PTT System Performance Evaluation in 3-D Imaging of Calibrated Defects

*Pulsed Thermal Tomography Nondestructive Examination of Additively
Manufactured Reactor Materials and Components*

Nuclear Science and Engineering Division

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prepared by

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Abstract

Research activity in this project is aimed at developing pulsed thermal tomography (PTT) architecture and algorithms for in-service non-destructive examination (NDE) of additively manufactured (AM) reactor components and materials. Recent advances in AM technology could allow cost-efficient fabrication of parts for operating reactors. However, because of stringent safety requirements, long-term performance of AM reactor components needs to be investigated before AM is widely accepted. Because of the complex shapes and significant surface roughness of components due to layer-by-layer welding process in AM, conventional methods might not be useful for in-service NDE of AM components. PTT is ideally suited for in-service NDE of AM metallic components because the method is non-contact, and offers high resolution 3-D imaging of material flaws. The objective of this report is to provide initial evaluate of PTT performance sin detecting calibrated flaws in reactor structural materials. Preliminary COMSOL models were developed to conduct computer simulations of PTT. In the experimental studies, high strength Stainless Steel 316 and Inconel 718 alloys were considered, as well as lower grade Stainless Steel 304, Nickel 200, and Hastelloy C276. Specimens investigated in this report consisted of approximately 1/4in-thick plates made out of these alloys using conventional manufacturing methods. The calibrated defects were created in the form of flat bottom holes (FBH) drilled in metallic plates. The diameters of FBH's varied from 1mm to 8mm, and their depths below the plate flat surface varied between 1mm and 6mm. The size of the smallest FBH was limited to 1mm because conventional mechanic drills were used for creating the holes. PTT imaging results have shown that 1mm-diameter FBH located 1mm and 2mm below the surface were detectable. Larger size FBH were detectable at greater depth. For example, 6mm-diameter FBH could be detected at 8mm depth. Image contrast varied slightly between the specimens, with the best reconstructions obtained in SS316 and C276 plates. In addition, a 2/3in-thick Inconel 718 nozzle plate produced with additive manufacturing method was imaged with PTT. It was shown that PTT can scan through the plate in approximately 20s. Several modes of 3-D data visualization were explored, including using ImageJ and MATLAB software packages.

1. Introduction

1.1. Background

Additive manufacturing (AM), or 3-D printing, is expected to play an increasing role in nuclear energy sustainability by providing fabrication options, which are not achievable with conventional manufacturing technologies. For example, in aging commercial reactors, AM provides rapid cost-effective option of replacing worn-out parts and components, including those for which original drawings are not available. With AM approach, an aging component is digitally scanned, and a new a replacement component is 3-D printed. Because conventional manufacturing is aimed at serial production of a large quantity of parts, AM reduces the cost of production when a small quantity of replacement parts is needed. Current exploratory studies involve fabricating AM parts for different fuel structural components using stainless steel and nickel super alloys [Bertali 2015, Freyer 2018]. However, because of stringent safety requirements, long term performance of AM printed reactor components needs to be investigated before AM is widely accepted.

While the field of additive manufacturing is rapidly advancing due to improved characterization of printed parts and real-time study of processes, there remain significant limitations, which may introduce defects into additively manufactured metal components. Porosity can be introduced into AM parts due to incomplete melting of the powder particles or insufficient overlapping of the melt pools [Cunnigham 2017]. Oscillations in the surface of the melt pool caused by rapid heating and cooling result in powder ejection and splattering of the melt, resulting in surface roughness and porosity [Zhao 2017]. Furthermore, improper cooling rates can cause the formation of non-equilibrium phases and residual stresses [Kampen 2011, Sames 2016], requiring post-process heat treatments [Lewandowski]. Monitoring the integrity of 3-D printed components requires use of in-service nondestructive examination (NDE) methods. Examinations are assumed to be taking place on installed 3-D printed components during scheduled reactor shutdown intervals. Because of the complex shapes and significant surface roughness of components due to layer-by-layer welding process in AM, conventional methods might not be useful for in-situ NDE of AM components. In this project, we are developing pulsed thermal tomography (PTT) architecture and algorithms for in-service NDE of reactor components.

