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Fracture Control for Additive Manufactured Spacecraft Structures

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Abstract

This paper discusses how the intent of current NASA fracture control requirements may be applied to "fracture critical" additive manufactured spacecraft hardware. Fracture control is a multi-discipline design and certification methodology that is applied in order to mitigate catastrophic failure of structures resulting from growth of an undetected crack-like defect. The methodology is defined in existing spacecraft standards and is required by NASA on all human-rated space structures. Recently, standards have been published by NASA to define materials and processes requirements for certain metallic additive manufactured hardware, but procedures for fracture control implementation on additive manufactured parts are not yet addressed in detail in any standard or guidance document.

The discussion contained herein is necessary at this time as new guidance in this area should be founded collaboratively by the technical community at large including industry, academia, and government. Three Fracture Control Certification Methods are proposed for discussion. Additionally, a concept for "Design for AM fracture control" is introduced. The goals of this paper are to further expose the need for maturing additive manufacturing fracture control guidance in the spacecraft industry and to generate discussion on what this guidance should consist of.

Keywords: fracture control, additive manufacturing, fracture critical

Acronyms/Abbreviations

Additive Manufactured (AM)
Critical Initial Flaw Size (CIFS)
Computed Tomography (CT)
Fracture Control Certification Methodology (FCCM)
Johnson Space Center (JSC)
Laser Powder Bed Fusion (LPBF)
Materials and Processes (M&P)
Material Property Suite (MPS)
Marshall Space Flight Center (MSFC)
Non-destructive Evaluation (NDE)
Non-fracture Critical (NFC)
Qualified Metallurgical Process (QMP)
Process Control Reference Distribution (PCRD)
Part Production Plan (PPP)
Statistical Process Control (SPC)

1. Introduction

Human-rated spacecraft structures are often subject to fracture control requirements for certification [1,2,3]. Fracture control is a multi-disciplinary certification methodology centered around the goal of mitigating catastrophic hazards resulting from growth of an unknown pre-existing crack-like defect. The methodology generally is levied on projects where an added level of safety and/or reliability is desired to protect loss of life or loss of a valuable asset. For example, current NASA projects that implement fracture control are the Orion deep space exploration vehicle (human-rated) and the James Webb Space Telescope (valuable national asset).

The approach taken by fracture control at its core is to (1) identify all "fracture critical" parts where failure of that part has a catastrophic consequence (2) perform Non-destructive Evaluation (NDE) on fracture critical parts, and (3) demonstrate by test and/or analysis that fracture critical parts are damage tolerant. This methodology effectively embeds in the structural design approach that all critical parts can survive mission requirements assuming that they contain undetectable defects at the time of launch.

NDE and damage tolerance assessment methods are established for most metallic and composite hardware consisting of legacy materials and manufactured using legacy processes. Additive manufactured (AM) hardware introduces challenges related specifically to NDE and damage tolerance that make it difficult to apply fracture control using existing NASA requirements and guidance. This paper is a discussion of how the intent of existing fracture control requirements may be met in fracture critical AM spacecraft hardware.

1.1 Literature Review

AM technology has been around for several decades. While rapid prototyping has historically been the main use of AM in the spacecraft industry [4], in recent years actual flight parts are being produced. AM structures offer advantages in design and manufacturing efficiency and as a result are expected to continue to be used more and more in the future. In the modern spacecraft industry, design and manufacturing efficiency are particularly useful as long lead-small production runs are common. Plus, AM can enable highly optimized functionality as is often desired to achieve demanding performance or weight targets.

The biggest application of AM flight parts in the spacecraft industry so far is in rocket engine components where in some cases the entirety of all engine components are made using AM techniques [5]. NASA Marshall Space Flight Center (MSFC) has been involved in development of rocket engine AM parts since 2010 [6]. This development has included propulsion components such as injectors, combustion chambers, nozzles, and spark ignition systems as shown in Figure 1.

