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The relationship between In-Process Quality Metrics & Computational Tomography

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Introduction:

The drive to certify and qualify additively manufactured metal parts is heralding new methods of quality assurance that will ultimately allow AM end users to take the much needed “leap of faith” that is required to foster confidence in AM. Sigma labs has developed such a methodology that mines and identifies thermal signatures of the melt pool disturbances and respective discontinuities using emission spectroscopy. Thermal signatures are defined as In-process quality metrics™ (IPQMs ®) that indicate process anomalies and inconsistencies. The evolution of thermal signatures advances the digital thread that is much needed by certification and standard authorities.

Producing a high-quality metal laser powder bed fusion part relies on controlling many input variables. For the most demanding applications, like aerospace and defense, there is still uncharacterized variation in the process which leads to expensive and lengthy post-process part validation. Using Co-Axial Planck Thermometry provides a verified thermal signature in both temperature and coordinates.

The In-process quality metrics™ (IPQMs ®), Thermal Emission Density (TED™) and Thermal Emission Planck (TEP™) are non-destructive analysis methods which allow the user to see internal thermal signatures and melt pool disturbances. TED™ is representative of the input process parameters and material response. TEP™ is representative of the temperature of the region of energy deposition. Both IPQMs® are calculated automatically and are available during the process and immediately after build completion.

Computational Tomography (CT) makes use of high energy X-Ray radiation to allow a user to see the internal structure of a part without destructive testing. Key uses of CT within industry have been metrology, flaw detection and failure analysis[1]. Currently CT is a tried and trusted inspection method for high risk additive manufactured parts. Accurate interpretation of CT is complicated by geometric effects such as beam hardening, material opacity to X-ray radiation and beam edge defocusing. For novel geometries special care needs to be taken with respect to fixturing the parts, orienting the parts relative to the beam, and choosing the appropriate X-ray energy. For additive manufacturing production this adds considerable cycle time, cost and is a limiter to adoption.

In this paper we show how the combination of IPQM® and CT enriches the user’s understanding of flaw detection and reduces risk in parts that are not CT inspected. Lastly, we introduce a framework for using CT results to establish confidence in IPQMs® as a complementary quality standard for part qualification.

In-Process Data Structure and CT Data Structure

CT data is often provided in a volumetric format, often a stack of images which represents the X-Ray intensity for a given volume. IPQM data is readily comparable to CT data because it also is a stack of images representing data values for a given volume. Data obtained from the PrintRite3D system has a spatial resolution fixed in the X&Y planes but variable resolution depending of the layer height used during the process. For the data presented in this paper, the layer thickness was 30µm so the IPQM data had a spatial resolution of 100x100x30µm. The CT data was collected with a spatial resolution of 90x90x90µm.

Hardware:

Co-Axial Planck Thermometry is implemented by directing relevant light from the build process to a series of photodetectors using a system of mirrors and lenses seen in Figure 1.

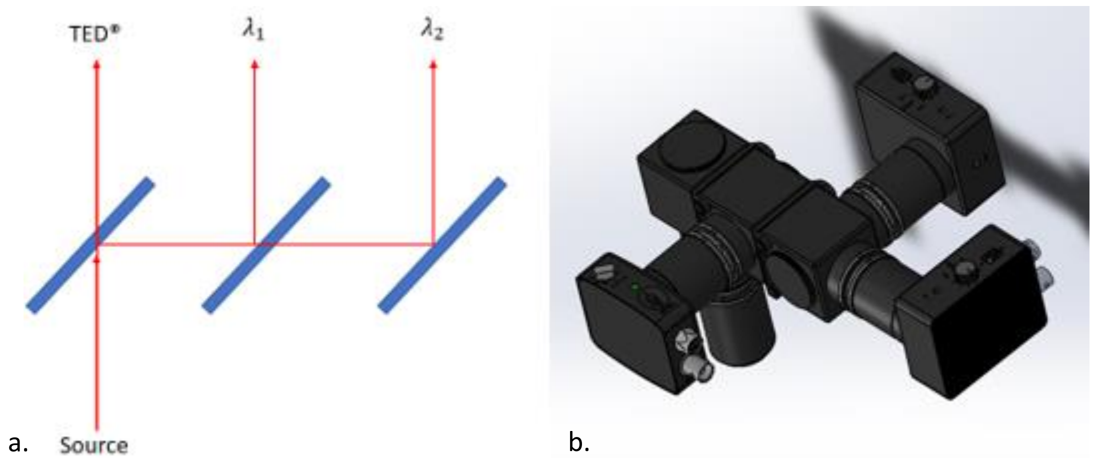


Figure 1: a, Co-Axial Planck Thermometry optics diagram. b, Mechanical design

Experimental Set Up:

All parts were built on an EOS M290 using Praxair Ti64 alloy. The part is representative of a topology optimized bracket, requiring extensive support structures. The in-process data was collected using PrintRite3D software. Two parts were built, one where the build conditions lead to a crack in the bracket arm, and another where the conditions were nominal, and no crack propagated.

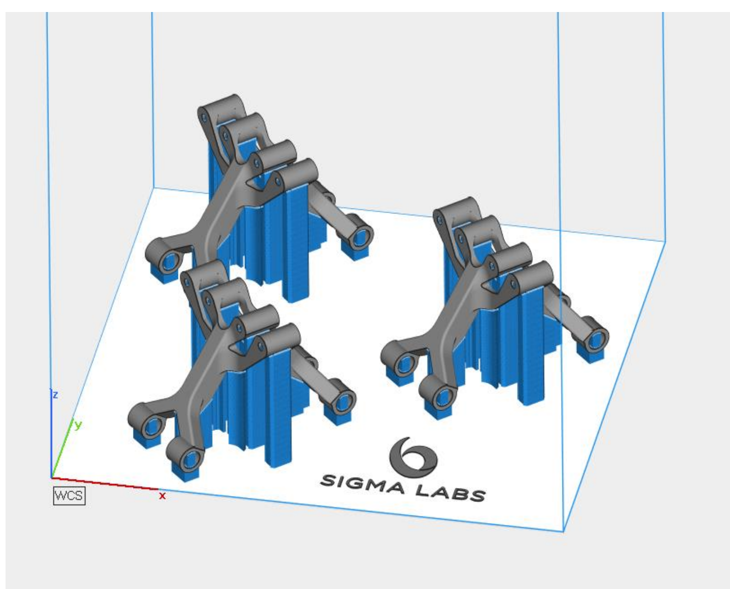


Figure 2: Build Layout

Results:

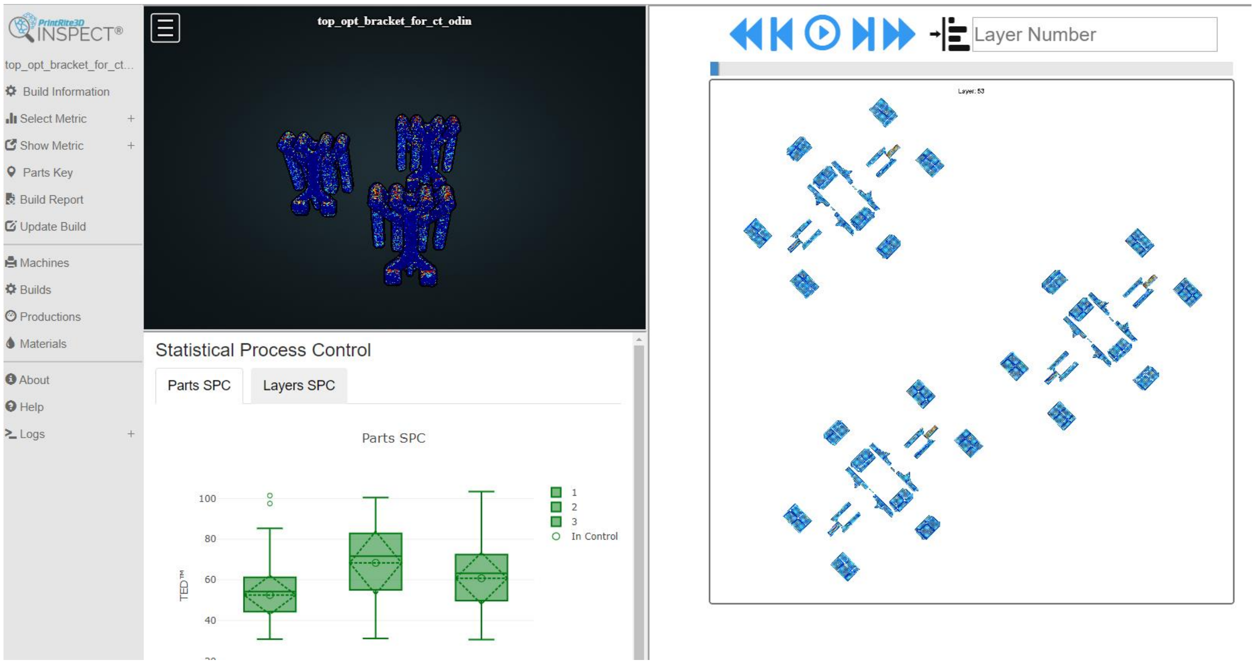


Figure 3: Screenshot of build process collected by PrintRite3D

In addition to the automatically performed standard analysis, stacks of images were obtained for each IPQM®. This analysis focuses mainly on the IPQMs, TED, TEP and their derivatives, TED Sigma and TEP Sigma. Image stack analysis is identical for IPQM and CT as shown below. First step for both processes is to load the image stack and then threshold the data to reduce the dataset to only the volumes containing part information, as shown in figure 3 below.

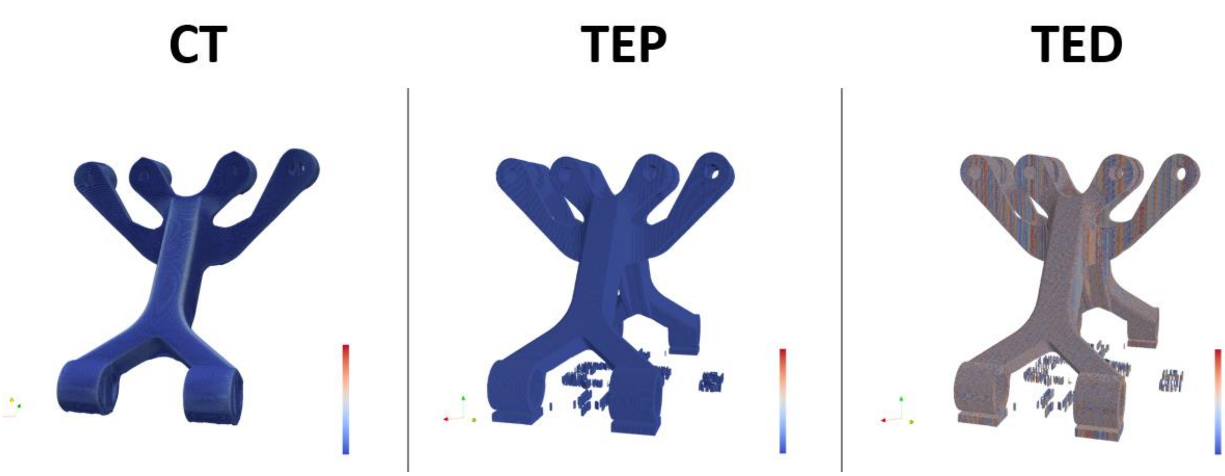


Figure 3: Screenshot of CT, TEP and TED datasets spatially aligned

Two cross-sectional slices were obtained for the CT, TED, TED Sigma, TEP and TEP Sigma datasets. The slice locations were selected around a surface crack in one of the parts shown in figure 4 below.