PTT obtains reconstruction of material internal defects by monitoring surface temperature transients following thermal pulse applied to material surface. The method is non-contact, with measurements performed from stand-off distance from one side of the specimen. An imaging camera with megapixel array of detector elements acquires an image of a large section of material. This allows for detection of flaws with minimal amount of mechanical scanning, as compared to image acquisition which requires point-by-point raster scanning of the specimens [Heifetz 2018]. Alternative NDE approaches may consist of X-ray CT, neutron CT, ultrasonic imaging and Eddie current imaging. Table 1 lists comparative technical merits of different methods evaluated according to the following criteria: non-contact measurement ability, compact size, parallel processing (as opposed to point by point raster scanning), and one-sided measurement. The X-ray and neutron CT is difficult to use for in-situ NDE. In addition, high resolution imaging can be obtained for small components only. Ultrasonic imaging can be used in-situ, but the method

critically depends on coupling between ultrasonic transducer and the surface of AM component. Because of surface roughness and complex shape, ultrasonic coupling is difficult to achieve. Ultrasonic and Eddy current imaging involves point-by-point raster scanning of the material. Therefore, according to Table 1, performance of PTT for in-service NDE of 3-D printed parts is expected to be superior to that of other approaches.

Table 1 – Comparative merits of PTT for in-service applications

Feature	X-Ray CT	Neutron CT	Ultrasonic	Eddie Current	Thermal Tomography
Non-contact	Yes	Yes	No	Yes	Yes
Compact	No	No	Yes	Yes	Yes
Parallel processing	Yes	Yes	No	No	Yes
One-sided	No	No	Yes	Yes	Yes

1.2. Introduction

Project objectives addressed in this report include development of performance metrics for PTT detection of flaw size and flaw location relative to material surface. The minimum flaw size, typically a region high porosity, encountered in additive manufacturing of metals is approximately 50 μ m. In general, smaller flaws can be detected closer to material surface, and the size of the smallest detectable flaw increases with increasing depth inside the material. Flaw detection capability of PTT depends on the temperature contrast gradient on the material surface. For a state of the art IR camera, detection threshold is 25mK. Detection of flaws is related to material thermal diffusivity, which is measure of heat transfer rate in the material. Prior work on PTT at Argonne consisted of imaging primarily ceramic matrix composite (CMC) materials. This report provides preliminary results of PTT performance evaluation in detection of calibrated flaws in high-strength metallic alloys commonly used as reactor structural materials. These include stainless steel 316 and Inconel 718 alloys, as well as lower grade stainless steel 304, nickel 200, and hastelloy C265. Calibrated flaws consisted of cylindrical flat bottom holes of variable diameter and depth drilled in metallic plates. The results obtained thus far indicate that PTT can image flaws 1mm in size, which is the smallest calibrated flaw created in metallic specimens. In addition, imaging of thick (2/3in) Inconel 718 nozzle plate printed with additive manufacturing method was performed. PTT was capable of imaging through the entire plate.

2. PTT System Description

2.1. Principles of PTT operation

PTT is based on monitoring the temperature decay on a sample surface after a pulse of thermal energy is applied gradually transfers inside the sample. Figure 1 shows schematic drawing and the photograph of the PTT laboratory system. Pulsed thermal imaging may be used to examine all the solid materials that have reasonable emissivity (say >0.5). The maximum imaging spatial resolution on the surface may potentially reach the infrared wavelength in the $5\mu\text{m}$ range with currently available commercial optics (although spatial resolution may degrade rapidly with depth due to thermal diffusion). When pulsed thermal energy is applied, a thin layer of material on the surface is heated instantaneously to a high temperature. In the PTT system at Argonne, flash lamp source Balcar ASYM 6400 delivers a pulse of $6400\text{J}/2\text{ms}$ thermal energy to material surface. Heat transfer then takes place from the heated surface to the interior of the sample, resulting in a continuous decrease of the surface temperature. The infrared camera, with proper calibration, captures the surface temperature evolution during the entire thermal transient period. Argonne PTT system shown in Figure 1 employs FLIR SC 4000 IR camera operating in $3\text{-}5\mu\text{m}$ wavelength band with maximum frame rate of 420fps records surface temperature transients $T(x,y,t)$ with 320×256 pixels array. The acquired thermal-imaging data therefore consist of a series of 2D images of the sample's surface temperature at consecutive time instants. This data set can be expressed as $T(x, y, t)$, where T is the surface temperature, (x, y) is the surface spatial coordinate, and t is the time. It is obvious that $T(x, y, t)$ is a 3D data set in which the time t domain is related to the depth z domain within the test sample.

$$z = (\pi\alpha t)^{1/2} \quad (1)$$

Where

$$\alpha = k / \rho c_p \quad (2)$$

and k is thermal conductivity, c_p is specific heat, and ρ is density. In pulsed thermal imaging, the thermal excitation applied by flash lamps is typically uniform over a large surface area, which results in a predominantly 1D heat transfer in the depth direction. Therefore, most data-processing methods perform 1D analysis in the time domain, based on theoretical heat-transfer models, to retrieve depth-related information such as variation of material properties or presence of defects below each surface position. Because thermal-imaging data already have 2D spatial resolution in (x, y) , an 1D analysis for all surface the positions completes the evaluation of the entire sample volume $(x, y, z(t))$. Reconstruction algorithm described in [Sun 2016, Sun 2018] provides a 3-D representation of material thermal effusivity

$$e = (\rho c_p k)^{1/2} \quad (3)$$

Which is a measure how material exchanges heat with its surroundings.

