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Diffusion bonding of investment cast γ-TiAl

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Intensive alloy development studies on intermetallic gamma (γ) based alloys in recent years has led to the development of several aerospace engine components using advanced γ-TiAl based alloys by ingot and powder metallurgical routes. These materials are of great interest to the aerospace industry owing to their very low density and good high temperature properties. Further application of this material will require the development of successful joining and cost effective fabrication methods. Joining of this intermetallic alloy by fusion joining processes, however, requires very careful process controlling, i.e. low cooling rates and very high preheat temperatures. On the other hand, solid state joining processes, particularly diffusion bonding, brazing, and friction welding, can readily be used to join this material. In the present work, successful application of solid state diffusion bonding to weld investment cast γ-TiAl alloys has been demonstrated. A series of diffusion bonds were produced without using an interlayer at temperatures ranging from 950 to 1100 °C with different pressure levels and holding times. Bonds have been characterized using optical and scanning electron microscopy. Defect-free bonds were achieved for all the conditions studied. The bond qualities were assessed by shear testing at room temperature. Reasonable shear strength levels were obtained by bonding at 1000 and 1100 °C for 3 h at pressures of 20 and 40 MPa, respectively. The bonds were also post bond heat treated at 1430 °C for 30 min, which improved the bond quality in all cases.

1. Introduction

Advanced gamma titanium aluminides are one of the most promosing intermetallic alloys for high temperature applications owing to their low density (3.7–3.9 g/cm^3), good oxidation and burn resistance, high modulus of elasticity, and high-temperature strength retention [1–4]. Although TiAl has very limited ductility at ambient temperature, it is possible to process this material at elevated temperatures, e.g. by extruding, forging or rolling. Recent studies have shown that fine-grained TiAl is superplastic at about 1000 °C [5–11], the maximum elongation reported being 540% at 1280 °C [11].

Sound joining of these alloys to themselves and to other high temperature materials is one of the keys to their successful integration into high temperature aerospace applications. To date, only a few studies have been published on fusion welding of this material. Fusion welding of this material can only be implemented with strict control of the welding process. Preheating between 700–800 °C is required to avoid solidification cracking which is encountered due to the limited ductility of gamma alloys at room temperature. Patterson *et al*. [12] have reported that a cooling rate of less than 300 °C/s is necessary to prevent cracking in electron beam welding of gamma alloys. Solid state welding (e.g. diffusion bonding, DB) has been proven to be more successful in joining gamma alloys. Several researchers [13–17] have demonstrated that defect free joints in gamma alloys can be produced by bonding at 975–1200 °C depending on the bonding pressure and time. However, most of these studies were carried out on cast gamma alloys. Another solid state joining process for gamma alloys is friction welding. Threadgill [18] has successfully demonstrated the possibility of achieving sound linear friction welds in these alloys. Moreover, the superplastic forming and diffusion bonding (SPF/DB) process is a very promising method of producing hollow aerospace engine or stationary gas turbine blades using this intermetallic material in the rolled plate condition. However, cast gamma alloys are less promising in this respect.

In the present study, investment cast γ-TiAl alloy with a thickness of ∼2 mm was diffusion bonded with different bonding parameters. The main aim of this work is to investigate the possibility of producing sound diffusion bonds in cast TiAl and the effect of post bond heat treatment (PBHT) on bond quality.

2. Experimental

The material used in this study was an investment cast gamma alloy with a chemical composition of Ti-47 at% Al-4.5 at% (Cr, Mn, Nb, Si, B), denoted as γ-TAB alloy. It was received as cast blocks of 100 × 100 × 40 mm. 2 mm thick sheets were sliced from these blocks and homogenized to minimize the scatter in mechanical properties of this cast material [17]. The homogenization was conducted by heat treating the material at 1300 °C for 10 h followed by slow cooling to 1000 °C, holding for 10 h at this temperature and furnace cooling. A series of diffusion bonds were produced using these sheets at temperatures between 950–1100 °C with a bonding pressure of 20–40 MPa and bonding times of 1 to 3 h. All bonds were produced under a vacuum of less than 4.5×10^{-5} torr (6.0×10^{-5} mbar). The test matrix is given in Table I.

The surfaces of the sheets were ground using 1200 grade SiC paper prior to bonding, which is considered to give optimum surface quality to achieve sound bonds in this material [16, 17]. Fig. 1 schematically shows the production of overlap joints. A second set of the bonds were post-bond heat treated at 1430 °C for 30 min. The reason for this heat treatment was to modify the as-cast duplex microstructure to a fully lamellar structure (exhibiting better fracture toughness). It was anticipated that this might also have a beneficial influence on bond quality.

TABLE I Test matrix

	Bonding parameters			
Test number	Temperature *T* (°C)	Pressure *P* (MPa)	Time *t* (h)	PBHT (1430 °C/30 min)
1-1	950	30	3	Without PBHT
1-2	950	30	3	With PBHT
2-1	1000	30	1	Without PBHT
2-2	1000	30	1	With PBHT
3-1	1000	30	3	Without PBHT
3-2	1000	30	3	With PBHT
4-1	1000	40	3	Without PBHT
4-2	1000	40	3	With PBHT
5-1	1100	20	3	Without PBHT
5-2	1100	20	3	With PBHT

Optical microscopy was used to investigate the microstructural development during bonding and to assess the quality of the bonds produced using various bonding parameters given in Table II. Non-standard shear specimens of 8 mm long and 5 mm width (bond area) were machined from overlap joints with and without PBHT and tested at room temperature at a loading rate of 0.25 mm/min to determine the shear strengths of the bonds, Fig. 2.

3. Results and discussion

3.1. Metallographic observations

The starting material used in the present study had a duplex microstructure (near lamellar) consisting of lamellar grains of alternating α_2 (Ti_3Al) and γ (TiAl) strips and some globular gamma grains, Fig. 3.

