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Determination of graphite sublimation rate in high enthalpy plasma flow using 'laser knife' method

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ABSTRACT

The experimental method to study a behavior of heat-resistant materials by the action of high-enthalpy plasma jets is developed. The main attention is focused on heating and thermal destruction of graphite samples. The argon plasma jet is generated by a plasmatron with an expanding anode channel providing a slightly divergent high-enthalpy laminar flow with the axial speed of 400–500 m/s, the diameter of 6–8 mm and high temperature which is not less than 10,000 K. The jet affects the isotropic graphite MPG-6 samples shaped in the form of a parallelepiped with the dimensions of 23 mm × 23 mm × 16 mm. A description of the method developed by the authors on the basis of the "laser knife" technique to determine the sublimation rate of heat-resistant materials is presented and the relevant time change in the sample material sublimation rate is analyzed. The shape and evolution of craters on the sample surface are analyzed. A nonmonotonic behavior in the sublimation is observed in the experiments. The maximum of sublimation rate is recorded when the initial warming up stage of the graphite sample is completed, which indicates the emergence and propagation of dislocations in graphite structure as it is heated to a temperature close to 3000 K.

1. Introduction

Unique properties of graphite such as its 'triple' point $T^* \geqslant 4700$ K [1–4], significant sublimation latent heat (enthalpy) value $H_s = 60$ kJ/g [5,6], the mechanical strength, high thermal conductivity and low linear expansion coefficient [2] make graphite and graphite based composites the best materials for thermal protection [7–9]. When calculating the sublimation rate of graphite-containing materials, great difficulties emerge from the lack of data on the sub-products composition (C_1, C_3, C_8 ..., clusters) and the relevant thermodynamic properties [10]. Therefore, it is critical to the practice of testing and creating the thermal protection materials to have direct measurements of material ablation rate under the controlled test conditions [9,11,12].

When the sample is fully wrapped by high-temperature gas or plasma jet, the best results of the sublimation rate can be provided by high-speed multi-position imaging (using tomography algorithms [13–15]), allowing continuously monitoring of the destroyed thermal protection coordinates [8]. In the case of 'internal' flow, particularly with the incoming plasma stream dimensions being smaller than the transverse size (diameter) of the target, the recessed parts appear on the destroyed surface whose video recording is difficult or even impossible. The method suggested is just intended for analyzing the directed plasma exposure followed by formation of a large-sized crater on the sample surface.

2. Setup and measuring technique to obtain the sublimation rate

Investigation of the graphite material mass loss rate under the action of a plasma jet was carried out as follows (see Fig. 1). The plasma was generated by a plasmatron (1) with an expanding anode channel and arc current of 200–300 A [16], which provides at its outlet a high-enthalpy slightly divergent laminar stream of argon plasma with the axial speed of 400–500 m/s, the diameter of the plasma stream of 6–8 mm and the axial temperature no less than 10000 K. The isotropic graphite MPG-6 samples (3) in the shape of a parallelepiped with the dimensions of 23 × 23 × 16 mm were subjected to a downward directed plasma jet (2). Since the plasma jet diameter d_0 is smaller than the diameter (or width) of the sample D_0, the sublimation mass loss occurs in two ways:

a) Rather fast graphite sublimation from the area directly affected by the plasma jet which results in recessing and widening of the crater.

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Nomenclature

a	radius of particle
b	height of laser knife trace
c	Gaussian function height
D	sample diameter
d_0	diameter of plasma jet
d_{cr}	diameter of crater
f	Gaussian function displacement on y axis
F_G	Gaussian function
H	enthalpy
H_s	enthalpy of a sublimation
I	spectral intensity
M	mass of sample
m	mass loss
$\bar{m}$	mass loss rate
q_0	specific absorbed power
S	surface area
T	temperature
T_r	brightness temperature
t	time
V	volume of crater
W_{abs}	power absorbed by sample
z_0	initial distance between the plasma torch's nozzle and graphite sample's surface
Δz	the sublimate 'cloud' thickness

Greek symbols

α	angle
ε	sample's surface emissivity
θ	angle of rotation
κ	absorption coefficient
λ	wavelength
μ	scattering coefficient
ν	pulse or frame frequency
ξ_0	Gaussian function displacement on x axis
ρ	density
σ	absorption or scattering cross section
$\bar{\sigma}$	the Stefan-Boltzmann constant
τ	optical thickness
χ	extinction coefficient
ψ	contour width in Gaussian function

