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# Characterisation of Diffusion Bond TiAl - Ti 6242 Joints

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## Abstract

The γ-TiAl based titanium aluminides are considered as candidates to replace the current materials in engineering applications at high temperatures due to their light weight and high temperature properties. On the other hand, Ti6242Si alloys offer tensile and long-term creep strength which is achieved through microstructural tailoring of alloys with increased α stabiliser content. The equiaxed, duplex and lamellar microstructures that meet the modern engine design demands qualify these alloys for aero-engine applications. Both materials are well studied for processing, characterisation and structural applications [1-3]. However, fully utilisation of these materials for demanding engineering applications necessitate advanced joining technologies where homogeneous material properties are retained with high deformation and crack resistant bonds.
The present paper reports on a systematic study being carried out on the diffusion bonding of γ-TiAl intermetallics and equiaxed α/β Ti6242Si alloy. Emphasis is put on the diffusion bonding process parameters of industrial interest, characterisation and properties of the joints. The process variables including temperature, pressure and time are optimised to produce joints with sound microstructure, bond quality and strength. The chemical composition and phase morphologies are studied using scanning electron microscopy and energy dispersive X-ray (EDX) analysis. Mechanical characterisation includes the standard tensile and micro tensile tests at ambient to high temperatures. Deformation, crack initiation and crack growth behaviours are studied on fracture surfaces and side surfaces of the tested diffusion bond joints.
**Keywords:** γ (TiAl) based titanium aluminides, Ti6242Si, diffusion bonding, crack initiation.

## 1 Introduction

Diffusion bonding (DB) is a solid state joining method based on the atomic diffusion of elements at the bonding interface. Recently, diffusion bonding has become a viable process in the fabrication of structural components and devices for aerospace and electronic industries.

The experience shows that the process parameter optimisation is of utmost importance in production of a defect free and high strength joint. The interface contact can be optimised by treatment of the surfaces to be bond by a number of processes. These include mechanical machining and polishing, etching, cleaning, coating and deformation at high temperature. Deformation of contacting surface areas during diffusion bonding allows material flow to produce full intimate contact at the joint interface as required for diffusion bonding [1,2]. Hence, surface treatment, selection of bonding temperature and pressure are the most important parameters of the diffusion bonding process. Furthermore, thermal conductivity, thermal expansion and bonding environment particularly affect the bonding process at high temperatures.

The Ti6242Si alloys with tailored microstructure [3,4] are well established materials used in aero-engine applications. Service performance improvement and environmental considerations demand a temperature increase associated with weight reductions. Therefore, intermetallics, based on $\gamma$-TiAl, are considered for high temperature engine applications [5,6]. However, their limited ambient temperature formability, low ductility and fracture resistance [7-9] necessitate an appropriate and reliable joining technology for production of joint components made of well established high temperature titanium alloy Ti6242Si with an advanced light weight intermetallic alloy TiAl. The prerequisite for such applications is the production of a defect free joint with acceptable strength without deterioration of the base metal properties. Therefore, process parameter optimisation is of utmost importance in the development of an industrial joining process such as diffusion bonding. Nakao et.al. [10] have demonstrated the potential for diffusion bonding of a binary $\gamma$-TiAl alloy at 1000-1200°C, nevertheless the bond failed at high temperatures. Yan and Wallach [11] have reported diffusion bonding of TiAl with emphasis put on the process parameters of surface finish, temperature and pressure. Defect free joints were produced with acceptable mechanical properties at temperatures as high as 1100°C. Cam et.al. [12] have reported on best diffusion bonding process of cast, rolled, and forged TiAl alloys at 1200°C, with recrystallized $\gamma$-grains at the bond interface. They also employed post bond heat treatment (PBHT).

Joining dissimilar materials of Ti6242Si and $\gamma$-TiAl, aiming at process parameter optimisation for industrial applications are scarcely reported [13]. The present paper reports on the process parameters study and properties of dissimilar Ti6242Si/$\gamma$-TiAl diffusion bond material. Defect free joints with reliable mechanical properties were produced at 900°C with polished specimen bond surfaces. Deformation and fracture studies were carried out on the cross-weld micro-tensile and standard tensile tested specimens. The authors' perspective for improved understanding of DB process for industrial production of engineering components is presented.