Figure 1 – Principle of pulsed thermal tomography: (left) Schematic drawing (right) Photograph of actual laboratory system

2.2. COMSOL modeling of PTT principle

Qualitative explanation of PTT performance is provided in COMSOL visualizations of heat transfer in a metallic plate containing a cylindrical flat bottom hole. COMSOL computer simulations were performed with Heat Transfer module. A 6mm-thick stainless steel plate with 8mm diameter flat bottom cylindrical hole located 3mm below plate surface is shown in Figure 2. The left panel shows the front view of the plate, while the right panel shows cross-section of the side view of the plate. Figure 3 shows time-resolved frames of thermal pulse propagating through the plate. The sequence of frames shows temperature distribution in the transverse cross-section of the plate. A uniform thermal pulse is incident from the right side and propagates to the left.

Figure 2 – COMSOL model of metallic plate with cylindrical flat bottom hole in the center (left) Front view (right) Side view of the plate

The sequence of frames in Figure 3 are arranged with increasing time, as indicated by the blue arrows. Warm colors (yellow, red) correspond to higher temperatures, while cold colors correspond to lower temperatures. As seen in Figure 3, thermal pulse diffuses uniformly through the plate, until the flat bottom is encountered.

Figure 3 – COMSOL simulation of heat propagation through metallic plate with cylindrical flat bottom hole. Frame captures at different times show heat propagation through transverse cross-section of the plate.

Note that the overall temperature of the plate is decreasing with time. Starting from the third panel in Figure 3, thermal resistance due to metal/air discontinuity causes delay in diffusion of heat above the hole. This leads to formation of localized temperature “hot” spot on the plate front surface directly above the defect. As discussed above, the depth of the defect location can be estimated from the knowledge of thermal diffusivity of the material and the time it takes for the first appearance of the “hot” spot. The radius of the defect can be estimated from the thresholded size of the “hot” spot on the surface. Qualitatively, the size of the “hot” spot on the plate surface increases with time. Thus, the frames corresponding to the earliest appearance of the “hot” spot provide the best estimate of the flaw size. In addition, procedure for thresholding of the surface “hot” spot needs to be developed for achieving best estimate. For example, a common thresholding criteria is to define the radius as the set of points where the temperature decreases by a factor of $\exp(-1)$ relative to the maximum temperature point. These questions will be studied in more detail in the next phases of this project.

3. Development of Calibrated Defects in Metallic Specimens

3.1. Development of flat bottom holes in Stainless Steel 316 and Inconel 718 plates

Calibrated defects developed in this project for evaluation of PTT performance consisted of cylindrical flat bottom holes (FBH) of varying size and depth drilled in metallic plates. Producing FBH is a common approach to develop calibrated damage references for thermal tomography performance evaluation. One pattern of holes was designed for metallic plates made of high-strength stainless steel 316 (SS316) and Inconel 718 (IN718) alloys. A computer rendering of the pattern of holes is shown in Figure 4. Figure 5 provides a drawing with labels showing diameters and depths of the holes. Figure 6 shows the photograph of an SS316 plate with FBH. Note that there are two patterns of holes in the plates. Note that the holes diameter decreases along the lines parallel to the longer side of the plate, while the depth along each line is held constant. Along the lines parallel to the shorter side of the plate, the depth increases, while the diameter is fixed. Note that there are two patterns of FBH's on the plate: one with diameters 5,6 and 8mm and depths 2,3,4, and 5mm, and another one with diameters 1,2,3, and 4mm and depths 1,2,3 and 4mm.

Figure 4 – 3-D rendering of FBH pattern in SS316 and IN718 metallic plates

Figure 5 – Design of FBH of different diameters and depths relative to plate surface

Figure 6 – Photograph of FBH pattern in SS316 plate

3.2. Development of flat bottom holes in Stainless Steel 304, Nickel 200 and Hastelloy C276 plates

Another set of FBH was designed for metallic plates made out of lower strength grade stainless steel 304 (SS304), Nickel 200 (Ni200), and Hastelloy C276 (C276). The design of pattern of these FBH's is shown in Figure 7. A photograph showing the C276 plate with FBH is displayed in Figure 8. In this pattern, hole diameters are 1,2,4 and 8mm, while depths are 1,2,3,4,5 and 6mm. Along the lines parallel to the longer plate side, FBH diameter is fixed while depth decreases. Along the lines parallel to the shorter plate side, FBH depth is constant while the diameter decreases.

