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Joining of TiAl intermetallic by self-propagating high-temperature synthesis

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Abstract This study reports on a novel approach for joining TiAl by self-propagating high-temperature synthesis (SHS). The Ti, Al and C powders were applied in the joining process with the assisted electromagnetic field. The microstructure analysis revealed that a dark $TiAl_3$ reaction layer existed at the interface. The TiC particles and multilayer granular structures of the Ti–Al system were found in the reaction products. It was noted that the porosity was inevitable in direct SHS joining. In order to improve the joining quality, Ag-based brazing foil was inserted between the powder compacts and the TiAl substrate. Molten brazing alloy during SHS reaction improved the wettability of the interlayer to TiAl substrate and filled well into the holes in the reaction products. With the application of Ag-based brazing alloy, the density increased and the joining quality improved.

Introduction

Titanium aluminide is a potentially attractive material for high-temperature structural applications owing to its high melting point, low density and high oxidation resistance [1–5]. Like most intermetallics, however, the properties of TiAl make it difficult to join. For example, high melting point of TiAl makes conventional fusion welding difficult [6]. Diffusion bonding and brazing of TiAl are both relatively low in efficiency, and are mostly carried out in a vacuum or protective atmosphere [7–9]. Clearly, innovative methods for joining TiAl are needed for application in the field of aerospace.

Self-propagating high-temperature synthesis (SHS) represents a promising technique for the production of a wide variety of ceramic and intermetallics [10–13]. SHS technique has been used for joining many materials with high melting points [14–18]. The joining process can be performed at room temperature without furnaces. The reactive compacts can act as local heat source for joining many materials [19]. Since heating is localized to the interface during joining, temperature sensitive components or materials can be joined without thermal damage [20]. However, the energy generated by most reactants is not enough and, therefore, conventional SHS joining cannot reach high strength. This study investigates the joining of TiAl in air using self-propagating HTS. The powders with large exothermic enthalpy and the assisted electromagnetic field were applied in the joining process in order to improve the joining quality.

Experimental procedure

All the experiments were carried out with the mixture of high purity (99.9%) Ti, Al and C powders. The reactive powders were dry-mixed thoroughly in a tumbler ball mill and cold pressed at a pressure varying from 75 to 150 MPa into disc specimens of 10 mm diameter and 0.5 mm height. The resultant variation in the green density was from 55% to 65% of theoretical density. The composition of the mixture is shown in Table 1. The second powder was selected for joining because of its best reaction quality.

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Table 1 SHS reaction results of different powders

No.	Element (wt%)			SHS reaction
	Ti	Al	C	
1	65.6	32.4	2	×
2	68.8	25.2	6	√
3	66.2	29.8	4	√
4	83.4	12.6	4	×

The TiAl-based alloys being welded in this research had nominal composition of Ti–48Al–2Cr–2Nb. The tensile strength of this alloy is 370 MPa. The sizes of metallographic observation specimens and tensile test specimens were Ø 10.0 mm × 1.5 mm and Ø 10.0 mm × 20 mm, respectively. All joined surfaces were polished by SiC papers up to grit 1200 and ultrasonically cleaned by acetone prior to SHS joining.

Schematic of the electromagnetic field-activated pressure-assisted SHS joining apparatus is shown in Fig. 1. The joining of TiAl was carried out in air on the induction heating equipment. The heating rates varied between 3 °C/s and 5 °C/s. These different green compacts were sandwiched between the TiAl based metals for direct SHS joining. After joining process, the microstructure and phase composition of reaction products were characterized employing scanning electron microscopy (SEM) with electron probe X-ray microanalysis (EPMA) and X-ray diffraction (XRD).

In order to improve the joining quality, Ag-based brazing alloy was used in the joining process. The nominal composition of the selected Ag-based brazing alloy was 72Ag–28Cu and the thickness of the brazing foil was about 100 μm. The brazing foil, which was inserted between the powder compacts and TiAl substrate, was only applied on one side to investigate the effect of the brazing alloy on the microstructure and joining quality. Tension tests were performed by a universal testing machine (Instron 1186) to evaluate the joining quality, as shown in Fig. 2. Tension was applied to the specimen at a constant speed of 1 mm/min.

