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Effects of gap filler and brazing temperature on fracture and fatigue of wide-gap brazed joints

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The influence of gap filler content on the fracture, fatigue crack initiation and propagation of AISI 316 stainless steel wide-gap brazed with nickel-based filler metal has been investigated. The brazed joints were found to consist of eutectic, intermetallic compound and solid solution. The volume of solid solution was observed to depend on the gap filler content and brazing temperature. Tensile tests with extra small strain gauge bonded at the centre of the joints showed that the strength and elongation of the brazed joints increased with brazing temperature, and the addition of gap filler was able to improve the load-carrying capacity of the brazed joints only when the brazing temperature was high enough. Fatigue crack initiation and growth under displacement amplitude control were also carried out. Crack closure in the brazed joints was determined by means of back face strain on the compact tension specimen used. The introduction of gap filler was able to increase the fatigue and fracture resistance of the brazed joints when a suitable brazing temperature was used. Crack deflection, branching and uncracked ligament bridging behind the crack tip were observable along the crack paths. Experimental results showed that gap filler was able to enhance the crack closure caused by roughness and ligament bridging.

1. Introduction

High-temperature brazing, which has been widely used in industry, has been demonstrated to be able to produce high-performance joints with good static and dynamic load resistance as well as high corrosion resistance [1]. In order to obtain good performance joints, the joints to be brazed are required to have a capillary clearance from 0–0.15 mm for conventional brazing. However, when it is difficult to maintain this clearance due to machining and assembly errors, wide-gap brazing is often used. Filler metals used in high-temperature brazing often contain melting-point depressants which may form eutectic structure and intermetallic compounds with nickel and chromium, which decrease the load-carrying capacity of the joints, especially in wide-gap brazing. Lugscheider and Partz's work [2] showed that the maximum brazing clearance free from brittle phase is smaller than 0.1 mm. Therefore, in wide-gap brazing, brittle phase must be taken into consideration. For wide-gap brazing, a mixture of filler metal and high-melting point gap filler may be employed [3, 4]. The gap filler acts as a sink for the melting-point depressants and as a sponge both to produce capillary attraction and to retain the filler metal.

Shear and thermal fatigue of soldered joints where eutectic structure coarsening was considered as the fatigue mechanism [5–7] have been studied. Little work on the fatigue behaviour of the brazed joints has, however, been reported in the literature, even though brazed joints are more often required to endure mechanical and thermal fatigue [8]. Although similarity between soldered and brazed joints exists, there is also great difference between them. For example, a soldered joint often possesses large ductility, while a high-temperature brazed joint exhibits only less than 1% elongation [9]. The microstructures of the brazed joints contain many brittle phases, which cause the joint to be very brittle. Even in side-grooved specimens, fatigue crack propagation could not be easily controlled [10, 11], so that the fatigue crack propagation behaviour and mechanism are still unclear.

In this work, the effect of gap filler and brazing temperature on fracture and fatigue properties of the brazed joints were investigated. Fracture behaviours within the brazed joints were obtained by means of extra-small strain gauges bonded at the centre of the brazed joints. The influence of gap filler on crack morphology, crack closure and shielding in the brazed joints were also studied.

2. Experimental procedure

The parent metal chosen in the present study was stainless steel AISI 316 6 mm thick. For brazing, Nicrobraze no. 150 was selected as the filler metal, while Nicrogap no. 116 was used as gap filler. The characteristic temperatures and the chemical compositions of the materials are shown in Table I. A commercial liquid cement, consisting mainly of acrylic polymers with trichloroethane solvent, was employed as binder. The gap to be brazed was machined using

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electric discharge machining (EDM). The clearance of the gap was set at 0.9 mm. The two machined surfaces were then ground with emery paper, cleaned and degreased by soaking and agitating for about 10 min in a bath of acetone on an ultrasonic cleaner. The filler metals were then preplaced over the gap as shown in Fig. 1. A sheet of ceramic paper was attached at the bottom of the gap while Nicrobraz green stop-off was painted near the edges of the joint at the top as well as the bottom to prevent any flow of liquid-phase material out of the joint area. Brazing was carried out in a resistance tubular furnace at a brazing temperature between 1150 and 1225 °C in a vacuum of about 5×10^{-5} mbar for 10 min. The overfilling was machined off after brazing.

