Solid State Diffusion Bonding Process—A Review

Aravinda T 1*, Dr. Niranjan H B 2, Dr. Satish Babu B 1, Dr. Udaya Ravi M 1

1 School of Engineering, Presidency University/Department of Mechanical Engineering, Bengaluru, India
2 Sambhram Institute of Technology/Department of Mechanical Engineering, Bengaluru, Karnataka, India

*Email: sagar.aravind@gmail.com

Abstract—The present paper reports on the various diffusion bonding techniques using atomic diffusion of elements at the interface. The bonding process is used mainly for joining dissimilar metals. However, two similar metals can also be bonded with or without using an interlayer. Dissimilar materials include metal-ceramic; interlayer can also be used if necessary, in between the interfaces. The other methods of joining would probably interfere with the microstructure of the base metal at the point of interface. Various methods of joining like welding create reaction between the materials in the molten pool. Residual stresses would not appear at the bonding site, neither has it created thermal gradients using diffusion technique. Distortion observed in diffusion bonding is quite less compared to other joining process. It is also observed that the interface retains similar mechanical and physical properties as that of the base material. The strength at the interface depends on parameters like temperature, pressure and time taken for contact while forming the solid state bond.

Keywords: — Diffusion Bonding; Interlayer; Interface;

1. Introduction

Aluminium matrix composites (AMCs) are prospective materials for innumerable applications owing to their good physical properties. Several reinforcements can be added to AMCs in order to increase their mechanical properties [1-3]. Nowadays, structural materials in vehicles are being replaced by composite materials [4]. The idea of diffusion bonding to join MMCs is extensively used since there are complications of using conventional methods during fusion process [5]. These were problems related to formation of brittle phases during the interfacial reactions between the matrix alloy and reinforcements. Processes like fusion welding are not feasible for joining of composites. Metal Matrix Composites (MMCs) may not mix with metals owing to decreased flowability of the welding pool and viscosity [6]. There is also an undesirable chemical reaction between reinforcement and matrix which is undesirable. Flaws like porosity are commonly observed in solidified form. A review is made on the recent developments involving diffusion bonding processes.

2. Diffusion bonding involving powders:

Ji-hua Huang et al. [7] used Al-Cu and Al-Si powders during the reactive bonding of SiCp/6063 MMCs. Slurries were prepared by mixing suitable powders of Cu, Si, SiC and Al powders with ethanol in required proportions. SiCp/6063 MMC were then coated by the slurries prepared. Finally, reactive bonding process was performed under a definite temperature and pressure for a specified time under a vacuum. The interlayers formed by the powders were found to have a dense joining layer. A hypoeutectic microstructure was observed in the bonding. Upon close observation, they could find porous zones in large numbers in the site of joining layer. This could bring down the shear strength of the joints.

Urena et al. [8] used AA2024 alloy, reinforced with SiC particles with a volume % of 13. The composite was prepared by using compo casting process. A 13 mm thick plate was extruded to perform the diffusion process. The specimen surfaces were thoroughly mechanical grinded with SiC particles embedded in the emery sheets. The material was then degreased using ultrasonic waves in an acetone bath. An aluminium-lithium alloy in the form of a foil was used as an interlayer. A temperature of the range of 480 to 520° C, pressure between 3-6MPa and time of 60-120 min was
maintained during the entire process. Vacuum was used to stop oxidation if any. Microstructural characterization was carried out using SEM and mechanical tests were conducted on the bonded specimen using Universal Testing Machine (UTM). Urena et al. concluded that if higher deformations were used with thickness reductions up to 25%, the Aluminium-Lithium layer would plastically flow thereby reducing voids from bonding interfaces. The maximum shear strength of 50 MPa was recorded under normal conditions of applying deformation at 12%, however no much increase was observed even though the bonding deformation was increased to 25%.

Janghorbhan [9] successfully produced multilayered ceramic-metal composites using polycrystalline alumina and different Al alloys through solid state diffusion bonding. The composites were fabricated at a temperature of 610°C. A 2-hour duration time was used under a compressive stress of 3 MPa. A spinel structure was observed for one of the composites containing Mg and Si in the alloy. However, another phase that is rich in Si and Mg was also noticed.

Several researchers [10-11] have reported that the bonding interface between matrix/matrix is mainly responsible for obtaining better joint during composite diffusion welding compared to reinforcement/reinforcement and matrix/reinforcement. The welding joint produced by diffusion, hinders to have a strong joint at the interfaces mentioned. Liu Liming et al. [12] worked on the welded joint for the composite Al2O3p/Al 6061 and predicted the existence of a critical temperature at the matrix/reinforcement interface. The composite exhibited better diffusion bonding at the critical temperature. The bonding at the critical temperature involved all the three interfaces namely reinforcement/matrix/reinforcement.

