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Application of Stress Sensing Coatings on Metal Substrates with a Sub-surface Notch

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The application of photo-luminescent α-alumina nanoparticles in coatings allows for various structural materials to be evaluated nondestructively for their state of stress and damage. The ability of a coating composed of α-alumina particles within an epoxy matrix, to monitor the stress in the substrate was investigated by using photoluminescence piezospectroscopy (PLPS) in this work. In particular, the capability of the coating to detect stress concentrations on AL2024 tensile substrates with a subsurface notch was experimentally evaluated. Two volume fractions of α-alumina nanoparticles in the piezospectroscopic (PS) coatings were considered to compare the sensitivity of the coatings with respect to nanoparticle content. As the sample was loaded, it was found that the 10 vol % alumina PS coating captured the location and size of the stress concentration due to the subsurface notch at lower applied loads and more accurately than the 1 vol% PS coating. The use of the PS coating can be extended to applications for structural health monitoring so that preventive measures to be taken before failure.

I. Nomenclature

$\Delta\nu$ = frequency shift
Π_{ij} = PS coefficients (or PS tensor)
σ_{ij} = stress tensor
$\overline{\Delta\nu}$ = average frequency shift
Π_{ii} = trace of the PS tensor
σ_{jj} = trace of the stress tensor

II. Introduction

Nondestructive evaluation (NDE) methods are utilized in the aerospace industry for aircraft maintenance, quality assurance, and investigation of the properties of newly developed materials. Metals are commonly used in aerospace structures, but they tend to age over time and become susceptible to flaws[1]. These flaws then give rise to high stress concentrations and can result in structural failure. There is a need for the advancement of reliable and high performance NDE methods for structural health monitoring for detection of stress concentrations and degradation in material properties by local damage. Photo-luminescent stress sensing coatings have been recently developed and shown to provide a viable method for NDE of structures [2–4]. Using photo-luminescent α-alumina nanoparticles as part of a coating material allows for stress and damage sensing on aerospace structures. The laser excitation of these nanoparticles results in characteristic spectral emissions, called R-lines, consist of R1 and R2 peaks which can be monitored for shifts that correlate to stresses in the nanoparticles induced by substrate stress. Figure 1 shows a concept of a photo-luminescent coating for stress sensing of an aerospace structure.

The stress sensing method, known as piezospectroscopy (PS), involves characterization of the stress state from the emitted signal, which is a non-equilibrium emission of radiation due to photon excitation [5]. When the the α-alumina nanoparticles within the coating are subjected to stress, the peaks in the R-line shift from its original or reference position obtained from unstressed particles. This phenomenon, called the PS effect, is demonstrated in Figure 2.

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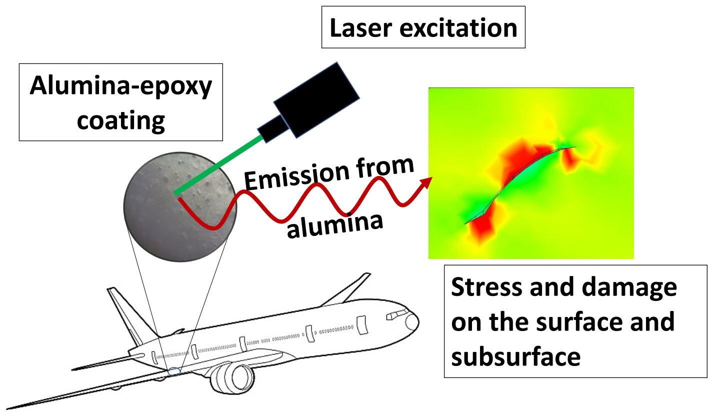

Fig. 1 A schematic of photo-luminescent coating for stress sensing application

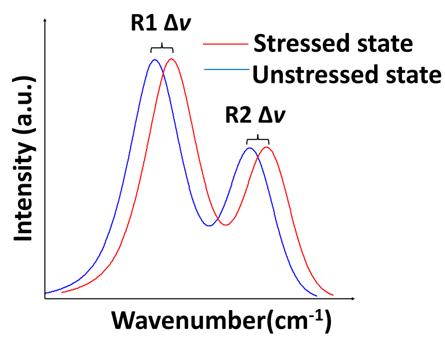

Fig. 2 Stress state characterized by shifts of the R1 and R2 peaks from the unstressed state

