Developing Diffusion Bonding Windows for Joining Powder Metallurgically Produced Pure Aluminium and Pure Copper

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ABSTRACT

In this investigation, pure aluminium (Al) and pure copper plates manufactured by powder metallurgy (P/M) technique were bonded by diffusion bonding. Joining of these materials by fusion welding is difficult because of the formation oxide films and brittle intermetallic compounds in the bond region which affect the quality of bonds. However, diffusion bonding is a suitable process to join these materials without much difficulties. In this investigation, an attempt was made to develop the diffusion bonding windows to join pure Al with pure Cu plates produced by P/M technique using different combinations of process parameters such as bonding temperature, bonding pressure and holding time The quality of bonds was checked by the microstructure analysis. Diffusion bonding windows (DBW) presented in this paper will act as reference maps for selecting appropriate process parameters to join pure Al with pure Cu plates fabricated by P/M technique.

Key Words: Pure aluminium, Pure copper, Powder metallurgy, Diffusion bonding window

1.0 INTRODUCTION

Diffusion bonding is an advanced solid state joining process and it is an important fabrication technique for making components in electronic, nuclear and aerospace industries [1,2]. This technique provides novel joining operation for similar and dissimilar materials. Aluminum has found very wide application at aerospace and automotive industries due to their high strength; corrosion and wear resistance [3]. Copper has good features such as high electrical conductivity, thermal conductivity and hence used in power industries, electrical appliances machinery and automobiles [4]

Joining dissimilar materials by conventional fusion welding technique causes severe thermal cracking and easy formation of brittle intermetallic compounds in the weld region [5]. The crack, distortion and segregation produced using fusion welding technique can be avoided by [6] diffusion bonding technology. Hence the diffusion bonding technique is recommended to join these dissimilar materials by the researchers. The selection of diffusion bonding process variables affecting the interfacial structure, morphology and compound is critical to get the quality of bonds [7].

As diffusion bonding is formed from atomic migration across an interface, there is no metallurgical discontinuity at the interface and therefore mechanical properties and microstructure in the bonded region are not different from the base metal. Solid state diffusion bonding is a process that joins components parts together without use of secondary phases, solvents or liquid. Diffusion bonding can be achieved by applying a static pressure to achieve intimate contact for certain amount of time at high temperature well below the melting temperature of the metals [8]. Since diffusion bonding is done between 40% and 80% of the melting point of the materials, no phase transformation or micro structural changes can occur during welding [9]. Diffusion is promoted by high temperature, since

adhesion necessary for the bonding process. The excessive heating the residual stress becomes large [10]. Hence the bonding strength decreases and those literatures focus on phase formation, microstructure analysis, hardness at the interface of diffusion layer and their influence on bonding strength. The bonding pressure has to be enough to ensure a tight contact between the joining surfaces of these materials and it should be sufficient to aid in the deformation of surface and fill the voids in the weld zone. Also the holding time could be sufficient for intimate contact between the materials. Given sufficient time, the voids will disappear completely [11].

The predominant process parameters in diffusion bonding are bonding pressure, temperature and holding time. Mahendran et al. [15] developed diffusion bonding windows for joining AA2024 aluminum and AZ31B magnesium. Joseph Fernandus et al. [16] developed Temperature-Time and Pressure-Time diagrams for diffusion bonding AZ80 magnesium and AA6061 aluminium alloys and these materials obtained from the rolled plates. However, no information is available on diffusion bonding of P/M produced pure Al/Cu dissimilar materials. Hence the present investigation was carried out to construct diffusion bonding windows for joining P/M compacts of pure Al and pure Cu and the details are presented in this paper.

2.0 EXPERIMENTAL WORK

Square shaped specimens (50mmx50mm) were manufactured from pure Al and pure Cu by powder metallurgical technique. The prepared specimen thickness of Cu was 3mm and Al was 5mm. The specimens prepared by P/M technique were displayed in **Fig. 1(a), 1(b)** and these were machined to make flat surfaces by milling and then cleaned in acetone just before diffusion bonding.