3. Diffusion bonding involving metal alloys in a solid form:
Mojtaba Jafariana et al. [13] worked on the interfaces of joints involving AZ31-O Mg and Al 6061-T6 diffusion bonding. Mechanical properties like hardness were measured using a standard hardness tester. A thermally O and T6 tempered aluminium alloy was used for the aluminium and magnesium joints. Diffusion of maximum number of magnesium atoms occurred to aluminium alloy while using AZ31-Mg/Al-6061-O. A micro hardness of 140 HV was observed in the diffusion zone. However, failure was observed while evaluating fracture surfaces from brittle intermetallic phases.

The difficulty in joining dissimilar metals like magnesium-aluminium is due to the formation of brittle intermetallic and oxide films in the joint region. Mahendran et al. [14] discusses about joining magnesium-aluminium through diffusion bonding technique. However, three main variables are responsible for the integrity of the bond namely, reaction time, pressure and temperature. Hardness and strength of the dissimilar joint was found out using response surface method and concluded that reaction temperature is mainly responsible for the strength of the joint.

Seyyed Salman Seyyed Afghani et al. [15] studied on the diffusion bonding method involving dissimilar alloys of Al 7075 and Mg AZ31. A pressure of around10-35 MPa, temperature of 430-450 °C with a reaction time of 60 min were selected as process parameters under a vacuum of 13.3MPa. The interfacial transition zone was characterized using energy-dispersive X-ray Spectroscopy (EDS), X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM), and found the presence of interfacial compounds, such as Al3Mg, Al12Mg17, and α(Al) solid solution. With increasing temperature, there was an increase in diffusion of aluminium atoms in to magnesium alloy. Fractographic analysis indicated predominantly of brittle and cleavage type, with cracks propagating from the brittle phase of Al3Mg2.

4. Diffusion bonding involving interlayers:
Jian Zhang [16] Used Ni interlayer while joining magnesium and aluminium through diffusion bonding technique. A vacuum furnace was used under a pressure of 1 X 10-3 Pa to hold the Mg-Ni-Al assembly. A reaction temperature of 673, 683, 703, 713, 723 and 733 K was used for 90 min. The results suggested that the interlayer was responsible to eliminate the formation of Al-Mg interfacial compounds. The micro hardness was recorded at 255 HV due to the presence of Mg2Ni phase. With
increasing reaction temperature, the shear strength of the diffusion joints increased and then gradually decreased.

A copper foil was used as an interlayer by Nami et al. [17] in between two samples of insitu processed Al/Mg2Si composite prepared through gravity metal mold casting. The composite with the interlayer was placed in a vacuum chamber (30Pa) and the bonding was carried out at 540 °C for a time duration of 90, 120 and 150 min at a pressure of 6 MPa. The shear strength of the prepared samples increased with increasing bonding duration.

5. Diffusion bonding involving glass as substrate:
Field-assisted diffusion bonding is used as a major process during the preparation and assembly of pressure sensors, microfluidic devices and accelerometers [18- 19]. Liu CR et al. [20] worked on the field assisted diffusion bonding process of glass wafers with aluminium foils. A three layer sample of glass/aluminium/glass was placed in an oven so that the two glass wafers were connected to the negative electrode and aluminium film was electrically to the positive electrode. A temperature of 350-450°C and voltage of 400-700 V was used under a pressure of 0.05MPa. The bonded material showed an increase in tensile strength with increasing temperature and applied voltage.

6. Importance of process parameters in diffusion bonding:
Reference maps were prepared by Balasubramanian et al. [21] for aiding welding and design engineers while selecting proper diffusion bonding parameters. Temperature–time and pressure–time diagrams were treated as diffusion bonding windows while working on diffusion bonding of magnesium and aluminium alloys. To predict lap shear strength of the bonded joints, empirical relationships were developed. Further, to optimize the parameters involved in diffusion process, response surface methodology was used.

7. Conclusion
Diffusion bonding could be used efficiently to join substrates in powder form/solid form with metal alloys. Diffusion bonding can be used to overcome the problems associated with fusion welding. Process parameters like temperature, pressure and holding time play a vital role in the diffusion bonding phenomenon. A critical temperature was recorded for the bonding process for getting an ideal bond. Shear strength and tensile strength of the joints was directly dependent on the reaction temperature used during the bonding process. Diffusion bonding technique at a critical temperature aids in having an efficient joint since all the interfaces like reinforcement/matrix/reinforcement are involved in the joining process unlike in conventional diffusion welding joining process.

8. Conflict of Interest
"The authors declare no conflict of interest".

9. Author Contributions
Aravinda collected information from various research related papers; Niranjan analyzed the paper; Aravinda, Udaya Ravi and Satish wrote the paper; all authors had approved the final version.

