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Direct joining of 2D carbon/carbon composites to Ti–6Al–4V alloy with a rectangular wave interface

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Abstract

Direct joining of 2D carbon/carbon composites (C/Cs) to Ti–6Al–4V (Ti64) has been studied theoretically and experimentally by constructing a rectangular wave interface (RWI) between C/Cs and Ti64. The joining surface of C/Cs was grooved into a rectangular wave surface, on which a Ti64 layer was then clad at 1680–1710 °C to form a pre-joining clad sample. The clad sample was then diffusion bonded to a Ti64 plate at 900 °C to form a final joined sample. The residual stresses in the clad or joined samples were estimated by Finite Element Analysis. The microstructure of joined sample was examined by SEM, and the strength of joined sample was evaluated by compressive shear strength tests. The simulation results indicated that the residual stresses were more beneficial to crack arrest for the clad or joined samples using the RWI instead of a flat interface. The experimental results showed that the sound joined samples were obtained with the shear strength as high as 41.63 MPa.

Keywords: Joining; C/C composites; Titanium alloy

1. Introduction

Carbon/carbon composites (C/Cs) have low density, good wear resistance, and superior thermo-mechanical properties even at temperatures above 2000 °C. Therefore, C/Cs are expected to be used in many thermal structures of advanced aerospace crafts, such as rockets, space shuttles, supersonic planes, etc. [1–3]. One of the most important characteristics of these structural parts is that they often are required to be joined to a metal, such as Ti alloy, which has high specific strength and can withstand high working temperatures. However, C/Cs-metal joint has a strong tendency to cracking or even fracturing during cooling down from joining temperature because of the large thermal residual stresses caused by the thermal expansion mismatch between the two heterogeneous materials.

Using either stress relief buffer (SRB) or functionally graded materials (FGMs) as the joining interlayer is a general method of releasing the thermal residual stress in the joining of ceramic-metal or heterogeneous ceramics [4–8]. The material, to be served as the SRB interlayer, should have low yield strength and low elastic modulus. Therefore, pure metals such as Ni, Cu and Al were generally the candidates [9–12]. The successful joining of C/Cs to Al [13] or Cu [14,15] has been reported. However, due to their low melting points and low strengths at high temperatures, Ni, Cu and Al are not applicable for thermal structures as joined metal or SRB interlayer.

FGMs have a designable gradient in composition, and then exhibit a desirable gradient in coefficient of thermal expansion (CTE), and therefore FGMs can effectively accommodate the thermal expansion mismatch between the heterogeneous materials to be joined. However, it is difficult to apply a FGMs interlayer to the C/Cs-metal joining, because the C/Cs surface generally have many inherent process-induced pores and cracks, which need to be filled by the joining interlayer during the joining process to increase joining area and avoid stress concentration [16,17]. But the melting will destroy the composition gradient of the FGMs interlayer.

In fact, the use of SRB or FGMs as interlayer mainly aims at constructing a three-dimensional (3D) joining region, which supplies a transition region for the residual stress to change gradually. Yet, such a 3D region can also be achieved by constructing a wave joining interface. Fig. 1 presents a 3D joining region with

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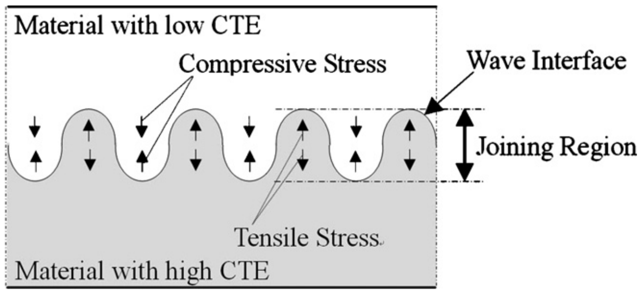

Fig. 1. A schematic showing the alternating structure of the wave interface.

an alternative structure of the two joined materials. Such alternative structure, if designed properly, can regulate the thermal properties of the joining region, and then releases the thermal residual stresses. Moreover, due to the thermal mismatch of the both joined materials, the wave (or 3D) interface can produce a field with alternating tensile and compressive stresses in the joining region, as shown in Fig. 1. Rao et al. [18] found that this kind of stress field was favorable to crack arrest. In addition, the joining with the wave interface does not need any joining interlayer. Consequently, it is reasonable to reckon that the method of joining with a wave interface may be suitable for the joints of heterogeneous materials used at high temperatures.

