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# Pore formation in iron micro-spheres by plasma procedure

Ioan Bica

*Department of Physics, West University of Timisoara, Bd. V. Parvan, No. 4, 1900 Timisoara, Romania*

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**Abstract**

The paper presents the mechanism of hollow Fe micro-sphere production in Ar plasma jet. The required condition for cavity (pore) formation and the dependence of the pore radius on the plasma jet velocity are derived. Technological data concerning the micro-sphere production are given and comparison between the model predictions and experiment is made.


*Keywords:* Iron micro-spheres; Pores; Superficial energy; Inertial forces

## 1. Introduction

Micro-spheres are particles, hollow inside, with a diameter ranging between 1 and 100 μm. They are interesting from a scientific and practical standpoint. The scientific interest lies in the formation [1] and the formation mechanisms [2] of micro-spheres. The practical interest for iron micro-spheres is related to the transport of working substances, as exemplified in [3]. Interesting applications of iron micro-particles are the biological ones, as shown in [4–6].

In all cases, it is necessary for the micro-sphere wall to have pores. They are needed for the introduction of working substances in the micro-spheres. The production of iron micro-spheres with pores, in plasma jet, is a reality [1]. However, the production of pore micro-spheres in increased quantities and with a pre-established pore diameter is a necessity.

Consequently, in what follows, we show the mechanisms of iron micro-sphere formation as well as the dependence of the pore diameter on the velocity of the plasma jet.

## 2. Model

### 2.1. Stages in micro-sphere formation

The carbon-steel electrode is introduced uniformly in the plasma. In the electrode-plasma interaction, the electrode is melted. The electrode velocity is correlated with that of the plasma jet. At the temperature $T_0$ of the plasma, the metal drops change into vapors. The temperature of the vapors instantaneously reaches the temperature of the plasma. The molar concentration $C_0$ of the vapors is low by comparison with that of the gas.

Consequently, the vapors can be assimilated to an ideal gas. If $m_{0i}$ is the mass of vapors, then the radius $r_{0i}$ of the sphere of vapors results, according to [7], from the relation:

$$r_{0i} = \left(\frac{3}{4\pi}\frac{m_{0i}}{\mu}\frac{1}{C_0}\right)^{1/3} \tag{1}$$

in which $\mu$ is the molar mass of the iron vapors.

The vapor spheres (Fig. 1a) are driven by the plasma jet. The vapor-gas interface reaches regions of temperatures $T_1$ equal to the temperature of the dew point temperature for iron, and changes into a liquid membrane (Fig. 1b). The molar concentration of the so-formed liquid phase drops is [7]:

$$C_c = C_0 \exp\left(\frac{\Delta E}{\Re \cdot \Delta T}\right) \tag{2}$$

where $\Delta E$ is the activating energy of condensation, $\Re$ the universal constant of ideal gases, and $\Delta T = T_0 - T_1$ the undercooling.

The process of liquid membrane formation takes place at constant pressures. The liquid membrane vapor sphere radius

*E-mail address:* ibica2@yahoo.com.

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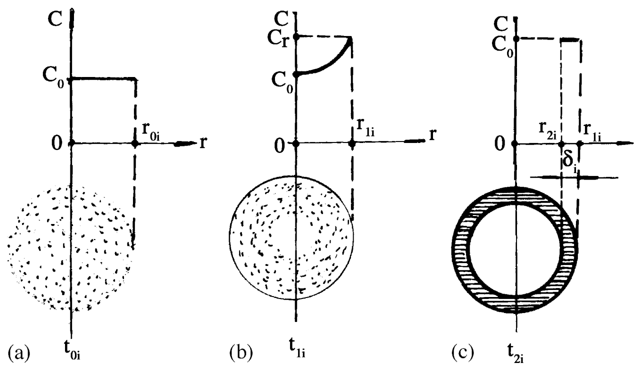


Fig. 1. The stages of micro-sphere formation in plasma jet: (a) $t_{01}$, the moment of formation of vapor sphere of radius $r_{0i}$; (b) $t_{1i}$, the moment of formation of liquid membrane of radius $r_{2i}$; (c) $t_{2i}$, the moment of formation of micro-sphere of radius $r_{2i}$. $\delta_i = r_{1i} - r_{2i}$ wall thickness; $C_0$, molar concentration of vapors; $C_c$, critical concentration of germs in liquid phase [2,7].

is [2]:

$$r_{1i} = r_{0i}\sqrt[3]{\frac{T_1}{T_0}} \tag{3}$$

Inside the sphere, the temperature is $T_0$, and on the membrane, the temperature is $T_1$ ($T_1 < T_0$).