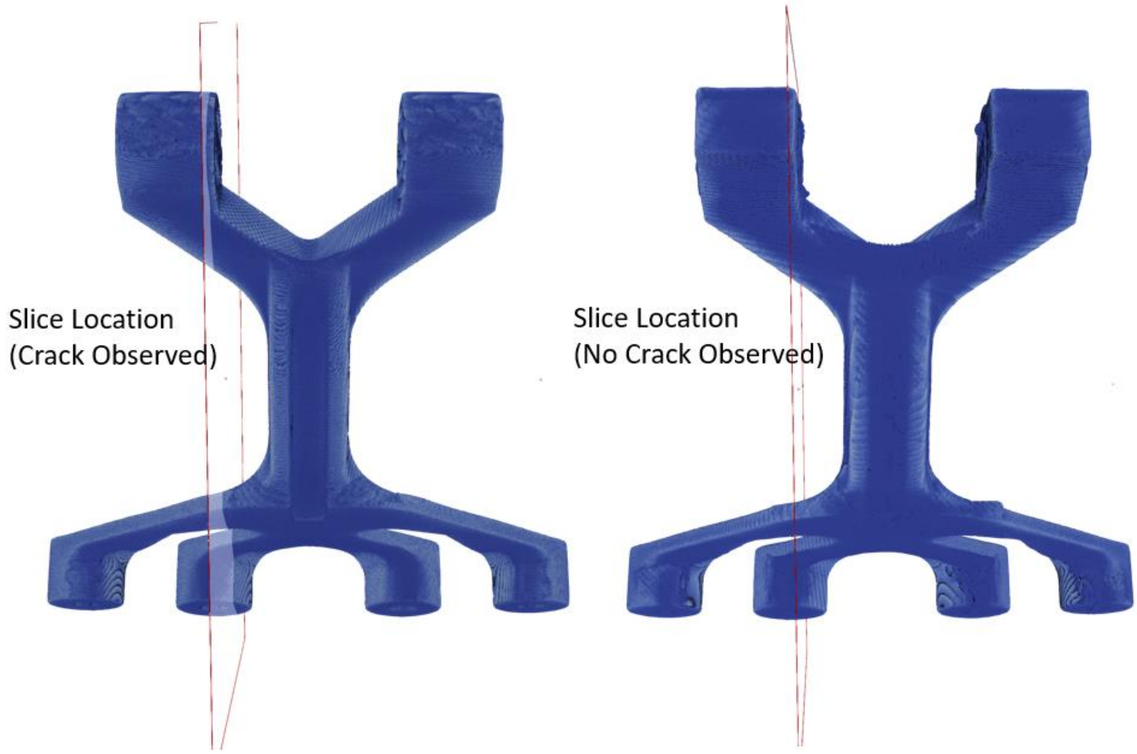


Figure 4: Screenshot of CT dataset with slice locations identified

The crack is circled in the CT cross-section shown in figure 5 below. It is representative of a critical to quality defect that can dramatically affect the performance of a part.

