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Resistively heated filaments are used to manufacture ceramic fibers. When an ac power source is used for heating, the temperature of the filament oscillates. These oscillations influence the deposition rate on the surface of the filament. An analysis of this problem is presented, and it is also shown that these oscillatory effects diminish as the filament gauge increases. The analysis can help to decide whether an ac or a dc power source should be used. [Key words: resistivity, heating, filaments, temperature, oscillations.]

I. Introduction

FOR the manufacture of some ceramic fibers, a thin filament is mounted between two electrodes inside a cylindrical reactor (e.g., quartz tube), or in the case of continuous fiber production, the filament is pulled through a set of conducting seals. In batch reactors the filament is mounted in a tensile state, and in continuous reactors the pulling action through the seals applies a tensile load on the filament. The filament is resistively heated to 1150 to 1350 K, and a gaseous mixture containing the reactive precursors flows axially along the fiber and reacts on the fiber surface to form a protective ceramic coating.[1]

During experiments conducted in the Laboratory for Ceramic and Reaction Engineering with tungsten filaments, it was observed that the filament underwent oscillations when an ac source was used. In some cases, the oscillations changed in amplitude and wave number during the course of the reaction. These observations prompted our investigation into the matter. Our analysis indicates that the vibration of the filament is caused by thermal stresses in the filament. The ac source causes oscillating filament temperatures, and the alternating thermal expansion leads to periodic changes in the axial tensile stress of the filament. The thermal stresses are superimposed on the applied tensile stress in the filament and will influence the final strength of the filament. A better understanding of these effects is important, because the final strength of the fiber depends on the stresses which are present during the manufacturing stage.

Apart from the disastrous effect that the vibrating filament has on the deposited film's quality, temperature oscillations also lead to oscillations in the deposition rate. However, the analysis shows that the amplitude of the temperature oscillations decrease with the cube of the filament diameter and these oscillatory effects become small when the filament gauge increases. Therefore, under certain conditions it may be possible and more economical to use ac rather than dc heating.

Thin filaments which are electrically heated are also used in other technologies. Examples of these applications are found in the catalytic oxidation of hydrocarbons on Pt wire[2] and the deposition of diamond films by the hot-filament technique.[3] It is the purpose of this note to communicate some of our experiences with ac heating of thin filaments and to report the results of our analysis.

II. Results and Discussion

Only the results will be discussed and interested readers are referred to a more detailed analysis.[4] In Figs. 1 and 2 the temperature of a 100 and 10 μm tungsten filament, respectively, are shown as functions of time. The temperatures were calculated for the position midway between the mounting blocks, which are 30 cm apart. The filaments were heated to a mean temperature of 1200 K in both cases, using a 50 Hz ac source. The heat transfer coefficient was taken as $U = 250$ W/m$^2 \cdot$ K. One immediately notes that the amplitude of the oscillations increased from $\approx$30 to 300 K as the diameter of the filament decreased from 100 to 10 μm. The maximum amplitude of the temperature oscillation is described by the following:

$$\Delta T_{\max} = \frac{16 I^2 \rho_R}{\pi^2 D^3 U} \frac{\left\{\cos\left[\tan^{-1}\left(\frac{2}{a}\right)\right] + \frac{2}{a}\sin\left[\tan^{-1}\left(\frac{2}{a}\right)\right]\right\}}{\left(1 + \frac{4}{a^2}\right)} \tag{1}$$

where I is the current (in amperes), ρ_R is the resistivity, D is the filament diameter, U is the heat transfer coefficient, and a is a dimensionless parameter ($a = 4U/D\omega\rho C_p$). The frequency
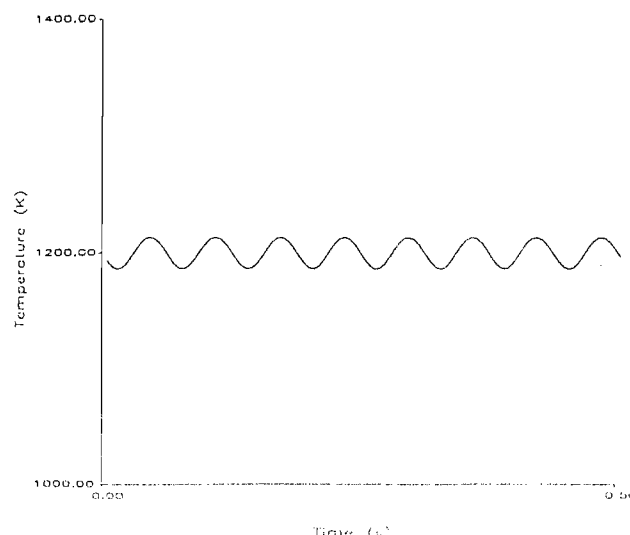

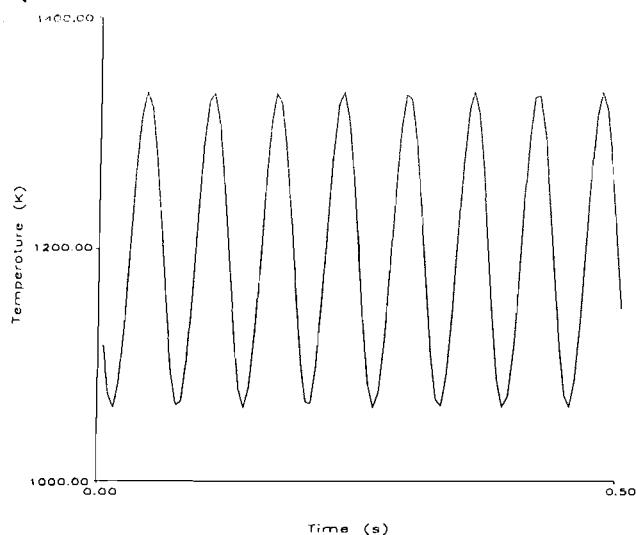Fig. 1. Temperature oscillations of a 100 μm filament.

