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X-ray computed tomography of a titanium aerospace investment casting

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ABSTRACT

This case study demonstrates the type of non-destructive analysis possible using X-ray micro computed tomography (microCT) for a titanium aerospace investment casting of 225 mm in its longest axis. The advantages of the method are highlighted while the limitations are also discussed. Recently the method has become more accessible and affordable due to multi-user service facilities and the analysis has become simpler due to software and hardware improvements. This case study demonstrates a typical analysis including defect detection, wall thickness and part to CAD comparison, which can be done in less than 4 h, while simpler results are possible in under 1 h. This will be particularly useful for industries requiring quick but detailed non-destructive analysis.

Introduction

The X-ray microCT technique has been applied in industrial applications since the early 1990s, see for example an article by Bossi and Georgeson [1]. Since then the systems have evolved, as have the computing power of analysis workstations. MicroCT has since become a standard non-destructive test method for analyzing high-value components or to optimize production processes. Various names are used to describe the same technology: industrial CT, microCT, X-ray tomography, X-ray scanning, CT scanning. There are relatively few reported examples of how powerful this technology is for routine analysis and how simple the analysis procedure is, when using commercial systems and commercial analysis software. Some examples are reported by Simon and Sauerwein [2] and Wells [3] for light metal castings and though not recent, demonstrate clearly the potential of the method. Reinhart [4] demonstrates the application of software to industrial CT analyses with some details of the software operation. Besides automated analysis for quality inspections, industrial CT is also used widely for dimensional metrology applications, as explained by Kruth [5]. There have been numerous materials characterization studies using X-ray CT especially at very high resolution, see for example Kastner et al. [6], but its application to macroscale samples in the 100 mm range is not as widely reported and not always understood. A recent review article covering the various recent applications of industrial CT is given by Maire and Withers in [7].

The practical use of X-ray computed tomography is limited by the cost of ownership of the systems, but as microCT service facilities become more widely available, the method is set to grow for non-destructive analysis of castings in particular. Traditional non-destructive test methods such as radiographic testing and ultrasound can be used to detect internal defects

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successfully but some of the advantages of X-ray tomography are the ability to visualize all internal defects in full 3D with high detail detectability, see the shapes and sizes of the defects in relation to the features of the object, do automatic defect analysis, wall thickness analysis and part-to-CAD or part-to-part comparisons. Virtual sectioning of the sample at any direction allows self-inspection by the quality testing engineer. It is also possible to analyze components before and after treatment or at different stages of manufacturing or even different stages in the life cycle of the component (e.g. monitoring wear of component), due to the non-destructive nature of the analysis. This can be done as standard analyses in a short period of time: typically a high quality scan and full detailed analysis would require 3–4 h, at a current commercial rate of US$120 per hour at the Stellenbosch CT facility, while reduced quality and larger batches can be done at lower rates. The aim of this paper is to demonstrate the type of analysis possible and demonstrate how it can be used effectively for a practical example: a titanium aerospace casting.

Material and method

In this work, a titanium aerospace investment casting was analyzed by X-ray micro Computed Tomography (X-ray microCT). The geometry cast and evaluated was supplied by Boeing, and was supplied to CSIR as a design file. This geometry is used to benchmark titanium casting processes and suppliers against aerospace standards. Key features of interest are internal pockets, lugs, and varying thicknesses. Typical evaluations are dimensional, internal soundness, surface finish, and mechanical properties. The sample was supplied to the Stellenbosch University CT Scanner Facility for analysis.

The sample dimensions were $225 \times 120 \times 75$ mm^3 at its widest points and cast in a titanium alloy.