The bonds produced at 950 °C/30 MPa/3 h and 1000 °C/30 MPa/1 h exhibited no unbonded areas (defect-free), but the bond interfaces are clearly visible, Fig. 3a and b, respectively. Recrystallized gamma grains formed during bonding at the bond interface were very fine indicating that the bonding time was not long enough to allow sufficient diffusion across the bond interface from the mating surfaces. The formation of these equiaxed gamma grains at the original bond interface is due to asperity deformation on mating surfaces under the applied bonding pressure [16, 17].

Defect-free bonds were also produced at 1000 °C/30 MPa/3 h and 1000 °C/40 MPa/3 h, Fig. 3c and d, respectively. The recrystallized gamma grains formed at the interfaces were still fine and rendered the bond interface distinguishable.

Increasing bond temperature gives rise to an increase in the diffusion coefficient and thus the atoms move more readily, leading to formation of larger grains at the bond interface. Hence, defect-free bonds with an almost invisible bond interface due to large grain size of

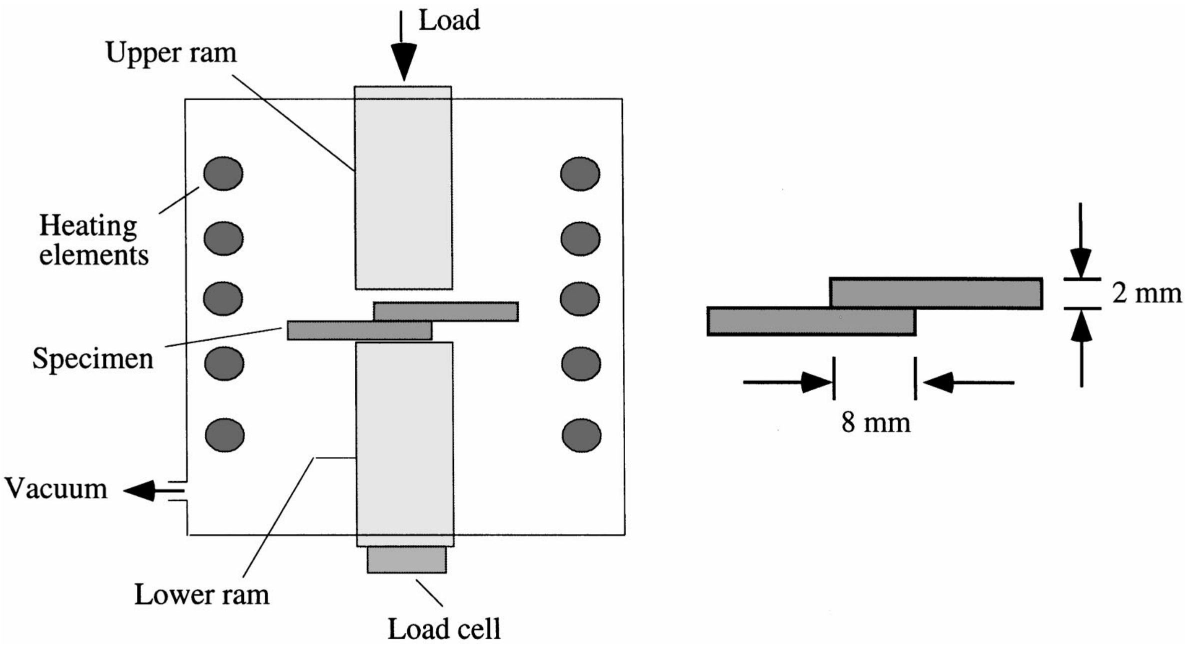

Figure 1 Experimental setup for the production of overlap joints (weld length = 25 mm from which 4 shear specimens with a width of 5 mm extracted).

TABLE II Bonding conditions and results of compression overlap shear tests

Test number	Bonding parameters	Shear strength (MPa)*	Fracture location
1-1	$T = 950\,^{\circ}$C, $P = 30$ MPa, $t = 3$ h Without PBHT	164,293 259,269	50% Along bond interface
1-2	$T = 950\,^{\circ}$C, $P = 30$ MPa, $t = 3$ h PBHT (1430 °C/30 min)	392,396 373,375	In base metal
2-1	$T = 1000\,^{\circ}$C, $P = 30$ MPa, $t = 1$ h Without PBHT	48,31 351,141	Predominantly at bond interface
2-2	$T = 1000\,^{\circ}$C, $P = 30$ MPa, $t = 1$ h PBHT (1430 °C/30 min)	371,416 441,439	In base metal
3-1	$T = 1000\,^{\circ}$C, $P = 30$ MPa, $t = 3$ h Without PBHT	165,326 207,352	50% Along bond interface
3-2	$T = 1000\,^{\circ}$C, $P = 30$ MPa, $t = 3$ h PBHT (1430 °C/30 min)	453,449 418,443	In base metal
4-1	$T = 1000\,^{\circ}$C, $P = 40$ MPa, $t = 3$ h Without PBHT	308,343 334	In base metal
4-2	$T = 1000\,^{\circ}$C, $P = 40$ MPa, $t = 3$ h PBHT (1430 °C/30 min)	466,442 397,420	In base metal
5-1	$T = 1100\,^{\circ}$C, $P = 20$ MPa, $t = 3$ h Without PBHT	262,323 373,339	In base metal
5-2	$T = 1100\,^{\circ}$C, $P = 20$ MPa, $t = 3$ h PBHT (1430 °C/30 min)	439,459 441,449	In base metal

*At least three specimens were tested for each condition.