The change in stress can be quantified by the frequency shift based on the PS coefficients as shown in Equation 1 [6]:

$$\Delta\nu = \Pi_{ij}\sigma_{ij} \tag{1}$$

where $\Delta\nu$ is the frequency shift, Π_{ij} represents the PS coefficients (or PS tensor), and σ_{ij} is the stress tensor. Equation 1 can be reduced to Equation 2, which assumes that the stress state the α-alumina nanoparticles is hydrostatic. In this equation, $\overline{\Delta\nu}$ is the average frequency shift, Π_{ii} is the trace of the PS tensor, and σ_{jj} is the trace of the stress tensor.

$$\overline{\Delta\nu} = \frac{1}{3}\Pi_{ii}\sigma_{jj} \tag{2}$$

The piezospectroscopic technique was used in the past in diamond-anvil pressure cells to monitor pressure based on the R-line fluorescence of ruby [7], for computing residual stresses in ceramic oxides [6], and monitoring the stresses in the thermally grown oxide (TGO) layer within thermal barrier coatings (TBCs)[8]. The stresses in the TGO layer relax during the lifetime of the TBC and the piezospectroscopic measurements have the capability to track this stress thereby serving as a technique to estimate the remaining life and damage of turbine blade ceramic coatings. Our recent efforts have extended the applicability of the technique by modifying the deployment of the photo-luminescent materials in order to achieve stress sensing of structural materials under load.

Earlier work from our group has shown that the sensitivity of PS can be tailored [2, 9–11]. It has been found that the addition of α-alumina nanoparticles within a polymer matrix results in a nanocomposite that exhibits stress sensing capability. It is known that stress within the particles in a nanocomposite depend on the particle size, shape, dispersion and volume fraction. Varying the parameters of the reinforcing nanoparticles allows for tunability of the stress sensing coating. Increasing the particle volume fraction up to a certain level increases the sensitivity of the coating to applied loads [2]. Freihofer et al. [4] demonstrated the capability of PS coatings in monitoring stress in an open-hole tension (OHT) composite laminate under mechanical load and detecting damage initiation before failure occurs. The OHT carbon fiber reinforced polymer (CFRP) substrate with a PS coating consisting of 20 vol% of α-alumina nanoparticles in epoxy matrix was manufactured and tested. Using the nanocomposite coating, it was possible to detect internal ply damage at 76 % failure load, while the damage surfaced at 92 % failure load as measured by digital image correlation (DIC) [4].

Motivated by the previous studies, the application of stress sensing coating is currently being investigated so that it can be extended to several materials and complex loading scenarios. This study is part of the study on the capability of the PS coating to detect stress concentration and damage due to subsurface notch in a metallic substrate. Polymer nanocomposite coatings with 1 vol% and 10 vol% of α-alumina have been applied to AL 2024 tensile specimens with a notch on the back of the substrate on which the coating is applied. The spectral data from the specimens under tensile load are compared for stress and damage sensing capability of the coatings.

III. Experimental Setup

AL 2024 tensile substrates were coated with PS coatings consisting of 1 vol% and 10 vol% α-alumina nanoparticles with an average particle size of 150 nm within an epoxy matrix. The substrates were machined and prepared in accordance with ASTM E8-04 [12]. In order to capture and monitor the development of the subsurface damage, a 0.25" $\times$ 0.16" $\times$ 0.08" notch was introduced in both substrates on the face opposite of the surface where the coatings had been applied.

Figure 3 shows the experimental setup for data collection for stress sensing on an aluminum sample using the PS method. A servohydraulic MTS universal testing machine was used to apply uniaxial tensile load to the samples until failure load was reached. A crosshead displacement rate of 1 mm/min was used for the displacement controlled tensile tests. PL scans of the coatings were conducted at every 4 kN increment while the load was held constant.

