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Surface Roughness and Design for Additive Manufacturing: A Design Artefact Investigation

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Abstract

Laser Powder Bed Fusion (LPBF) brings the possibility to manufacture innovative near-net-shape part designs. But unfortunately, some designed surfaces suffer from rough surface finish due to characteristics of the LPBF process. This paper explores trends in managing surface roughness and through a space industry case study, a proposed process that uses Additive Manufacturing Design Artefacts (AMDAs) is used to investigate the relationship between design, surface roughness and fatigue. The process enables the identification of design uncertainties, however, iterations of AMDA's can be required.

Keywords: additive manufacturing, surface roughness, design for additive manufacturing (DfAM), design for x (DfX), design methods

1. Introduction

Additive Manufacturing (AM), often referred to as 3D printing, is the direct manufacturing of a component from a 3D CAD model through a layer-by-layer material addition process (Gibson et al., 2015). The metal AM process Laser Powder Bed Fusion (LPBF), which uses a laser as its heat source and builds parts through the melting of powder material, is attractive for use in space applications as it provides the opportunity to manufacture near-net-shape innovative weight saving part designs. Such designs can utilise AM for the part consolidation of spacecraft components. Part consolidation focuses on the reduction of product costs, optimisation of assembly and performance improvement through product design/redesign to minimise/reduce the part count (Tang and Zhao, 2016; Yang and Zhao, 2018). Satellite maker Optisys LLC used AM to enable a 100-to-1 part reduction for a metal aerospace micro-antenna product demonstrator, achieving a 95% weight saving and reductions in production costs by 20-25% and non-recurring costs by 75% (Overton, 2017). Consolidated AM parts can have high complexity designs and, due to the inherent nature of the process, can require additional support structures to ensure a successful build. However, designs with closed internal sections cannot include support structures due to being inaccessible for removal upon completion. These unsupported areas, such as the internal roofs of enclosed structures, lack sufficient heat conduction pathways during the build process. Hence the cooling of material is slower, and the molten material flows through to the powder bed beneath, causing a fusion of melted and un-melted powder on the exposed surface (dross) (Feng et al., 2020). Intrinsically linking dross formation and rough surfaces to design choices such as inclination angle, curvature, and surface thickness (Jones et al., 2021). These types of process specific characteristics are reasons why Design for AM (DfAM) is an emerging field. Laverne et al. (2015) define three types of DfAM methods; opportunistic DfAM, where there are no limits to AM's feasibility, enabling designers to explore the geometric complexities offered by AM. Restrictive DfAM methods, which account for the full limits of AM brought through the characteristics of AM machines and a product’s manufacturability. Thirdly, dual DfAM methods, which combine the two approaches, aiding a designer in the realistic utilisation of AM's potential. The development of AM specific design tools is necessary to enable designers to fully utilise the capabilities of AM technologies and to think outside the constraints of traditional manufacturing, but within the new functional constraints of specific AM processes. The intrinsic link between material-machine-geometry of parts made through AM means that there is a requirement for the designer to not just be innovative, but also to be realistic. For example, by achieving the benefits of part consolidation but not compromising material properties due to induced defects such as surface roughness. This requires a deep understanding of issues like the effect of rough surfaces on AM fatigue performance and its relationship with design factors. Design factors, such as the choice of AM part build orientation, have a direct effect on the surface properties, the support structure requirements and in turn the post-processing time and cost (Ahn et al., 2007). This choice is complicated when consolidating parts, as consideration for support removal and surface improvement must be had when conducting the DfAM. Borgue et al. (2019) develop a design support to aid decisions related to consolidation of space products which accounts for the costs of post processing a consolidated design. Surface defects however can still exist in AM products after post processing activities (Atkinson and Davies, 2000). Thus, in cases where the post processing costs are too high, an understanding of material properties due to surface condition is needed to decide whether a consolidated part design is practicable. Literature indicates that the inherent surface roughness of LPBF parts in the as built state has a negative impact on fatigue performance (Wycisk et al., 2014). Also, Masuo et al. (2018) summarised the primary factors of AM part fatigue performance to be microstructure, build direction, defects (i.e., surface roughness) and residual stress. Masuo et al. (2018) found that as built Ti-6Al-4V specimens performed one third lower than post processed specimens. As post processing to improve properties can be costly, improving the surface quality of the most critical locations may be the most economical way to enhance fatigue resistance. In design cases where this is impossible there is a requirement to understand process-structure-property-performance relationship of the AM material (Yadollahi and Shamsaei, 2017).

