

An Investigation on the Modeling of Heat Distribution and Atomic Diffusion in the Joining of the AA2024-T4 to AA6061-T6 by TLP Process

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Abstract

The simulation of heat distribution has long been applied for estimating optimal time for heat treatment process in an attempt to optimize the energy consumption. Aluminum alloys have been used to achieve appropriate strength-to-weight ratio and reduce the fuel consumption. In the present research, heat distribution modeling was performed for joining AA2024-T4 to AA6061-T6 in the TLP process utilizing MATLAB R2016b. For this purpose, thermal properties and density of the base alloys and the clamp were extracted from respective ASM standards and applied in the coding. Finally, 1D, and 2D simulations were run to simulate the heat distribution over the base metal at the process temperature. Moreover, the time required to have the copper diffused into the interlayer was estimated through the simulations. The diffusion depth of the Sn into the base metal (Al) was further modeled at different points in time. A Sn-2.5Bi interlayer with two different thicknesses (50 and 70 microns) was also evaluated through actual experiments.

Keywords: TLP, Modeling by MATLAB, AA2024-T4, Heat Distribution, Atomic Diffusion.

1. Introduction

The joining of AA2024-T4 and AA6061-T6 [1] has been widely applied in the aerospace and electromotive industries [2, 3]. Joining dissimilar alloys in aerospace and electric automotive industries can enhance the strength-to-weight ratio and thus increases the fuel or energy efficiency. A. AlHazza et al. [4]. AA2024 is a corrosion-resistant alloy with the copper content of 4%. Its density is 2.7g/cc; it has shown the ability for precipitation hardening [5]. The tensile yield strength of AA2024-O is 75.8 MPa while the tensile yield strength of AA2024-T4 is 324 MPa [2, 5]. Solidus temperature of AA2024-T4 is 502°C and solution temperature of AA2024-T4 is 256°C [1, 5]. So far, transient liquid phase (TLP) bonding of Al7075 to Ti-6Al-4V has been carried out using 22- μ m thick Cu interlayers giving rise to the highest bond strength (to Al) of 19.5 MPa after a bonding time of 30 min [4]. The used of the Sn-3.6Ag-1Cu interlayer by A. N. Alhazaa et al. [6]. Also employed transient liquid phase bonding of Al7075 to Ti-6Al-4V using 50 μ m thickness Sn-10Zn-3.5Bi and Sn-4Ag-3.5Bi films as interlayers. The highest bond strength of 30 MPa and 36MPa were also achieved by M. S. Kenevisi et al. [7, 8]. Diffusion bonding of Al2024 to Ti-6Al-4V was conducted using Cu/Sn/Cu resulting in the highest bond strength of 37MPa at 510°C under vacuum (7.5×10^{-5} Torr) with 60 min bonding time by M. Samavatian et al. [9]. Cu-22Zn interlayer was also used by Samavatian et al. [10].

Transient liquid phase bonding of two dissimilar alloys (Al 2024 and Ti-6Al-4V) was achieved using Cu-22Zn interlayer at 510 °C under the vacuum (7.501×10^{-5} Pa) for 60 min bonding time giving rise to the maximum tensile strength of 37 MPa. Transient liquid phase bonding of Al2024 to Ti-6Al-4V was carried out using 50- μ m thick Sn-5.3Ag-4.2Bi film as interlayers resulting in the highest bond strength of 62 MPa at 453°C by A. Anbarzadeh et al.[11]. Eutectic temperature of Sn-0.7Cu and Sn-2.13Mg composition (227°C and 203.5°C) by Hugh Baker et al [12] which is less than the temperature of the TLP process (253°C). Considering the heat cycle used in a TLP process for bonding the two metals, one may raise the question of how much time does it take to obtain uniform temperature in the bonding position once the furnace temperature reaches the predetermined level in each cycle? In the present work, MATLAB R2016b was used to obtain an estimation of the temperature distribution across the bonding area for further analysis. We used a layer of Sn-2.5Bi alloy with either of two thicknesses (50 and 70 microns) at 253°C as the interlayer. In the atomic diffusion model, the content of copper in the Al2024 (4.1 wt. %) and Al6061 (0.23 wt. %) was assumed to be constant and equal on both sides of the interlayer. The modeling was performed in 1D mode by ignoring the effect of other alloying elements.

2. Materials and Methods

Table. 1. given the chemical composition of the base alloys. Considering the small thickness of the Sn-2.5Bi interlayer (50 microns) compared to the base

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metals, no separate coding was considered for thermal modeling of this layer. Fig. 1. demonstrates the fabrication of the base metals onto the base clamps. Thermal properties and density of the base metal and the clamp were extracted from ASM material datasheets [5, 13], with the results reported in Table. 2. Fig. 2. shows the thermal cycle encountered in the TLP process.