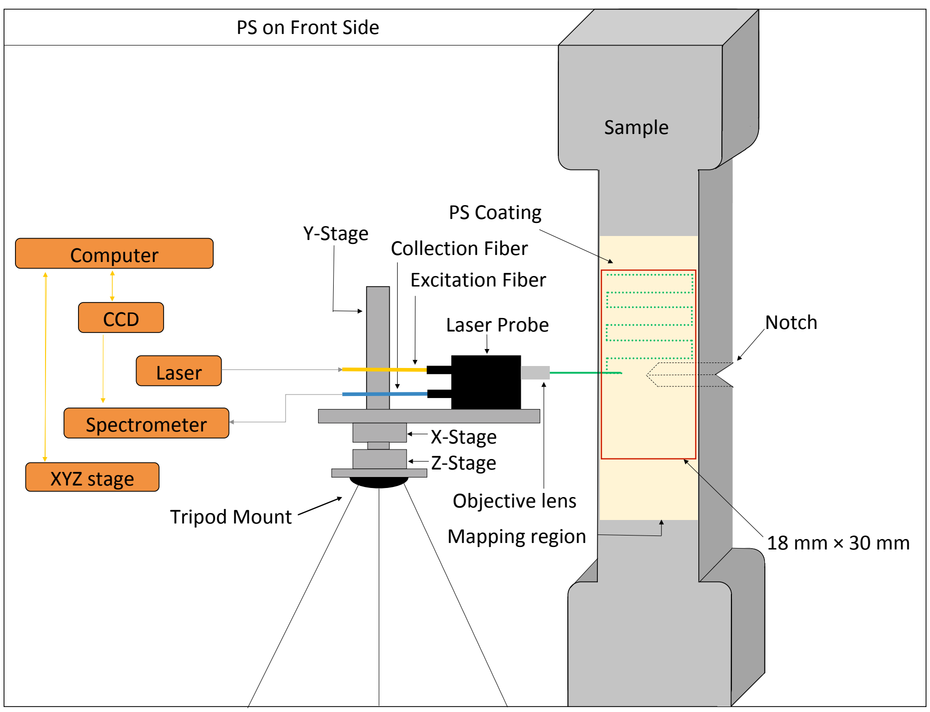

Fig. 3 The experimental setup is presented in this schematic. Note that the aluminum sample is enlarged to clearly show the PL point-wise scan pattern.

The PL scan was performed using a portable piezospectroscopy system developed in-house [13]. This system consists of a Princeton Instrument Pixis 100 charge coupled device (CCD), Acton SP2150 spectrometer, a 532 nm continuous laser source, and an InPhotonics Inc. RPB Raman probe. The probe and CCD are mounted on an XYZ stage to collect measurements over a designated area. A laser power output of 30.1 mW and 10.6 mW for the 1 vol% and 10 vol% samples, respectively, were used to excite the α-alumina nanoparticles in the PS coatings of both samples during loading. The laser power was chosen based on the spectral emission of the PS coatings, which is dependent on the amount of α-alumina nanoparticles present within those coatings. The PL scans were taken at each hold with a map size of 18 mm × 30 mm with spatial resolution of 200 μm.

