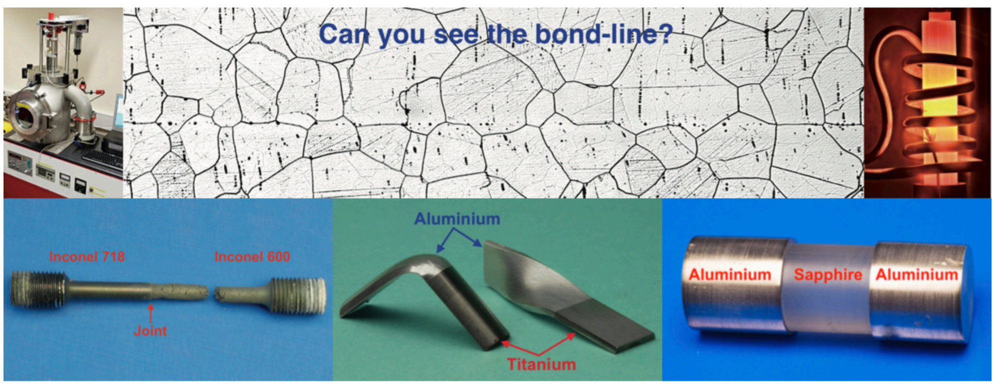
The Open University

SYMPOSIUM OF WORLD EXPERTS IN DIFFUSION BONDING

The Open University, UK

20–21 June 2017



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SYMPOSIUM OF WORLD EXPERTS IN DIFFUSION BONDING

The Open University, UK | 20–21 June 2017

Tuesday 20 June 2017 (morning session)	
09:00	Registration & Coffee
09:30	Opening & introduction of participants
09:45	**1- Reaction-assisted diffusion bonding of dissimilar materials** Sofia Ramos - *University of Coimbra, Portugal*
10:15	**2- In-line surface treatment and diffusion bonding – a novel approach for joining challenging materials** Stefan Habisch - *Chemnitz University of Technology, Germany*
10:45	**3- Gallium-assisted diffusion bonding of stainless steel to Ti** Arijit Laik *Bhabha Atomic Research Centre (BARC), Mumbai, India*
11:15	Coffee break
11:45	**4- Design & manufacturing large scale diffusion bonding hot presses** Jan Pfeiffer *PVA Löt- und Werkstofftechnik GmbH, Germany*
12:15	**5- Solid-state diffusion bonding of WC-Co alloy** Makoto Igarashi *Mitsubishi Materials Corporation, Japan*
12:45	Lunch break

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Tuesday 20 June 2017 (afternoon session)	
13:30	**6- Effect of gallium treatment in diffusion bonding of copper to aluminium die cast (ADC) alloys** Touyou Ohashi[1] & Amir Shirzadi[2] *[1]Mitsubishi Materials Corporation, Japan* *[2]The Open University, UK*
14:00	**7- Verification of diffusion bonding for industrial applications** Nick Ludford *The Welding Institute, UK*
14:30	**8- Diffusion bonding alloys with stable surface oxides *e.g.* aluminium and superalloys** Amir Shirzadi *The Open University & Cambridge Joining Technology, UK*
15:00	Coffee break & visit to Open University's diffusion bonding lab
16:00	Bus departs for Cambridge (invited speakers and sponsors only)
17:30	Sightseeing in Cambridge
19:00	Formal dinner at King's College, Cambridge
22:00	Departure from Cambridge for Milton Keynes
23:00	Arrival in The Open University Campus

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Wednesday 21 June 2017 (morning session)	
09:00	Registration + Coffee
09:30	**9- Modelling of transient-liquid-phase diffusion bonding under temperature gradient** Hamid Assadi *Brunel University London, UK*
10:00	**10- Simulation of a diffusion bonding system** Felix Gemse *ifw - Jena, Germany*
10:30	**11- The interfacial microstructure and bonding mechanisms in diffusion bonded similar/dissimilar Ti and TiAl alloys** Hong Li *Northwestern Polytechnical University, Xi'an Shaanxi, China*
11:00	**12- Nanoparticle enhanced transient liquid phase bonding process** Tahir I. Khan *University of Bradford, UK*
11:30	**13- Diffusion bonding of titanium to itself and to aluminium** Amir Shirzadi *The Open University & Cambridge Joining Technology UK*
12:00	Lunch break & visit to Open University's diffusion bonding lab