Figure 7 – Design of FBH of different diameters and depths relative to plate surface in SS304, Ni200, and C276 plates

Figure 8 – Photograph of FBH pattern in C276 plate

4. PTT Imaging of Calibrated Defects in High Grade Alloys

4.1. Imaging of flat bottom hole plates

The FBH metallic plates were imaged with PTT from the flat side of each plate. Figure 9 shows the photograph of the setup with the flat side of the plate facing the flash lamp and the IR camera. The back side of plate with visible FBHs is shown in the right panel of Figure 9. For better absorption of thermal energy, all specimens were spray-painted with washable graphite paint. Distribution of incident thermal pulse on the plate is not uniform because the flash light illuminates the metallic plate at an angle. To compensate for this, we have fitted the intensity distribution in the camera frame containing a flash with a polynomial, and then used this polynomial for correction of image intensity in every subsequent frame. The plates were imaged with 320x256 array of pixels at 200Hz resolution rate. The total imaging time to acquire frames for reconstruction of each plate is approximately 10seconds. In the grayscale images, brighter and darker areas indicate higher and lower effusivity, respectively.

Figure 9 – Imaging of FBH from flat side of the plate: (left) Front view (right) Rear view

4.2. PTT imaging of Stainless Steel 316 plate with flat bottom holes

Stainless steel 316 (SS316) is frequently used for manufacturing pressure vessel components in light water and advanced reactors because of the alloys high strength and resistance to corrosion [Kultgen 2018]. The SS316 plate was with thickness of 6.22mm (0.25in). produced with conventional metal fabrication techniques. FBH holes in the plate were created by drilling. Because of material high strength, the smallest hole which be created is 1mm diameter. Thermal diffusivity of the SS316 plate was first measured in transmission geometry to determine $\alpha=3.72\text{mm}^2/\text{s}$. This number agrees well with literature value of $\alpha=3.529\text{mm}^2/\text{s}$ [Kim 1975].

Figure 10 shows reconstructed images of larger FBH at different depths in the material. The left panel of Figure 10 shows the imaged area of the plate. The right panel shows reconstructed parallel plane slices estimated at 2mm, 3mm, 4mm, and 5mm depth. As expected, only the first column of FBH drilled at 2mm depth appear in the parallel place slice at 2mm depth. The column

of FBH drilled at 2mm and 3mm depth appear in the plane slice reconstructed at 3mm depth. The pattern continues with three and four columns of FBH appearing in the 4mm and 5mm depth plane slices, respectively. As expected, imaging contrast is better for larger FBH located closer to the surface of the plate. The smallest FBH in the imaged plate area with 5mm diameter can be seen as a faint signature in the 5mm depth reconstruction.

Figure 10 – Reconstruction of larger FBH in SS316 plate. (Left) Imaged area. (Right) Reconstructed parallel plane slices at 2mm, 3mm, 4mm and 5mm depths

Figure 11 shows vertical cross-section reconstructions obtained from the stack of parallel plane slices. The left panel of Figure 11 shows reconstructed parallel plane slice at 4mm depth with vertical lines labeled $i=58$, $i=124$, and $i=195$ (i and j correspond to the indices of individual pixels in the 320×256 imaging matrix of the camera). The vertical lines are drawn through FBH of decreasing size but located at the same depth. Corresponding vertical cross-section reconstructions labeled $i=58$, $i=124$, and $i=195$ with FBH's located at 2mm, 3mm, and 4mm depths, respectively, and are shown in the right panel of Figure 11. Note that the larger diameter hole (8mm) is located on the right side of the each of the vertical reconstruction cross-sections, and the size of the FBH decreases from right to left in the sequence of 8mm, 6mm and 5mm diameters. As expected, reconstruction contrast decreases with decreasing FBH size and increasing depth. Relative sizes of the FBH in the same cross-section slice can be seen to be decreasing right to left. Qualitatively, the FBH in the cross-section slice corresponding to $i=124$ appear to be deeper than the FBH in the cross-section slice corresponding to $i=58$. Similarly, the FBH in the cross-section slice labeled $i=195$ are deeper than those of the cross-section slice corresponding to $i=124$. Because of blurring

due to diffusion of the thermal pulse with depth, reconstructed FBH appear as truncated cone shapes.

Figure 11 – Reconstruction of larger FBH cross-sections in SS316 plate. (Left) Parallel plane slice at 4mm depth with vertical lines drawn through same-depth different size FBH (Right) Corresponding cross-section plane slices

Figure 12 shows reconstructions of parallel plane slices of smaller FBHs in the SS316 plate. The left panel of Figure 12 indicates the imaging area of the plate. The right panel of Figure 12 contains reconstructions of parallel plane slices at 1mm, 2mm, 3mm and 4mm depths. All FBH down to 1mm size are visible at 1mm depth place slice. At 2mm depth, holes down to 2mm size are clearly visible, and there is a faint signature of the 1mm-diameter FBH. At 3mm depth, the smallest visible FBH is the 2mm-diameter one. At 4mm depth, the 3mm FBH can be detected. Note that these are preliminary qualitative observations. With additional signal processing and thresholding, visibility of smaller size FBH might be enhanced.

