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Laser-beam welding of SiC fibre-reinforced Ti–6Al–4V composite

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Three- and ten-ply SiC fibre-reinforced Ti–6Al–4V composites were joined using a laser beam. With a 300 μm thick Ti–6Al–4V filler metal, fully penetrated welds without apparent fibre damage, could be obtained in welding directions both parallel and transverse to the fibre direction by controlling the welding heat input. Excess heat input resulted in the decomposition of SiC and subsequent TiC formation, and also caused degradation of joint strength. The welding of the three-ply composite in which full penetration was achieved at lower laser power, exhibited higher flexibility in heat input than that of the ten-ply composite. Heat treatment at 1173 K after welding improved the joint strength because of the homogenization of the weld metal and decomposition of TiC. The strengths of the transverse weld joints after the heat treatment were approximately 650 and 550 MPa for the three- and ten-ply composites, respectively. With the welding direction parallel to the fibre direction, the strengths both parallel and transverse to the weld joint were equivalent to those of the base plate.

1. Introduction

The high strength-to-weight ratio and the superior high-temperature properties of metal matrix composites (MMCs) make them attractive materials for aerospace structures and gas turbine engines. Among MMCs, mainly aluminium alloy-based and titanium alloy-based composites have been developed [1, 2]. Continuous fibre-reinforced titanium alloy-based composites are more attractive than aluminium alloy-based composites for high-temperature applications [3].

To make practical complex engineering components from such MMCs, a technique for joining MMCs to each other and to monolithic materials is a key technology. In the past, fusion welding [4], diffusion bonding [5] and brazing [6] have been applied to the joining of aluminium alloy matrix composites. However, successful joining has not yet been reported. In titanium alloy-based composites, few works have been reported concerning their joining. Although in the joining of MMCs several joining processes, such as those mentioned above, should be investigated, of them fusion welding has the greatest flexibility in joint types. From an engineering viewpoint, therefore, it is important to study the feasibility of fusion welding.

In the welding of MMCs, the fusion zone and heat-affected zone should be minimized to avoid degradation of mechanical properties due to fibre–matrix reaction at elevated temperature. From this point of view, laser-beam welding seems to be the most feasible fusion welding process, because the laser beam can provide a controllable heat source with high energy density. In the present work, the applicability of laser-beam welding to SiC fibre-reinforced Ti–6Al–4V composites has been investigated.

2. Experimental procedure

2.1. Materials

The composite materials used in this work were three- and ten-ply continuous SiC fibre-reinforced Ti–6Al–4V composites (denoted 3-ply and 10-ply composites, respectively). SiC fibres (SCS6: Textron Inc., 140 μm diameter with 35 μm carbon core) made by chemical vapour deposition and 80 μm thick Ti–6Al–4V foils were stacked alternately and consolidated by hot pressing under a vacuum of 2.0×10^{-3} Pa, using a holding temperature of 1173 K, an applied uniaxial pressure of 73.5 MPa and a holding time of 3.6 ks. The volume fractions of fibres for the 3-ply and 10-ply composites were approximately 42% and 45%, respectively. Typical mechanical properties at room temperature for the 10-ply composite are shown in Table I. The tensile strength exhibited approximately 90% of the rule of mixture (ROM) strength, calculated from the matrix strength of 988 MPa and the mean fibre strength of 4964 MPa.

TABLE I Mechanical properties of 10-ply SiC/Ti–6Al–4V composite

Ultimate tensile strength (MPa)	Young's modulus (GPa)
2462	214

0022–2461

2.2. Laser-beam welding

Welding was carried out using a Mitsubishi 2.5 kW CO_2 laser. In the preliminary stage, interactions between laser beam and the composites were investigated on bead-on-plate welding. Laser-beam irradiations were performed on the 10-ply composite specimens, 20 mm wide by 80 mm long, transverse to the fibre direction with varying process parameters, i.e. a focal position of -1 mm to $+3$ mm, a laser power of 0.3–1.5 kW and a travel speed of 8.33–50.0 mm s^{-1}, using a continuous wave single-mode beam.

A cross-section of a weld bead in a low heat input condition is shown in Fig. 1. SiC fibres in the fusion zone were melted and sublimated, and many cracks were introduced in it. Brittle phases such as titanium silicides and titanium carbides were identified in the weld metal by electron probe microanalysis (EPMA). The formation of the brittle phases seems to be caused by reactions of titanium with silicon and carbon produced by a decomposition of SiC. Under higher heat input conditions, cracks were introduced more severely and the welded zone was completely fractured. As a result, it was impossible to weld the composite directly with an irradiating laser beam.

