Application of on-site positron annihilation lifetime spectroscopy system as non-destructively shot peening evaluation technique

N. Uesugi[1], M. Yamawaki[2], K. Hattori[1], Y. Watanabe[1*]

1. Toyo Seiko Co., Ltd., Japan
2 National Institute of Advanced Industrial Science and Technology, Japan

* Corresponding Author: y_watanabe@toyoseiko.co.jp

Abstract

Positron annihilation lifetime spectroscopy (PALS) is a non-destructively technique to study open-volume lattice defects such as vacancies or dislocations, which is used for fatigue, aging and shot peening inspection. In this work, we developed a portable PALS apparatus that has the ability for on-site measurement. We developed the light-shielding technique which enable us to do on-site measurement. Furthermore, we downsized the apparatus size using Monte Carlo simulation technique. We validated that the developed portable apparatus have the same shot peening potential as the conventional system. We concluded that the developed portable apparatus is sufficiently able to capture the change caused by shot-peening time.

Keywords Non-destructive inspection, Positron annihilation analysis, Lattice defects

Introduction

Positron annihilation lifetime spectroscopy (PALS) is a technique that can detect lattice defects in solids. Lattice defects affect various properties (e.g., mechanical properties), therefore PALS is used for investigating fatigue damage or ageing. PALS technique is also effective in inspecting shot-peened parts. Shot peening produces plastic deformation, and the amount of induced lattice defects is dependent on a shot peening quality. In other words, the amount of lattice defects induced by shot peening increases with the intensity of shot peening increasing. Therefore evaluating the lattice defects leads us to inspect shot peened parts. One of the most significant advantages of PALS is measurement depth. A positron penetrates as ten times deeper than the X-ray generally used in industry, which means that PALS can measure areas non-destructively deeper than the X-ray.

In previous work, we developed the anti-coincidence (AC) method, which made it possible to measure with a single specimen [1]. We also developed a desktop-type PALS apparatus implementing the AC method. However, it is necessary to place the specimen into a dark box in the desktop apparatus for accurate measurement. Therefore a larger specimen needs to be cut, which leads to destructive inspection.

We developed the portable PALS apparatus, which has the ability for on-site measurement [2]. The portable apparatus has a “dark-box-less” structure and small-sized gamma detectors, which leads to convenience for various on-site applications. In this research, we optimized the light-shielding technique, which enables the “dark-box-less” structure to be capable of sufficiently accurate measurement. Furthermore, we optimized the detector layout to improve the counting rate. We applied an MPPC® device (Hamamatsu Photonics K.K.) for the positron detector, which allowed the gamma detectors to be more efficient layout. We conducted Monte Carlo simulation to evaluate the counting rate for various detector layouts with the MPPC.

Positron annihilation lifetime spectroscopy

A positron is an anti-particle of electrons. When a positron and an electron collide, they annihilate each other with two gamma rays emission. The time between the detection of gamma rays due to positron emission and positron annihilation corresponds to the lifetime of positron. The positron lifetime is inversely proportional to electron density at the site where positrons are annihilated. If lattice defects exist in a specimen, positrons are trapped and annihilated there. Since electron density is lower in such defects, positron lifetime becomes longer than a defect-free specimen.

Fig. 1 shows the schematic diagram of our developed PALS system. The system consists of two gamma-ray detectors and a positron detector. The gamma-ray detectors are used to detect positron emission, while the positron detector is used for the AC method. The positron detector comprised a plastic scintillator plate, a photodetector, and a sealed Na-22 positron source with two 7.5 μm thickness Kapton films. Placing a specimen on the positron detector leads to irradiation of positrons into the specimen.

