NASA'S CERTIFICATION AND QUALIFICATION CHALLENGES FOR ADDITIVELY MANUFACTURED HARDWARE: WHAT IS NEXT?

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ABSTRACT
In 2021, NASA released NASA-STD-6030 "Additive Manufacturing Requirements for Spaceflight Systems" to create qualification and certification strategies for mature metallic and non-metallic AM materials and technologies. While these standards have had an immediate impact on the additive manufacturing (AM) industry, there remain many challenges that have yet to be overcome. NASA and its partners in academia and industry are working together to proactively address these issues. One of the most critical needs is a Probabilistic Damage Tolerance Assessment (PDTA) approach, which includes the development of computational modeling, understanding the "effect of defects", and the implementation of in-situ process monitoring and inspection techniques.

1. INTRODUCTION

Additive manufacturing (AM) is increasingly investigated for critical spaceflight applications due in large part to the advantages afforded by AM in terms of cost, schedule, and development time. In 2021, NASA released NASA-STD-6030 "Additive Manufacturing Requirements for Spaceflight Systems" [1] to create qualification and certification (Q&C) strategies for mature metallic and non-metallic AM materials and technologies. While NASA-STD-6030 does much to establish the basis for AM Q&C, AM technology evolution continues at a rapid pace bringing new technical challenges to be overcome. Many of these challenges are rooted directly in the AM technology, such as having a multitude of lasers on a laser powder bed fusion (L-PBF) AM machine or interpreting the capability and reliability of the data stream from the evolving sensor suites now becoming commonplace on many AM machines. Another aspect of the AM challenge in Q&C has to do with the type of hardware that users desire to produce which places the most complicated of geometries into critical applications. Most often this leads to an unfortunate combination of critical AM parts that offer little or no access for quantitative, post-build surface and volumetric non-destructive evaluation (NDE).

For NASA, such critical applications are subject to a set of requirements intended to prevent catastrophic failure of a component due to an undetected defect. The requirement set is defined in NASA-STD-5019 "Fracture Control Requirements for Spaceflight Hardware" [2], and the associated discipline is known as Fracture Control.

AM materials pose challenges to traditional approaches to Fracture Control due to increased variability in material quality, higher potential for flaws, limited heritage, and the aforementioned inspection challenges. These challenges in particular, where geometric flexibility afforded by the AM process leads to designs that are difficult to inspect, leaves critical AM applications without clear, quantitative rationale for fracture control.

NDE inspections are foundational to most Fracture Control rationale in that the inspection bounds the flaw size that might go undetected in the component. As part of Fracture Control, components are shown to be "damage tolerant", meaning the component can fulfill the mission requirements even if a flaw were present in the component in the location with the most significant impact on structural integrity. Most designs are not tolerant to arbitrarily large flaws, so an inspection is required to bound on the size of this critical flaw is bounded by. The initial flaw size for the damage tolerance analysis corresponds to the largest flaw that an NDE inspection might miss.

In the absence of reliable inspections to bound initial flaw sizes, Fracture Control requirements cannot be met through traditional approaches. Thus, alternative rationales are needed to support certification of Fracture Critical AM hardware with limited or no post-build inspectability. Fracture Critical AM components with limited inspectability will be flown on future NASA missions. Such components present a potentially significant risk to those missions.

The approach for developing rationale for un-inspectable AM components may be based on flaw state characterization, identification and control of process escapes, and probabilistic damage tolerance analyses. The Project was divided into subtasks to investigate each of these topics.

2. FLAWS VS. DEFECTS

In many fields, including AM, the terms “flaws” and “defects” are used interchangeably. However, in the NDE discipline, these terms have distinct meanings and implications. ASTM Standard E1316-22a “Standard Terminology for Nondestructive Examinations” [3] defines a “flaw” as an imperfection or discontinuity in a material. A “flaw” is distinct from a “defect.” A defect is a flaw that is rejectable per a specified acceptance criterion. Thus, the term “defect” implies that a discontinuity or imperfection (a flaw) has been assessed for suitability for some application. Many AM flaws that arise as a natural aspect of the AM process are extremely small and when acting individually are unlikely to have significant impact on structural integrity in most cases. In such cases, AM material imperfections will not constitute a rejectable condition; thus, using the term “flaw” to refer to the generalized set of AM material imperfections, in alignment with ASTM E1316, is appropriate. This terminology also serves to clarify that not all AM flaws represent a rejectable condition and, in many cases, AM material containing flaws will be perfectly acceptable for structural applications.

AM flaws arise from a multitude of conditions, some of which are innate to the AM process, at least at the current state of technology, and others which can potentially be avoided because they stem from a deviation to the intended process operation. Using the distinction between those flaws that arise as a natural consequence of the AM process and those that result from a process deviation provides a framework for considering the range of potential defects in an AM part. The primary benefit of this hierarchy is that is lends itself to the systemic application of process controls to eliminate or reduce the likelihood of defect states through deliberate process qualification and characterization followed by the application of Process Failure Modes and Effects Analysis (P-FMEA) tools to help control the escape that lead to flaws. These process control foundations become an important anchor to developing a damage tolerance rationale for a particular component. Within the scope of AM flaws, two flaw categories are proposed: inherent flaws and process escape flaws.

