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Design, manufacture and characterisation of X-ray Computer Tomography (XCT) calibration artefacts for space hardware qualification

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Abstract
Additive manufacture (AM) has many potential space hardware applications, particularly to enable the manufacture of flexural and optical components with novel geometries to achieve optimal performance and reduced mass. The effect of unwanted cavities or inclusion defects on printed components presents the need to verify the absence of cavities by a non-destructive testing method prior to expensive and time-consuming finishing processes such as single point diamond turning. X-ray Computer Tomography (XCT) is proposed for this application. This paper describes the manufacture and characterisation of a calibration artefact to verify the XCT measurements. The artefact cavities are smaller than most previous attempts, ranging from 120 µm to 30 µm in diameter. Several iterations of the manufacturing process incorporated certain mechanical design improvements. High precision machining centres from Kern Microtechnik Gmbh were used for the manufacture of the calibration artefacts. Commercially available solid carbide drill bits are produced in the required sizes but require sympathetic usage and careful handling techniques to achieve the required results. High magnification video equipment was used to monitor the drilling process in real time. Several techniques were compared to characterise the calibration artefacts including high magnification stereo microscopy, high depth-of-field optical microscopy, multi-sensor coordinate measuring machine and scanning electron microscopy. The characterisation of each hole is key to its final use for calibration. Finally, the calibration artefacts were pressed into a precisely matched hole in a sample AM flexure piece. The assembly was then scanned by XCT to quantify the difference between the direct characterisation and in-direct estimation of the artefact cavities.

Manufacturing (CAM) Drilling Metrology Micromachining

1. Introduction

Additive manufacture (AM) of space hardware components carries many advantages compared to conventional subtractive techniques including reduced mass, more freely optimisable shapes and reduced component count. Mirrors [1] and flexures [2] are areas where the advantages of AM can be used to improve component performance.

The potential inconsistency of AM material raises an issue when used for critical flight hardware, where fatigue cycles can cause small internal defects to form cracks and eventual failure. The European Space Agency has published a standard [3] for AM quality assurance which mandates increased levels of inspection for components subject to fatigue.

Non-destructive testing methods are therefore required to verify the absence of unwanted cavities and inclusions. It is helpful if the testing can be carried out immediately after the AM process to avoid the cost of secondary processes such as single point diamond turning on flawed components.

X-ray Computer Tomography (XCT) has been used in recent projects to characterise the internal properties of AM parts; Tawfik [4] provides a thorough overview of the technique and associated advantages and disadvantages. Using XCT to verify low volume AM space hardware fits well with the described advantages and limitations.

Therefore, a calibration artefact was designed to be assembled into an AM part, and used to refine the XCT analysis, therefore increasing confidence in the quantification of porosity. A recent review of reference standards for XCT metrology of AM [5] shows that previous attempts have been made to produce verifiable internal cavities for XCT calibration.

For example, Hermanek and Carmignato [6] produced micro milled hemispherical cavities in aluminium. This work differs by using micro drilling, fitting the pins with semi-permanent interference, and significantly reducing targeted defect volume.

An initial prototype assessed feasibility. Once externally validated, an improved design and process were used to produce a subsequent prototype. Multiple metrology techniques were utilised to characterise the cavities. Finally, metrology and XCT results from both iterations were compared and future improvements suggested.

2. Initial prototype

The initial task was to produce a proof-of-concept split dowel with internal micro drilled features. This dowel was then pressed into a precisely matched hole with a carefully engineered interference fit of just a few micrometres in an AM sample piece.

2.1. Design

The basic design (figure 1) proposed a 3 mm diameter pin split in half longitudinally from aluminium 6082-T6 alloy, the same base material as the AM sample used to achieve a similar grey value in XCT analysis. One half of each pin contained micro drilled holes ranging from 120 µm to 30 µm diameter with exact depths twice the nominal hole diameter. The pins were designed with a light interference fit to an interpolated hole milled in a sample AM flexure.

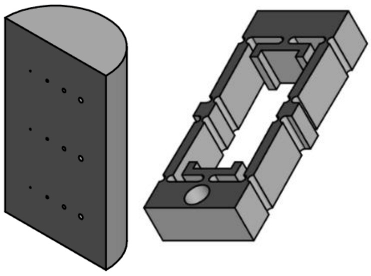

Figure 1. Concept Design Models L-R One half pin, AM sample flexure

The split face on each half dowels was machined with extra material for holding the part. Dowels with interference holes and a clearance hole and slot were used along with socket head cap screws to assemble the pin prior to machining the outside diameter (figure 2). The proof-of-concept pin was machined with as much support as possible.