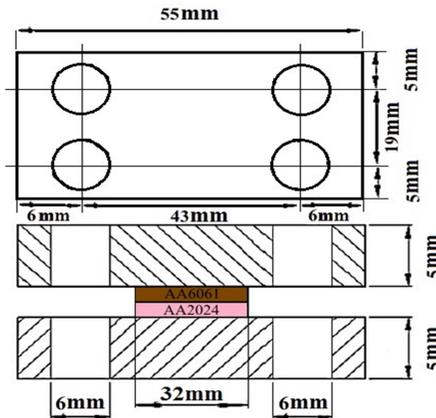


Fig. 1. Configuration of the sample against the steel made clamps.

In the simulations, the internal alloy temperature was taken as being equal to the heating step in Fig. 2. (240°C), while the side surface temperatures were

assumed to be equal to the furnace temperature (253°C). In the 1D modeling, the simulation length was equal to the joint width, *i.e.* 32 mm. In order to undertake 1D simulation of the bonding of AA2024-T4 to AA6061-T6, 1D code were developed to draw the plot of the distribution diagram (Fig. 3). The 2D thermal modeling codes were developed following the same approach but for 6 sec after achievement of the desired temperature in the furnace. Interestingly, the Al was cooled from its base because of its contact with the lower node. In the coding, the value of the atomic diffusion coefficient was equal to 1% of the atomic diffusion coefficient of copper into molten tin, as reported by C. H. Ma et al. [14] being equal to $D = 9 \times 10^{-15} \text{ m}^2 \cdot \text{sec}^{-1}$, which was equal to the value of atomic diffusion coefficient obtained for the atomic diffusion of copper into tin through the TLP process, as reported by H. Y. Zhao, et al. [15] and G. Erdelyi, et al. [16]. In a series of experiments performed at 250°C, H. Y. Zhao et al. [15] placed a single layer of tin with a thickness of 20 microns in between two copper sheets. He observed that the copper was distributed uniformly across the interlayer within about 8 sec. The diffusion coefficient of Sn into Al was adapted from the research by G. Erdelyi, et al. [16] ($D = 27 \times 10^{-12} \text{ m}^2 \cdot \text{sec}^{-1}$).

Table. 1. Chemical composition of the metals used in this experiment (wt. %).

Alloys	Elements (wt.%)						
	Al	Cu	Mg	Mn	Cr	Fe	Si
AA2024-T4	Bal.	4.1	1.4	0.5	0.02	0.31	0.29
AA6061-T6	Bal.	0.23	0.92	0.05	0.23	0.26	0.62

Table. 2. The extracted from ASM datasheet for coding at 253°C [5, 13, 17].

Alloy	Density (kg/m ³)	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)
Al6061-T6	2700	167	896
Al2024-T4	2780	121	875
4130 Steel	7850	40	523

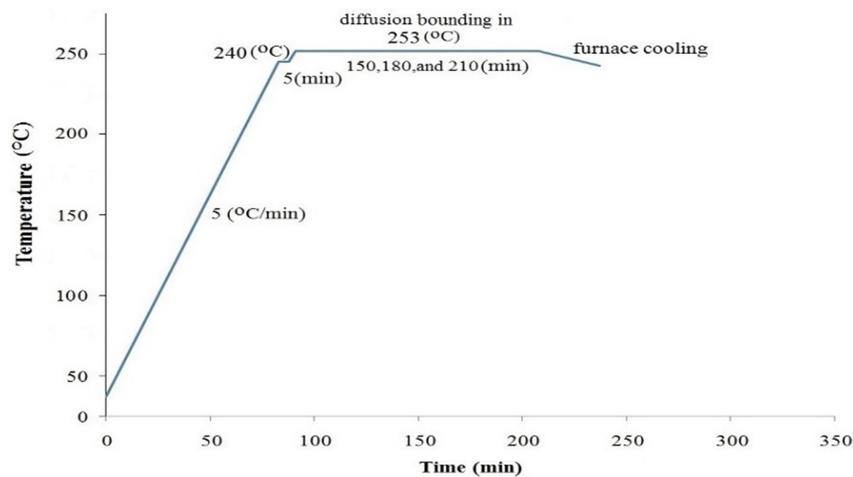


Fig. 2. Heat treatment diagram for AA2024-T4 to AA6061-T6 joints using Sn-2.4Bi interlayer.