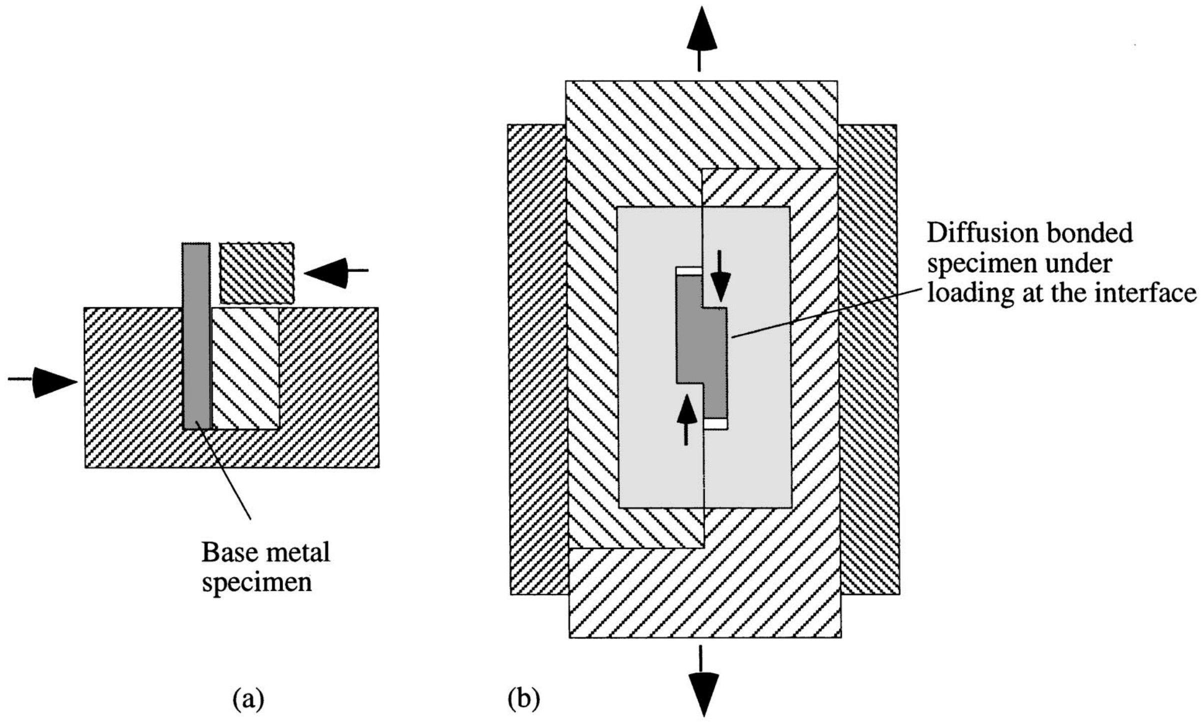

Figure 2 Shear testing of: (a) base metal and (b) overlap specimens.

the recrystallized gamma which formed were produced at 1100 °C/20 MPa/3 h, Fig. 3e.

A fully lamellar structure was obtained in all the bonds after the PBHT. Furthermore, the PBHT improved the bond quality due to higher interdiffusion at 1430 °C, making the bond interface invisible even in the case of the bonds made with a combination of low temperature and bonding time, Fig. 4.

3.2. Single overlap shear tests

Compression overlap shear tests were carried out on all the bonds produced to assess their integrity. Table II summarizes the results of shear tests. Optical metallography was also conducted on the bonds after shear testing to examine the fracture process and to determine the fracture locations. These observations are also summarized in Table II. It should be pointed out that in the case of fracture taking place in base material, the results do not represent intrinsic shear strengths of the bonds but indicate reasonably strong bonds.

Base material exhibited a shear strength of 430 MPa in the homogenized condition. This was also given the same PBHT to determine the effect on shear strength. It was found out that the PBHT increased the shear strength of base material from 430 to 475 MPa due to the change in the microstructure from a duplex to fully lamellar structure.

Bonds made at 950 °C/30 MPa/3 h, 1000 °C/30 MPa/1 h, and 1000 °C/30 MPa/3 h failed predominantly

