

Characterizing Effects of Potential Build Induced Artifacts in L-PBF Components

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Additive manufacture (AM) is utilized for rocket engine component production. Witness marks are visible lines across the surface of an AM part that result from variation in build process. Witness marks have been used as justification to scrap a part with little to no evidence. The probability of witness mark occurrence is relatively high and greatly increases AM part production costs and schedule risks. The objective of this study was to quantify the impact of witness marks generated by intentional build pauses and characterize functional characteristics of the AM components. CT, μ -CT, metallographic, and mechanical test results indicate that witness marks are a surface phenomenon that do not propagate into the bulk of a part and had no statistically significant change on microstructure or properties in AlSi10Mg.

I. Nomenclature

<i>AM</i>	=	additive manufacture
<i>CT</i>	=	computer tomography
<i>E</i>	=	modulus of elasticity
<i>GPa</i>	=	giga-Pascal
<i>HCF</i>	=	high cycle fatigue
<i>LCF</i>	=	low cycle fatigue
<i>LOF</i>	=	lack of fusion
<i>L-PBF</i>	=	laser powder bed fusion
<i>MeV</i>	=	mega-electron volt
<i>MPa</i>	=	mega-Pascal
<i>MSFC</i>	=	Marshall Space Flight Center
<i>SEM</i>	=	scanning electron microscopy
<i>UTS</i>	=	ultimate tensile strength
<i>VAI</i>	=	Volunteer Aerospace Inc.
<i>YS</i>	=	yield strength
<i>Z</i>	=	build direction
ϵ	=	elongation
μ -CT	=	micro-computer tomography
μ m	=	micrometer
wt%	=	weight percent
%TD	=	percent theoretical density

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II. Introduction

Additive manufacture (AM) is utilized in production of liquid rocket engine components due to increased design flexibility, reproducibility, improved properties, lower cost, and shorter lead times when compared to traditional methods. Large scale builds utilizing Laser Powder Bed Fusion (L-PBF) machines can result in long build times on the order of several weeks. Machine rates vary from a few thousand dollars to tens of thousands of dollars per week depending platform size and it is of critical importance to minimize the scrap rate for cost and schedule control. Witness marks or witness lines are visible horizontal lines across the surface of AM parts that result from modification in layer time, layer thickness, or other variation in the build process [1]. The most commonly reason witness marks result is from build pauses due to the planned addition of powder, particularly for tall components. Unexpected reasons for build pause can be attributed to machine interrupts or facility power outage. During the build process the part is at elevated temperature but cools during the build pause causing the part to experience minor shrinkage. After restart the machine continues the scan strategy with the assumption that the part is at the heated geometric size, meaning that the first few layers appear slightly oversized until the part reaches thermal equilibrium and the part and scan geometries again match. The resulting geometric mismatch produces a witness mark across the entire part at the pause build height. Appropriate operations can mitigate the possibility of these witness marks; however, due to the current state of AM technology the probability of witness mark occurrence(s) per build is still relatively high.



Fig. 1 L-PBF component with witness marks.

Witness marks can be confused with inter-laminar lack of fusion (LOF) defects. For example, a short feed occurs when there is non-uniform powder distribution across a build layer due to an insufficient powder usage. The machine operator or process monitoring system detects the short feed and increases the powder quantity to provide uniform powder distribution. If a sufficient number of layers are printed before a correction subsequent powder addition results in layers that are too thick for the laser scan to obtain full melt pool penetration to the substrate beneath the powder layer since build parameters are designed for a specific layer thickness. The layer has insufficient density becomes a LOF delamination defect resulting in a planar crack that can be visible on the surface or detectable with x-ray CT.