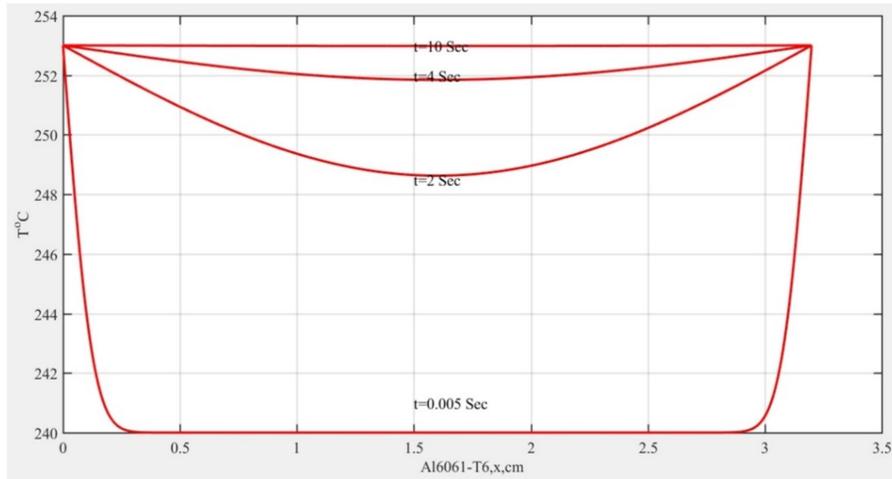


Fig. 3. Results of 1D thermal modeling of the AA6061-T6.

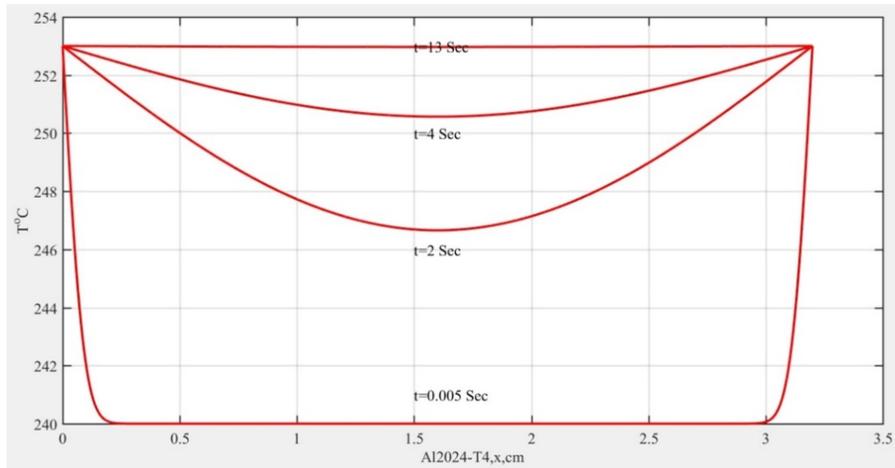


Fig. 4. Results of 1D thermal modeling of the AA2024-T4.

3. Results and Discussions

The results of 1D thermal modeling of the AA6061-T6 and AA2024-T4 are presented in Fig. 3. and Fig. 4. respectively. The results of 2D simulation of the heat distribution over the joint are shown in Fig. 5.

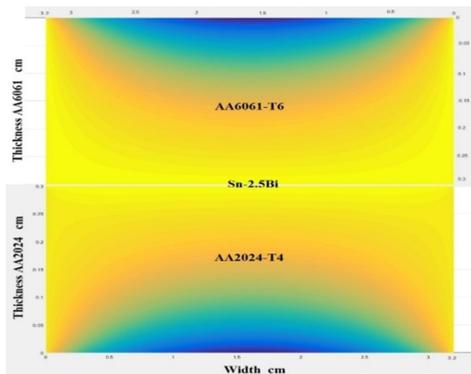


Fig. 5. Results of 2D simulation of heat distribution over the joint at 10th sec at 253°C.

The results of the 1D simulation suggest that the temperature exhibits a uniform distribution across the entire sample in a maximum of 13 sec after the furnace temperature reached 253°C Fig. 4.

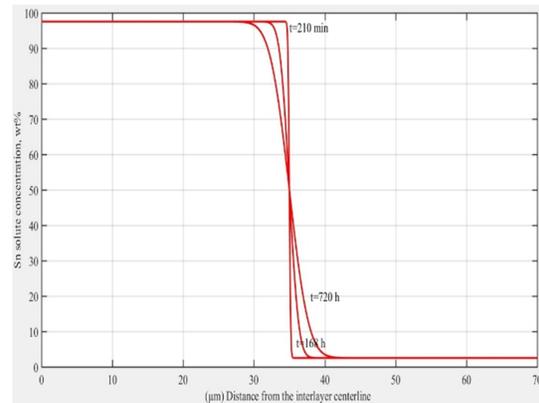


Fig. 6. Results of 1D simulation of atomic diffusion of Sn into Al at 253°C.