2.2. Manufacture

Initial work was carried out on a Kern MMP milling machine with a video microscope. A minimal quantity lubrication (MQL) was used with a compressed air blast to aid the machining process and to prevent a build-up of aluminium swarf on the tool edges.

The split line face was machined with a 3mm 3 flute endmill and a 0.02mm final depth of cut, 0.015mm feed per tooth at 9000rpm with a 50% stepover.

The micro drills used to produce the features all had a 120° inclusive tip angle. A spotting drill was used to reduce wandering on the conventional drill entry. A single supplier provided micro drills in the required diameter; due to a breakage, the 60 µm drill was replaced by an available 50 µm drill from different supplier. Table 1 shows cutting parameters derived from manufacturer provided documentation and empirical experience.

Table 1 Final cutting parameters

Drill diameter (µm)	Feed (mm/rev)	Speed (rpm)	Depth (µm)
30 (Spot)	0.002	10 000	12
120	0.003	10 000	240
90	0.002	10 000	180
50	0.002	10 000	100
30	0.001	10 000	60

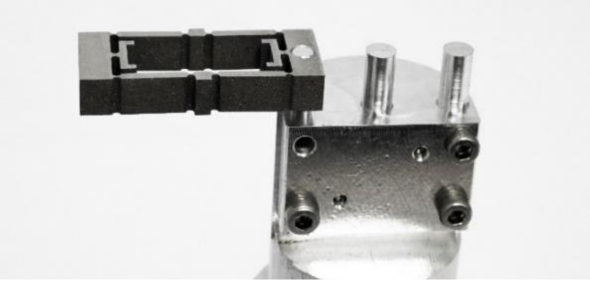

Figure 2. Flexure assembled to a blank split dowel

Drills were retracted for swarf clearing at depth increments of 10% tool diameter. The spindle speed seems quite slow for the drill size but is necessary to avoid burning out the drill tip.

2.3 Assembly

The two halves were assembled, milled to final cylindrical form and pressed into the AM sample piece (figure 2). CNC Wire electro-discharge machining (WEDM) was then used to separate the pin from the support with minimal force compared to milling or sawing.

2.4 Stereo microscopy

Figure 3. Initial prototype hole pattern under Leica stereo microscope

The surface finish achieved (figure 3) with the Kern MMP machine and carbide endmill was rough enough that the smallest holes are difficult to locate with conventional stereo microscopy. This is not ideal as the small drills tend to wander on rough surfaces.

2.5 XCT metrology

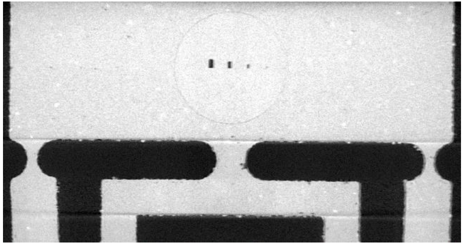

Figure 4. Initial prototype XCT slice image

An initial XCT was carried out (figure 4) and the reconstructed slices had a motion blurring artefact. The calibration cavities and pin boundary are visible. A positional error is apparent between the cavity locations and the central axis of the pin.

3. Subsequent Prototype

Feedback from the initial stage presented several challenges:

1. Some pins did not have micro drilling visible by XCT
2. On disassembly these pins did not have micro holes
3. The split line between the pins was evident on XCT
4. Machining processes were very time consuming.

3.1. Design

The missing holes were traced back to datum resetting error on assembled pin machining. Rather than using full support with no visual indication of the micro hole position (figure 5a), two further strategies were trialled: minimal (figure 5b) and targeted support (figure 5c) under the pin area. Table 2 shows methods and outcomes.

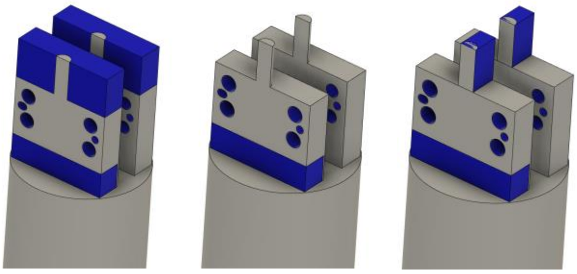

Figure 5. L-R Full support (a), Minimal Support (b), Targeted Support (c)

Targeted support seemed to have the best overall performance and was subsequently used throughout.