2.1 Inherent Flaws

An <u>inherent flaw</u> is a flaw that is representative of the characterized nominal operation of a qualified AM process. There are two main implications of this definition. First, the inherent flaw has been “characterized” through an assessment of the nominal flaw state in the material produced by the AM process. With the potential exception of the extreme tail of the distribution on the large side, inherent flaws are expected to be common enough that direct characterization is possible. The characterization of flaw state includes an assessment of flaw size and rate of occurrence. The characterization should also account for influence factors that affect flaw states, such as variations in thermal history. Second, the inherent flaw state is associated with a qualified AM process, so that a nominal material condition is defined and controlled. For NASA applications, “qualified” implies that the AM process meets the requirements of NASA-STD-6030, including the associated process controls, traceability, and material characterization requirements. A qualified and locked AM process is necessary to define an inherent flaw state so that a consistent material quality baseline is established.

A significant risk in quantifying the inherent flaw state arises from inadequate characterization at the time of process development and qualification. If the qualified process creates significant defects that remain undetected and/or uncharacterized during qualification, these deficiencies will invalidate the rationale associated with the controls on the inherent flaw state. The parts may contain unknown inherent flaws. Each part produced must be evaluated and qualified that it represents the intended implementation of the process and reflects only the known inherent flaw state. An example of an inherent defect that could escape detection due to inadequate process qualification could be defects at the contour-to-core interface in L-PBF due to inadequate refinement of those parameters. A proper and thorough qualification of the AM process and the resulting AM part are essential.

Since the inherent flaw state represents the nominal process operation of an AM process, the effect of the inherent flaws on material properties, such as tensile, fatigue, thermal conductivity, etc., is expected to be accounted for within the material characterization work performed as part of process qualification. NASA AM requirements are intended to ensure consistency in the AM process, which implies that properties are generated on material that is representative of the nominal process flaw state. Thus, it may be reasonably assumed that material characterization data, used to support component designs and assessments, reflects the impact of the inherent flaw state, particularly if influence factors that may cause variability between coupon-level material assessments and AM components have been appropriately considered.

The expectation that the inherent flaw state is represented in the basic material characterization is appropriate for typical structural assessments. For fracture control, some knowledge of the bounding size of the inherent flaw is necessary. If quantifiable NDE is in place, the reliable detection capability of the NDE is commonly used. If no NDE is feasible, the bounding conditions of the inherent flaw size may be estimated through extreme value statistical methods, or be bounded by practical arguments based on the physics of the AM process when operating within normal bounds.

2.2 Process Escape Flaws

The second category of AM flaws in this framework is the process escape flaw. Process escape flaws are those that not inherent and are the result of some sort of deviation from the nominal operation of the AM process. This category includes many types of flaws, e.g., keyhole pores, lack-of-fusion, or unconsolidated powder. Flaws in this category have in common that they originate from a process escape. So, in controlling these flaws, we concentrate on preventing the escape rather than focusing solely on the character or geometry of the flaw. Many process escapes can manifest themselves in a variety of flaw types. A well-controlled AM process should have a very low occurrence rate of process escape flaws. Processes that produce high frequencies of process escape flaws should be considered out of control and thus require improvement. Most critically, process escape flaws may or may not be detectable.

Inherent and process escape flaws are not defined by their size, although inherent flaws are anticipated to be small, and process escape flaws are expected to be generally larger, depending on the associated failure mode. These two categories are also not defined directly by occurrence rate, but they naturally reflect this because the inherent flaw state is always expected and process escape flaw should be rare.

Defining these two general categories of flaws allows for systematic evaluation and prevention of the flaw states within the process qualification and characterization to define control the inherent flaw state and the controls of the P-FMEA methodology employed during operations to control the process escape flaw state.

Note that the term “rogue flaw” is commonly used within the damage tolerance discipline to refer to an exceedingly rare flaw with severe impacts on the structural integrity of a component. The term for “process escape flaws” was chosen to avoid the connotations associated with “rogue flaws” regarding rarity and severity. Unfortunately at this time in AM, process escape flaws are not exceedingly rare as implied by the “rogue flaw” nomenclature. And they also may or may not be severely impactful on the structural integrity of an AM component. Instead, process escape flaws are distinguished only by the fact that they occur due to off-nominal operation of the AM process.

2.3 Example Flaws

Some examples of inherent and process escape flaws follow. The examples shown are intended to demonstrate flaws that are representative of a generic, qualified L-PBF process. Note that the inherent flaw population must be evaluated for each particular process, and the examples shown may not intended to be broadly applicable for all processes.

