Rapid Assessment of Surface Treatment Effectiveness and Degradation by Direct Field Measurement

Curtis A. Rideout
Positron Systems, Inc.
411 S. Fifth St.
Boise, ID 83702
208-514-4572
curtr@positronsystems.com

Abstract—Conventional nondestructive inspection (NDI) technologies do not have the ability to reliably and efficiently measure and quantify the effects of surface and subsurface residual stresses in aerospace structures. As part of a National Science Foundation Small Business Innovative Research (SBIR) program and several commercial projects, Positron has successfully demonstrated the ability to apply Induced Positron Analysis (IPA) in a single measurement to nondestructively quantify shot peen and cold expansion induced residual stress and relaxation effects in single crystal superalloys, steels, titanium and aluminum. IPA has demonstrated the ability to quantitatively measure residual stress effects throughout the operational life-cycle of the structural material – from determining the effectiveness of the initial treatment to tracking the operationally-induced changes over the life of the treated component. Use of IPA to nondestructively quantify surface and subsurface residual stress effects in critical structural, turbine engine, and gearbox materials and components will significantly improve the understanding of the effects of material treatments and operational usage on the durability and fatigue life of critical components at the microscale level.[1]

Table of Contents

1. Introduction

The generation of compressive residual stresses on material surfaces (e.g., shot peening, laser peening, cold rolling, etc) and in structural holes (i.e., cold expansion) have long been recognized as methods for enhancing the fatigue life of components in aircraft structures by imparting compressive residual stresses that retard crack initiation and crack growth. Material surface treatment and cold expansion are performed to extend the life of structures and components by inducing compressive residual stresses at fatigue-critical locations to inhibit crack initiation and propagation. The ability to detect and quantify surface and subsurface residual stress effects in aerospace materials, structures and components in a reliable and efficient manner presents significant challenges to conventional NDI technologies.

Accurate measurement of initially induced and operationally degraded residual stress effects with conventional NDI methods is difficult because of the inability to detect damage more than a few microns into a cold worked surface, especially in textured materials such as wrought aluminum. Therefore, accurate characterization of initial surface treatment effectiveness (e.g., shot peening and cold expansion) and the subsequent material condition, along with quantifying operational usage induced stress relaxation, are key issues in maintaining the structural integrity and readiness of aerospace platforms; including structural components, turbine engines, and power trains.

Numerous analytical and experimental programs have been conducted to assess the effectiveness of surface treatments and cold expansion to determine the extent to which the fatigue life of operational components is extended. Direct measurement of cold work induced residual stress profiles in aircraft structural materials (e.g., 2000 series aluminum), has proven to be a challenge; even in a laboratory environment, due to material characteristics (e.g., grain size and texturing effects) and the three-dimensional nature of the surface treatment or expansion process.[1,2] Further, current methods of measurement are typically destructive and are not readily field deployable. The cold expansion or shot peening processes, especially when used during refurbishment and repair operations, can be problematic in ensuring that the correct degree of compressive residual stress is achieved, since the surface or hole is often damaged from service as a result of wear, corrosion, scoring, distortion, cracking, etc. It is a common practice to remove damage by surface preparation or reaming of holes prior to the cold expansion process. Surface residual stresses are primarily induced in the top 1.0 mm of the surface, whereas the cold expansion process primarily involves radial expansion of the hole by forcing a tapered mandrel through the hole.

Induced Positron Analysis (IPA) volumetric and surface techniques (IPA-V and IPA-S) have demonstrated the capability to detect and quantify induced residual stresses and operationally-induced stress relaxation effects in

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aerospace and power generation turbine engine structures and components. Positron has successfully demonstrated the capability of IPA-S in experimental studies to accurately and reliably detect cold expansion levels in 2000 series aluminum and other materials such as nickel based superalloys. The IPA-S emitter patch can be positioned inside components or cold worked holes to measure residual stress effects to a depth of up to 3 mm. Consequently, this technology is suitable for use as a portable, high-speed, low-cost inspection technology for quantifying residual stresses on treated surfaces and in cold expanded holes, and for use in subsequent periodic inspections to assess operational effects on the residual stress condition. The IPA-S process is also suitable for measuring some types of operational damage such as corrosion and surface fatigue damage.

