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Defect imaging of structural objects using positron annihilation spectroscopy

A.W. Hunt [a,b,*], R. Spaulding [a], J. Urban-Klaehn [a], J.F. Harmon [a,b], D.P. Wells [a,b]

[a] Idaho Accelerator Center, Idaho State University, Pocatello, ID 83209-8263, USA
[b] Department of Physics, Idaho State University, Pocatello, ID 83209-8106, USA

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Abstract

Two techniques have recently been developed to quickly and easily apply positron annihilation spectroscopies to large structural components found in civil engineering, aviation, etc. In this paper, the authors discuss how to extend imaging capabilities to these new techniques, which will enable defect imaging similar to that obtained with positron micro-beams but at much larger sample sizes. Preliminary two-dimensional defect imaging results are presented from a highly damaged 30.5×30.5 cm copper plate.

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1. Introduction

The discovery by DeBenedetti et al. that the γ-rays emitted from positron–electron annihilations in a solid are sensitive to the electrons' momenta ushered in the use of positrons as a probe of condensed matter systems [1]. The utility of this probe was further enhanced by the realization that positrons have a propensity to trap in sub-nanoscale defects (mono-vacancies, di-vacancies, dislocations, etc.) [2–4]. Hence, methods involving positron annihilation spectroscopy have become well-established for detecting and studying sub-nanoscale defects at sizes and concentrations too small for other methods [5–11]. These sub-nanoscale defects are often important to the formation or prevention of macroscopic damage and/or material failure. Consequently, positron annihilation spectroscopies could be an excellent

* Corresponding author. Address: Idaho Accelerator Center, Idaho State University, Pocatello, ID 83209-8263, USA. Tel.: +1 208 282 5966; fax: +1 208 282 5878.
E-mail address: huntalan@physics.isu.edu (A.W. Hunt).

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nondestructive testing technique for detecting damage in structural materials, well before physical damage signs are present.

Most contemporary materials studies using positrons today, implant the positrons into the material under study from mono-energetic positron beams. Research conducted with these beams have been extremely successful because they permit the creation of defect depth profiles and lateral defect images when scanning positron micro-beams are employed [6,10,12–16]. However, only the top tens of micrometers can be probed and the overall sample size has been limited to a few cm^3 because of the vacuum system in which the material under study must be placed [6,17]. This makes positron annihilation defect studies in large structural components difficult and its use has not been extensively adopted for nondestructive testing.

Two techniques, both of which use electron accelerators to create bremsstrahlung photon beams, have been developed that allow positron annihilation spectroscopies to be easily and quickly applied to large samples. In the first technique, which has been successfully commercialized, the material under study is activated by a high-energy bremsstrahlung beam (endpoint energy of ~20 MeV), causing ${}^{A}X(\gamma,\mathrm{n})X^{A-1}$ reactions in its constituent nuclei [18]. Since the resulting radioisotopes are neutron deficient, they have a tendency to be positron emitters. Then standard positron annihilation techniques such as Doppler broadening spectroscopy or positron lifetime spectroscopy can be utilized. In the second technique, positron–electron pairs are directly created in the sample by a bremsstrahlung beam below the neutron emission threshold (~10 MeV) but above the pair creation threshold (1.022 MeV) thereby avoiding material activation [19–21]. During irradiation a well shielded HPGe detector records the annihilation γ-rays for standard Doppler broadening analysis. Assuming at least two sides of the sample are accessible, these methods can interrogate specimens that are ~40 g/cm^2 thick due to highly penetrating nature of the bremsstrahlung and annihilation photons.

While neither of the photon induced positron annihilation methods have been used to create lateral defect images, both have this capability when combined with a scanning system. In this paper the authors report on preliminary defect imaging results obtained by photo-activating a highly damaged 30.5×30.5 cm copper plate. In addition, three-dimensional defect maps can be created by using computed tomography techniques. These approaches extend the microscopic defect imaging capabilities of positron annihilation spectroscopies to large scale structural components.

2. Defect imaging by photo-activation

A 6.4 mm thick 30.5×30.5 cm OFHC copper plate was bent around a 3.2 mm radius to a 90° angle. The plate was then bent back to its original flat shape, creating a linear highly damaged region along the centerline of the plate. To ensure uniform irradiation, the plate was then placed ~2 m from a 2.2 mm tungsten converter at the end of an electron LINAC. A 28 MeV, 16 μA electron beam impinged on the converter creating the bremsstrahlung photons that were incident on the copper plate. The dominate nuclear reactions were ${}^{65}\mathrm{Cu}(\gamma,\mathrm{n}){}^{64}\mathrm{Cu}$ and ${}^{63}\mathrm{Cu}(\gamma,\mathrm{n}){}^{62}\mathrm{Cu}$. Both resulting radioisotopes are positron emitters with half-lives of 12.7 h and 9.74 min respectively. Neither isotope emits any intense γ-rays and consequently there was no interference with the positron annihilation signal.

The plate was irradiated for a total of 2.5 h, after which it had a dose rate of 600 mR/h on contact. In initial experiments the short half-life of ${}^{62}\mathrm{Cu}$ was found to be problematic because it caused the count rate in the HPGe detector to change rapidly relative to the scan speed, which in turn affects the detector's energy resolution. Thus, the plate was allowed to cool for 2 h, permitting the ${}^{62}\mathrm{Cu}$ to decay through 12.3 half-lives at which point the dose rate on contact was 20 mR/h. The plate was then mounted on a two axis translation stage in front of a collimated 28% relative efficiency HPGe detector. The translation stage had an accuracy and reproducibility better than 0.5 mm. The HPGe detector had a 9.5 mm diameter lead collimator, which was 5.1 cm thick, and was shielded by 10.2 cm of lead