2.3.1 Example inherent flaws

Examples of inherent flaw types are pores, small lack-of-fusion, and inclusions. Each of these can have multiple causes and can be further sub-divided. Pores, such as those shown in Fig. 1, are small voids in the material that have a variety of causes and morphologies. Reduced gas solubility upon cooling and solidification shrinkage are two mechanisms that affect traditional cast as well as AM materials. Mechanisms for porosity common to AM include the formation of keyholes (shown in Fig. 2) due to excess input energy, hollow powder particles that contain gas that cannot escape the melt pool, as shown in Fig. 3, and entrapped inert gas from the build chamber. Lack-of-fusion flaws (Fig. 4) are characterized by interfaces within the material that do not form a metallurgical bond. These can be caused by insufficient energy input with respect to cooling conditions, irregular cavity shapes that are difficult to fill with the melt pool, and evaporation or condensation within gas pores that inhibit complete melting. Inclusions can take several forms; one example, shown in Fig. 5, is a large ejecta particle that redeposited on the powder bed and was sintered in subsequent laser passes. Other forms of inclusions include non-metallic particles that form or become entrapped in the material. They can be caused by reactions between the base material and the build environment, particularly oxygen. An example is the nitride particle shown in Fig. 6, that formed during melting due to high nitrogen content in the powder or by trapping and reacting with nitrogen process gas. Other types of inherent flaws may be present given the specific physics of the AM process.

The risk of unknown inherent flaws must be concluded through thorough process qualification and part evaluation and qualification. Examples of defects which may be inherent to a poorly developed process include microcracks, like shown in Fig. 7, due to poor parameter choice in a difficult AM alloy. Fig. 8 illustrates the prior stated example of poor contour-to-core interface caused by inadequate build parameter development. A poor scan strategy within a part combined with inadequate energy application can cause small volumes which the powder is not fully sintered, leaving pockets of unconsolidated powder like the one shown in Fig. 9. Each of these examples of unknown inherent flaws must be precluded in the process and part qualification stages.

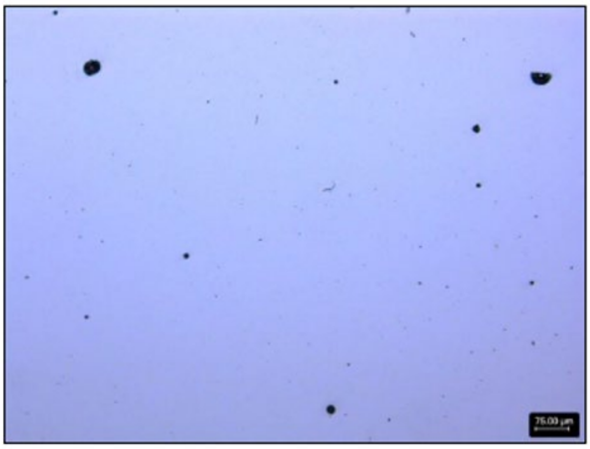

Figure 1. Example of typical porosity found in a build.

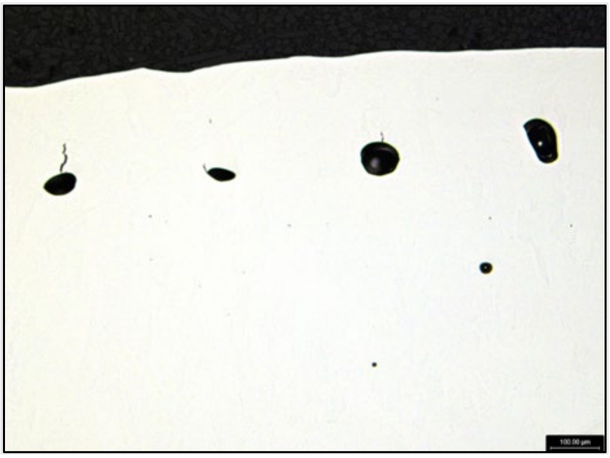

Figure 2. Example of keyholing

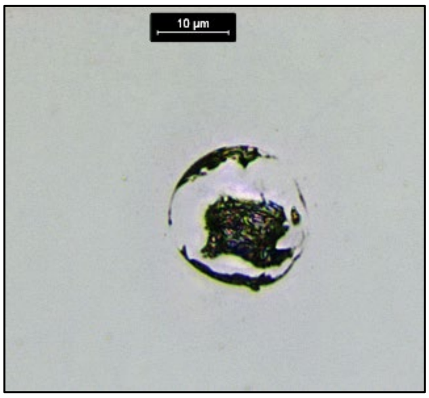

Figure 3. Example of an incompletely melted powder particle with entrapped porosity.