Figure 13 shows vertical plane cross-sections reconstructions for the smaller FBH in SS316 plate. The left panel in Figure 13 displays parallel plane cross-section at 3mm depth, with vertical lines $i=58$, $i=108$, and $i=158$ (corresponding to the column labels of the camera 320x256 pixel array), drawn through FBH of different sizes located at the same depth. Corresponding vertical plane cross-section slices are shown in the right panel of Figure 13. As in the case of the larger FBH shown in previous figures, the larger FBH in each cross-section slice is on the right. The FBH's are arranged in a sequence of 4mm, 3mm, 2mm, and 1mm diameters. One can see that in each cross-section slice, the relative size of each cross-section decreases from right to left. The reconstruction of the smallest hole with 1mm diameter can be seen in the cross-section slice corresponding to 1mm depth. At 3mm depth, only the 4mm-diameter hole is visible. As in Figure 11, the shapes of reconstructed FBH's appear as truncated cones.

Figure 12 – Reconstruction of smaller FBH in SS316 plate. (Left) imaged area (Right) reconstructed parallel plane slices at 1mm, 2mm, 3mm and 4mm depths

Figure 13 – Reconstruction of smaller FBH in SS316 plate. (Left) Parallel plane slice at 3mm depth with vertical lines drawn through same-depth different size FBH (Right) Corresponding cross-section plane slices

4.3. PTT imaging of Inconel 718 plate with flat bottom holes

Inconel 718 (IN718) is used for manufacturing of components inside the pressure vessel as an alternative to SS316. The 7.4mm (0.3in) thick IN718 plate used in this project was produced with conventional metal fabrication techniques. FBH in the plate were created by drilling. Because of the material high strength, the smallest hole which could be drilled out is 1mm diameter. Transmission geometry measurement of was performed to determine thermal diffusivity to be $\alpha=2.82 \text{ mm}^2$ for this plate. Note that thermal diffusivity of IN718 plate is smaller than that of the SS316 plate. Therefore, quality of reconstruction for IN718 specimen is expected to be lower than what was observed for SS316 plate.

Parallel plane slice reconstructions of larger FBH's in the IN718 at various depths are shown in Figure 14. Left panel of Figure 14 shows the imaged area, which consists of larger FBH's in the IN718 plate. The right panel of Figure 14 shows parallel plane slices at 3.2mm, 4.2mm, 5.2mm, and 6.2mm depth. The first three reconstructed images show clearly identifiable FBH's, while the last reconstruction at 6.2mm depth is becoming difficult to interpret. The smallest FBH of 5mm size can be seen in the 5mm depth plane slice.

Figure 14 – Reconstruction of larger FBH in IN718 plate. (Left) Imaged area. (Right) Reconstructed parallel plane slices at 3.2mm, 4.2mm, 5.2mm and 6.2mm depths

Reconstructions of cross-section plane slices of larger FBH are shown in Figure 15. The left plane of the figure shows parallel plane slice at 5.2mm depth with vertical lines $i=54$, $i=126$, and $i=194$ (corresponding to pixel column index in the 320x256 array) drawn through FBH of decreasing

size but located at the same depth. The right plane of Figure 15 shows corresponding vertical cross-section slices reconstructions. The cross-section labeled $i=54$ shows reconstructions of FBH of size 8mm, 6mm, and 5mm located at depth 2mm. The cross-sections $i=126$ and $i=194$ shows reconstructions of the same size FBH located at depths 3mm and 4mm, respectively. In each cross-section slice, the size of FBH is decreasing right to left. The smallest 5mm-diameter hole is visible at 3mm depth ($i=126$). At 4mm depth, the 5mm-diameter FBH has very faint signature. Compared to similar size and depth FBH for SS316, the images for IN718 are slightly more blurred. This is to be expected since thermal diffusivity of IN718 is smaller than that of SS316.