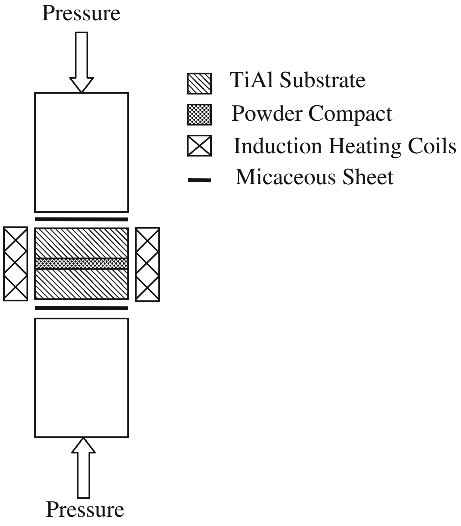

Fig. 1 Schematic of the electromagnetic field-activated pressure-assisted SHS joining apparatus

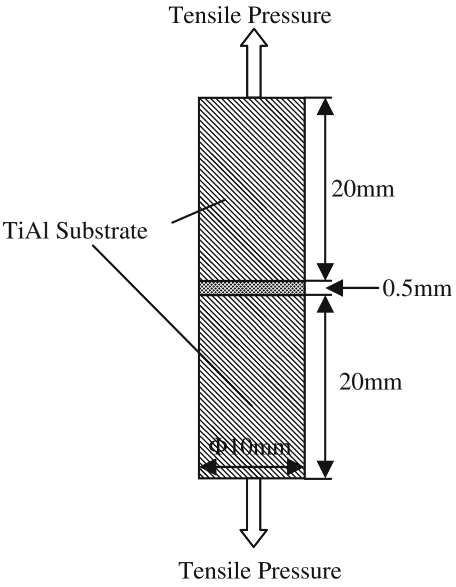

Fig. 2 Schematic of tensile test

Results and discussion

Back-scattered electron (BSE) image of the direct SHS joint is shown in Fig. 3(a) and a corresponding figure taken at higher magnification is shown in Fig. 3(b). This micrograph clearly indicated formation of reaction layers in the reaction zone. Adjacent to the TiAl substrate, a thinner dark reaction layer was observed at the interface. Multi-layer granular structures were found in the interlayer and dark phases were also distributed between the structures.

Quantitative chemical analyses were performed in order to identify various phases across the joint as shown in Table 2. According to Table 2, Ti and Al elements were detected at locations B, C, D and Ti, Al, C elements were found at locations A, E, F. It was found that Ti:Al (at%) at locations A,C,D and E were approximately 1:3, 3:1, 1:1 and 1:3, respectively. It was noted that the images at location B, C and D were homogeneous and no other color particles existed in these zones. The BSE photo was imaged according to the chemical composition of elements, and thus it was confirmed that the zones at location B, C

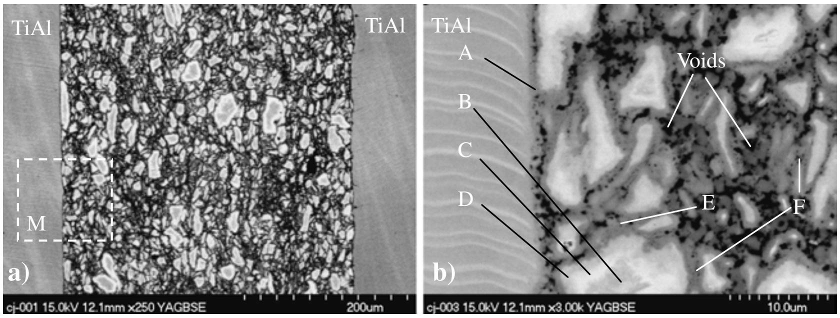

Fig. 3 Back-scattered electron images of the joint microstructure (**a**) overall joint interface (**b**) magnification (location M)

Table 2 Quantitative chemical analyses of the different micro structural elements of the joint

At%	A	B	C	D	E	F
Ti	24.76	95.24	72.74	48.53	23.58	52.64
Al	74.28	4.76	27.26	51.47	75.18	22.99
C	0.96	/	/	/	1.24	24.37
Phases	$TiAl_3$	Ti	Ti_3Al	TiAl	$TiAl_3$	TiC+ (Ti,Al)

and D were composed of uniform phases (shown in Table 2).