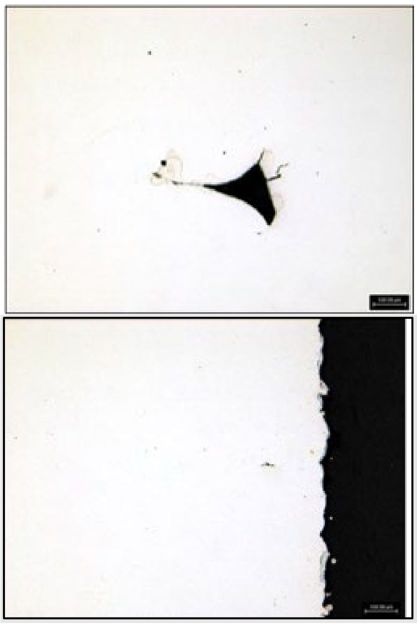

Figure 4. Examples of lack-of-fusion flaws

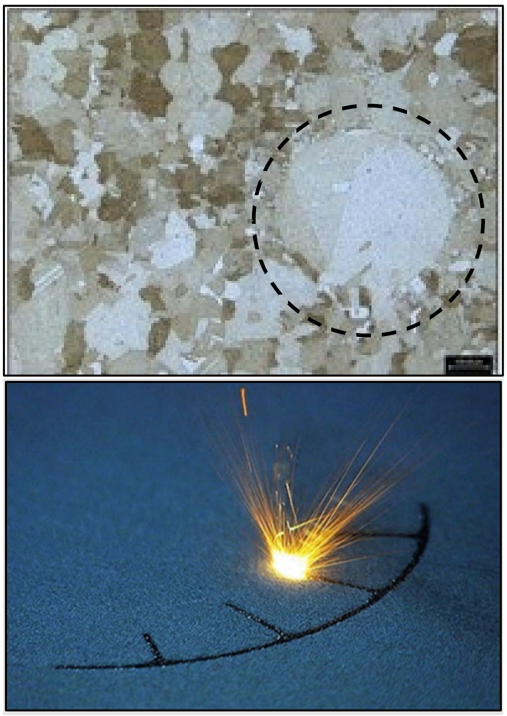

Figure 5. Example of an embedded ejected particle (left) and an example of ejected particles happening during processing (right).

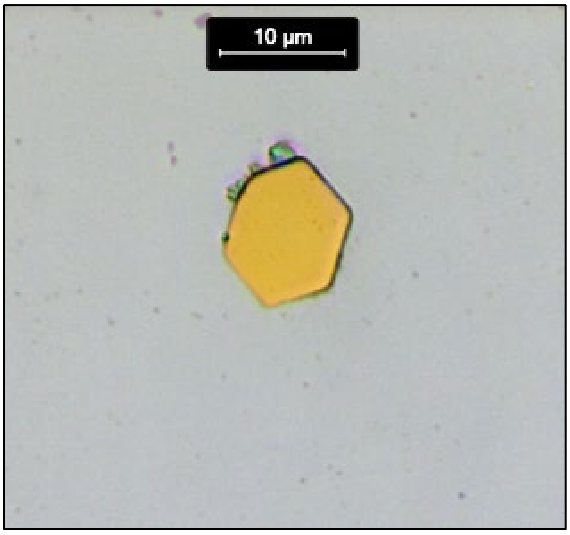

Figure 6. A nitride particle formed during the AM build process.

2.3.2 Examples of process escape flaws

Process escape flaws are associated with some sort of failure in the AM process; examples include cracks, unconsolidated material, and widespread structured porosity. In fact, each of the types of flaws illustrated in the inherent flaw category (lack of fusion, spatter, etc.) could also be examples of process escape defects depending upon how the escape manifests. There are defects that occur exclusively due to escapes. Commonly these reveal themselves concentrated or ordered groupings of typical defects. For example, Fig. 10 shows an occurrence of structured porosity caused by insufficient powder due to a short feed.

Some process escape flaws are immediately obvious and would usually stop a build from completing under reasonable monitoring conditions. Examples might include flaws leading to recoater damage, significant component delamination, or significant layer misalignments. Other process escape flaws may not be detectable and could be present in a completed part. Examples might include defects due to missed scan paths due to machine instruction errors, embedded foreign object debris, or powder contamination. A change in the frequency of process escape flaws is indicative that the AM process has shifted from the original qualification state and additional investigation into the process is needed.