Figure 15 – Reconstruction of larger FBH cross-sections in IN718 plate. (Left) Parallel plane slice at 5.2mm depth with vertical lines drawn through same-depth different size FBH (Right) Corresponding cross-section plane slices

Figure 16 shows reconstructions of smaller FBH in IN718 plate. The left panel shows the imaged area of the plate. The right panel shows the imaged area of the plate. The right panel shows reconstructed parallel plane slices at 2.2mm, 3.2mm, 4.2mm, and 5.2mm depths. The smallest hole with 1mm diameter is faintly visible in the 2.2mm depth plane slice. The plane slice at 3.2mm depth show the first three columns of the FBH. The smallest visible FBH is the one with 2mm diameter. Reconstruction at 4.2mm depth shows blurry images of holes, with the smallest FBH of 3mm diameter. The plane reconstructed at 5.2mm shows faint indications of FBH with 3mm and 4mm diameters.

Figure 17 shows vertical cross-section reconstructions of the smaller FBH in the IN718 plate. Parallel plane slice at 3.2mm depth is shown in the left part of the figure with vertical lines labeled $i=58$ and $i=108$ drawn through the FBH of decreasing size, which are located at the same depth in the plate. As in the prior discussion, i is the index of the pixels column in the 320x256 array. Right panel of Figure 17 contains corresponding vertical cross-section reconstructions. The

images labeled $i=58$ and $i=108$ correspond to FBH's located at 1mm and 2mm depths, respectively. The images show vertical profiles of FBH with diameters 4mm, 3mm, 2mm, and 1mm, with the FBH size decreasing from right to left. Because of blurring with increasing depth, the shapes of FBH cross-sections appear to be dome-shaped. Qualitatively, the images provide enough information to detect decrease in FBH sizes. The smallest FBH which can be observed is the 2mm-diameter hole. As mentioned above, the quality of reconstruction of FBH in IN718 plate is lower than that in the SS316 plate because of lower value of thermal diffusivity on IN718.

Figure 16 – Reconstruction of smaller FBH in IN718 plate. (Left) Imaged area. (Right) Reconstructed parallel plane slices at 2.2mm, 3.2mm, 4.2mm and 5.2mm depths

Figure 17 – Reconstruction of smaller FBH cross-sections in NI718 plate. (Left) Parallel plane slice at 3.2mm depth with vertical lines drawn through same-depth different size FBH (Right) Corresponding cross-section plane slices

5. PTT Imaging of Calibrated Defects in Lower Grade Alloys

5.1. PTT imaging of Stainless Steel 304 plate with flat bottom holes

Stainless steel 304 (SS304), which has lower corrosion is frequently used for manufacturing components outside of the reactor pressure vessel, such as piping [Kultgen 2018]. Transmission of flash light pulse through 9.45mm (0.37in) thick SS304 plate determined that $\alpha=3.89\text{mm}^2/\text{s}$. This number is fairly close to the literature value of $\alpha=3.237\text{mm}^2/\text{s}$ [Kim 1975]. Because of similar values of thermal diffusivity of SS316 and SS304, the quality of reconstructed PTT images is expected to be comparable.

Figure 18 shows reconstructions of FBH at smaller depths in the SS304 plate. Left panel of Figure 18 shows the imaged area of the plate. Right panel shows parallel plane slices reconstructions at 1mm, 2mm, and 3mm depths. The smallest FBH with 1mm diameter can be seen in both 1mm and 2mm depth plane slices. Vertical plane cross-section reconstructions similar to those presented in Section 4 were obtained for SS304 plate, but are not presented in this report.

Figure 19 shows reconstructions of FBH at larger depth in the SS304 plate. Left panel shows the imaged area. The right panel shows reconstructed parallel plane slices at 4mm, 5mm and 6mm depth. The FBH with diameters 4mm and 8mm can be seen in the images up to 6mm depth. However, smaller holes are difficult to distinguish.

Figure 18 – Reconstruction of smaller depth FBH in SS304 plate. (Left) Imaged area. (Right) Reconstructed parallel plane slices at 1mm, 2mm, and 3mm depths.

Figure 19 – Reconstruction of larger depth FBH in SS304 plate. (Left) Imaged area. (Right) Reconstructed parallel plane slices at 4mm, 5mm, and 6mm depths

5.2. PTT imaging of Nickel 200 plate with flat bottom holes

Nickel 200 (NI200) is a lower strength alloy than IN718. As a result, NI200 is used less frequently in nuclear applications. In this project, PTT of NI200 is investigated for comparison of reconstruction with other alloys. Transmission measurement of thermal pulse through 10.08mm (0.4in) NI200 was used to determine thermal diffusivity $\alpha=20.69\text{mm}^2/\text{s}$. This is a much higher value than those of SS316, SS304 and NI718. Therefore, reconstruction quality at greater depth is expected to be better for NI200 compared to other alloys.

Figure 20 shows reconstructions of smaller depth FBH in the NI200 plate. The left panel of Figure 20 shows the area of the plate which was imaged. The right panel shows reconstructed parallel plane slices at 1.3mm, 2mm, and 3mm depths. The FBH with 2mm diameter are clearly visible at all depths. However, the smallest FBH with 1mm diameter is difficult to detect in the plane slice images. This finding is not consistent with relatively high contrast of observed for 2mm-diameter FBH, and needs to be studied further during next quarter of the project.