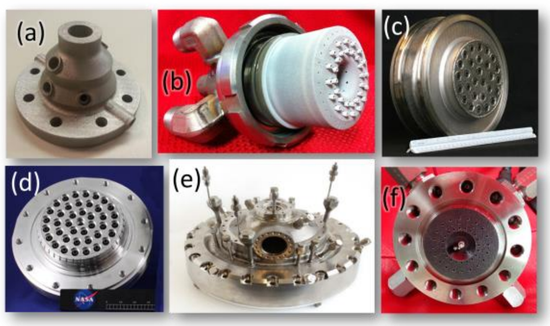

Fig. 1. Examples of Rocket Engine Components Produced at NASA MSFC [6] (a) 100# LOX Propane Injector tested 2013, (b) 1.2K LOX Hydrogen tested 2013, (c) 20K LPS Subscale tested 2013, (d) Methane 4K Injector tested 2015, (e) LPS 35K Injector tested 2015, (f) CH4 Gas Generator Injector tested 2017.

Airbus Safran Launchers undertook development of AM liquid propellant injectors for use on the Ariane 6 launch vehicle [7]. Through this exercise, they identified many design, manufacturing, and acceptance activities needed that are unique to AM structures. Among these activities, the items most relevant to fracture control included manufacturing process controls, surface treatment, NDE techniques, material property characterization, and acceptance testing. Material property characterization occurred by building test coupons in parallel to flight hardware and comparing to equivalent parts manufactured using a heritage previously qualified forging process.

"In-orbit" manufacturing is another new application for AM technology. A joint technical-business assessment found that nano-satellite trusses, antennae, solar panels, and structural repairs are feasible applications for in-orbit manufacturing within 3-5 years of the date of the assessment [8]. Other AM applications in the space industry range from existing secondary structures on non-human-rated spacecraft [9] to future techniques where ground structures are printed from lunar regolith [10].

One ongoing project at NASA Johnson Space Center (JSC) is qualification and certification of an AM pressure vessel. While certification of the vessel is ongoing at the time of this paper, the project is notable in that it is one of the first safety critical AM parts planned to be flown on a NASA human-rated spaceflight structure. The vessel and images from qualification burst testing are shown in Figure 2.

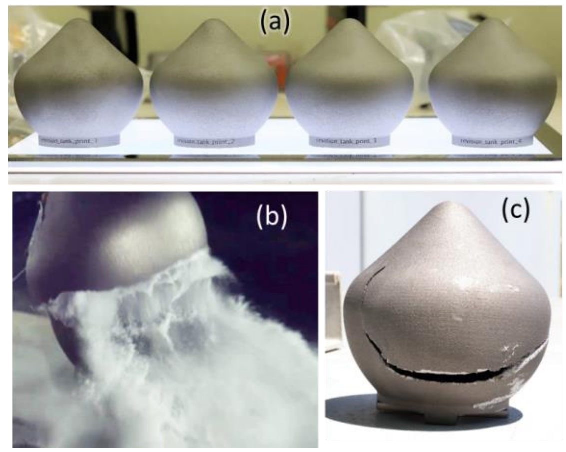

Fig. 2. NASA JSC AM Pressure Vessel, (a) test coupons, (b) burst test failure, (c) test coupon after burst test.

NDE of AM hardware is less mature as a discipline than NDE of parts made using more traditional manufacturing techniques. Gaps in AM NDE capability were identified and discussed in a NASA review [10]. In the context of fracture control, these gaps include a lack of reference/standard test samples, low maturity of finished part NDE, lack of in-situ process monitoring, and lack of standards. Dye penetrant and eddy current surface NDE are techniques that may be applied, however, they are not useful on rough as-built surfaces so post-process surface improvement such as machining or electro-polishing must be performed. Ultrasonic testing may be useful in detecting embedded voids or weak deposition layers, but can be challenging on rough as-built surfaces as well. The most promising technique so far for AM parts is x-ray computed tomography (CT) due to the fact that it is possible to detect internal features in parts with some degree of geometric complexity. One drawback of this technique is that it is not effective at detecting closed cracks (such as touching layers with incomplete fusion).

An example of AM part x-ray CT is shown in Figure 3 where a "tankifold" (combined tank and manifold printed as a single part) recently developed at NASA JSC is shown. Internal fluid passages and cavities are clearly visible, though as mentioned, closed crack-like features would not necessarily be detected.