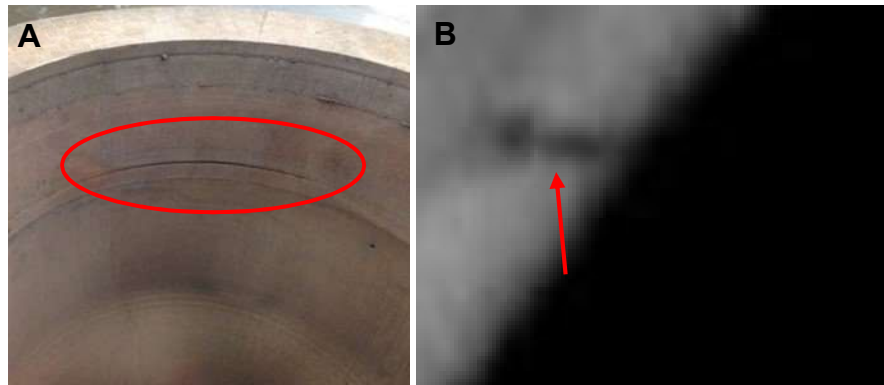


Fig. 2 Example of short feed induced LOF defect (A) and CT image of LOF defect (B).

Although the mechanisms and resulting part quality between a build artifact such as a witness mark and a build defect are substantially different, witness marks are sometimes thought to be indicative of poor build quality and considered by some to be grounds to scrap a part. There is little evidence to warrant such a perception and rejecting a component solely on the basis of a witness mark greatly escalates AM production costs. Rather than scrapping a part with a witness mark, a more advantageous approach is to determine the magnitude of impact on performance as a function of spatial location within an AM build. The objectives of this study are to evaluate the impact of witness marks generated by intentional build pauses and characterize functional characteristics of the resulting AM components produced through L-PBF. Results provide a more quantitative success/failure criteria to assess build issues and has the potential to improve build success rate, reduce production costs, and facilitate flight certification.

III. Methodology

NASA Marshall Space Flight Center (MSFC) developed a process for flaw detection of AM L-PBF components. The process had been previously applied the MSFC GE Concept Laser X-Line 1000R using IN718 to evaluate witness. The procedure was repeated on the Volunteer Aerospace Inc. (VAI) X-Line 1000R using AlSi10Mg discussed here.

A. Specimen Manufacture

VAI printed all AlSi10Mg components on four different builds. Each build was purposefully paused for increased period of time in order to accurately represent potential build interruption behavior and measure the impact of temperature change and oxygen exposure during the interruptions, which are known to induce witness marks. The specimen inventory included two CT gauge blocks, two CT bars with engineered defects, 4 metallography bars, and 12 cylinders to be machined into tensile bars. The semi-major axis of all specimens with the exception of the gauge blocks was aligned with the build direction (Z).

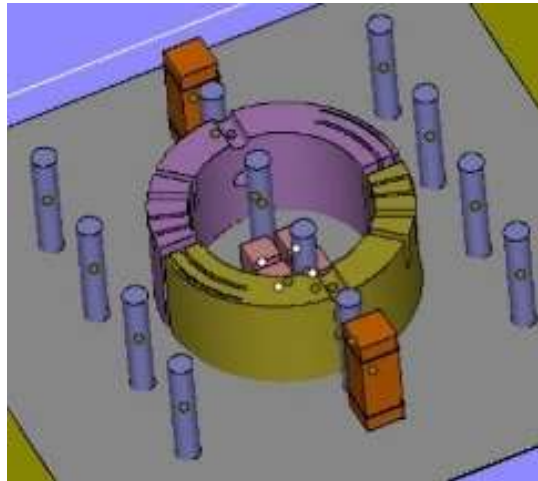


Fig. 3 Specimen build layout

After printing the components underwent thorough powder removal then were cut from the build plate. The build test matrix includes four build conditions with varying degrees of build history. *Build 1* was completed with no pause using standard VAI optimized AlSi10Mg build parameters with the build plate temperature maintained at 200 °C under argon. Specimens had no visible witness marks and are used as control specimens. Typical precautionary measures were taken to mitigate the risk of outside environmental factors effecting the success of the build. *Build 2* consisted of a 1hour build pause with the build plate temperature maintained at 200 °C under argon. The specimen inventory is the same as Build 1 but with the interruption occurring at the specimen gauge section mid-height. The delay simulates a brief expected build delay, such as powder refill. *Build 3* also included a 1 hour pause with the build plate allowed to cool to room temperature under argon followed by the build chamber re-zeroed after heating to initiate restart. The build delay simulates extended interruption such as unexpected machine maintenance. Finally, *Build 4* was a 24 hour build pause with the build chamber allowed to cool to room temperature and exposed to air followed by the build chamber re-zeroed after heating to initiate restart. The delay simulates a complete power failure including the loss of environmental argon protection, the heated build plate, and require reinitializing and re-zeroing the AM machine before initiating build re-start.