Due to the low density, high strength and good high-temperature properties of Ti alloy, the joining of C/Cs to Ti alloy has potential applications in many thermal structures of advanced aerospace crafts [19]. Singh et al. [20,21] brazed Ti-tubes to C/Cs plates using commercial filler metals, TiCuNi, TiCuSil and Cu-ABA at 910–1040 °C. However, micro-cracks occurred in the joining regions, and the highest tensile strength of joints was as low as 0.33 MPa.

In this paper, an innovative method for joining C/Cs to Ti–6Al–4V (Ti64), by constructing a rectangular wave joining interface, was numerically and experimentally studied for aiming at obtaining a robust C/Cs–Ti64 joint for thermal structural applications.

2. Experimental procedures and numerical simulation method

2.1. Materials

The 2D C/Cs was fabricated with CVI techniques (from National Key Laboratory of Thermostructure Composite Materials, Northwestern Polytechnical University, China). The preform for the composites was a lamination of carbon fiber layers pinned with carbon fibers through the layers. The fiber volume fraction and the density of the C/Cs were 54% and 1.64 g/cm^3, respectively. The metal to be joined to C/Cs was commercially available Ti64 alloy. Prior to the joining, C/Cs and Ti64 were cut into cubic specimens of 22 mm × 18 mm × 5.5 mm and 22 mm × 18 mm × 2.5 mm, respectively.

2.2. Experimental procedures

Since there are some process-induced pores and cracks at the joining surface of C/Cs, filling these defects with the joining material is necessary as mentioned above. Therefore, prior to joining, the joining surface of C/Cs was clad with Ti64. The pores and cracks within C/Cs are beneficial to decreasing of C/Cs modulus and the release of residual stresses induced in joining. Therefore, it is not necessary to fill the inner pores or cracks of the C/Cs.

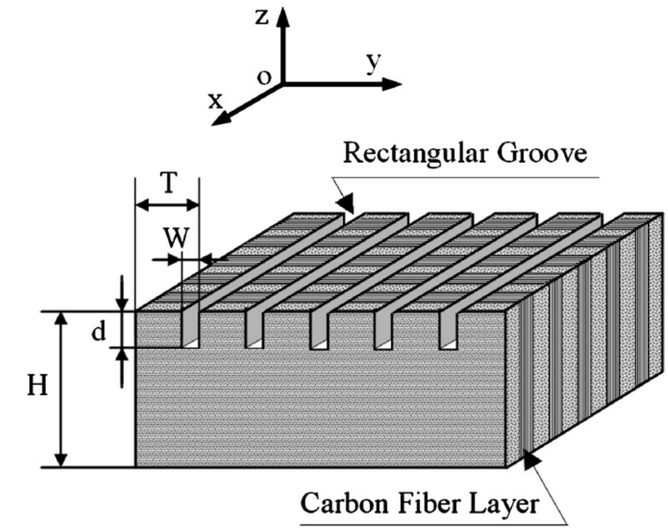

Fig. 2. A schematic showing the structure of rectangular-grooves on the 2D C/Cs joining surface.

2.2.1. Cladding C/Cs with Ti64

Before cladding, the joining surface of C/Cs was machined into a rectangular-groove surface, as shown in Fig. 2. The width of the groove, W, was fixed as 0.35 mm, and the distance between the two adjacent grooves, T, was 1.05 mm. Taking into account a high ratio of the groove depth, d, to the C/Cs thickness, H, may be detrimental to the strength of C/Cs plate, the depth of the groove was ranged between 0.3 and 1.6 mm, which means the ratio of d/H was controlled in the range of 0.05–0.29. The orientation of the grooves, as indicated in Fig. 2, was designed to be perpendicular to the carbon fiber layers, so as to release the thermal stress effectively with a less damage to the C/Cs. Due to the significant anisotropy in elastic properties of the C/Cs, the Young's or shear modulus in the direction parallel to the carbon fiber layers (y-direction in Fig. 2) is about 2–4 times higher than that in the direction perpendicular to the layers (x-direction in Fig. 2) [22–24], which would induce higher thermal residual stresses [25]. Therefore, the grooves were arranged along the x-direction (see Fig. 2); accordingly, the CTE in y-direction was expected to increase gradually from C/Cs to Ti64 after Ti64 filling into the grooves. For comparison, a C/Cs specimen with a flat joining surface was also prepared.

The Clad samples were obtained through induction heating of Ti64 sheet (22 mm × 18 mm × 2 mm) on the flat or grooved surfaces of C/Cs at 1680–1710 °C for 0.5–1 min in vacuum of 3.2×10^{-3} Pa. However, the clad sample with the flat C/Cs–Ti64 interface split along the interface during the cooling process of cladding, then the further joining to the Ti64 plate was cancelled; whereas the clad sample with the rectangular wave interface (RWI) retained its integrity. The Ti64 cladding layer of the latter