A 300 μm thick Ti–6Al–4V filler metal, therefore, was inserted between 20 mm by 20 mm composite sheets and the laser beam was scanned on the filler metal, as shown in Fig. 2. The welding directions were both parallel and transverse to the fibre direction. The weld was made in a shielding box whose atmosphere was displaced by argon gas. The welding conditions for the 3-ply and the 10-ply composite specimens are summarized in Table II. After welding, the 3-ply specimens welded with a laser power of 0.72 kW and the 10-ply specimens welded with a power of 0.96 kW were heat treated at 1173 K for 3.6 and 14.4 ks under a vacuum of 1.3×10^{-3} Pa.

The microstructures of the welded zone were investigated by optical microscopy, scanning electron microscopy (SEM), EPMA and transmission electron microscopy (TEM).

2.3. Tensile testing

Tensile tests were performed on an Instron-type testing machine at room temperature, using a crosshead speed of 8.33×10^{-3} mm s^{-1}. Tensile specimens, as shown in Fig. 3, were cut from the welded plates. The

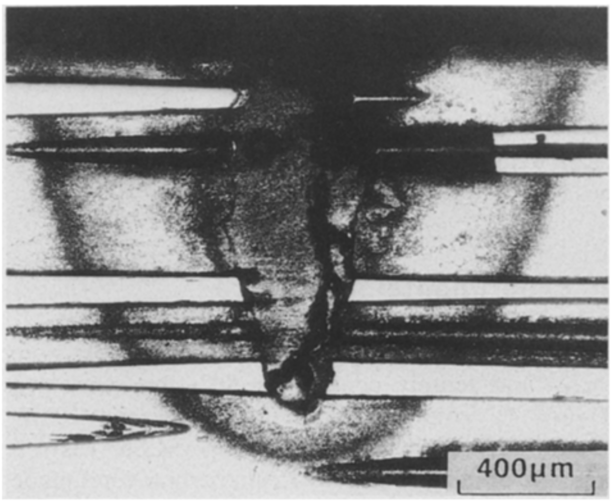


Figure 1 Cross-section of bead-on-plate weld.

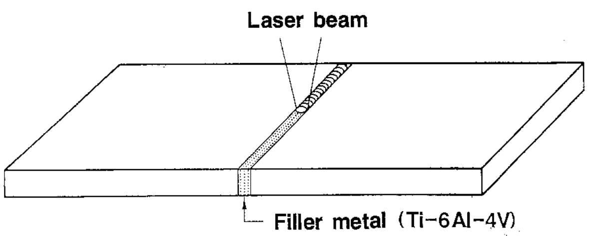


Figure 2 Schematic illustration of the laser-beam welding procedure.

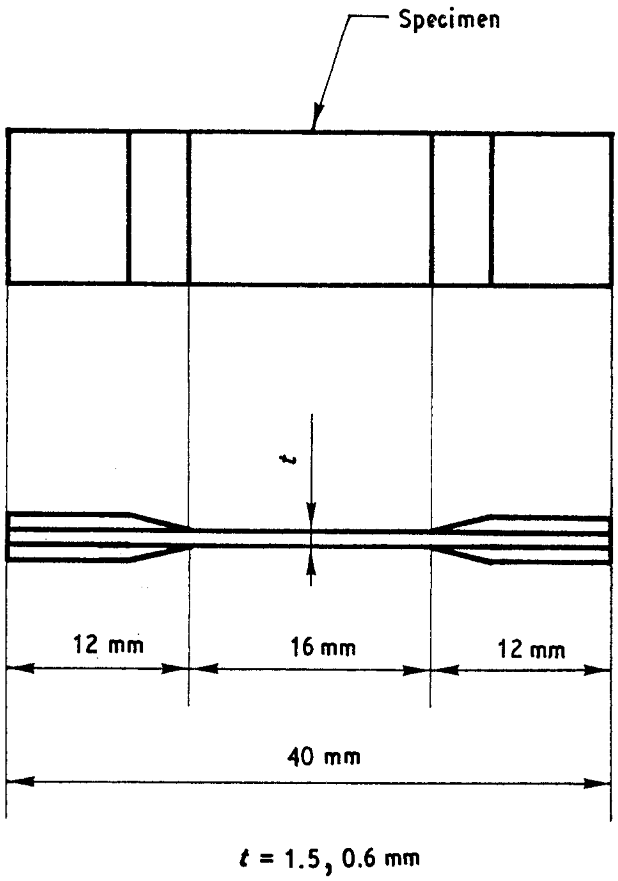


Figure 3 The shape of the tensile specimen.

TABLE II Laser welding conditions

	Average laser power (kW)	Focal position from surface (mm)
3-ply composite	0.64, 0.72, 0.80, 0.88, 0.96	±0
10-ply composite	0.88, 0.96, 1.04	−0.5

Beam mode, single mode; pulse frequency, 300 Hz; duty ratio, 80%; welding speed, 83.3 m ks^{-1}.