For the space industry to utilise AM for critical components, methods to evaluate impact of surface roughness on fatigue properties are needed for engineers to understand how to design with AM surfaces. Presently there is an apparent lack in design guidance available to engineers on how to consider surface roughness during the design phase (Obilanade et al., 2021). ISO standard ISO/ASTM TC261 (2018) is available to aid the testing of an AM processes geometric capability, however the artefacts in the standard are unable to describe complex geometries. Ahn et al. (2007) create a genetic algorithm that relates surface roughness and LPBF parameters to propose a part orientation with minimal surface roughness removal requirements, however this method focusses on reduction of roughness with the expectation of post processing removal and does not describe internal roughness. Surface roughness of AM as-built parts continues to be an area holding back the adoption of AM within fatigue loaded components.

The purpose of this paper is to present a descriptive study that follows the industrial implementation of a previously proposed DfAM process that uses product-specific AM Design Artefacts. In particular, the process is used to investigate uncertainties related to surface roughness during the design of a rocket engine component. This paper presents an evaluation of the results from the first iteration of the DfAM process and the design logic for the second iteration of the process. Additionally, this work provides an up to date understanding of the state of the art in DfAM and surface roughness through a literature study building on the literature study of Obilanade et al. (2021). Compiling current knowledge on the relationship between design choices, AM process characteristics and as built surface roughness.

2. Surface roughness DfAM state of the art

In the pursuit of guidelines and methods that aid designers in the space industry in the use of AM, a literature study reviewing the state of the art in how to consider surface roughness in design was conducted. Building on the initial study of Obilanade et al. (2021), articles pertaining to LPBF, design and surface roughness were reviewed and categorised. The same PRISMA methodology and the terms ("design for additive manufacturing" surface AND roughness) for a narrow search and ("additive manufacturing" roughness AND powder) for a broader search were used. The aim of this updated study was to acquire and review new AM surface roughness design articles and to investigate trends in surface roughness research over a one-year period. Figure 1 graphically compares the categorisation of papers published over the one-year period. The first study results, detailed method, category definitions and initial findings summary can be found in Obilanade et al. (2021).

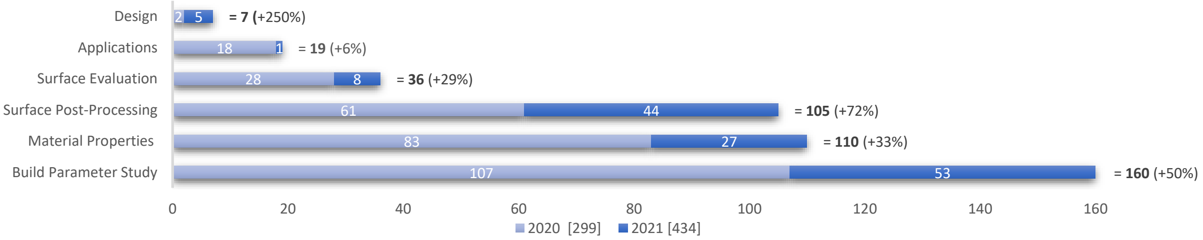

Figure 1. Paper categorisation chart showing number of relevant papers found during first review in 2020 and second review in 2021 [total # papers]

The first study categorised 2 out of the 299 relevant search articles as "Design", on repeat of the study one year later, an additional 135 relevant papers were found and 5 of those articles were categorised as Design, summarised in Table 1. Two articles provide modelling and simulation methods for DfAM while the remaining three provide specific surface roughness design problem solutions.