The IPA-S nanotechnology is based upon the physics of positron annihilation. Positrons are sensitive to defects, damage, and treatment induced changes in materials as they initiate at the atomic microstructural level. Changes induced by surface coatings, treatments and fatigue or corrosion damage cause a change in the positron energy distribution response signal in the materials. The positron response will change according to the size of the induced defect/damage and the intensity of induced changes or defects, providing a characteristic signature as to the component's current condition as related to the "as-manufactured" baseline. The IPA technology provides early indications of impending degradation or failure of treated components and can be used in the assessment of the relative effectiveness of competing surface coating/treatment technologies. The technical basis for the use of IPA-S technology, the equipment used (including field portable equipment) and case histories such as the analysis of shot peening treatments/near surface residual stress in variety of materials, coating assessments and heat treatment assessments will be discussed.

2. IPA Measurement Process

The IPA-S technology, and related IPA-V technology, used in this research were developed by the Idaho National Laboratory (INL). The IPA-S technology is a near-surface inspection and measurement technology that uses an IPA-V system to produce a positron emitting source material that generates high energy positrons (3-5 MeV) which can be used to measure dislocation damage effects at depths up to 3 mm in the material being measured for a near-surface damage assessment. New advances in IPA-S probe development have resulted in a reusable, longer life configurable IPA-S probe in excess of 180 days that no longer requires the IPA-V technology for production. The IPA-S source production process is completely self-contained with no external exposure of individuals to any radiation field effects.

The IPA-V technology is a volumetric measurement technology that can measure damage to depths of up to 2.0 inches in steel and 3.5 inches in titanium. This technology is a new addition to material characterization technologies that have specific applications to almost all materials industries. IPA-V extends the current limited use of traditional, surface positron annihilation measurement technology to a much broader range of applications, allowing the technique to be used as a more general-purpose, nondestructive assay technique, including the volumetric assay of rocket propellant materials. The IPA technologies have shown remarkable potential in the identification and measurement capabilities for material assessment that include:

- Identification of atomic lattice defects <10 microns in size.
- Measurement uncertainties on the order of less than 1%.
- Multi-layer defect detection in metals and composites.
- Cross-sectional analysis.
- Assessing lattice structure change/plastic deformation at less than 1%. Crack initiation/loss of plasticity = 100%.

The IPA-S process induces positrons into the near-surface region of materials/components to depths up to 3mm. The positrons react with the various dislocations and changes in the atomic lattice structure by annihilating with the different types of electron energies associated with lattice structure damage and change. The annihilation energy distribution is measured by a germanium detector system and correlated to a damage/material characteristic change database. Although positron beam spectroscopy (PAS) has been around for decades and is a proven technology, IPA is a revolutionary advancement over previous positron beam spectroscopy where the previous positron penetration and defect detection depths were significantly limited and impacted by surface characteristics. With the deeper depth of inducement of positrons by IPA-S, the depth of defect detection for IPA-S is only limited by the attenuation of the annihilation gammas to be measured by the germanium detector; and is related to the material density. This thickness for receipt of the measurement response can be up to 1 inch of interfering exterior materials, allowing assessment of internal damage to be detected externally by the germanium detector. Figure 1 shows the IPA-S process where the IPA-V technology can be used to make the IPA-S probe and Figure 2 depicts the formation and subsequent thermalization of the positron as it travels through the lattice structure, searching for a lower charge density region (defected area), where it becomes trapped and then annihilates with an electron.

Positron annihilation occurs when a positron encounters an electron and their mass is converted into pure energy in the form of two gamma rays. If the positron and the electron with which it annihilates were both at rest or with little momentum at the time of decay, (i.e., in a defect), the two gamma rays would be emitted in exactly opposite directions 180 degrees apart), with an energy of 511 keV (0.511MeV),

