. 5 shows the solidification microstructure of pure Nicrobraz 150 after the ADB process. In Fig. 5, beside the matrix of nickel solid solution (γ-phase), two intermetallic compounds were observed in the whole solidification microstructure. The phase marked A is a nickel boride phase while that marked B is a γ-phase: it might be identified as a nickel–nickel boride eutectic phase. The acerose phase C is a chromium boride, being precipitated on the matrix of the nickel–nickel boride eutectic phase. Quantitative chemical analysis revealed the chemical compositions for the three phases, as outlined in Table 2.

The results of quantitative analysis show chromium boride with lesser amounts of nickel but the amount of carbon contained is higher. Boron and carbon are the interstitial atoms and the solubility of B and C in Cr is low (0.7 at.% B at 1100°C, 0.3 at.% C at 1532°C) [12]: it might be the C instead of the B position.

Fig. 6(a) shows the microstructure of a 40 wt.% Nicrobraz 150 sample after the ADB processing. There are no pores



Unit : cm

Fig. 4. Schematic representation of the automatic thermal cycling furnace used in this study.

Table 2
Compositional analysis of the phase in specimens with pure Nicrobraz 150 brazing alloy

Element	A		B		C	
	wt.%	at.%	wt.%	at.%	wt.%	at.%
Ni	79.94	72.33	87.05	70.42	2.75	1.52
Cr	18.01	18.38	7.44	6.79	80.55	50.16
B	0.51	2.50	2.42	10.59	11.15	33.36
C	1.53	6.80	3.09	12.20	5.54	14.96

observed in the whole brazed zone, when Nicrobraz 150 filled up between the additive metals. The microstructure at high magnification is shown in Fig. 6(b). The matrix and secondary phase (blocky phase) are more clearly observed. Island-like blocky boride phases were precipitated in the additive metal. Table 3 shows the chemical compositions for the two phases. The results of quantitative analysis indicates that the blocky phase is based on a chromium boride phase with lesser amounts of cobalt, aluminum, nickel, tantalum, and titanium, and it is comparatively rich in molybdenum,

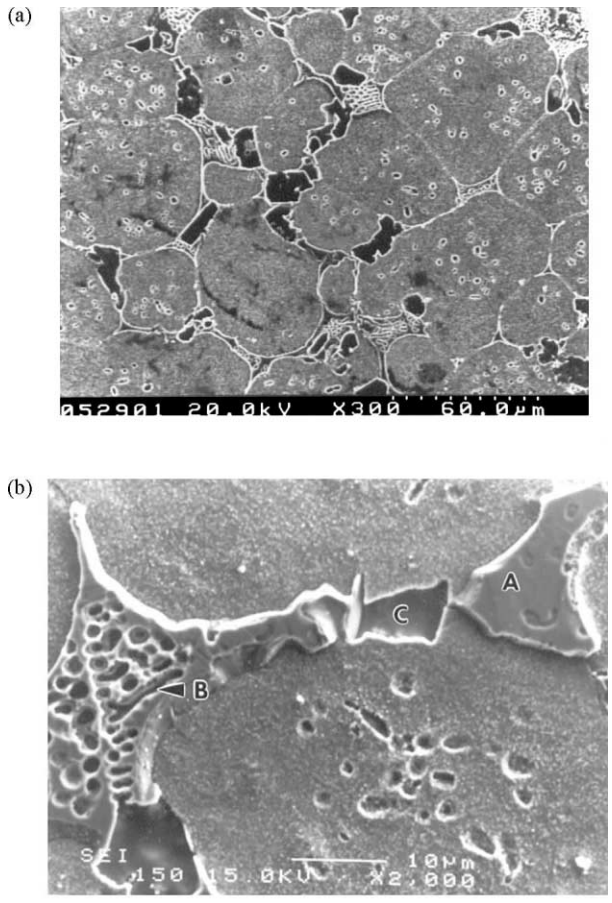


Fig. 6. Microstructures (SEM) of brazed joints produced by a mixture containing 40 wt.% Nicrobraz 150: (a) low magnification (×300); (b) high magnification (×2000). The nickel boride phase is shown by marker A; the γ-phase by marker B; the chromium boride phase (blocky phase) by marker C.

Table 3
Compositional analysis of the phase in specimens containing 40 wt.% Nicrobraz 150 brazing alloy

Element	Matrix		Blocky phase	
	wt.%	at.%	wt.%	at.%
Ni	76.248	67.473	4.753	2.957
Cr	4.789	4.783	68.858	48.349
Co	5.833	5.140	1.917	1.188
Al	0.594	1.144	0.006	0.008
Ti	5.117	5.548	0.257	0.196
Ta	2.276	0.654	0	0
Mo	0.248	0.134	5.978	2.275
Nb	1.394	0.779	0.038	0.015
W	0.366	0.103	4.467	0.887
B	1.447	6.946	7.135	24.083
C	1.687	7.295	6.591	20.041

tungsten, and carbon. The matrix of the Nicrobraz 150 brazing alloy is predominantly nickel boride with reduced amounts of boron and carbon, but contains a higher concentration of cobalt, titanium, and tantalum.