Table 1. Summary of newly categorised design papers

Reference	Material	Issue	Design Solution
(Klingaa et al., 2020)	17-4 PH Stainless Steel	Horizontal cooling channels have high dross formation when made via AM, hence have a reduced performance compared to design models.	Creates a python code for the design of complex cooling channels, the new model allows for a realistic simulation of AM built cooling channels that account for surface roughness in the as built state.
(Zhou et al., 2020)	316 Stainless Steel	Horizontal flow channels suffer as above. In hydraulic component friction loss is hard to account for and design components correctly.	Defines an equation that relates roughness to friction factor for a more accurate calculation of friction loss in hydraulic flow channel design.
(Zhou et al., 2021)	316 Stainless Steel	A continuation of the above, addressing the lack of understanding in designing fluid channels of varying diameters at varying build angles for AM.	Provides specific design guidelines for fluid channels of varying pipe diameters. Enabling the accounting of friction loss and AM effects when designing hydraulic components.
(Jones et al., 2021)	AlSi10Mg	The effect of part geometry on the size and number of defects in AM and defect definition lacks understanding.	Links local inclination angle, curvature and surface thickness to geometric error and surface quality. Creating a CAD tool to predict post build surface roughness and defects due to geometry during the design phase.
(S. Azar et al., 2021)	AlSi10Mg	Fatigue performance of AM materials is poor due to stressed regions with areas of rough surfaces.	Focusing on regions unable to be post processed, they develop a software suit to optimize build orientation for fatigue life improvement. Treating surface roughness as a function of build angle.

All relevant articles obtained in the first search had been published over the ten-year period prior to the search, on conducting the secondary search one year later, the number of relevant papers increased by 45%. The number of Design articles increased 250% according to our categorisation. Design articles however account for less than 2% of the obtained relevant articles. Articles pertaining to the post processing of surface roughness increased 72%, the second highest percentage increase of all categories. Though post processing methods can be utilised to improve surface quality, the time savings and cost reductions obtained by using an AM process may be lost due to any extensive post processing requirements.

Confirming the conclusions of Obilanade et al. (2021), there is little support for design engineers who want to consider how surface roughness from an AM process affects the final product. The review shows that design articles are a small percentage of the total number of articles and that interest in developing tools for designers, in particular with regards to surface roughness, is increasing.

3. Research Method

The DfAM process under investigation is the AM Design Artefact (AMDA) process proposed by Dordlofva and Törlind (2020), shown in Figure 2. The AMDA process is a proposition of a systematic way to create artefacts that investigate specific AM design uncertainties related to the AM process and part geometry. Like the Prototype for X framework of Menold et al. (2017), the AMDA process focuses on constraining the design of a prototype to test the relevant critical assumptions. The process is to be used in parallel with the design of an AM product, supporting DfAM through iterative testing to evaluate AM design opportunities. Dordlofva and Törlind (2020) conducted three industrial case studies, one of which followed the design of a rocket engine turbine manifold focusing on exploiting the possibility to consolidate parts through using AM, Figure 2 (a). In their study the AMDA process is used as a systematic way to identify, explore, and decrease AM design uncertainties related to manufacturing the manifold in one piece. The turbine manifold has a gas channel and due to build chamber size limitations must be printed on its flat side with the roof vertical to the build direction. As it is not possible to remove support structure from the channel, the roof must be designed to be unsupported. Therefore, a series of artefacts were designed to evolve possible roof designs (Dordlofva and Törlind, 2020), as shown in the evolve section of the graph in Figure 2 (b).