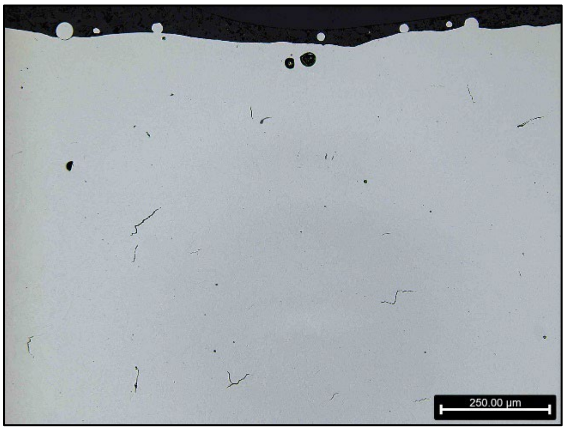

Figure 7. Example of microcracking

Figure 8. Example of contour-to-core interface porosity

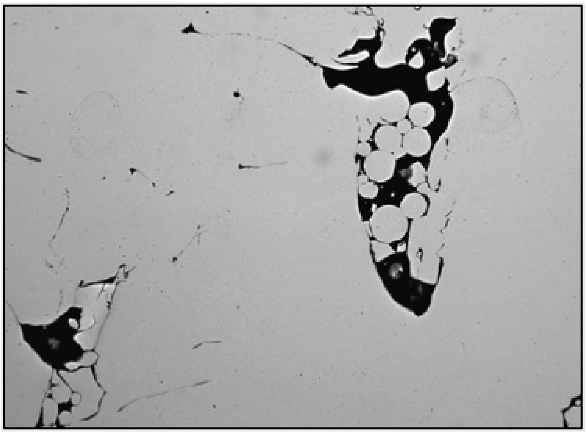

Figure 9. Example of unconsolidated powder

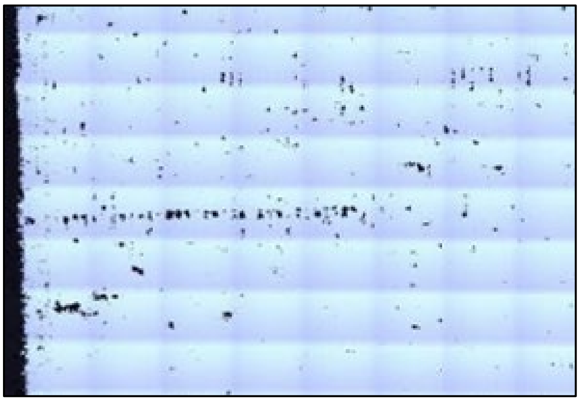

Figure 10. Example of structured porosity caused by a short feed

3. A PHILOSOPHY FRACTURE CONTROL FOR UN-INSPECTABLE COMPONENTS

The concept of the inherent and process escape flaw distributions provides a systematic approach to assess risk associated with un-inspectable AM components. The following discussion assumes Class A AM components per NASA-STD-6030 “Additive Manufacturing Requirements for Spaceflight Systems” that are produced via a Class A Qualified Material Process (QMP-A) or equivalent. Fracture critical components are, by definition, associated with a catastrophic failure mode; therefore, fracture critical components are, by definition, Class A AM components per NASA-STD-6030. The level of effort described would not typically be required of components of lower criticality, although the assessments described may be beneficial to overall AM component integrity analysis for parts with lower classifications.

3.1 AM Process Assessments

While ever-improving, current metallic AM processes do not produce perfectly dense material. All practical implementations of metallic AM processes generate some degree of porosity, flaws, or voids, even when operating nominally. Off-nominal process operation, however, has the potential to result in severe flaws. Since flaws are currently an unavoidable reality of metal AM processes, systematically defining, characterizing, and controlling for flaws represents an AM process-level assessment that can be used as a foundation for developing fracture control rationale for un-inspectable components.

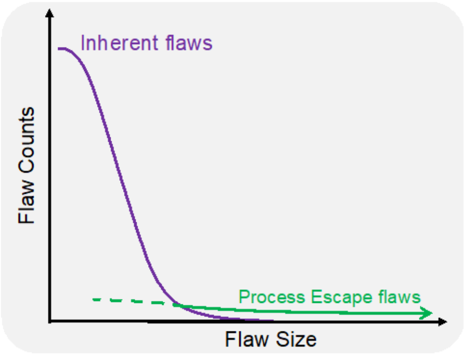

Figure 11. Notional AM Flaw Distributions

3.1.1 Inherent Flaws

In a well-controlled AM process, inherent flaws are typically small but tend to be frequent. The frequency with which inherent flaws occur supports direct characterization of inherent flaw distributions, whereby the occurrence rates of inherent flaws can be directly estimated. A notional inherent flaw distribution is shown in Fig. 11.

Appropriate characterization of the inherent flaw distribution is critical for the application to fracture control rationale. To be robust, the inherent flaw state characterization should include material that reflects the edges of the process box; that is, the flaw state distribution represents the process working at its acceptable limits. This allows both for conservative estimates of the inherent flaw population and improves coupon-to-part transferability by covering potential flaw population variations arising from a particular build geometry. Broadly applicable flaw state characterization might be accomplished by adjusting machine parameters to generate material reflective of the variability within the AM process; however, care must be taken to ensure that artificial machine parameter adjustments remain appropriately indicative of the nominal process operation. A more appropriate approach might be to produce bespoke “flaw state characterization” coupons or builds that are designed to represent challenging build geometries.

NASA-STD-6030 currently requires assessments of the material quality for the establishment of a QMP, including cursory evaluation of flaw states. A full evaluation of the inherent flaw state expands upon this existing requirement by providing a statistical definition of the inherent flaw state that can be used to inform fracture control assessments.

As described prior, with the exception of rare large flaws in the tail of the inherent flaw distribution, the effects of the inherent flaw distribution are included during the material characterization and no special treatment for flaw assessment is necessary, assuming critical flaw sizes for a part are reasonably beyond the tail of the inherent flaw distribution. In this case, the inherent flaws manifest as variability within the material property values, similar to more established variability sources such as chemistry limits and heat treatment tolerances. The rationale is based on controlling the AM process such that the resulting material remains within the characterized inherent flaw state.

3.1.2 Process Escape Flaws

Whereas inherent flaws are expected to be common enough for direct characterization, process escape flaws are expected to be relatively rare, or at least uncommon enough to preclude direct characterization. As a result, screening for process escape flaws requires understanding the potential sources of the process escape flaws, which requires understanding the potential failure modes associated with the AM process. The P-FMEA analysis provides a framework for systematically evaluating AM process failure modes and assessing the potential resulting process escape flaws.