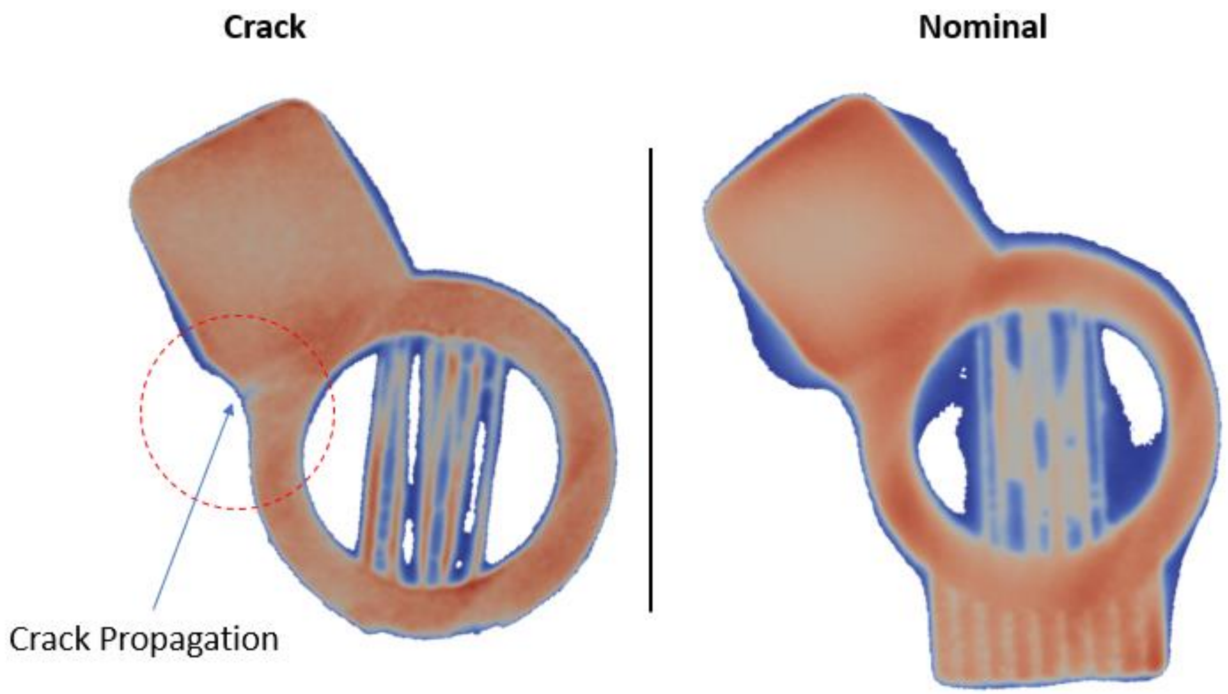


Figure 5: Screenshot of CT dataset slices, part with crack (left), corrected part (right)

The crack morphology in the part is easily identified visually as the circled region that penetrates the body of the part, as shown in figure 5. Note the variation in intensity as a function of part geometry; this is due to insufficient X-ray penetration into the substrate, also known as beam hardening. Also note that this beam hardening occurs at the crack region, hindering the analysis. This technique is susceptible to multiple types of artifacts aside from beam hardening, such as noise, Compton scattering, streak artifacts, ring artifacts and partial volume effect.[2] Thus, interpretation of CT results requires detailed background knowledge, experience with the process and understanding of the properties of the material.

The in-process metrics were sliced along the same plane and analyzed in the same way as the CT data.

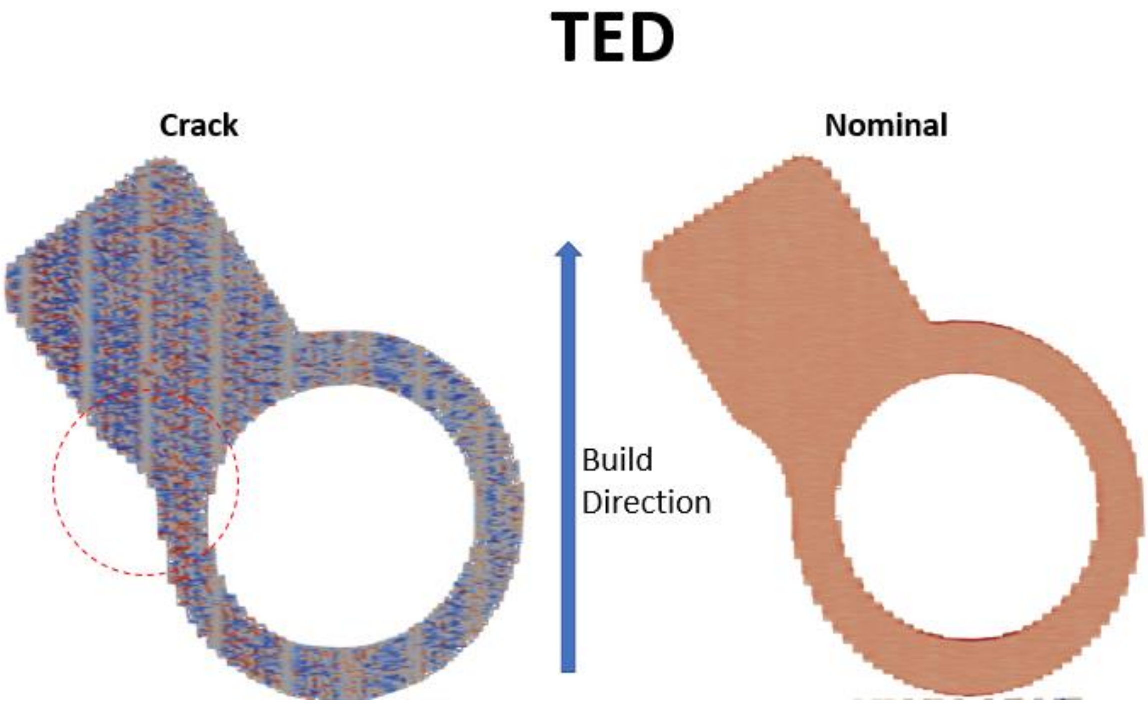


Figure 5: Screenshot of TED dataset slices

TED is representative of the input process parameters and/or material response. Note the TED values in the slice to the left vary in intensity significantly more in TED for the nominal slice to the right. The input parameters were different for the cracked part on the left compared to the part on the right. Input parameter changes such as laser hatch spacing lead to the characteristic vertically aligned stripes on the left.