The polished and chemically treated specimens were stacked in the die which was made by 316 L stainless steel. The diffusion bonding set up was shown in **Fig. 2.** The specimens were heated up to the bonding temperature by induction furnace. The heating rate of furnace was 10^{o}C/min. The required pressure was simultaneously applied to the certain time. Thus, the bonding was completed and then the bonding samples were cooled to the room temperature before removal from the chamber of diffusion bonding machine. By this procedure 34 joints were fabricated by using various combination of bonding temperature, bonding pressure and holding time and they are displayed in **Fig.3**. The microstructure analysis was carefully carried out to reveal the formation of diffusion layer and to measure its thickness at the interface of the joints by using a optical microscope. The copper side was etched by a solution containing ethanol, $FeCl_3$ concentrated HCL, whereas the aluminum side was etched by using keller's solution to reveal the microstructure. The different conditions of process parameters used to fabricate the diffusion bonds are presented in **Table 1.**

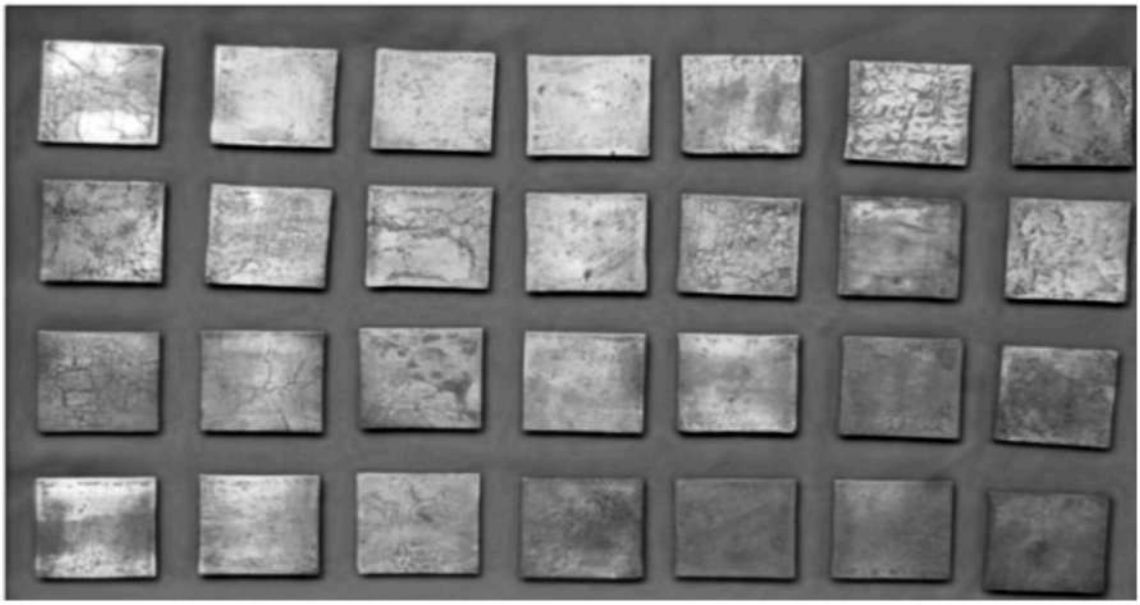


Fig. 1(a) : P/M Pure Copper plates

Table 1 : Experimental Results

Joint No.	Bonding Temperature (°C)	Bonding Pressure (Mpa)	Holding Time (min)	Bonding (Yes or No)
1	200	10	30	No
2	200	20	60	No
3	250	10	30	Yes
4	300	10	30	Yes
5	325	10	30	Yes
6	350	10	30	Yes
7	375	10	30	Yes
8	400	10	30	Yes
9	425	10	30	Yes
10	450	10	30	Yes
11	300	10	15	Yes
12	300	10	90	Yes
13	300	5	120	Yes
14	350	2	30	No
15	350	5	30	Yes
16	350	15	30	Yes
17	350	20	30	Yes
18	350	10	15	Yes
19	350	10	45	Yes
20	350	10	60	Yes
21	350	10	75	Yes
22	350	5	15	Yes
23	400	5	60	Yes
24	400	15	75	Yes
25	400	20	5	Yes
26	450	5	90	Yes
27	450	10	15	Yes
28	450	15	60	Yes
29	450	10	75	Yes
30	450	20	75	No (Deformed)
31	475	10	30	No (Deformed)
32	500	10	30	No (Deformed)
33	500	10	15	No (Deformed)
34	550	10	10	No (Deformed)