Tensile testing of the brazed joints was carried out under stroke control at a crosshead speed of 0.1 mm min^{-1} using an Instron 8501 universal testing machine. The geometry and dimensions of the specimen are shown in Fig. 2. In order to obtain deformation data within the brazed joint, a strain gauge with gauge length of 0.2 mm was bonded at the centre of the 0.9 mm wide joints. During tensile testing, the load and strain were recorded using the TML Portable Data Logger (Model TDS-302).

TABLE I Nominal compositions and characteristic temperatures of materials used in the study

Material	Ni	Cr	Fe	Si	Mo	B	Solidus (°C)	Liquidus (°C)
No. 150	Bal.	15	–	–	–	3.5	1055	1055
No. 116	80	20					1390	1440
AISI 316	12	17	Bal.	0.8	2.5	–	–	–

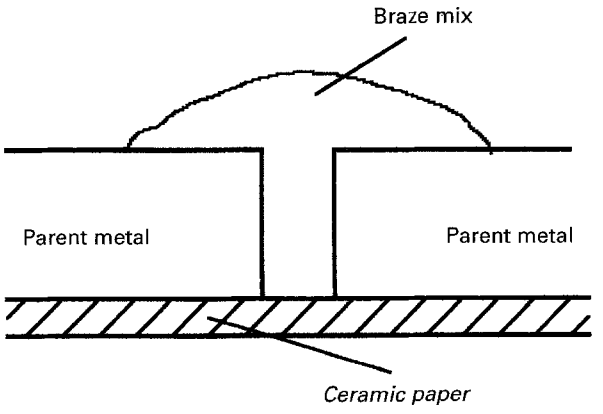

Figure 1 Wide-gap brazing with preplacement.

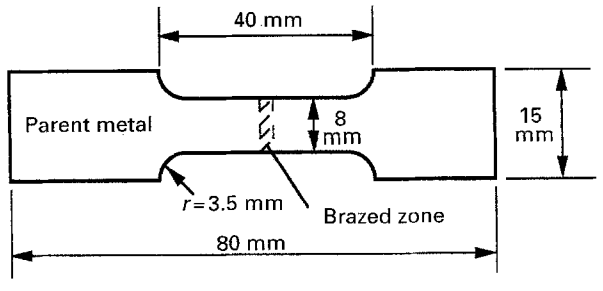

Figure 2 The geometry of the tensile test specimen.

Fatigue crack initiation and propagation tests were performed using a compact tension specimen (CT) as shown in Fig. 3. The specimen contained a through-thickness crack of 13 mm length and 0.25 mm width cut by EDM wire machining. Specimens were cyclically loaded at a load ratio (ratio of minimum to maximum load) of 0.1 and frequency of 50 Hz (sine wave) in the high-resolution, computer-controlled electro-servohydraulic Instron 8501 testing machine, operating under closed-loop displacement control. All tests were conducted in controlled ambient air condition of 25 °C and 65% relative humidity. Load amplitude was monitored at regular intervals during the fatigue test. A travelling microscope with a resolution of 10 μm was used to measure the crack length in the CT specimen. A crack growth of about 0.1–0.3 mm from the starter notch was taken as crack initiation. Unloading compliance measurements using back face gauges were used to assess the extent of fatigue crack closure in terms of closure load, P_{cl}, at the first contact of the fracture surfaces during unloading. The value of P_{cl} was calculated from the highest load where the elastic unloading compliance line deviated from linearity. For the CT specimen, stress intensity factor was computed from the applied load, P, crack length, a, test piece thickness, B, and width, W, using [2]

$$K = (P/BW^{1/2})f(a/W) \quad (1a)$$

where

$$f(a/W) = \{[2 + (a/W)][0.886 + 4.64(a/W) - 13.329(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4]\}/[1 - (a/W)]^{3/2} \quad (1b)$$

The microstructure and fatigue crack morphology within the brazed joints were observed under an optical microscope while the fracture surfaces were examined by means of a Jeol JSM-T330A scanning electron microscope.

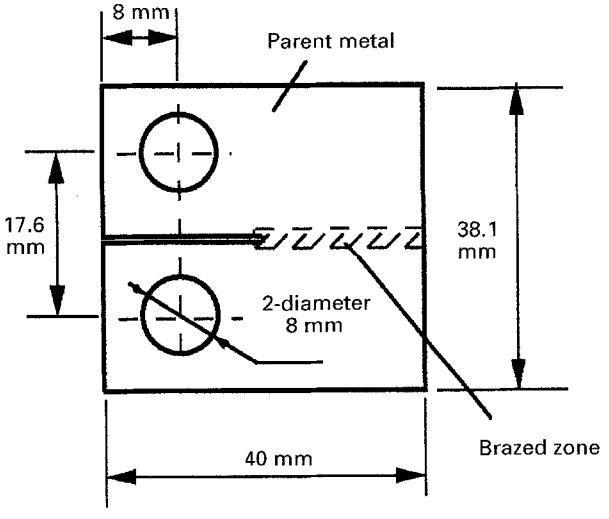

Figure 3 The compact tension specimen.