Table 2 Split dowel support outcome

Support Type	Positive Outcomes	Negative Outcomes
Full support all around	Least chatter	No failsafe on datuming Potential for release of material stress
0.1mm support around	Best for datuming Minimised release of stress	Highly visible chatter on diamond milled surface
5mm support underneath	Failsafe for datum location	Some released stress Some chatter visible under magnification

3.2. Manufacture

To improve the split-line flatness, a 10mm diameter single point Mono Crystalline Diamond (MCD) milling tool was used to skim the mating faces prior to micro drilling and pin assembly. The tool was used with a 0.005 mm final depth of cut, 0.005 mm feed per tooth at 9000 rpm and full width of cut. While a radiused tool corner would have improved surface finish, the available tool was chamfered.

Better precision and higher efficiency were achieved by using a Kern Micro HD with hydrostatic guideways and linear motors. Increased machine accuracy reduced the need for manual adjustments and higher acceleration reduced cycle times. Low runout polygonal tool holders ensured acceptable tool runout of under 2 µm without adjustment. A Blum LC50 laser enabled fully automatic tool measurement with the video microscope used for confirmation. Minimal datum change was achieved by using 3+2 axis indexing.

Higher acceleration could have been used to increase drilling speed, but the drilling parameters were kept from the initial attempt and time was saved by not warming the tools. Local experience suggests that below 12 000 rpm the Micro HD is highly thermally stable without tool dwelling. Table 3 shows a comparison between the machines used in this paper and common industry standard CNC machining centres.

Table 3 Machine comparison

Machine	Positioning Accuracy (µm)	Z axis Acceleration (m/s^2)	Spindle Speed (rpm)	Tool TIR (µm)
Industry Standard	7	5	12 000	~10
Kern MMP	5	0.5	50 000	<3
Kern Micro HD	<2	20	42 000	<2

3.3 Stereo microscopy

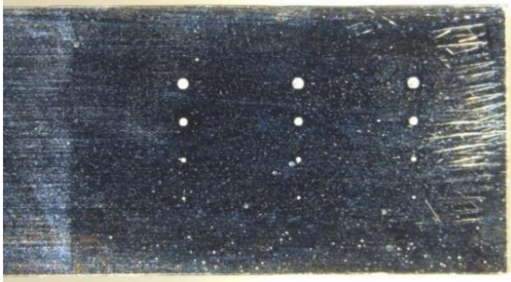

Figure 6. Subsequent prototype hole pattern under stereo microscope

Much higher surface quality (figure 6) was achieved with the MCD tooling, and the smallest holes were visible at a lower magnification. Chatter from insufficient support can also be observed on the free end of the pin.

3.4 High depth-of-field microscopy

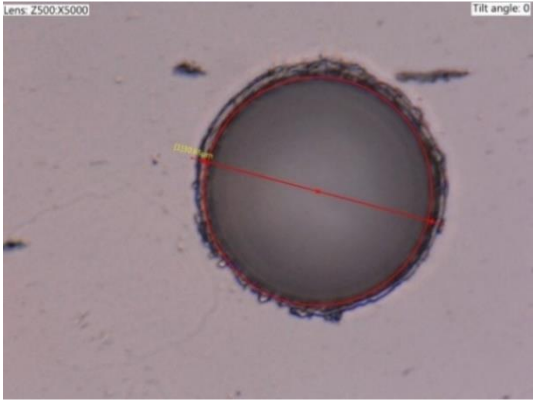

Figure 7. Subsequent prototype 30µm hole under Keyence

High depth-of-field microscopy on a Keyence VHX-5000 provided some initial dimensional results (figure 7). Focus scanning was also attempted on one of the larger holes but did not provide useful data due to the aspect ratio of the hole. The presence of a micro burr around the holes in the 2 µm to 3 µm range was also noted. This was expected from the micro drilling process and was exceptionally hard to remove without damage.

3.5 Optical coordinate measuring machine (CMM)

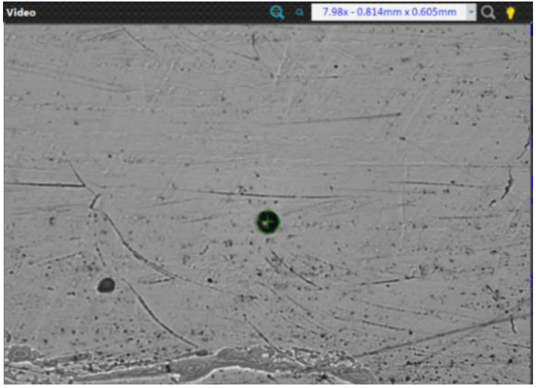

Figure 8. Subsequent prototype 30µm hole under Vantage 300

The optical coordinate measuring machine (OGP Vantage 300) had lower magnification than the Keyence VHX-5000 or SEM but this was balanced by 3D model input functions, edge detection capability and a recent manufacturer calibration. Due to ease of measurement, all the holes were measured (figure 8) with the CMM.

