An experimental and computational study of the interaction between the jet of an ICP torch and a cylindrical substrate

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Abstract: Steel and quartz cylindrical rods of various diameters have been exposed to the jet of a low power inductively coupled plasma torch operated at atmospheric pressure. The flow-substrate interaction has been studied with Schlieren imaging (for flow characteristics) and infrared measurement techniques (for temperature values on the substrate); experimental results are complemented with simulation ones.

Keywords: ICP torch, thermal plasmas, plasma simulation, Schlieren imaging, infrared measurements

1. Introduction

Several industrial processes can possibly make use of Inductively Coupled Plasma (ICP) torches in the interaction with either a static or a rotating cylindrical substrate; this is the case for high purity silica overcladding of preforms for the production of optical fibers [1], as well as in some calibration procedure for high precision measurement of physical properties of materials [2] and, generally, in the frame of thermal treatment techniques, with or without chemical synthesis and deposition of materials. The investigation of thermo-fluid-dynamic phenomena in the downstream plasma region of interaction with the substrate is important in order to characterize and then optimize these processes, also taking advantage of the many operating and geometric parameters intrinsic in the use of ICP plasmas. In order to obtain data useful for characterizing these processes, several diagnostic techniques can be used to study ICP discharges and jets impingement, like High Speed Imaging (HSI) and Schlieren Imaging (SI). Processes involving the interaction of plasma sources and substrates, like in ICP-MS technology and in processes of outside vapour deposition of pure silica for the production of optical fibers, have also been studied by means of 2D and 3D numerical simulations, with the assumptions of Local Thermal Equilibrium (LTE) and laminar flow [3, 1]. Turbulence effects caused by jet impingement and their influence on heat transfer mechanisms can be taken into account by means of physical models, whose reliability requires a proper experimental validation. In this work, the interaction of the jet of an ICP torch with a cylindrical stainless steel (SS) or quartz substrate has been experimentally studied by means of SI and of an IR temperature sensor. The data so obtained have been used to validate and “tune” numerical simulations performed using the commercial Computational Fluid Dynamics (CFD) software Fluent® (ANSYS), implemented with User Defined Functions (UDFs).

2. Experimental setup and results

The cylindrical substrates are made of SS AISI 304 and quartz (NHI®-1100, Heliositalquartz). Rods of different diameters (4, 8, 25 mm), placed at different distances from the torch exit (30, 40 mm) were used. For a single case in SS a tube was used (outer diameter 25 mm, inner diameter 20 mm). The ICP torch, connected to a solid state generator and a matching network (Stolberg HF-Technik), has been operated in Ar at 13.56 MHz and 500 W at atmospheric pressure, with a flow rate of 16 slpm (2 slpm central gas, 14 slpm sheath gas).

Fig. 1. Setup for infrared measurement of the temperature of the substrate.

SI diagnostics of the interaction between the jet of the ICP torch and the cylindrical substrate has been accomplished using a Z-type setup already used in previous works [4].
Two different experimental configurations have been investigated with SI: the first with the rod axis coaxial with the collimated beam of the light source, while the second with the rod axis perpendicular to both collimated beam and torch axis. Temperature on the surface of the substrates has been measured using an IR sensor (CTLaser LT CF1, Optris) designed to give the mean temperature in a circular spot as small as 1 mm in diameter. The IR sensor has been calibrated by measuring the emissivity of the SS and quartz substrates for a range of controlled temperatures by means of a hot plate heater and a thermocouple. Then temperature values on the surface of the cylindrical rods placed in the gaseous effluent zone were measured. As shown in Fig. 1, the IR sensor was placed at a distance of 7 cm from the substrate, in order to minimize the sensor spot size, and pointed sideways at the substrate surface, directly below the torch outlet. In Table 1 results of temperature measurements for SS substrates of different diameters are presented, for two distances from the torch exit. Fig. 2 shows SI frames acquired from two perpendicular points of view of the plasma jet impinging on the surface of an 8 mm diameter SS rod placed at 30 mm from the torch exit. Fig. 3 presents SI frames for a different experimental configuration (4 mm diameter SS rod at 40 mm from the torch exit).

Table 1. Temperature measurement on SS substrates (°C)

<table>
<thead>
<tr>
<th>Distance exit of the torch-axis of the substrate (mm)</th>
<th>Diameter of the rod (mm)</th>
<th>4</th>
<th>8</th>
<th>25*</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td></td>
<td>270</td>
<td>235</td>
<td>N.A.</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>260</td>
<td>203</td>
<td>230</td>
</tr>
</tbody>
</table>

*= a tube was used, O.D. 25 mm, I.D. 20 mm
N.A. = Not Available

3. Numerical model and results
The interaction between the jet of an ICP torch and a cylindrical substrate for all different experimental geometries has been simulated using ANSYS Fluent. User-defined scalars (UDS) have been used to solve electromagnetic field equations [5], with calculated thermodynamic and transport coefficients of argon-air mixtures [6] under LTE condition. In order to limit the computational effort, a 2D axisymmetric simulation of the plasma region, consisting of the inner volume of the torch and a portion of the torch outflow region has been performed: velocity and temperature fields obtained at the outlet of the torch were used as a boundary condition for a 3D simulation, to study the interaction between the plasma jet and the substrates. Reynolds Stress Models (RSM) were used to properly reproduce the transition from laminar to turbulent phenomena induced by the presence of the substrate, while radiative cooling of the substrate was taken into account using the Discrete Ordinates model. Table 2 shows the maximum value of calculated temperature on the surface of SS and quartz substrates. In Fig. 4 velocity vectors are plotted on two orthogonal planes. The 8 mm diameter substrate is placed at 30 mm from the torch outlet, which is the same setup configuration shown in Fig. 2. Turbulence phenomena can be observed in proximity of the wall of the substrate and along its upper surface.
Fig. 3. SI frames from two perpendicular points of view - one perpendicular (on top) and one parallel (below) to the substrate axis - of the region where the ICP effluent impinges on a SS rod of diameter 4 mm and placed at 40 mm from the exit of the ICP torch.

Table 2. Maximum temperature (°C) calculated on the substrate

<table>
<thead>
<tr>
<th>Distance exit of the torch-axis of the substrate (mm)</th>
<th>Diameter of the rod (mm)</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SS</td>
<td>Quartz</td>
<td>SS</td>
</tr>
<tr>
<td>30</td>
<td>284</td>
<td>371</td>
<td>252</td>
</tr>
<tr>
<td>40</td>
<td>242</td>
<td>317</td>
<td>213</td>
</tr>
</tbody>
</table>

4. Conclusions
Differences between calculated and measured temperatures on the substrates were lower than 7%. SI frames show strong similarities with the torch outflow profiles that can be obtained by simulation. Future studies will concern the analysis of the plasma effluent interaction with substrates of different geometries and materials, under rotation and/or translation, also using simulation tools to characterize such plasma assisted processes.

Fig. 4. Vector velocity field (m/s) for a SS rod (diameter 8 mm) at a distance of 30 mm from the torch exit on two perpendicular planes - one perpendicular (on top) and one parallel (below) to the substrate axis.

5. References