Subscripts and superscripts

abs	absorption
cr	crater
exp	exposition
h	warming-up time
max	maximum
sc	scattering
subl	sublimation
surf	surface

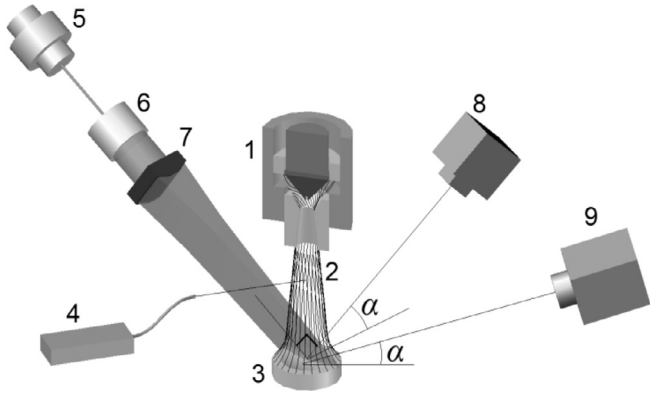

Fig. 1. Synchronized measurement circuit. 1 – plasma torch; 2 – plasma jet; 3 – the sample; 4 – fiber optic spectrometer AvaSpec3648; 5 – the laser source; 6 – telescope; 7 – cylindrical lens; 8, 9 – high-speed cameras, 10 – interference filter.

b) Sublimation from the sample surface heated by thermal conductivity with no direct plasma exposure. The sample heating due to heat release on the crater surface is such a fast process that, according to pyrometric measurements, the temperature of the side surfaces of the sample reaches 2000 K in 8–10 s. at the arc current of 200 A and the specific heat flow within the affected area of $q_0 \geqslant 500$ W/cm^2.

Two-position visualization by synchronized cameras Motion Pro (position 8, 10 frames per second) and VS-Fast (position 9 on Fig. 1, 10–50 frames per second, exposure time is 50 μs) allows us to reveal the time change in the sample boundaries (side dimensions of the sample and its height h(t)) and ultimately the sample volume variation. Thus we can establish the second component of the sample mass loss. The combination of long focus lens with a system of extension rings permits cameras to register the image of the jet–sample interaction region on a 1:3 scale over the whole period of observation with saving of up to 3000 frames in the buffer memory. In this case, the spatial resolution is about 30 μm.

A detailed study of the rate of the sample ablation from the area directly subjected to the plasma jet was performed by a "laser knife" method described in this paper. The key point is recording the laser knife trace on the sample surface, which deepens as the matter sublimates from the crater. The laser knife itself is formed by the system comprised of a pulsed laser LCM-DTL-319QT with a pulse repetition frequency up to 10 kHz, pulse duration 7 ns, wavelength 527 nm and pulse energy up to 100 μJ (position 5) combined with the laser beams focusing elements – telescope (position 6, provides widening of the laser beam to a diameter of about 25 mm) and a cylindrical lens (position 7, with a focal length of 500 mm). The system formed a laser trace approaching 1 mm in width on the top surface of the sample and passing through the epicenter (the 'stagnation' point) of the plasma jet. The trace of this "knife" (see diagram on Fig. 1) on the surface of the sample is recorded by a camera Motion Pro X3 (position 8) in the mode of 10 frames per second and a 1 μs exposure. To improve the quality (contrast) of the laser trace image, an interference filter (position 10) with a wavelength $\lambda_0 = 525$ nm was periodically placed in front of the camera. Video frames taken at a current of 200 A both with a 525 nm filter and without the filter are shown in Fig. 2a, b. It should be noted that due to the sublimation of the sample surface the zero (baseline) level of the top (facing incoming plasma stream) sample surface is gradually lowers, as follows from the frames in Fig. 2b, c, d. The data on this shift can be used to determine the sample volume decrease.

To measure the plasma temperature in the interaction zone as well as the temperature of the heated surface of the sample a fiber-optic spectrometer AvaSpec 3648 (position 4 in Fig. 1) is used. The radiation intensity of the sample surface was calibrated