## 2 Experimental

### 2.1 Materials

The forged Ti-6Al-2Mo-4Zr-2Sn-0.1Si alloy (Ti6242Si) had equiaxed microstructure with $\beta$ distributed at $\alpha$-grain boundaries that has been designed for long-term creep strength [4]. The $\gamma$-TiAl intermetallic alloy was Ti-47Al-4.5(Cr, Mn, Nb, Si, B) (at.%) referred to as $\gamma$-TiAl (TAB) [13]. The $\gamma$-TAB was vacuum arc melted, investment cast, and hipped at 1185 °C under 140 MPa for 4 hrs. The microstructure containing network of borides was composed of large transformed $\alpha_2/\gamma$ lamellar colonies of 300-3000μm in size with finer primary $\gamma$ formed at lamellar colony boundaries.

### 2.2 DB Specimens

DB specimens of 14x14x4 $mm^3$ were used for preliminary tests, followed by specimens of 20x30x30 $mm^3$ for further investigation of process parameter optimisation and mechanical tests. The specimens were electric discharge machined (EDM), surface ground to 2400 grade SiC paper, polished with 0.05 μm $SiO_2$ solution followed by ultrasonic cleaning with acetone. Some specimens were electropolished to study the effect of surface finish on bond quality in determining optimum process parameters.

### 2.3 Diffusion Bonding Setup

The DB system operates with max. load of 250kN, temperature of 1500°C measured using molybdenum coated thermocouple, working atmosphere of vacuum ($10^{-6}$ mbar) or inert gas (Ar or He). The experimental DB test matrix is depicted in Table 1.

**Table 1**. Diffusion bonding process data

| Temperature, °C | 825 | 850 | 900 | 950 |
|---|---|---|---|---|
| Pressure, MPa | 5, 8 | 5, 8, 10, 20 | 5, 10, 20 | 5, 10, 20 |
| Time, min | 30, 40 | 30 | 25, 30, 60 | 30 |

### 2.4 Metallographic Examination and Micro Tensile and Standard Tensile Test Specimens

Both types of specimens were sectioned from DB material using EDM with minimum heat input in order to avoid machining damage to specimens. One piece of sectioned DB material was taken for metallographic investigations in optical microscopy (OM) and scanning electron microscopy (SEM), whereas the other piece is taken for machining out the cross weld micro tensile specimens with DB located in the centre of the flat specimen of 21mm total length and 9mm gauge length, 2mm gauge width, and 0.5mm thickness.

### 2.5 Micro Tensile and Standard Tensile Tests

Tensile tests were carried out on a screw driven 50 kN universal tensile testing machine, for testing flat tensile and standard round tensile specimens at ambient temperature, 500°C and 700°C. The loading rate was 0.2 mm/min. An IMPAC hand held infrared pyrometer is used for temperature control on the specimens. The laser extensometer used for displacement measurements on the flat tensile specimens operated on the contrasting fringes principles employed on painted metal surfaces. The strain value is monitored online during the test. Standard tensile specimens were tested following the test procedure for tensile testing metallic materials [14].

## 3 Results and Discussions

### 3.1 Diffusion Bonding and Microanalysis

The present study aims at optimisation of the DB process for a possible qualification of the DB technology for industrial production in the light of previous experience made on Titanium and γ-TiAl alloys [1,2,10,12,13]. Higher process temperatures up to 1200°C and longer process time were used in the previous studies. These two variables are of main concern for quality of products and economics of the process for adoptability in industrial production line. Therefore, the process parameters, time, temperature and pressure chosen in Table 1 differ from the referenced works. In present study lower temperature, pressure and shorter process time are selected. Intensive preliminary work on small size, 14x14x4 $mm^3$, specimens was followed by up-scaled 20x30x30$mm^3$ specimens which led to optimum DB process parameters. Figure 1 depicts an overview of effect of process parameter variation on the DB process and bond quality. The DB microstructural details are seen to vary with selected values of parameters. Defect free bond is produced with parameter combination of 900°C/10MPa/30min on machined, ground, polished and ultrasonic cleaned specimen surfaces. Electro polishing of specimen surfaces prior to DB did not improve the bond quality. The process parameter with temperatures below 800°C produced bonding failures in form of pores and un-bonded zones along the DB line. On the other hand, DB process at 950°C led to extensive deformation of Ti6242Si that would hinder integrity of the DB parts. Figure 2a shows a DB interface produced with the optimum parameter combination of 900°C/10MPa/30min where 1.51μm bond growth into TiAl is seen.