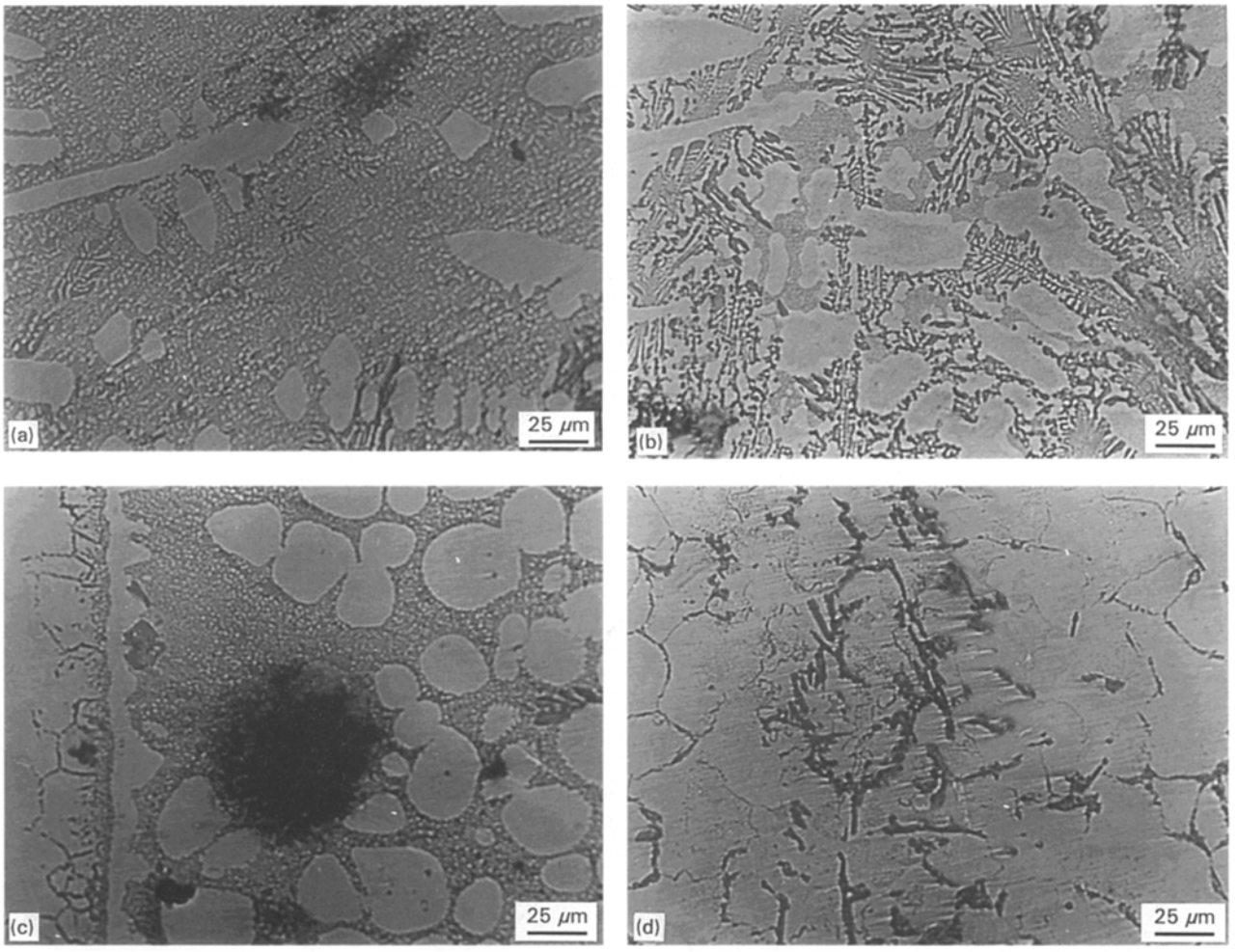

Figure 4 Microstructures of the brazed joints with different gap filler contents: (a) Nicrobraz no. 150 only, brazing temperature 1150 °C; (b) Nicrobraz no. 150 only, brazing temperature 1200 °C; (c) Nicrobraz no. 150 + 40% gap filler, brazing temperature 1175 °C (showing microvoid); (d) Nicrobraz no. 150 + 40% gap filler, brazing temperature 1225 °C.

