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Residual stress and fracture strength of brazed joint of ceramic and titanium alloy with the aid of laser deposited functionally graded material layers

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ABSTRACT

To improve the strength of a ceramic (ZrC-SiC) and a titanium alloy (TC4) brazed joint, laser deposited functionally graded material layers (FGM layers) between ZrC-SiC and TC4 were designed to reduce the residual stress in the brazed joint. A simulation model of the brazed joint was created to investigate the mechanism of residual stress reduction due to FGM layers. The results show that the residual stress component in the normal direction of the brazing interface (normal stress) is tensile at the ZrC-SiC edges and the in-plane residual stress component on the brazing interface is compressive in the ZrC-SiC adjacent to the brazing seam. The adoption of the FGM layers significantly reduces both the normal residual stress and in-plane residual stress. During the shear test, the normal stress concentrates at the ZrC-SiC edges near the brazing seam. By applying fracture forces 645 N and 1365 N measured in shear experiments to the ZrC-SiC/TC4 joint model and ZrC-SiC/TC4-FGM joint model respectively, the local fracture stress in the normal direction is identified to be 648 MPa and 671 MPa from both models, respectively. Although the fracture force for both models are quite different due to the difference of residual stress produced by brazing, the identified local fracture stress is close each other. The predicted cracking initial position is around the corner of the ZrC-SiC close to the brazed zone which is the same as observed in experiments.

1. Introduction

The ZrC-SiC ceramic and its applications to ultra-high temperature environments have been paid much attention due to its outstanding thermal stability, oxidation resistance and corrosion resistance [1–5]. On the other hand, the titanium alloy TC4 has the good ductility besides the high strength and lower thermal expansion at the high temperature compared with other light metals. Therefore, to join the ZrC-SiC and TC4 becomes a challenging research. One of the joining processes can be brazing. However, the difference of coefficient of thermal expansion (CTE) between TC4 and ZrC-SiC is very large, which induces large residual stress in the brazed joint. Then the joint strength is low due to the residual stress [6,7]. To reduce the residual stress and improve the strength of the brazed joint, the adoption of FGM layers were proposed by Pietrzak [8], Lee [9] and J.Q. Li [10]. Although some joining experiments for design of chemical composites of FGM layers and stress simulation for brazed joints with FGM layers have been performed, the residual stress reduction mechanism is rarely investigated.

To clarify the effect of the FGM layers on the residual stress and mechanical properties of the brazed joint, the residual stress in the joint and its fracture strength need to be investigated. Numerical simulation is an effective approach to the residual stress in the welded and brazed joints [11–14]. Recently, lots of researches focus on the residual stress in the ceramic and metal brazed joints. Zhong et al simulated the graphite/Cu brazed joint and showed a stress concentration on the edge of the graphite near the brazing seam [15]. K. Nagatsuka et al simulated the residual stress in the SiC and WC-Co brazed joint and indicated that the stress concentration position in the ceramic was corresponding to the crack initiation in the joint [13]. Pietrzak et al analyzed the effect of the FGM layers on the residual stress distribution in Al_2O_3 and steel brazed joint. The adoption of the FGM layers reduced the residual stress in Al_2O_3 significantly [8]. It was also reported that the FGM layers have a dominated effect on the residual stress concentration. Lee et al joined Al_2O_3 and Si_3N_4 using FGM layers and simulated the residual stress in the brazed joint [9]. The FGM layers made the position of the peak residual stress in the joint move to the FGM layers from the ceramic side. The above researches indicated that the residual stress in the joints is reduced through using the FGM layers. However, the mechanism of residual stress reduction with the FGM layers is not revealed clearly. Therefore, it is important to analyze the effect of the FGM layers on the

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residual stress in the joint deeply.

During the shear test, the fracture force of the brazed joint is strongly influenced by both the internal residual stress generated during the brazing process and the external stress due to the applied shear force. But the effect of the brazing residual stress on the fracture strength of the brazed joints during the shear test is rarely reported. Up to now, only Wang et al [14] calculated the stress distribution and focused the Mises equivalent stress in the Si_3N_4/Invar brazed joint during the shear test process. However, the research about the cracks in ceramics indicates that the cracking position and its propagation direction in the fracture process of ceramics cannot be predicted by Mises equivalent stress and may be dominated by a certain stress component [13]. Therefore, the investigation of the relation between the dominant stress component in the brazed joint and the fracture of the brazed joint during the shear test, is meaningful to reveal the fracture of the joint and evaluate the reliability of the joint. According to the above two aspects, the simulation works in this study contain two parts. Firstly, the effect of the FGM layers on the residual stress distribution in the brazed joints should be analyzed. Secondly, the stress distribution during the shear test process need to be analyzed.

In this study, the ZrC-SiC and TC4 brazed joint, ZrC-SiC and TC4-FGM brazed joint were designed and prepared. Then, shear fracture test was performed. The above two processes were both simulated using nonlinear FEM. Through comparing the stress distribution in the brazed joints during the brazing and during shear experiment, the effect of FGM layers on the residual stress and total stress in the shear testing was studied. In addition, the local fracture stress perpendicular to the brazing interface was identified and the fracture behavior was discussed.

