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Solid state diffusion bonding of Al2024 sheets

Joining of similar metal sheets of Al-2024 with and without hematite ore particulates in between the sheets was performed through the solid-state diffusion bonding process by means of compression testing machine. During joining process, heat was applied to the specimen through the customized die in which electric heating elements were inserted. The specimens were subjected to continuous compressive plastic deformation by using compression testing machine for different holding times. Microstructural analysis confirms that solid-state bonding depends on the process parameters used. Tensile testing result shows that, strength of the joint increases with increase in holding pressure and time.

Keywords: Diffusion bonding, interlayers, tensile strength

1.0 Introduction

Mass reduction for military, aerospace and automobile applications is crucial to reduce fuel consumption, and exhaust emissions. For electric vehicles, decreasing weight increases their driving range. Aluminium based alloys being lightweight are considered for military, aerospace and automotive stricture building application (Wang et al., 2008; Yan et al., 2008). Solid-state diffusion bonding (DB) is a technique through which flat interface joints can be produced at higher temperatures by applying a specific pressure for a time period varying from a few minutes to a few hours without degrading the properties of material. However, DB of aluminum alloys in open air environment is challenging (Lee et al., 1999). Especially, formation of aluminium oxide film layer (Al_2O_3) on faying interface of metals which can significantly reduce joint strength. More reliable joining method is what most of the industries are looking for to allow application of aluminum-based alloys in military, aerospace and automobile industry. Further, it is noted that during the recent years, composite materials produced through diverse techniques (Boppana, 2019; Boppana and Dayanand, 2020a; Boppana et al., 2020b; Guruprasad et al., 2015) have been used in various applications. There is a constant demand to fabricate materials through diverse strategies.

The main problem associated with the DB of aluminium based alloys is presence of surface oxide film on the mating surfaces. This surface oxide film hampers the joining process by acting as obstacle for the formation of bonding across the surfaces (Kazakov, 1985). Moreover, the surface oxide layer has limited solubility in base metal and is very stable even at elevated temperatures. In order to extend the application of aluminium based alloys, many processes have been adopted. To overcome these drawbacks related to the presence of oxide film layer on the surface, few methods had been recommended and investigated. In general, these techniques may be categorized into (a) the use of vacuum (b) the use of protective atmosphere (c) the use of interlayers and (d) situ surface treatment; however, these techniques are also used in conjunction with each other (Kenevisi et al. 2013; Urena et al., 2000; Kurgan, 2014; Huang et al., 2007).

The techniques mentioned above are most effective in eliminating the oxide film layer from the faying surface and result in good quality joints. However, simpler methods which can produce cost effective products would be more desirable. In this article we report the new customized die design to produce DB products by using compression testing machine in open air environment.

2.0 Experimental work

Commercially available Al2024-T0 sheet of 1.6 mm sheet were cut into strips of 25.4 mm width, and 101.6 mm length for lap joining, as shown in Fig.1. The chemical composition of Al2024-T0 sheets is listed in Table 1. The DB experiment was conducted using a custom-made die installed in a compression testing machine (Model CTM-2000KN, Datacone), as illustrated schematically in Fig.2. Temperature controller was integrated into DB system to provide heat source to the dies. The dies were made up of tool steel. Specimens are placed between the dies and the complete experimental set up is shown in the Fig.2.

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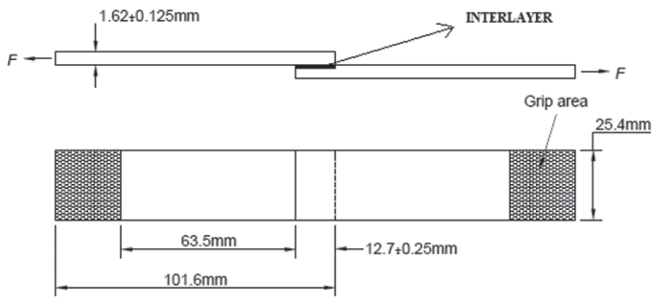
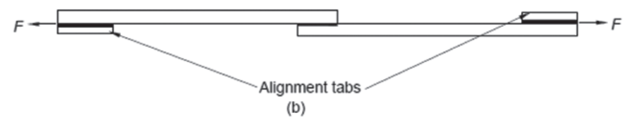
TABLE 1: CHEMICAL COMPOSITION OF ALUMINUM ALLOY 2024-T0