3. Results and discussion

3.1. Microstructures

Microstructures of the joints brazed with addition of different gap filler contents are shown in Fig. 4. Because Nicrobraze no. 150 possesses the eutectic composition, the joint with no addition of gap filler consists of almost full eutectic structure (nickel-based solid solution and intermetallic compounds) as shown in Fig. 4a. For joints with gap filler, discrete solid-solution phase can be seen to be distributed in the eutectic structure matrix. The volume fraction of solid solution was observed to increase with the gap filler content and brazing temperature. Joints brazed at 1225 °C with 40% gap filler consist almost entirely of solid solution (Fig. 4d). Because the gap filler is Ni–Cr alloy, although some reaction occurs between gap filler and filler metal, the gap filler does not melt but remains as single solid-solution phase. Microvoids can be seen in the joints (Fig. 4c) and the frequency of their occurrence increases with the addition of gap filler and the reduction of brazing temperature.

3.2. Tensile tests

The strengths and elongations of the joints brazed with different gap filler contents and brazing temperatures are shown in Figs 5 and 6. It is evident that all

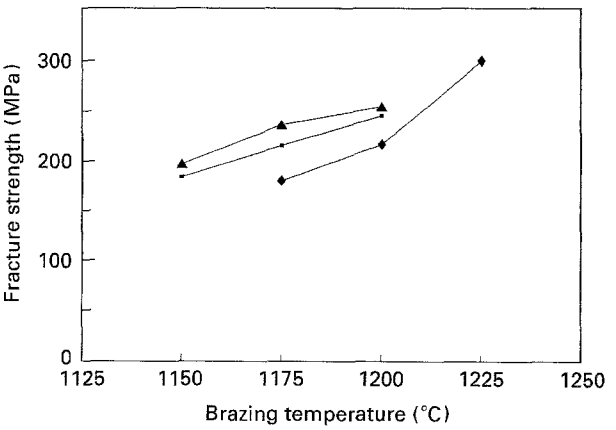

Figure 5 The effect of gap filler and brazing temperature on the strength of the brazed joints. Gap filler content: (■) 0%, (▲) 20%, (◆) 40%.

brazed joints are brittle because their fracture strains are very low. With addition of 20% gap filler, an increase in fracture strength and elongation of the joints was observed. However, for the joints brazed with an addition of 40% gap filler, an even lower strength and elongation than those without gap filler was recorded when brazed at 1175 and 1200 °C. Figs 5 and 6 also show a dramatic increase in strength and

ductility when the joints were brazed at a higher temperature of 1225 °C.

Fractographs of the brazed joints after tensile testing are shown in Fig. 7. The fracture characteristic of the joint with Nicrobraz no. 150 only is quasi-cleavage (Fig. 7a and b), while that of Nicrobraz no. 150 with the addition of 40% gap filler appears to possess some ductile pattern. Some tear deformation can be discerned to occur at the interface of gap filler and matrix although the fracture seems to go by the gap filler powder (Fig. 7c).

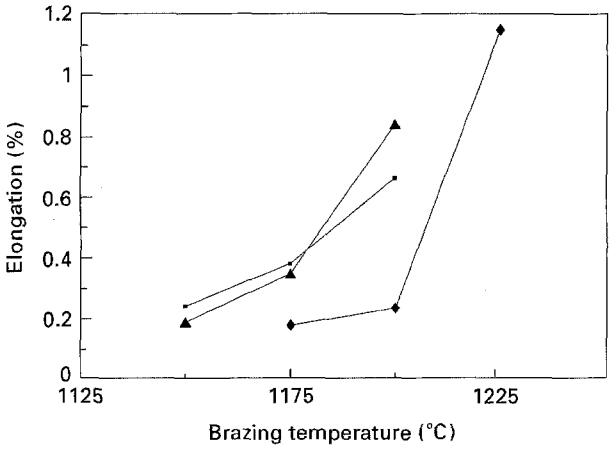

Figure 6 The effect of gap filler and brazing temperature on the elongation of the brazed joints.

Among the brazing parameters investigated, brazing temperature appears to be the most important factor. In order to obtain good brazed joints, suitable brazing temperature has to be selected. For joints brazed with filler metal only, it was observed that the strength and ductility of the joints increased with brazing temperature. The higher the brazing temperature, the less the eutectic structure, and the more were the solid solution and coarse intermetallic compound in the microstructure of the joints.