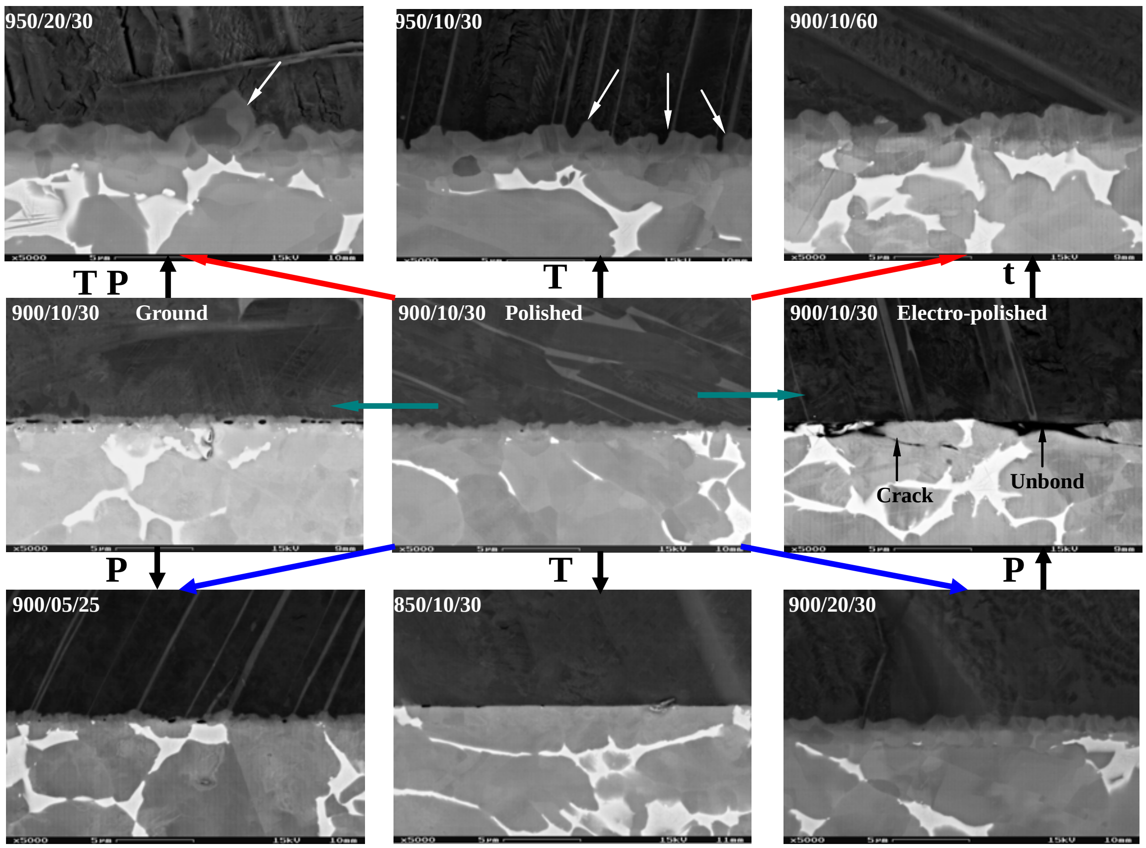
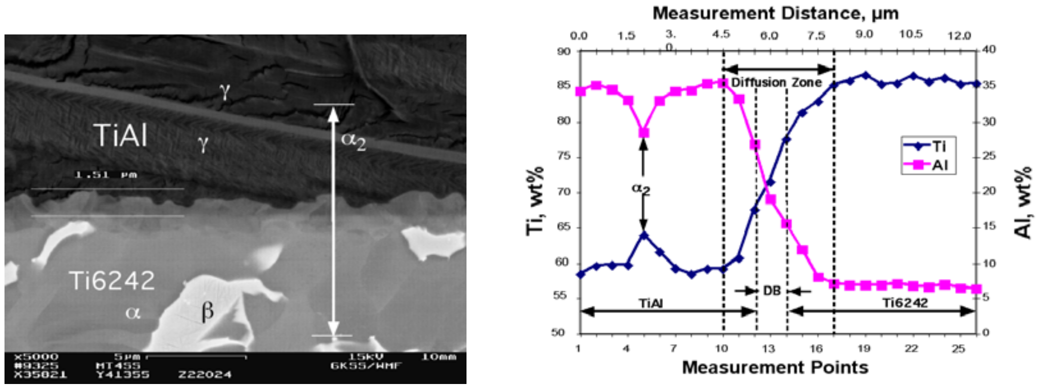