IV. Results and Discussion

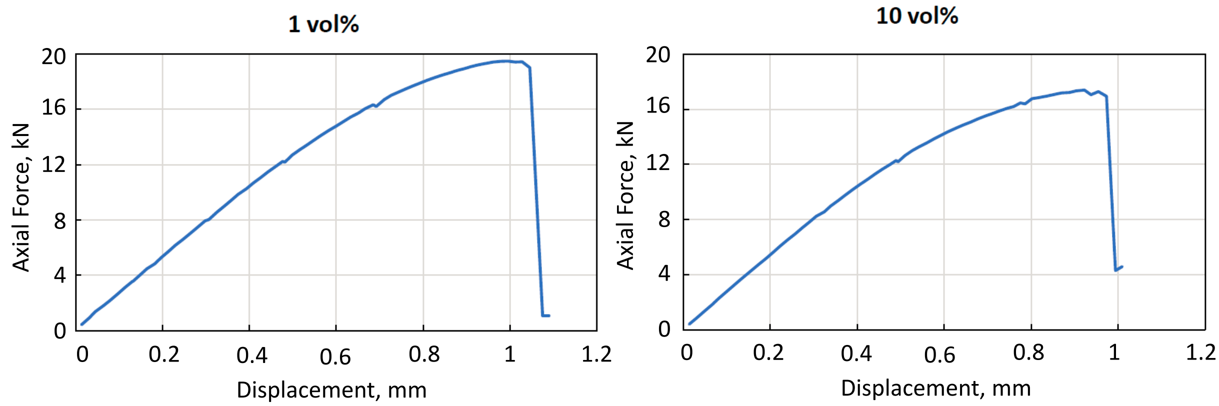

Fig. 4 Load-displacement response of the AL2024 tensile sample with stress sensing coating with 1 vol% and 10 vol% α-alumina nanoparticles

Figure 4 shows the tensile response of 2024 aluminum tensile specimens with 1 vol% and 10 vol% PS coatings. Similar stiffness was measured from both tests, which indicated that the coating had no affect on how the aluminum specimens responded to the applied tensile load. The results presented here are focused on the photo-luminescent measurements from the coatings during the tensile tests. An example signal response, in the form of R-lines, from each sample are shown in Figure 5. The R-lines correspond to the PL scan of one point on each sample at zero applied load. The R1 peak positions from both PS coatings are at 14,402 cm^{-1} at zero load. The peak positions are used as a reference to determine the peak shifts in response to the applied tensile load on the samples. The intensity count was found to be affected by the volume fraction of α-alumina nanoparticles in the coating. Specifically, the intensity from the coating with 10 vol% α-alumina nanoparticles had almost double the intensity compared to the coating with 1 vol% of α-alumina nanoparticles.

The peak shift maps obtained from the PL scans on the coated surface, on the opposite side of the notch on each sample, are shown in Figure 6 for each load step until failure. These maps were plotted from 90 × 150 point-wise scans to cover an area of 18 × 30 mm^2 at a spatial resolution of 200 μm. They indicate the full field stress state of the coating (and therefore the substrate) for each area that was mapped. A higher or rightward peak shift indicates larger tensile stress. By comparing the peak shift maps for increasing loads, it is seen that both coatings showed signs of gradually increasing tensile stress. It was observed that the stress is relatively uniform on the surface up to about 8 kN of load for the 10 vol% and 12 kN for the 1 vol%. However, the peak shift map from the 10 vol% PS coating was able to capture the effect of the stress concentration associated with the subsurface notch earlier compared to the 1 vol% PS coating. The notch effect was observed in the peak shift maps of the 10 vol% PS coating starting at 8 kN load. The down shifts were observed in the peak shift maps starting from the 8 kN load until post failure due to the stress concentration arising from the subsurface notch that causes stresses to be redistributed around the notch as the load is applied. This observation indicates that the PS coating is capable of detecting the location of subsurface damage initiation. Furthermore, the size of the stress concentration area due to the subsurface damage showed more prominently and compared well with the notch size on the peak shift maps from the 10 vol% PS coating as compared to the maps from the 1 vol% PS coating. Overall, the observed stress state of the coating was found to qualitatively resemble that expected from the global loading in the tensile specimen with a subsurface notch.