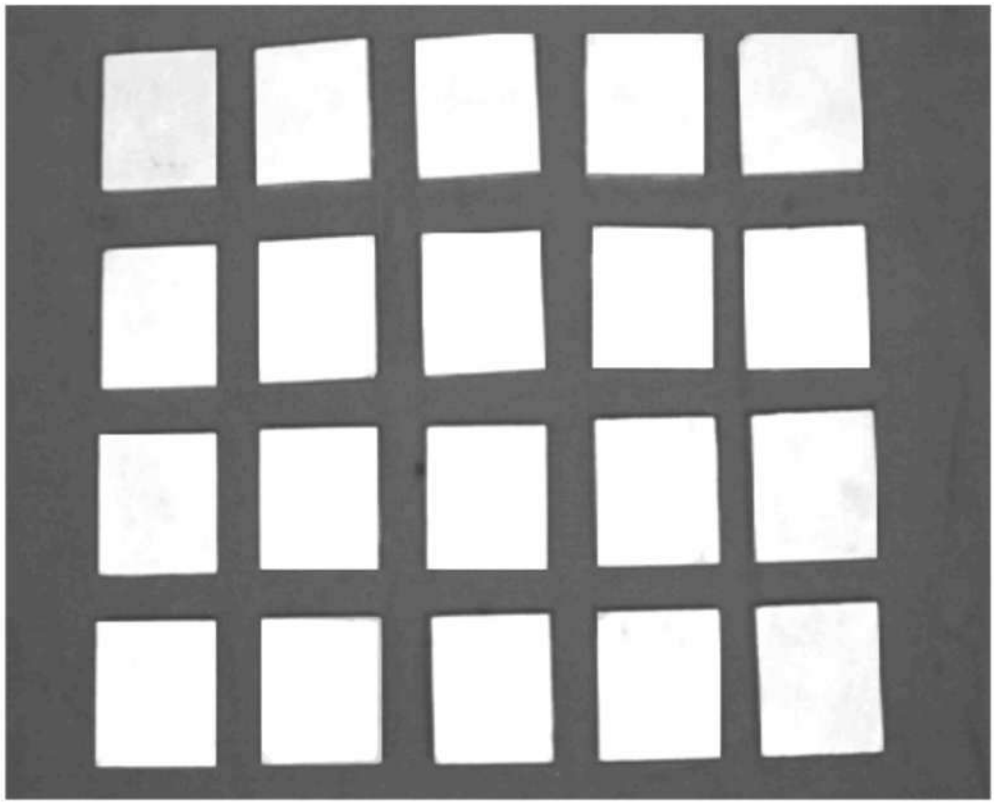


Fig. 1(b) : P/M Pure Aluminum plates

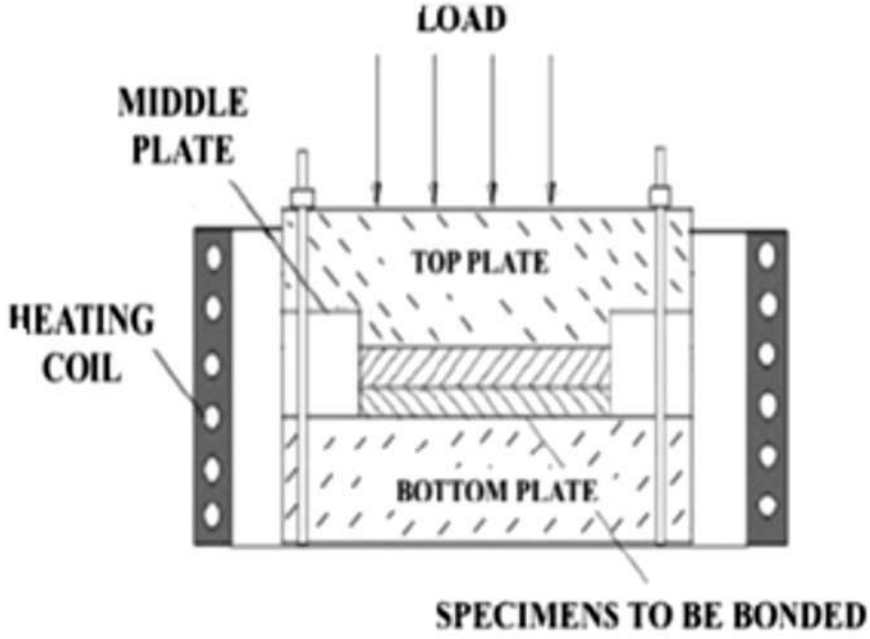


Fig. 2 : Configuration of the diffusion bonding set up

Fig. 3 : Some of the fabricated diffusion bonds

3.0 DEVELOPING DIFFUSION BONDING WINDOWS (DBW)

The experiments were conducted with temperature range of 200 – 550°C, the pressure range of 2-20 MPa and the time range of 5–120 min. From the experiments, the following inferences were obtained

I) No bonding was occurred between pure Al and Cu, if the bonding temperature was lower than 250°C and this was due to the insufficient temperature to cause diffusion of atoms of between to these two materials **(Fig. 3a).**

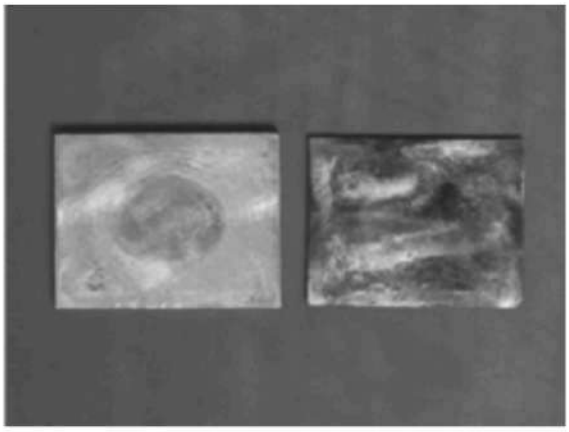
