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Arc-jet testing of ultra-high-temperature-ceramics

Raffaele Savino [a], Mario De Stefano Fumo [a], Diego Paterna [a], Andrea Di Maso [a,*], Frederic Monteverde [b]

[a] *Dipartimento di Ingegneria Aerospaziale, University of Naples "Federico II", P.le V. Tecchio 80, 80125 Naples, Italy*
[b] *Institute of Science and Technology for Ceramics, Via Granarolo 64, 48018 Faenza, Italy*

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ABSTRACT

The article deals with arc-jet experiments on different ultra high temperature ceramics (UHTC) models in high enthalpy hypersonic non-equilibrium flow. Typical geometries of interest for nose tip or wing leading edges of hypersonic vehicles, as rounded wedge, hemisphere, and cone are considered. Temperature and spectral emissivity measurements have been performed using pyrometers, an IR thermocamera and thermocouples. The details of the experimental set-up, the test procedure and the measurement are discussed in the text. The UHTC materials have been tested for several minutes to temperatures up to 2050 K showing a good oxidation resistance in extreme conditions. Differences between the various model shapes have been analyzed and discussed. Numerical–experimental correlations have been carried out by a computational fluid-dynamic code. The numerical rebuilding also allowed to evaluate the catalytic efficiency and the emissivity of the materials at different temperature.

1. Introduction

Re-entry from Low Earth Orbit (e.g. ISS crew return re-entry, space planes, space tourism) and from space exploration missions (e.g. from Moon) requires careful considerations about system concept design and trajectory definition, especially when the objective is to improve safety of the mission.

Recently an alternative way to re-enter Earth's atmosphere, improving safety and lowering maintenance costs, has been proposed based on slender vehicles with sharp edges, flying at moderate angles of attack. Sharp leading edges would imply lower aerodynamic drag, improved flight performances and crew safety, due to the larger cross range and maneuverability along with more gentle re-entry trajectories [17,16,7,15]. The temperature at the tip of the leading edge is inversely proportional to the square-root of the leading edge nose radius, and the reduced curvature radius results in higher surface temperature than that of the actual blunt vehicles that could not be withstood by conventional thermal protection system materials.

A new class of ceramics (UHTC) has been proposed for thermal protection system (TPS) on hot structure concept. Metallic diborides, such as zirconium, hafnium and titanium with different additives, are candidates for thermal protection materials in both re-entry and hypersonic cruise vehicles because of their high melting points (>3000 K) and excellent chemical stability [1,29,2,8,5]. UHTC materials can be fabricated by hot pressure sintering process and machined in the desired shape by electroerosion; in particular, the addition of SiC or $MoSi_2$ as sintering aid allows achievement of highly dense bodies by hot pressure sintering and at the same time improves the oxidation resistance due to the development of a silica protective coating [11,26]. These materials are also characterized by high hardness and high electrical and thermal conductivity; in particular the relatively high thermal conductivity is useful in order to reduce the stagnation point temperature. Indeed, when considering re-entering bodies, the convective heat transfer entering the surface is partly conducted to the solid and partly re-radiated into the atmosphere. When a steady state is achieved, global radiative equilibrium is established, in the sense that the (surface) overall convective heat flux is perfectly balanced by the overall surface radiative flux, and, if the material thermal conductivity is high, a relatively low equilibrium temperature is achieved.

The heat flux distribution over typical geometries of nose and wing leading edge of space vehicles exhibits the typical length dependence, i.e. inverse square-root of the distance from the stagnation point which is also proportional to the boundary layer thickness (boundary layer thermal protection) [14,18]. Thus there is a relatively small heat flux at distances sufficiently downstream of the leading edge. This suggest adoption of a massive thermal protection system only in the tip region of the vehicle, while the remaining major part of the vehicle's surface can be free from heavy protections.

Arc-jet testing represents the best ground-based simulation of a re-entry environment, in different ways. On one hand, it provides the possibility to explore the oxidation behavior of these materials under extreme conditions. On the other hand, the materials response to large heat fluxes is evaluated through the determination of two important parameters, i.e. emissivity and catalytic efficiency.

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* Corresponding author.
E-mail address: dimasoandrea@email.it (A. Di Maso).

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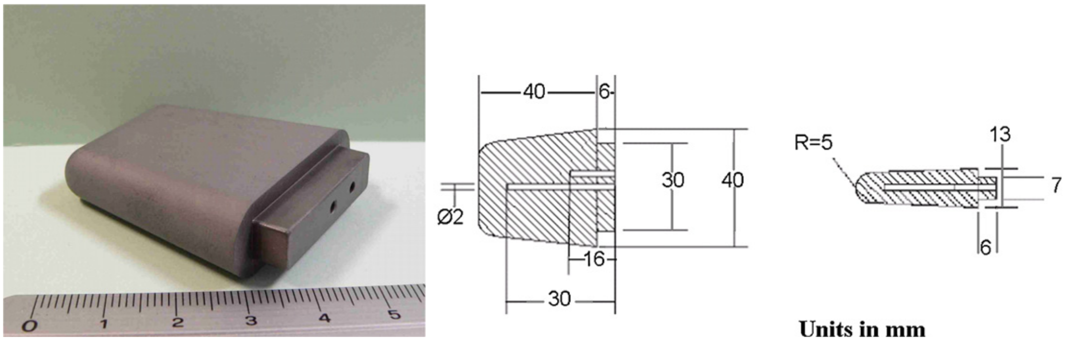

Fig. 1. Image and drawings of the model with the thermocouple holes, for the tests in DLR (Germany).

