Simulations about the effect of heat treatment temperatures on the properties of diffusion bonded Mg/Al joints

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Abstract. In this study, Finite elements method (FEM) was used for simulations on the annealing treatment. And the distributions of residual stress were obtained from the results of simulations. Besides, in order to study the mechanical properties. Composite plates of AZ31B magnesium alloys and 6061 aluminum alloys were fabricated by vacuum diffusion bonding method. Then experiments about annealing, measurement of residual stresses and tension test were also carried out. The results of residual stresses obtained by X-ray diffraction (XRD) were compared with the results of simulations. It can be thought that the results of residual stress obtained from simulations and that from experiments are in a good agreement. What's more, The residual stress after annealing at 250°C is the least of all, while the tensile strength is the strongest. On the basis of results of simulations and experiments, the conclusion can be obtained that 250°C is the most appropriate annealing temperature.

1 Introduction

Magnesium is the lightest metal [1]. As the use of magnesium alloys, the weight of components can be reduced significantly. However, it's corroded easily. While aluminum alloys have attractive mechanical and metallurgical properties, including high strength and excellent corrosion resistance [2]. So wide and cross applications of these two metals make the connection of Mg/Al dissimilar metals inevitable[3]. For example, the Mg-Al laminated armor is used in tanks and armored vehicles[4], Mg/Al complex structure is used in aerospace engines and components[5,6,7]. So it is significant to achieve reliable connection of Mg/Al dissimilar metals. Presently, there are many studies about welding of magnesium and aluminium. And there are many welding methods that have been used to join Mg alloys and Al alloys. However, no matter which technique is used, if the brittle and hard intermetallic compounds, such as Al₃Mg₂ and Mg₁₇Al₁₂ were formed in

the joints. The performances of welded joints will be deteriorated seriously[8].

In this study, for the purpose of improving the tensile strength, simulations on annealing treatment were applied to search for the apposite annealing temperature. Besides, experiments on annealing treatment were also carried out. What's more, residual stress and tensile strength were investigated in this work.

2 Simulations

During the processes of diffusion bonding and heat treatment, along with the change of temperature, microstructure will transform, and at the same time, thermal stress emerges. If the stress exceeds the elastic limit, plastic deformation will result from it. A series of varieties don't emerge individually but interact on each other. The theory system related is constructed and called metallo-thermo-mechanics, which is the foundation of thermal treatment analysis.

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When AZ31 magnesium alloy and 6061 aluminum alloy is joined by the method of diffusion bonding, diffusion between the elements Mg and Al should be considered. Diffusion phenomenon can be analyzed by Fick's law and expressed as the following equation:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad (1)$$

Where C is the concentration of element, D which is a function of C , is diffusion coefficient standing for the diffusion property of material, and can be express using the following equation:

$$D = K_0 \exp(K_1 C) \quad (2)$$

Where K_0 and K_1 are coefficients. Generally speaking, if the influence resulted from the variety of microstructure is ignored, the diffusion equation can be expressed with the element's concentration C :

$$\dot{C} = \text{div}(D \text{grad} C) \quad (3)$$

The boundary condition is represented as the following equation:

$$-D_c \text{grad} C \cdot n = \beta_c (C - C_w) \quad (4)$$

Where β_c is the concentration of gas around, C_w is the concentration of elements around.

If the energy in objects is represented as $e = g + T\eta + tr(\sigma \varepsilon^e)$, then the first law of thermodynamics can be wrote as:

$$\rho \dot{e} - tr(\dot{\sigma} \varepsilon) + \text{div} h = 0 \quad (5)$$

If Fourier law ($h = k \text{grad} T$) is used, plastic work and transformation latent heat is not considered, items that relate elastic strain and hardening coefficient are ignored, then equation (5) can be wrote as the following equation:

$$\rho c \dot{T} - k \text{div}(\text{grad} T) = 0 \quad (6)$$

Where ρ is the density of material, c is specific heat, k is thermal conductivity. When the coefficient of heat transfer and the temperature of fluid that is in touch with the objects are changeless, boundary condition is expressed using the following equation:

$$-k \text{grad} T \cdot n = h(T)(T - T_\omega) \quad (7)$$

Where n is a vector whose direction is outward from the surface of objects. T_ω is temperature around. $h(T)$ is the coefficient of heat transfer between object and environment. Generally, coefficient of heat transfer is a function of temperature T , which can be obtained from the experiment value of cooling curve [9].