B. Macroscopic CT Don-Destructive Evaluation (NDE)

The AlSi10Mg semi-circular CT gauge blocks are shown in Figure 4A and CT bars as shown in Figure 5. Each CT specimen was found to have visually observable witness parks and underwent inspection using the 2 MeV Linatron CT at NASA MSFC. The Linatron is a high energy source capable of scanning large components and can compensate for the intrinsic losses when scanning high atomic number materials. However, one of the disadvantages of the Linatron CT is the relatively low spatial resolution due to a larger voxel diameter compared to other CT instruments. The two semi-circular gauge blocks had a variety of coarse engineered geometric features such as holes, variable wall thickness sections, and enclosed holes of various sizes. The internally closed features are filled with un-melted trapped powder that cannot be removed post-build since they intentionally designed to be inaccessible. Seventy scans of the gauge blocks were obtained in order to characterize spatial geometric variation as a function of the build direction (XZ plane) and perpendicular to the build direction (XY plane) as shown in Figure 4B. The resulting images allow for clear discernment of the coarse geometric features with sufficient resolution to identify some of the finer features. It has been shown that conventional CT is able to identify planar LOF defects, such as those produced by a short-feed that occurred during the build process. Often, such a coarse defect is visible to the naked eye as a crack on the exterior of the part facing away from the recoater blade and in severe cases across the entire part. However, the Linatron CT was not able to detect the witness marks even when repeated scans occurred at areas of known witness mark locations. The results indicate that conventional CT has insufficient resolution to identify a witness mark within a part, even when the part is manufactured from a low atomic number material such as AlSi10Mg with relatively low radio-opacity. CT results indicate that finding a witness mark made from higher atomic number materials with much higher radio-opacity is not possible. Higher resolution inspection methods were then applied to determine if these finer engineered defects and witness marks could be detected.

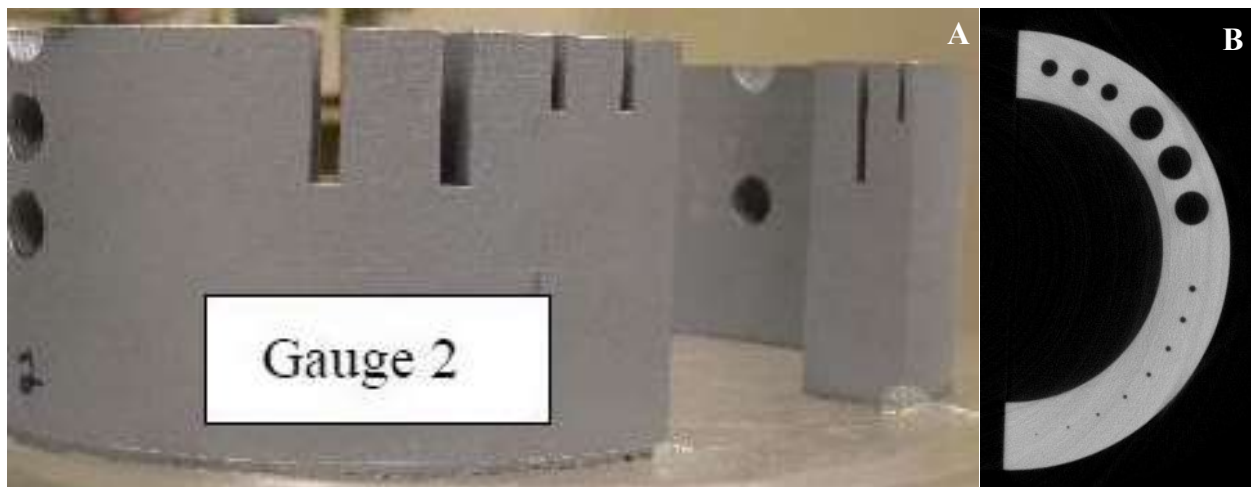


Fig. 4 CT gauge specimens (A) and 2 MeV Linatron image in the XY plane (B).