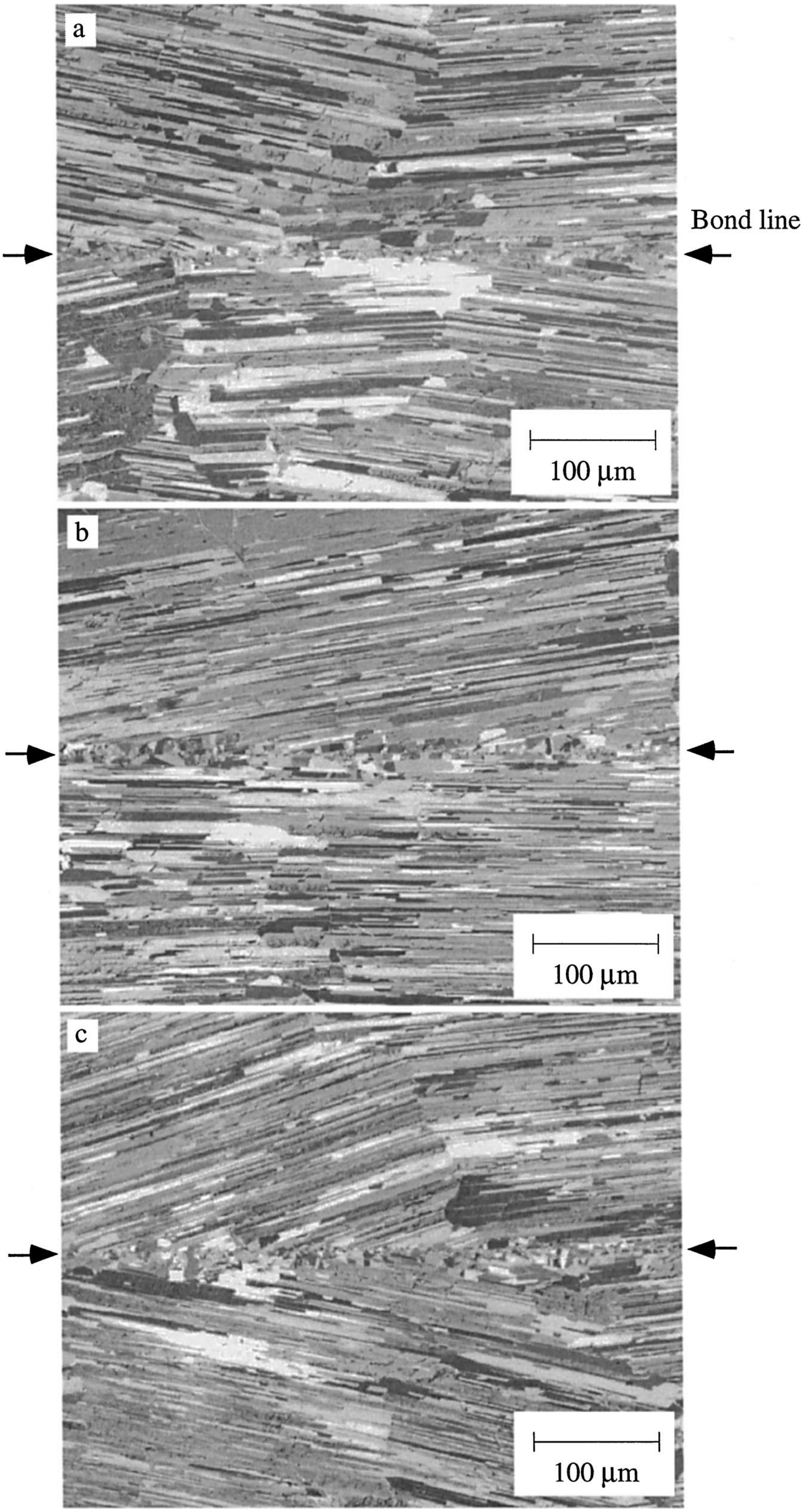

Figure 3 Microstructure development in the bonds produced with the parameters: (a) 950 °C, 30 MPa, 3 h, (b) 1000 °C, 30 MPa, 1 h, (c) 1000 °C, 30 MPa, 3 h, (d) 1000 °C, 40 MPa, 3 h, (e) 1100 °C, 20 MPa, 3 h. (Arrows indicate the original bond interface). (*Continued*)

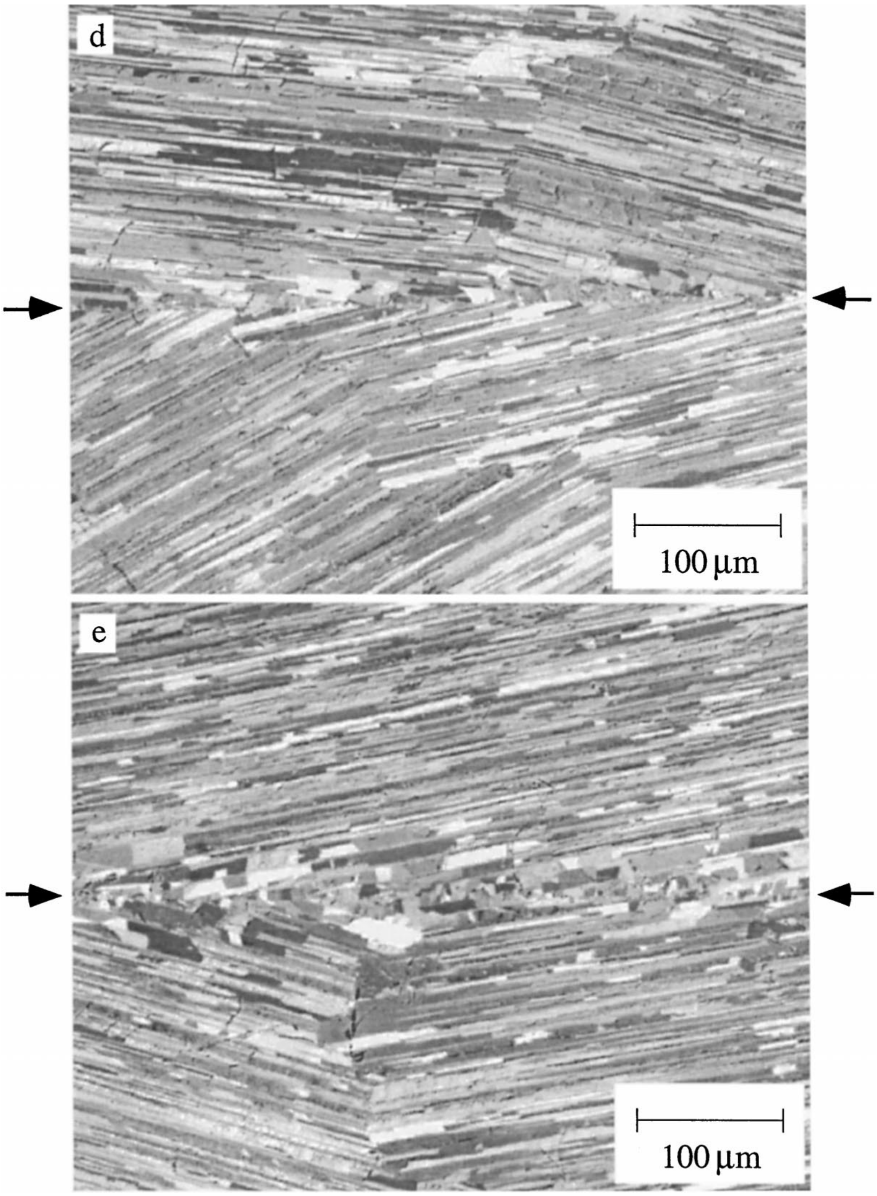

Figure 3 (*Continued*).