Figure 21 shows reconstructions of larger depth FBH in NI200 plate. The left plane of the figure shows the imaged area of the plate. The right plane shows reconstructed parallel plane slices at 4mm, 5mm and 6mm depths. FBH with 4mm and 8mm diameters can be seen at all depths. FBH with 2mm diameter has a faint signature in the 4mm-depth plane slice. Smaller FBH are difficult to observe in the images.

Figure 20 – Reconstruction of smaller depth FBH in NI200 plate. (Left) Imaged area. (Right) Reconstructed parallel plane slices at 1.3mm, 2mm, and 3mm depths

Figure 21 – Reconstruction of larger depth FBH in NI200 plate. (Left) Imaged area. (Right) Reconstructed parallel plane slices at 4mm, 5mm, and 6mm depths

5.3. PTT imaging of Hastelloy C276 plate with flat bottom holes

Hastelloy C276 is a high-temperature alloy frequently used for manufacturing high-temperature molten salt reactor components. Transmission of thermal pulse through 6.65mm thick C265 plate was used to determine thermal diffusivity $\alpha=2.67\text{mm}^2/\text{s}$. This value is smaller than those of SS316, SS304 and NI200, and comparable to that of IN718. Therefore, quality of reconstructed images is expected to be similar to those of the IN718 plate reconstructions.

Figure 22 shows reconstructions of parallel plane slices of smaller depth FBH. The left panel shows the imaged area of the plate. The right plane shows reconstructed parallel plane slices at 1mm, 2mm and 3mm depths. The smallest FBH with 1mm diameter is clearly visible in 1mm depth plane slice, and weakly visible in 2mm depth slice. The 2mm and 4mm diameter FBH are visible in the 3mm depth plane slice. High-contrast images of small FBH in C276 are not completely consistent with the small value of thermal diffusion, and needs to be investigated further.

Figure 22 – Reconstruction of smaller depth FBH in C276 plate. (Left) Imaged area (Right) Reconstructed parallel plane slices at 1mm, 2mm, and 3mm depths

Figure 23 shows parallel plane slices of larger depth FBH in C276 plate. The left plane of the figure shows the imaged area of the plate. The right plane of the figure shows reconstructions of parallel plane slices at 4mm, 5mm, and 6mm depths. The FBH's with 4mm and 8mm diameters are visible in the in the plane slices at 4mm and 5mm depths, while no information can be obtained from the plane slice at 6mm depth.

Figure 23 – Reconstruction of larger depth FBH in C276 plate. (Left) Imaged area (Right) Reconstructed parallel plane slices at 4mm, 5mm, and 6mm depths

6. PTT Imaging of Additively Manufactured Inconel 718 Nozzle Plate

Nozzle plate was produced at Westinghouse using direct laser sintering (DLS) commercial additive manufacturing metal printer. The plate is 17mm (2/3in) thick with approximately 8in by 8in cross-section. The plate is almost twice thicker than the plates with FBH discussed in Section 3. A photograph of the nozzle plate is shown in Figure 24. The nozzle plate contains a large number of through holes. The nozzle plate was imaged with PTT to evaluate the capability of the method to scan thicker specimens. In addition, several options for visualization of 3-D data were explored.

Transmission measurement determined thermal diffusivity to be $\alpha=6.25\text{mm}^2/\text{s}$. This number is larger than that for IN718 plate discussed in Section 4.3. The explanations for observation of larger thermal diffusivity of the nozzle plate could be because additively manufactured IN718 has different thermal properties than conventionally manufactured IN718. In addition, the through holes in the nozzle plate could have an impact on transmission measurements of thermal conductivity.

Figure 24 – Photograph of additively manufactured IN718 nozzle plate

Parallel plane reconstruction slices at estimated depths of 1mm, 2mm, 3mm, and 4mm are shown in Figure 25. The dark concentric circles in the figure correspond to spacer anchors, which are used for alignment of the plate during additive manufacturing process.

Figure 26 shows zoomed-in reconstruction smaller area of IN718 plate. The left plane of the figure shows a parallel plane reconstruction at 1mm depth. Two horizontal lines labeled $j=80$ and $j=165$ correspond to the indices of rows of the 320×265 array of pixels in the imaging camera. Vertical cross-section plane reconstructions corresponding to lines $j=80$ and $j=165$ are shown in the right plane of Figure 26. The first image corresponding to $j=80$ line shows vertical cross-section profiles of two equidistant holes. The second image corresponding to $j=165$ line shows vertical

cross-section profiles of two holes separated by a longer distance as compared to the three holes in the first image. An important feature is that front top and back surfaces of the IN718 nozzle plate are distinguishable in both images. This shows that PTT is capable of imaging through 17mm thick plate. Total imaging time was 20.93s, which is almost twice as long the time needed to image the plates discussed in Sections 4 and 5.