C. Micro-Focus CT (μ -CT) NDE

Like the AlSi10Mg semi-circular CT gauge blocks the CT bars include several engineered defects in the bottom and top third of the block, indicated by printed circumferential gauge lines. CT bar dimensions measure 25.4 mm x 25.4 mm x 75 mm (XYZ). The internal engineered defects include spheres and cubes, that when printed will be filled with un-melted powder and from previous experience appear as a lower density regions in CT images. Internal spherical defect radii vary in size from 0.25 mm, 0.5 mm, 0.75 mm, and 1.0 mm. Internal defect cubes were 10 x 10 mm (XY) with variation in Z from 50 μ m, 100 μ m, 150 μ m, and 200 μ m. The middle third the CT bars have no defects and is the intended region where the witness marks will be located resulting from the planned build pause and re-start. The CT bars were used to establish the printer geometric resolution as it correlates to the minimal detectability limit of the macroscopic and μ -CT used for inspection. As mentioned, the MSFC Linatron generated seventy eight scans of CT bars 2, 3, and 4 and only one small low density region was identified in all three bars at the same XY position and Z elevation. The low density region corresponds to one of the larger engineered defects. As with the CT gauge blocks the scan images were unable to resolve evidence of the witness marks within the parts at known witness marks locations easily observable through visual inspection of the component external surface. As expected, in order to identify the finer internal engineered defects a higher resolution method would be required.

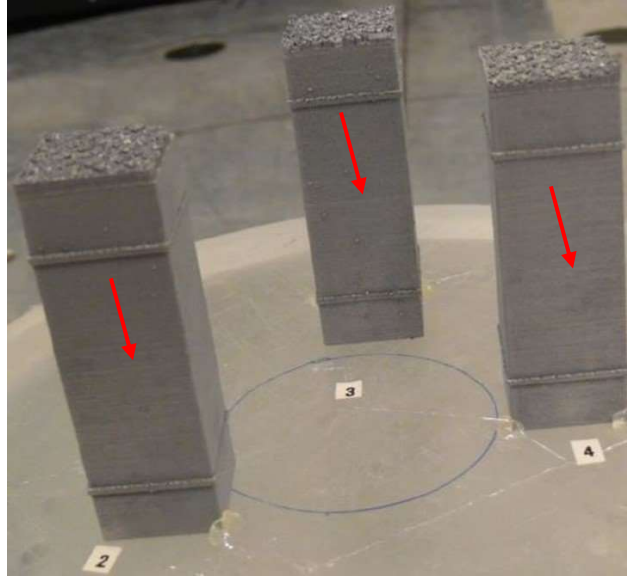


Fig. 5 CT bars 1, 2, and 3 with red arrows indicating the witness marks.