along the bond interface, Table II, and thus exhibited lower shear strength values, Fig. 5, owing to non-optimized bonding conditions, i.e. low temperature, low pressure or insufficient time. This was expected due to the presence of visible bond interfaces (fine recrystallized gamma grains) making the bond region a preferable crack path in these bonds as shown in Fig. 3. Fig. 6 shows a shear test specimen which failed predominantly along the bond interface. The bonds made at 1000 °C/40 MPa/3 h and 1100 °C/20 MPa/3 h, on the other hand, failed predominantly in base material away from the bond interface, which clearly indicates that the bonds are stronger. The highest shear strength value in the as-bonded condition was 373 MPa. This was still lower than that of the base material, i.e. 430 MPa, and was achieved with the bonding parameters of 1100 °C/20 MPa/3 h. As expected this bond displayed an almost invisible bond interface. This can be explained by the fact that as the recrystallized gamma grains grow across the bond interface the crack growth through these grains becomes harder in contrast to the bonds with very fine gamma grains at the interface where the crack propagates in a planar fashion through the grains. The results of fractography support this fact. Fracture surfaces of the bonds failing along the bond interface are very smooth in the case of the bonds containing very fine gamma grains at the bond interface whereas the bonds with coarser gamma grains at the interface exhibited a much rougher fracture surfaces, Fig. 7. As seen from Fig. 5, it can also be concluded that an increase in bonding temperature, pressure or time for a given set of other parameters increases the shear strength of the bond produced.

After the PBHT, all the bonds failed in the base material, Fig. 8, indicating that the bond quality was improved significantly even in the bonds produced with non-optimized parameters, Table II. Shear strength values equal to that of base material were obtained after PBHT. The increase in shear strength after PBHT was more significant in the case of weaker bonds, Fig. 5.

From a combination of optical metallography and compressive overlap shear testing, it was concluded that

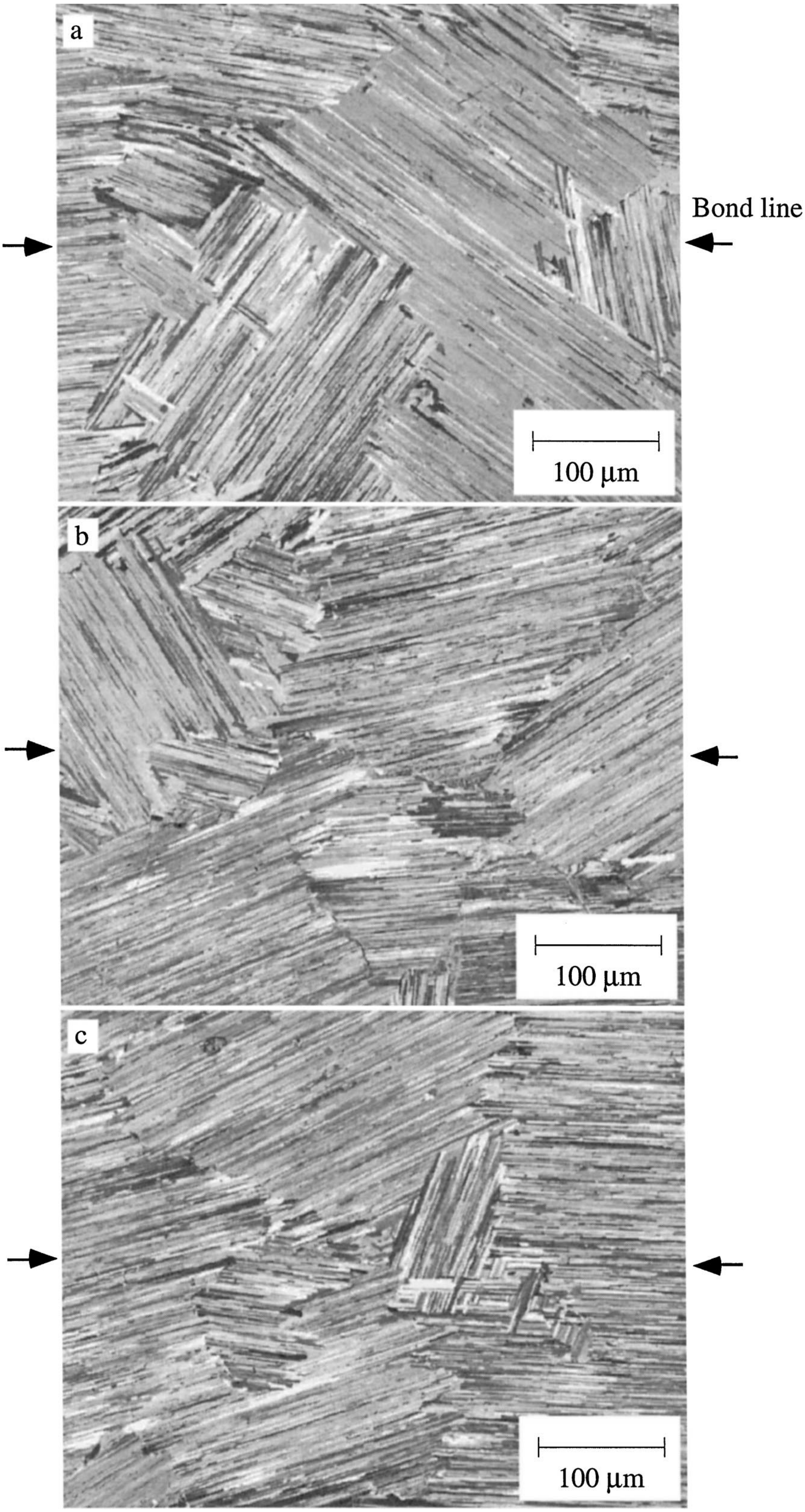

Figure 4 Microstructural development after PBHT (1430 °C/30 min) in the bonds produced with the parameters: (a) 950 °C, 30 MPa, 3 h, (b) 1000 °C, 30 MPa, 1 h, (c) 1000 °C, 30 MPa, 3 h, (d) 1000 °C, 40 MPa, 3 h, (e) 1100 °C, 20 MPa, 3 h. (Arrows indicate the original bond interface). (*Continued*)

