Solid-state diffusion bonding

C. Voican [1], C. Stănescu [2]
[1] Technical College of Bucharest, Romania, [2] "Politechnica" University of Bucharest, Romania
E-mail: voicancristiana@yahoo.com

Keywords

Diffusion bonding, solid-state welding, bonding area, metal-metal interface

1. Introduction

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 elevated temperature which aids interdiffusion at the surface layers of the materials being joined [1].

Welding processes can be classified into two main categories:

1. Liquid-phase welding, e.g. all fusion welding processes such as conventional arc welding, laser welding and electron beam welding.

2. Solid-state welding, e.g. forge welding, friction stir welding, explosive welding and solid-sate diffusion bonding.

In the former case, bonds are established by the formation and solidification of a liquid phase at the interface while, in the latter case, the applied pressure has a key role in bringing together the surfaces to be joined within interatomic distances. Although precise details are not known about the actual methods used by early blacksmiths and craftsmen, it is evident that solid-state welding has been used for more than a thousand years. For instance, the famous ancient Japanese and Damascus swords were made by hot forming a piece of high carbon iron into thin strips. Each strip was then folded in two halves lengthwise which were themselves again welded to each other by hammering at high temperatures. This process was repeated tens of times in order to improve the strength and toughness of the swords.

2. Solid-state diffusion bonding

Solid-state diffusion bonding is a process by which two nominally flat interfaces can be joined at an elevated temperature (about 50%-90% of the absolute melting point of the parent material) using an applied pressure for a time ranging from a few minutes to a few hours [2].

Advantages of solid-state diffusion bonding:

a) The process has the ability to produce high quality joints so that neither metallurgical discontinuities or porosity exist across the interface (Figure 1).

b). With properly controlled process variables, the joint would have strength and ductility equivalent to those of the parent material. Failure of the diffusion bonded aluminium samples (bonds 1 and 2) (Figure 2), subjected to tensile force, occurred in the parent alloy (shown by arrows) and away from the bond line.

3). Joining of dissimilar materials with different thermo-physical characteristics, which is not possible by other processes, may be achieved by diffusion bonding. Metals, alloys, ceramics and powder metallurgy products have been joined by diffusion bonding.

Figure 1. Optical micrograph of the diffusion bond in a cobalt-base superalloy, free from flaws, voids and loss of alloying elements

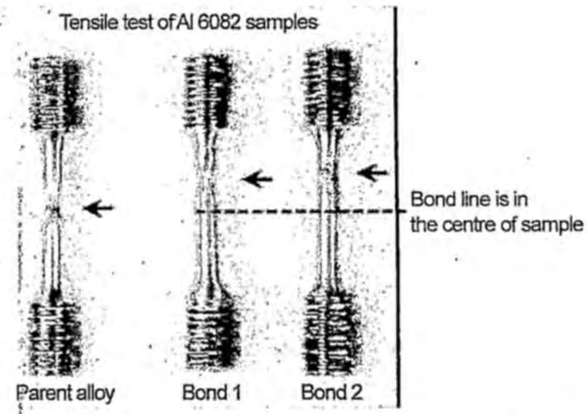

Figure 2. Failure of the diffusion bonded aluminium samples, bonds 1 and 2 diffusion bonded aluminium samples

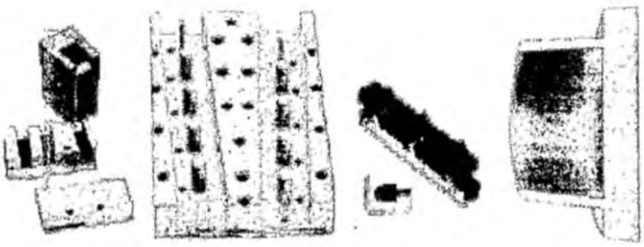

Figure 3. Representative high-precision components which fabricated from aluminium (left) and stainless steel (right) using diffusion bonding.

High precision components with intricate shapes or cross sections can be manufactured without subsequent machining (Figure 3). This means that good dimensional tolerances for the products can be attained.

Apart from the initial investment, the consumable costs of diffusion bonding are relatively low as no expensive solder, electrodes, or flux are required (although the capital costs and the costs associated with heating for relatively long times may be high).

Diffusion bonding is free from ultraviolet radiation and gas emission so there is no direct detrimental effect on the environment, and health and safety standards are maintained.

3. Limitations of diffusion bonding

1. Great care is required in the surface preparation stage. Excessive oxidation or contamination of the faying surfaces would decrease the joint strength drastically. Diffusion bonding of materials with stable oxide layers is very difficult. Production of thoroughly flat surfaces and also precise fitting-up of the mating parts takes a longer time than with conventional welding processes.

2. The initial investment is fairly high and production of large components is limited by the size of the bonding equipment used.

3. The suitability of this process for mass production is questionable, particularly because of the long bonding times involved.

Variants of solid-state diffusion bonding are also referred to by the following terms:

- diffusion welding
- solid-state bonding
- auto-vacuum welding
- isostatic bonding
- hot press bonding
- pressure bonding
- pressure joining
- thermo-compression welding

Problems with solid-state diffusion bonding:

a. The aim in diffusion bonding is to bring the surfaces of the two pieces being joined sufficiently close that interdiffusion can result in bond formation. There are two major obstacles that need to be overcome in order to achieve satisfactory diffusion bonds.

b. Even highly polished surfaces come into contact only at their asperities and hence the ratio of contacting area to faying area is very low.

c. In most metals, the presence of oxide layers at the faying surfaces will affect the ease of diffusion bonding. For some metals and alloys, their oxide films either dissolve in the bulk of the metal or decompose at the bonding temperature (e.g. those of many steels, copper, titanium, tantalum, columbium and zirconium), and so metal-to-metal contact can be readily established at the interface. The joining of these materials is relatively straightforward and is not included in this review. However, if the oxide film is chemically stable, as for aluminium-based alloys, then achieving a metallic bond can be difficult.

