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Original Research Article

Relief of residual stress in Al_2O_3/Nb joints brazed with Ag-Cu-Ti/Cu/Ag-Cu-Ti composite interlayer

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ABSTRACT

Ag-Cu-Ti/Cu/Ag-Cu-Ti composite interlayer was successfully designed to braze Al_2O_3 ceramic and Nb. The effect of the addition of Cu interlayer with various thicknesses on the microstructure, residual stress and mechanical properties of the brazed joints was investigated by finite element modeling (FEM) computation combined with experimental verification. The results showed that the layered Ag-Cu-Ag solid solution structure formed in the Al_2O_3/Nb brazed joints when the composite interlayer was used. Moreover, the thickness of TiO + Ti_3Cu_3O reaction layers adjacent to the Al_2O_3 ceramic substrate did not change obviously regardless of the Cu foil thickness. The maximum residual stress in the whole brazed joint always appeared in the Al_2O_3 ceramic substrate nearby the interlayer, but it was reduced from 384 MPa to 119 MPa when a 150 μm thick Cu foil was added. The variation of calculated residual stresses as a function of Cu foil thickness, which was verified by X-ray measurement, exhibited a consistent with Al_2O_3 ceramic strain energy. Thus, the calculation of Al_2O_3 ceramic strain energy could be a good criterion to evaluate the joint shear strength because the fracture occurred in the Al_2O_3 ceramic. The reduction of detrimental residual stress was primarily attributed to the increased plastic strain energy of Cu interlayer. The FEM and experiment results indicated that the ability of plastic deformation of the interlayer played a key role in determining the residual stress in the brazed joint, providing a method for improving the bonding properties of ceramic and metal.

1. Introduction

Al_2O_3 is an important engineering ceramic that has been widely applied in many fields due to its superior high-temperature properties and resistance to corrosion [1,2]. However, like most other ceramics, the inherent rigidity and brittleness of Al_2O_3 ceramic limit its structural application, especially the manufacture of components with complex structures. As a refractory metal, niobium has good plasticity, corrosion resistance and weldability [3,4]. The components with both ceramic and metal properties can be obtained by the successful joining of Al_2O_3

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ceramic and Nb. Vacuum brazing is an effective way to realize the bonding of dissimilar materials due to its convenience and high joint quality [5–7]. However, it is difficult to fabricate a strong Al_2O_3/Nb joint because of the significant differences in the physical and chemical properties between the Al_2O_3 ceramic and Nb. Detrimental thermal stresses were produced inevitably in the brazed joint as a result of different mechanical responses of ceramic and metal cooling from brazing temperature to room temperature. If the residual stress is high enough in the ceramic substrate, failure can occur even if the external force is relatively small [8,9]. Therefore, it is necessary to reduce the harmful residual stress as much as possible to improve the strength of the ceramic-metal brazed joints. Considerable effort has been made to relieve the residual stresses by the design of the interlayer material [10–14]. The most frequently solution is to add particles or whiskers with low coefficient of thermal expansion (CTE) into the brazing alloy to fabricate the composite filler metal. Yang et al. [13] reported that the maximum tensile stress in SiO_2-BN ceramic could be decreased from 230 MPa to 142 M Pa in SiO_2-BN/Invar brazed joint when 3 wt.% BN particles were added into Ag-Cu-Ti brazing alloy. The reduction of residual stress was mainly attributed to the decrease of CTE of the brazing seam caused by BN additives. However, Zhou et al. [15] reported that the residual stress of Si_3N_4/steel brazed joint was reduced obviously by adding Cu interlayer with a large CTE. It can be concluded that the addition of soft interlayer with low yield strength was also an effective method to improve the joint strength.

The reduction of residual stress by adding Cu interlayer has been reported in Si_3N_4/steel [16], Si_3N_4/Invar [17], and Si_3N_4/stainless steel brazed joints [18]. More specifically, Wang et al. [17] studied the effect of the addition of Cu interlayer on the absorption of residual stress produced in Si_3N_4/Invar brazed joint by FEM analysis combined with tensile strength. The results showed that the optimal thickness of Cu interlayer for reducing the residual stress was 200 μm. The plastic deformation was not sufficient for a thin Cu interlayer while a thick one caused low mechanical property of a brazed joint. However, little work has been carried out on analyzing the effect of Cu interlayer on the residual stress and strength of brazed joints by taking into account the actual joint microstructure. Moreover, the mechanism for residual stress relief as a result of the addition of Cu interlayer has not yet revealed systematically.

