NIST Advanced Manufacturing Series 100-4

Findings from the NIST/ASTM Workshop on Mechanical Behavior of Additive Manufacturing Components

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National Institute of Standards and Technology
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U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie May, Under Secretary of Commerce for Standards and Technology and Director

Abstract

Valuable information was gathered from a broad representation of the additive manufacturing (AM) community (150 attendees from industry, academia, and government (research and regulatory agencies)) during this workshop to understand what is needed to enable broader acceptance and increased use of metal AM in fatigue and fracture critical applications. The main needs identified during the workshop were: 1) comprehensive understanding of processing-structure-properties-performance (PSPP) relationships, 2) mature process and material models, 3) trustworthy in-process monitoring and control, 4) effective non-destructive inspection techniques, 5) predictive design tools, 6) traditional qualification framework, and 7) rapid qualification framework. Of these main needs, fatigue and fracture research and standardization efforts show the largest potential to effect understanding of PSPP relationships, and during the workshop many specific areas of interest were identified and prioritized. In general, PSPP investigations should consider statistical variation and utilize both experimental and modeling efforts. A curated AM materials database was deemed highly beneficial to the PSPP effort. PSPP understanding will facilitate development of in-process monitoring and control, non-destructive inspection techniques, and predictive design tools. The main standardization opportunities identified include standard reporting procedures for AM to enhance understanding and facilitate comparison to other results. Evaluation of current fatigue and fracture test methods as well as non-destructive inspection methods were other standardization needs. Finally, a standardized traditional AM qualification framework using the currently available AM processes and inspection techniques was deemed highly necessary, and many felt that regulatory agencies should play a leadership role in this effort.

Keywords

Additive manufacturing; 3-D printing; mechanical properties; fatigue; fracture

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Cover Photo

Fracture surface of AM (electron beam melting (EBM)) titanium alloy (Ti-6Al-4V) high-cycle fatigue (HCF) fracture surface showing crack initiation at internal defect. (Credit: Nik Hrabe, NIST [1])

1. Introduction

1.1 Background and Workshop Goal

The sale of additive manufacturing (AM) products and services is projected to exceed US$6.5 billion worldwide by 2019 [2]. Despite this financial success, there are no instances currently of metal AM use in fatigue and fracture critical applications [3, 4]. This represents the motivation to hold this workshop. The main goal of the workshop was to understand the current needs to achieve broader acceptance and use of AM metals in fatigue and fracture critical applications. The scope of the workshop was limited to metal AM and fatigue and fracture considerations.

This report of the workshop findings details needs and potential action items, for both research and standardization efforts, identified during the workshop. There are many standards development organizations (SDOs) currently active in AM standardization, including: ASTM international (committees: F42 additive manufacturing, E08 fatigue and fracture, E07 nondestructive testing, and F04 medical and surgical materials and devices), ISO (TC 261), SAE international, American Society of Mechanical Engineers (ASME, committee Y14.46), and American Welding Society (AWS, committee D20). In an effort to coordinate AM standardization efforts among multiple SDOs, America Makes and American National Standards Institute (ANSI) have formed the Additive Manufacturing Standardization Collaborative (AMSC).

A recent economic analysis of the AM industry identified similar needs as those identified in this workshop, and they estimated the potential impact of improvements in these areas of need to lead to approximately US$4 billion savings [5]. It is important to put the findings of this workshop in the context of existing AM roadmaps. However, as there are currently several AM roadmaps [6-17], comparison and synthesis of these AM roadmaps is first necessary, and this will be accomplished in a separate effort.

1.2 Workshop Description

The workshop was jointly organized by ASTM International and the National Institute of Standards and Technology (NIST) and included invited speakers, discussion lead by an expert panel, and facilitated breakout sessions. All of this was an effort to receive input from as many of the attendees as possible. A detailed workshop agenda can be found in the appendices at the end of the report.

1.3 Participants

Over 150 people attended the workshop from a broad range of the AM community: industry (aerospace, medical device, etc.), academia, and government (research and regulatory agencies). A full list of workshop attendees can be found in the appendices at the end of the report. Invited speakers and expert panelists are listed in (Table I).