3.6 Scanning electron microscope (SEM)

The SEM (Hitachi TM-1000) produced the highest resolution images (figure 9) for consistent edge detection. High levels of user input which resulted in time-intensive individual measurements meant only a sample of holes were measured. A micro burr is also visible around the hole.

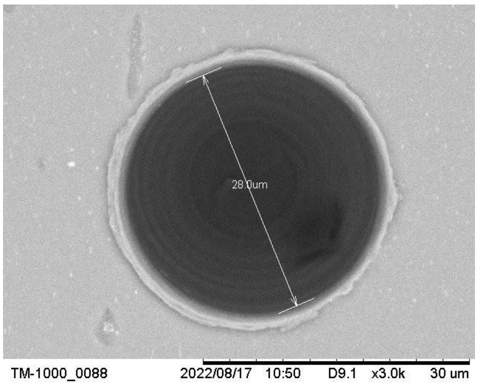

Figure 9 Subsequent prototype 30µm hole under SEM

3.7 Metrology comparison

The metrology methods used to characterise the artefacts prior to XCT analysis are summarised in table 4.

Table 4 Metrology comparison

Method	Advantages	Disadvantages
Stereo Microcope	Fast process with verification of hole existence and mating surface quality	No dimensional verification
High depth of field Microscope	Ease of setup	Slow to measure each hole with manual detection
Optical CMM	Ease of use with automated edge detection and programming	Low magnification and resolution plus the highest uncertainty
Scanning Electron Microscope	Lowest uncertainty and consistent edge detection	Slow process to set up and measure multiple holes

3.8 XCT metrology

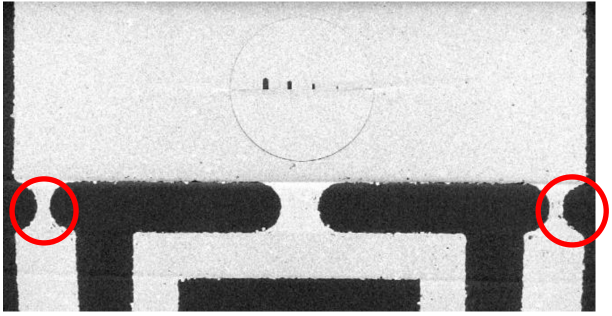

Figure 10. Second attempt XCT slice image

Further XCT metrology was carried out. Due to optimisation, a clearer image (figure 10) was obtained. The calibration artefact cavities can be observed as well as potential AM defects. The narrow flexure arms, identified by red circles, are of particular interest due to their effect on flexure integrity.

4. Results

Following consultation with experienced users across all the metrology equipment used, it was thought best to use the SEM data as baseline for the XCT calibration data, which means using SEM data as a reference when choosing the threshold value. XCT images were processed in Avizo software, and different thresholding techniques were explored, all while using SEM data as the baseline measurement. The findings are published [7] as part of the wider development of AM for space hardware.

5. Conclusion

XCT calibration artefacts were produced in Aluminium 6082-T6 using micro drilling and diamond milling to present verified cylindrical cavities down to 30 µm in diameter. Improvements throughout the project ensured the final deliverable had higher quality than the original proof-of-concept.

One of the major differences to prior work is that the calibration artefact is inside the calibration part, increasing the chance of the XCT grey value being the same as the measured part. Another difference is the use of micro drilling as opposed to milling, which makes a smaller cavity more manufacturable.

Due to the current need to insert a calibration artefact into each AM component, a further transferability study should be carried out to assess the results on using a single artefact to calibrate XCT for a batch of the similar components to reduce the volume of calibration artefacts required. Material-specific calibration is required for XCT, the micro drilling techniques demonstrated are applicable to use on other common aerospace alloys.

The orientation of the micro drilling in relation to the pin should be changed from radial to axial. This reduces the available space for drilling but improves manufacturability. Retention between the two halves of the pin could be implemented using threads or self-locking tapers. This would mean some of the advantages of previously published work [6] would also be incorporated while maintaining the advantages of the current work such as smaller cavities and insertion within an AM component.

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