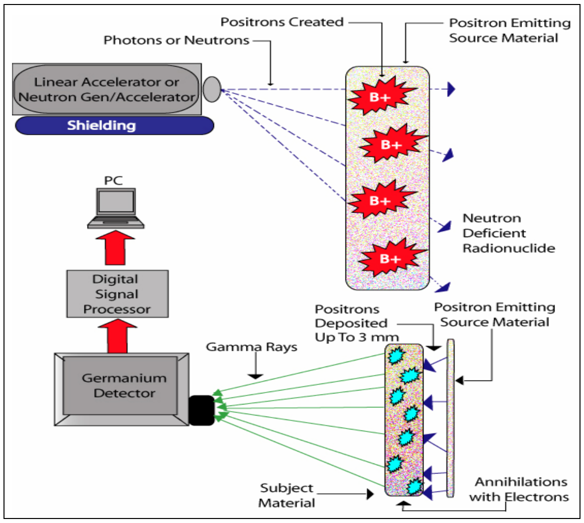

Figure 1 - IPA-S Process Using IPA-V

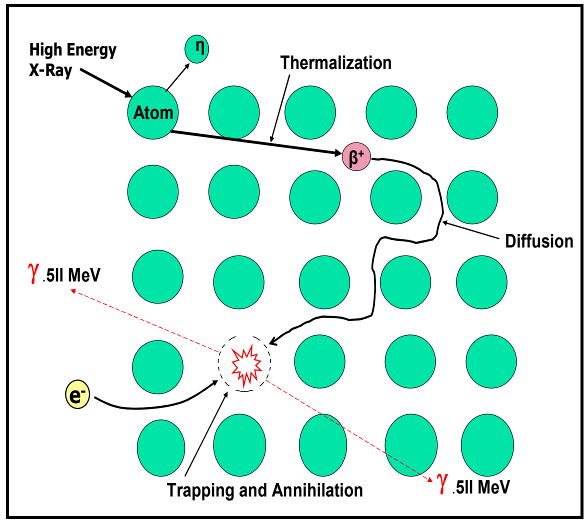

Figure 2 - Positron Lifecycle

whereas if the annihilation occurs in a location without defects, the gamma ray measured has incremental, measurable differences from 511 keV (Conservation of Energy). The energy level of the annihilation gammas released is indicative of the level of damage.

Positron annihilation measurement data can be analyzed by several methods that provide different types of information concerning the extent of residual surface or volumetric stresses. These data can then be converted to remaining life estimates through standard regression and statistical methods that can be used to relate operational damage (e.g., operational hours) and integrated off normal damage effects to the measured positron annihilation response. Measurements on a range of components from new through end-of- life can then be used to define statistical bounds that identify the likelihood of failure for the component being examined.

The positron data analysis is based on characterization of the shape of the 511 keV peak. The annihilation energy (511 keV) of the annihilating positrons is incrementally affected by the momentum energy of the electron with which the positron annihilates. Defects contain a higher ratio of free electrons to core electrons than non-defected materials. This phenomenon can be explained by the tendency of free (conduction) electrons to lose energy and slow down or stop in the defect. Core electrons have a much higher linear momentum than do free electrons. Thus, gamma rays from annihilation events involving free electrons are more likely to approximate the energy (511 keV). This characteristic makes it possible to detect the presence of defects from the energy spectrum of the gamma ray emission when the positron and electron interact. Additional information on the measurement process and data analysis can be obtained from a variety of available literature.[3,4,5,6,7,8,9]

3. Residual Stress Measurements

Several projects have been performed that utilize the IPA-V and IPA-S processes to not only measure the initial effectiveness of surface treatments but to assess the relaxation of some of these processes due to thermal and mechanical effects that simulate the effects of operational damage on the components. The following sections address IPA-S measurements performed to assess initial surface treatment effectiveness and the effect of simulated operational degradation of the treated material, followed by real world applications and inspections.

Figure 3 shows the basic application of the IPA-S technique, beginning with the developed IPA-S positron emitting source, either from an external patented process or through the application of IPA-V, and a suitable material. In either case, the IPA-S probe can be configurable in size and shape to provide assessment capability in a variety of complex geometries and situations.