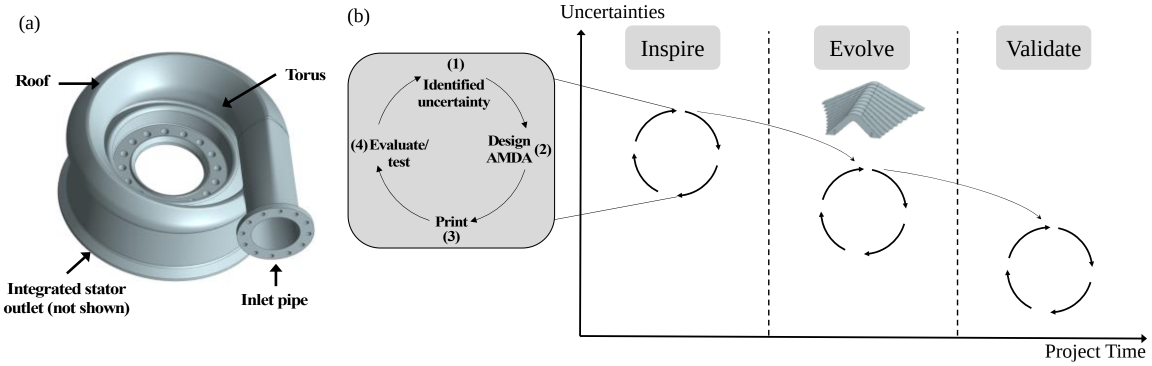

Figure 2. a) The case study rocket turbine manifold with integrated stator, b) the design process with AMDA's as a support and artefacts designed to explore unsupported roof design solutions (inside graph), adapted from (Dordlofva and Törlind, 2020)

Once a roof design solution was chosen there was also the uncertainty of the impact of design related surface roughness on the mechanical properties of this roof section. Hence to validate the roof design, an artefact was designed and fatigue tested to investigate this feature. Their results indicated an impact of geometry, surface roughness and material properties on fatigue life. However, the artefact was deemed not to be fully representative of the design uncertainty due to process characteristics causing geometrical deviation to the artefact.

Through an interactive collaboration with the case company, the continuation of the use of the AMDA process to validate the surface roughness impact on fatigue properties is described in this paper. This collaborative research approach enables the interaction with a user (i.e., the design engineer) of the AMDA process. By using this approach new knowledge can be developed to produce new theories and concepts that have a higher validity due to the critical reflections between researcher and user (Svensson et al., 2015). An analysis of the first artefact iteration unknowns and how they influence surface roughness, the LPBF process and part material properties is conducted. The new process and design knowledge is then used to develop a second design artefact iteration that accounts for the newly identified AM process characteristics that impact design. The second iteration is then proposed to investigate the relationship between AM design, surface roughness and fatigue more accurately and representatively.

4. AMDA industrial case study

The results of the first iteration of the AMDA process are described and a second design iteration is proposed in the following sections. The first iteration of the AMDA's, the 'A' artefacts, were designed during the initial research of Dordlofva and Törlind (2020). The second design iteration of the AMDA, the ‘B’ artefact, was developed during the study presented in this paper. The geometries of the artefacts are given in Figure 3 and their geometrical values are given in Table 2. The following sections describe the artefacts and their design in more detail.

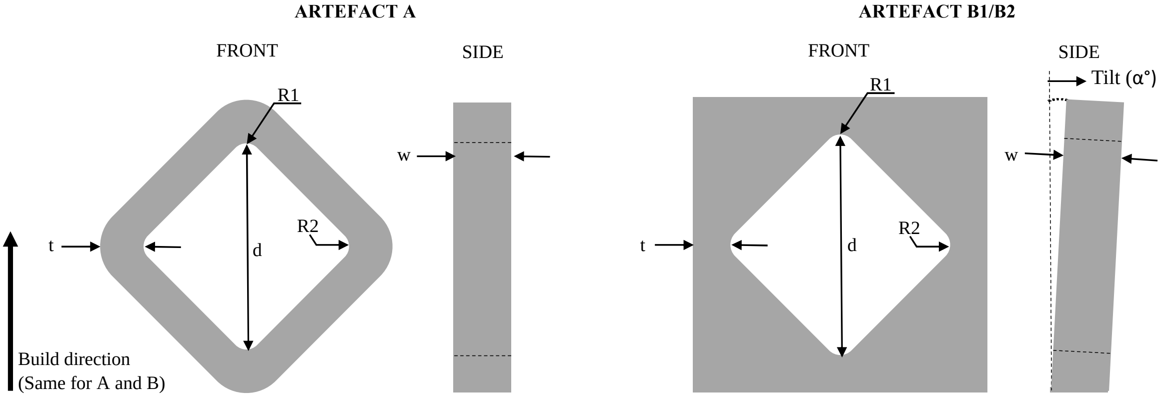

Figure 3. Diagram of artefact iteration A (left) and artefact iteration B1/ B2 (right)