P-FMEAs are common manufacturing process evaluation tools used to identify and address manufacturing risks. The PFMEA analysis identifies the ways in which a process can fail and assigns rankings to each failure mode based on the severity, the occurrence rate, and the detectability of the process failure. The scores, commonly ranked on a 10-point scale, are then multiplied to produce a Risk Probability Number (RPN). The degree to which a process failure is detrimental to the appropriate application of that process can be evaluated by comparing RPN values for different process failures. Commonly, failure modes with a RPN value higher than some threshold would be subject to process improvements intended to reduce the RPN value below the threshold.

In the context of Fracture Control for AM, the P-FMEA provides a means to thoroughly assess the AM process and identify the potential process escape flaws that can occur. From there, rationale can be developed to preclude flaws from each failure mode. Multiple rationales are envisioned. For some process failure modes, high detectability or low severity might be sufficient rationale to deem resulting process escape flaws as non-credible. For others, physics-based rationale might be used to conservatively bound the size and occurrence rate of the potential resulting process escape flaw. In cases where flaws may be credible and no reliable bounds on size and occurrence are possible, assessments of the flaw probabilities may be developed to support probabilistic damage tolerance assessments. A notional process escape flaw distribution is shown in Fig. 11. The P-FMEA itself is intended to be performed based on the AM process with no assumptions regarding the actual components that might be produced using that process. This component-agnostic approach allows for flexibility in applying the P-FMEA. The component-agnostic approach manifests most significantly in severity scores, which should be based on the degree to which a flaw arising from a process failure might affect the material integrity, rather than the impact on a specific component. However, the rationale for precluding process escape flaws for a particular component might rely on component-specific logic, as appropriate.

P-FMEAs are not required by NASA-STD-6030. Instead, the P-FMEA is a supporting analysis used to develop process control rationale with adequate rigor to meet fracture control requirements. The application of P-FMEA rigor may vary based on the part/process classification: for a QMP-A producing Class A (Fracture Critical) AM components The P-FEMA is likely to be fully executed, but may be considerably less rigorous for a QMP-B process and is generally unnecessary for a QMP-C process.

4. AM COMPONENT ASSESSMENTS

Once the AM process-level assessments of flaw state distributions are defined, component-specific assessments regarding critical initial flaw size (CIFS) and flaw detection capabilities are performed. Fig. 12 shows an overlay of CIFS and NDE capability on the nominal flaw distributions. Note that the lines drawn for CIFS and NDE capability are notional and are expected to shift based on local conditions. Fig. 12 represents a undesired case of CIFS smaller that the detection capability, which is discussed later.

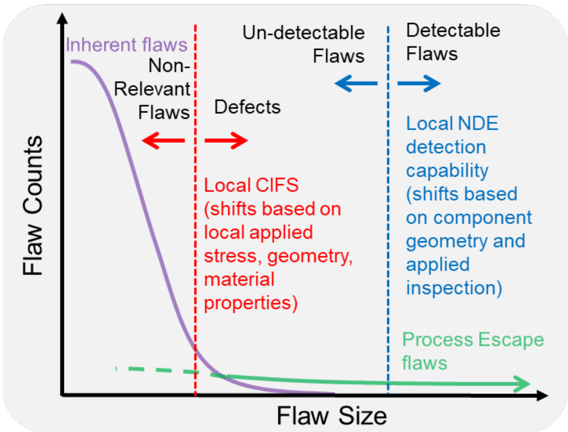

Figure 12. Example of Component-Level Assessments

4.1 Critical Initial Flaw Size (CIFS)

The CIFS is the smallest initial flaw that will cause component failure within the mission life, with an appropriate factor of safety (4x, per NASA-STD-5019A). Flaws larger than the CIFS can be expected to lead to a higher risk of component failure during service; such flaws are defects. Flaws smaller than the CIFS may be expected to be benign; if so, such flaws are non-relevant. The CIFS analysis calculates the smallest flaw size that would lead to component failure within the desired service life, thus any flaw that size or larger would cause failure. The CIFS varies throughout a component, driven primarily by applied stress and the component geometry. Commonly the smallest CIFS present in the component is used for assessments and multiple control points may need to be analyzed to determine the bounding CIFS. For AM applications, a more localized evaluation of CIFS at multiple points in the component might be necessary, particularly to support comparison with localized NDE detection capabilities, or to account for material property or flaw state variability.

4.2 Minimum detectable flaw size

The minimum detectable flaw size is the smallest flaw size that can be detected with NDE with a sufficient degree of reliability. Typically, this flaw size is defined as the flaw size that can be detected 90% of the time with a 95% confidence [4]. Minimum detectable flaw sizes vary locally, depending on the geometry of the component and the applied NDE technique. Some NDE techniques are limited to surface features, while others are intended for volumetric inspections. AM components can challenge traditional NDE, for example, due to rough surfaces or complex geometries that limit line-of-sight. These complexities will affect existing standard minimum flaw size estimates.