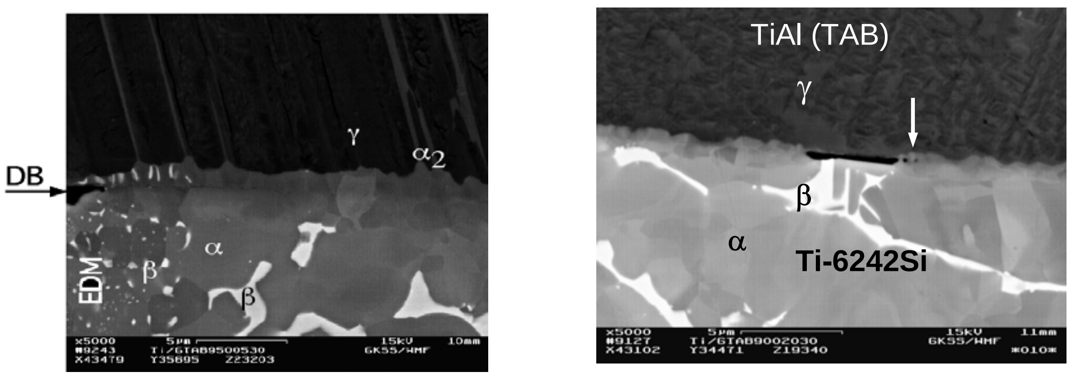

**Figure 1.** Overview of the experimental process parameter variation and diffusion bond quality

A cross weld EDX analysis along the line starting in γ-TiAl and ending in Ti6242Si, as marked on Figure 2a is depicted in Figure 2b. The variation of main alloying elements of Ti and Al are seen at $\alpha_2$ and across the diffusion zone of 4μm and DB interface of 1.5 μm along the marked line seen in Figure 2a. The diffusional growth front into TiAl (TAB) shows irregularity pointing out the effect of bond surface preparation. The effect of alloying elements hence the phases, and contact surface quality on DB is seen in Figure 3a.




a) b)

**Figure 2.** Diffusion bond Ti6242Si-γTiAl(TAB) at 900°C/10MPa/30mins. a) bond interface with microstructural components and EDX analysis line marked across the bond zone (5 µm marker), b) EDAX analysis along the marked line in a) showing the variation of the main alloying elements.




a) b)

**Figure 3.** a) Diffusional growth into $\alpha_2$ with substructure formation in α of Ti6242Si. Thermal damage by EDM with β dissolution and bond failure are seen at the machined surface zone. b) Bond deficiency and pore formation (arrow) in diffusion zone (5 µm marker).

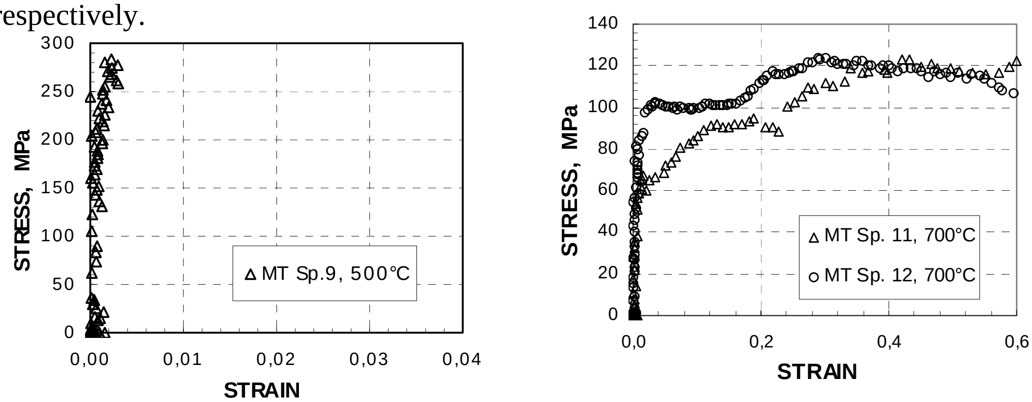
The diffusional growth from Ti6242Si into γ-TiAl is faster at high Ti containing phase $\alpha_2$. The EDAX analysis showed that $\alpha_2$ phase formed during diffusion has about 20 at.% Al. There is negligible change of composition and microstructure within the base materials beyond the diffusion zone. This is an advantage of the DB process producing weld joint without conventional weld heat affected zone. It is also observed that overheating during EDM machining may cause dissolution of β on the machined specimen surface of Ti6242Si as seen in Figure 3a. This affects the bonding process leading to a poor bond quality along the diffusion bonding process line. A bond deficiency which can also be seen in Figure 3b may be related to the bond surface preparation and efficiency of process variables particularly the temperature. Such bonding defects can be eliminated by improving the bonding specimen surface quality and increasing the process pressure and temperature.