Table 2. AMDA artefact geometries (all internal angles 90°)

AMDA	Diagonal width, d [mm]	Artefact width, w [mm]	Thickness, t [mm]	Inner radius, R [mm]
A	45	12	8	4
B1 (as built)	44	12	8.5	4
B2 / B1 (machined)	45	12	8	4

4.1. Iteration A

The aim of the design was to investigate the 'roof' radius (R1) and to compare it with a reference radius (R2). The design of the ‘A’ artefact and the value for R1/2 were set to resemble the internal roof geometry of the manifold design shown in Figure 2 (a). The learning objective of this design was to investigate the internal surface roughness of this manifolds proposed roof design and its impact on mechanical properties. As the aim of the investigation was to understand the fatigue behaviour at R1 of these types of sections and its predictability, any similar R value would suffice. Upon build completion, visual inspection of R1 indicated a much rougher surface compared to that of R2, as shown in Figure 4.

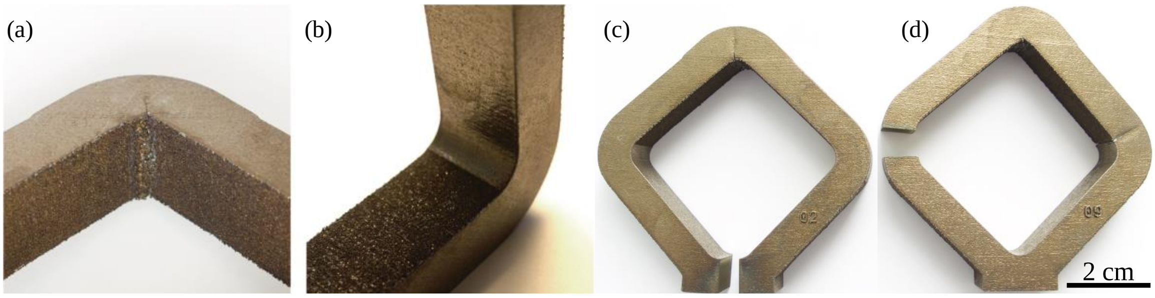

Figure 4. Image of 'A' artefact surface condition; a) Roof radius R1 and b) Reference radius R2 (view is bottom up). Image of 'A' artefact after fatigue testing; c) Roof radius and d) Reference radius showing off radius failure [Courtesy of P. Åkerfeldt, Luleå University of Technology]

Ten ‘A’ artefacts were printed and their R1 and R2 radii were measured. The average geometric deviation from the artefact design for R1 was -1.18mm equalling an average deviation of 29.5%. Comparatively the average geometric deviation for R2 was -0.03mm equating to under a 1% average deviation as can be calculated from Table 3.

Table 3. AMDA artefact radius measurement values

ID	1	2	3	4	5	6	7	8	9	10	$\bar{x}$
R1 (mm)	2.67	2.84	2.76	2.8	2.51	2.81	2.78	2.89	2.83	3.3	2.82
R2 (mm)	4.13	3.95	4.06	3.96	3.94	4	4.03	3.87	3.92	3.84	3.97

This is a significant difference in deviation from the design for two identical geometries. The geometrical inaccuracy of R1 was attributed to a high level of dross formation. Additionally, the smaller radius may have been caused by an AM distortion issue termed "transversal shrinkage" (Kokkonen et al., 2016). Transversal shrinking describes the occurrence of an abrupt distortion point in a part at the layer plane that two separately built islands of a part join (ISO/ASTM 52911-1-19, 2019).

In the case of the ‘A’ artefacts, the layer plane is the plane at which the two arms, the individually built islands, join to form the roof. As the ‘A’ design is perpendicular to the build plate the entirety of the junction plane is on one continuous layer. As the two arms of the artefact are built separately layer by layer, the junction plane at which the two arms join experiences thermal stresses from the opposing islands and are dragged by the two, causing a shift of the layer as it cools (Kokkonen et al., 2016). As can be seen at radius R1 on the artefact in Figure 4 (a),(c) and (d); this phenomenon leaves a visible line on the part at the junction plane.