ii) If the bonding temperature was higher than 450°C, then no bonding was occurred between these materials and this leads to the melting of pure Al due to high temperature **(Fig. 3b).**

iii) If the bonding pressure was below 5 MPa, no bonding was occurred because less number of contact points by which diffusion of atoms occur between the materials **(Fig. 3c).**

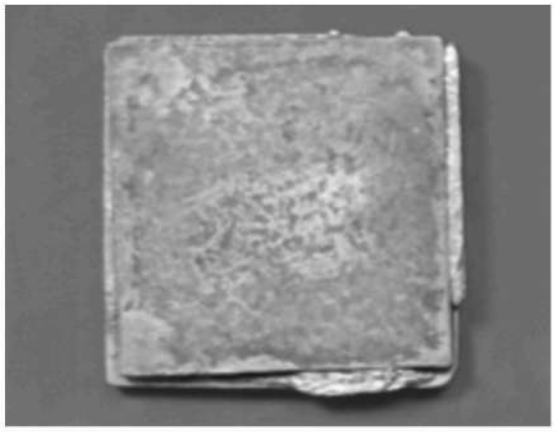
iv) When the bonding pressure was higher than 20 MPa, the materials got plastic deformation which causes the reduction in thickness and bulging at the edges **(Fig. 3d)**.

v) If the holding time was below 5 min., the bonding could not be occurred because of the insufficient time which causes to take place the diffusion reaction **(Fig. 3e)**.