In practice, because of inevitable surface roughness and also the presence of oxide layers on most faying surfaces, it is neither feasible to bring together the surfaces of two pieces within interatomic distances nor to establish complete metal-to-metal contact by simply putting two pieces together. See Ref. [3] for various aspects of the effects of surface oxides on interface morphology and bond strength, and a summary of the existing approaches used to overcome the oxide problem.

4. Mechanism of solid-state diffusion bonding

During the first stage, the asperities on each of the fay ing surfaces deform plastically as the pressure is applied. These asperities arise from the grinding or polishing marks that have been produced in the surface finishing stage (Figure 4).

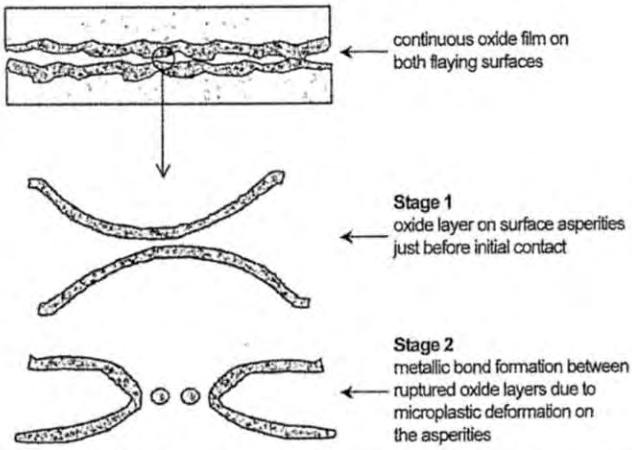

Figure 4. The mechanism of solid-state diffusion bonding can be classified into two main stages

The microplastic deformation proceeds until the localised effective stress at the contact area becomes less than the yield strength of the material at the bonding temperature. In fact, initial contact occurs between the oxide layers that cover the faying surfaces.

As the deformation of asperities proceeds, more metal-to-metal contact is established because of local disruption of the relatively brittle oxide films which generally fracture readily. At the end of the first stage, the bonded area is less than 10% and a large volume of voids and oxide remains between localised bonded regions.

In the second stage of bonding, thermally activated mechanisms (creep and diffusion) lead to void shrinkage and this increases further the bonded areas.

5. Diffusion bonding makes waves

The joining of aluminium and aluminium base alloys to themselves and to other metals has long created problems because of the tenacious layer of surface oxide which is always present.

The difficulties become more acute when melting of the components to be joined is not an option. Shirzadi and Wallach have recently developed a technique for diffusion bonding such materials (Figure 5).

Some advanced materials cannot be welded by conventional techniques because the high temperatures involved would destroy their properties. For such materials, diffusion bonding is an attractive solution because it is a solid state joining technique, which is normally carried out at a temperature much lower than the melting point of the material.

For joining aluminium alloys, insertion of a thin copper or zinc interlayer, allows a low melting point eutectic phase to be formed at a temperature about 100°C lower than the melting point.

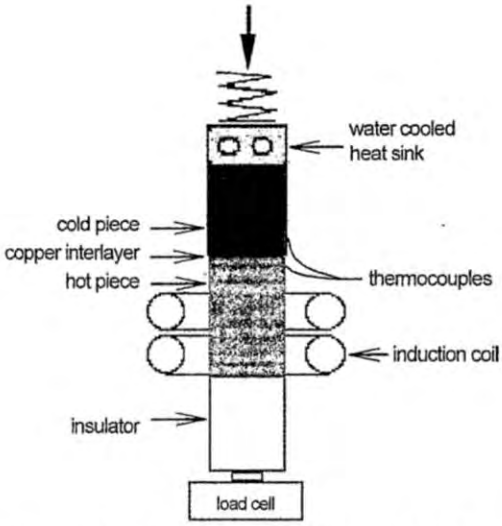

Figure 5. Equipment used for temperature gradient diffusion bonding

Even with this technique, the bond strengths produced are lower than the parent metal because of the planar bond interface which contains oxides and included particles.

6. Conclusions

The new technique is based on imposing a temperature gradient across the surfaces to be joined to produce a non-planar (sinusoidal) interface which effectively increases the bonding area or metal to metal interface. This is an exciting development, as it is possible to change the shape of the interface from being planar to cellular, and up to fully dendritic depending on the temperature gradient imposed.

Shear test results on aluminium-based composites and alloys show shear strengths up to parent metal values. It is anticipated that this technique can be used for joining dissimilar metal combinations, metal matrix composites and possibly nickel based materials.

References

[1] Singer, C., Holmyard, E.J., Hall, A.R. and Williams, T.I. (1958): A History of Technology, Oxford University Press.

[2] Kazakov, N.F (1985, English version): Diffusion Bonding of Material, Pergamon Press.

[3] Shirzadi, A.A. and Wallach, E.R. (2004): A new method to diffusion bond superalloys, Science and Technology of Welding and Joining, Vol. 9, No. 1, pp 37-40.

Lecture presented at the 5th International Conference "Innovative Technologies for Joining Advanced Materials", Timisoara - Romania (June 16-17, 2011)