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Wednesday 21 June 2017 (afternoon session)	
13:00	**14- Diffusion bonding of AA7075 aluminium alloy** Yan Huang *Brunel University London, UK*
13:30	**15- Diffusion-bonded laminated Al heat exchangers used in jet engines** **16- Application of diffusion bonding in testing materials** Amir Shirzadi *The Open University & Cambridge Joining Technology UK*
14:30	**Open discussion & closing remarks**

Reaction-assisted diffusion bonding of dissimilar materials

A.S. Ramos[1], S. Simões[2], A.J. Cavaleiro[1], F. Viana[2], M.F. Vieira[2], J. Morgiel[3], M.T. Vieira[1]

[1]University of Coimbra, Portugal
[2]University of Porto, Portugal
[3]Polish Academy of Sciences, Cracow, Poland

Reactive multilayers (MLs) are a class of energetic materials composed of tens, hundreds, or thousands of alternating individual layers of at least two reactants having a large heat of formation and high adiabatic reaction temperature. These metastable materials show potential as localized heat sources for joining applications.

In this context, sputtered reactive MLs with nanometric period (Λ, bilayer thickness) have been used to enhance the diffusion bonding process, taking advantage of their exothermic and nanocrystalline character – reaction assisted diffusion bonding (RADB). The reactive MLs allow the diffusion bonding temperature, pressure and/or time to be reduced. The possibility of providing an interface zone with intermediate properties constitutes another asset that makes the RABD process particularly promising for joining dissimilar materials.

The feasibility of using Ni/Al, Ti/Al and Ni/Ti reactive ML thin films to assist the diffusion bonding process has been demonstrated. Similar TiAl and dissimilar TiAl/Steel and TiAl/Inconel diffusion bonding experiments using Me/Al (Me = Ti or Ni) ML thin films as filler material were performed with success. High quality joints, without pores or cracks, were achieved; a shear strength close to 320 MPa was obtained when diffusion bonding TiAl at 900ºC/ 5 MPa/ 1h using a Ni/Al ML with Λ = 14 nm. Joining of NiTi to itself, to Ti6Al4V and to stainless steel has also been processed by RABD using Ni/Ti MLs. Sound joints were obtained at temperatures as low as 600ºC, indicating that these MLs allow diffusion bonding at considerably less demanding conditions.

Ni/Al and Ti/Al ML thin films with intermediate period (10 to 25 nm) seem the most promising reactive filler for the diffusion bonding experiments. Ni/Ti thin films also constitute a good option for joining NiTi shape memory alloys.

In-line surface treatment and diffusion bonding – a novel approach for joining challenging materials

P. Mayr & S. Habisch

Chemnitz University of Technology, Germany

For diffusion bonding, the surface condition is a critical factor especially for the weldability of oxide forming metals and advanced materials. In order to improve diffusivity and thus the joint properties, it is necessary to treat the joining surfaces immediately before the joining process. Any regeneration of the oxide layer before joining would impair weldability and deteriorate joint properties.

Therefore, a unique concept for an in-line surface treatment and diffusion bonding was developed. A diffusion bonding chamber coupled to a glove box, to treat specimens and transfer samples under inert atmosphere was established. Surface treatments included for example grinding, milling and different chemical treatments. Results have shown that surface treatments strongly influence topography, microstructure and therefore free energy. Improved joint properties can be achieved or bonding temperature for temperature sensitive materials can be significantly reduced applying this in-line technology. Joining strategies for various metals and dissimilar combinations, such as Al-Al, Al-Mg, Ni-Ni, Mo-Mo and Cu-Nb are presented.

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Ga-assisted diffusion bonding of stainless steel to titanium

A. Laik[1], A.A. Shirzadi[2], R. Tewari[1] & G.K. Dey[1]

[1]Bhabha Atomic Research Centre (BARC), Mumbai, India
[2]The Open University, UK

Diffusion bonding of stainless steel to titanium using the novel method of “Ga-assisted diffusion bonding” has been investigated in the present work. The microstructural evolution and interfacial reactions during the processes of joining were studied in detail using various analytical techniques.

