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Finite-element analysis of residual stresses in Al_2O_3–TiC/W18Cr4V diffusion bonded joints

Shen Xiaoqin [a,b,*], Li Yajiang [a], U.A. Putchkov [c], Wang Juan [a], Huang Wanqun [a]

[a] Key Lab of Liquid Structure and Heredity of Materials, Ministry of Education, Shandong University, Jingshi Road 73, Jinan, Shandong 250061, China
[b] School of Mechatronics Engineering, Shandong Jianzhu University, Fengming Road, Jinan, Shandong 250101, China
[c] Materials Science Department, Bauman Moscow State Technical University, Moscow105005, Russia

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ABSTRACT

The residual stress distribution in Al_2O_3–TiC/W18Cr4V diffusion bonded joints was calculated using finite element method (FEM). The effects of pressure and interlayer on the axial stress and shear stress were also studied. The results show that the gradients of the axial stress and shear stress are great near the joint edge and are flat near the center of the joint. The maximal tensile axial residual stress is reached on the ceramic side at the ceramic/interlayer interface. The maximal shear residual stress is at the two interfaces of ceramic/Ti interlayer. With the increase of bonding pressure, the maximal tensile axial stress decreases and the compressive axial stress increases. But there is small effect of pressure on the shear stress. With Ti–Cu–Ti interlayer instead of Ti interlayer, the maximal axial residual stress has little decrease and the maximal shear residual stress decreases greatly. Near the edge of the joint, Ti–Cu–Ti interlayer reduces the residual stresses. The site of shear fracture in Al_2O_3–TiC/W18Cr4V diffusion bonded joints agrees with the simulated residual stress distribution.

1. Introduction

Al_2O_3–TiC ceramic matrix composites composed of Al_2O_3 matrix and TiC reinforcing particles have been widely used as cutting tools recently, because of their high strength, hardness, chemical stability and excellent wear resistance [1–2]. But the inherent rigidity and brittleness of Al_2O_3–TiC ceramic make it hard to machine and manufacture large-sized or complex-shaped components. Diffusion bonding is an advantageous technology for producing ceramic/metal joint. High residual stresses will originate close to the interface due to the large difference in elastic modulus and thermal expansion coefficient of the ceramics and metals when cooling down from the bonding temperature. Such stresses can affect the mechanical strength of the joints. To reduce the residual stresses in ceramic/metal joint, interlayers with appropriate material properties are usually adopted [3–5]. The stress distribution in diffusion bonded joint is very complex and exact measurements are difficult. So FEM is usually used to analyze the residual stress distribution and the effects of diffusion bonding variables [6–11].

In this paper, the distribution of axial residual stresses and shear residual stresses in Al_2O_3–TiC/W18Cr4V diffusion bonded joint was studied using FEM, the effects of pressure and interlayer material being taken into account. The shear fracture location was experimentally studied to verify the calculation.

2. Experimental and FEM model

2.1. Experimental

An Al_2O_3–TiC ceramic matrix composite test piece (ϕ50 mm × 3 mm) made by hot pressure sintering (HPS) and a W18Cr4V high-speed tool steel test piece (ϕ50 mm × 1 mm) were diffusion bonded using an interlayer of 0.1 mm Ti foil or 0.02Ti–0.06Cu–0.02Ti (the numbers indicate foil thickness in mm) foil for reliable joining and stress relief. Bonding was performed at 1130 °C for 60 min with a pressure of 5 ~ 30 MPa in a vacuum chamber of 10^{-5} Pa. Then the joint is cooled down to room temperature at a

* Corresponding author. Address: Key Lab of Liquid Structure and Heredity of Materials, Ministry of Education, Shandong University, Jingshi Rd. 73, Jinan, Shandong 250061, China. Tel.: +86 531 88392924; fax: +86 531 82609496.
E-mail address: shenxiaoqin@mail.sdu.edu.cn (X.Q. Shen).

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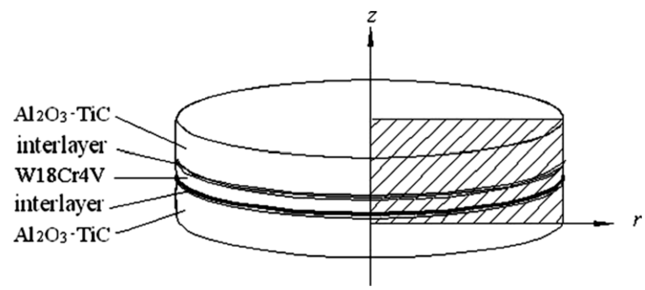

Fig. 1. Schematic diagram of the diffusion bonded joint.

cooling speed of 10 °C/min. The diffusion bonded joint is schematically shown in Fig. 1. Shear fracture morphology and phase composition on the fracture surface were studied to verify the FEM calculation results.