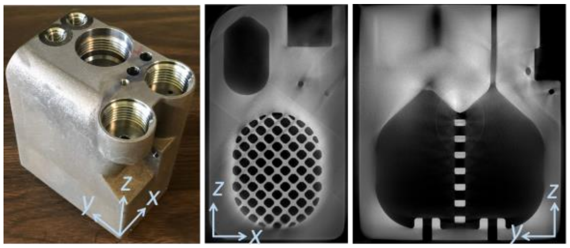

Fig. 3. NASA JSC AM tankifold CT.

Generally, NDE of the quality and reliability needed to support a fracture critical designation of an AM part is challenging and is another area where better standardization and guidance are ultimately needed.

1.2 AM Regulation Development

AM hardware standards have been in development since 2013 [11]. The main organisations currently involved in development of AM standards are NASA, ASTM International, International Organisation for Standardisation, American Welding Society, Society of Automotive Engineers, American Society of Mechanical Engineers, the National Institute of Standards and Technology (NIST), and the Federal Aviation Administration (FAA). The Additive Manufacturing Standardisation Collaborative (AMSC), consisting of many organisations, was established in 2016 to address the need for improved AM standardisation [12]. One of the first activities completed by the collaborative was a standardization roadmap and gap analysis identifying areas where no published standards exists. While fracture control is not specifically called out as one of the 89 identified gaps, one of the "NASA applicable" gaps is related to part classification which has an important role in the implementation of fracture control.

In 2016, Lockheed Martin held an internal quality summit on AM hardware. While, not addressing fracture control directly, the outcome was a checklist process for producing AM parts including those deemed as flight critical or primary structure [12]. Similarly, General Electric has developed their own internal qualification and certification approach [11].

In the aircraft industry, the rule for new fabrication methods states that they must be substantiated by testing. In the case of AM spacecraft parts, this would then generate the questions (1) What testing is needed? (2) Are the tests also new and non-standard?, and (3) What effects on properties, reliability, and performance do attributes like anisotropy, inherent material anomalies, location-specific properties, or residual stresses have? [13].

Since 2015, the FAA and Air Force Research Lab have been holding workshops aimed at maturing qualification and certification activities for aircraft AM hardware [14]. The ASTM and the NIST held a joint workshop in 2016 where the need to enable more fatigue and fracture critical applications was identified [15]. The workshop included discussion on the relationship between M&P issues and fracture performance including the important role of witness coupons to verify properties. Some of the biggest factors in part quality related to fatigue and fracture performance are presence of defects, anisotropy, test similitude to parts, and surface roughness. Specifically, a defect and surface roughness may affect crack growth initiation, anisotropy may complicate analysis and predictions needed for certification, and test similitude complicates any test-based rationale being used for certification [13].

2. NASA Materials and Processes Requirements for Additive Manufacturing Certification

The currently released NASA MSFC standard and specification for the Laser Powder Bed Fusion (LPBF) processes, are the most commonly used standard and specification for AM metallic spaceflight hardware [16,17]. Although MSFC-STD-3716 and MSFC-SPEC-3717 were created specifically for LPBF process, the approach of these documents can be applied to other AM processes to build critical spaceflight hardware. The NASA MSFC approach establishes process control starting with the qualification of the process, continuing through producing a qualified part, while maintaining statistical control to verify process integrity. These items are all controlled through an Additive Manufacturing Control Plan.

Foundational process controls are crucial to creating repeatable and reliable AM parts. Following the NASA MSFC approach, these process controls must be implemented and documented through a quality management system in order to maintain traceability. As part of these controls, AM facilities and equipment must be qualified, maintained, and calibrated, along with documented personnel training that includes all who are involved through the process of qualifying and producing parts. The controlling of these types of processes is not a new concept. For example, welding of spaceflight hardware requires similar equipment and facility documentation and controls.