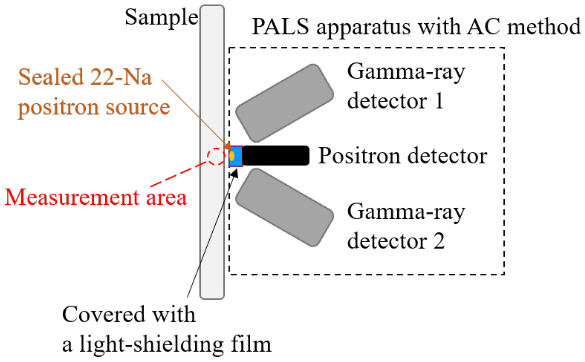

Fig. 1 The diagram of PALS with the AC method

Experimental Methods

The positron detector needs to be light-shielded to prevent the internal photodetector from ambient light. In order to develop a "dark-box-less" structure, we covered the positron detector with light-shielding films. We applied an Al-deposited Kapton film as a shielding film instead of a simple shielding film (e.g., Ti foils). The deposited film makes it possible for the shielding layer to be thin, maintaining a shielding ability. Moreover, Kapton film is of the same material as the sealant of the positron source. Positrons have a definite lifetime in Kapton; thus, the noise signals from Kapton can be separated by analysis. We evaluated various Al-deposited films to thicken the Al deposited layer.

To downsize and lighten the apparatus, we conducted Monte Carlo simulations to evaluate the counting rate for various detector layouts. We used Geant4 (ver. 10.4) [3], a simulation tool kit of the passage for particles through matter. Like our PALS system described above, we placed two gamma-ray detectors and a positron detector. The material information was based on the database of Geant4. In addition, we experimentally evaluated the time resolutions for some layouts and compared them with the simulation results.

We prepared the shot-peened stainless steel SUS304. The specimen size was 15 mm × 15 mm × 2 mm to use the desktop apparatus (with a dark box system) for the measurement. Table 1 shows the shot peening conditions.

We used the developed apparatus to conduct a PALS measurement on the shot-peened specimen and compared the results with those obtained from the desktop apparatus to validate the developed apparatus. We used the analysis software, IPALM [4], to identify the positron annihilation lifetime. Furthermore, we compare the PALS results with the full width at half maximum (FWHM) of Bragg peak from the (311) plane. The FWHM was measured by μ-X360 (Pulstec Industrial Co., Ltd.).

Table 1 Applied shot peening conditions

Shot media	Conditioned cut wire Φ0.3 mm, HV500 (typ.)
Air pressure [MPa]	0.20
Coverage [%]	50, 90, 95, 100, 200

Experimental Results and Discussions

Fig. 2 shows three Al-deposited Kapton films irradiated with white light from the back. The deposit thickness and the number of deposit layer affected the shielding efficiency, and the 500 nm deposited film had higher shielding efficiency than the 300 nm one. Nevertheless, some irradiated light passed through the film, which indicates that it is not sufficient to use for the positron detector. On the other hand, the film deposited on each side had the highest shielding efficiency despite the thinnest thickness (total 200 nm). These results indicated the presence of the pinholes, which were randomly distributed on a deposited layer. The pinholes could not shield the irradiated light, which caused the film to degrade the shielding efficiency. In the case of the each side deposited film, the light could pass through the film only when the pinholes are present at same position on each layer. Therefore it seemed that the each side deposited film had the highest shielding efficiency. The results indicated that increasing the number of thin deposited layers is more efficient than a single thick deposited layer to make the amount of the thickness of deposited layer thinner. Finally, we adopted the total Al-deposit thickness to 400 nm by performing 200 nm Al deposition on each side of the Kapton film.


300 nm Al on one side 500 nm Al on one side 100 nm Al on each side

Fig. 2 Image of Al deposited Kapton films irradiated with white light from the back.

Table 2 shows the positron lifetime measured by various shielding methods. There was nothing between the positron source and the specimen in the desktop apparatus, which means that contamination did not occur. In the case of shielding with simple Ti foils (thickness of 6 um), the positron lifetime was higher than the desktop one, which means that such thick foils affected the measurement accuracy. On the other hand, the positron lifetime was almost the same as the desktop one in the case of shielding with the Al-deposited film. This result shows that the deposition enabled the degradation from the shielding film to be negligibly small. Based on these results, we developed the "dark-box-less" system enabling accurate positron lifetime measurements using the Al-deposited shielding film.