X-ray CT scans were done using a General Electric Phoenix V|Tome|X L240, using 220 kV and 250 µA for X-ray generation, including beam filters of 1 mm tin and 0.1 mm copper, at a resolution of 158 µm. X-ray projection images were recorded at 500 ms per image, with 2000 images in one slow stepwise rotation of the sample. Reconstruction of 3D volume data was done with system-supplied Datos 2.2, using a beam hardening correction module incorporated into the software to reduce beam hardening artefacts, using a beam hardening correction factor of 7.5 (values from 0–10 are possible). Analysis was performed with Volume Graphics VGStudioMax 2.2 including its additional modules for defect analysis, wall thickness analysis and part to CAD comparison. The analysis involves contrasting slice images appropriately to remove background noise (possibly by doing an additional image filtering if required), followed by surface determination using the automatic function which selects the midpoint between the material and air in the data histogram. By activating the advanced function, the local vicinity of the selected surface is investigated for sharpest slope to ensure the surface is accurately defined. The defect analysis used the VGDefX2.2 algorithm, with 2 mm minimum defect and functions activated for neighbourhood checking and ignoring streak artefacts. The accuracy of the surface fit function limits the accuracy of all analyses, but which should be within the scan resolution, i.e. <0.16 mm. The accuracy of the wall thickness analysis is therefore 0.16 mm. The accuracy of the part to CAD comparison is in theory also 0.16 mm but in practice this is limited to the quality of alignment/registration of the CAD and CT data sets.

Results and discussion

Digital X-ray projection images are recorded, of which one example is shown in Fig. 1. Clearly, it is possible to use this type of image for quick part inspections, as well as move the sample around and view sections at higher resolution in 2D. For best CT results, the sample is mounted at an angle in order to minimize artefacts in CT reconstruction. In the case of a digital X-ray image, pores are visible as brighter areas, while solid regions are darker. However, thicker regions along the line of sight of the X-ray beam are also darker. Therefore major defects are visible but the difficulty lies in the complexity of the component, causing difficulty in an unbiased assessment of the defects using 2D radiography alone.

An X-ray microCT scan involves recording thousands of digital X-ray images as in Fig. 1, at various angles around the object during a slow rotation of the object. The 3D data set is reconstructed from the digital X-ray images, to generate a volume data set. This data can be visualized and analyzed in different ways, and comprises volumetric pixels (voxels) at every point in the scan volume, with a grey value representing the density and atomic mass of the material at that point. The resolution of the image and detail detectability is limited by the focal spot size of the X-ray source, the geometrical magnification and the digital X-ray detector. In this work the resolution was 0.158 mm. The sample size limits the achievable resolution due to geometrical magnification and a finite detector size. This follows a roughly linear relationship – the "factor 1000 rule of thumb" is that if a sample is 50 mm wide, 50 µm resolution is achievable, for example. This is one of the limitations of the technique, since defects or features smaller than twice the scan resolution will not be detectable under most scan conditions. Hence the smallest defect positively identified in this scan would be approximately 0.3 mm in diameter. However, high scan quality can improve the situation slightly, and surface determination can have accuracy as good as the scan resolution.

Virtual sectioning can be applied to the sample in any direction. Fig. 2 shows such a CT slice image, where brighter regions correspond to more dense material and dark areas represent air, hence black spots are voids. Some beam hardening artefacts are seen in the form of bright and dark image effects, but these do not affect the defect analysis, at the levels here. This type of image artefact can become overwhelming when larger or more dense parts are scanned which limits the applicability of the method, especially for automated analysis as presented here, to smaller samples and lighter metals. However, even though this limitation might become problematic for automated analysis and striking 3D images, simple slice

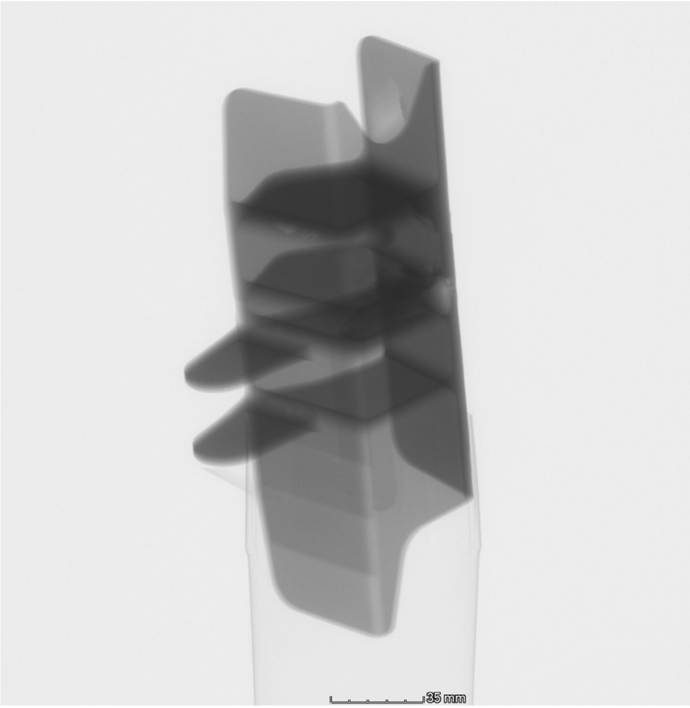

Fig. 1. Digital X-ray image of investment casting.

