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Response time scales of anodized-aluminum pressure-sensitive paints

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ABSTRACT

The response time scales of anodized-aluminum pressure-sensitive paints (AA-PSPs) are characterized by measuring their luminescent lifetimes and response times to a step-like pressure change. The luminescent lifetime is measured by a picosecond fluorescence measurement system at atmospheric conditions. The results show that the twelve AA-PSPs tested fall into two groups according to their luminescent lifetimes; one group includes AA-PSPs with organic luminophores and the other one includes AA-PSPs with metal complex luminophores. The former possesses the lifetime on the order of one nanosecond and the latter possesses that on the order of hundred nanoseconds. The AA-PSPs are also characterized by the response time to a step change in pressure generated in a shock tube. It is observed that the 90% rise times to a step change in pressure are on the order of 10 μs and range from 30 μs to 50 μs, which lie within the tolerance caused by the thickness uncertainty in fabricating the anodized-aluminum layer. It is also found that the luminescent lifetimes are 2–4 orders of magnitude shorter than the step response times.

1. Introduction

The pressure-sensitive paint (PSP) technique has been widely used in aerospace applications [1]. The system uses an optical technique to relate the PSP signal (luminescence) to the surface pressures on a testing model (Fig. 1). By acquiring the luminescence as an image, we can obtain global pressure information instead of pointwise information that may result in wide applications in pressure detection fields. The PSP is composed of a molecular pressure probe (luminophore) and a supporting matrix. The former is sensitive to oxygen, which can be related to the oxygen pressure as well as the test gas pressure. The latter keeps the luminophore on the model surface and functions as a media to transport the gaseous oxygen to the luminophore. A conventional PSP uses a polymer matrix that greatly limits the oxygen permeation or diffusion. This slows the response time of a PSP to a pressure change; the response time of this type of PSP is on the order of sub-seconds to seconds [1].

At present, anodized-aluminum pressure-sensitive paint (AA-PSP) demonstrates the fastest response time of all PSPs reported [2]. This PSP provides an open structure of anodized aluminum as a supporting matrix (Fig. 2). The structure enables the gaseous oxygen to interact directly with luminophores on the porous surface, which provides fast response to pressures on the order of 10 μs. By using its fast response, AA-PSP has been applied to a short-duration testing [3–5], unsteady pressure measurement [6–9], and unsteady flow visualization [10–12].

The time scales of pressure-sensitive paint (PSP) are the time-limiting factors in the short-duration testing, global unsteady flow measurement and visualization. Based on its components, the response time scale of a PSP can be categorized by the luminescent lifetime and response time. Sakaue and Sullivan reported that a thinner coating gave faster response time which was on the order of 10 μs [13]. Kameda et al. modeled the response time related to the pore diameter, d, and the layer thickness, h; the response time is proportional to d and inversely proportional to the square value of h [2]. To design AA-PSPs for various unsteady measurement purposes, it is necessary to study further on its response time scale focused on the other parameter of AA-PSP: luminophore. Sakaue studied the luminophore-application process on an anodized aluminum to extend the choice of luminophores for AA-PSPs [14]. He reported that an optimum polarity of a solvent existed in the luminophore-application process (dipping deposition). Steady-state characteristics, such as the pressure sensitivity and signal level, were dependent on this process (Fig. 3(a) and (b)). However, the effect on luminophore-application process to the AA-PSP time scales, such as the luminescent lifetime and response time, has not been studied. We characterize these time scales experimentally. The luminescent lifetime was characterized by a picosecond fluorescence-measurement system, and the response time was characterized by a shock tube. Both provided a step change of excitation or pressure. The time scales are characterized by the time

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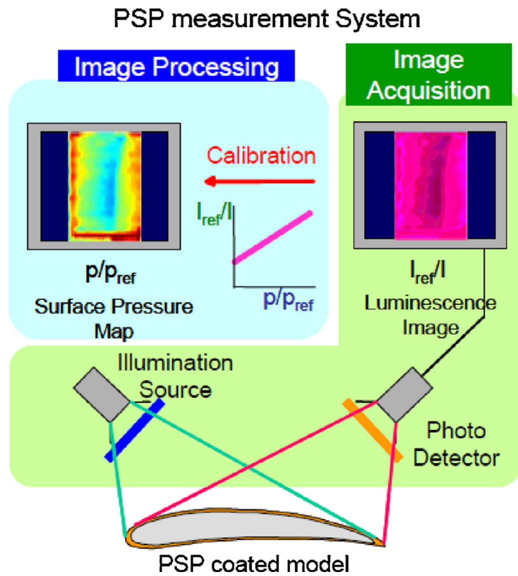

Fig. 1. Pressure-sensitive paint (PSP) measurement system.

delay from these changes. Most of the luminophores were selected from major groups used as a PSP probe.