The possible mechanisms of phase changes at the joint interface during diffusion bonding, with and without Ni-interlayer, have been identified. Layers of FeTi and $(Fe,Cr)_2Ti$ intermetallic compounds were found to form at the reaction zone in the case of direct bonding while in the presence of Ni interlayer, (Fe,Ni)Ti and Fe_2Ti phases formed in the reaction zone. A layer of a-Fe was observed on the steel side of the reaction zone in both the cases, probably due to the enrichment of Cr at the interface.

The diffusion of Ga led to formation of a layer of a-Ti, while the diffusion of Fe and Ni assisted in the formation of a duplex a+b Ti phase on the Ti-side of the interdiffusion zone. The joints fractured along the intermetallic layers at the interface, during tensile testing, with some limited component of ductile behaviour.

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Design & manufacturing large scale diffusion bonding hot presses

J. Pfeiffer & U. Broich

PVA Löt- und Werkstofftechnik GmbH, Germany

The results of several investigations and research efforts have shown the vast potential of diffusion bonding for a large variety of advanced materials. Especially the combination of low bonding temperatures, no necessity liquid phase with supreme joint properties are opening possibilities for both optimising joints and new applications. However, most of the research on fundamentals and possibilities of the bonding have been done on small-scale samples, as the bonding machines are usually of a small scale. Only limited industrial-scale applications can be noticed. Nowadays it became possible to construct machines with pressing plate sizes exceeding 1600 x 600 mm². As the up-scaling of such equipment represents a very complex task, several machine-relevant peculiarities arise, which has to be known for the potential user.

In the presented contribution, an insight onto designing issues of large scale systems will be given, based on the main processing parameters (temperature, pressure). Thus topics, like pressing systems, heating and cooling strategies and affiliated infrastructure will be shown.

Due to the necessity to incorporate this equipment into more industrial scale environment topics such as acceptance as well as machine qualification procedures and requirements have to be considered and will also be discussed in the contribution.

In the final part, an exemplary overview of machine types and applications will be given.

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Solid-state diffusion bonding of WC-Co alloy

M. Igarashi & K. Fujiwara

Mitsubishi Materials Corporation, Japan

WC – Co based cemented carbide has high mechanical properties, so it is mainly used as a material for cutting tools. However, cemented carbide is expensive because it contains rare metal as the main component. Therefore, in the cutting tool, the cutting edge part made of cemented carbide bonded with the cutting tool body made of inexpensive alloy is preferable.

Currently, brazing method is common in cemented carbide bonding, but there is a problem with the reliability of bonding strength especially on high temperature, so new bonding method to replace brazing method is demanded. Then, we have studied solid-phase diffusion bonding method of cemented carbide by using metal interlayer.

Solid-phase diffusion bonding of the cemented carbide was performed by using Ti, Ni and Cu foils as interlayer .Two cemented carbide bodies contacted via interlayer are held around 800 ° C while applying a load. As a result of share test, cemented carbide bonded with Ti foil show higher bonding strength compared to Ni and Cu foils .Therefore, we focused on Ti foil and further investigated the influence of bonding temperature, time and reaction-layer between cemented carbide and Ti foil.

As a result, it was found that bonding strength strongly depends on the thickness of reaction layer and maximum bonding strength was performed at thinner reaction-layer. Average bonding strength of this solid-phase diffusion bonding exceeds that of conventional brazing at lower bonding temperature. Moreover, most of the fracture occurs inside the cemented carbide rather than reaction layer. These result shows solid-phase diffusion bonding method of cemented carbide could be alternative of brazing method.

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Effect of gallium treatment on diffusion bonding of copper to aluminium die cast (ADC) alloys

T. Ohashi[1] & A.A. Shirzadi[2]

[1]Mitsubishi Materials Corporation, Japan
[2]The Open University, UK

Power Inverters are electronic devices that change direct current (DC) to alternating current (AC) and have vast applications particularly in electric cars and trains. Efficient cooling systems are required to keep the integrated semiconductors below a certain temperature. Normally a copper plate is placed between the inverter's substrate and the aluminium-based heat sink. Clearly having a very good conductivity between the copper and the heat sink is essential to prevent overheating of the semiconductors. In some devices, special greases are used to establish a "thermal bridge" between the copper and the aluminium heat sink. However, even the best available greases have high thermal resistivity, which can considerably limit the inverter's performance. This problem could be solved by direct diffusion bonding of the copper plate to the aluminium heat sink.