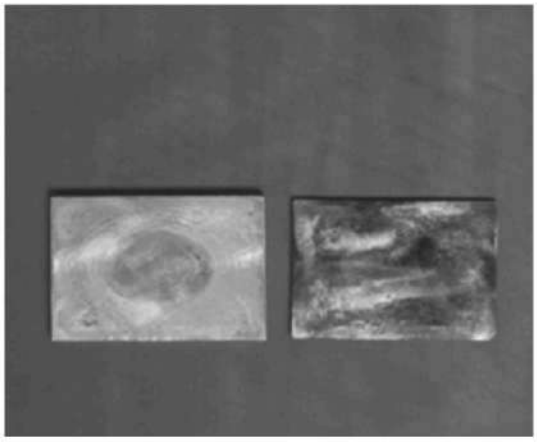
vi) When the holding time is greater than 120 min., the grains growth was excessive and lead to the melting of pure Al (**Fig. 3f**).



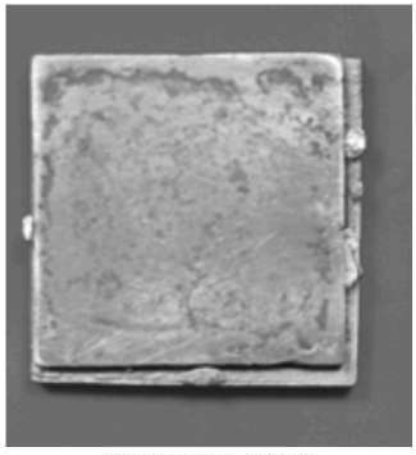
(a) Temperature < 250°C



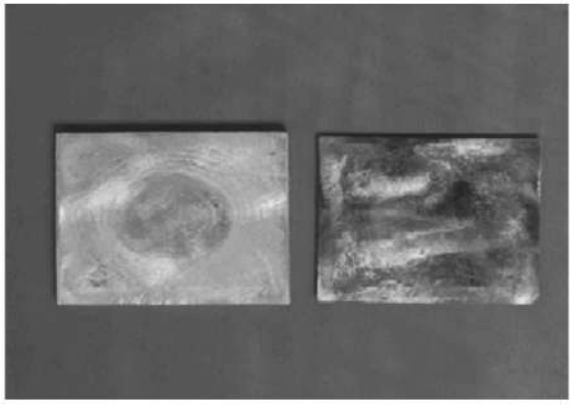
(b) Temperature > 450°C



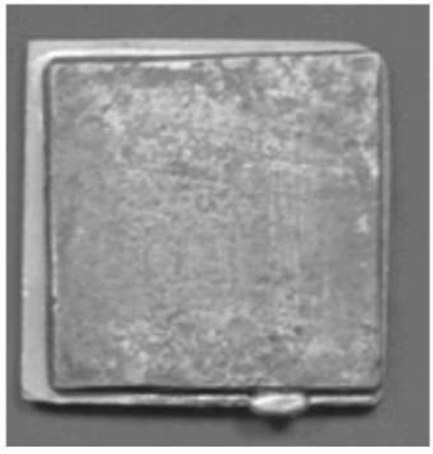
© : Pressure < 5 MPa



(d) Pressure > 20 MPa



(e) Time < 5 min



(f) Time >120 min

Fig. 3 : Photographs of fabricated bonds using lower and upper limit process parameter

3.1 Developing Temperature -Time (T - t) diagram

Temperature -Time (T- t) diagram was constructed keeping holding time in X axis and bonding temperature in Y axis. To find out the processing limits, the bonding temperature and holding time were varied at constant pressure of 5 MPa. Similarly, the experiments were conducted to find out the working limits for the bonding pressure of 10 MPa, 15 MPa and 20 MPa respectively. In this way, these points were used to construct the DBW for these pressures and they are displayed in **Fig. 4 (a - c)**. The selection of diffusion bonding process parameters inside window region was yielded good bonding between pure Al/Cu and this was validated by conducting some experiments again. From the Temperature - Time diagram, the following inferences can be obtained. If the bonding pressure increases, the holding time of bond decreases with irrespective of the temperature. However, the bonding pressure does not have significant influence on bonding temperature