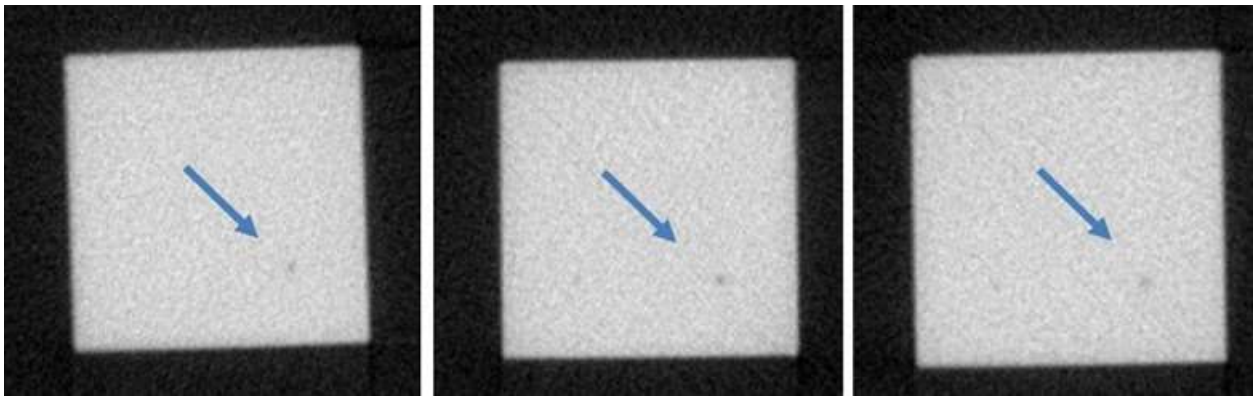


Fig. 6 2 MeV Linatron CT images of the CT bars 1, 2, and 3 identified low density spots in the XY plane as indicated by the blue arrows.

3D Engineering Solutions was contracted to inspect the three CT bars using μ -CT. As expected, the significantly higher resolution of μ -CT was able to detect the finer engineered flaws when compared to the 2 MeV Linatron. As shown in Figure 6A the μ -CT was able to detect edge porosity at the perimeter of the parts, which is prototypic of L-PBF and is a consequence of the overlap between in-fill and contour scan strategies. In addition, the μ -CT was able to detect the full-range of engineered defects at a significantly higher spatial resolution to the Linatron CT as shown in the comparison between Figure 7B and Figure 7C. However, even with the significantly higher resolution the μ -CT scan results were unable to resolve any indication of the witness marks within the material. It must be noted that μ -CT is not necessarily practical for inspection of large components or high production rate scenarios due to the small voxel size, long scan times, very large data files, and cost. μ -CT was utilized in this study as a brute-force technique to determine if witness marks could be resolved and would not recommend wide-spread utilization unless the AM components are small with fine geometric features. Examples would include thin-walled pressure bearing geometries where porosity across the wall could constitute a failure in service life. As mentioned previously AlSi10Mg is a relatively low atomic number alloy with low radio-opacity, meaning that x-rays penetrate relatively easy into the part and yield a high signal-to-noise ratio resulting in improved image resolution. The consequence is that if CT and μ -CT are unable to resolve witness marks in a part made of a low radio-opacity material such as AlSi10Mg it will be very difficult if not impossible to detect witness marks when components are printed from higher atomic number radio opaque materials such as iron, nickel, cobalt or refractory based alloys [2], [3]. Since neither the 2 MeV Linatron CT

nor the μ -CT NDE methods were to successfully able to resolve witness marks in the specimen interior, the next step is to conduct destructive microstructural examination of the CT block and bars. Microstructural characterization is the most capable with respect to detection of trace evidence for evidence that witness marks that could potentially propagate into the bulk of an L-PBF components.