### 3.2 Micro Tensile Testing

Flat micro tensile and round standard tensile specimen geometries were chosen for mechanical property determination of the DB material. The bond strength may be determined in shear loading or bending as the service loading of the final product as well as the easy of testing is concerned [12]. Micro tensile testing of flat tensile specimens, although not standardised yet, provides measurement of local properties of the materials with microstructural variation. The test specimens may be machined out of a narrow process zones of joints. A further benefit of flat micro tensile specimens is that deformation behaviour may be studied both locally as well as across the process zone. On the other hand, the standard specimens are too large to be machined out of DB samples with tensile loading axis along the DB process zone. Therefore, the standard tensile specimens are machined out across the DB zone (cross-weld) where main loading axis in tensile testing is perpendicular to the diffusion zone plane. Such specimens, however, deliver tensile data in the weakest direction of the joint. The determined mechanical property data from standard tensile tests are compared with those from micro tensile tests.

### *3.2.1 Stress-Strain Behaviour*

The stress–strain behaviour of the DB material is determined in micro tensile testing using laser system. The results are depicted in Figures 4a and 4b for 500°C and 700°C tests, respectively.




a) b)

**Figure 4.** Stress-strain diagrams of Ti6242Si/TiAl DB at 900°C/10MPa/30mins from micro tensile tests at a) 500°C, b) 700°C.

The temperatures 500°C and 700°C are chosen for service application temperatures of Ti6242Si and TiAl alloys, respectively. Note that TiAl has higher fracture strength at 500°C though it is brittle. The scatter in the data is caused by the fracture along the TiAl lamellae. Therefore, the determined properties are microstructural orientation dependent as they sample local mechanical properties. On the other hand, the test temperature of 700°C is too high for Ti6242Si that shows a lower yield strength and higher fracture strain as the DB material fails preferably within the Ti6242Si side of the cross-weld specimen.

Standard tensile specimens were also tested at 500°C and 700°C in order to compare the mechanical property data with those determined in micro tensile tests. The stress–strain diagram is depicted in Figure 5. An excellent agreement is seen in 500°C test data between micro tensile and standard tensile specimens both in terms of stress and strain values. However, the stress and strain values at 700°C are much different in micro tensile and standard tensile tests. The tensile strength is halved and the strain is as high as 40 times in micro tensile tests that of standard tensile test value measured at max. stress, $\sigma_{UTS}$.

