cate that the average size of sheets for the chemically exfoliated GO sheets can be controlled by modifying the oxidation and exfoliation procedure. These results should enable further investigation of the physical and chemical properties of graphene with different size, and hold great promise for a broader range of technological applications in many fields.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.carbon.2009.07.045.

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ZrC ablation protective coating for carbon/carbon composites

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ABSTRACT

A zirconium carbide (ZrC) protective coating was deposited on carbon/carbon (C/C) composites by atmospheric pressure chemical vapor deposition. The phase compositions, surface and cross-section microstructures, and anti-ablative properties of the coatings were investigated. Results show that the method is an effective route to prepare a dense and thick ZrC coating on C/C composites. The coating can effectively protect C/C composites from ablation for 240 s in an oxy-acetylene torch system with a mass ablation rate of 1.1×10^{-4} g/cm^2 s and a linear ablation rate of 0.3×10^{-3} mm/s.

Carbon/carbon (C/C) composites are attractive materials for use in high-temperature structural components such as reentry vehicle nose tips, rocket, and nozzles [1]. In these critical environments in planetary entry, and other energy dissipation application, the C/C composites will be subjected to thermochemical ablation by oxidation and evaporation due to high

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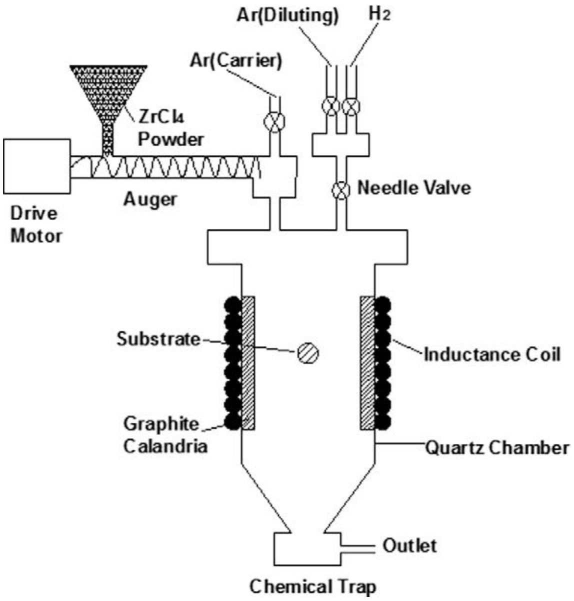

Fig. 1 – Schematic of atmospheric pressure chemical vapor deposition system.

temperature (>3273 K), and mechanical erosion by high-pressure gas and high-velocity grains [2]. Clearly, the broadened use of C/C composites as these high-temperature structural materials will require the development of effective oxidation or ablation protection. Preparation of hard ceramic coatings on C/C substrates is considered as a promising method [3].

James and James [4] have stated that, silicon-based ceramic coatings, like SiC and Si_3N_4, could meet the requirement below 2073 K. As for higher temperature, the protective coatings are based on the use of refractory carbides including TaC, HfC and ZrC. So far, ZrC coatings have been widely applied for cutting tools, in the nuclear industry as well as for electronic devices [5]. But in the open literature little systematic work on ZrC coating for C/C composites has been carried out. Compared to TaC or HfC, ZrC has a lower density, but higher hardness, strength and modulus [6]. Therefore, we pay more attention to ZrC ceramic coating system.

In the present work, we try to deposit ZrC ceramic coatings on the surface of C/C substrates by atmospheric pressure chemical vapor deposition. The phase compositions, microstructures and anti-ablative properties of the as-prepared ZrC coatings were investigated.

As shown in Fig. 1, an atmospheric pressure chemical vapor deposition system is designed for coating deposition. It is worth noting that an improvement has been made in the precursor supply system. The conventional vaporizer, always with problems of vapor condensation and agglomeration [7], has been replaced by a special powder carrier, which can better control the throughput of solid precursor. Small specimens ($\Phi 30 \times 10$ mm) as substrates were cut from bulk 3D-C/C composites with a density of 1.8 g/cm^3. The selected deposition system for ZrC coating was $ZrCl_4 + C_3H_6 + H_2 + Ar$, of which, $ZrCl_4$ was used as zirconium precursor, C_3H_6 as carbon source, H_2 as reducing gas and Ar as carried gas. The delivery rate for $ZrCl_4$ powder was 1.6 g/min, and the gas flow rates of C_3H_6, H_2 and Ar were 30, 400 and 400 ml/min, respectively. The deposition temperature and time were 1623 K and 3 h, respectively.

The anti-ablative properties of coated samples were tested with an oxy-acetylene torch system, with flow rates of oxygen

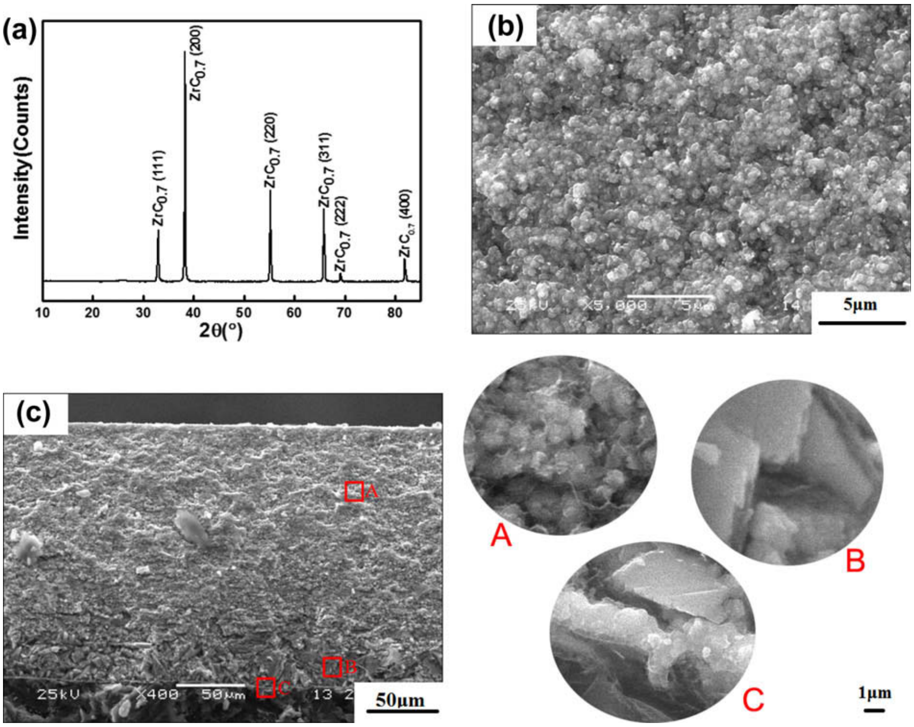

Fig. 2 – Phase composition and morphology of ZrC coating deposited on C/C composites. (a) Surface XRD pattern; (b) surface SEM image; (c) cross-section SEM image. The enlarged images in lower right corner correspond to the regions A, B and C.