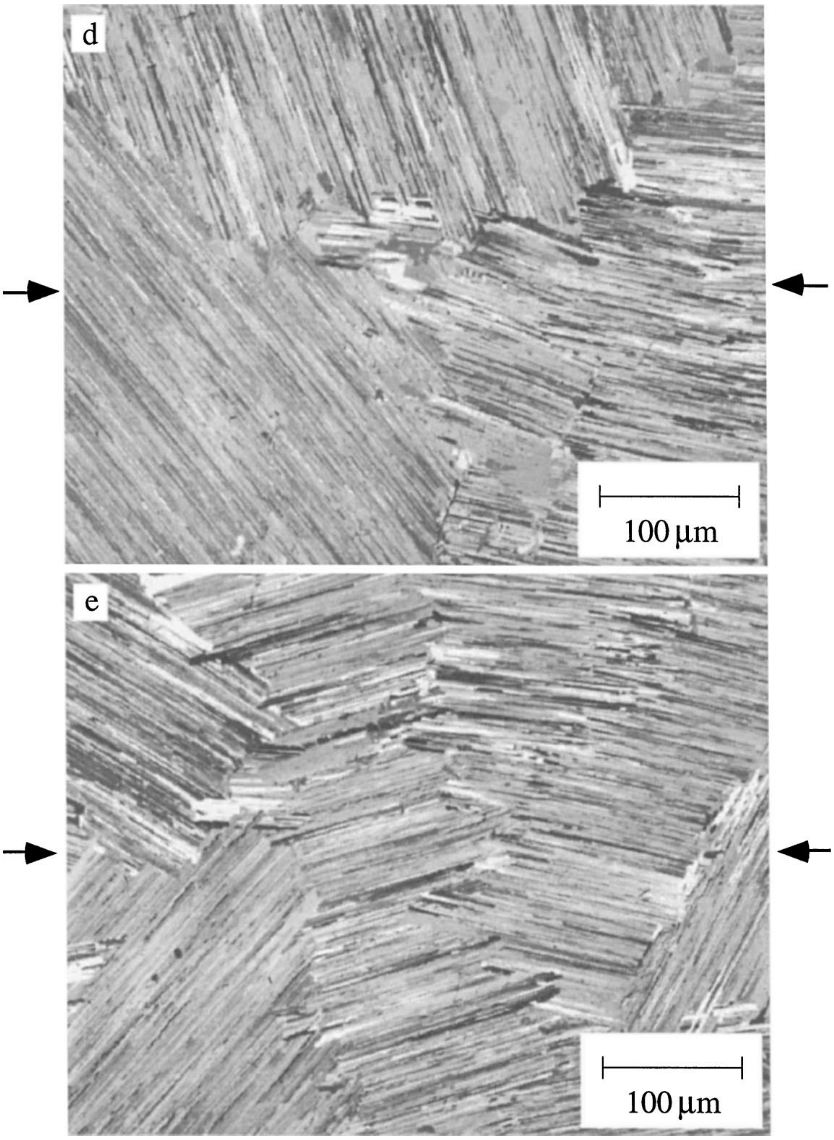

Figure 4 (*Continued*).

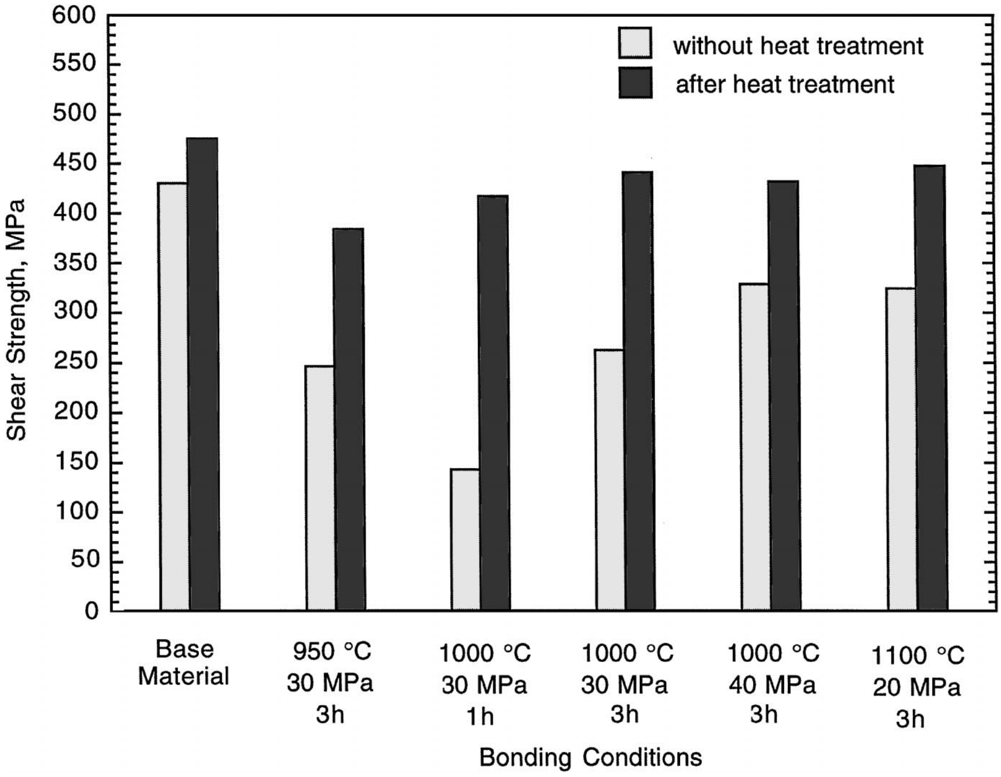

Figure 5 Shear strengths of the base material and the bonds produced with different bond parameters with and without PBHT.