Elements	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Wt. %	0.4	0.4	4.128	0.488	1.37	0.09	0.11	0.09	Balance



(a) Single -lap joint



(b)

Fig.1: Configuration of the joint

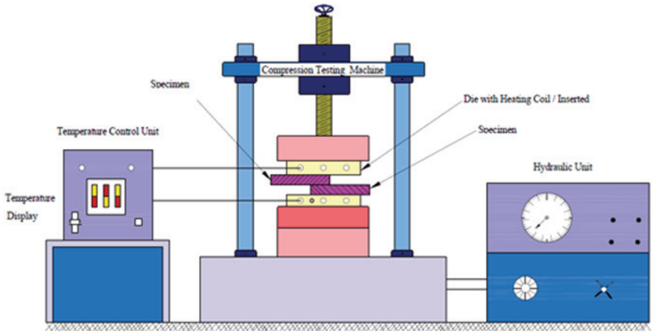


Fig.2: Schematic diagram of the experimental set-up

DB was carried out using a compression testing machine with and without the interlayer. The specimens were prepared by setting the temperature at 400°C with different loads and holding time which are tabulated in Table 2. Very few studies have been conducted on DB method in open air mainly because of oxide layer formation which will restrict the bond formation at the interface (Zuruzi et al., 1999; Barrena et al., 2009; Bushby and Scott, 1995; Matsumae et al., 2018). The DB process parameters are being selected based on the literature survey. A DB temperature of 400°C is found to be more suitable for aluminium alloy 2024-T0, as shown by trial runs results. Consequently, DB temperature of 400°C is used in during the process. In present work, DB holding time of 20, 25 and 30 min were considered based on results of trial run. Initially, specimens were arranged with joint configuration as shown in Fig.1. The specimens were placed carefully between the dies with joint set up such that grind marks produced on the surfaces were parallel. The temperature is gradually increased till it reaches set temperature and allowed to stabilize for 10 min. Once temperature reaches steady state, compressive load is applied by using compression testing machine under different holding times. All the specimens were prepared by applying compressive load on the area of 12.7 mm length × 25.4 mm width as shown in Fig.1.

The selected holding pressure is related to the compressive yield stress of the material. Nevertheless, the application of pressure that is equivalent to the yield stress was found to be insufficient and pressure greater than the yield stress value was utilized for majority of the specimens. In this study, a load of 80, 100 and 120 kN were selected based on the trial run. Prior to the joining process, specimens were ground with P80-grit size sand paper to produce rough surface (Zuruzi et al., 1999) and treated with acetone and ethanol to remove oil and any other contaminations on the faying surface of specimen (Kazakov, 1985). Surface preparation is major for successful bonding of specimen at the interface (Gouge and Chandel, 2005).

