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Technical Paper

An investigation on joining of Al6061-T6 to AZ31B by microwave hybrid heating using active braze alloy as an interlayer

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ABSTRACT

Active braze alloy is used as an interlayer material to join AZ31B to Al6061-T6 by microwave hybrid heating. The phase compositions of the reaction layer and the microstructure aspects are investigated using Scanning Electron Microscopy (SEM), Energy Dispersive X-Ray spectroscopy (EDX) and X-ray diffraction (XRD). Intermetallic compounds of Aluminum, Magnesium, Silver and Oxygen i.e. $Mg_{55}Al_{40}Ag_5$, $Al_{60}Mg_{38}Ag_2$, $MgAl_2O_4$ and TiO were found to be formed in the reaction layer. Hardness of intermetallic towards the aluminum parent material is high i.e. 4.31 GPa. This is due to the formation of intermetallic that are brittle and hard in nature. The tensile shear strength of the joint was evaluated. The formation of intermetallic compounds i.e. $Al_{60}Mg_{38}Ag_2$, $MgAl_2O_4$ and TiO are responsible for the poor strength.

1. Introduction

The application of Aluminum (Al) alloys and Magnesium (Mg) alloys in automobile and aerospace industries have been expanding by the virtue of low density and high specific strength. Moreover, the damping property of Mg and the creep resistance of Al has boosted the application of these alloys which makes the joining of Al and Mg alloys as the requisite.

Several researchers have employed different processes like diffusion bonding [1–4], resistance welding [5], Tungsten inert gas welding [6], Friction Stir Welding [7–9], Laser Welding [10,11], Laser weld bonding [12–14] to join Aluminum alloy to Magnesium alloy. All these processing routes have confirmed the formation of brittle intermetallic compounds (IMCs) such as Al_3Mg_2 and $Al_{12}Mg_{17}$ in the transition zone. To prevent the formation of Aluminum- Magnesium IMCs the most widely used method is to insert an interlayer between the two. Many materials like Ni, Zn, Fe, Ag, Sn, Ti and Cu have been used as interlayers and the strength of the joint is reported to have improved [15–22].

The use of Microwave Hybrid heating for processing of metals has gained recent interest owing to less power and time consumption [23]. This is because of the fact that microwave energy is directly converted into thermal energy by molecular interaction of atoms with the electromagnetic field. When microwaves are incident on matter they are absorbed or the power is dissipated into the matter in the form of heat. The dielectric response of a material is represented by loss tangent or the efficiency of the material to convert absorbed energy into heat [24]. The loss tangent (tan δ) is given by

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{1.1}$$

Where,

ε'' = dielectric loss factor (ability of the matter to store energy)

ε' = permittivity (ability to material to polarize on application of electric field)

Microwave energy has found many applications in sintering, joining, chemical synthesis of different materials like ceramics, polymers and biomaterials [25].

In metals and most conductors the conversion of electromagnetic field energy to thermal energy occurs in a very thin layer. This thickness is termed as skin depth, d.

$$d = \sqrt{\frac{\rho}{\pi f \mu_0 \mu'}} \tag{1.2}$$

Where,

ρ = electrical resistivity of a material

f = frequency of the alternative magnetic field

$\mu_{o=}$permeability of free space

μ' = permeability (response of material to a magnetic field)

Higher the permeability, lesser will be the penetration of electromagnetic wave into the material. However with the increase in

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temperature the resistivity of the metal increases due to more rapid vibration of electrons resulting in more collisions of the electrons, thus increasing skin depth. Effect of microwave on heating metal powders was first observed by Walkiewicz et al. [26] in the year 1988 where he exposed many materials, including many metals. They reported partial heating of metal powders up to 228 °C for Cu and 384 °C for Ni. Roy et al. [23] in 1999 accomplished full sintering of metal powders by microwave of 1.4 kW power where finer microstructures and better properties could be obtained at lower cost. Subsequently, successful application of microwave energy for sintering of metal powders have been reported [27–30]. Although the application of microwave hybrid heating has been applied majorly for joining similar bulk metals [31–36], yet the use of this technology has not been frequented for joining dissimilar metals. Srinath et al. [37] have reported the successful metallurgical joining of stainless steel to mild steel along with complete melting of the powder interface layer by microwave hybrid heating. The ultimate tensile strength achieved by them was 346.6 MPa. Microwave brazing of Shape memory alloys to nickel alloy and to Stainless steel was investigated by Van Der Eijk et al. [38]. They concluded that the formation of sound metallurgical bond owed to the presence of active metal (Ti) in Ag- based braze alloy. They also reported various phases of AgNiTi and CuNiFeTi on the brazed area.