2. Simulation models of brazed joints for strength evaluation

2.1. Brazing process and materials properties

Before brazing the ceramic ZrC-SiC and titanium alloy TC4, two layers of FGM were deposited on TC4 surface (briefly named by TC4-FGM). The Layer I was deposited on the TC4 surface with the scanning speed of 6 mm/s and the laser power of 1100 W. Meanwhile, SiC powders were only injected into the melt pool of the TC4. The Layer I was obtained after the solidification of the melt pool, which has 20%SiC and 80%TC4 in the volume fraction. Then, in depositing the layer II, the mixed powders of 40%TC4 and 60%SiC were injected into the new melt pool (laser power: 800 W, scanning speed: 3 mm/s). Finally, the Layer II with 39%SiC and 61%TC4 formed. The average thicknesses of the two composite layers are both near 0.4 mm. Then, the ceramic ZrC-SiC, titanium alloy TC4 and TC4-FGM were cut into small piece with the size of $5 \times 3 \times 3$ mm and $10 \times 20 \times 3$ mm respectively for brazing. The chemical components of the brazing filler is 70Ti-15Cu-15Ni (wt%) which is here named as TiCuNi filler. The brazing was performed in a vacuum furnace with the vacuum level of 5×10^{-3} Pa. During the brazing experiment, the specimen were held at 650°C for 120 min and 800°C for 30 min to remove the residual stress in the FGM layers, and then the specimen were heated to 970°C. At 970°C, the liquid braze filler reacted with the base materials, and the brazing was achieved. Finally, the brazing specimens were cooled down to the room temperature from 970°C at a speed of 5°C/min. The cross sections of the joints are schematically shown in Fig. 1. In the brazed joint, two typical zones (Zone A and Zone B) form as the brazing seam. The Zone A is made up of Ti-Cu-Ni compounds. The Zone B contains Ti based solid solution and Ti-Cu-Ni compounds, and the volume fraction of Ti-Cu-Ni compounds is about 30%. The properties of the Ti-Cu-Ni compounds are assumed according to the properties of Ti-Ni, Ti-Cu and Ti. Because the CTE of the Ti-Cu-Ni compound is near to that of the Ti based solid solution and the volume fraction of Ti-Cu-Ni is low, so the CTE of the Zone B is replaced by that of the Ti based solid solution. The Ti based solid solution is assumed similar to the commercial pure Ti. The FGM layers are composed of TC4 and SiC, so the Young modulus and Poisson ratio of the FGM layers are calculated by Eq. (1) based on the linear mixed rule.

$$P = P_m(1 - V_r) + P_r V_r \tag{1}$$

where P indicates the properties such as Young's modulus and Poisson ratio of the composite materials, P_m and P_r are the properties of matrix materials (TC4) and reinforcement (SiC) respectively, V_r is the volume fraction of reinforcement in the composite materials. The CTE of the FGM layers between the room temperature to 450°C was measured through experiment, and the CTE of the FGM layers are assumed based on the measured results. In addition, the yield strength σ_{yield} of the Zone B and FGM layers is calculated by Eq. (2) according to the research [16].

$$\sigma_{yield} = \sigma_{yield}^{m}[V_r(s + 2)/2 + V_m] \tag{2}$$

Where, σ_{yield}^{m} is the matrix yield strength of composite materials. V_r and V_m are the volume fraction of reinforcement and matrix in the Zone B and FGM layers. The s is a parameter relating to the size of reinforcement and it is 1.0 for convenience in our study due to the random distribution of the reinforcements. The properties of the materials used in the simulation are summarized in Fig. 2. The ZrC-SiC is assumed to the thermal elastic material and its yield strength is not listed in the Fig. 2. The Young' modulus of the ZrC-SiC at high temperature is assumed based on its value at room temperature. The thermal elastic-plastic material model is applied to the Zone A, Zone B, FGM layers and TC4 of brazed joints. The properties of the TC4 at high temperature are assumed based on its property at low temperature.

2.2. FE models for residual stress and strength simulation

In this study, the residual stress of the brazed joint was simulated using in-house research program JWRIAN [17–20], a finite element code developed by Joining and Welding Research Institute based on 3D thermal conduction and thermal elastic plastic theory, and strength analysis was performed using software LS-DYNA [21]. Fig. 3 shows the FE models and dimensions of the ZrC-SiC/TC4 joint and ZrC-SiC/TC4-FGM joint. In the ZrC-SiC/TC4 joint, the thickness of Zone A and Zone B was measured in five samples. The thickness of Zone A is between 0.051 mm and 0.065 mm, while the thickness of Zone B is between 0.215 mm and 0.231 mm. In order to build the mesh and models conveniently, the approximate thickness of Zone A and Zone B in the model is assumed to be 0.056 mm and 0.224 mm respectively. In the ZrC-SiC/TC4-FGM joint model, the approximate thickness of Zone A and Zone B in the ZrC-SiC/TC4-FGM joint model is assumed to be 0.01 mm and 0.11 mm respectively after measuring the dimensions of the joint. The Zone A and Zone B are under the ZrC-SiC, and their dimensions are too small to be marked in Fig. 3. The total element numbers in these two models are 265,490 and 309000, respectively. The total node numbers in the two models are 290,867 and 335493, respectively. Their degrees of freedom (DOF) of the nodal displacements in these two models are 872,601 and 1006479, respectively. According to the previous research [6], the solidification temperature of the braze filler can be assumed about 900°C. Therefore, the residual stress in the brazed joint is only generated when the temperature is lower than the solidification temperature during cooling process. Because the temperature in the vacuum furnace decreases at a low speed of 5°C/min during the cooling process. Therefore, a uniform temperature distribution and uniform cooling in the brazing specimen can be assumed. In the residual stress analysis, the initial temperature at all nodes of the FE models is set to 900°C and then cools down to room temperature (assumed 0°C in this study) uniformly. In addition, the bottom surface of the TC4 is fixed to constrain the rigid movement of the brazed joint.

Fig. 4 shows the shear test process and the simulation models for the shear test of the brazed joint. The shear test process is shown in Fig. 4(a) and the fracture shear force could be obtained. Firstly, the