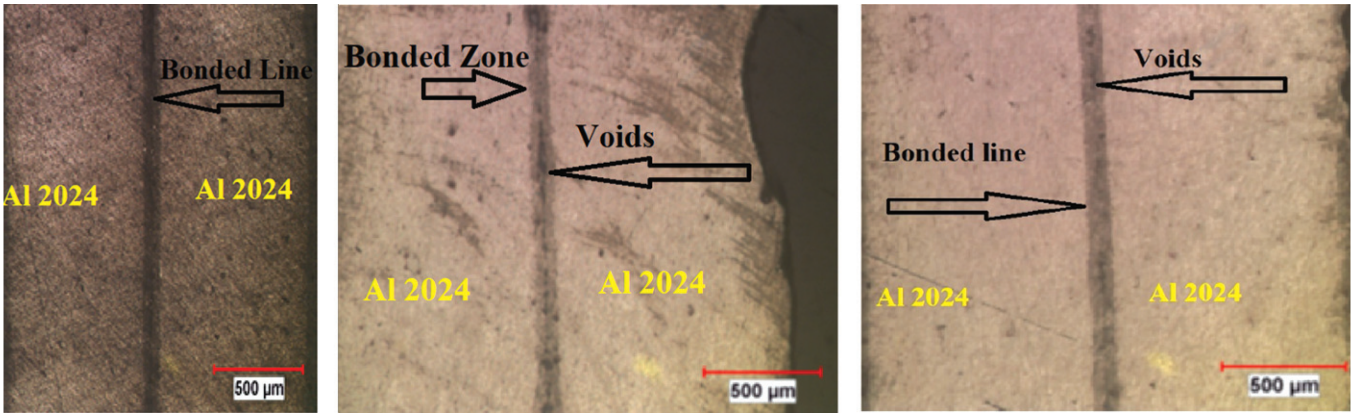
The specimen was placed in the die in lap joint configuration and the temperature was gradually increased through temperature controller unit till it reached the set temperature and allowed to stabilize for 10 min. Once the temperature is stabilized, compressive load is applied on the specimen through compression testing machine for a specific duration of time. Load was gradually released and specimens were taken out from the die and cooled in open air room temperature. Through this procedure, Al2024-Al2024 and Al2024-Fe_2O_3-Al2024 joints were prepared with various combinations of pressure, holding time and temperature.

2.1 TEST MATERIALS USED

The specimen material used in the present work is commercially available Al 2024-T0 sheet of 1.6 mm thick sheet. Al 2024-T0 is to be joined by using DB processes using powders of Fe_2O_3 (45µm in size with 2% weight fraction) as interlayers; and others without using Fe_2O_3 interlayers at

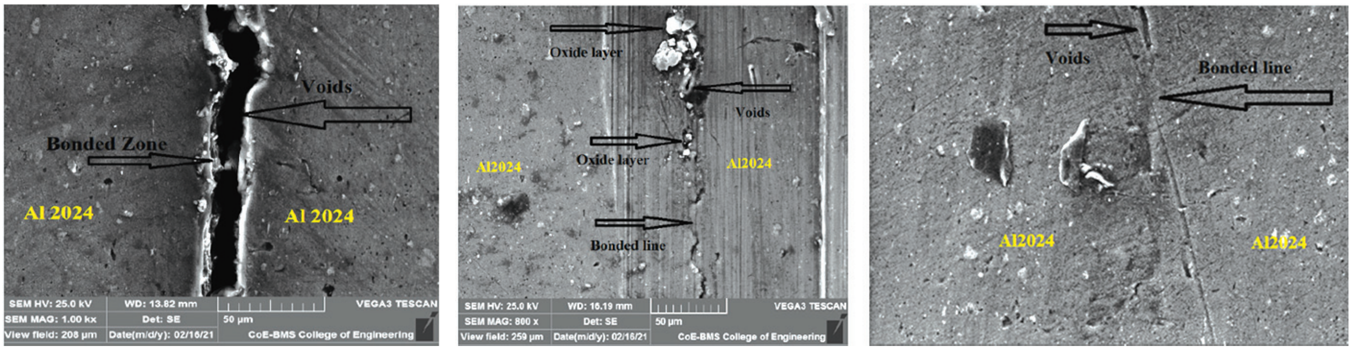
TABLE 2: PARAMETER SETTINGS TO BOND AL2024-T0 SHEETS WITH AND WITHOUT INTERLAYERS

Specimen name	Process parameters (holding temperature/ holding load/ holding time) (°C/KN/min)	Interlayer
S1	400, 80, 20	None
S2	400, 100, 25	None
S3	400, 120, 30	None
S4	400, 80, 20	Fe_2O_3
S5	400, 100, 25	Fe_2O_3
S6	400, 120, 30	Fe_2O_3