In this study, Ag-Cu-Ti/Cu/Ag-Cu-Ti composite interlayer was used to braze Al_2O_3 ceramic and Nb. The FEM analysis was used to calculate the magnitude and distribution of residual stress in the brazed joints, and the model was built on the basis of actual joint microstructure from the SEM results. The relationship between the variation of residual stress and Al_2O_3 ceramic strain energy was discussed. Additionally, the measurement of residual stress and the shear test were performed to verify the accuracy of FEM calculation.

2. Experiments and modeling

2.1. Experimental procedures

The base materials used in the experiments were Al_2O_3 ceramic block and pure Nb plate. The purity of polycrystalline Al_2O_3 ceramic was 95%. The received Al_2O_3 ceramic block was cut into the samples with the dimension of $5 \times 5 \times 5$ mm^3 by a diamond cutting machine. Nb plate was cut into small blocks with the size of $10 \times 15 \times 2$ mm^3 for brazing. The surfaces of the brazing sample were hand abraded to 1200# by SiC sand paper. The Ag-Cu-Ti/Cu/Ag-Cu-Ti composite interlayer was used to braze Al_2O_3 ceramic and Nb. Ag-27.6Cu-1.5Ti foil with a thickness of 100 μm was used as the active brazing alloy. The Cu foil with the thickness of 50, 100, 150, 200, and 300 μm was inserted between the Ag-Cu-Ti foils as a residual stress relief layer. Two layers of single Ag-Cu-Ti foil were used as the contrast experiments to reveal the influence of Cu foil. All samples were cleaned in acetone by ultrasonic for 10 min prior to vacuum brazing. The brazing assembly was maintained with a graphite fixture to ensure the whole samples in a close contact. Then, the assembled samples were put into a vacuum furnace to do the brazing experiments. The vacuum level of the furnace was higher than 7×10^{-4} Pa during the whole brazing process. The brazing temperature was 840 °C with a dwell time of 10 min. The heating rate was 10 °C/min and the cooling rate was set to be 5 °C/min. After the brazing experiments, the cross-section of the brazed joint was characterized by a scanning electron microscope (SEM, JSM-7800) equipped with an energy dispersive spectrometer (EDS). The phase of reaction layer in the joint was identified by X-ray diffractometer (XRD, D8-ADVANCE) after dissolution of the sample in a nitric solution. The residual stress at the surface of brazed Al_2O_3/Nb samples was measured using XRD technique (RIGAKU D/max 2500 V/PC). The shear strength of the joint was tested by a universal testing machine (MTS E45) at a constant loading speed of 0.2 mm/min. A schematic diagram of the shear experiment was shown in Fig. 1. The sample was mounted on a fixture and the external force was added to one side of Nb until the specimen was fractured. The value of the shear strength was the average of three samples under the same experimental condition. Moreover, the fracture surface of the brazed joint after shear test was observed with a digital microscope (VHX-2000).

2.2. Model description

The residual stresses were produced in the Al_2O_3/Nb brazed joints during the cooling process owing to the mismatch of

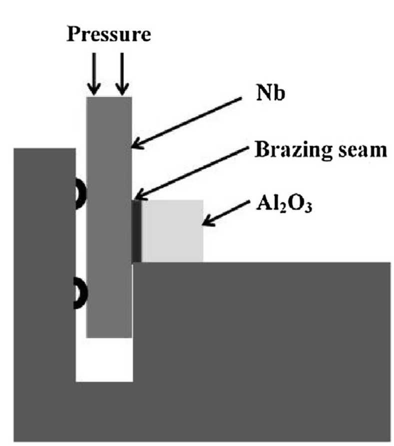

Fig. 1 – Schematic diagram of shear test.