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FUNDAMENTALS OF SOLID-STATE DIFFUSION BONDING

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Introduction

Solid-State Diffusion bonding (SSDB) is a joining process wherein the principal mechanism is interdiffusion of atoms across the joint interface at an elevated temperature of about 50%-90% of the melting point of the material in the Kelvin scale. The International Institute of Welding (IIW) has adopted a modified definition of solid-state diffusion bonding, proposed by *N. F. Kazakov* who is credited as the pioneer in the field [1].

"Diffusion bonding of materials in the solid state is a process for making a monolithic joint through the formation of bonds at atomic level, as a result of closure of the mating surfaces due to the local plastic deformation at an elevated temperature which aids interdiffusion at the surface layers of the materials being joined."

The SSDB process requires applying compressive loads on the joint interface for a time ranging from a few minutes to a few hours depending on the material. The higher the bonding pressure the shorter the bonding time, however, the pressure is limited by the amount of plastic deformation permissible on the components. The diffusion bonding of most materials has to be carried out in vacuum (normally below 10^{-3} mbar) or in an inert gas (argon or nitrogen) in order to reduce oxidation of the joint surface at elevated temperatures. Given the absence of a liquid phase, precise surface preparation is required to ensure minimum gap between the mating surfaces.

It is literally impossible to establish a full contact in interatomic scale by pushing the parts against each other. Even highly polished surfaces contain peaks and troughs and come into contact only at their peaks, resulting in a very low contact areas compared to the entire mating area. Besides, the presence of tenacious native oxide layers affects the ease of diffusion bonding by blocking metal-to-metal contact. Apart from a few exceptions where oxide films dissociate at the bonding temperature (e.g. titanium and silver), achieving a metallic bond in alloys with chemically stable surface oxides (e.g. aluminium and its alloys) can be a challenging task.

Mechanism of SSDB

The mechanism of bond formation during SSDB of the alloys with stable surface oxide can be classified into two main stages [2,3]. In the early stage, the asperities or surface peaks yield and deform plastically under the applied compressive force. As the micro-deformation proceeds, more metal-to-metal contact is established because of local rupture of the thin and brittle oxide films. Figure 1 schematically shows the end of this stage, when the bonded area is still less than 10% of the entire surface and a large volume of voids and surface oxide remain at the joint interface.

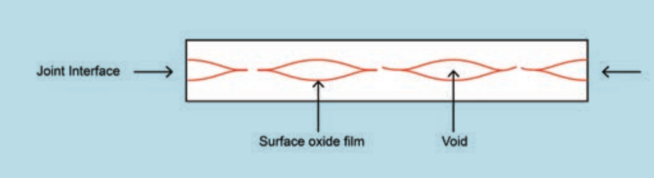

Figure 1: Schematic presentation of joint interface at early stages of solid-state diffusion bonding

In the subsequent stage of diffusion bonding, the thermally activated mechanisms lead to void shrinkage and this increases the bonded areas. According to the *"Diffusion Hypothesis"*, the difference in the energy level of the surface atoms and that of the bulk atoms is the main driving force behind the interatomic diffusion across the joint interface [1].

Figure 2 shows how the use of higher bonding temperatures and/or longer times expedited the annihilation of the voids, hence increased bonded area fraction.