(a) 400°C, 80 kN, 20 min (b) 400°C, 100 kN, 25 min (c) 400°C,120 kN, 30 min

Fig.3: (a) (b) (c) Optical microscope images of joints processed at different process parameterswithout using interlayers



(a) 400°C, 80 kN, 20 min (b) 400°C,120 kN, 25 min (b) 400°C, 120 kN, 30 min

Fig.4: (a) (b) (c) SEM images of the bonded samples without using interlayer

different bonding conditions in open air environment. The material to be diffusion bonded in this work was cut into sample of size 24.4mm × 101.2 mm × 1.6 mm. The slurry was prepared by mixing Fe_2O_3 ore powder (interlayer) with ethanol and were coated on the surface of samples to be joined. The DB process was performed at temperature of 400ºC for holding time of 20-30 min under the load of 80 to120kN.

Interface of diffusion bonded joint was analyzed through OM (optical microscopy), and SEM (scanning electron microscopy) to analyze the microstructural characterization of interfacial region. Mechanical testing was also carried to know the ultimate tensile test of the prepared joint.

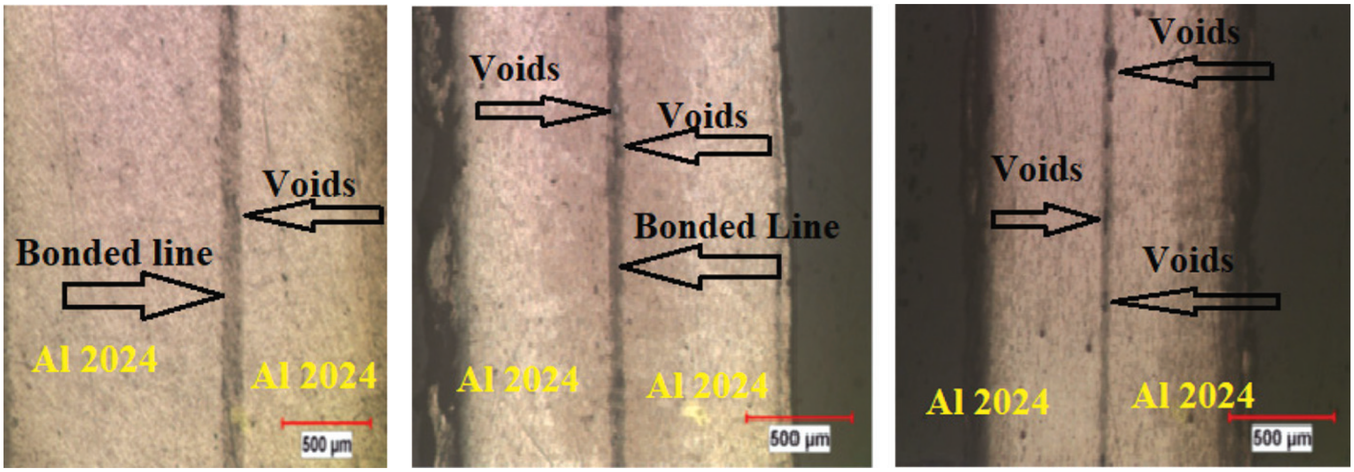
3.0 Results and discission

3.1 MICROSTRUCTURAL CHARACTERIZATION OF JOINTS

Interface of bonds are analyzed by using OM and SEM to know the characteristics of interface regions. Analysis of all the samples were done by keeping the orientation perpendicular to the axis of the diffusion bonded joint. As stated earlier, while preparing samples, three process parameters namely temperature, pressure, and time were considered (Lee et al., 1999). The samples prepared with and without interlayers are shown in Table 2. The interface micrograph images of the bonded specimens for different holding time, load and temperature without interlayer is shown in Figs.3 and 4. Images of all samples were taken perpendicular to the axis of the diffusion bonded joint.