Because of the thermal gradient generated in the sphere (Fig. 1b), elements of vapor volume move towards the membrane. Once they arrive on the membrane, a transport of substance occurs through diffusion, followed by vapor condensation.

After a short time [2,7], the place of the vapor element is taken by another vapor element. The process is repeated until there are no vapors left inside the sphere in Fig. 1b.

At the end of the process, a liquid phase wall micro-sphere is formed, of thickness $\delta$ (Fig. 1a).

### 2.2. Pore formation

The iron micro-spheres as emerging from the Ar plasma jet are still liquid, showing a large cavity whose content is Ar gas [6] at temperatures generally exceeding that of the melt.

The micro-sphere velocity is $\vec{v}_j$ (the plasma jet velocity).

On leaving the jet, the velocity of the micro-spheres ($\vec{v}_m$) in the pooling medium decreases from $\vec{v}_j$ to $\vec{v}_m$, causing a force density:

$$|\vec{f}| = \frac{\rho(v_j^2 - v_m^2)}{2r} \cong \frac{\rho v_j^2}{2r} \tag{4}$$

where $\rho$ is the density of the gas inside the cavities and $r$ the mean of the outer and inner micro-sphere radii, $r_1$ and $r_2$, respectively.

For thin-walled micro-spheres, one may approximate $r$ to $r_2$. The inertial force $\vec{f}$ has the same direction as $\vec{v}_j$, but the sense is opposite (Fig. 2).

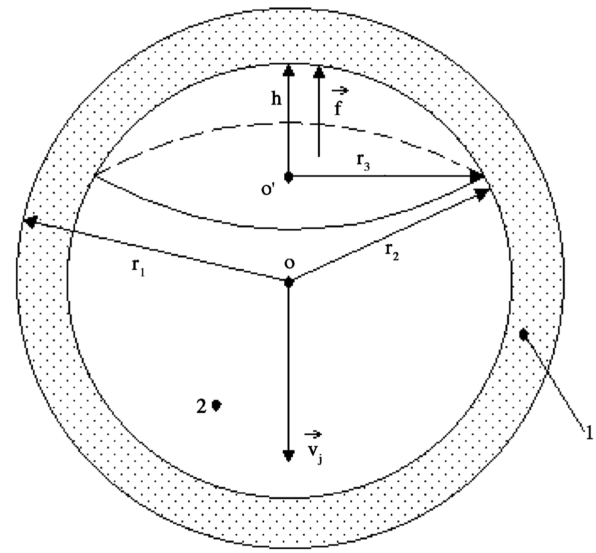


Fig. 2. Micro-sphere (model): (1) liquid micro-sphere wall; (2) gas (Ar). $r_1$, Outer radius, $r_2$, inner radius, $r_3$, radius of the sphere cap (of the micro-spheres); $h$, height of the spherical cap; $\vec{f}$, inertial force; $\vec{v}_j$, micro-sphere velocity (equal to that of the plasma jet).

According to the third principle of dynamics, the micro-sphere will react with the force density:

$$|\vec{f}'| = \frac{3}{4}\sigma\frac{h}{r_2^3} \tag{5}$$

where $h$ is the height of the spherical cap in Fig. 2 and $\sigma$ is the surface tension coefficient.

For $|\vec{f}|$ exceeding $|\vec{f}'|$, i.e.:

$$\frac{3}{2}\sigma\frac{h}{r_2^2} < \rho v_j^2 \tag{6}$$

the spherical cap is removed, this leading to the formation of a large pore.

From the schematic drawing in Fig. 2, one obtains:

$$h = r_2\left[1 - \sqrt{1 - \left(\frac{r_3}{r_2}\right)^2}\right], \tag{7}$$

where $h < r_2$.

Here $r_3$ is the equivalent radius of the pore. If the plasma jet has circular cross-section, then the radial distribution of velocity is:

$$v_j = v_0\left[1 - \left(\frac{R}{R_j}\right)^2\right], \tag{8}$$

where $v_0$ is the axial velocity, $R$ the distance from the symmetry axis to a point on the circular cross-section of the plasma jet, and $R_j$ the plasma jet radius.

If Eqs. (7) and (8) are introduced in expression (6):

$$\frac{3}{2}\frac{\sigma}{r_2}\left[1 - \sqrt{1 - \left(\frac{r_3}{r_2}\right)^2}\right] < \rho v_0^2\left[1 - \left(\frac{R}{R_j}\right)^2\right] \tag{9}$$

is obtained.