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Fabricating thick-section carbon fiber/silicon carbide composites by machining-aided chemical vapor infiltration

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A B S T R A C T

Chemical vapor infiltration (CVI) is a prominent process for fabricating carbon fiber/silicon carbide (C/SiC) composites. However, the preparation of enclosed-structure or thick-section C/SiC composites/components with CVI remains a challenge, since the difficulty of densification increases. Here, machining-aided CVI (MACVI) is designed, in which infiltration-assisting holes are utilized (machined) to increase matrix deposition. To validate the approach, thick-section (10 mm thick) C/SiC composites were fabricated by MACVI. Porosity analysis and microstructure characterization were performed on the fabricated MACVI C/SiC composites and their CVI counterparts, showing a density increase up to 12.7% and a porosity decrease up to 32.1%. The mechanical behavior of the fabricated MACVI C/SiC composites was characterized, showing an increase of flexural strength by a factor of 1.72 at most. Besides, the toughness also largely increases. Both the porosity decrease and the strength and toughness increase brought by MACVI demonstrate its effectiveness for fabricating stronger and tougher enclosed-structure or thick-section ceramic matrix composites/components.

1. Introduction

Overcoming low fracture toughness of monolithic ceramics, continuous fiber reinforced ceramic matrix composites (CMCs), e.g., carbon fiber/silicon carbide (C/SiC) composites, have broad application in both aeronautics and astronautics [1–5]. Maintaining the merits of ceramics: low density, thermal and corrosion resistant, they mainly perform as thermostructural materials [6–9]. To fabricate fiber reinforced CMCs, chemical vapor infiltration (CVI), in which a minimum mechanical damage to the reinforcing fibers can be achieved, is the favorite choice [10–13]. CVI process is a powerful and versatile bottom-up approach, where various high modulus fiber reforms can be infiltrated with weak interphase (laminar structure) and different dense matrices to form the required CMCs [14–17].

As the application of CVI C/SiC composites rapidly grows, demands for C/SiC composites/components with enclosed structure or thick section have increased. The fabrication of these special CMCs by CVI, however, remains an issue, since both the enclosed structure and the thick section are factors that hamper the matrix deposition in CVI and increase the difficulty of obtaining qualified well-infiltrated CMCs, due to the vapor transport character and the "bottleneck effect" [18] of CVI. Therefore, improving the matrix deposition in CVI to attain qualified enclosed-structure or thick-section C/SiC composites/components is of much concern.

Approaches to better matrix deposition, mainly focus on utilizing auxiliary physical fields, e.g., thermal field or (and) pressure field, with which sequenced matrix deposition or (and) fast convection in mass transfer can be achieved [14,19–21]. Among them, forced CVI (FCVI) is a typical process using both pressure filed and thermal field to achieve the fabrication of thick-section (12.7 mm thick) CMCs [14,20]. The utilization of physical fields, however, increases the complexity of apparatus and diminishes the flexibility of CVI in a way that different shapes of CMC composites/components can not be simultaneously infiltrated.

In this study, we demonstrate an approach, machining-aided CVI (MACVI), where infiltration-assisting holes, performing as gas channels, are used to facilitate the matrix deposition. Specifically, infiltration-assisting holes that perform as channels for gaseous precursors are machined on partially infiltrated C/SiC composites, to increase the matrix deposition in the subsequent infiltration cycles (Fig. 1a). Following the above, thick-section (10 mm thick) two dimensional (2D) MACVI C/SiC composites were fabricated. Investigation on their microstructures and mechanical performances demonstrates both material and mechanical enhancement with more matrix deposited (up to 32.1% decrease of porosity) and higher load carried (up to 72% increase of flexural strength).

Distinct from the approaches using all kinds of auxiliary physical fields, MACVI increases the matrix deposition in a way that the

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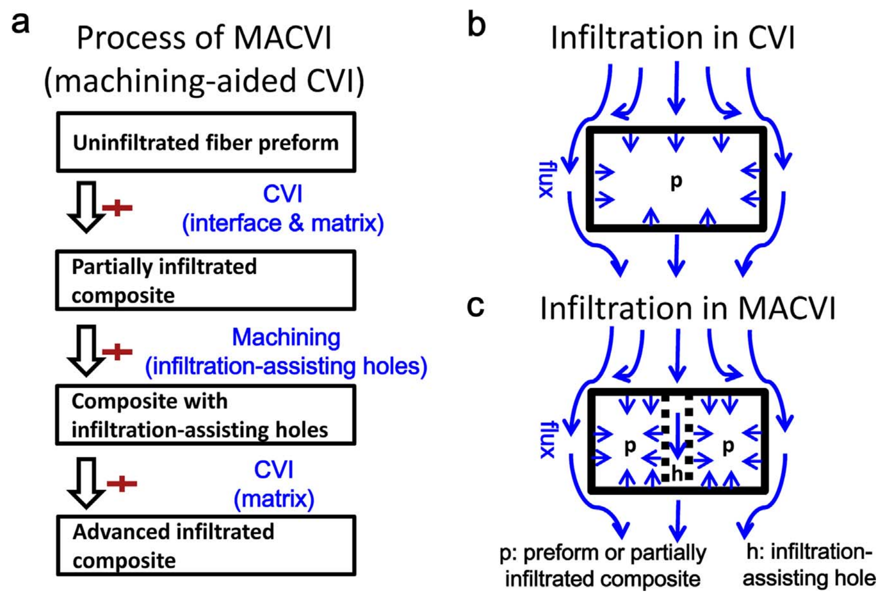