Table 2 Mean positron lifetime using various shielding methods

	Positron lifetime [ps]
With dark box (the desktop apparatus)	105.4 (±1.2)
Shielding with Al-deposited film (totally 300 nm)	104.9 (±1.2)
Shielding with Ti foils (totally 6 μm)	120.2 (± 1.2)

Fig. 3 shows an image during the counting rate simulation by Geant4. The results identify that it is effective for improving the counting rate to place the positron source near the center of gravity of gamma-ray detector. On the other hand, the positron source is integrated with the positron detector. Therefore, it is limited to bringing the gamma-ray detectors close to each other due to collision. We applied an MPPC device for the positron detector. MPPC is a solid state photomultiplier. An MPPC leads the positron detector to be thinner than the one with a conventional photomultiplifier (Shown in Fig. 3). We varied some layout parameters (e.g., an angle between gamma detectors) and evaluated the counting rate.

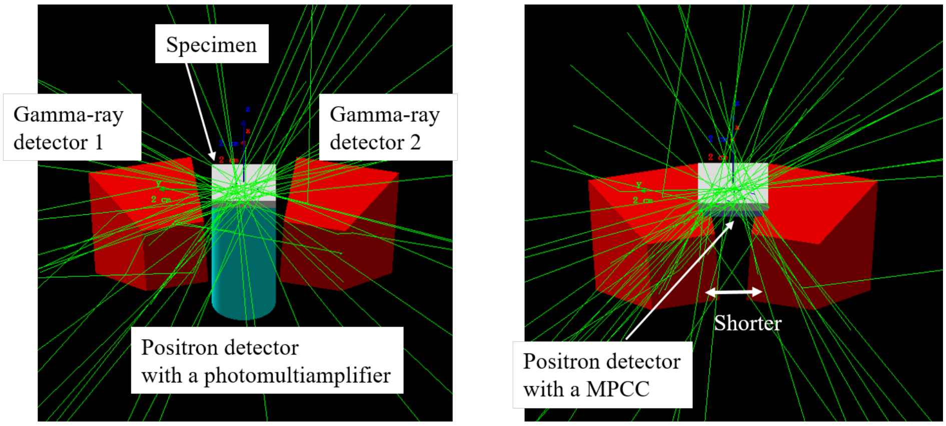

Fig. 3 Simulation by Geant4
(Left: Simulation with a photomultiamplifier, Right: Simulation with a MPPC)

Fig. 4 shows the developed portable apparatus implementing the above works: the light-shielding technique and the detector layout. We validated that the developed portable apparatus has the same potential for shot peening evaluation as the desktop apparatus.

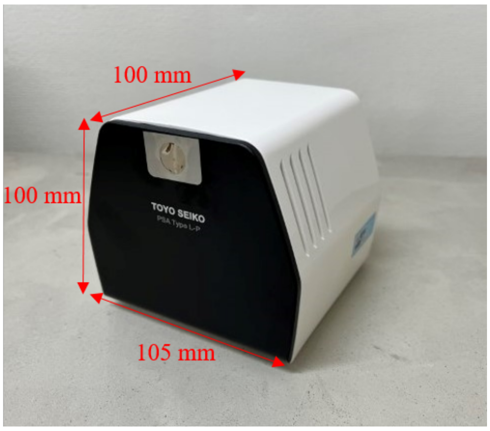

Fig. 4 An overview of the developed portable apparatus

Fig. 5 shows the plot of the change in the 'mean' positron lifetime based on the coverage. The 'mean' positron lifetime measured by the portable apparatus was monotonously increased with the increase in shot-peening time. The 'mean' positron lifetime measured by the desktop apparatus was also monotonously increased with the increase in shot-peening time. The elongation of the 'mean' positron lifetime implies that more positrons are trapped by defects, as shot-peening introduces defects, increasing the defect density. The 'mean' positron lifetimes measured by the portable and desktop apparatus agree well. Therefore, the developed portable apparatus has a sufficient ability to capture the change caused by shot-peening time.

Fig. 6 shows the plot of the FWHM of XRD profile on the coverage as well as Fig. 5. Mean positron lifetime is also showed in Fig. 6 to compare the both. The FWHM increased with the increase in shot peening time, resulting in the dislocations induced by shot peening. In the comparison of the PALS result, there were difference around the full coverage region. The positron lifetime increased more explicitly than the FWHM values in the region. PALS has a high sensitivity for vacancies, not only dislocations. Furthermore, the measurement depth of PALS is ten times deeper than XRD. These difference seemed to result in the difference on the shorter shot peening specimens.