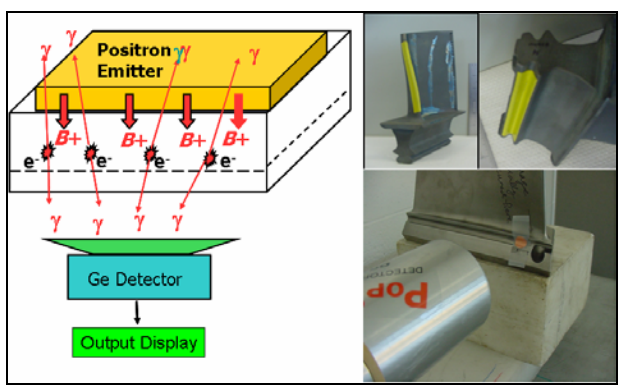

Figure 3 – IPA-S Probe Application

Figure 4 shows the IPA-S process being used to measure the blade pictured in Figure 3 above. Basic Testing Service Center IPA equipment is shown. Figure 5 provides the current system under development (est. March 2007) which incorporates the complete IPA-S detector and analysis system in the size of a large briefcase, minus the laptop computer (USB connection) and the positron emitter probes.

Figure 4 – IPA-S Measurement System

Figure 5 – IPA-S Compact Portable (In Development)

Shot Peening Assessment for Turbine Blades

Near-surface IPA-S measurements were performed on prepared CMSX-4 nickel-based superalloy samples to provide baseline data for subsequent simulated operational tests and to assess the effectiveness of the technique to measure various intensities of the shot peening process. Test specimens of steel and CMSX-4, were prepared and measured at incremental shot peening intensities ranging from 0-20A (as referenced to Almen strip comparison). The CMSX-4 samples were then subjected to a range of fatigue and thermal conditions to assess relaxation effects and to assess subsurface residual stresses. The IPA-S technology proved to be highly sensitive to the surface treatment intensity and accurately measured the relaxation of the residual stresses produced by varying degrees of simulated operational conditions. In addition, the tests demonstrated IPA-S technology's ability to quantify subsurface residual stress effects in test specimens.

Results from the near-surface IPA-S measurements for the initial CMSX-4 coupons and follow-on evaluation of thermal and mechanical effects on the surface treatment effectiveness and relaxation are shown in Figure 6. These results indicate that the IPA-S measurement dynamic range (from no shot peening through 20A) is 0.0223 with uncertainties less that 0.1%. These data clearly show the ability of the IPA-S process to quantify surface residual stress effects with a single measurement, as the IPA-S process is sensitive through entire thickness of the surface treatment.

Figure 6 also shows the thermal and thermomechanical effects on the surface residual stresses induced in the CMSX-4 coupons by shot peening. The initial characterization results are shown with a 2 standard deviation (2σ) or 95% confidence level error bounds that were determined by a model that calculates the average error for a list of x,y values in a regression. These bounds provide an initial estimate of what might be considered to be no relaxation effects due to thermal or mechanical fatigue effects. In addition to the new condition residual surface stress data, near surface IPA-S measurement results are shown for the thermal effects results where the samples were heated to 1000°C for periods of 100 and 500 hours, fatigue testing at 300°C and fatigue testing at 700°C.

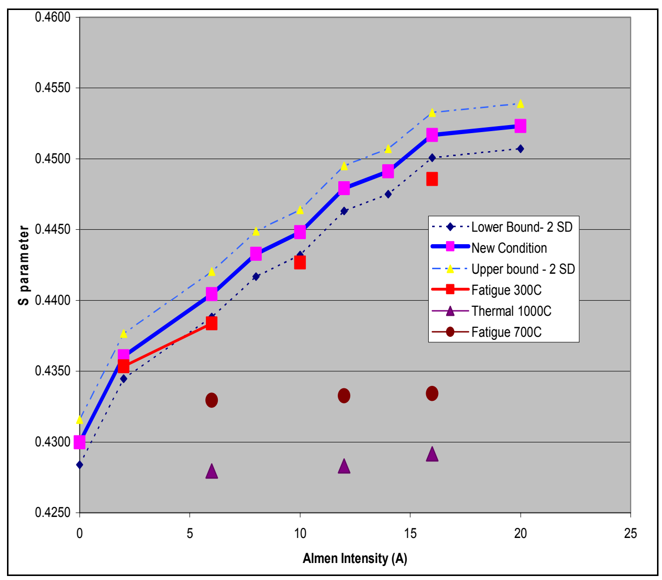

Figure 6 – IPA-S Near-Surface Shot Peening Response and Thermal and Mechanical Effects on Surface Residual Stress