When gap filler is applied, the case seems to be similar to that in a composite. The strength of a composite, σ_c, can be estimated using the rule of mixtures which yields [13]

$$\sigma_c = f\sigma_r + (1 - f)\sigma_m \quad (2)$$

where f is the reinforcement volume fraction, σ_r the reinforcement strength, and σ_m the matrix strength. Therefore, the strength of a composite will increase with the fraction of reinforcement phase only if σ_r is greater than σ_m.

In the present experiment, it was observed that not all joints could be improved by the addition of gap

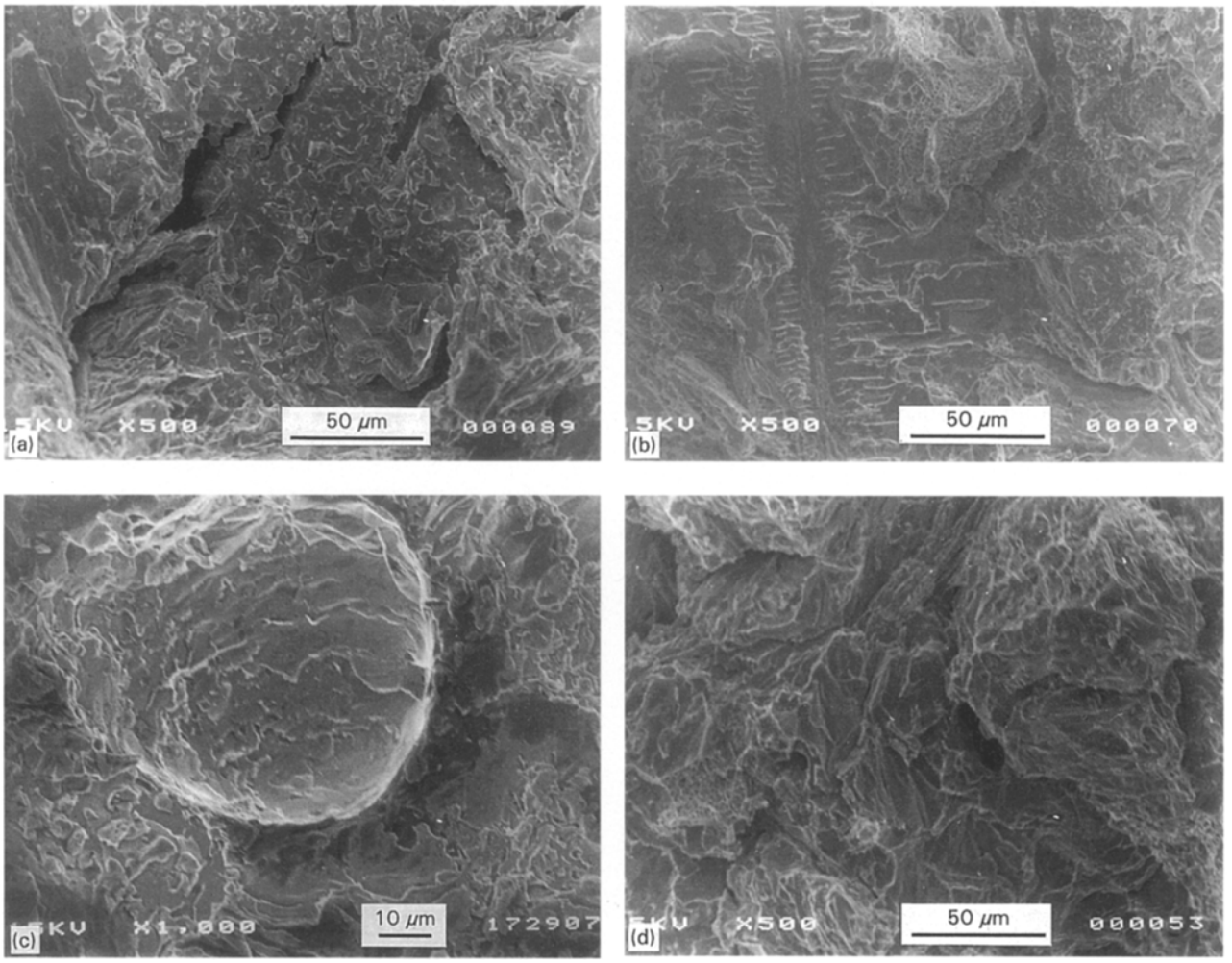

Figure 7 SEM fractographs of brazed joints after tensile fracture: (a) Nicrobraz no. 150 only, brazing temperature 1150 °C; (b) Nicrobraz no. 150 only, brazing temperature 1200 °C, (c) Nicrobraz no. 150 + 40% gap filler, brazing temperature 1200 °C, (d) Nicrobraz no. 150 + 40% gap filler, brazing temperature 1225 °C.