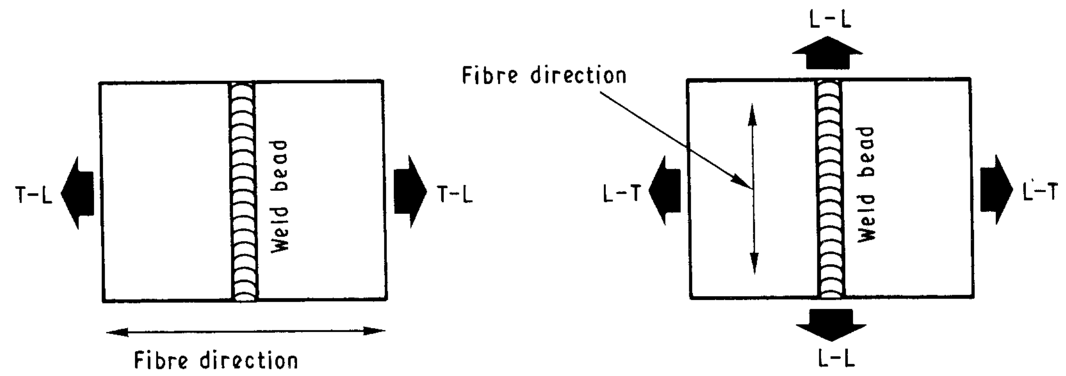


Figure 4 Relations between the specimen axis and fibre direction.

relationships between the specimen axis and the fibre direction are shown in Fig. 4. The tensile specimens of transverse weld with the axis parallel to the fibre direction, and those of longitudinal weld with the axes parallel and transverse to the fibre direction are denoted T–L, L–L and L–T specimens, respectively.

3. Results and discussion

3.1. Transverse welding

Figs 5 and 6 show the cross-sectional structures of transverse welds of the 3-ply and 10-ply composites, respectively. No apparent damage to SiC fibres nor cracks were observed in the fusion zones. It is obvious that the filler metal was effective in preventing damage of the fibres due to laser irradiation.

The tensile strengths of the weld joints are shown in Table III. One or two specimens were tested for each welding condition. The maximum strengths were obtained at laser powers of 0.72 and 0.96 kW for the 3-ply and 10-ply composites, respectively.

In both composites, the filler metal was not melted completely and an unbonded part existed at the bottom of the weld joint at the lowest laser power because

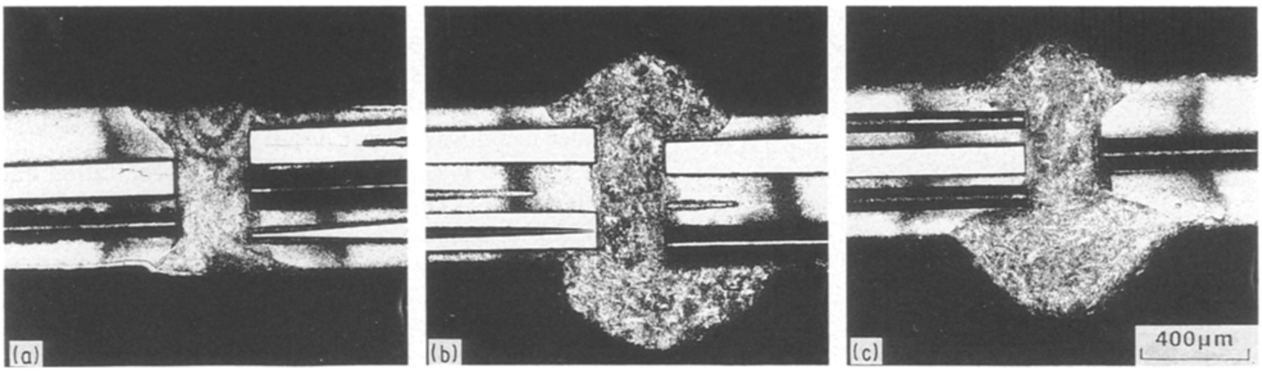


Figure 5 Cross-sections of the laser-beam weld in a 3-ply SiC/Ti–6Al–4V composite. Average laser power: (a) 0.72 kW, (b) 0.88 kW, (c) 0.96 kW.