Five ‘A’ Artefacts were tested under 10 Hz sinusoidal cyclic loading to ASTM E466-15 (ASTM, 2002) with a load range aiming for failure at 10,000 cycles (R= 0.1) (Dordlofva and Törlind, 2020). At R2 the point at which the parts failed occurred slightly beside the radius as can be seen in Figure 4 (d). The failure occurred at the transition from smooth to rough surface (compare Figure 4 (b)) where the artefact arm design changes from a radius to an unsupported 45° overhang surface. Such that microstructural issues like pores, notches, and other defects can be the instigator of the arm failure at that specific point (du Plessis and Beretta, 2020). Surface roughness induced notches have been shown to drastically reduce fatigue performance of metal LPBF parts (Nicoletto et al., 2020, 2018). Du Plessis and Beretta (2020) found that notches deeper than 50µm have a likelihood of initiating cracks irrespective of the surface roughness. The results of the testing highlighted two AM uncertainties that were not thought of during the design of the ‘A’ Artefact: (i) the impact of transversal shrinkage on fatigue behaviour at R1, and (ii) the possible instigation of failure from rough surface at R2. These unexpected failure behaviours warranted a second design iteration of the artefact. The second iteration artefact will account for learnings from the first to provide a true validation for the initial design uncertainty under investigation.

4.2. Iteration B

Based on the initial results it was decided that the rhombus shape would remain due to its simplicity to test a roof surface (R1) and a reference surface (R2) in one artefact. There were two major design changes made when evolving the artefact to iteration B: a tilt and the square geometry thickness (see Figure 3, right and Table 2. The tilt was introduced to counteract the impact of the transversal shrinkage and improve the geometric accuracy of R1. When the B artefacts are built with a tilt, the R1 junction plane is not entirely at one layer. Instead, it will gradually connect over several layers, reducing the impact of the thermal stresses as the layers cool. In addition, for industrial applications a gradually inclined roof improves the buildability of larger geometries, such as manifolds, as local inclination angle has a strong effect on the manufacturability of an LPBF part (Jones et al., 2021). Hence the introduction of a tilt in iteration B makes the artefact more representative of a real-world application designed for LPBF. The fatigue results from testing the ‘A’ artefacts provided Dordlofva and Törlind (2020) an indicative idea of the fatigue performance of a representative roof section.

However, due to the dross formation, geometry tested was not a continuous radius of 4mm as intended. hence the 'B' artefact designs tilt will address this unknown to minimise the effect of dross and reduce the geometric deviation from the radius under investigation.

To address the artefact failing off-radius at R2 as explained above, the B artefact arm thickness now increases from the radius. Iteration A had a consistent arm thickness giving the arm of the artefact the same strength properties throughout. Now that the B artefact thickness varies through its square geometry, the failure should occur where the thickness is smallest. Removing a variable that is not related to the condition of the radius design. Hence making the artefact more representative of the design uncertainty under investigation i.e., the influence of surface roughness on fatigue performance of the designed radius.

A hypothesis from the design engineers participating in the study was that, due to LPBF being a vertical manufacturing process, there is a difference in heat transfer as the R1 and R2 radius surfaces are built. The R1 radius is normal to the build direction whereas the R2 radius is perpendicular to it. Consequently, resulting in the two radii varying in the way material forms as their geometries solidify, meaning their material microstructures differ. The microstructural differences in these regions may have an additional impact on the fatigue irrespective of the surface condition. Therefore, the scope of testing for iteration B was widened to include an examination of material microstructure, hence the iteration B artefacts have two designs for fatigue testing (shown in Table 2 above). One to test the as-built surfaces and a second to investigate a machined surface through including material for removal in post process. B2 will be fatigue tested as built while B1 will be machined to the same geometry as B2, minimising the effect of surface roughness to investigate the microstructural fatigue performance design factor. In addition to radius measurements the surface profile for the radii of the 'A' artefacts were recorded, sample set representative examples are shown in Figure 5.