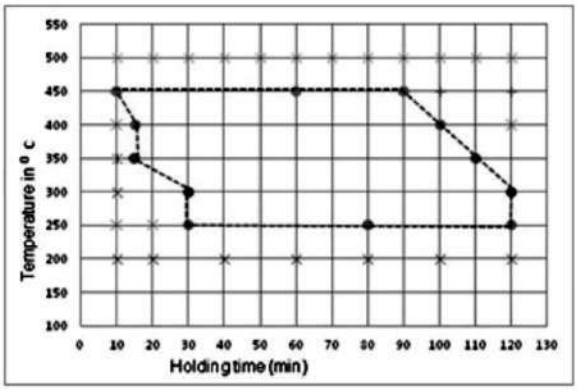
3.2 Developing Pressure -Time (P - t) diagram

The Pressure -Time (P - t) diagram was constructed keeping holding time in X axis and bonding pressure in Y axis. To find out the processing limits, the bonding pressure and holding time were varied at constant temperature 350°C. Similarly, few more experiments were conducted to find out the working limits for the bonding temperature of 400°C and 450°C respectively. By these points Pressure -Time (P - t) diagram was constructed for three bonding temperatures and they are displayed in **Fig. 5 (a - c)**. The selection of diffusion bonding process parameters which are inside the window, always yielded good bonding between pure aluminum and pure copper. From the (P-t) diagram, the following inferences can be obtained. If the bonding temperature increases, the holding time of bond decreases with irrespective of the bonding pressure. However the bonding temperature does not have significant influences on the bonding pressure.

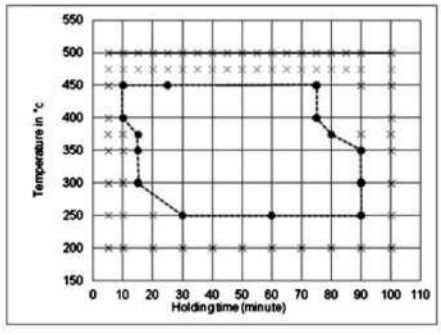
4.0 DISCUSSION

Microstructure analysis was carried out using a light optical microscope to check the formation of diffusion layer at the interface. The copper side was etched with a solution containing 50 ml of nitric acid and 50 ml water whereas the aluminium side was etched with Keller's solution. The optical micrographs of diffusion bonded Al and Cu joints are shown in **Fig. 6**. The main objective of the paper is to identify the processing limits for joining P/M produced Cu and Al plates by diffusion bonding process and to construct diffusion bonding windows using those process parameter limits. Hence, characterization of diffusion bonds is not carried out. However, the results obtained from the earlier work carried out in our centre on diffusion bonding of wrought Al and Cu plates are presented below.

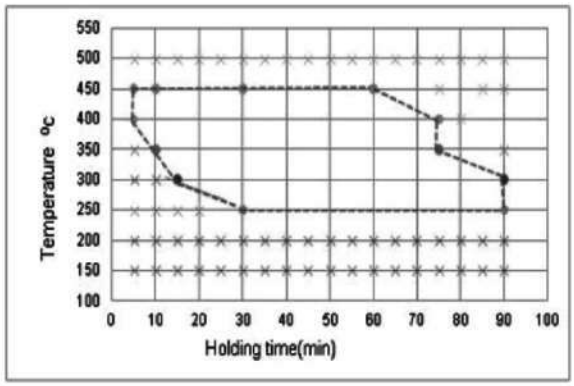
A very thin layer of thickness 1.39 m was formed under the bonding temperature of 425 ºC, holding time of 10 minutes and hardness of 50 Hv and exhibited shear strength and bonding strength of 26 MPa and 42 MPa respectively. The interface contains 42.9 % of Cu and 57.07 % of Al along with the intermetallic phases of $MgAl_2O_4$, Al_2O_3, SiO_2, FeN, AlCuFe. A very thick diffusion layer of 17 µm was formed under the bonding temperature of 550°C, holding time of 90 minutes and bonding pressure of 16 MPa. This interface recorded a hardness of 100 Hv and exhibited shear and bonding strength of 32 MPa and 54 MPa, respectively. The interface contains 63.05 % of Cu and 36.95 % of Al along with the intermetallic phases of $MgAl_2O_4$, SiO_2, Fe_7C_3, BC, BN, $MgAl_2O_4$, and $MgSiO_4$. Bonding temperature, bonding pressure and holding time have directly proportional relationship with diffusion layer thickness (DL) and interface hardness (IH). Interface hardness is showing directly proportional relationship with diffusion layer thickness [17].