filler as shown in Figs 5 and 6. When brazing at 1175 and 1200 °C, the addition of 40% gap filler not only did not increase the strength of the joint but actually decreased it. In fact, in the brazed joint, the reinforcement phase and matrix could not simply be mixed, and the interaction between them during brazing has to be considered. Therefore, the resultant strength should come from contributions due to matrix, gap filler and their interaction. In this case, Equation 2 should be rewritten

$$\sigma_B = (1-f)\sigma_F + f\sigma_G + \sigma_i \quad (3)$$

$$\sigma_B - \sigma_F = f(\sigma_G - \sigma_F) + \sigma_i \quad (4)$$

where σ_B is the strength of the braze, σ_F and σ_G are the strength of filler metal and gap filler, respectively, σ_i is the effect of interaction between gap filler and filler metal. σ_i is dependent on the brazing parameters. If $f(\sigma_G - \sigma_F) + \sigma_i < 0$, a decrease in strength will result. Because σ_G is higher than σ_F, strength decrease occurs only when σ_i is a negative value. At the brazing temperature, the filler metal melts but the gap filler remains in the solid state. Diffusion of element and precipitation take place where boron in the liquid (matrix) diffuses into the gap filler powder, reacts with chromium and nickel, and precipitates as boride, so that brittleness of the matrix decreases, resulting in a favourable effect. In another aspect, liquid fills the space between solids (gap filler). The extent of filling depends on the fluidity of the liquid and their interfacial tension. The shrinkage of liquid after brazing should, therefore, also be considered because brazing defects such as microvoids may be produced. The latter will give a negative contribution to the strength of the joint. The effect of the interaction between the filler metal and gap filler on the strength of the joint depends on the competition of those two aspects. When a lower brazing temperature was used, the negative effect was larger; the joint strength could not be improved by the addition of gap filler. On the other hand, as the brazing temperature increased, boron could easily diffuse, and the fluidity of the liquid and the extent of wetting increased. The beneficial effect in this case caused the strength of the brazed joint to increase.

3.3. Fatigue behaviour

Fig. 8 shows the fatigue crack initiation lives of the joints brazed with different gap filler contents and brazing temperatures. All specimens were cyclically loaded under a displacement amplitude of 0.03 mm. The fatigue crack propagation rates of the brazed joints are graphically shown in Fig. 9. In spite of some scatter, the remarkable improvement on fatigue crack initiation and propagation resistance of the brazed joints due to the introduction of gap filler is clearly evident as long as the brazing temperature is high enough.

The nature of the fatigue crack paths was clearly revealed from optical microscopy of the polished surfaces of the CT specimens. As shown in Fig. 10, a fatigue crack predominantly propagates along the

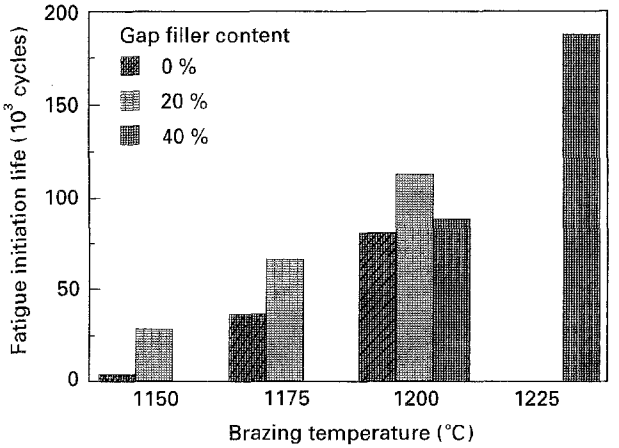

Figure 8 Fatigue crack initiation life of brazed joints.