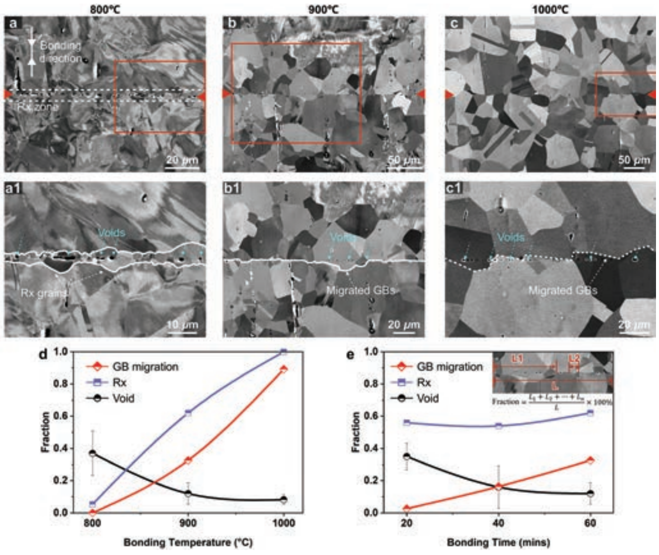

Figure 2: Effect of increasing bonding temperature and time on the reduction of interfacial voids due to recrystallisation (Rx) and grain boundary (GB) migration during diffusion bonding of stainless steel 316L [4]

The joining of dissimilar materials with different thermo-physical characteristics (e.g. aluminium to steel) which is not possible by conventional fusion welding, has been done by solid-state diffusion bonding. Metals, alloys, ceramics and powder metallurgy products also have successfully been joined by solid-state diffusion bonding. However, diffusion bonding dissimilar alloys may result in the formation of undesirable and brittle intermetallics if the bonding temperature and time exceed the optimum levels. In some case interlayers are used to reduce the formation of brittle intermetallics.

Approaches to overcome surface oxide problem

As mentioned above, the presence of surface peaks and troughs (e.g. machining or grinding marks) and native oxide films hinder bringing two faying surfaces within interatomic distances and establishing metal-to-metal contact. The surface waviness and roughness can be improved by polishing and lapping of the faying surfaces. The presence of surface oxide films is a far more challenging issue and this why most of the research work in the field aims to minimise or eradicate the effect of stable surface oxides.

The majority of surface oxide films are brittle and very thin (a few nanometre on a freshly polished aluminium), therefore

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they rupture when the alloy is subjected to a large amount of plastic deformation during SSDB (normally 40% or more). The disruption of the oxide promotes metal-to-metal contact and increases joint strength. Clearly this approach has limited applications due to the substantial deformation of the parts being joined.

Some active alloying elements, such as magnesium and lithium in aluminium alloys, can interact with and break up the continuous and amorphous surface oxide at an interface to form an array of discrete particles. A good correlation between bond strength and the extent of broken oxide was observed, leading to the conclusion that the greater the content of these elements; the greater the disruption of the oxide layer and consequently the higher the bond strengths [2].The effects of active elements in interlayers, inserted in joint, have widely been researched – see [2] for more on interlayer-assisted diffusion bonding.

Several surface preparation methods have been developed which are based on the chemical and non-chemical removal or modification of surface oxide films prior to SSDB process. Using such approaches, excellent solid-state bonds in various alloys have been achieved. As shown in Figure 3, if the surface oxides are removed or modified sufficiently, the bond lines become virtually invisible as the microstructures of the joint interfaces are identical to those of the bulk alloys [5].

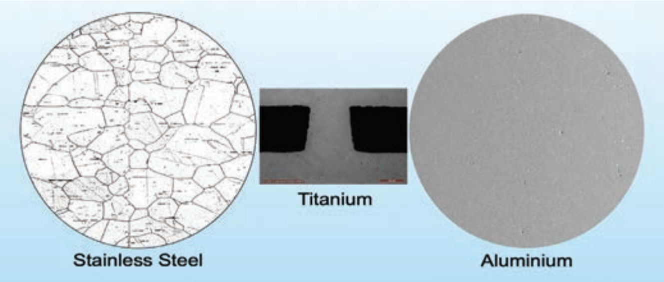

Figure 3: Virtually defect-free bond lines in the diffusion bonded structural alloys

More recently, a new technology is developing to minimise the bonding time and improve the bond integrity by applying cyclically pulsative forces [6]. Alternative approaches include removing surface oxide in high vacuum followed by bonding without exposure to atmosphere.

The complexity of an apparatus capable of in-situ surface oxide removal and bonding renders very limited applications for this method. Interestingly, SSDB is a very promising method for joining materials in space due to ambient high vacuum.