(a) Bonding pressure of 5 MPa

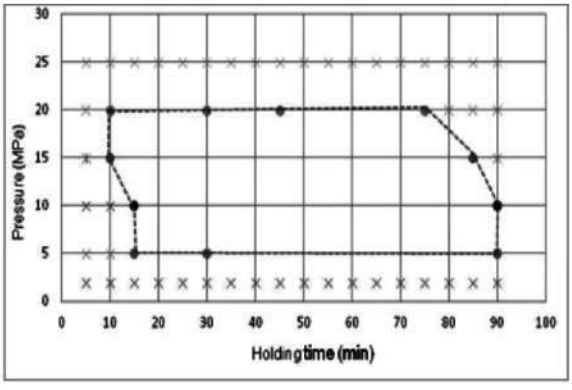


(b) Bonding pressure of 10MPa

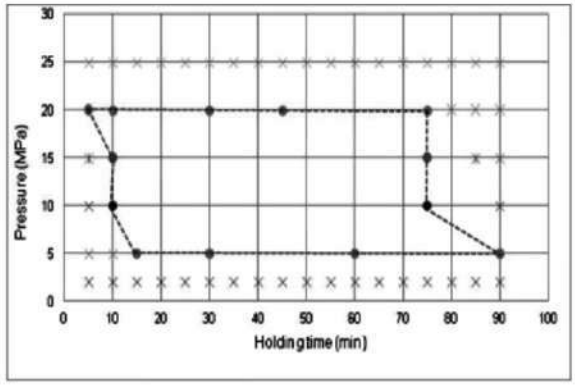


c) Bonding pressure of 20 MPa

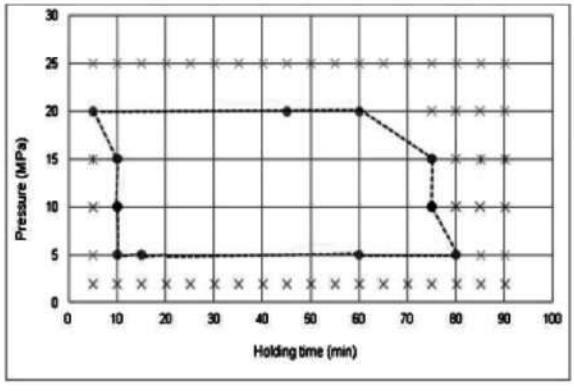
Fig. 4 : Temperature –Time (T-t) diagrams