The results can be summarized as follows. Nicrobraz 150 brazing alloy can be well wetted on the surface of an IN738 additive metals and substrate since there are no pores in the whole brazed zone. However, the constitution of pure Nicrobraz 150 after the ADB process is similar to a mixture containing Nicrobraz 150 and additive metal; both include two brittle intermetallic compounds (nickel boride and chromium boride).

3.3. DF4B

The micrography in Fig. 7 shows the microstructure of the pure DF4B brazing alloys after ADB treatment at 1190°C. Acerose chromium boride was observed, marked C, in the whole microstructure, the honeycomb structure being nickel–nickel boride eutectic phase. An important result of this microstructure is that, γ′-phase (marked D) was precipitated, which appears white in the figure.

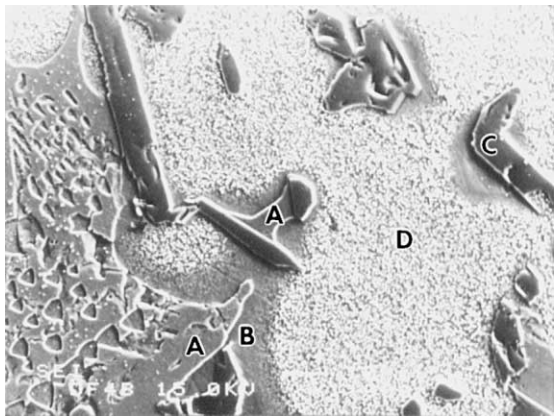


Fig. 7. Microstructure (SEM) of a brazed joint produced by pure DF4B. The nickel boride phase is shown by marker A; the γ-phase by marker B; the chromium boride phase by marker C; the γ′-phase by marker D.

Table 4
Compositional analysis of the phase in specimens with pure DF4B brazing alloy

Element	A		B		C	
	wt.%	at.%	wt.%	at.%	wt.%	at.%
Ni	72.44	69.68	71.79	59.40	0.64	0.41
Cr	12.40	13.44	8.09	7.53	87.21	62.13
Co	12.84	12.31	11.54	9.52	0.60	0.37
Al	1.53	3.22	2.22	3.98	0.01	0.01
Ta	0.54	0.17	1.84	0.49	0.50	0.11
B	–	–	1.67	7.53	8.62	29.53
C	0.26	1.19	2.86	11.54	2.42	7.45

The results of composition analyses are shown in Table 4, showing chromium boride with lesser amounts of nickel, cobalt, and tantalum: however, carbon is still higher. Fig. 8(a) is a typical microstructure of a joint specimen after the ADB process with 40 wt.% DF4B brazing alloy plus 60 wt.% IN738 additive metal. Note that the blocky phase is still present. However, the matrix was not clearly observed, in contrast to the case for brazing alloy Nicrobraz 150 (see Fig. 7). The blocky boride phase was observed within the additive metal, and a darker matrix phase are present alongside the blocky phase. The results of compositional analyses are shown in Table 5. A higher concentration of carbon in the boride phase is evident: these carbon atoms might have diffused from the carbon in the DF4B brazing alloy. The stoichiometry of the irregular blocky-like darker phase along the blocky boride phase was analyzed to be a γ'-phase, containing some Ti and Al atoms which had diffused from the additive metal. Compared with the ADB Nicrobraz 150 matrix, the concentration of Al varied from 1.144 to 13.656 at.%, Ta varied to 1.160 at.% and boron was decreased to zero.