Table 1
Rounded wedge test conditions in DLR.

	FC1	FC2
$\dot{m}$ (g/s)	45	50
P_{02} (Pa)	8000	7400
I (A)	954	500
ΔV (V)	780	927
H_0 (Mj/kg)	9.7	6.05

High values of emissivity and low values of surface catalytic efficiency are desired for the above mentioned applications as they reduce temperature gradients and thermal stresses in the structure, thus enabling the vehicle to operate under relatively high enthalpy flow conditions.

In previous works [12,24] the authors carried out at plasma torch test at relatively high total enthalpies (typical of atmospheric re-entry environment) but at atmospheric pressure (test chamber pressure = 1E5 Pa), i.e. in subsonic flow conditions.

The objectives of the present experiments are to characterize the behavior of UHTC models in real hypersonic non-equilibrium conditions typical of atmospheric reentry and in particular: 1) to investigate the boundary layer thermal protection in a relatively sharp configuration and 2) to characterize the behavior of the UHTC material at relatively high temperature, low pressure (test chamber pressure at about 200 Pa) and oxidizing environment typical of atmospheric re-entry by exposing small-sized specimens at extreme temperature conditions.

In this paper, the arc-jet tests are carried out on three models with different geometries: a rounded wedge with 4 cm length, a small hemisphere and a small sharp cone. All models are of the same material composition: zirconium diboride and silicon carbide ceramic (15% vol.).

Two different arc-jet facilities were used for experimental tests, the L2K facility at the DLR in Cologne (Germany) for the rounded wedge, and the SPES facility at the Department of Aerospace Engineering of the University of Naples (Italy) for the hemispherical and conical samples.

Fluid dynamic numerical simulations are carried out in order to rebuild, through computational fluid dynamic (CFD) modeling, all the experimental tests and to evaluate the catalytic efficiency of the material with respect to oxygen and nitrogen surface recombination reactions.

2. Arc-jet testing of UHTC rounded wedge in L2K facility

2.1. Test model

During the first test campaign a UHTC rounded wedge with two different angles of attack (0° and 25°) was exposed at two different flow conditions of the L2K facility at the DLR in Cologne (Germany). The test model has a length of 40 mm, a wedge angle of 2.5° and a curvature radius of 5 mm (Fig. 1). The UHTC model was machined from a single piece (a massive cylinder). The model was inserted in a copper support to interface with the facility support system. For the condition at the angle of attack of 25° a copper adapter was applied to the support. In particular the UHTC model was drilled by electroerosion to obtain two holes for the inner thermocouples.

The temperature evolution of the model surface was measured by a ratio pyrometer Maurer GmbH Optoelektronik, Q-PMRS-65-d (temperature range 1073–2273 K, spectral range 0.85–1.1; 0.95–1.1 μm; accuracy 1%), a single wavelength pyrometer Maurer GmbH Optoelektronik, TMRS-85-2-d (temperature range 1173–2273 °C, spectral range 0.85–1.1 μm, accuracy 1%), a single wavelength pyrometer Minolta, Cyclops 152A (temperature range 823–3273 K, spectral range 0.7–1.1 μm accuracy 1%), an infrared thermocamera, AGEMA Thermovision 570 was also employed (temperature range 623–2273 K, spectral range 8–14 micron, accuracy 2%). Two type K thermocouples were mounted into the specimen at 16 mm and 30 mm from the leading edge.

2.2. Facility DLR

The experimental tests have been carried out in the L2K facility available at DLR of Cologne (Germany). The facility is an arc-heated (Huels type) plasma wind tunnel which is described in detail by Esser and Gulhan [4]. Mass flow rates are in the range between 5 $\mathrm{g\,s^{-1}}$ and 75 $\mathrm{g\,s^{-1}}$ and the maximum total enthalpy is 20 $\mathrm{Mj\,kg^{-1}}$. The nozzle geometry is characterized by conical convergent (35° half angle), a circular throat with diameter of 29 mm, a conical divergent with 12° half angle terminating with a diameter of 100 mm. The nominal Mach number at the exit is $M = 3.9$. The Mach number calculated by CFD computations at the model location ($x = 12$ cm from the exit) is $M = 4.7$. The facility is operated setting the electrical current (I) and the mass flow rate ($\dot{m}$), measured with a flow meter based on Coriolis effect, with accuracy of 1%. The voltage (ΔV) depends on input parameters. The two different selected test conditions, belonging to the facility operating envelope, are summarized in Table 1, labelled as FC-1 and FC-2. The model was held in position by a mechanical arm, and located 12 cm away from the nozzle exit. The test condition FC-2 for the rounded wedge has been performed with two different angles of attack (AoA = 0 and 25°). Mass flow rates, reservoir pressures, test chamber pressures, current and voltage are directly measured. In addition, the stagnation point pressure (p_{02}) at the model location is measured by a pitot probe.

2.3. Experimental results

Tests characterized by different duration (from 60 up to 180 s) have been performed for each of the flow conditions (see Table 2). Fig. 2 shows a CCD image of the flow at the exit nozzle imping-