Examination of the IPA-S near surface measurements for the specimens that were fatigue tested to a level of 81 ksi at 300°C as shown in Figure 6 indicates that the combined low temperature and fatigue cycles may have a limited effect on the surface residual stresses produced by the shot peen intensity. The results indicate that fatigue testing at 300°C has little or no effect on specimens that were shot peened at the lower Almen intensities, whereas the specimens processed at the higher Almen intensities experienced a residual stress relaxation values that fall below the lower 2σ boundary. These data suggest that higher intensities of residual stress may relax at a faster rate than do the lower intensities. It is apparent from the Figure 6 data that increased temperatures have the most significant effect on residual stress relaxation.

The second phase of this project was to apply the IPA-S shot peening measurement database in the assessment of shot peening intensity and relaxation under operational conditions for similar turbine engine blade materials. Several sets of turbine engine blades were provided for inspection to determine the following:

- Can IPA-S effectively measure surface treatment residual stress effects in complex geometry?
- Can IPA-S be used to nondestructively certify surface treatment applications such as shot peening?
- Can IPA-S detect field, operational relaxation effects?

Figure 7 shows the blade configuration and the blade root region of interest that was shot peened and required certification compared to a known reference and Figure 8 shows the testing results.

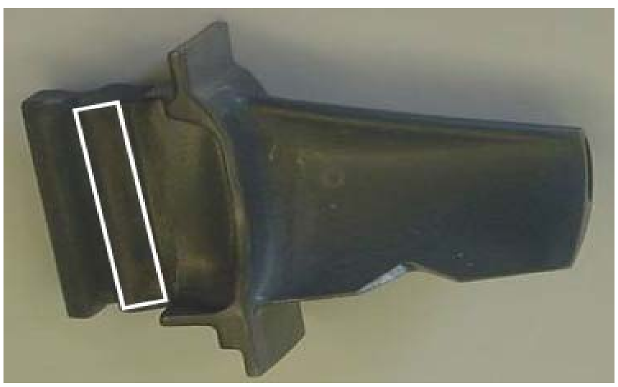

Figure 7 – Turbine Engine Turbo-Fuel Pump Blade

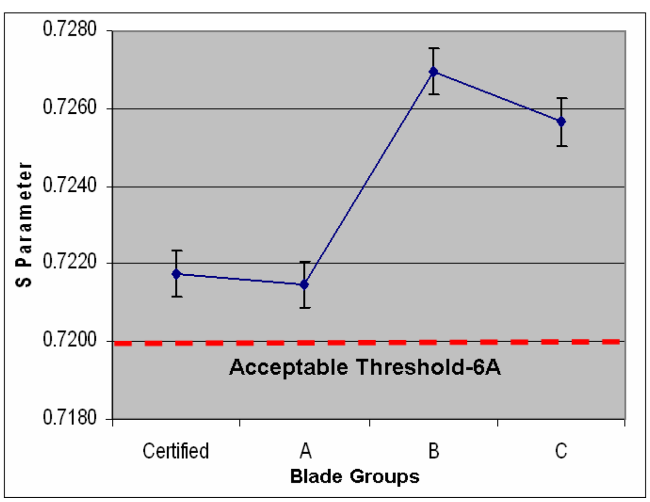

Figure 8 – Turbine Fuel Pump Blade Assessment

A grouping of blades were assessed using IPA-S to determine if the desired 6A level of shot peening (as determined by Almen strip method) had been achieved or exceeded in the blade root region. As Figure 8 shows, all blades tested were found to have acceptable levels of shot peening present based upon measurement of the certified blade, with several blades exhibiting better than 6A intensity. Blades in Group A typically were closer to the certified blade value as compared to Groups B and C. Upon further examination, it was noted that Group A blades had experienced initial testing at operational temperatures, resulting in some relaxation of the shot peen produced residual stresses.