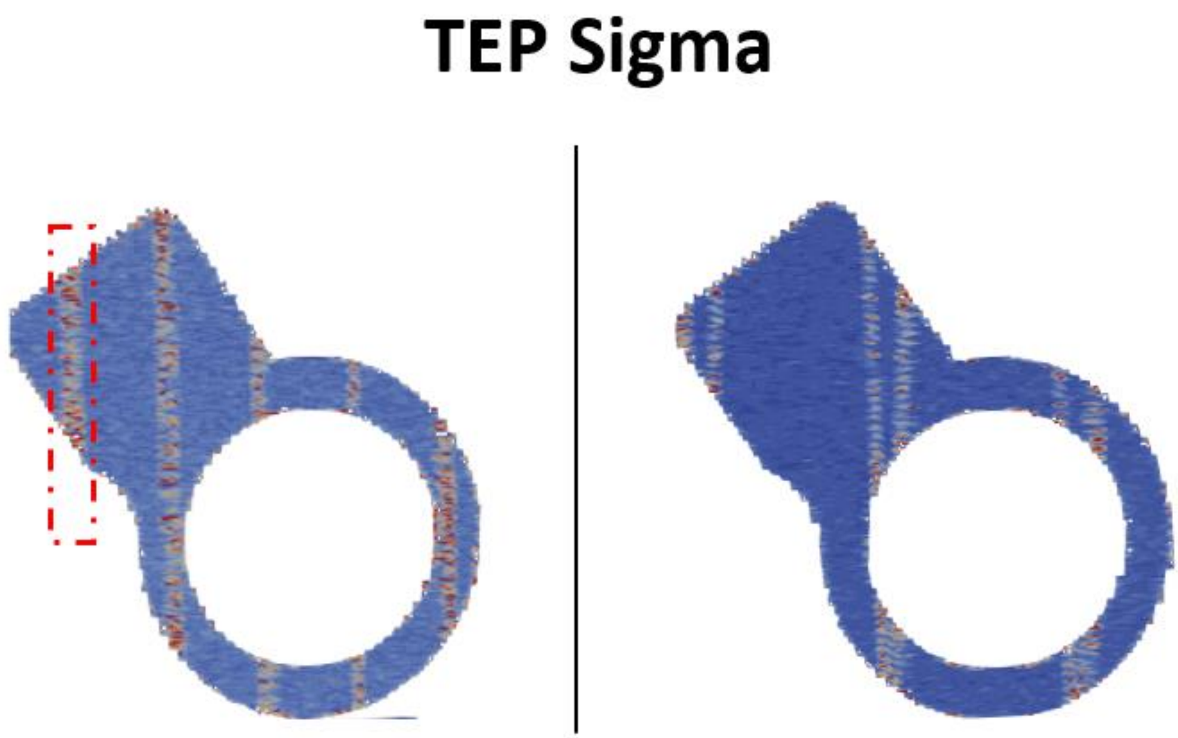


Figure 6: Screenshot of TEP Sigma dataset slices

Note the shade of TEP Sigma on the left slice is significantly lighter than for the slice on the right. This shows the left slice has more thermal variation for the entire slice. High thermal variation is associated with residual stress and linked to crack formation. Also note the highlighted vertically aligned regions of high (reddish) TEP Sigma values; these regions correspond to locations of laser stripe overlap.