Once equipment and facility controls, along with personnel training, are in place, a Qualified Metallurgical Process (QMP) can then be developed. Once the process parameters are determined these are locked down and become part of the QMP. These parameters may include details such as (1) feedstock size, distribution, morphology, cleanliness, packaging, and reuse; (2) fusion parameters such as layer thickness, power, speed, hatch spacing, and atmosphere controls; and (3) fusion parameters that test the limits of the process to variation due to items such as thermal history effects, scan patterns, part geometry, and post-build thermal processing that includes the evolution of microstructure from as-built to any hot isostatic pressing and/or heat treating processes. All of these items play a part in generating design values and in maintaining process control. This parameter set will be evaluated for microstructure, surface texture and detail, and mechanical properties which are tested to ensure consistency, reliability, and adequate property performance. Methods of producing and maintaining proper equipment and facility controls along with developing a QMP are described in MSFC-SPEC-3717.

All of the data generated through the generation of a QMP are maintained within the Material Property Suite (MPS), along with any data generated using the QMP to develop material property data, such as design values. The MPS data is also used to produce the Process Control Reference Distribution (PCRD) which is used to generate Statistical Process Control (SPC) acceptance criteria for witness testing. Witness testing is performed on all MPS and production builds and uses multiple acceptance criteria to detect systemic process control deviations. The design values generated from the MPS are generated from statistically substantiated values that should also account for sources of variability within the AM process. The PCRD demonstrates nominal expected performance of the AM process for that material using a specific QMP. Typically there are four PCRDs associated with each MPS: ultimate tensile strength, yield strength, elongation, and fatigue life. From these PCRDs, SPC acceptance criteria can then be generated for witness test evaluations. An example of the simplest approach uses minimum strength and elongation, a range for mean value, and a range for standard deviation. For clarity, PCRD acceptance criteria are not the same as the design values. The PCRD will be updated and evaluated with new witness testing periodically to maintain SPC.

The last part of the NASA MSFC standard approach requires that the part be qualified. This begins with assessing the part upfront by assigning part classification for the consequence of failure, structural demand, and AM process risk where AM process risk is a measure of how challenging the part is to build and be inspected. Part classification communicates the risk associated with each AM part and establishes the level of process controls and evaluations needed to ensure a safe and reliable AM part. A Part Production Plan (PPP) is used to document all aspects of the AM part process including but not limited to: part design, build file, powder removal, stress relief, build plate and support removal, thermal processing, surface finish, and NDE. One of the crucial aspects of the PPP is developing and testing a pre-production article that is evaluated through not only NDE and surface quality inspection methods but also destructively tested by taking mechanical samples from critical or highly loaded areas and evaluating microstructure. The pre-production article is essential to evaluating and correlating the witness data with actual part production, especially since NDE and other typical methods for successfully evaluating traditional manufactured parts may be limited when it comes to AM parts.

The NASA MSFC process to producing qualified AM parts can be summarised as follows:

1. Generate a qualified process with a locked parameter set - QMP
2. Develop material properties for design using a QMP - MPS
3. Create a PCRD utilizing the MPS data to inform the SPC acceptance criteria – process control
4. Develop a qualified part process - PPP

All of the steps in part qualification depend on one another and cannot stand alone. This approach requires continual data collection and process monitoring updates in order to maintain a consistent process that is necessary for building critical spaceflight hardware.

As mentioned, the prior discussion was a description of the NASA MSFC M&P approach for process control and generating material properties. The MSFC standards for this approach do not contain requirements for structural certification or fracture control. In practice, once the NASA MSFC M&P approach has been executed, structural verification may be the next step in overall certification of the part using material data generated by M&P. It may be less definitive sequentially when fracture control is implemented, but both structural verification and fracture control implementation are separate activities not covered by the NASA MSFC M&P approach.

3. Fracture Control of AM Hardware

Fracture control is a multi-discipline design and certification methodology that is implemented in order to mitigate catastrophic failure of structures resulting from growth of an undetected crack-like defect. Consistency and quality control are one of the biggest challenges in AM hardware, so in this context, damage tolerance and NDE are important where the fundamental goal is to demonstrate that a part will not fail due to a defect that was not detected.