Figure 25 – Reconstruction of parallel plane slices of NI718 nozzle plate at 1mm, 2mm, 3mm and 4mm depths

Additional tasks included exploring new options for 3-D data visualization and presentation. Figure 27 shows a screen capture of ImageJ software, in which the parallel plane slices and vertical cross-sections were assembled into a 3-D viewing format. Warmer and colder colors indicate higher and lower effusivity, respectively. The cursor shown by the cross-hairs in Figure 27 allows the user to view the parallel plane slices in the main window by diving into the stack of frames. For the cursor location in the main window, the horizontal line through the parallel plane slice selects a depth-resolved cross-section plane, which can be viewed in the smaller window at the bottom window. The vertical line of the cursor in the main window selects another depth-resolved cross-section plane, which can be viewed in a smaller right window on the right. For the graphic in Figure 27, the horizontal line of the cursor cross-hairs passes through three holes and the spacer. Depth-resolved cross-section profile of these can be seen in the small window at the bottom. The vertical line of the cursor cross-hairs passes through seven holes and grazes the spacer. Depth-resolved cross-section profile of these can be viewed in the small window on the right. The cross-hairs in the small windows at the bottom and on the right correspond to the parallel plane slice depth and horizontal/vertical position as selected by the user in the main viewing window.

Figure 26 – Zoomed-in reconstruction of IN718 nozzle plate. (Left) Horizontal plane reconstruction at 1mm depth. (Right) Vertical cross-section plane reconstructions

Figure 27 – Screen capture of 3-D imaging of Inconel 718 nozzle plate with ImageJ software package.

Figure 28 shows another option of 3-D data visualization of the IN718 nozzle plate using MATLAB software. The 3-D data is visualized via projections on three orthogonal x-y, x-z and y-z planes. The planes can be moved independently in 3-D space by the user. Figure 28 shows one particular configuration of three orthogonal planes. Warmer and colder colors indicate higher and lower effusivity, respectively.

Figure 28 – 3-D imaging of NI718 nozzle plate reconstructions with MATLAB

7. Conclusions

Pulsed thermal tomography (PTT) is a non-destructive method for 3-D imaging and detection of flaws in material based on heat transfer characteristics. The method involved non-contact measurements, with flash lamp depositing heat on material surface, and infrared (IR) camera measuring transient material surface temperature. Reconstruction algorithms provide 3-D information about the material. PTT is well suited for in-service examination of additively manufactured materials because of non-contact mode of operation and small system size. Typical defects encountered in additively manufactured metallic parts include regions of high porosity and low density due to manufacturing process flaws, as well as delamination and cracks which could develop while the part is in-service. Such defects should provide high contrast to imaging with PTT because of strong dependence of thermal conductivity and effusivity on material density.

The objective of this report is to provide initial evaluation of PTT performance in detecting calibrated flaws in reactor structural materials. Preliminary COMSOL models were developed to conduct computer simulations of PTT. In the experimental studies, high strength Stainless Steel 316 and Inconel 718 alloys were considered, as well as lower grade Stainless Steel 304, Nickel 200, and Hastelloy C276. Specimens investigated in this report consisted of approximately 1/4in-thick plates made out of these alloys using conventional manufacturing methods. The calibrated defects were created in the form of flat bottom holes (FBH) drilled in metallic plates. The diameters of FBH's varied from 1mm to 8mm, and their depths below the plate flat surface varied between 1mm and 6mm. The size of the smallest FBH was limited to 1mm because conventional mechanic drills were used for creating the holes. PTT imaging results have shown that 1mm-diameter FBH located 1mm and 2mm below the surface were detectable. Larger size FBH were detectable at greater depth. For example, 6mm-diameter FBH could be detected at 8mm depth. Image contrast varied slightly between the specimens, with the best reconstructions obtained in SS316 and C276 plates. In addition, a 2/3in-thick Inconel 718 nozzle plate produced with additive manufacturing method was imaged with PTT. It was shown that PTT can scan through the plate in approximately 20s. Several modes of 3-D data visualization were explored, including using ImageJ and MATLAB software packages.

Next phase of the project work will investigate detection of imprinted flaws in additively manufactured SS316 and IN718 metallic specimens. In addition, imaging of smaller FBH will be investigated by drilling sub-mm holes using electrical discharge machining (EDM) drill. Further, preparations will be made for development of compact PTT system for qualification at the MIT reactor viewport.

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