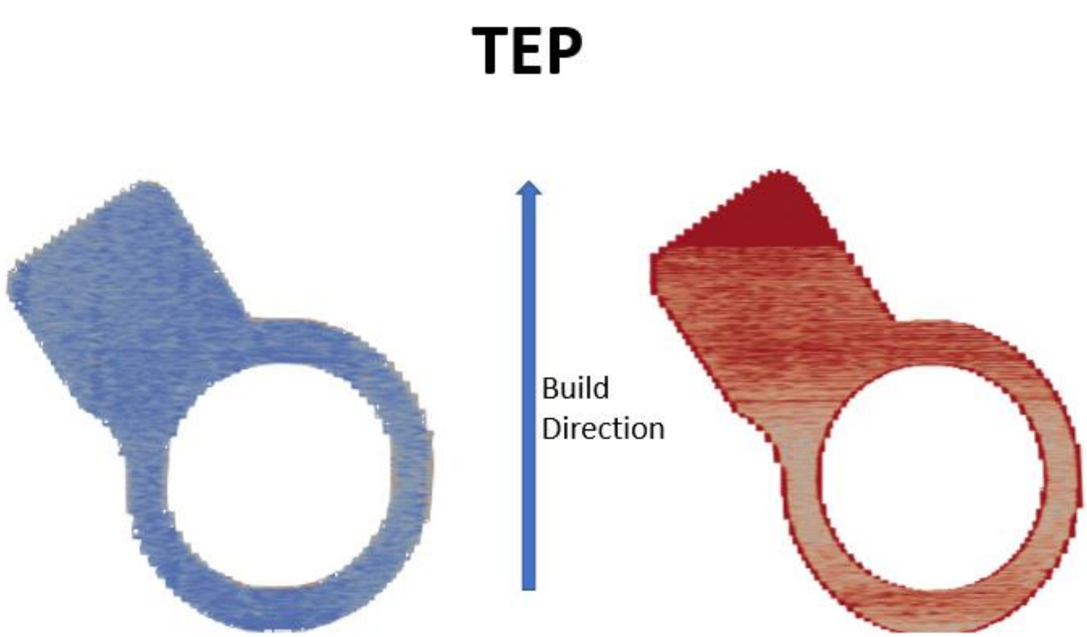


Figure 5: Screenshot of TEP dataset slices

Note the clear difference in color between the left slice and the right in Figure 5. TEP is representative of the temperature of the region of energy deposition. One can infer that the temperature for the left region was consistently lower.

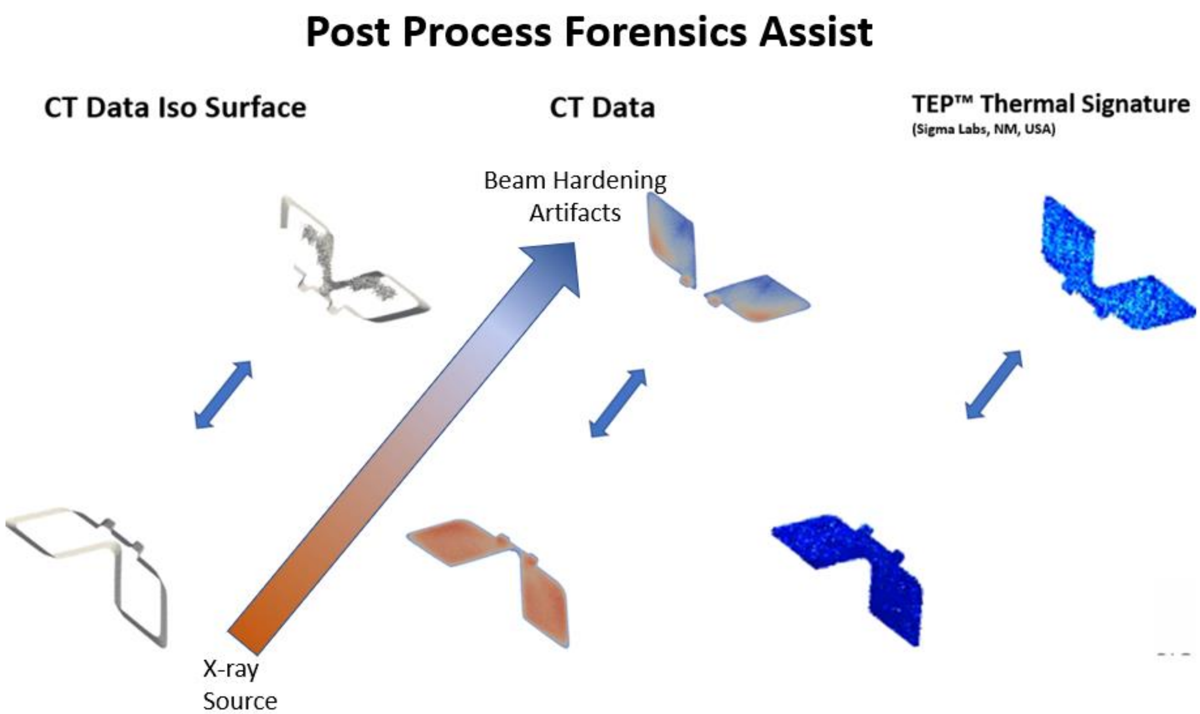
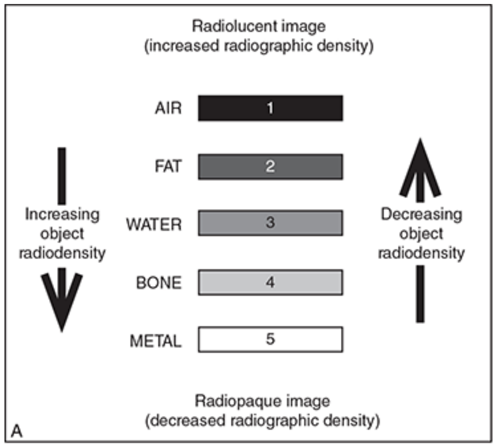