Fracture control also helps to reinforce quality through process controls, inspection, and traceability. If comprehensive M&P standards are used, fracture control does not necessarily need to be duplicative but can act as a supplement to provide any additional details not already covered such as damage tolerance, proof testing, or NDE. The remaining discussion in this paper on fracture control implementation assumes considerations related to process control, obtaining material properties, and verification of as-built properties as they are addressed per the NASA MSFC M&P documents [16,17] or another similar method.

One of the main steps in fracture control implementation according to existing requirements is to identify all parts that are "fracture critical", or all parts that if failure were to occur, a catastrophic hazard would result. Generally, human-rated structures are considered in this context and a catastrophic hazard is defined as a loss of life. Some projects may also define a catastrophic hazard as loss of mission or loss of a valuable asset. To date, AM parts have largely been excluded from use in fracture critical applications. The following is a discussion on how fracture control may be implemented on AM fracture critical parts. Recall, the fundamental existing challenges with implementing fracture control on AM are:

- Immature NDE methods and standards
- Lower confidence in part quality and consistency compared to legacy manufacturing methods
- Understanding, testing, and predicting failure modes

For the remaining discussion, it is necessary to define three concepts: the Critical Initial Flaw Size (CIFS), a proof test, and a leak check. The CIFS is defined as the crack-like flaw size at the worst case location and orientation in a part that is predicted to precisely meet the defined service life and residual strength requirements (i.e., a margin of safety equal to zero on damage tolerance of the flaw).

A proof test is a ground based mechanical test on a flight part that causes stresses in the part exceeding maximum flight loads by a predesignated "proof factor" (the proof test load is defined by the limit load times the proof factor). Ideally a proof test achieves two things. First, it demonstrates that the part can survive a quasi-static load greater than it will ever see again in service, thereby providing confidence that a static strength failure later is unlikely to occur (but still possible if continued fatigue crack growth occurs after the proof test further degrading residual strength). Second, a proof test should load a part such that if a pre-existing crack-like defect, a_{crit}, were present that causes the residual strength of the part to be exceeded, a failure would occur in the test, thereby revealing its defective nature before flying. Furthermore, the a_{crit} defect must be smaller than or equal in size to the CIFS. If this condition is met, the proof test can be said to screen the part, just as NDE otherwise would, for the critical defect. If this condition is not met in an early design iteration, changes to geometry or loading may help.

Overall, proof testing can be an effective certification method, but the extent to which limit load can be enveloped by the required factor at all locations in the part is highly dependent on part geometry and flight load complexity. Pressurized parts such as tanks or tubing are most suitable for proof testing as the dominant flight load (pressure) may be easily recreated on a ground test fixture.

A leak check entails pressurization up to a predetermined factor applied to maximum flight loads and measurement of leakage at locations of concern during that pressurization. The leak check may be performed according to project requirements. For example, NASA commonly requires a leak check pressurization at the maximum design pressure (i.e., factor of 1.0) using Helium as the pressurant for the test. The success criteria of the leak check should be a measured leak rate less than an allowable threshold defined by the project.

3.1 Implementation Approaches

One option to consider for implementation of fracture control is to treat AM hardware the same way that castings and welds are treated in existing fracture requirements [3]. Welds are addressed directly in current NASA documentation and the requirements include proof testing, post-proof test NDE (surface and volumetric), and damage tolerance analysis. The reason for specific requirements for welds is because of an increased risk of introducing flaws at weld locations. This is analogous to AM parts except that the entire part may share this same increased risk.

Often if one or more components of the fracture control methodology for welds cannot be met, a bespoke "alternate approach" may be developed that is deemed to meet the intent of the requirement but consists of a combination of NDE, process control, proof testing, damage tolerance analysis, and other case-specific details. Despite similarities with welds, AM parts likely will fall short of complete compliance with existing requirements if they are treated like welds due to NDE challenges. However, it is a useful starting point and a fracture control implementation for AM parts may resemble methodologies developed for welds that also are non-compliant.

Three Fracture Control Certification Methodologies (FCCM) are proposed for implementing on fracture critical AM parts. The approaches described should not be considered as requirements or even as early versions of requirements. They are presented here for the purpose of generating discussion and encouraging critical thought.