10. References
[1] Boppana, S. (2020) In Situ Synthesis of Titanium Carbide in Pure Aluminium. Journal of Materials Science and Chemical Engineering, 8, 1-10. doi: 10.4236/msce.2020.81001.
[2] Boppana, S.B., Dayanand, S. Impact of Heat Treatment on Mechanical, Wear and Corrosion Behaviour of In Situ AlB2 Reinforced Metal Matrix Composites Produced by Liquid Metallurgy Route. J Bio Tribo Corros 6, 33 (2020). https://doi.org/10.1007/s40735-020-0324-7.
[3] Boppana, Satish Babu, Samuel Dayanand, MR Anil Kumar, Vijee Kumar, and T. Aravinda. "Synthesis and characterization of nano graphene and ZrO2 reinforced Al 6061 metal matrix composites." Journal of Materials Research and Technology 9, no. 4 (2020): 7354-7362.
[4] Guruprasad T, Satish B, Maruthi B, Pramod K, Manjunatha H. Bus body structural strength analysis through FEA. Int. J. Technol. Res. Eng, vol. 2, pp. 2494-8, July 2015.
[5] Partridge PG, Dunford DV (1991) The role of interlayers in diffusion bonded joints in metal-matrix composites. J Mater Sci 26: 2255-2258.
[6] Zhang XP, Ye L, Mai YW, Wei GF (1999) Investigation on diffusion bonding characteristics of SiC particulate reinforced Al metal matrix composites. Compos A 30: 1415-1421.
[7] Jihua Huang, Yueling Dong, Jiangang Zhang, Yun Wan, Guoan Zhou (2005) Reactive Diffusion Bonding of SiCp/Al Composites by Insert Powder Layers with Eutectic Composition. J Mater Sci Technol 21(5): 779-781.
[8] Urena A, Gomez de Salazar JM, Escalera MD (1996) Diffusion bonding of an aluminium-copper alloy reinforced with silicon carbide particles using metallic interlayers. Ser Mater 35(11):1285-1293.
[9] Janghorbhan K (2009) Multilayer diffusion bonding of polycrystalline Al2O3 to Al alloys containing Sr, Mg and Si. Iran J Sci Technol B, 33 (B3): 241-251.
[10] Ellis MBD, Joining of aluminium based metal matrix composites (2013) Int Mater Rev 42 (2): 41-54.
[11] Liu YL (1996) A study on flow stress of Al-SiC composites deformed in a large range of strain. Scr Mater 35: 253-259.
[12] Liu Liming, Zhu Meili, Pan Longxiu, Wu Lin (2001) Studying of micro-bonding in diffusion welding joint for composite. Mater Sci and Eng A 315: 103–107.
[13] Mojtaba Jafariana, Mohsen Saboktakin Rizib, Morteza Jafariand, Mehrdad Honarmande, Hamid Reza Javadinejadb, Ali Ghaherib, Mohammad Taghi (2016) Effect of thermal tempering on microstructure and mechanical properties of Mg AZ31/Al-6061 diffusion bonding. Mater Sci and Eng A 666:372-379. http://dx.doi.org/10.1016/j.msea.2016.04.011.
[14] Mahendran G, Babu S, and Balasubramanian V (2009) Analyzing the effect of diffusion bonding process parameters on bond characteristics of Mg-Al dissimilar joints. J Mater Eng Perform 19(5):657-665.
[15] Seyyed Salman Seyyed Afghani, Mojtaba Jafrian, Moslem Paidar, Morteza Jafarian (2016) Diffusion bonding of Al 7075 and Mg AZ31 alloys: Process parameters, microstructural analysis and mechanical properties. Trans. Nonferrous Met Soc. China 26:1843-1851.
[16] Jian Zhang, Guo-Qiang Luo, Qiang Shen, Lian-Meng Zhang, Zhi-Jun Huang (2016) Characterization of diffusion-bonded joint between Al and Mg using a Ni interlayer. Rare Met 35(7): 537-542.
[17] Nami A, Halraee A, Adgi H, Hadian A (2010) Investigation on microstructure and mechanical properties of diffusion bonded Al/Mg2Si metal matrix composite using copper interlayer. J Mater Process Technol 210: 1282-1289.
[18] Wallis G, Pomerantz DI (1969) Field assisted glass-metal sealing. J Appl Phys 40 (10):3946-3949. https://doi: 10.1063/1.1657121.[19] Shoji S, Kikuchi H and Torigoe H (1998) Low temperature anodic bonding using lithium aluminosilicate-p-quartz glass ceramic sensors. Sens Actuators A 64:95-100.
[20] Liu CR, Zhao EJF, Lu XY, Meng QS, Zhao YP, Munir ZA (2008) Field-assisted diffusion bonding and bond characterization of glass to aluminum. J Mater Sci 43:5076–5082.
[21] Balasubramanian V, Joseph Fernandus M, Senthilkumar T (2013) Development of processing windows for diffusion bonding of aluminum/magnesium dissimilar materials. Weld World 57:523-539. https://doi.org/10.1007/s40194-013-0048-0.