Figure 6: Comparison of Iso-Contour CT Data (left), CT Intensity (center), TEP (right)

An additional slice location was also analyzed, the location of the slice is shown in Figure 6 above. This slice highlights the limitations of CT scanning strategy with respect to part geometry. An Iso-contour is shown on the far left. This represents portions of that data that are at the same value. A specific value was chosen that normally represents the exterior of the part. Because the iso-contour goes into the body of the part in to top section and not the bottom, this shows insufficient X-ray penetration for the top section. Because of the nature of how we collect IPQMs, artifacts resulting from cross section thickness that appear in CT do not contaminate the IPQM data. Therefore, we know the variation in IPQM is attributable to thermal variation in the part. The TEP non-uniformity of one part versus the other in the figure above is indicative of a thermal signature. Radiodensity, the opacity to the X-ray portion of the electromagnetic spectrum, is high for metals compared to most materials, as shown in Figure 7 below.



Source: Lynn N. McKinnis, Michael E. Mulligan: *Musculoskeletal Imaging Handbook: A Guide for Primary Practitioners*: www.FADavisPTCollection.com

Figure 7: Radiolucent/radiodensity of various materials

Radiodensity represents a unique challenge to the additive manufacturing industry compared to other industries. Medical imaging generally deals materials/tissue of low radiodensity and consistent geometries. Additive manufacturing deals with materials that have very high radiodensity and can have widely varying and complicated geometries with internal features.

Conclusions:

The complementary nature of CT and IPQM technologies as inspection methods is clearly demonstrated in the cross-section comparisons. The inherent variation in CT as a function of geometry is not present in the IPQM data, allowing more meaningful interpretation of CT results and intuitive understanding of what is a real defect and what is X-ray beam hardening. The thermal signatures presented in both TEP and TED show the conditions that lead to the CT defects observed. CT and IPQM assist the user for finding regions for detailed inspection. The two processes together provide the user with a complete picture of what flaws are in the part and what conditions during the process lead to the flaw propagation. This facilitates focusing of post process inspection resources and provides a clear path to the gradual reduction in post process inspection as confidence increases in the use of IPQM thermal signatures. Specific IPQM thermal signatures can be used to help one optimize part design, decide which parts to send for CT analysis and finally, understand the conditions that allowed the flaw to occur while it was being produced.

References:

1. *Evans, Ll. M.; Margetts, L.; Casalegno, V.; Lever, L. M.; Bushell, J.; Lowe, T.; Wallwork, A.; Young, P.; Lindemann, A. (2015-05-28). "Transient thermal finite element analysis of CFC–Cu ITER monoblock using X-ray tomography data". Fusion Engineering and Design.* ***100****: 100–111. doi:10.1016/j.fusengdes.2015.04.048. Archived from the original on 2015-10-16.*

2. Herman, G. T., Fundamentals of computerized tomography: Image reconstruction from projection, 2nd edition, Springer, 2009