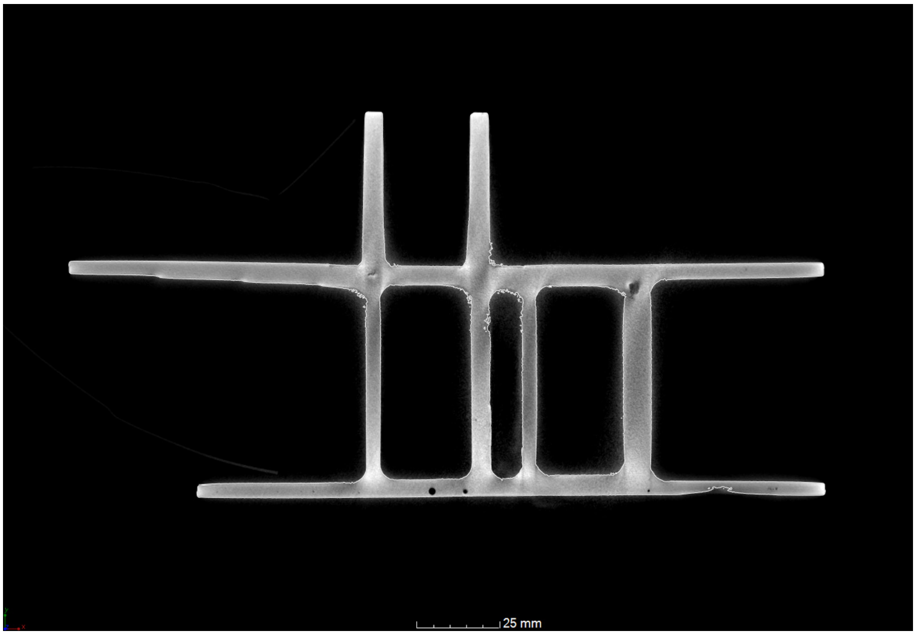

Fig. 2. CT slice image of the casting.

images can still be used effectively to find defects even in images with significant artefacts. Slice images are the simplest form of CT data analysis – i.e. scrolling through 1000 images from one side to the other through the object, and no special software is required for this viewing.

An automatic defect analysis was performed on the microCT scan of the sample, this involves finding voids and classifying them, in this case according to volume. Largest voids are coloured in red, smallest in blue and the 3D image made semi-transparent to view the location, shape and sizes of the defects. This is shown in Fig. 3, while additional material includes a 3D rotation video of this analysis. Such videos provide a good overview of the analysis, while a self-rotation in