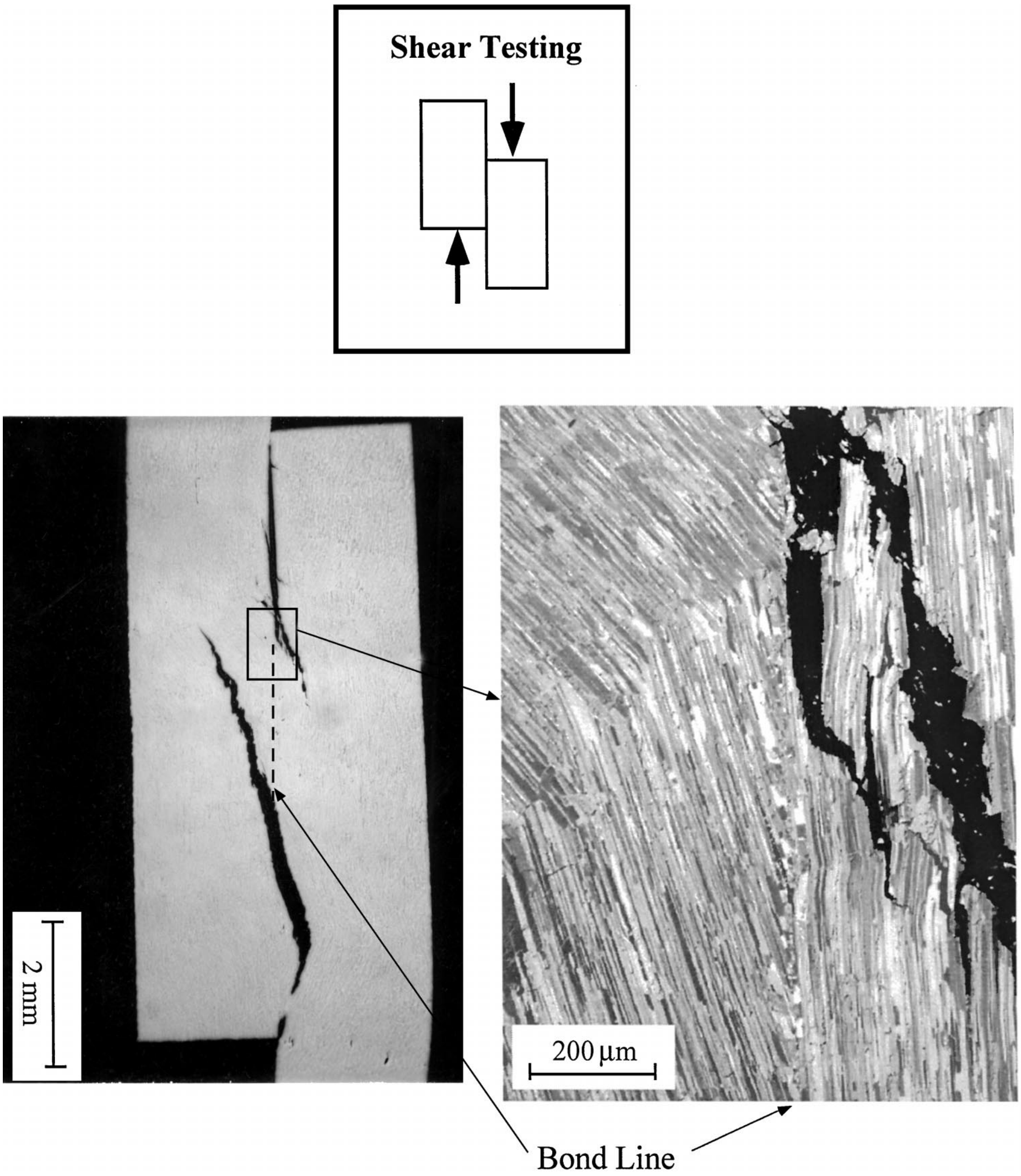

Figure 6 Compression overlap shear testing of the bond produced at 950 °C/30 MPa/3 h: failure initiated at the interface and remained predominantly along the bond line.

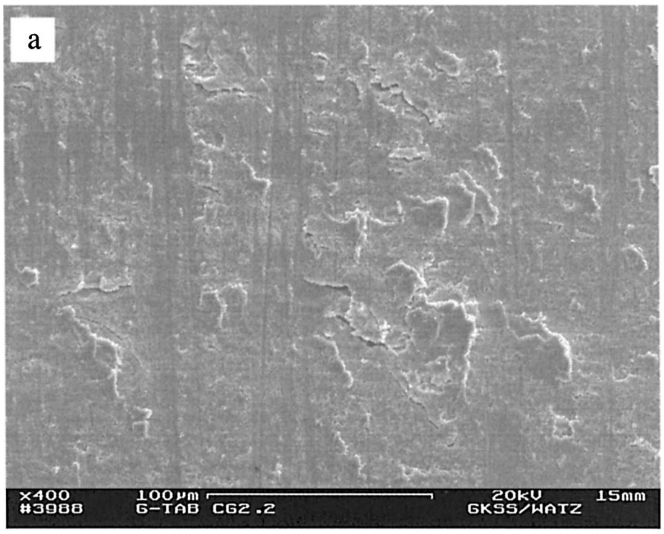

Figure 7 Fracture surfaces of the bonds failing along the bond line: (a) the bond produced at 1000 °C/30 MPa/1 h, note predominantly intergranular fracture of gamma grains recrystallized along the bond line during bonding and unbonded areas with grinding lines and (b) the bond produced at 1100 °C/20 MPa/3 h, predominantly intergranular fracture of gamma grains and no indication of unbonded areas. (*Continued*)

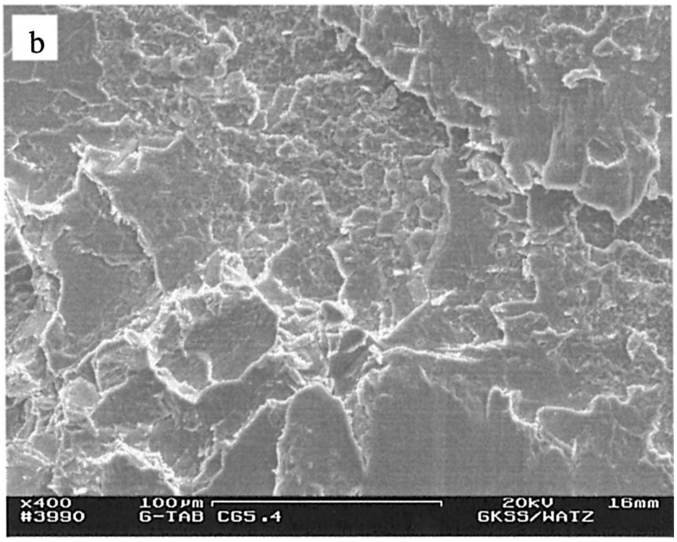

Figure 7 (*Continued*).