Fig. 2. Temperature oscillations of a 10 μm filament.

Fig. 3. Oscillations in reaction rate on a 10 μm filament.

of the ac source is ω, and the density and specific heat capacity of the filament are ρ and C_p, respectively. Equation (1) gives a simple relation between physical conditions and the maximum amplitude of the temperature oscillation. Any temperature-dependent process on the surface of the filament (e.g., deposition, thermoionic emission, or a catalytic reaction) will also oscillate, and the magnitude of this oscillation can now be easily established.

To illustrate the effect that this oscillating temperature will have on the deposition process, consider the coating of tungsten fibers by boron (BCl_3 and H_2 as precursors). Details of the process and the kinetics in particular were published elsewhere.[1] The rate of boron deposition is described by the following equation:

$$R_B = 17e^{-15600/T}[f_1 - f_2]\frac{kmol}{m^2 \cdot s \cdot kPa} \qquad (2)$$

where f_1 and f_2 denote forward and backward reaction rates, respectively:

$$f_1 = \frac{K_{eq}^1 X_{BCl_3} X_{H_2}}{X_{HCl}\left[1/p - K_{HCl}X_{HCl}\right]}$$

$$f_2 = \frac{X_{HCl}^2}{K_{eq}^2 X_{H_2}\left[1/p + K_{HCl}X_{HCl}\right]}$$

For illustrative purposes, we will consider average values for all molar fractions as $X_{BCl_3} = 0.05$, $X_{H_2} = 0.949$, and $X_{HCl} = 0.001$. Then the following relationship results:

$$R_B = 17e^{-15600/T}\left[X_{BCl_3}X_{H_2}\frac{e^{2-5640/T-6.8\times10^8/T^3}}{X_{HCl}\left(0.01 - 0.0249 X_{HCl}e^{4982/T}\right)} \right.$$
$$\left. - \frac{X_{HCl}^2}{X_{H_2}e^{(.37\exp(0.0069T)-3321)/T}\left(0.01 + 0.0249 X_{HCl}e^{4982/T}\right)} \right]$$

Using the oscillating temperature shown in Fig. 2, the relative rate can be calculated and it is shown in Fig. 3. The relative rate is defined as $R_B(T)/R_B(1200)$, where the mean temperature is 1200 K. The rate has a maximum of 6.3 times the value of R_B (1200) and decreases to 1/10 of this value. Note that the time scale in the figure presents real time. The period of the oscillations in all cases, is 1/16 of a second (i.e., $2\pi/100$). This example illustrates the effect of the ac source on the deposition rate. But the temperature oscillations also affect the final strength of the fiber.
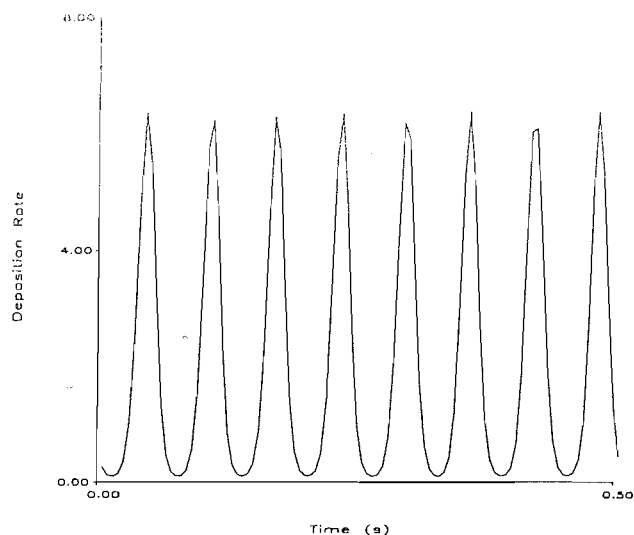
If the filament is mounted so at all times a net tension is maintained, the filament can potentially start to vibrate. In practice, the filament is tightened between the electrodes before the current is switched on. After the required temperature is reached, the filament is usually slack and it is tightened again before deposition is started. The second tightening puts a tension on the filament and if any vibrations are observed, the tension is further increased. This arbitrary tightening of the filament can be avoided, if one analyzes the stability of the governing equation and understands the underlying mechanism. It is important to know the tensile load during deposition, because it will affect the final strength of the ceramic fiber. To maintain a net tension in the filament, the tension used in its mounting will vary between two limits as described by the following equation:

$$P > \sigma > \sigma_{min} = \frac{\gamma\left\{\cos\left[\tan^{-1}\left(\frac{2}{a}\right)\right] + \frac{2}{a}\sin\left[\tan^{-1}\left(\frac{2}{a}\right)\right]\right\}}{2a\left(1 + \frac{4}{a^2}\right)}$$

$$(3)$$

where P is the maximum tensile strength. The parameter γ is defined as $\gamma = E_Y\alpha I^2\rho_R/A^2\omega\rho C_p$ where E_Y is the Young's modulus, α is the thermal expansion coefficient, and A is the cross-sectional area of the filament. σ_{min} is also the lower bound on the applied tensile stress, and the right-hand side of Eq. (3) gives the minimum applied tension on the filament during the manufacturing stage.

In more general terms, this analysis can be used for any ac-heated thin-filament technology, provided that the temperature dependence of the process under consideration is known. An example is the deposition rate expression (Eq. (2)) which can be used together with Eq. (1) to determine the magnitude of the oscillations in the deposition rate. Alternating-current heating can be considered for a process, if the effects of the oscillations are sufficiently small.

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