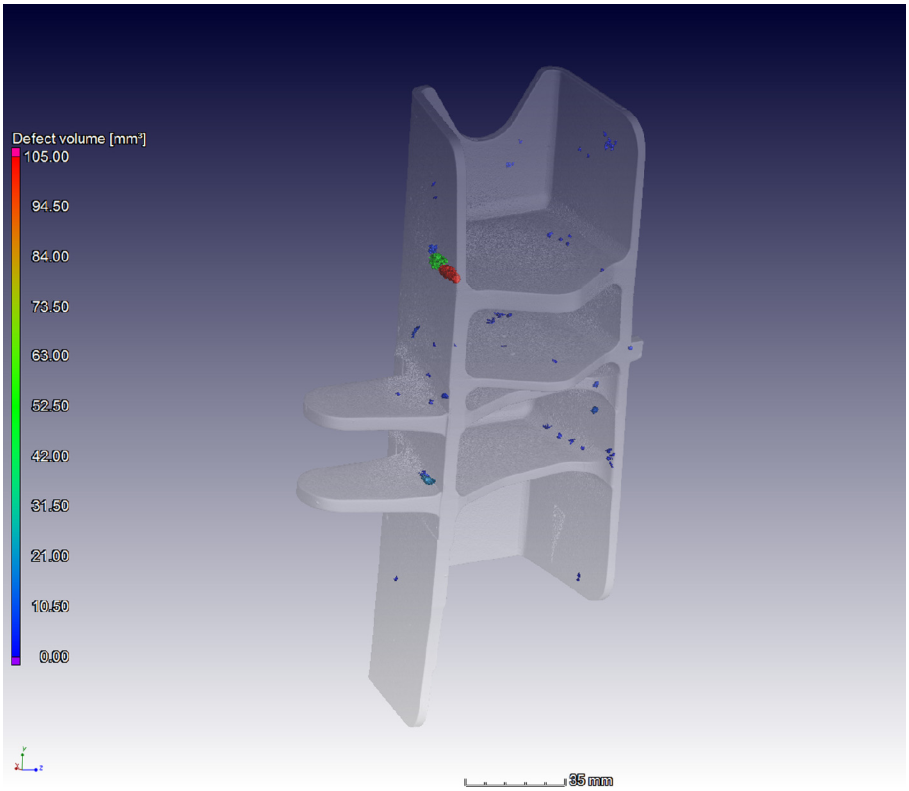

Fig. 3. Defect analysis indicating the location, shape and size of each defect larger than 2 mm.

any direction is possible in the software. In this example defects smaller than 2 mm diameter were excluded to simplify the analysis. The defect analysis results can be further analyzed and sorting can be done based on surface area, shape factor e.g. sphericity, or the information can be represented as a histogram of void sizes, such analyses are interesting for advanced materials analysis studies.

Another automatic analysis possible is wall thickness analysis. This calculates the thickness of walls in the object. These results can be visualized by colour-coding the walls based on their thickness. Fig. 4 shows the 3D image result, with most walls in the region of 4–5 mm. A single thick wall of about 8 mm is seen and a dent in the side of the object on the top right produces a thinner region of about 2 mm. Once again, the limitation on this automated analysis is the lack of image artefacts, thereby allowing an accurate surface fit, which is the basis of the wall thickness calculation. The surface fit function finds the interface between material and air in 3D space, and this interface is not clear under conditions of image artefacts.

The CAD file (STL format) was loaded and used for a comparison with the scan data. This involves a surface fit to the scan data, a best-fit alignment of the fit-surface scan data to the CAD data, and an automatic calculation of the deviation between the two. The results are shown in Fig. 5, where the deviation result is shown with colour-coding from red to blue for the two extremes. The part was supplied as-cast, and therefore the CAD file was within (inside) the scan data in most places (blue) but at some places the scan data was within the CAD data, which means that shrinkage could have occurred. Besides understanding where to do post-casting machining, angular and other deviations become visually clear, as the top left region shows. More detailed analyses can be done within the analysis software or the CT data can be exported as a CAD file (STL format) for analysis by design engineers in their own CAD softwares.

Conclusion

It has been demonstrated in this case study that very useful information can be obtained from automatic analysis of X-ray microCT scans of a casting. The simplest result is a stack of 2D slice images which provides a clear view of the inside of the part, especially for quick inspections of large numbers of parts. This requires no special software. Automated analyses include defect analysis, wall thickness analysis and part to CAD comparisons, which were demonstrated here. These automated analyses require high image quality and image artefacts affect the potential to apply these properly, which limits the size and density of the samples achievable for this type of analysis. The example presented is titanium and of 225 mm in its longest dimension, with approximately 6 mm wall thickness. Any sample up to this size in titanium or aluminium would work equally well, while steel parts would have more artefacts due to X-ray penetration limits, therefore