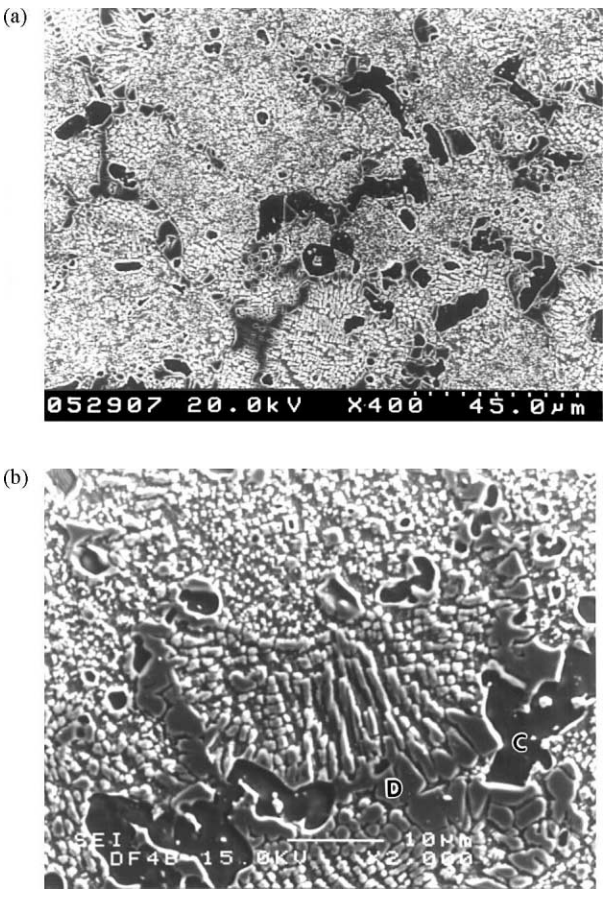


Fig. 8. Microstructures (SEM) of brazed joints produced by a mixture containing 40 wt.% DF4B: (a) low magnification (×400); (b) high magnification (×2000). The chromium boride phase (blocky phase) is shown by marker C; the γ'-phase (darker phase) by marker D.

Table 5
Compositional analysis of the phase in specimens containing 40 wt.% DF4B brazing alloy

Element	Darker phase		Blocky phase	
	wt.%	at.%	wt.%	at.%
Ni	73.337	67.269	4.673	3.373
Cr	3.474	3.596	70.230	57.209
Co	6.064	5.539	3.725	2.678
Al	6.844	13.656	0.018	0.028
Ti	4.548	5.111	0.528	0.467
Ta	3.899	1.160	0.684	0.160
Mo	0.256	0.144	5.816	2.568
Nb	0.545	0.316	0.108	0.049
W	0.339	0.099	5.777	1.331
B	0.008	0.040	6.081	23.811
C	0.685	3.070	2.360	8.325

3.4. Mechanical properties

Based upon the microstructural analysis of specimens joined by 30 wt.% DF4B filler metal, there existed numerous pores in the whole brazed zone. In the specimen joined by 50 wt.% DF4B filler metal, many hard-brittle intermetallic phases of chromium boride appeared. Therefore, the specimens joined by 40 wt.% filler metals, Nicrobraz 150, and DF4B, plus 60 wt.% additive metal were selected for tensile testing, and designated as ''Nicro'' and ''DF4B'' specimens, respectively: ''BM'' represents a specimen of IN738 base metal.

Fig. 9 presents the results of tensile tests. All of the tested specimens were found to have broken at the joint region. The ultimate tensile strength (UTS) of the DF4B specimen at 980°C is nearly identical to that of the base metal specimen, 38 kg/mm^2 vs. 40 kg/mm^2, and its UTS at room temperature achieves 85% of that of the base metal specimen. However, Nicro specimens showed poor tensile properties at all testing temperatures.

3.5. Cyclic oxidation

The corresponding weight gain data for the cyclic-oxidation experiments at 980°C are shown in Fig. 10. The initial

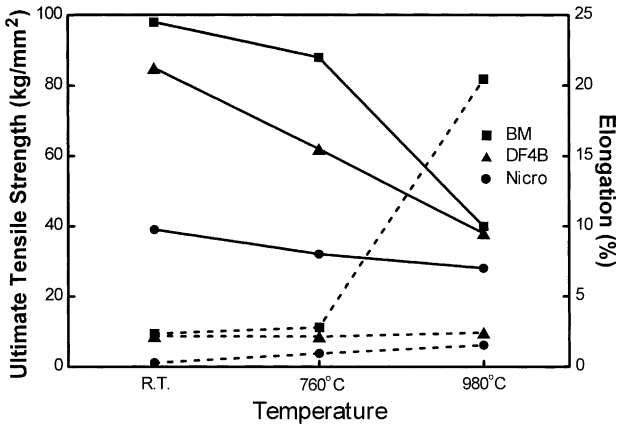


Fig. 9. The results of the tensile strength test obtained for the ADB joint and base material.

oxidation rate for all ADB specimens was higher. The weight gain of the base metal specimens showed quasi-parabolic oxidation kinetics. In contrast, the weight gain of all ADB specimens was highly variable: it might be that the brazed area included a few pores.

Weight gain of the DF4B specimens was not observed, there being an evident weight loss up to 200 cycles. Fig. 11(a) shows the cross-sectional morphology of the 80D50 (50 wt.% DF4B mixed to 50 wt.% additive metals, brazing temperature 1180°C) brazed area after 205 cycles. The IN738 base materials revealed a continuous and homogeneous oxide layer, which compares with the oxide layer of the brazed area in its non-densification and a small amount of oxide spalling.