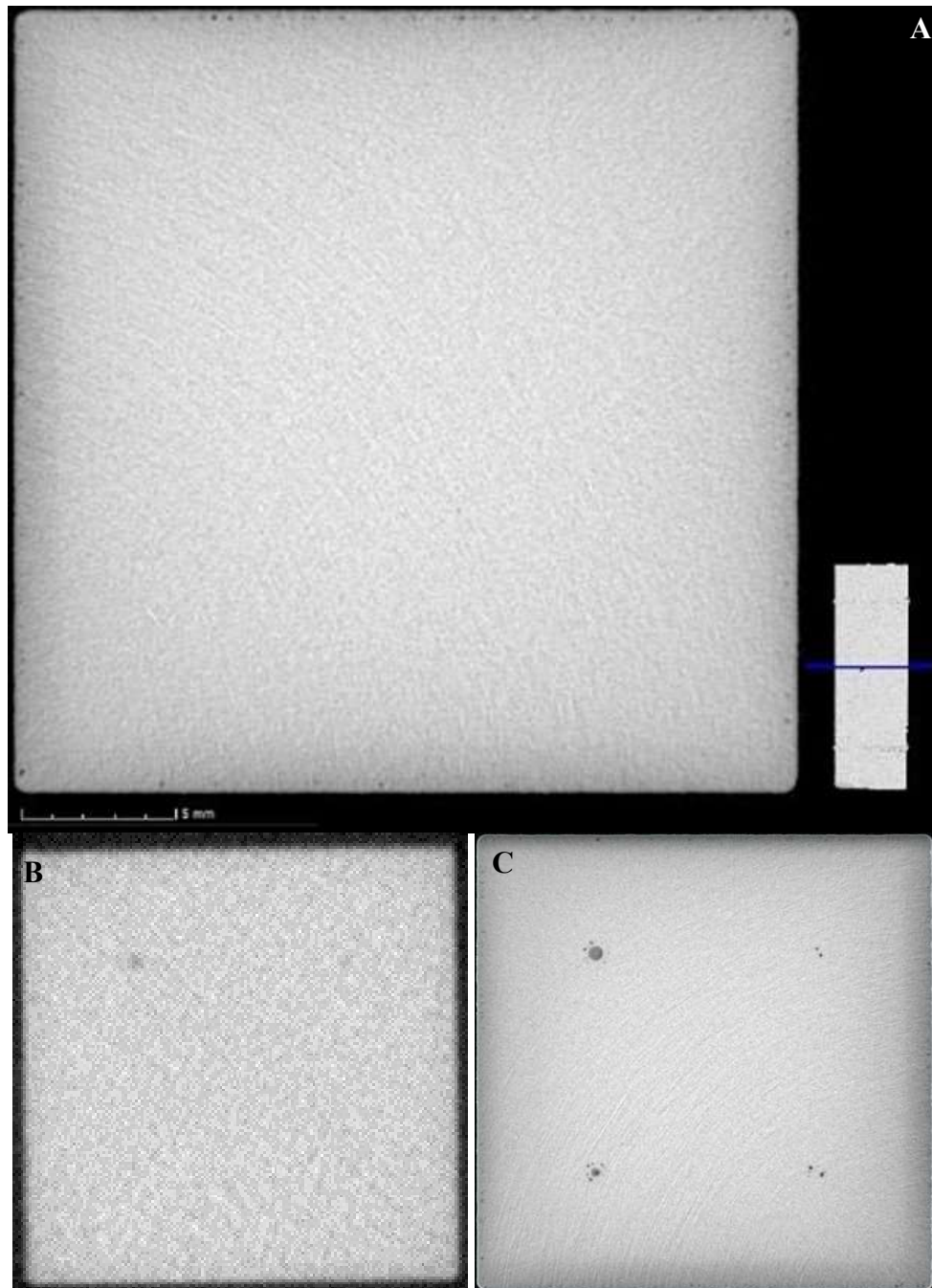


Fig. 7 μ -CT image of Bar 4 in the XY plane at the known location of a witness mark (A). No indication of the witness marks is identifiable; however, prototypic edge porosity is easily observable. Comparison of the Bar 4 specimen in the XY plane of the (B) 2 MeV CT image showing only the largest engineered defect and (C) the μ -CT image with substantially higher resolution showing all engineered defects.

D. Microstructural Characterization

Four metallography blocks were printed in each of the four builds. Metallographic blocks were sectioned, mounted, ground, polished, and underwent optical microscopy and scanning electron microscopy (SEM) to determine the extent that witness mark have on the microstructure at low and high magnifications. Optical micrographs at 50x show a homogeneous and dense L-PBF structure with no excessive porosity, LOF defects, or any other indications of potential loss of integrity. One of the CT blocks was sectioned perpendicular to the visible witness mark on the surface (Figure 8A) in order to determine if the witness mark propagated into the part itself. After metallographic preparation optical micrographs were obtained and show no evidence of witness marks impacting the part internal microstructure as shown in Figure 8B. SEM micrographs at 500x (Figure 8C) show spherical pores with a mirror-like finish, which is typical of gas-type porosity seen in L-PBF printing from reactive materials such as Al-based alloys. The majority of the porosity was observed to be distributed within 500 μm of the surface, which is typical considering the core and counter scan path interface zone. Even less porosity is seen deeper in the specimen. The lack of microstructure irregularities at the location of known witness marks provide strong evidence that witness marks are a surface feature phenomenon that likely have legible impact on mechanical properties.