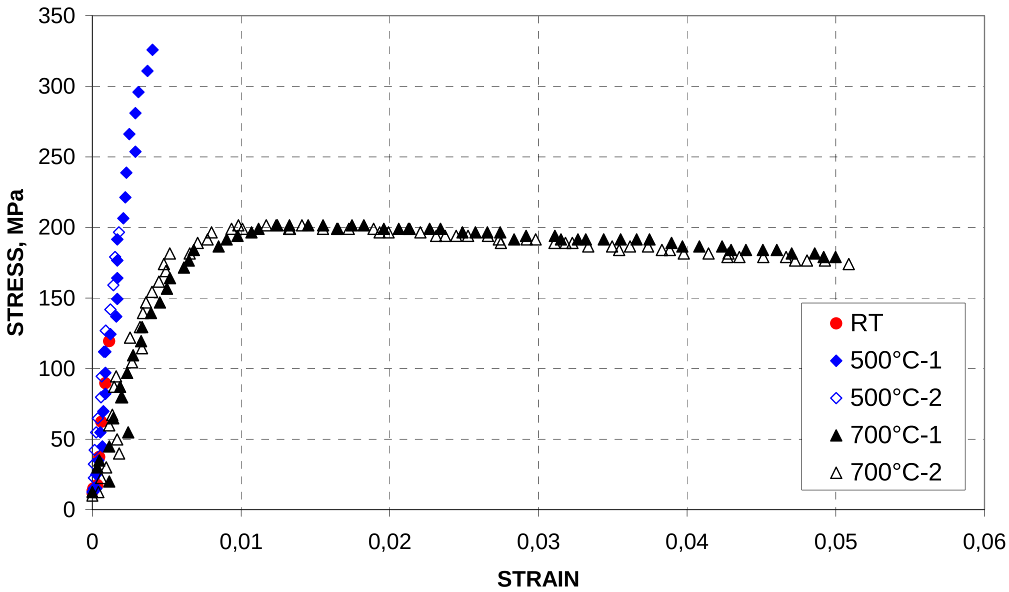
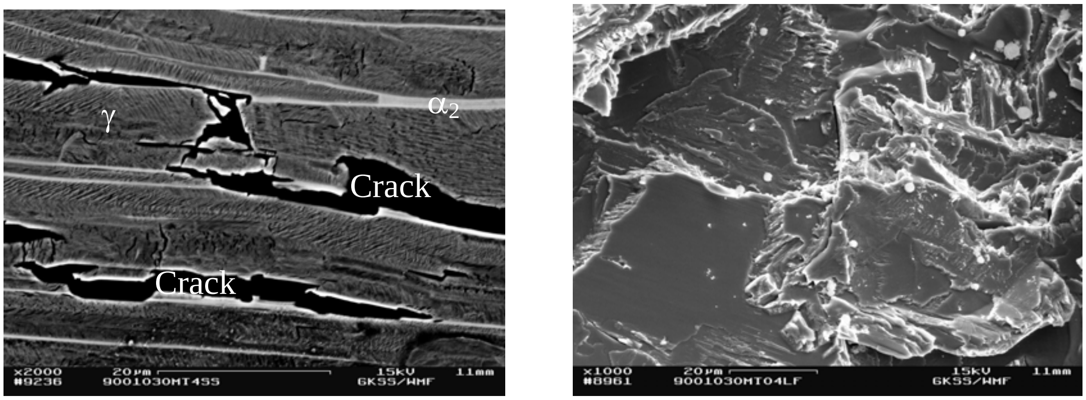



**Figure 5.** Stress-strain diagrams of Ti6242/TiAl DB at 900°C/10MPa/30mins from standard tensile tests at a) 500°C, b) 700°C.

### *3.2.2 Deformation and Fracture Behaviour*

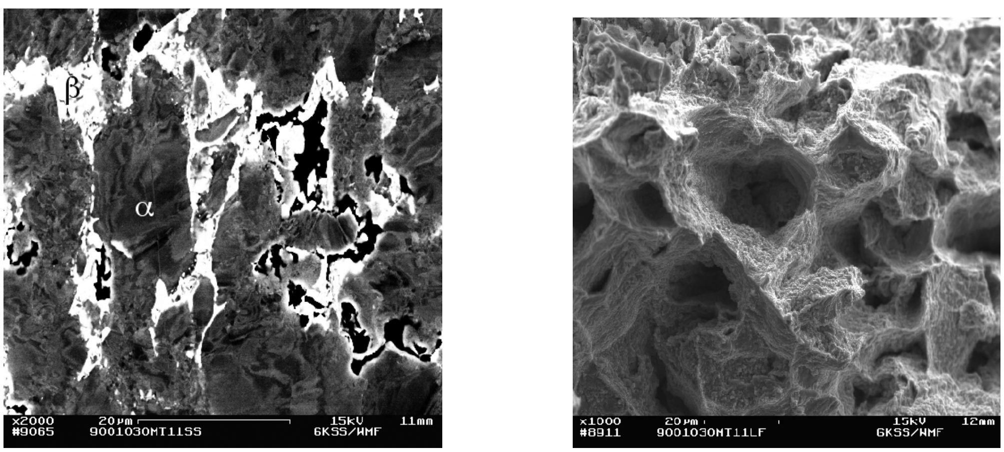
The microscopic examination of the tested specimens in OM and SEM showed strong bonding of the materials produced with the determined optimum DB process parameters of 900°C/10MPa/30min. Deformation and fracture behaviour of the DB materials were studied on polished side surfaces of tested specimens using polarised light in OM and fracture surfaces in SEM. The damage on side surfaces (Fig. 6a, 7a), and fracture mode on fracture surfaces (Fig. 6b, 7b) are shown in Figures 6 and 7 for tests at 500°C and 700°C, respectively.