3.1.1 FCCM-1: Damage Tolerance Fracture Analysis

FCCM-1 consists of performing damage tolerance flaw growth analysis assuming the minimum detectable flaw size at the worst case location and orientation. In addition to the fracture analysis, a proof test and an acceptance leak check on pressurized hardware are needed. FCCM-1 relies on a NDE technique that can reliably find flaws equal to or larger than the CIFS at all locations of concern. The NDE technique should be a certified process that can reliably find 90% of critical flaws with a 95% confidence level. Russell et al. also noted that for fracture critical parts, the CIFS may be used to help define the needed NDE capability [11].

Sufficient and reliable NDE may be challenging for certain AM parts due to surface finish, internal geometric features, other irregular part geometry, or the presence of hard-to-find closed cracks. This challenge may be counteracted by designing a more structurally robust part as, generally, the more robust a structure is the lower the stresses are and therefore the larger the CIFS, thereby making it easier to find using NDE. This approach may be optimized by only locally driving up the CIFS at critical stress locations or at locations where NDE is not effective. If the CIFS cannot be reliably found using NDE, FCCM-1 is not a valid methodology to certify a fracture critical part.

Additionally, a proof test and leak check on flight hardware should be performed for pressurized parts. The proof factor may be calculated using Eqn. (1)

$$Proof\ factor = burst\ factor\ x\ \frac{1.5}{2.0} \tag{1}$$

Recall, the proof test pressure is determined by multiplying the maximum design load (limit load) by the proof factor. The ultimate strength requirement for a tank is defined by the limit load multiplied by the burst factor. The burst factor should be defined by the project. Note, the ratio included in Eqn. (1) is also used in existing industry requirements for composite overwrapped pressure vessels [18].

The proof test should be accompanied by a fracture analysis with the proof loading applied in order to determine flaw size, a_{crit}, that is being screened by the proof test at all locations. Ideally, a_{crit} determined under the proof test load is *smaller than or equal to* the CIFS determined under flight loading.

The proof test analysis should be correlated with the test experimentally using strain gauges or digital image correlation (or another similar technique to measure linear elastic response). Additionally, a burst prediction should be made using the analysis (i.e., stresses exceed ultimate strength of the part). A post-proof test NDE should be performed in order to assess if any previously undetected defects were opened up during the proof test. Finally, at least one test article should be loaded to failure for a burst prediction correlation.

3.1.2 FCCM-2: Damage Tolerance Simulated Service Life Test

FCCM-2 is similar to FCCM-1 except that instead of a damage tolerance analysis based on the minimum flaw size that a reliable NDE technique can find, simulated service life damage tolerance testing is performed where parts containing intentional defects are subjected to a flight-like load spectrum. FCCM-2 may be used in cases where NDE is not of sufficient fidelity or reliability to support FCCM-1. The success criteria of a simulated service life test should be that none of the defects grow to the extent that a structural failure occurs or any other catastrophic hazard would be introduced.

Test articles should consist of a full scale flight-like part, or if this is not feasible, a realistic representative test coupon. The test articles should contain all defects of concern which generally at a minimum should include crack-like surface flaws at worst-case locations and orientations. If NDE is not used as the basis for initial flaw size definition, some other rationale should be used to size initial defects such as the CIFS determined by analysis or a probabilistic understanding of expected flaws. Multiple defects may be placed in one test specimen in order to assess damage tolerance at various locations of interest in a single test. Embedded defects may be introduced deliberately in the AM manufacturing process if this technique is shown to produce realistic flaws based on an understanding of flaw types that may occur unintentionally for the part-specific process being used. Other techniques for introducing flaws may include laser or electrical discharge machining. Note that introduced defects may require “pre-cracking”, where the flaw is loaded in fatigue until a “natural” sharp crack-tip is formed. Generally, “blunt” defect fronts are more resistant to growth under load, so pre-cracking is performed to capture a worst-case condition in terms of propensity for crack growth. Physical access limitations and complex loading needed to pre-crack defects may cause the introduction of flaws to be the most challenging aspect of FCCM-2.