When plastic materials are with load, elastic or plastic deformation will occur. The generalized Hooke's law is applicable to three-dimensional stress and strain, and can be expressed using the equation (8):

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^e + \dot{\varepsilon}_{ij}^p + \dot{\varepsilon}_{ij}^T \quad (8)$$

Where $\dot{\varepsilon}_{ij}$ is total strain rate, $\dot{\varepsilon}^e$ is elastic strain rate, $\dot{\varepsilon}_{ij}^p$ is plastic strain rate, and $\dot{\varepsilon}_{ij}^T$ is thermal strain rate. Especially, elastic strain rate and thermal strain rate are expressed with the following equation.

$$\begin{cases} \dot{\varepsilon}_{ij}^e + \dot{\varepsilon}_{ij}^T = E_{ijkl}^e \dot{\sigma}_{kl} + \beta_{ij} \dot{T} \\ \beta_{ij} = \frac{\partial E_{ijkl}^e}{\partial T} \sigma_{kl} + \alpha_{ij} \frac{\partial \alpha_{ij}}{\partial T} (T - T_0) \end{cases} \quad (9)$$

Where α is linear expansion coefficient, and is temperature difference. E_{ijkl}^e is a coefficient that is represented as equation (10):

$$E_{ijkl}^e = \frac{1}{2G} \left\{ (\delta_{ik} \delta_{jl} + \delta_{il} \delta_{jk}) - \frac{\nu}{1+\nu} \delta_{ij} \delta_{kl} \right\} \quad (10)$$

Where ν and G are Poisson's ratio and shear modulus [19]. Plastic strain rate is expressed as equation (11):

$$\begin{cases} \dot{\varepsilon}_{ij}^p = \frac{1}{G} \left(\frac{\partial F}{\partial \sigma_{mn}} \sigma_{mn} + \frac{\partial F}{\partial T} T \right) \frac{\partial F}{\partial \sigma_{ij}} \\ \frac{1}{G} = - \frac{1}{\frac{\partial F}{\partial \kappa} \frac{\partial F}{\partial \sigma_{kl}} \sigma_{kl}} \\ F = F(\sigma, T) \end{cases} \quad (11)$$

Where F is Mises yield function.

First, the definitions of mixture and maxing rule are explained. Intermetallic compounds, such as Al_3Mg_2 and $\text{Mg}_{17}\text{Al}_{12}$ will generate during the diffusion process of magnesium alloy and aluminum alloy. It is thought that there are many micro-structures mix together. Mixture contains N compositions whose volume fraction are ξ_I ($I = 1, 2, \dots, N$), and if all the volume fractions are together, then 1 will be obtained. It can be expressed as:

$$\sum_{I=1}^N \xi_I = 1 \quad (12)$$

If the property of composition I is represented by χ_I , then the property χ contains all the properties of N compositions. Therefore, the property χ can be expressed as equation (13), which is called maxing rule [10].

$$\chi = \sum_{I=1}^N \chi_I \xi_I, \quad \xi_I (I = 1, 2, \dots, N) \quad (13)$$

According to the maxing rule, the coefficients of AZ31 magnesium alloy and 6061 aluminum alloy, and all the coefficients that relate the Intermetallic compounds of Mg and Al are calculated. Then simulations were carried out. Temperature conditions were 200°C, 250°C, 300°C and room temperature 20°C. It was thought that the interface can't move during diffusion process. Therefore,

restrict was only applied to the contact surface, so that it can't move any directions. Then simulations were carried out.

3 Experimental

AZ31B magnesium alloy sheets and 6061 aluminum alloy sheets were successfully joined using vacuum diffusion bonding method in the equipment with atmosphere of argon. The size of sample was shown as Fig.1. The joining temperature was 440°C and the flowing rate of gas was set as 150ml/min. Before diffusion bonding, the oxide layers on the surfaces of substrates were cleaned using abrasive papers (GRIT 240, 600, 800, 1200) and polished with polishing cloth and polishing compound. Then the grinded sheets were wiped with acetone. After vacuum diffusion bonding, the samples were used for the annealing treatment experiments. The heat treatment temperatures were 200°C、250°C、300°C, and the holding time was 60min. Then cooled down to the room temperature in the electric furnace.

Fig.1 The size of specimen

In order to investigate the distribution of residual stress of the specimens annealed at different temperatures, residual stress was measured by XRD (X-Ray Diffraction). Based on residual stress testing principle, and used x-ray whose wavelength was λ . First, radiate the specimen with different incident angles, and obtained the corresponding diffraction angle 2θ , then the slope M of 2θ - $\sin^2\psi$ (generally, ψ was set as 0°, 15°, 30°, 45°) can be calculated. In addition, the relationship between 2θ and $\sin^2\psi$ can be obtained, then residual stress σ can be calculated according to the following equation:

$$\sigma = K \cdot \Delta 2\theta / \Delta \sin^2\psi = K \cdot M \quad (14)$$

Where K is the stress constant of x-ray diffraction analysis, which can be expressed as:

$$K = -\frac{1}{2} \cdot \cot \theta_0 \cdot \frac{E}{1+\nu} \cdot \frac{\pi}{180} \quad (15)$$

Where E is the elastic modulus of material, θ_0 is the diffraction angle without stress, ν is Poisson's ratio [11].