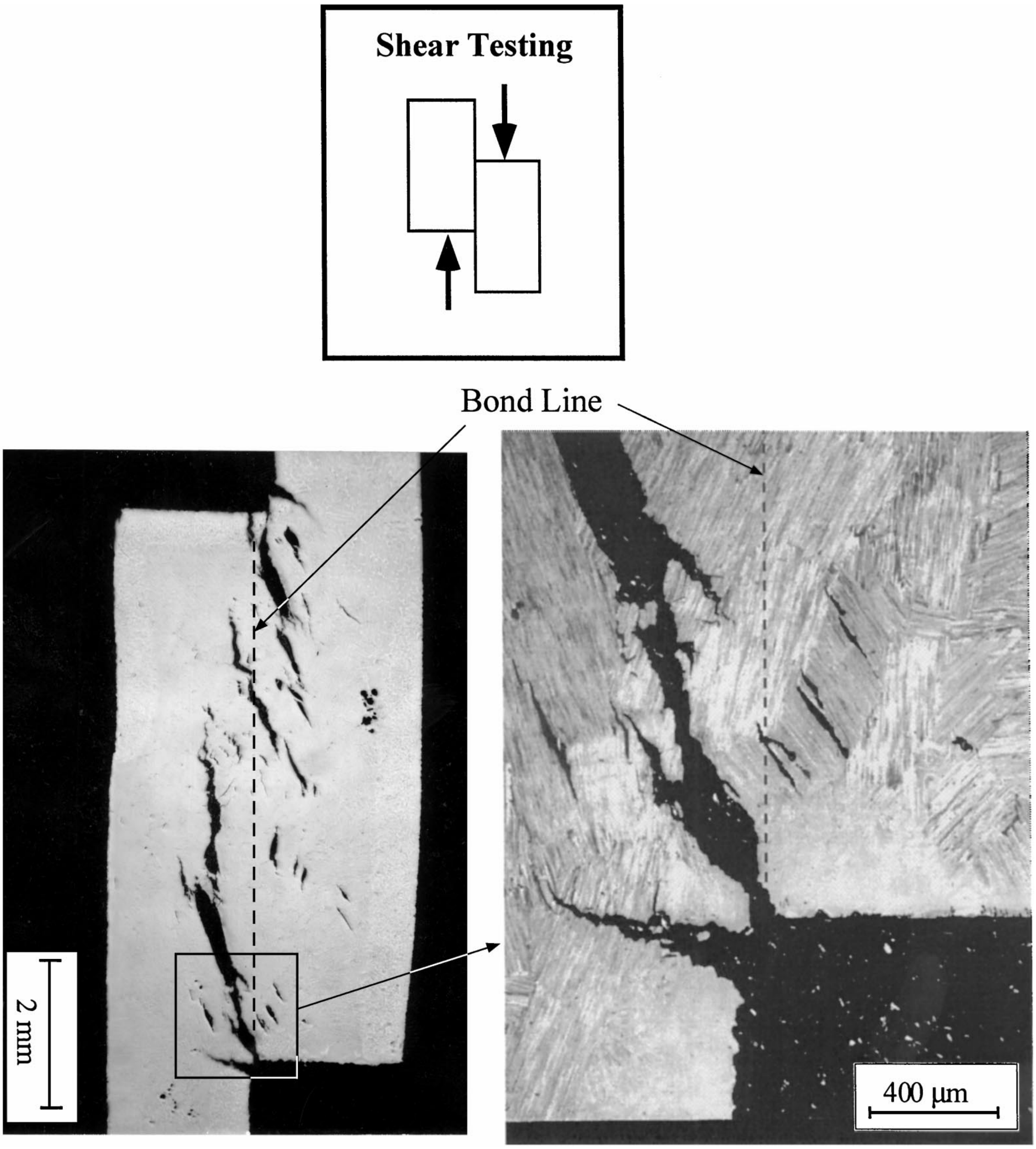

Figure 8 Compression overlap shear testing of a bond produced with non-optimized parameters (1000 °C/30 MPa/1 h) after PBHT (1430 °C for 30 min). It is worth pointing out the improvement of the bond quality after PBHT (invisible bond interface) even in a bond produced with non-optimized parameters leading to failure in base material with multiple fracture locations (note intact bond interface).

sound bonds can be obtained in investment cast gamma alloy. However, the shear strength of the joints is lower than that of the base material. PBHT improves the bond quality even for bonds produced with non-optimized parameters and shear strength values similar to that of base material can be achieved.

4. Conclusions

The following conclusions have been drawn:

- All the bonds produced exhibited no defects, i.e. unbonded areas or pores, but in the bonds produced with non-optimal conditions the bond line was visible.
- Recrystallized gamma grains were formed in all the cases due to asperity deformation at the bond interface under the applied pressure. The size of these grains rises with an increase in bonding temperature and time. The growth of recrystallized gamma grains at the bond interface makes the bond line invisible, thus increasing bond interface quality.
- An increase in bonding temperature, pressure or time for a given set of other parameters increases the bond quality. Bonds in the as-bonded condition exhibited lower shear strength than the base material.
- PBHT made the bond interface invisible and improved bond quality significantly in all cases. The improvement in shear strength by PBHT is more pronounced for non-optimal bonds. Base metal shear strength levels have been achieved in bonds by PBHT.

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