Note that the geometry of an AM component might make NDE inspection impractical or impossible. In such situations, there may be no minimum detectable flaw size; the blue line in Fig. 12 may not be applicable. In this "un-inspectable" component scenario, any CIFS would be lower than the NDE detection capability.

4.3 Risk Scenarios

The relationships between the CIFS, the minimum detectable flaw size, and the inherent flaw distribution define the risk scenario for a component and thus the appropriate approach towards a Fracture Control rationale.

4.3.1 Risk Scenario 1: CIFS within inherent flaw distribution

Risk Scenario 1 involves a situation where the CIFS falls within the inherent flaw distribution regardless of NDE detection capability. Fig. 13 shows the outcomes of the process- and component-level assessments corresponding to Scenario 1. In this Scenario, the probability of a critical flaw in a critical location is high since inherent flaws have high frequencies of occurrence. Thus, this Scenario represents an unacceptable risk. Two options are available: either refine the AM process to lower the size associated with the inherent flaw distribution or change the component design to increase the CIFS.

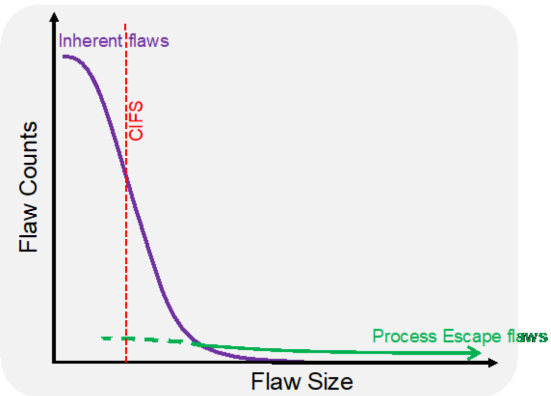

Figure 13. Illustration of Risk Scenario 1, where the CIFS is within the inherent flaw distribution.

4.3.2 Risk Scenario 2: CIFS smaller than minimum detectable flaw size

Risk Scenario 2 involves a situation where the CIFS is below the minimum detectable flaw size, but the CIFS is above the tail of the inherent flaw distribution. Note this scenario would apply for the "un-inspectable" AM component, regardless of CIFS. Fig. 14 illustrates this Scenario. In this Scenario, the risk associated with the inherent flaw is mitigated in that the CIFS is sufficiently above the inherent distribution, making the inherent flaws non-relevant. The rationale must then focus on controlling or detecting the process escape flaws.

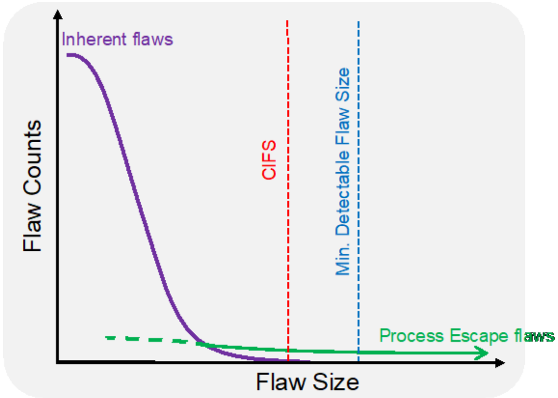

Figure 14. Illustration of Risk Scenario 2, where the CIFS is below the detection capability but above the inherent flaw distribution.

Process escape flaws may be assessed using the P-FMEA approach to identify potential process failures, assess the risk associated with each process failure, and develop rationale to prevent, detect, or characterize the distributions for each process failure.

Assessments of the risks associated with the process escape flaws lend themselves to probabilistic damage tolerance approaches, where a probability of failure is calculated from damage tolerances calculations based on the probability of a critical flaw being present in the component. Probabilistic assessments may facilitate the development of a rationale that relies on demonstrating an acceptably low probability of failure due to process escape flaws and a lack of sensitivity to the inherent flaw distribution. Such a rationale may lead to a risk-based acceptance, requiring a waiver to the NASA-STD-5019 damage tolerance requirements, or may be sufficient to justify a risk-neutral alternative approach. Typically, an approved alternative approach is considered to be commensurate with the baseline risk associated with accepted practices.

Risk Scenario 2 relies on the CIFS being beyond the practical limit of the tail of the inherent flaw distribution, but how that is determined remains an open question. The proximity of the two sizes and how well the quantities are known or bounded will determine how they are treated. A probabilistic approach using conservative estimates of the flaw size and occurrence rate in the tail of the inherent flaw distribution would be required if there is any plausible overlap between the CIFS and the tail of the distribution. Note that there is an expectation that the tail of the distribution can be truncated through arguments of practical inherent flaw size limits based on the physics and length scales of the AM process.

4.3.3 Risk Scenario 3: CIFS larger than minimum detectable flaw size

Risk Scenario 3 involves a situation where the CIFS is above the minimum detectable flaw size. Thus, the critical flaw can be detected reliably by NDE. This represents the nominal, baseline risk condition and meets NASA-STD-5019 requirements. Fig. 15 illustrates this Scenario. Note that Risk Scenario 3 also requires that the CIFS be sufficiently above the inherent flaw distribution.