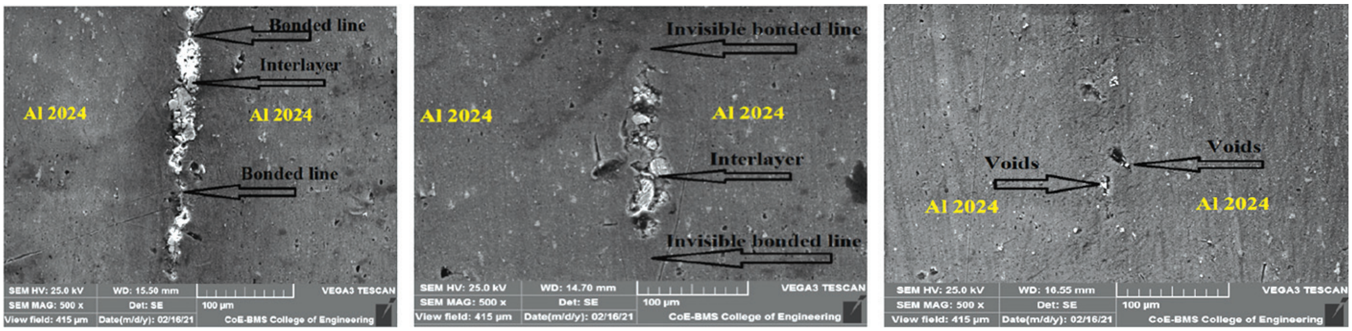
The optical micrographs of the samples bonded joints (S1, S2, S3) processed at 400°C with loading conditions of 80kN, 100kN, and 120 kN and time are shown in Fig.3(a) (b) and (c). A thin diffused region is observed between Al/Al joint and the same is noticed in the samples with interlayers shown in Fig.5(a) (b) and (c). As the load and holding time is increased, it is noted that diffusivity increased at the interface region and also thickness of the interface region is reduced with good bonding at the interface. Figs.3 (c) and 5 (c) reveal the diffused interface between the base metal and interlayer with few voids at some places.

Fig.4 reveals the effect of bonding time and load at 400ºC on the bonding interface. For a bonding time of 20 min, voids and other interface defects are observed with oxide layer at the interface due to entrapment of atmospheric air, which indicates incomplete bonding at the interface. For a holding time of 30 min and load of 120 kN, bond line was less evident (but not completely eliminated) and interface defects on the bonded line were reduced with few voids at some places (Urena et al., 2000). It can be concluded that because of short bonding time, diffusion time would have been insufficient for



(a) 400°C, 80 kN, 20 min (b) 400°C, 100 kN, 25 min (c) 400°C, 120 kN, 30 min

Fig.5: (a) (b) (c) Optical microscope images of the bonded sampleswith interlayer



(a) 400°C, 80 kN, 20 min (b) 400°C, 100 kN, 25 min (c) 400°C, 120 kN, 30 min

Fig.6: SEM images of the bonded samples with interlayers

bonding and also the load applied was insufficient to break the oxide film layer present at the interface.

SEM images from Fig.6 reveals the effect of bonding holding time and load at 400°C on the bonding interface. For a bonding time of 20 and 25 min, voids and interface defects were associated with the interlayeras shown in Fig.6(a) and (b), which indicates that, at lower holding time and load,bonding does not progress evenly throughout the bonding surface due to less metal-to-metal contact and presence of oxide layer at the interface. For holding time of 30 min and load of 120 kN, bond line was less evident (but not entirely eliminated) and interface defects on the bonded line were reduced with few voids at some placesas shown in Fig.6(c) (Gouge and Chandel, 2005). It is also evident that, for 30 min holding time and load of 120 kN, interlayer will get diffused into the base metal along with the surface oxide layer. It can be claimed that, at higher holding time and load,disruption of surface oxide layers is possible with increased diffusivity of interlayer into the base metal at the interface which results in good bonding.