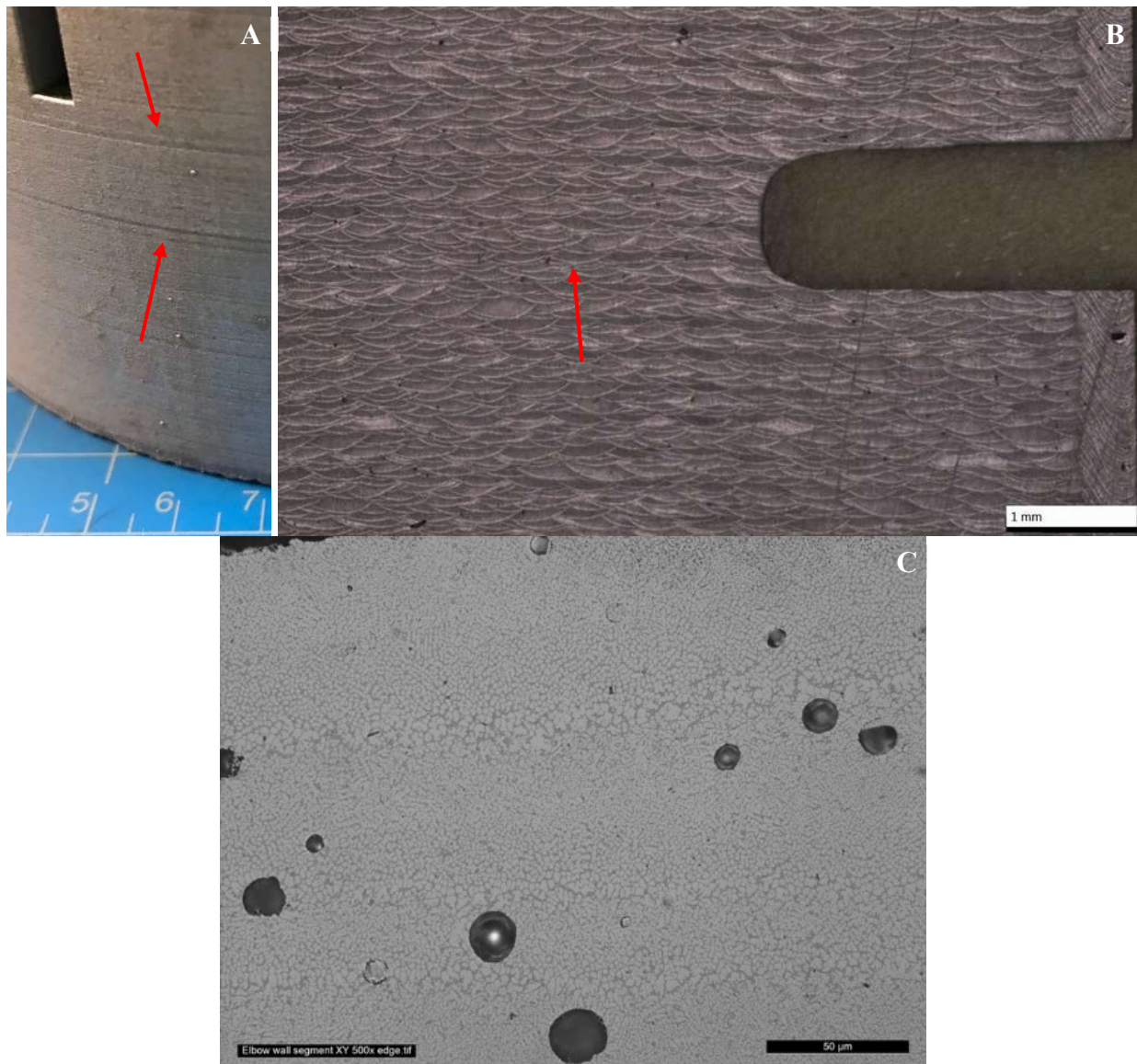


Fig. 8 Witness marks across gauge block (A), cross section optical micrograph at 50x (B) and SEM micrograph at 500x showing edge and gas porosity but no indications of the witness mark (C).