The reaction products were identified by XRD (Fig. 4). Three different phases were detected in the interlayer. TiAl was the main product of the reaction. Additionally, small amounts of $TiAl_3$ and TiC were identified. From the photograph of joint (Fig. 3), there were Ti and Ti_3Al phases dispersed in the interlayer. However, there were no Ti and Ti_3Al found in the X-ray result because the contents of their phases were too low.

It was noted that large amounts of voids were found in the reaction products. The porosity of the products was characteristic of products synthesized by SHS. These voids were inevitable due to the differences in specific volume between products and reactants, the evaporation of impurities, the expansion of the gas trapped in the voids of the reactant compact and the Kirkendall effect. Nevertheless, the porosity near the joining interface was relatively lower.

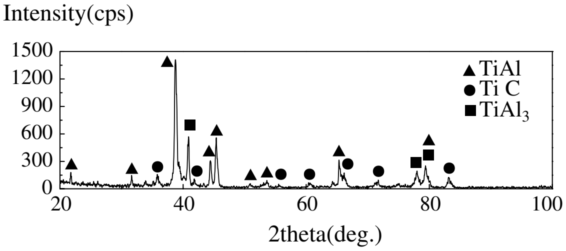

Fig. 4 XRD pattern of the reaction products

The microstructure results were in good agreement with the reaction mechanism. When the temperature reaches the melting point of Al, Al particles first melt and then spread around the Ti powder surface. After the melting of Al, liquid Al reacts with solid Ti to form $TiAl_3$. The process is driven by liquid Al–solid Ti interactions. The ignition occurs after the supplied energy has melted the Al completely. After the formation of $TiAl_3$, reaction between Ti and C forms TiC compound. Ti or the Ti-rich phase is identified in the core of the granular structure, which is surrounded by phases gradually richer in Al, grading to $TiAl_3$. In the joining process, the temperature in based materials is relatively lower. It is difficult for the reactive compacts to react completely because the heat generated in the reaction rapidly transfers to the based metal. The assisted electromagnetic field provides energy and accelerates the rate of atomic diffusion in the interlayer. When powder compacts were used in the absence of an assisted field, no self-sustaining reaction was occurred for any of the powders in Table 1. But when an electromagnetic field was imposed, self-propagating waves were initiated for the second and the third powder compacts, as shown in Table 1.

In order to increase the density of the reaction products, Ag-based brazing alloy was used in the joining process. Fig. 5 presents the microstructures at the joining interface in etched condition. The brazing foil, which was confirmed to join well with TiAl substrate and reaction products, was inserted between the powder compacts and TiAl substrate. Densification was achieved in the interface as well as in the products.

It was considered that the molten brazing alloy during the joining process infiltrated well into the voids in the reaction products and the boundary of each powder. The white zones in Fig. 5 were Ag-rich matrixes. The dark grains were TiC phases and the light grains were residual Ti particles. Ti_3Al phases were distributed between TiC and Ti particles. The molten brazing alloy moved to the opposite interface. The local fusion of TiAl substrate was found at the interface. Almost no porosity was found when Ag-based brazing alloy was applied.