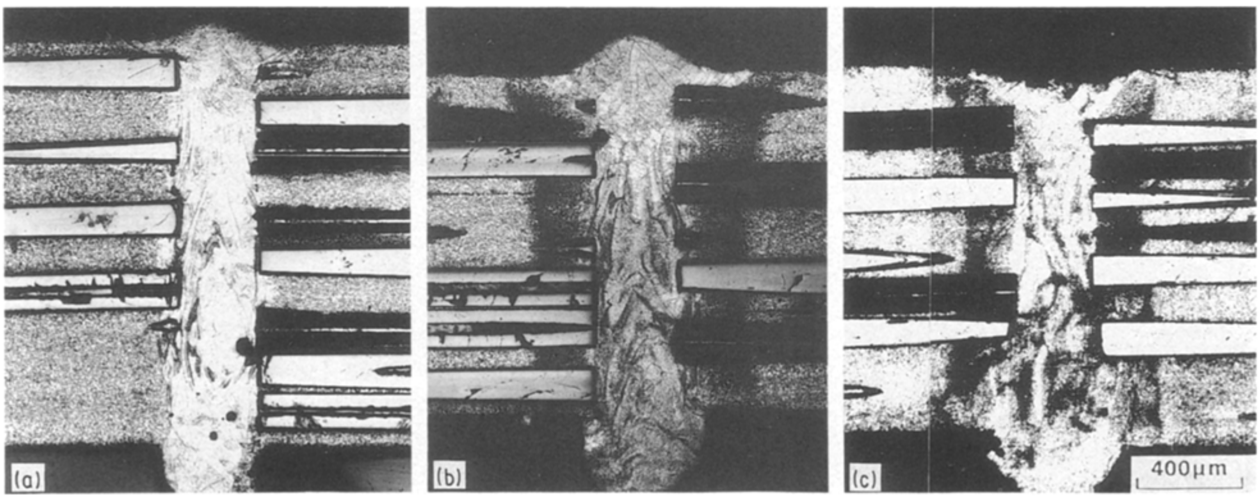


Figure 6 Cross-sections of a laser-beam weld in 10-ply SiC/Ti–6Al–4V composite. Average laser power: (a) 0.88 kW, (b) 0.96 kW, (c) 1.04 kW.

TABLE III Results of the tensile test for transverse laser weld joints

Average laser power (kW)	Ultimate tensile strength (MPa)	
	3-ply composite	10-ply composite
0.64	238	–
0.72	592, 662	–
0.80	549	–
0.88	517	173
0.96	526	403, 523
1.04	–	66

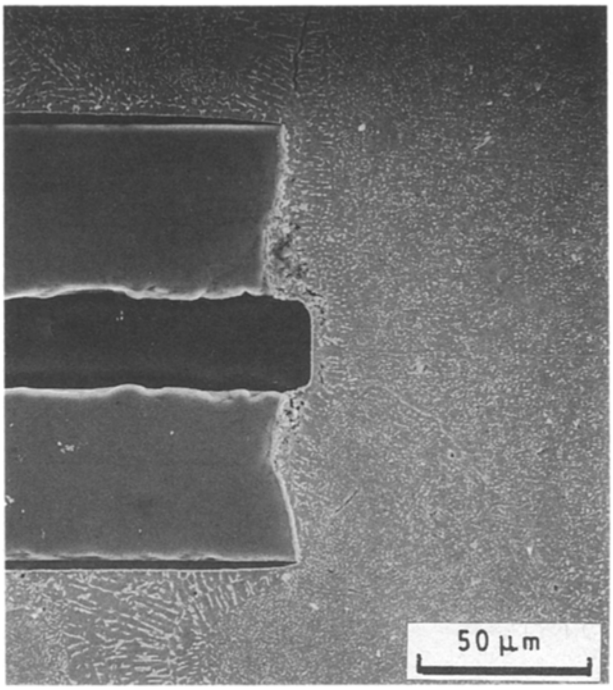


Figure 7 Scanning electron micrograph near a damaged fibre observed in the weld with a laser power of 1.04 kW.

of insufficient heat input. This is responsible for the low strength.

The 10-ply composite specimen welded with the highest heat input of 1.04 kW also exhibited considerable low strength. As shown in Fig. 6c the damage to fibres was observed at the fusion boundary more obviously under this welding condition, cf. Fig. 6a and b, and darkly etched regions existed near the damaged fibres. Fig. 7 shows a scanning electron micrograph of an area near a damaged fibre observed in Fig. 6c. Several small particles and some microcracks existed near the damaged fibre and this region corresponded to the darkly etched region in Fig. 6c. Fig. 8 shows an X-ray line profile of carbon across a particle in Fig. 7 and EDX analysis of it. Because carbon and titanium were detected, the particle must be TiC. TEM observation also showed that the particle was TiC, as shown in Fig. 9. TiC particles were probably formed by a reaction of titanium with carbon which was produced by decomposition of SiC fibres due to the laser irradiation. Although the formation of titanium silicides was not recognized in this experiment, they might also be formed in the darkly etched region.

Fig. 10 shows the distributions of micro Vickers hardness across the weld zones. The weld metal with a laser power of 1.04 kW was considerably hardened by the formation of TiC as compared to those with laser powers of 0.88 and 0.96 kW. The low strength of the weld joint with a laser power of 1.04 kW, therefore, seems to be caused by the formation of the brittle phase of TiC. As a result, the optimum heat input for the welding of the 10-ply composites with a 300 µm filler metal was a laser power of 0.96 kW.