These IPA-S measurements provide a direct method for determining and assessing the response of laboratory specimens and operational components to changes in surface residual stresses as a function of various types of operational damage including thermomechanical effects. Models for thermomechanical fatigue damage and annealing characteristics can be developed based on the study results. The IPA-S process can be used nondestructively to monitor the life cycle of operational components to assess surface residual stress effectiveness and thermomechanical degradation. This capability has numerous applications relative to characterization of initial shot peening and surface treatment effects, aging assessments, reapplication of shot peening effects and annealing recovery of components such as turbine blades.

Cold Expansion Measurements

A feasibility study was performed to measure the effect of cold expansion on holes in 2124-T851 aluminum plates. Two aluminum test plates were prepared by Fatigue Technology Inc. (FTI). Each plate had nine holes with varying hole diameters. The hole diameters were chosen to provide applied expansion levels from 0% to 5.2%. The mandrel was pulled in the direction so that it exited on the side of the plate on which the IPA-V measurements were performed. After the cold expansion process, the hole diameters were measured and the holes were then final reamed to a diameter of 0.312 $\pm$ 0.002. IPA-S and IPA-V measurements were also performed to assess the effectiveness of the cold expansion processes on a number of 2024 aluminum plates.

The holes were cold worked from expansion levels of 0% (no cold work) to 2.1%, 3.1%, 3.8%, 4.2%, and 5.2% cold expansion levels per the standard split-sleeve process. Three holes in each plate were cold worked to the same level. S-parameter measurements were taken at each of the holes in both plates using IPA-V and IPA-S. As shown in Figure 9, the data indicate that there is a well-defined relationship between the expansion level and IPA-V/IPA-S measured S-parameter. As the expansion level increases, the amount of plastic deformation increases and the measured S-parameter increases.

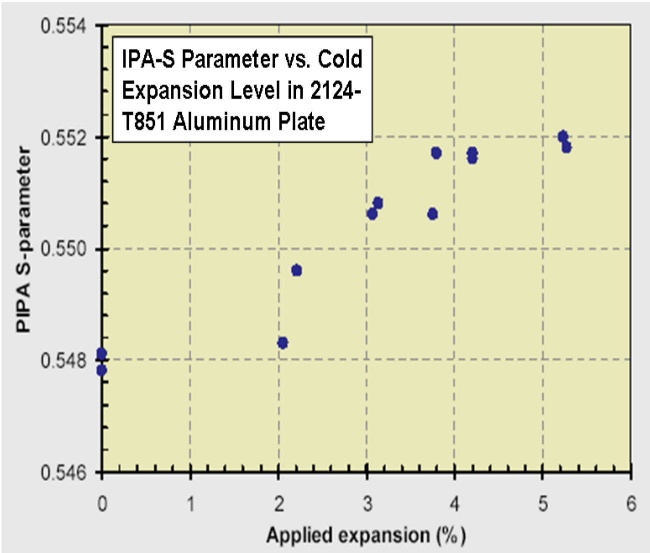

Figure 9 – IPA-S Response to Cold Expansion in 2124-T851 Plates

IPA-S surface measurements were also performed around the top surface of the cold expanded holes to assess damage within 0.25 cm (0.1 in) from the edge of the hole and from 0.1 to 0.2 inches from the hole. The dislocation densities are higher on the top surface around the edge of the hole as compared to those on the inside of the hole (+0.0026). These results are shown in Figure 10 and are consistent for all hole locations. The measurements within 0.1 inch produce the highest results with a consequent reduction in nominal damage further away from the hole.