An attempt is made to correlate mechanical behaviour of the material to the deformation and fracture behaviours presented in Figures 4-7. The absence of notable plastic deformation at 500°C was expected from previous studies of TiAl [5,8,9,15]. The present results indicate the success of the DB process with determined process parameter set of 900°C/10MPa/30min, that yield defect free bond as discussed above. The specimens did not fail at DB zone in tensile testing. All specimens tested failed in base material within the gauge and some outside the gauge at the specimen shoulder at 500°C. The optimum choice of DB process parameters, enabled high quality defect and pore free diffusion bonds along with narrow diffusion process zone with finer grain structure. Cracking along lamellae (Fig.6a) in large lamellar colony of γ-TiAl (TAB) lead to planar cleavage as observed on the fracture surface (Fig.6b). Note that the lamellae orientation was perpendicular to the main loading axis that is the easy mode fracture. Hence, the reported strength values reflect the lamellar bond strength of the TAB material. This is due to the high yield strength (515MPa) of the Ti6242Si component of the cross weld specimen at 500°C [4]. The failure on TiAl side of the cross-weld Ti6242Si-TiAl took place at measured fracture strength of 280MPa. Crack path deviation and secondary cracking in γ (Fig. 6b) can increase the fracture toughness but dos not affect the strength of the material considerably [7]. This observation directs attention to the importance of finer colony size and duplex microstructure of TiAl intermatallics for improved strength particularly to overcome texture and directional property variation for design and application purposes [15].




a) b)

**Figure 6.** a) Deformation in γ and cracks along $\alpha_2/\gamma$, b) brittle fracture along interfaces and through γ in TiAl (TAB) of DB cross weld micro-tensile specimen tested at 500°C (20 µm marker).




a) b)

**Figure 7.** a) Deformation with substructure formation in α and cracks along α/β boundaries and fracture in β, b) fracture surface of a) with grain/phase boundary failure through β in Ti6242 of DB cross weld micro-tensile specimen tested at 700°C (20 µm marker).

There was no considerable damage observed in the DB zone of the cross-weld specimen. The measured yield strength of Ti6242Si at 700°C decreased to a value of about 100 MPa from 515 MPa at 500°C. Such low stress sets a limit for a possible application of the bi-material components. Furthermore, the jumps observed in stress-strain curve are related to fracture of β phase (Fig. 7a), whereas extensive deformation and recrystallization seen in α phase accommodate large deformation. Fracture topography shown in Figure 7b corresponds to the fractured β network within α matrix in Figure 7a.

The further study will include fracture mechanics studies using tensile and compact type (C(T)) specimens. The fracture resistance of DB joint will be determined by locally inducing crack in DB zone and loading the specimen at different rates. The deformation behaviour of the DB zone will be studied using SEM and TEM.

## 4 Conclusions

The present study provide data for optimum DB process parameters of temperature/ pressure/ time, that is 900°C/ 10MPa/ 30min, and DB surface conditions of ground and polished surface for producing defect free joints. However, diffusion kinetics need to be studied for a comprehensive understanding of the DB process for further optimization of process parameters. Micro tensile tests proved the soundness of the joint produced with the determined optimum process parameters.

The specimen failure occurred in lamellae of TiAl ($\gamma$-TAB) at 500°C indicate dependence of mechanical properties on microstructural orientation in testing. The fracture mode is also test temperature dependent as expected for the studied DB joints. TiAl ($\gamma$-TAB) is rather brittle at 500°C, whereas testing temperature of 700°C is too high for Ti6242Si. Extensive plastic deformation in $\alpha$, and failure along $\beta$-phase are observed in Ti6242Si at 700°C.

Micro tensile testing is particularly useful in determining the properties of narrow welds and heat affected zone of weld joints without a need for microstructural simulation of heat affected zone.

Standard tensile tests were done on DB cross-weld specimens for comparison with the data determined on micro tensile specimens. The tensile data from micro tensile and standard tensile tests at 500°C agree well, however, the data obtained at 700°C differ considerably.

Further work is needed to study fracture resistance and deformation, including crack initiation and growth in notched specimens.

## 5 Acknowledgements

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