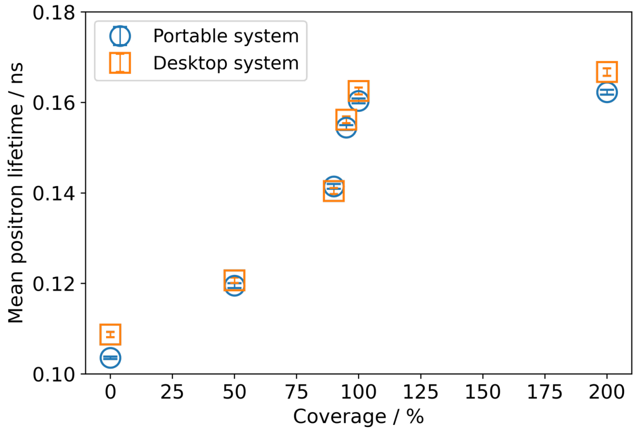

Fig. 5 The mean positron lifetime of shot-peened stainless steel obtained by the portable and desktop apparatus.

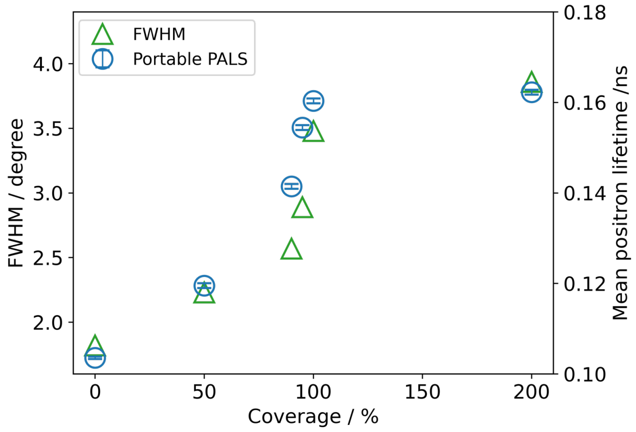

Fig. 6 The FWHM of X-ray line profile of the shot-peened specimens.

Conclusions

We developed the light-shielding technique, which enabled the apparatus to be "dark box less" and optimized the detector layout. We developed the portable PALS apparatus implementing the above works. The apparatus has an ability for on-site measurement, which means that PALS measurement is available for any size of target parts.

We evaluated the performance of the developed apparatus using shot-peened stainless steel; the apparatus could capture the difference in the average positron annihilation lifetime due to increased defect density by shot-peening as well as the conventional desktop apparatus.

We are developing several techniques for short-time measurement [5] and applying them to the developed portable apparatus. It is expected that the ability of short-time measurement with the portable apparatus allows PALS to be widely applied in industry, e.g., fatigue inspections or shot peening inspections.

Acknowledgement

This research was supported by METI Monozukuri R&D Support Grant Program for SMEs Grant Number JPJ005698.

References

[1] M. Yamawaki, Y. Kobayashi, K. Hattori, and Y. Watanabe, *Novel System for Potential Nondestructive Material Inspection Using Positron Annihilation Lifetime Spectroscopy*, Jpn. J. App. Phys., Vol. 50, (2011) 086301

[2] M. Yamawaki; N. Uesugi, Y. Kobayashi, *Development of a small and light portable positron annihilation lifetime measurement equipment for on-site measurements,* Jpn. J. App. Phys., Vol. 61, (2022) 066503

[3] S. Agostinelli et al., *Geant4—a simulation toolkit* , Nucl. Inst. Meth. A, Vol. 506 (2003) 250-303.

[4] M. Yamawaki, K. Ito, K. Hattori, and N. Uesugi, *Development of a commercial positron annihilation lifetime measurement system*, Journal of Physics: Conference Series, Vol. 791, (2017) 012038.

[5] M. Yamawaki; N. Uesugi, Y. Kobayashi, *Feasibility study of non-destructive defect analysis by positron annihilation lifetime measurement*, Jpn. J. App. Phys., Vol. 59, (2020) 066502