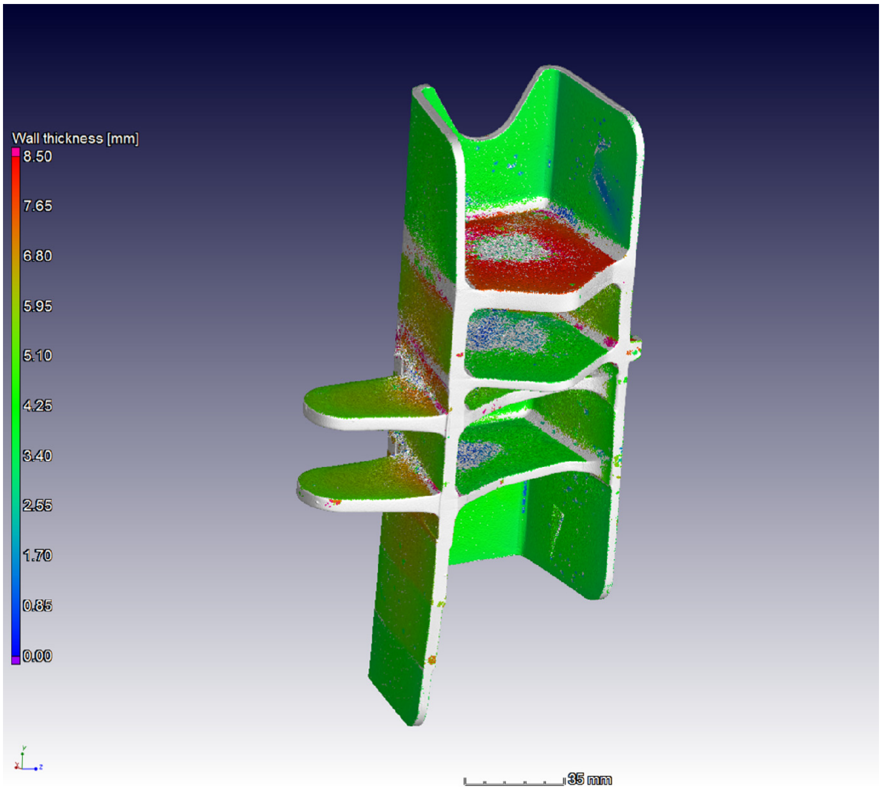

Fig. 4. Wall thickness analysis of the casting.

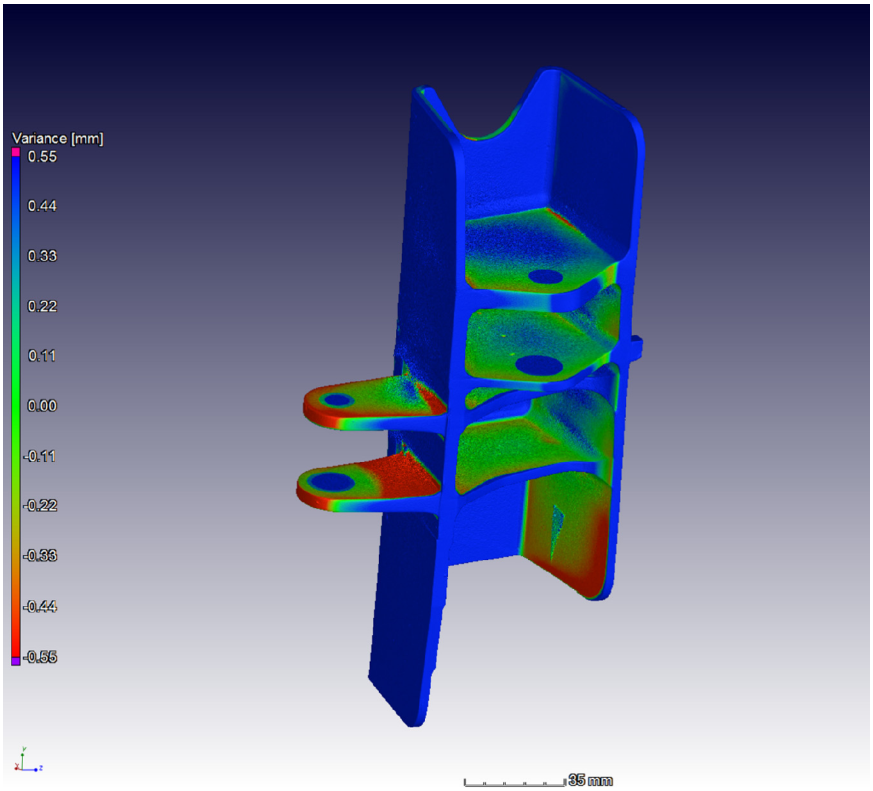

Fig. 5. Part to CAD comparison of the casting.

steel samples should be smaller to achieve the same quality. It would be of particular interest to industrial companies that the nondestructive analysis reported here was performed in less than 4 h. For lower quality and hence less stringent testing requirements, smaller components or large batches of samples, this time and hence cost can even be significantly reduced further.

Additional materials include videos and image stacks are available. For more information please visit http://blogs.sun.ac.za/ctscanner/titanium-aerospace-investment-casting/.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.csndt.2015.03.001.

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