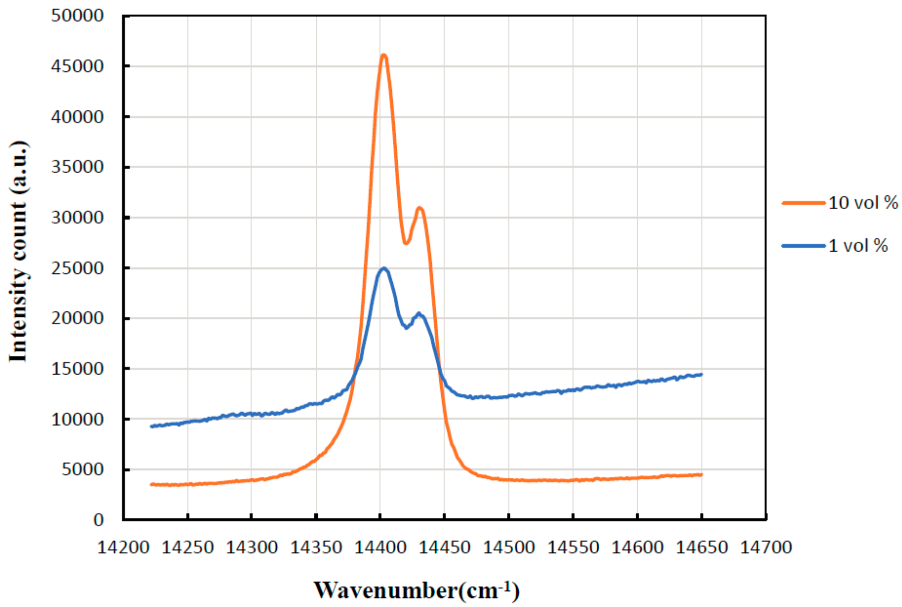

Fig. 5 R-lines obtained from each sample at zero applied load

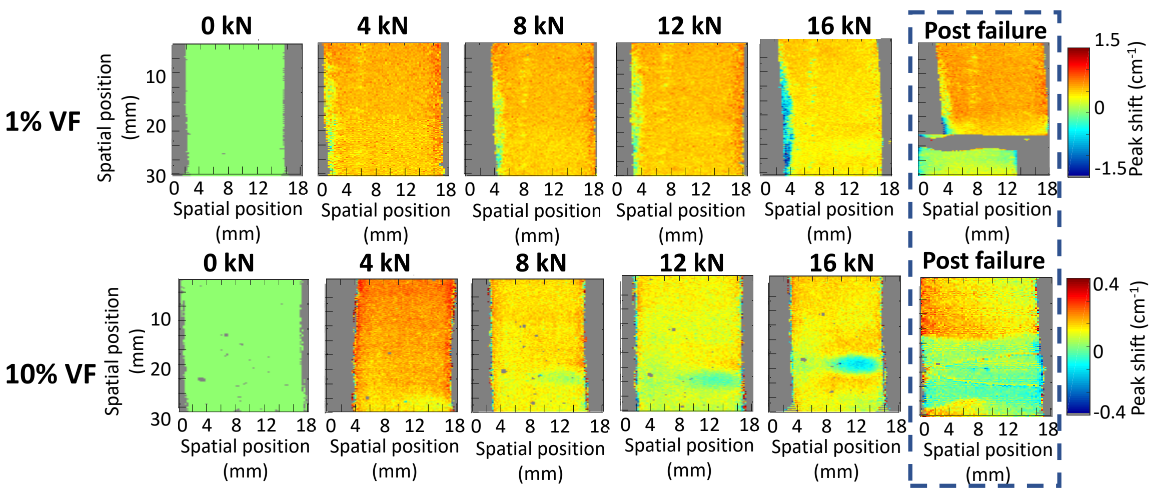

Fig. 6 R1 peak shift maps with increasing tensile load.

V. Conclusions and Future Work

PS coatings with 1 vol% and 10 vol% α-alumina nanoparticles in epoxy matrix were applied to 2024 aluminum tensile substrates for stress sensing and damage detection. PL scans were taken during the tensile tests using a custom-made portable piezospectroscopy system. The coatings were capable of determining full-field stress, including the stress concentration due to the subsurface notch on the aluminum substrates. Further, the PS coating with higher volume fraction (10 vol%) of α-alumina nanoparticles showed higher stress sensitivity than the PS coating with lower volume fraction (1 vol%) of α-alumina nanoparticles. The 10 vol% PS coating was able to capture the notch effect earlier and the notch size more closely than the 1 vol% PS coating. To conclude, the PS coating can provide high spatial resolution images of stress fields and damaged zones specifically when the damage is subsurface or hidden such as on internal surfaces of aerospace structures. In future work, full field deformation measurements obtained via DIC and finite element analysis will be used to compare the results from the stress sensing coating.

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