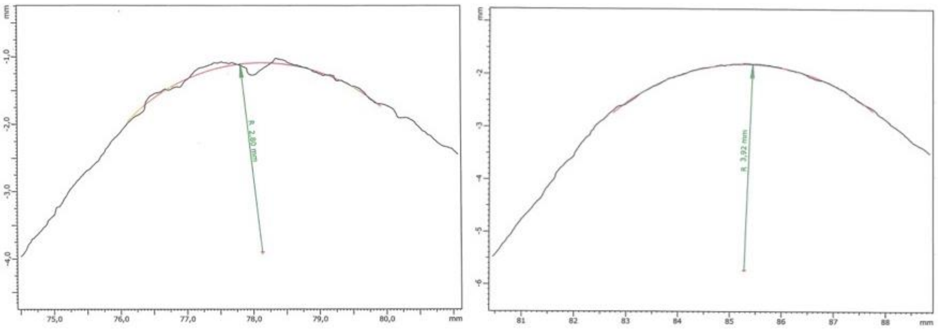

Figure 5. Graphical surface profile of an AMDA 'A' Artefact R1 (left) and R2 (right)

As seen in Figure 5 the example R1 profile is rather jagged and very non-linear, in comparison the R2 profile is much smoother and linear. The profile result of R1 highlights how varied the detail of an AM part geometry can be from its intended design due to issues such as dross formation. The jagged profile indicates sharp notches within the radius area, these notches alter the average radius of the geometry and decrease the fatigue performance due to being stress concertation points for crack initiation (du Plessis and Beretta, 2020).

5. Discussion

The AMDA process can be used to inspire, evolve, and validate identified design uncertainties related to AM. The ‘A’ artefact in the industrial case study aimed to validate the understanding of the design-roughness-fatigue relationship for the roof of an enclosed manifold section. However, in using this AMDA process, the ‘A’ artefact identified previously unknown process characteristics (transversal shrinkage and the transition roughness) that impact the artefact design. The characteristics impact to design needs to be considered for an accurate investigation into the relationship between design, roughness, and fatigue properties. Hence, the ‘A’ artefact evolved our understanding of the AM process and lead to the design of the ‘B’ artefact aiming for a more accurate representation. The AMDA process supports the detailed design of a product through providing understanding of these process characteristics’ impact on design. As one minimises uncertainties and gains AM process knowledge when investigating a design consideration, the AMDA process bring an awareness to design issues that will affect the final design. In general, the AMDA process may not generate a final design validation but may be used as a vehicle towards a specification that enables validation.

The AMDA process is reminiscent of the build, test, feedback, and revise model of spiral product development as described by Cooper (2014). In the presented case study, the purpose is to identify and reduce uncertainties by iterative design evolutions, until an understanding of the initial design uncertainty is obtained. When designing the first artefact a designer must use their current AM knowledge to break down a design's features to focus the first artefact on the main uncertainty, as each iteration incurs time and financial costs. However, consequently, the level of AM knowledge will also impact how fundamental the uncertainties are that need investigation. In each iteration a new design artefact is built which once tested either reduces uncertainty or exposes an unknown uncertainty i.e., AM process characteristics that impact design. The 'A' artefacts provided an idea of the relationship between design, roughness, and fatigue. But, due to the geometrical deviations from the design, did not provide the small radius knowledge required. Each iteration of the AMDA process reduces the number of uncertainties while the designer obtains a better idea of the AM process and how to evolve the chosen design to account for the design uncertainties. From the case study the designer has learnt of new process characteristics that impact design and that to investigate the initial design uncertainty, changes are needed in the next artefact iteration. The new understanding has led to two AMDA design changes, firstly the 'B' artefact design now integrates mitigation for transversal shrinkage through the tilt. Secondly, the 'B' artefact reduces the non-reference surface roughness influence by changing the thickness, focusing the artefact failure point to the reference radius under investigation. Generally, come the final AMDA, the nth iteration, the designer has reduced uncertainties and is provided with a clear understanding of designs effect. Thus ideally, a design specification with no remaining uncertainties can be made that enables the validation of a final design solution. A description of the case study through the AMDA process is presented in Figure 6.