Loading in the simulated service life test should encompass whatever the minimum service life requirement is. For example, NASA requirements commonly call for a scatter factor of four, i.e., a minimum capability of four service lives. Embedded defects and their growth should be characterized at the end of the test by destructive or non-destructive means to observe that they were implemented as intended and to quantify any growth that occurred. Crack growth mapping of flaw size versus applied cycles should be obtained to the point of failure if possible. Finally, flaw growth observed during the test should be compared to fracture coupon test data in order to demonstrate similitude between flight unit behaviour and expected fracture mechanics material data. If this similitude is established, there may be rationale to extend the damage tolerance analysis to other locations in the part. For pressurized hardware, a proof test and leak check should also be performed according to guidance described in FCCM-1.

3.1.3 FCCM-3: Proof Test

FCCM-3 involves performing a proof test similar to that which is described in FCCM-1. Proof testing is most effective where a simple load applied in a lab test set-up (such as pressure) can effectively simulate and envelope expected flight loads at all locations in the part. Tanks or other pressurized hardware may be best suited for FCCM-3.

For pressurized hardware, the proof test should follow guidance described in FCCM-1. If there are locations of concern where the CIFS is not screened by the proof test, zone-specific or custom NDE should be implemented at these locations that can reliably detect the CIFS. Consider also local redesign in these zones such that stresses are reduced thereby increasing the CIFS so that it can be screened by the proof test or be reliably detected by NDE. Addressing local regions not enveloped by the proof test in this manner should be minimal. FCCM-3 is not an appropriate approach if the region(s) uncovered by proof test is widespread throughout the part.

In addition to the proof test, residual strength and proof test coverage mapping should be performed. Residual strength mapping in this case consists of writing a static strength margin at all locations in the part assuming that a defect sized according to either the CIFS or the NDE capability is present.

3.1.4 Discussion

Each of the FCCM approaches proposed here are intended to cover a different scenario where implementation of existing fracture control practices is impossible or impractical. The intent of each FCCM is to mitigate catastrophic failure of structures resulting from growth of an undetected crack-like defect. Recall that in taking this approach, the design requirements for all critical parts include demonstration of continued structural integrity and performance throughout the entire service life even if an undetected defect is present. Each FCCM achieves this goal by differing combinations of damage tolerance assessment, NDE, proof testing, and leak testing.

FCCM-1 assumes a robust NDE capability and is most in-line with fracture control implementation on parts built using legacy manufacturing techniques. The analogy mentioned of treating AM parts similar to welds is the closest in FCCM-1.

FCCM-2 assumes a lower quality NDE capability and therefore relies on a full scale test to demonstrate damage tolerance. Beyond NDE limitations, FCCM-2 may be considered useful in scenarios where even greater uncertainty exists. For example, rocket engine components were identified as one of the main applications of AM hardware so far in the spaceflight industry. Rocket engine components may preclude fracture mechanics analysis (FCCM-1) due to the extreme thermal environment. Proof testing (FCCM-3) can be challenging also if loading and part geometry are complex. However, a full scale damage tolerance test, FCCM-2, may be achievable if the AM build process is able to intentionally include crack-like flaws at any location desired. If FCCM-2 is taken, a qualitative CIFS analysis should be performed with the goal of understanding critical flaw locations and orientations and designing the test article with this information in mind.

Finally, FCCM-3 is intended for parts where development of a proof test that is not overly expensive or complex can envelop flight loading at all locations in the part. For example, pressurized hardware may be well suited for this approach.

A final thought on fracture control of AM parts is regarding the single dominant crack assumption often used with fracture control of parts built from heritage manufacturing techniques (i.e., forged, wrought, etc.). The assumption is that in a given part, there is only likely to be a single crack initiation location. It is worth reconsidering this assumption for an AM part if there is any chance that the microstructure includes small undetectable flaws that are widely distributed or clustered in multiple locations. The concern in this scenario is that there may be damage tolerance for a crack at any one initiation site, but if initiations at multiple sites coalesce, the resulting crack(s) may lead to failure. The single dominant crack assumption may be valid for an AM part if it is shown through fatigue testing specimen post-mortem observations that the phenomena described is not likely to occur.