2. Background

2.1. Characteristic time scales

There are two characteristic time scales based on the components of AA-PSP, such as the luminophore and anodized aluminum. One is the luminescent lifetime, and the other is response time caused by gas diffusion in pores of anodized aluminum. Assume that the excitation of the luminophore is continuous, and a step change of oxygen concentration occurred from $[O_2]_{initial}$ to $[O_2]_{step}$ at the initial time ($t = 0$). If the luminescent intensity, $I_{(t)}$, follows the first order decay, it has the time constant of τ_{Lu}, which is the luminescent lifetime [2].

$$I_{(t)} = I_{(0)}\left[r_\tau + (1 - r_\tau)\exp\left(-\frac{t}{\tau_{Lu}}\right)\right] \quad (1)$$

where r_τ is the ratio of τ_{Lu} and $\tau_{initial}$, such as $r_\tau = \tau_{Lu}/\tau_{initial}$. Here $\tau_{initial}$ is the lifetime before the step change and $I_{(0)}$ is the luminescent intensity at $t = 0$.

An anodized aluminum can be considered as a straight cylindrical pore [15]. In our present experiment, the pore diameter, d, was on the order of ten nanometers. In such condition, the gas diffusion is dominant by the Knudsen diffusion [2].

$$D = d\sqrt{\frac{8R_gT}{9\pi}} \quad (2)$$

where D is the Knudsen diffusion coefficient, R_g is the gas constant for a unit mass, and T is the temperature. Winslow et al. described the response time by the gas diffusion in a PSP layer (diffusion-based model) [16]. If the response time is due to the gas diffusion without the luminophore dependence, a theoretical value at the 90% pressure rise, $\tau_{90\%}$, is described as,

$$\tau_{90\%} = 0.85\frac{h^2}{D} \quad (3)$$

Based on Eq. (2), D is proportional to the pore diameter, d. Eq. (3) tells us that a wider pore diameter and a thinner anodized-aluminum layer give fast response time. Considering d of 20 nm and h of 10 μm for an anodized-aluminum layer in our present study with T of 298 K and R_g of 287 J/kg K, D is calculated to be 3.1×10^{-6} m^2/s [2]. Then, $\tau_{90\%}$ in our case is calculated as 27 μs.

2.2. Luminescent intensity related to pressure

A step change of pressure was used to characterize the response time of AA-PSP. To compare with the theoretical estimation in Eq. (3), the time delay of a 90% change in the step pressure was defined as the response time of AA-PSP, τ_{AAPP}. The luminescent intensity, I,

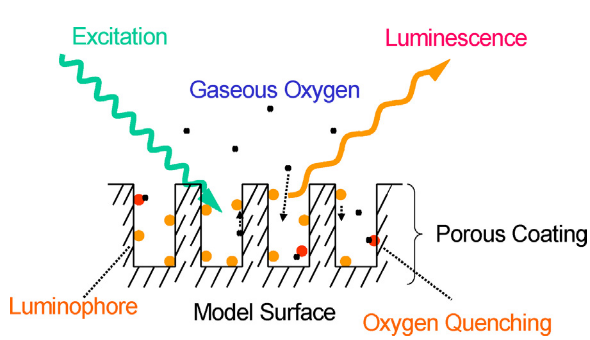

Fig. 2. Schematic description of anodized-aluminum pressure-sensitive paint (AA-PSP).

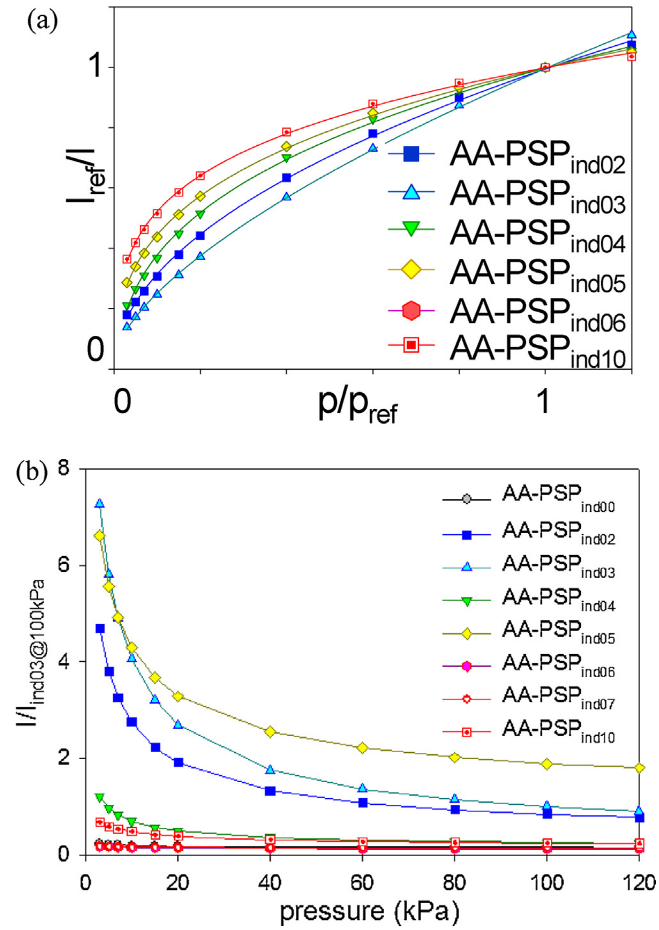

Fig. 3. Variation in the steady-state characterizations by the luminophore application process (obtained from Sakaue [14]). Subscript describes the polarity index of the solvent used for the luminophore application process. (a) Pressure sensitivity. (b) Signal level.