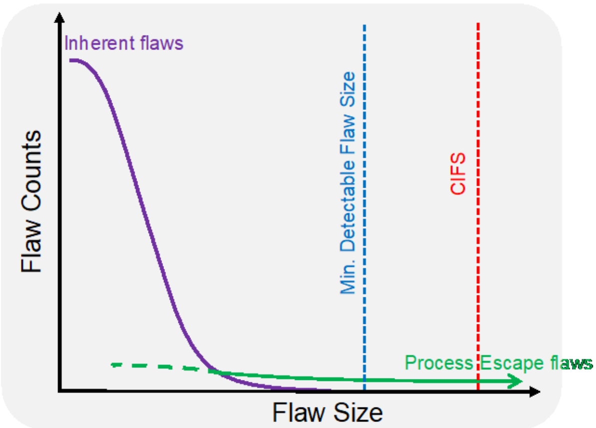

Figure 15. Illustration of Scenario 3, which CIFS larger than the detection limit.

While desirable, Scenario 3 may not be possible for some AM components. However, some regions within a component may be compatible with Scenario 3; in such cases, those zones would represent baseline risk, and would not require further rationale beyond the demonstration that the CIFS is detectable.

Part-Zoning

Traditional damage tolerance approaches are typically based on evaluation of the worst-case CIFS within the part based on bounding conditions. The variability in AM hardware due to geometric complexity, flaw state variation, and NDE accessibility may make the traditional, bounding approach either insufficient or overly conservative. A "Zone-based approach" has been proposed [5] to appropriately account for additional variation in AM parts, and the Risk Scenario approach previously described lends itself to the part-zoning paradigm.

Zones are typically defined by regions with similar geometry, similar NDE, or similar local stresses. The choice of appropriate zones requires engineering judgment and should be primarily driven by these similarities. Features that cause significant shifts in the expected NDE probability of detection or the inherent flaw state should be treated as distinct zones.

5.0 THE ACCOUNTING CHALLENGE AND AVAILABLE MITIGATIONS

In closing, it is important to emphasize that the described approach relies heavily on accounting for and understanding all potential flaw states in AM parts. These include un-identified flaws and/or extreme values in the inherent flaw distribution as well as unidentified process escapes that are not mitigated and may lead to flaws.

5.1 Unanticipated or extreme values in the inherent flaw distribution

Complete accounting of the inherent flaw distribution is dependent on thorough process and part qualification to identify all flaws associated with the process as it is defined and when it operates within its proper limits. While the frequency of inherent flaws distribution is expected to support direct characterization, some extreme values in the inherent flaw distribution may be sufficiently rare that they will not be readily observed and thus not well represented in the baseline mechanical property definition. Probabilistic approaches in the fracture control process are useful for assessing the risk associated with these rare, extreme inherent flaws, assuming that appropriate extrapolations to extreme values are possible.

Truncating the extreme values of the inherent flaw distribution through physics rationale or available quantitative NDE may be useful to contain the risk associated with the extreme inherent flaw.

5.2 Un-identified process escape flaws

The P-FMEA approach is only as good as the rigor associated with the development of the P-FMEA. Process escapes that are not identified during the P-FMEA represent a risk because they are not accounted for in the rationale and may not have mitigations established. The risk of an inadequate P-FMEA may be reduced by pooling resources and experience to develop an appropriately comprehensive listing of potential AM process escapes. With AM machines and technologies rapidly evolving, the user must remain aware that the risk of unknown-unknowns may be significant.

5.3 Mitigating process escapes through In-situ monitoring

In-Situ Monitoring describes several techniques which are used to monitor the build process for indications of process deviation during the process. These in-process inspections can often provide an indication of escapes or flaws which would be more difficult to detect post-production; for example, flaws in internal channels or flaws that will otherwise by obscured by later material additions are difficult to detect post-build. The current state of in situ monitoring technology is frequently challenged to quantitatively identify and size flaws directly. The technologies are typically monitoring for the conditions that may lead to flaws rather than the flaws themselves. In this case, they are one step removed from the traditional role of NDE. They are looking for probable causes rather than flaws directly. This is not incompatible with the approach described in this paper. For process escape flaws in AM parts, the emphasis herein is on identifying the escape that may lead to flaws and mitigating or precluding that escape as identified in the P-FMEA.

The current state of the art of in-situ monitoring allows for establishing confidence in the consistency in the AM process and for detecting a number of notable process escapes. A monitoring system that can establish a monitoring baseline for a component that can be used as a “fingerprint” for subsequent production of that component provides confidence that the AM process is operating as intended, many process escapes of concern are not present, and the inherent flaw state is consistent.

Thus, many forms of in situ monitoring technology are ready for this role of mitigating escapes even if they are not suitable for direct flaw detection. This makes the current in situ technology valuable in this framework by helping to preclude certain identified process escapes that are known to lead to flaws. In an ideal future scenario, the in-situ monitoring would be capable of detection of detrimental AM flaws directly and allow for AM components to be either repaired or discarded before additional time and resources are expended on their construction.

6. REFERENCES

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