Diffusion bonding of pure copper to an aluminum die cast (ADC) alloy, with and without gallium treatment, was attempted in this work. The results clearly showed that the gallium treatment, prior to bonding process, reduced the density of Kirkendall voids in the copper substantially.

It is suggested that diffusion imbalance between the copper and aluminium alloy was less in the gallium-treated samples, probably due to removing or modifying the oxide film on the surface of aluminum alloy.

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Verification of diffusion bonding for industrial applications

Nick Ludford

The Welding Institute, UK

Diffusion bonding is a solid state joining technique, typically selected for bespoke, high value applications. Process development requirements include identification of appropriate diffusion bonding temperature, time and applied load. The effect of surface finish and the use of potential interlayers at the bondline also need to be considered during process development.

This presentation will review a number of different techniques used to assess the bondline during the diffusion bonding development process and how verification of the assembly may be achieved once a component has been diffusion bonded.

Diffusion bonding alloys with stable surface oxides *e.g.* aluminium and superalloys

A.A. Shirzadi

The Open University & Cambridge Joining Technology, UK

Diffusion bonding is normally used to bond the alloys, composites and ceramics, which cannot be joined using conventional welding processes such as arc or laser welding. However, the presence of stable surface oxides has been a major obstacle when diffusion bonding most metallic materials. The presentation will outline three new and fundamentally different approaches, which are capable of producing high integrity diffusion bonds in the alloys with stable surface oxides. These methods are based on the following concepts:

1- Modification of surface oxide distribution leading to changes in morphology of the bond interfaces and the formation of sinusoidal bond-lines with strengths as high as those of the parent alloys.

2- Removal of stable surface oxides using a non-chemical process to enable formation of solid-state joints with high strengths.

3- Exploitation of surface oxide for flux-free brazing aluminium alloys in air.

Modelling of transient-liquid-phase diffusion bonding under temperature gradient

M.A. Jabbareh[1], H. Assadi[2] & A.A. Shirzadi[3]

[1] Hakim *Sabzevari University, Iran*
[2] *Brunel University London, UK*
[3] *The Open University, UK*

Imposing a temperature gradient (TG) when transient liquid phase (TLP) diffusion bonding reduces the process time substantially and results in reliable joints with shear strengths as high as those of the parent material.

The present contribution provides an overview on the analytical and numerical modelling of solidification at the interface during TG-TLP diffusion bonding, based on which the processing time and the conditions leading to the formation of non-planar interfaces can be predicted. This includes a multiple-grain phase-field model of microstructure development during TG-TLP diffusion bonding. The results of modelling also provide new insight to the general problem of morphological instability during melting.

Simulation of a diffusion bonding system

A.Fey, S. Jahn, S. Dahms & F.Gemse

ifw - Günter-Köhler-Institut für Fügetechnik und Werkstoffprüfung GmbH Germany

Finding the right set of bonding parameters is always a challenge in diffusion bonding. Especially the bonding of larger parts requires a homogeneous load and temperature distribution to get achieve high quality bond. Recipes available from publications are not always helpful, as every part geometry and every bonding system has its own thermal behavior. One solution to enhance the parameter development and reduce the number of necessary experimental steps could be the Simulation of the diffusion bonding process. Actual FEA models are based on the brazing process and often start their calculations on the part surface. Furthermore, the press system, and therefore the load distribution and its thermal influence are not included.

In this contribution, a furnace based FEA-model to calculate the temperature und load distribution for diffusion bonding in vacuum will be presented. Which contains all important components of the diffusion bonding system (heating elements, isolation or press ram). The model will be presented as well as boundary conditions and FEA results.

The interfacial microstructure evolution and bonding mechanisms in the diffusion bonding of similar/dissimilar Ti and TiAl alloys

H. Li & M. Li

Northwestern Polytechnical University, Xi'an Shaanxi, China

In last five years, the joining of steel to steel, Ti to Ti and Ti to TiAl has been conducted by diffusion bonding in our research group. Three migrating types of interfacial grain boundary (IGB) were found in the diffusion bonding of steels, which are related to the void size and location.