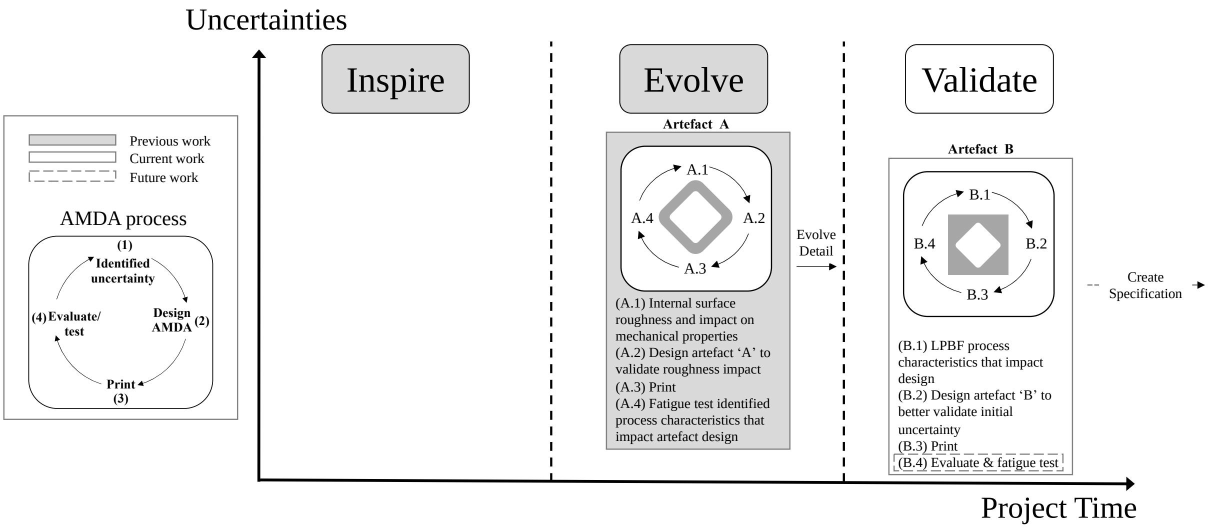

Figure 6. The design process using AMDAs to reduce design uncertainties, by validating the surface roughness impact on fatigue properties. Based on Dordlofva and Törlind (2020)

Surface roughness specific DfAM methods and processes commonly focus on reducing roughness through aiding a designer in selecting a build orientation with the best surface condition (Ahn et al., 2007; S. Azar et al., 2021). However, design cases like the studied manifold can only be built in one direction due to build chamber size restrictions. Rather than aiding surface roughness reduction, the AMDA process has enabled the designer to understand its impact on material properties so that the design can be optimised. A key element of the AMDA process is the confirmation of designs relationship to the different AM uncertainties as one works through the iterations. Enabling the simultaneous definition of solutions to multiple design uncertainties. Whilst also defining the significance of each uncertainty, enabling an evolution of a design to account for their hierarchy of influence.

6. Conclusions

For design engineers to utilise AM to manufacture complex and or critical spacecraft structures, an understanding of how design choice impact's part performance is compulsory throughout development. The degree of part surface roughness has been shown to be a critical indicator of part performance and is intrinsically linked to design choices. Through the examination of the use of a DfAM process that utilises design artefacts to explore and resolve AM design uncertainties, this work has highlighted various design issues that need to be considered when designing metal AM parts with closed internal sections. Additionally, this case study has extended the understanding of how AMDA's can be used in practice. The AMDA process has shown the importance of using a systematic approach to identifying and resolving design uncertainties. This work describes a refined proposal for a design evolution of an AMDA in practice. The 'B' artefact design requires further evaluation to verify that the design changes can provide the understanding of surface roughness as intended. Future work will focus on practical testing of these artefacts, enabling the verification of the design-roughness-fatigue relationship. Additionally, work should focus on further developing and validating the systematic AMDA process for generic uncertainties. Providing design engineers with a support when exploring the capabilities of AM in space (or other industrial) applications, enabling them to bring about novel design solutions for the final frontier. If in the future an AMDA design fully describes a design specification of a product it could potentially be utilised for qualification and acceptance testing.

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