However, the weight gain of Nicro specimens goes through a maximum and a decrease to 150 cycles. This decrease is due to oxide spalling and oxygen ion diffused rapidly into brazing area, the oxidation path of the fracture micrography of which is shown in Fig. 11(b).

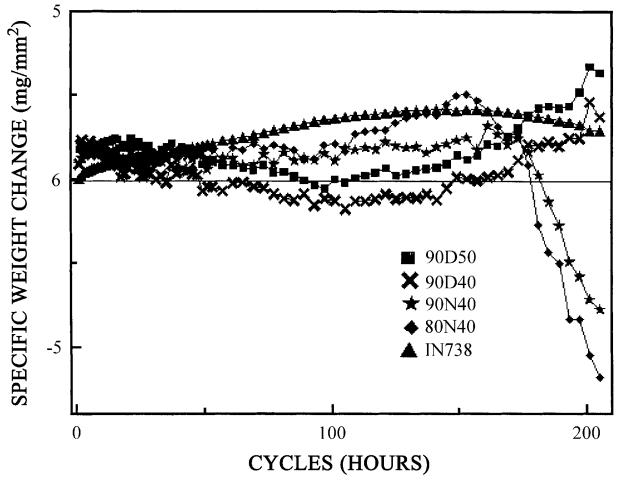


Fig. 10. The relationships between the specific weight gain of the base material and the ADB specimens. 90D50: mixture containing 50 wt.% DF4B and 50 wt.% additive metal, brazing temperature 1190°C; 80N40: mixture containing 40 wt.% Nicrobraz 150 and 60 wt.% additive metal, brazing temperature 1180°C.

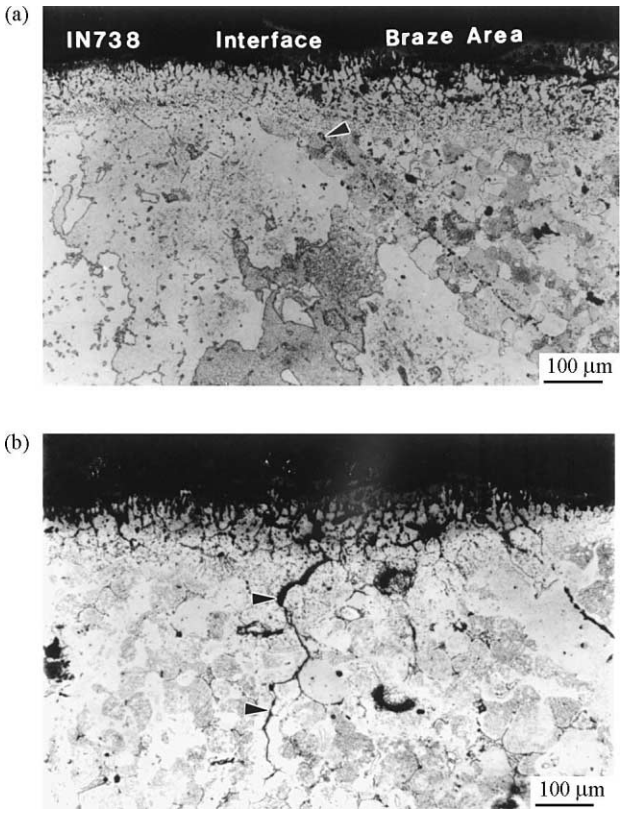


Fig. 11. Cross-sectional view of the ADB area: (a) mixture containing 50 wt.% DF4B, brazing temperature 1180°C after 205 cycles of oxidation; (b) mixture containing 40 wt.% Nicrobraz 150, brazing temperature 1190°C after 150 cycles of oxidation. The arrows indicate the penetrating oxidation path into the brazed area.

4. Conclusions

Wide-clearance ADB techniques using various brazing alloys were evaluated by tensile tests and furnace thermal cyclic tests within the temperature range of from 25 to 980°C. Microstructures of ADB joint and results of tensile tests and thermal cyclic tests were discussed in this study and the concluding remarks are summarized as follows:

1. The Nicrobraz 150 brazing alloy mixed with an additive metal after ADB processing showed the presence of two intermetallic phase: (a) nickel boride; (b) chromium boride; however, that formed on the DF4B brazing alloy is only chromium boride and gamma-prime phase instead of nickel boride.
2. The results of the tensile tests showed that ADB specimens brazed by 40 wt.% DF4B at 1190°C exhibited 85% of the tensile strength of the IN738 base materials at room temperature and retained the same strength as that of the base materials at 980°C: however,

the Nicrobraz 150 brazing alloy showed poor tensile properties at all testing temperatures.

3. The results of thermal cyclic tests showed that ADB specimens with Nicrobraz 150 were decayed after 150 cycles, whilst DF4B had no obvious weight change until 205 cycles.

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