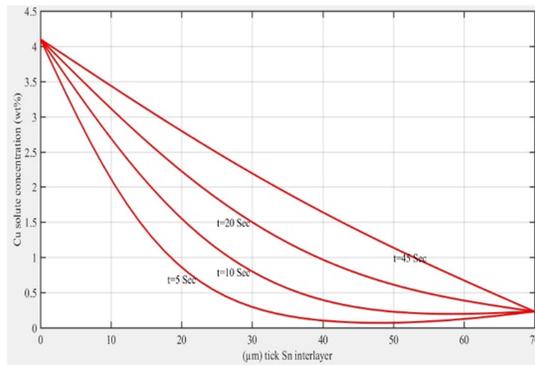


Fig. 7. Results of 1D simulation of atomic diffusion of Cu into Sn at 253°C.

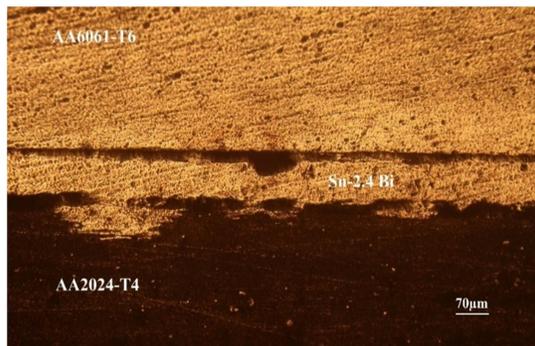


Fig. 8. Microstructures of the diffusion bonding after 210 min for 70 μm-thick Sn-2.4Bi interlayer.

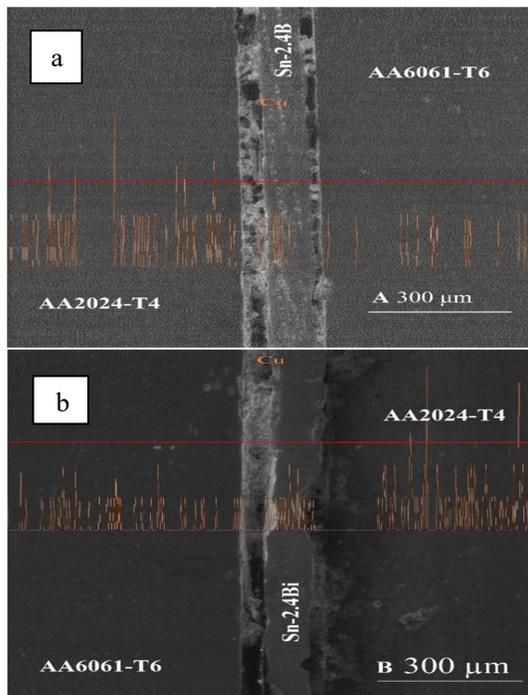


Fig. 9. Cross-section EDS (Cu) element line scan for joint- at bonding time of 210 min for (a) 70 μm-thick Sn-2.4Bi interlayer and (b) 50 μm-thick Sn-2.4Bi interlayer.

Moreover, the diffusion rate of the copper from the base metal into the interlayer was significantly higher than that of the tin content of the interlayer into the base metal. Fig. 6. and Fig. 7.

Fig. 6. shows the results of 1D simulation of the atomic diffusion of Sn into Al, while Fig. 7. gives that of Cu into Sn. the element tin cannot penetrate rapidly into aluminum alloys at 253°C, but the penetration of copper elements into the interlayer of tin is rapid.

Fig. 8. shows the microstructure of bonded joint. AA2024 alloy has more copper element than AA6061 alloy. This causes more mixing at the junction of the AA2024 alloy with the interlayer. However, the atomic penetration of the interface layer into the base metal after staying at 210°C for 210 minutes is negligible.

Fig. 9. shows the cross-section EDS (Cu) element line scan for joint. Proves the accuracy of the simulation result of the atomic penetration of the copper element from the base metal into the interlayer.

4. Conclusions

1. The results of the 1D simulation suggest that the temperature exhibits a uniform distribution across the entire sample in a maximum of 13 sec after the furnace temperature reached 253 °C.
2. Cu elements were more abundant than Al in the Sn-2.4Bi interlayer at 253°C.
3. According to the simulation results of Fig. 6. and Fig. 7., the element tin cannot penetrate rapidly into aluminum alloys at 253°C, but the penetration of copper elements into the interlayer of tin is rapid.
4. the study of the cross-section joint the line scan proves the accuracy of the simulation result of the atomic penetration of the copper element from the base metal into the interlayer.

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