Fig. 1. (a) Schematic of the process of MACVI. (b and c) Schematic of the gas transport in CVI and MACVI.

flexibility of CVI is maintained while no high-energy and high-cost modifications are made. Also, for components designed with holes, e.g., cooling holes, it merges the post-fabrication hole-machining with the fabrication process (CVI) to both increase the matrix deposition and reduce the possible material damage caused by machining. In addition, a post-processing (filling/sealing) of infiltration-assisting holes can be designed which offers the MACVI high flexibility in application.

2. Experimental

2.1. Materials

Two kinds of specimens of thick-section (10 mm thick) 2D C/SiC composites were fabricated by MACVI, following the process illustrated in Fig. 1a. The percent open areas (POAs, the ratio of the area of infiltration-assisting holes to the area of specimen surface on which infiltration-assisting holes are machined) of the two kinds of specimens are 1.69 and 3.38, respectively, with the same hole diameter (2 mm). As comparison, another kind of specimens, the CVI counterparts were fabricated without the machining of infiltration-assisting holes. The difference of CVI and MACVI in terms of gas transport is depicted in Fig. 1b and c. Other geometry details of specimens are shown in Fig. 2a.

Specific fabrication process was as follows. Firstly, 2D carbon fiber (T300, Toray, Japan) preforms were prepared by laminating tabby carbon cloths layer by layer. The fiber volume fraction V_f was ca. 40%. Secondly, the interphase layer of pyrolytic carbon (PyC) was deposited on carbon fibers with C_3H_6 at the nominal temperature 900 °C. Then, methyltrichlorosilane (MTS, CH_3SiCl_3) carried by H_2 was utilized in CVI to infiltrate matrix SiC in the preform. Temperature at 1100 °C, a ratio of H_2:MTS at 10:1 and a pressure of 4 KPa were the nominal conditions for the matrix deposition. The deposited SiC is polycrystalline β-SiC (cubic crystal structure) with a preferred orientation of the crystal plane (111). After 4 deposition cycles with 80 h/cycle, the partially infiltrated C/SiC plates were machined to obtain the specimens shown in Fig. 2a, with infiltration-assisting holes introduced or not. The final step was successive cycles of matrix deposition, which is essential to further densify the partially infiltrated specimens, until no more matrix can be infiltrated.

2.2. Characterization

Flexural strengths of specimens were measured through a three-point bending test (SANS CMT 4304, Shenzhen, China) with a span of 90 mm and a loading rate of 0.5 mm/min at room temperature. To understand the data scattering, five specimens were tested for each kind. The Archimedes method was utilized to measure their densities

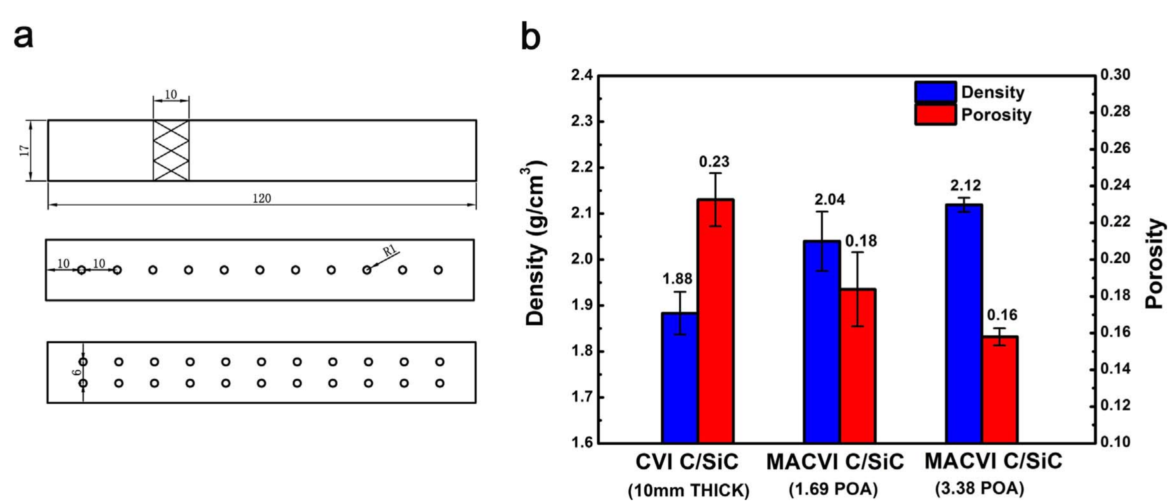

Fig. 2. (a) Schematic of the thick-section 2D C/SiC specimens fabricated by CVI (top) and MACVI (middle and bottom). (b) Densities and porosities of the corresponding specimens.