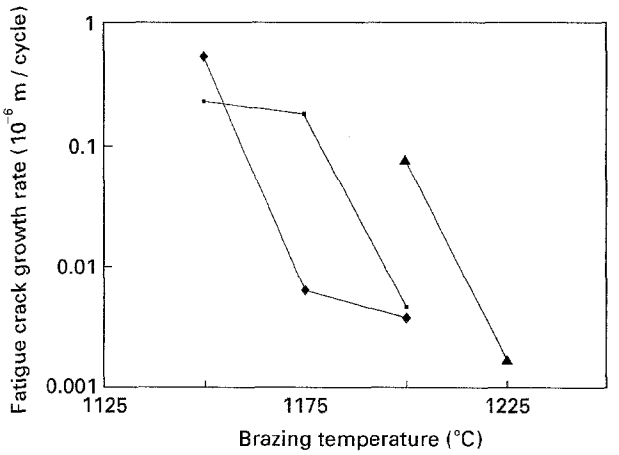

Figure 9 Fatigue crack growth rate of brazed joints ($\Delta K \sim 9\ \mathrm{MPa\,m^{1/2}}$).

eutectic structure or intermetallic compounds of the brazed joint. Evidence of frequent crack deflection, branching and uncracked ligament bridging behind the crack tip are observable along the crack paths especially when a lower brazing temperature was used. The phenomenon observed here is somewhat similar to that in ceramics [14, 15]. The degree of crack tortuosity seems to increase with gap filler content. More microcracks were observed near the main crack in the joint brazed with Nicrobraze no. 150 only, than those with the addition of gap filler (Fig. 10a, b). Crack paths similar to those in the ductile phase-reinforced intermetallic composite [16] were also observed. Moreover, small cracks have been found to exist in front of the crack tip in the joints both with gap filler and without gap filler (Fig. 10c, d). This indicates that the addition of gap filler did not change the mechanism of fatigue crack growth.

Fig. 11 shows the relationship between load and back face strain where deviations from linearity, referred to as the crack closure, can be observed. This is analogous to behaviour in metals [17] where such closure involves premature contact between the crack surfaces during unloading, so that the effective stress intensity amplitude is reduced. The closure load, P_{cl}, was determined at the highest load where the load–back face strain curve deviates from linearity. The present study shows that P_{cl} decreases as the brazing