4. Design for AM Fracture Control

An active area in AM technology development is known as “Design for AM”. This methodology takes the position that AM should be utilized beyond simply producing existing parts cheaper but actually enabling new product forms that are more efficient and/or functional that otherwise could not exist using legacy manufacturing methods [18,4]. A subset of “Design for AM” may be “Design for AM fracture control”. The following discussion on “Design for AM fracture control” is high level and serves only to introduce the concept.

One goal in “Design for AM fracture control” may be designing parts to be non-fracture critical (NFC). Failsafe is one NFC designation used by NASA [1] in fracture control to identify parts that, if failed, do not result in a catastrophic hazard. While a traditionally manufactured part may have a single load carrying member, an AM part may be created to have multiple smaller members with intricate geometry where if any one failed, the overall part would still sustain the design load.

Low risk is another NFC classification used by NASA [1] to identify lightly loaded parts that may have a catastrophic consequence of failure, but are highly unlikely to fail due to meeting strict criteria including, among other things, stresses less than 30% ultimate strength and fatigue analysis demonstrating 4 service lives with a factor of 1.5 on cyclic stress. In general, one of the strengths of AM hardware is that part geometry can be highly optimized for meeting strength allowable-based design criteria. While existing NASA MSFC M&P standards currently prohibit a NFC low risk classification for any AM part, strength-based optimisation strategies could be modified to target the low risk strength and fatigue thresholds specifically. While this would not qualify a part entirely for a low risk classification per NASA requirements, it may contribute to an overall certification methodology.

"Design for AM fracture control" may also include efforts to design parts able to be proof tested. As discussed, proof testing is most effective on hardware types that can be subjected to a simple load in a lab test apparatus that envelopes flight loading at all locations in the part. The example used previously is a tank where a single pressure load may accomplish this. For parts subjected to more complex loading and with more complex geometry, a fully enveloping proof test can be difficult.

AM techniques may offer opportunities to alleviate this challenge. At a conceptual level, some options could include building-in load application points, "lever arms" that could facilitate applying loads, or test fixture attachment points. The features could then be severed after the proof test is complete. Another option may be simulation of a proof test, mapping flight load coverage, and then optimising part design such that flight loads can be sustained, proof testing achieves full coverage on a part, and the proof test screens for the CIFS. An area of future work may include enhancement of optimisation algorithms to design for proof testing in parallel to flight loading.

Finally, another measure that may be taken, as mentioned in the FCCM-1 is intentionally driving the CIFS to be larger at locations of concern by increasing structural robustness. Within "Design for AM fracture control" this approach is based on the concept of treating NDE capability as part of the design constraints. The CIFS is a function of material properties, local geometry, and stress, so a mapping strategy may again be useful to identify initially non-compliant locations to target geometry changes to drive up the CIFS size such that it falls within NDE capabilities.

All of the concepts described within "Design for AM fracture control" are applicable outside of AM also, however, AM may offer increased ease of implementation due to an enhanced ability for geometric optimisation.

5. Conclusions

Human-rated spacecraft structures are often subject to fracture control requirements for certification. There is not existing NASA guidance or requirements specifically addressing fracture control certification of additive manufactured hardware. While there are ongoing efforts at various regulatory organisations to mature AM standards, including NASA Materials and Processes requirements, fracture control has yet to be addressed directly in the context of fracture critical spacecraft certification. Three different Fracture Control Certification (FCCM) methods are proposed that are meant to meet the intent of existing NASA fracture control requirements. FCCM-1 involves a "traditional" approach to fracture control where a part is shown to be damage tolerant to all flaws below the NDE detection capability. FCCM-2 is for cases where the NDE capability is insufficient for use of FCCM-1. FCCM-2 involves full scale simulated service life testing with defects included intentionally in test specimens. FCCM-3 is a proof test approach most applicable to parts where proof testing can effectively envelope flight loads at all location in the hardware. Finally, a "Design for AM fracture control" concept is introduced where it is proposed that structural design goals include considerations such as existing NASA non-fracture critical criteria, critical initial flaw size, and proof test coverage. Overall, fracture control implementation on AM parts needs continued collaborative discussion between spacecraft certification organisations and industry so that documented guidance and requirements may be improved.

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