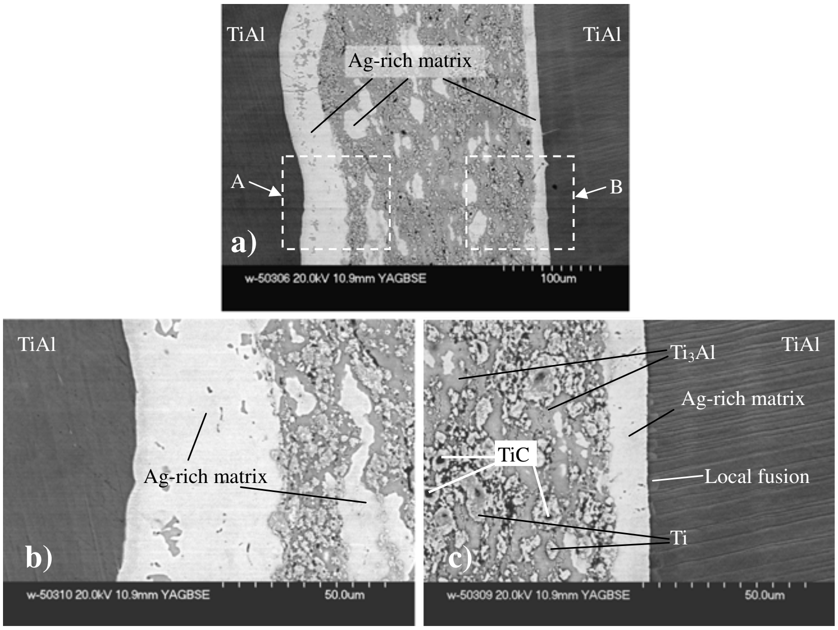

Fig. 5 Back-scattered electron images of the joint microstructure (**a**) overall joint interface region (**b**) joint region at the interface (location A) (**c**) joint region at the interface (location B)

The tensile strength of the joint was influenced strongly by the joining pressure as shown in Fig. 6. For direct SHS joining, the tensile strength was relatively lower. Because the contact of the joined surface was not sufficient and the density of products was lower, the strength was very low when the pressure was 1 KN. With increasing joining pressure, the contact became adequate and the porosity decreased, which resulted in the increase of strength. When the joining pressure reached 5 KN, the tensile strength was at a maximum. The SHS reaction was limited by further increase in the joining pressure. The weakening of the reaction leaded to a reduction in the strength of the joint. The joint failed when the joining pressure exceeded 6 KN.

When using the brazing foil on one side, the influence of joining pressure on tensile strength was similar to that of direct SHS joining. However, when brazing alloy was applied, the strength of joint was much higher than that of direct SHS joining under the same joining parameters. The main reason for the increase of strength using brazing alloy was the increase of density, as shown in Fig. 5. But there were still few voids dispersed in the reaction products, and thus the strength values in this study were lower than those of brazing with Ag-based brazing alloy [1]. It is important that the heating effect on the substrate was very small in the SHS joining process and the joint could be used in high-temperature conditions.

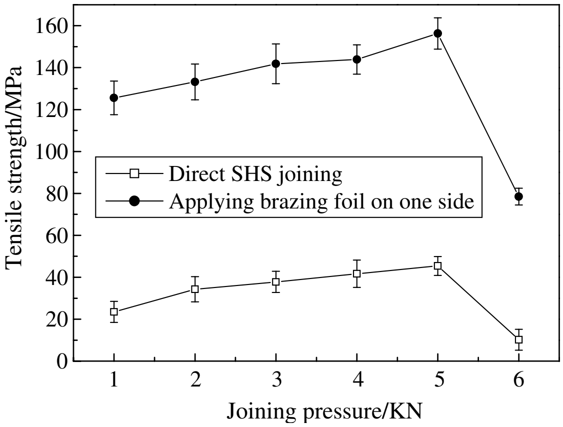

Fig. 6 Tensile strength of TiAl SHS joint

Conclusion

This study investigates the microstructure of SHS joining TiAl intermetallic using a Ti–Al–C interlayer. Both microstructure and tensile strength of the joint are extensively examined and important conclusions are summarized below.

(1) Joining of TiAl intermetallic by self-propagating HTS has been successfully performed with high efficiency.
(2) The typical microstructure of direct SHS joint consists of three different reaction phases. Adjacent to the TiAl substrate, a $TiAl_3$ reaction layer is found in the interface. Multi-layer granular structures of Ti–Al system and TiC phases are distributed in the interlayer. The porosity is unavoidable in direct SHS joining.
(3) When Ag-based brazing alloy is applied, the density increases greatly and no voids are found in the interlayer. Compared with direct SHS joining,

the tensile strength with brazing alloy increases greatly.

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