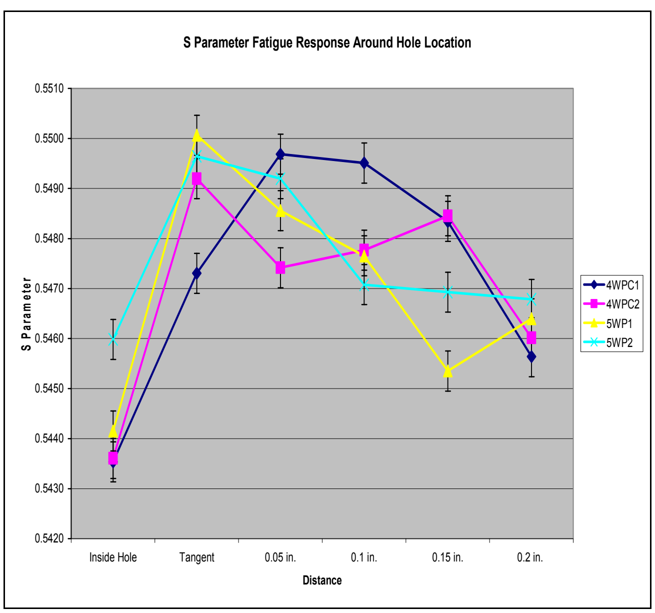

Figure 10 - IPA-S Surface Residual Stress Distribution around Cold Expanded Hole

4. Conclusions

Test and evaluation programs have successfully demonstrated the capability of the near-surface evaluation tool, Induced Positron Analysis-Surface (IPA-S) to quantify surface treatment effects, including both shot peening and cold expansion of fastener holes. In addition, tests have been performed to assess the effects of thermal, mechanical fatigue, and high temperature thermomechanical fatigue on the shot peened surface residual stress. Measurements were performed using 2124-T851 aluminum and a nickel-based superalloy (CMSX-4), which clearly demonstrated the capability of the induced positron technologies for measuring these types of induced residual stress. The CMSX-4 test measurements also provided nondestructive, quantitative measurement results on the changes in the induced surface residual stresses and the buildup of thermal, fatigue, and thermomechanical damage effects through the entire "pre-crack" damage range that is not detectable by other technologies. These results clearly demonstrate the ability of the IPA-S and IPA-V technologies for quantifying the effects of surface treatments, treatment relaxation, thermomechanical damage effects, and annealing.

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BIOGRAPHY

Mr. Curtis A. Rideout, Vice President, Marketing and Accounts Management for Positron Systems

Curt Rideout retired from the U.S. Navy in 2001 after 22 years as a nuclear submarine Commander, serving in senior leadership positions in varying capacities in the submarine community; including fast attack and ballistic missile submarines and three major operational command staffs. Mr. Rideout has extensive knowledge of nuclear reactors and engineering, including oversight of operations, maintenance and training programs for Navy nuclear power plants.

Currently he is in charge of marketing and business development for Positron Systems, focusing in the power generation, military, and government sectors, and provides technical expertise for the corporate office. Previously, Mr. Rideout managed the marketing and sales effort for TenXsys Inc., an innovative human and animal telemetry company, and was instrumental in achieving successful entry of the company's products into the Army and commercial customers.

Mr. Rideout has written and achieved nine successful Small Business Innovative Research (SBIR) Phase One contract awards, and one Phase Two award, with the Army, Navy, National Science Foundation, Missile Defense Agency and Air Force, and has been instrumental in the company's entry into the commercial aerospace community through his military and government contracts. For Positron, Mr. Rideout provides the overall marketing strategy and is responsible for overall account management.

Mr. Rideout was born in Boise, Idaho and enjoys many of the common outdoor activities associated with the mountains. He currently serves on the Boise State University College of Engineering Advisory Board and assists his community as a volunteer mediator and supporting the YMCA Strong Kids Campaign. He has Masters Degrees in Business Administration and Nuclear Operations, and a B.S. in Chemical Engineering.

Mr. Scott J. Ritchie, Vice President, Applications Engineering

Scott Ritchie has a broad management, operations, customer service and account management background in high technology industries. Mr. Ritchie has been responsible for the development and implementation of functional plans as an executive officer. For Positron Systems, Mr. Ritchie provides the primary project management role in addition to handling account management to support the marketing strategy.

Mr. Ritchie served as Vice President of Operations for Extended Systems, Inc. from 1995 through 2001 and was responsible for extensive improvements in the value added supply chain. Mr. Ritchie was responsible for successful ERP and ISO 9001 implementations and the development of an international supply chain while at Extended Systems.

From 1978 to 1995, Mr. Ritchie was employed by Hewlett-Packard and held a number of positions in manufacturing and material management including Manager of the Mexico International Procurement Office located in Guadalajara Mexico responsible for business and supplier development.

Mr. Ritchie is a native Idahoan and has been active in supporting local charities and community events. Mr. Ritchie enjoys time with his family, reading, golf and a variety of other outdoor activities.