E. Mechanical Property Evaluation

Twelve cylinders were printed with the semi-major axis aligned with the vertical Z direction. Cylinder diameter was 16 mm with a length of 75 mm that after printing were machined into tensile bars per ASTM E8. MSFC and VAI conducted tensile testing to determine mechanical properties of specimens built with witness marks in the gauge section in the as-built condition. There is an optimal stress relief heat treatment that could have been leveraged but was not applied since the builds were conducted at near the stress relief temperature. Mechanical testing provides property correlation to the build environment and engineered defects. Yield strength (YS), ultimate tensile strength (UTS), elongation at fracture (ϵ), and elastic modulus (E) results are reported in the table below. Build 1 mechanical test specimens (no witness marks) serve as a control for builds 2, 3, and 4. VAI contracted Element Materials Technology to conduct the tensile tests for each of the four build conditions. Agreement in strength and elongation to fracture values between builds are observed, with statistical variations falling within the reported standard deviation. Therefore, witness marks in the gauge section had no statistically significant impact on performance. Particular to build 1, only a single elongation to fracture data point is reported. Technical issues with the extensometer during the recording of the plastic deformation of 11 specimens of build 1 were encountered thus such values are not included on this discussion.

Table 1: Mechanical properties between builds 1 (control), 2, 3, and 4 (exhibited witness marks).

Build	YS _{avg} (MPa)	UTS _{avg} (MPa)	ϵ _{avg} (%)
1	170.19 ± 4.01	342.50 ± 4.66	6.5 ± -
2	171.68 ± 5.44	339.85 ± 4.86	7.08 ± 1.41
3	176.33 ± 4.45	346.40 ± 4.83	6.83 ± 1.13
4	178.86 ± 3.61	343.36 ± 3.68	6.88 ± 0.77

Lastly, tensile testing was conducted at MSFC and the resulting properties between the two load frames show good agreement as shown Table 2. In addition, results are well within mechanical properties published in the literature for L-PBF AlSi10Mg [4], [5]. The lack of variation in mechanical properties add additional evidence to indicate that the witness marks do not have an appreciable effect on the structure property relations of AM L-PBF components.

Table 2: Mechanical properties with witness mark across specimen gauge section.

Data Set	YS _{med} (MPa)	UTS _{med} (MPa)	ϵ _{med} (%)	E _{med} (GPa)
VAI - 3	176.33 ± 4.45	346.40 ± 4.83	6.83 ± 1.13	-
MSFC - 1	163.75 ± 0.69	337.71 ± 0.90	6.24 ± 0.84	72.19 ± 2.96

IV. Conclusion

An array of AlSi10Mg specimens were produced through L-PBF and paused for various time intervals to generate witness marks across the specimen surface. CT, μ -CT, metallographic, and mechanical test results indicate that witness marks are a surface phenomenon that do not propagate into the bulk of an AM component. Results also indicate that there is no statistically significant change of microstructure or mechanical properties in AlSi10Mg parts associated with the location of a known witness mark. These results will enable a greater degree of flexibility with respect to inspection of L-PBF components to differentiate between acceptable features of the AM build process from unacceptable flaws such as LOF defects and cracks. The ability to accurately assess build quality issues has the potential to improve build success rate and reduce production costs. Results from this study could assist to establish guidelines for acceptance criteria that manufacturers adhere to when building aerospace grade parts and to help the AM industry to make better informed decision on when to scrap a part versus continue with post-processing to then be placed into service. Witness marks do not appear to influence the tensile properties; however, this does not rule out potentially deleterious impact on low cycle fatigue (LCF) and high cycle fatigue (HCF). Surface finish has a heavy influence on the fatigue behavior and witness marks could potentially act as stress concentrators / fatigue initiation sites. Components that are anticipated to operate in a fatigue environment can undergo post-process surface finish modification to mitigate or eliminate the impact of witness marks. Additional efforts should investigate the impact of witness marks on LCF and HCF.

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