In the 3-ply composite welds, full penetration and maximum strength are obtained at a laser power of 0.72 kW. Because a marked damage to fibres due to the laser irradiation and subsequent TiC formation

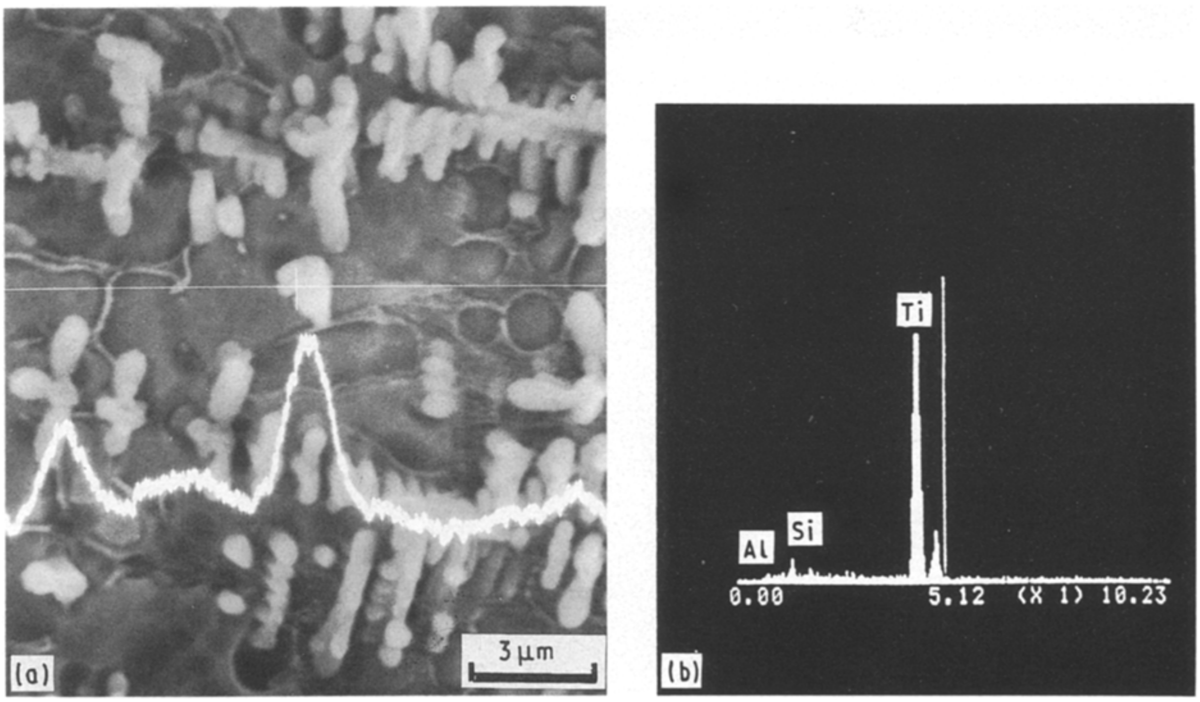
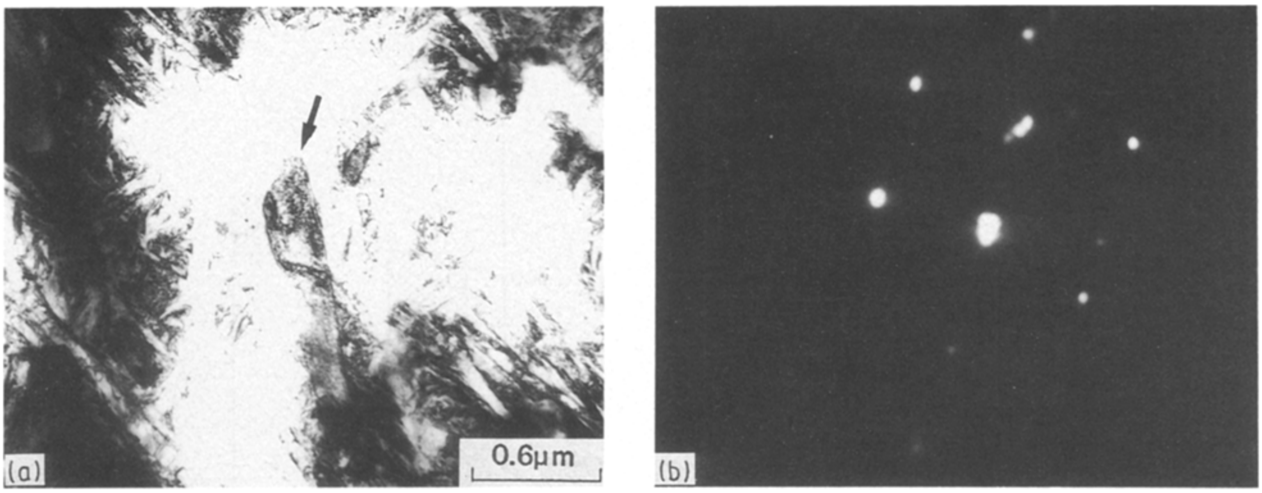


Figure 8 X-ray analysis of a particle observed near a damaged fibre in the weld metal. (a) Line profile of carbon. (b) EDX analysis of (a).