In this work, the feasibility of using an alloy of Titanium, Copper and Silver (TiCuSil) as an interlayer, for joining of Al6061–T6 to AZ31 B by microwave hybrid heating is investigated. The active metal alloy (TiCuSil) is used with a desire to prevent formation of Al-Mg IMCs. This paper discusses the phenomenon of joining of bulk metals by microwave hybrid heating, emphasising on the effect of microwave on the formation of intermetallic compounds. The time for microwave irradiation was varied and the joint was investigated by SEM, EDS and XRD. Intermetallic compound formation such as $Mg_{55}Al_{40}Ag_{5}$, $Al_{60}Mg_{38}Ag_{2}$, $MgAl_2O_4$ and TiO was observed. In addition the physics behind the joining of bulk metals by microwave hybrid heating is contained in the discussion.

2. Method

Aluminum (Al) alloy Al6061-T6 and Magnesium (Mg) alloy AZ31B samples of dimensions $26 \times 8 \times 6\,mm^3$ were prepared for this study. The samples were first ground flat by SiC paper of grade P220, P600 and P1200 and ultrasonically cleaned with ethanol in order to remove and impurities of the surface before joining. An interlayer of TiCuSil paste of average size 150 mesh (The Prince & Izant Companies) were applied between the Al alloy and Mg alloy and the assembly is clamped together with a pressure of approximately 15 MPa. Prior to this, a SEM micrograph (Fig. 1) of the TiCuSil powder were obtained using Zeiss EVO 50. Initial trials were carried with different crucibles of Alumina, Alumina-Silica and graphite and different susceptors like charcoal, graphite and α-SiC with varying time. For the same amount of time, when charcoal was used as a susceptor the interlayer only was partially melted. It was observed that the graphite crucible with graphite powder produced the best joint in the least amount of time. This is because of the concentration and redistribution of microwaves towards the graphite susceptor inside the cavity [39,40]. High heating rate while using graphite susceptor is due to the formation of microplasma [41] and the same is attributed to the joint formation.

The assembly was placed in a graphite crucible and surrounded by graphite powder. The total assembly was covered by alumina wool which acts as insulator. The crucible was placed inside a domestic microwave oven (IFB make 700W) as shown in Fig. 2. The microwave power was given for 7–10 mins and the detailed experiments are given in Table 1. Successful joints are cut across the cross-section of the joint region by abrasive precision cutting machine (Buehler ISOMET 5000). The microstructural analysis is done by Leica optical microscope followed by SEM images of the joint are taken by Zeiss EVO 50. Energy Dispersive X-Ray spectroscopy (EDX) is done by RONTEC's QuanTax 200 model. X-ray diffraction (XRD) analysis of the reaction region of the joint is done by Rigaku Ultima IV type II instrument having Cu-Kα radiation. A Nano Hardness Tester with a Berkovich diamond indenter was used to measure hardness across the joint region. Shear strength of the joint is also measured by Instron 5582 machine UTM machine. The Al6061-T6 and AZ31 B alloy of dimension $32 \times 8 \times 6\,mm^3$ were placed with an overlapping width of 20 mm and a crosshead velocity of 1 mm/min. 10 specimens were tested that were prepared using the best input parameter observed. The fractured surface was then observed under Field Emission Scanning Electrode Microscopy (FESEM) by FEI (model Quanta 200 F SEM).

Fig. 1. SEM image of the TiCuSil particles.

Table 1
Experiment details.

Exp. No.	Time (sec)	Result
1.	420 (7 min)	No joint
2.	480 (8 min)	No joint
3.	510 (8 min 30 s)	Joint successful but less strength
4.	525 (8 min 45 s)	Joint successful
5.	540 (9 min)	Joint burnt

3. Mechanism of joint formation

Microwave is absorbed by the graphite susceptor and it starts coupling with microwaves. The attenuated microwaves are reflected back from the dissimilar metal assembly initially. Also the interlayer thickness is very small ~150 µm for microwave to pass through. The heat generated in the graphite susceptor is transferred by conventional heat transfer to the interlayer assembly underneath. When the temperature of work piece increases, the penetration depth increases [42]. The microwave attenuates to the interlayer and starts coupling with the metal powder (TiCuSil). Thus heating of the interlayer by susceptor will increase the microwave heating capability of the interlayer. This heats up the interlayer rapidly compared to the bulk Al6061 and AZ31 B thus forming a metallurgical joint by microwave hybrid heating.