When the side of 6061 Al alloy was measured, 2θ was set as 140°, stress constant was -163.32MPa/°, tube type was Cr, wavelength was $\lambda\alpha$, and the size of collimator was $\phi 0.5\text{mm}$. While 2θ was set as 155°, stress constant was -79.14MPa/° at the side of AZ31Mg alloy. What's more, tube type, wavelength and the size of collimator were the same with 6061Al alloy. In addition, the 2θ of $\text{Mg}_{17}\text{Al}_{12}$ and Al_3Mg_2 were set as 150° and 145°, and stress constant were respectively -98.97MPa/° and -

126.22MPa/°. Then the results of residual stress were calculated at last.

Besides, tensile strength was tested by using tensile machine, and there are three specimens that were annealed at the same temperature were measured in every group. During the experiment, first, the parts were regulated into the same vertical plane, and the specimen was clamped, then loaded gradually until the specimen was fractured. What's more, all the specimens were tested respectively, and the tensile strength was obtained.

4 Results and discussions

The results of simulations are shown in Fig.2 a, b, c and d. The distributions of residual stress obtained by simulations at different temperatures are nearly the same, but the stress values are different from each other. Because of the phenomenon of stress concentration emerges at the edge of interface, in another words, the place will fracture easily.

Fig.2 The results of simulations, a : without annealing, b : annealing at 200°C, c : annealing at 250°C, d : annealing at 300°C

In this paper, the line crossing the edge of interface and the place where stress concentration emerges was named as measuring line. The line is 2mm distance from the edge(the measuring line is shown in Fig.2). Then the stress distribution along the line crossing the edge of interface and the place where stress concentration emerges was investigated. Based on the stress values at

the places of nodes on the measuring line and the distance between nodes, Fig.3 can be got, and it shows the distribution of residual stresses that were got by simulations. It can be thought that residual stresses in the interface are tensile stress, and the values of stresses near the interface are larger than other places. The stresses near interface at the treated conditions 200°C, 250°C, and 300°C are respectively 66MPa, 61MPa and 63MPa. When without annealing, the stress is about 71 MPa. In another words, The further from interface the smaller it will be. What's more, the residual stress turn to be compressive stress, when the place is far from interface and it nearly to be 0MPa in the further place.

Figure.3 The distribution of residual stress, obtained by simulation

The result of residual stress measured by XRD is shown in Fig.4. the diffraction peak of Al emerges in the place where 2θ is near 139° , and indices of crystal face is (311). While the diffraction peak of Mg occurs when the value of 2θ is near 152° , and indices of crystal face is (104). However, the diffraction peaks of intermetallic compounds near Al and Mg are respectively 139.4° and 143° [12]. It can be known that residual stress in the interface is tensile stress, and the value is the largest. The stress turns to be lower along with the increasing of the distance from interface. The residual stress nearly to be 0MPa in the further place.

Figure.4 The distribution of residual stress, measured by XRD

In addition, when the annealing condition is 300°C, the largest stress is about 51MPa, when annealing temperature is 200°C, the stress near interface is about 60MPa, while treated at 250°C, the largest stress is approximately 44MPa. However, when without annealing, the stress is about 65 MPa, which emerges at the place called interface. According to the annealing theories, The stress in the place where is far from the welded joints, turn to be smaller and smaller, and gradually close to 0 MPa. So it could be thought that the results of residual stress obtained from simulations and experiments are in a good agreement with the welding theory.

Stress is a vector, and the tensile stress is as plus, while compressive stress is as minus in this study. When stress emerges in materials, the mechanical behavior of materials will be effected. Such as fatigue strength, tensile strength and so on. What's more, fracture will also be result in. As the study above, the residual stress in the interface of Mg/Al alloy will effect the mechanical behavior of composite material. The bigger the residual stress is, the weaker the tensile strength will be. For the purpose of verifying the results on residual stress, the analysis about tensile strength is carried out as following.

The average tensile strengths of composite sheets treated at different annealing treatment temperature were obtained by tensile experiments. When the annealing temperature is 250°C, the tensile strength is the strongest, which is about 47MPa. However, when annealed at 200°C and 300°C, tensile strength are approximately 41MPa and 39MPa. While without annealing, the strength is about 37 MPa, which is nearly the same with what has been reported in other study[13]. As it is known that residual stress has important impact on the strength of materials. If the residual stress is tensile stress, then it will decrease the tensile strength of the materials and increase it's compressive strength. In contrast, the compressive residual stress will decrease the compressive strength and increase the tensile strength of the materials. So it is apparent that the results of the experiments about tensile strength is consistent with that of residual stress.

Conclusions

In this paper, simulations about annealing of bonded Mg/Al composite sheets, and experiments on residual stress, tensile strength were carried out. According to the outcomes of simulations and experiments, It can be thought that the residual stress after annealing at 250°C is 44MPa, which is the least of all. While the tensile strength after annealing at 250°C is 47MPa, which is the strongest. And the results got by simulations are in a good agreement with that of experiments. So the conclusion can be obtained that 250°C is the most appropriate annealing temperature.

Acknowledgments

This research work has been partially supported by the grant subsidy of the "Nano Project" for Private

Universities:2011-2014 from MEXT, Japan. This study was also supported by the “Advanced Science Research Laboratory” in Saitama Institute of Technology.

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