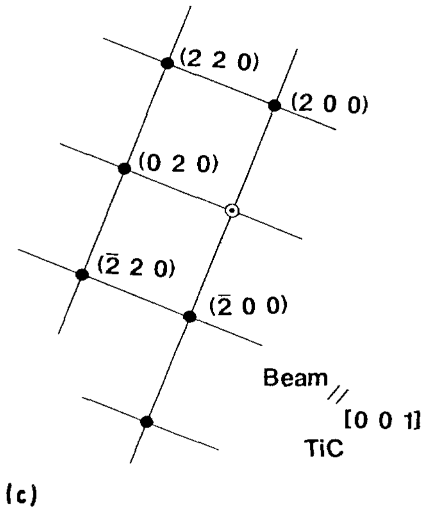


Figure 9 Transmission electron micrograph of a particle near a damaged fibre in the weld. (a) Bright-field image. (b) Electron diffraction pattern taken from (a). (c) Key diagram of diffraction pattern.

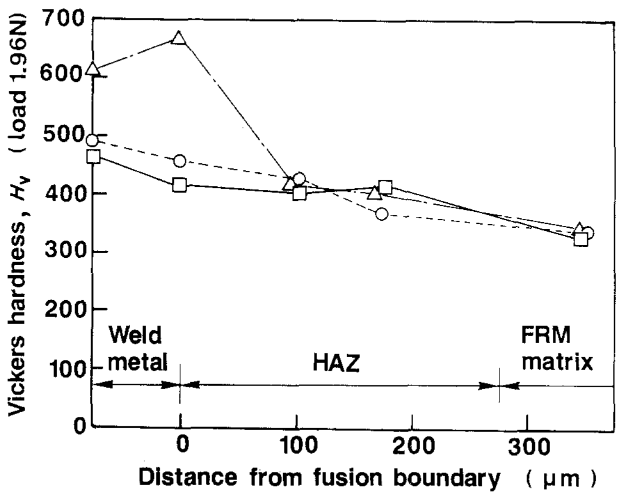


Figure 10 Distributions of micro Vickers hardness across laser-weld zones. Average laser power (kW): (□) 0.88, (○) 0.96, (△) 1.04.

did not occur up to a laser power of 0.96 kW, a degradation of the joint strength with increasing laser power was not so significant.

Consequently, in the case of using a 300 μm filler metal, the laser power should be limited to approximately 1 kW in order to avoid considerable fibre damage which causes a serious degradation of the joint strength. The welding of the 3-ply composites in which full penetration was achieved at lower laser power, therefore, seems to exhibit higher flexibility in the heat input than that of the 10-ply composites.

Carbon segregation and residual stress, which cause the degradation of the joint strength, may exist in the as-welded zone. Therefore, heat treatments at 1173 K after welding were applied in an attempt to improve the joint strengths. Fig. 11 shows the tensile strengths of the weld joints after the heat treatments. In both the 3-ply and 10-ply composites the joint strengths were increased by a 1173 K, 3.6 ks heat treatment. In particular, improvement in the latter was more marked. Fig. 12 shows a cross-sectional structure of the 10-ply composite weld after heat treatment. Compared with the as-welded structure (Fig. 6b), the darkly etched regions have disappeared. In fact, decomposition of TiC particles in the heat-treated weld metal was confirmed by SEM analysis. The improvement of joint strength by the heat treatment, therefore, contributes to homogenization of the weld metal and the disappearance of TiC.

The strengths of the transverse weld joints after the heat treatment were approximately 650 and 550 MPa for the 3-ply and 10-ply composites, respectively. Here, assuming the matrix-to-filler metal interface is joined completely and the fibre-to-filler metal interface is not joined at all, the joint strength is calculated from the following equation

$$\mathrm{UTS}_{\mathrm{joint}} = \mathrm{UTS}_{\mathrm{matrix}} \times (1 - V_f) \qquad (1)$$

where $\mathrm{UTS}_{\mathrm{joint}}$, $\mathrm{UTS}_{\mathrm{matrix}}$ and V_f are joint strength, matrix strength and volume fraction of fibre, respectively. In this case, the joint strengths are calculated to be 573 and 543 MPa for the 3-ply and 10-ply composites, respectively, using a matrix strength of 988 MPa. Because actual joint strengths exceed these values, it is apparent that at least the matrix-to-filler metal interface could be joined completely with this