2.2. FEM model

The FEM model is established for a 2-D axisymmetrical thermal elastic–plastic stress analysis to the diffusion bonded joint. Due to the axial symmetry of the joint (Fig. 1), an arbitrary meridian plane is selected to analyze the stress in the joint, with four-node axisymmetrical elements. The division of the finite element mesh is shown in Fig. 2. At the area near the interlayer, fine elements were used to determine the detailed stress distribution. In the calculation, Al_2O_3–TiC ceramic is assumed as elastic body and the high-speed tool steel W18Cr4V and the interlayer are as elastic–plastic bodies following Von Mises yield criterion and linear kinematic hardening rule. The material properties employed are shown in Table 1. The high temperature parameters of materials not shown in Table 1 are linearly extrapolated. Generally, as temperature increases, elastic modulus and yield strength decrease and thermal expansion coefficient increases. The increase of expansion and the decrease of yield strength will lead to the increase of the calculated stress. On the other hand, the decrease of elastic modulus will reduce the stress. So the adoption of room temperature properties for Al_2O_3–TiC, Cu and Ti should have not too big impact on the calculated stress.

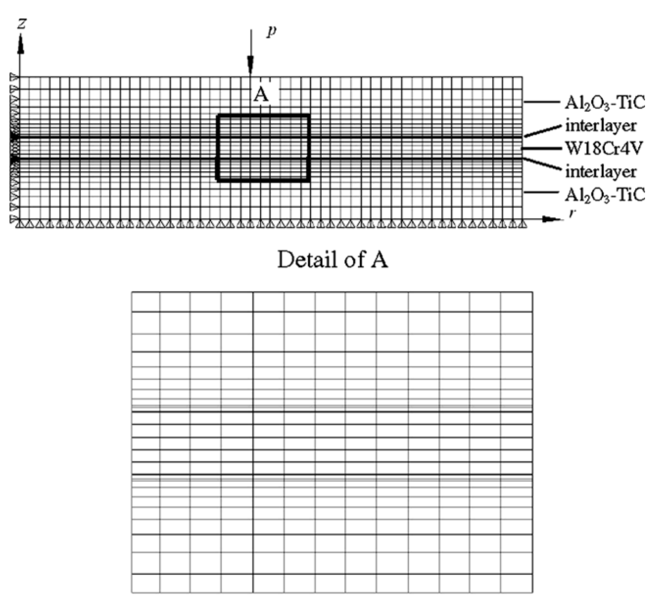

Fig. 2. The finite element mesh in the FEM calculation.

Because the lower side ceramic is placed on the supporting shoe of the pressure head during diffusion bonding, the nodes which belong to the ceramic bottom ($Z = 0$) are constrained in axial direction. And the nodes on the symmetrical axis Z are constrained in radial direction (see Fig. 2).

The external loading includes a uniform pressure p on the top surface and temperature changes.

The initial temperature of the model is the diffusion bonding temperature 1130 °C and the cooling speed is 10 °C/min.

3. Results and analysis

3.1. Distribution of axial stress and shear stress

Fig. 3 presents the distribution of axial and shear residual stress in Al_2O_3–TiC/W18Cr4V diffusion bonded joint which was bonded at 1130 °C for 60 min with a pressure 15 MPa using 0.02Ti–0.06Cu–0.02Ti interlayer. From Fig. 3 we can see that the axial and shear residual stresses both change greatly near the edge of the joint and the distribution of them near central symmetric axis Z is uniform. The maximum tensile residual stress of 30.1 MPa is located at the Al_2O_3–TiC ceramic side near interface at a distance of 4.5 mm from the edge. The maximum compressive residual stress is located at the W18Cr4V high-speed steel side at the edge($r = 25$ mm). Most area in the joint is under compressive residual stresses except the little portion symmetrical about W18Cr4V steel around the location of 4.5 mm from the edge. The maximum shear residual stresses at the two ceramic/Ti interfaces are nearly equal in magnitude but with reverse directions. So when external shear force is applied on the joint, the fracture easily occurs on the interface.

3.2. Effect of pressure on the stress

The role of pressure during the joining process is to establish the contact between the ceramic and metal. By applying compressive load, compressive deformation takes place near to the interface and induces the plastic deformation of the metal. To evaluate the expected beneficial effect of the compressive load, the residual stresses were also calculated. Fig. 4 shows the distribution of axial and shear residual stress in Al_2O_3–TiC/Ti interface which was bonded at 1130 °C for 60 min using 0.02Ti–0.06Cu–0.02Ti interlayer with different pressure. From Fig. 4a one can see that the axial stress has little change when $r \leqslant 15$ mm. When $r > 15$ mm, the axial stress rises until $r = 20.5$ mm to the maximum tensile stress. When $r > 20.5$ mm, the axial stress decreases until

Table 1
Material properties employed in FEM.

Property	Temperature (°C)	Elastic modulus (GPa)	Poisson ratio	Thermal expansion coefficient (10^{-6}(°C)$^{-1}$)	Yield strength (MPa)
Al_2O_3–TiC	25	375	0.33	8.5	–
W18Cr4V	25	198	0.3	–	235
	100	194	0.3	16.6	–
	600	157	0.3	18.2	176
	700	147	0.3	18.6	127
Cu	25	128.7	0.3	17.1	71
Ti	25	109.2	0.27	8.2	140