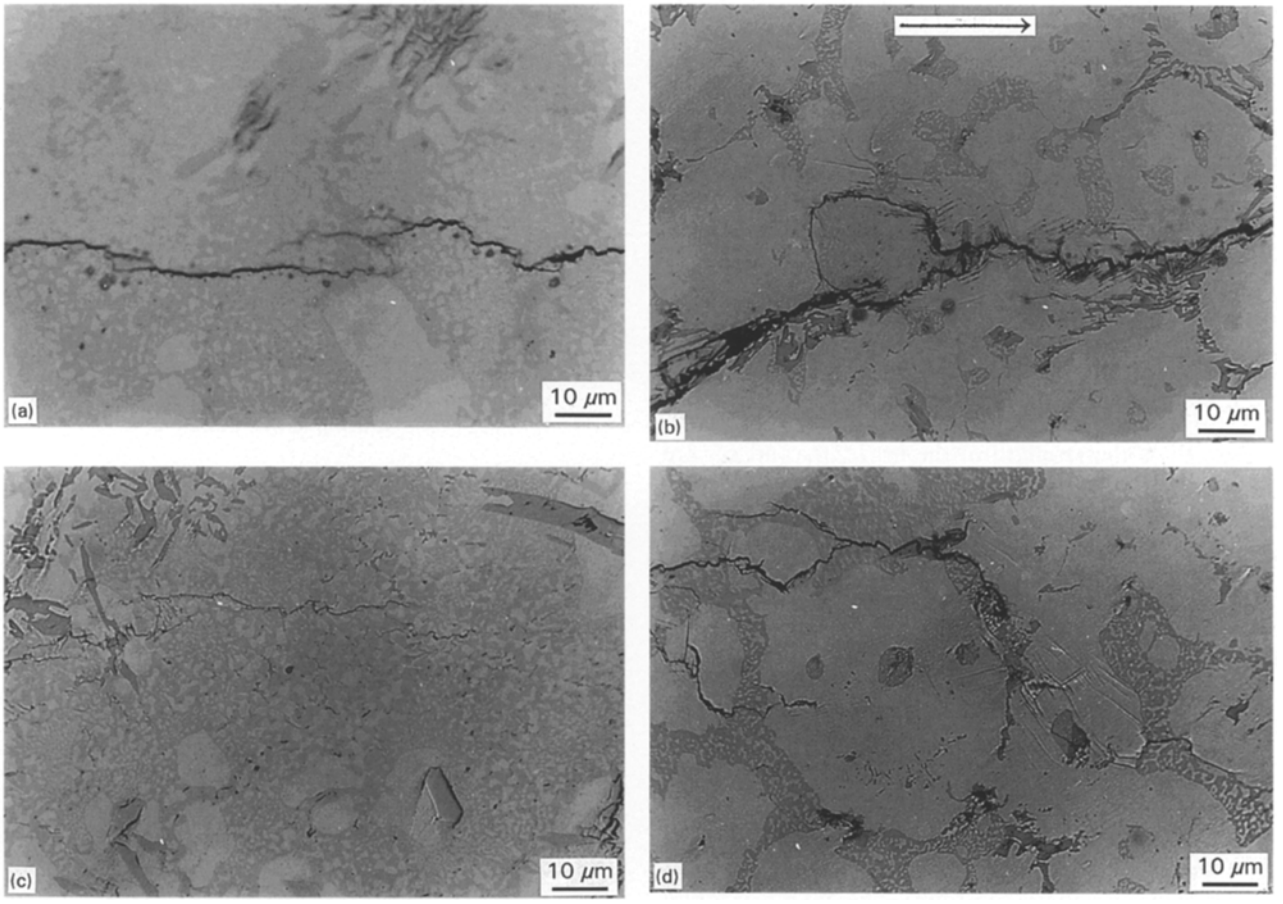

Figure 10 Fatigue crack characteristic morphologies in brazed joints: (a) Nicrobraz no. 150 only, brazing temperature 1150 °C; (b) Nicrobraz + 40% gap filler, brazing temperature 1200 °C; (c) Nicrobraz no. 150, brazing temperature 1150 °C (crack tip); (d) Nicrobraz + 40% gap filler, brazing temperature 1200 °C (crack tip).

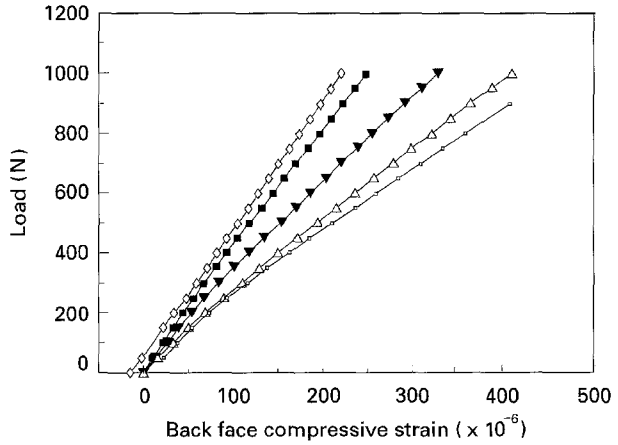

Figure 11 Load–back face strain curves for closure force determination. Gap filler/brazing temperatures: (□) 0%/1150 °C, (◇) 0%/1200 °C, (△) 20%/1150 °C, (■) 20%/1200 °C, (▼) 40%/1200 °C.

temperature increases and gap filler content decreases. Previous work of the authors [9] showed that fatigue crack closure in the joints brazed with nickel-based filler metals are mainly caused by roughness and ligament bridging. When gap filler was applied, the fatigue crack often goes by the gap filler powder resulting in more meandering along the crack paths. Moreover, gap filler also enhances tough phase bridging. Consequently, the addition of gap filler was able to increase the crack closure force.

4. Conclusions

1. Stainless steel wide-gap joints brazed with nickel-based filler metals are generally very brittle. As brazing temperature increases, eutectic structure decreases and solid solution increases. The strength, ductility as well as fatigue resistance of the brazed joints have been observed to increase correspondingly.

2. The strength of the joint brazed with addition of gap filler is attributed to three parts: matrix, gap filler and the interaction between the two, which are all functions of brazing temperature. If the brazing temperature is not high enough, the negative effect due to the unfilled spaces between solids surpasses the beneficial effect due to diffusion and precipitation of boron. This lowers the strength of the brazed joint even though gap filler was added. The addition of gap filler can improve the strength and ductility of the joint only when the brazing temperature employed is high enough.

3. Fatigue crack growth in the brazed joint was achieved by means of small crack initiation in front of the crack tip and merging with the main crack for the joints brazed both with and without gap filler.

4. The addition of gap filler can increase the extent of crack meandering which increases the crack closure load and hence retards crack growth. As long as a suitable brazing temperature was used, fatigue crack propagation resistance can be improved by the addition of gap filler.

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