The interaction mechanisms between void and IGB migration were discussed in detail. To improve the bonding quality, the large pressures were imposed in the diffusion bonding of Ti/Ti and Ti/TiAl, which obviously decrease the required temperature and time to obtain the metallurgical bond with high strength. We successfully performed the TC17/TC17 and TC17/TiAl bond with the microstructure and mechanical property comparable to that of base alloys at 30 MPa/860℃/10 min and 50 MPa/850℃/10 min with post heating, respectively.

The enhanced plastic deformation resulted from larger pressures evidently promotes the void shrinking and IGB evolution. Moreover, the atom diffusion is enhanced by larger pressures to improve the metallurgical bonding of Ti/TiAl.

Nanoparticle enhanced transient liquid phase bonding process

T. I. Khan

University of Bradford, UK

The transient liquid phase (TLP) bonding process is often used to join advanced alloys especially when it is not possible to use the solid-state bonding process due to high loads required or long bonding time necessary to produce sound joints. The TLP bonding process utilizes an interlayer, which melts at the joining temperature and then solidifies isothermally whilst held at this temperature. The choice of the interlayer composition and thickness will determine the microstructural developments within the joint region and influence the final mechanical properties of the joint.

The application of the TLP bonding process to particle dispersed metals such as oxide dispersion strengthened alloys and metal composites has shown some success, but a significant disruption and absence of strengthening particles within the joint region is often observed resulting in poor mechanical properties at the joint. In this study, results from TLP bonding of dissimilar metals and aluminium metal composites using interlayers containing nanoparticles as a way of controlling the extent of liquid formation and the rate of isothermal solidification will be presented.

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Diffusion bonding of titanium to itself and to aluminium

A.A. Shirzadi

The Open University & Cambridge Joining Technology UK

Titanium and most of its alloys are considered to be one of the most “diffusion bonding friendly” materials with vast applications in aircrafts and marine industries. For instance, the titanium fan blades in large jet engines have a hollow structure made by diffusion bonding. This desirable property of titanium is mainly because the inherent surface oxide is unstable at elevated bonding temperatures when it dissociates to titanium and oxygen. The freed oxygen readily dissolves in the bulk alloy allowing metal-to-metal contact to establish at the joint interface.

However, diffusion bonding of titanium to other materials is a challenging issue mostly due to the formation of undesirable intermetallic(s) at the joint interface, *e.g.* bonding Ti to Al. In some special cases when the bonding pressure and temperature are restricted (*e.g.* to maintain the original shape) bespoke bonding conditions need to be determined.

The presentation will outline the latest developments in diffusion bonding Ti to Al and its potential applications. A special case will also be presented, in which high-precision diffusion bonding was used to fabricate miniature Ti-based turbochargers for satellites.

Diffusion bonding of AA7075 aluminium alloy

Y. Huang

Brunel University London, UK

An AA7075 aluminium alloy was diffusion bonded in both as hot-rolled and superplastic states, using a novel surface treatment method and bonds having base metal strength and microstructure have been achieved.

The starting microstructures were found to have strong impact on the bonding process and the bond quality. In-situ high temperature optical microscopy and EBSD studies showed that the elimination of the initial bond interface was realized by the migration of unstable interfacial triple junctions in the superplastic state with an equiaxed fine grain structure, whereas, in the hot-rolled material, the controlling process for the formation of the metallurgical bond was found to be the recrystallization initiated from the bond region.

The results of bond strength tests and microstructural examinations are presented in the paper and the effect of the starting microstructures on bonding mechanisms and kinetics is discussed.

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Diffusion-bonded laminated Al heat exchangers used in jet engines

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Application of diffusion bonding in testing materials

A.A. Shirzadi

The Open University & Cambridge Joining Technology UK

Fuel/oil heat exchangers are critical components of modern jet engines. Their primary function is to cool the hot engine lubrication oil while heating the cold fuel coming from the fuel tank before it enters the combustion chamber. The fuel heating increases the engine efficiency substantially by recuperating the waste heat from the oil into the fuel. The fuel/oil pressures and temperatures required are increasing with the development of more efficient jet engines.

"Gallium-Assisted Diffusion Bonding" is used to join stacks of aluminium plates containing fluid flow channels; without the weaknesses inherent in traditional brazing. The article describes a new technology for manufacturing more efficient and lighter heat management systems than the existing methods.

The presentation will also include some examples of how diffusion bonding can be used for determining mechanical and physical properties of alloys.