Advantages of SSDB

As demonstrated above, SSDB has the ability to produce high quality and monolithic joints without large defects or porosity [2]. Using optimum bonding parameters (mainly temperature, pressure and time) the joints can have strength and ductility comparable to those of the parent alloy.

Conventional welding of dissimilar alloys or metal-to-ceramic is not possible due to their different thermo-physical characteristics. Capability of joining un-weldable materials is one of the most attractive features of SSDB.

SSDB allows fabrication of high precision component without a need for subsequent machining. Laminated Object Manufacturing (LOM) using diffusing bonding is one of the fastest growing techniques.

Apart from the capital investment, the consumable costs of SSDB are considerably low since no electrodes or flux are required.

Solid-state diffusion bonding is a more environmentally-friendly process than fusion welding processes which generate ultraviolet radiation and gas emission.

Limitations of SSDB

The stringent surface requirement is the most limiting factor. Any excessive oxidation or contamination of the mating surfaces can compromise the joint strength considerably. Therefore, pre-bonding preparation of the mating parts takes much longer times than with conventional welding processes.

The capital investment is very high particularly for bonding large components. For the same reason and due to long bonding times, the viability of this process for mass and cheap production is questionable.

Modelling SSDB

Analytical and more recently numerical modelling of SSDB can considerably reduce a need for costly and lengthy experimental trials [7,8]. For instance, a suitable range of bonding temperature and time can be estimated by conducting a basic analytical modelling. Generally optimisation of bonding pressure requires numerical simulations using Finite Element Modelling and so forth. However, none of the analytical or numerical models take the effect of oxide film in account. Therefore, application of these models remains limited to bonding the metals without stable surface oxides.

Diffusion bonder

A diffusion bonder is essentially a hot press which operates in vacuum. The bonding pressure and temperature are controlled independently. Radiation, conduction or induction heating can be used to heat the parts. Figure 4 shows the main components of a diffusion bonder with an induction heating system. The parts are placed between the lower and upper platens of the bonder surrounded by the water-cooled copper coil. The load is applied by a hydraulic or electric motor actuated piston. The load cell under the lower platen and a thermocouple in touch with the parts measure the load and temperature continuously and provide feedback to the control system. A diffusion or turbo-rotary vacuum pump, backed up by a rotary vacuum pump, is used to evacuate the chamber down to 10^{-3} mbar or lower.

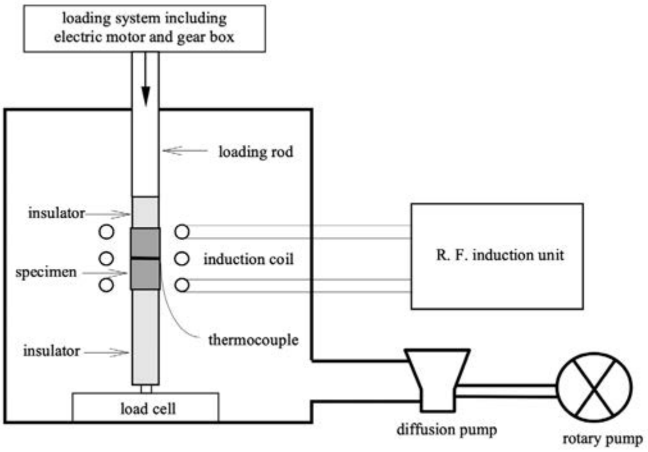

Figure 4: Schematic diagram of diffusion bonder and its peripherals

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Dr Amir Shirzadi has a PhD from the University of Cambridge and holds several patents in Diffusion Bonding. He has established a research lab at The Open University where he develops novel methods for joining un-weldable materials. He is also the Director of Cambridge Joining Technology and Fellow of TWI and IoM^3.

THE SCIENCE OF VACUUM BRAZING: ENSURING STRENGTH, RELIABILITY, AND PERFORMANCE IN JOINT DESIGN

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