(a) Bonding Temperature of 350°C

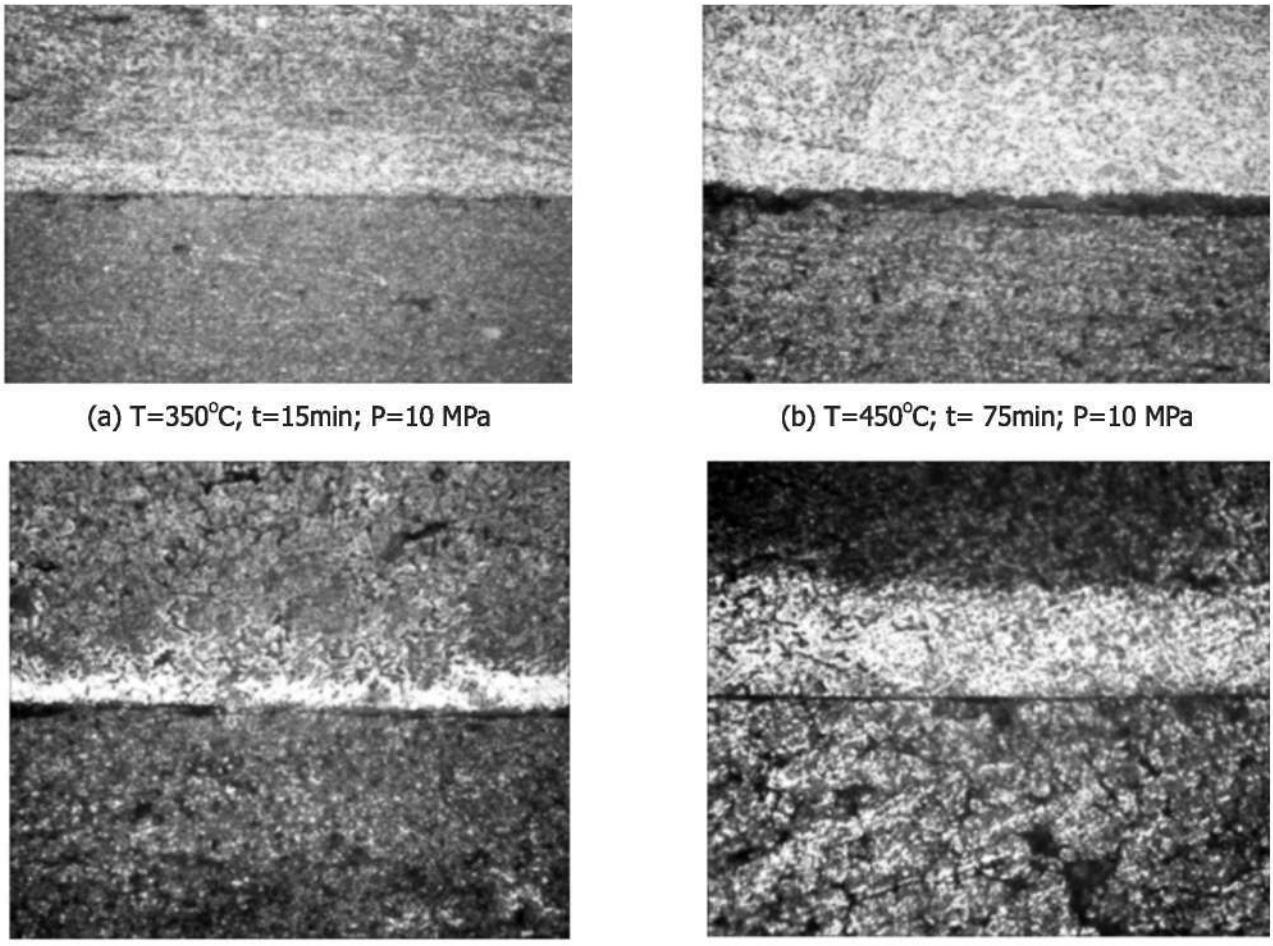


(b) Bonding Temperature of 400°C



(f) Bonding Temperature of 450°C

Fig. 5 : Pressure –Time (P-t) diagrams



(a) T=350°C; t=15min; P=10 MPa

(b) T=450°C; t= 75min; P=10 MPa

(c) T=350°C; t= 60 min; P=10 MPa

(d) T=350°C; t= 30 min; P=15 MPa

Fig. 6: Optical micrograph of interface region of pure Al/Cu diffusion bonds

5.0 CONCLUSIONS

In this investigation, the Temperature-Time (T-t) and Pressure – Time (P- t) diagrams were constructed and these diagrams will act as reference maps to the design and welding engineers to select the appropriate diffusion bonding process parameters to join P/M produced pure aluminum and pure copper plates.

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