3.2 TENSILE TEST

DB specimens are cut as per the dimensions mentioned in Fig.1. Tensile tests have been carried out on specimens to evaluate the strength of bonded joint by knowing the ultimate tensile strength. Table 3 shows the results of tensile strength specimen with and without interlayers.

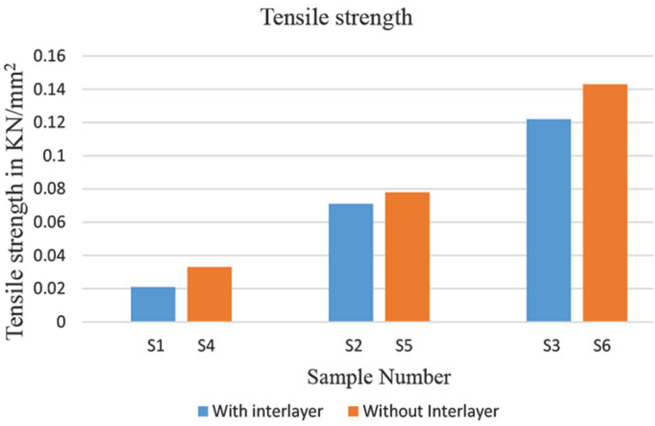


Fig.7: Comparison of tensile strength of joints prepared with and without using interlayer under various conditions

DB in air results in low bonded strength caused by fracture along the interface due to the existence of voids and oxide film layer on faying surface of base metal. The tensile strength of material specimen with interlayer decreased due

Table 3: Tensile Strength of specimens with and without interlayer

Specimen name	Process parameter (holding temperature/ holding load/ holding time) (°C/KN/min)	Interlayer	Peak load (KN)	Ultimate tensile strength (KN/mm^2)	Breaking load (KN)	Fracture location
S1	400, 80, 20	None	1.1	0.033	0.3	At interface
S2	400,100, 25	None	3.98	0.078	0.8	At interface
S3	400,120, 30	None	5.7	0.143	1.635	At interface
S4	400, 80, 20	Fe_2O_3	1.325	0.021	0.11	At interface
S5	400,100, 25	Fe_2O_3	2.9	0.071	0.92	At interface
S6	400,120, 30	Fe_2O_3	4.875	0.122	1.4	At interface

to reduced area of metal-to-metal contact and presence of surface oxide film layer at the interface (Barrena et al., 2009).The maximum ultimate tensile strength obtained with interlayer was 0.122kN/mm^2 prepared under a temperature of 400°C, load of 120kN and holding time of 30 min. The maximum ultimate tensile strength obtained without interlayer was 0.143kN/mm^2 having synthesized the joint at a temperature of 400°C, load of 120kN and holding of time 30 min. Fracture happened at interface of bonded joint for all the specimens (as per Table 3). The result indicates that, at lower holding time and load, tensile strength reduced mainly because of poor bonding at the interface due to presence of oxide film. Fig.7 shows the comparison of tensile strength with and without interlayers under various conditions.

4. Conclusions

- Al2024 alloy sheets with and without interlayers are successfully bonded using DB process. Metallographic investigations have revealed that bonding has happened across the bond line.
- Incomplete bonding at the interface of specimens was observed for few specimens. This might be due to the entrapment of atmospheric air on the bonding surfaces and presence of oxide film layer on the faying surface.
- The DB process parameters (temperature, holding time and load) have direct influence on joint interface region.
- Current study results are expected to contribute towards the development of solid-state joining process of aluminium alloy sheets with reduced cost.
- Optimum DB process parameters are found to be at temperature of 400°C, bonding load of 120 kN and holding time of 30 minutes to attain maximum tensile strength in the considered specimen.

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AN INVESTIGATION ON EMERGENCY RESPONSE SYSTEM DURING ANJAN HILL COAL MINE DISASTER USING CONTROL TASK ANALYSIS – A COGNITIVE APPROACH

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