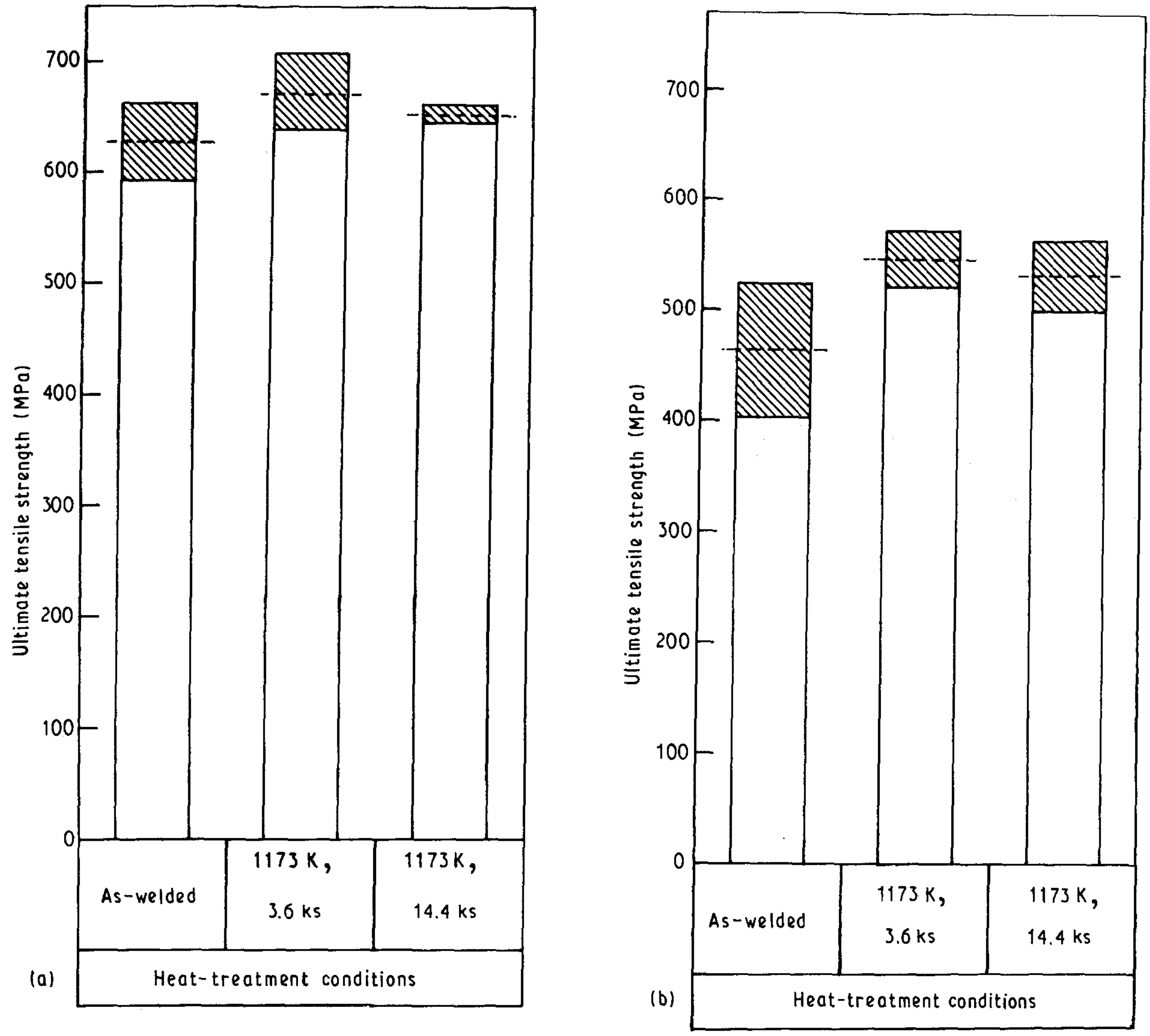


Figure 11 Tensile strengths of as-welded and heat-treated weld joints. (a) 3-ply SiC/Ti–6Al–4V composite. (b) 10-ply SiC/Ti– 6Al–4V composite. (– – –) Average values, ▧ data scatter.

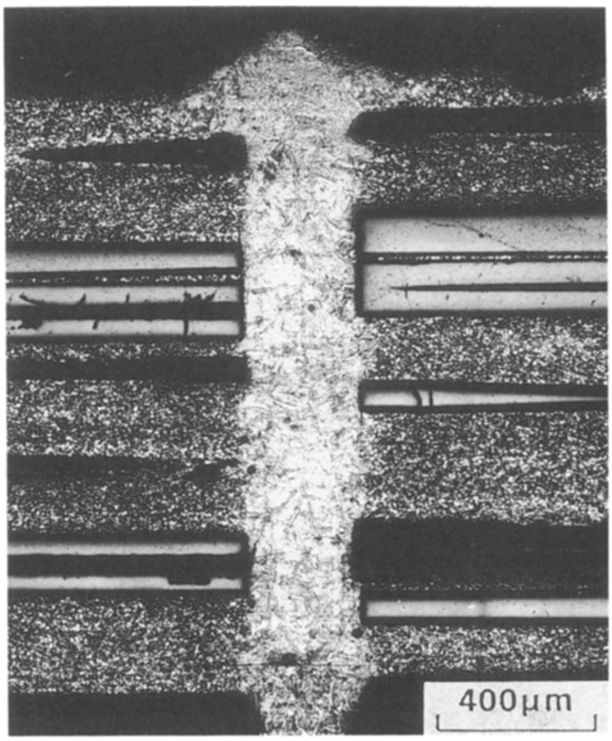


Figure 12 Cross-section of a laser-beam weld in 10-ply SiC/Ti–6Al–4V composite, welded with a laser power of 0.96 kW and heat treated at 1173 K for 3.6 ks.

welding process. The strengths of transverse weld joints, of course, are not high enough in comparison with the composites strength of approximately 2500 MPa, for joining to occur. However, the welding process is considered to be promising for joining the composites to monolithic materials, because the matrix-to-matrix will be joined completely.

3.2. Longitudinal welding

Fig. 13 shows the cross-sectional structure of a longitudinal weld of the 10-ply composites. No apparent damage to fibres was observed in the weld metal. The tensile strengths of the L–L and L–T specimens are shown in Table IV. Although the ultimate tensile strengths (UTS) in L–T orientation scattered largely, all five specimens tested were fractured in the base plates. A joint efficiency above 100% was obtained. It was not possible to measure exactly, the UTS of the L–T specimen, because slippage between the grip face and the specimen tab surface occurred at applied stresses above 1966 MPa. However, because the weld metal in which no reinforcement fibre existed was sufficiently narrow, the UTS of the L–T specimen will be comparable with that of the base plate. A successful joining could be achieved in longitudinal welding.

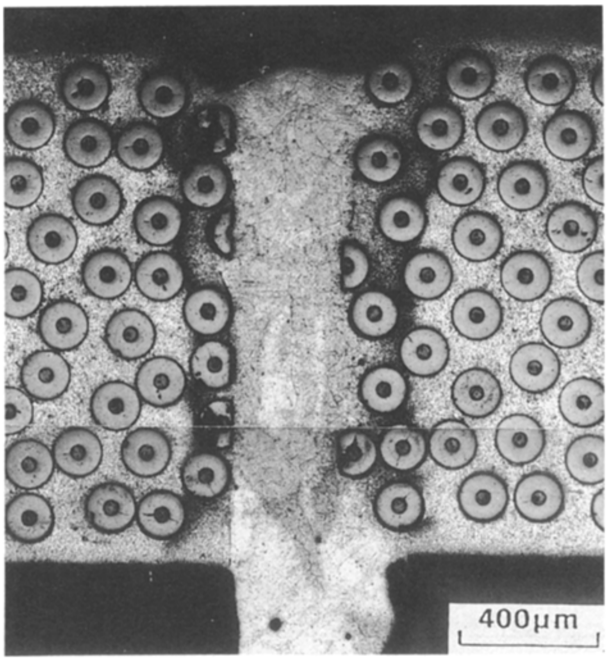


Figure 13 Cross-section of a laser-beam weld in 10-ply SiC/Ti–6Al–4V composite, welded parallel to the fibre direction (laser power of 0.96 kW).

TABLE IV Results of tensile test for the 10-ply composite welded parallel to the fibre direction with a laser power of 0.96 kW

	Ultimate tensile strength (MPa)
L–T specimen	79, 83, 87, 115, 118
L–L specimen	Above 1966

Consequently, it can be concluded that this welding process could be applied to joining composites to each other in the welding direction parallel to the fibre direction.

4. Conclusions

Three- and ten-ply SiC fibre-reinforced Ti–6Al–4V composites were joined to each other using a laser beam. The structure and the strength of the weld were examined. The following results were obtained.

1. To prevent direct damage of fibres by the laser beam, a 300 μm thick Ti–6Al–4V filler metal was inserted into the weld joint. By selecting optimum laser parameters, fully penetrated welds without apparent fibre damage were able to be obtained in welding directions both parallel and transverse to the fibre direction.
2. In the case of the welding direction transverse to the fibre direction, excess heat input resulted in the decomposition of SiC and subsequent TiC formation. This caused degradation of the joint strength. The welding of the 3-ply composites in which a full penetration was achieved at lower laser power, exhibited higher flexibility in the heat input than that of the 10-ply composites. Heat treatment at 1173 K after welding improved the joint strength. It may be caused by the homogenization of the weld metal and the decomposition of TiC. After heat treatment, the strengths obtained were approximately 650 and 550 MPa for the 3-ply and 10-ply composites, respectively.
3. With the welding direction parallel to the fibre direction, joint strengths in both L–L and L–T specimens were comparable with that of the base plate.
4. From these results, laser-beam welding can be applied to the joining of the SiC fibre-reinforced Ti–6Al–4V composites.

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