Table I. Workshop Speakers and Expert Panelists

LAST NAME	FIRST NAME	AFFILIATION
Beretta	Stefano	Politecnico Di Milano
Campbell	William	NASA Marshall
Gorelik	Michael	FAA
Gupta	Gautam	3D Systems
Klein	Robert	Stryker Orthopaedics
Kumar	Mukesh	ZimmerBiomet
McClung	R Craig	Southwest Research Institute
Phelps	Henry	Lockheed Martin
Reschetnik	Wadim	Paderborn University
Rollett	Anthony	Carnegie Mellon University
Simsiriwong	Jutima	Mississippi State Univeristy
Slotwinski	John	Johns Hopkins University Applied Physics Laboratory
Tilson	William	NASA Marshall
Wells	Doug	NASA Marshall

2. Workshop Findings

The specific needs identified during the workshop can be categorized into several main topics, each of which will be discussed in more detail in the following sections. Special attention will be paid to the specific role of fatigue and fracture in these main topics.

- *Comprehensive Understanding of Processing-Structure-Properties-Performance (PSPP) Relationships*
- *Mature Process and Material Models*
- *Trustworthy In-Process Monitoring and Control*
- *Rapid, Inexpensive, and Effective Non-Destructive Inspection Techniques*
- *Predictive Design Tools*
- *Rapid Qualification Framework*
- *Traditional Qualification Framework*

2.1 Comprehensive Understanding of PSPP Relationships

The concept of PSPP is that processing conditions dictate the structure of the resultant material, material structure dictates the material properties, and the material properties influence the performance of that material in a given application. Understanding the relationship between processing, structure, properties, and performance for a given material and application facilitates intelligent control and optimization of that material. This main topic holds the majority of relevance for fatigue and fracture considerations, and the majority of the workshop was spent discussing this topic.

There is a general lack of PSPP understanding with regards to fatigue and fracture behavior of AM metals, as can be seen in the literature [18, 19]. Therefore, it was a focus during the workshop to identify specific topics of interest in PSPP. One important general comment was made that statistical variation is an important aspect of PSPP investigations for metal AM. This variation can occur on multiple levels: within one build (e.g. location), across multiple builds on the same machine, between different machines of the same manufacturer and model, between different machines of different manufacturer or model. This variability is unquantified and would require time and money-intensive studies to evaluate, especially for fatigue properties. One workshop attendee reported large variations (mechanism unknown) in high-cycle fatigue results from different builds on the same machine, highlighting the need to understand AM process variability in the context of fatigue and fracture properties.

To provide focus to PSPP research efforts, workshop attendees were surveyed for their preferences within three categories: type of additive manufacturing technique, material, and fatigue and fracture properties (Figure 1). For each category, attendees were given multiple choices (including write-ins) and asked to identify which are important. Multiple selections within each category were allowed. The relative importance of each choice was considered to be the number of attendees that selected it as important divided by the total number of attendees surveyed. Therefore, it was theoretically possible that all choices in a category would have 100 % importance. In addition to the overall results (Figure 1A-C), the results from attendees in aerospace and medical device industries were separated and compared (Figure 1D-F).

When looking at all the results together from Figure 1, it is apparent that there are many AM techniques, materials, and fatigue and fracture properties of interest. This presents a significant opportunity to the research community to conduct impactful research. Comparing relative importance differences may help further focus future research efforts. There is a clear preference for laser-based powder bed fusion (L-PBF, Figure 1A), titanium alloy (Ti-6Al-4V, Figure 1B), and high-cycle fatigue (HCF, Figure 1C). It is also interesting to look at the differences in preferences for aerospace and medical device industries. Medical device industry seems to strongly prefer powder bed fusion AM techniques whereas aerospace is interested in both powder bed fusion and directed energy deposition (DED) AM techniques (Figure 1D). The aerospace interest in DED could be due to the need for larger parts in that industry coupled with the faster build speeds possible in DED. The aerospace industry interest in using AM for repair applications may also influence the relative interest in DED. Other than Ti-6Al-4V, material preferences differ between aerospace and medical device industry (Figure 1E). This makes sense considering the differing performance criteria for flight hardware compared to implantable material. The differences in fatigue and fracture property preference between medical device and aerospace industries (Figure 1F) may be due to differences in design strategies between the industries.

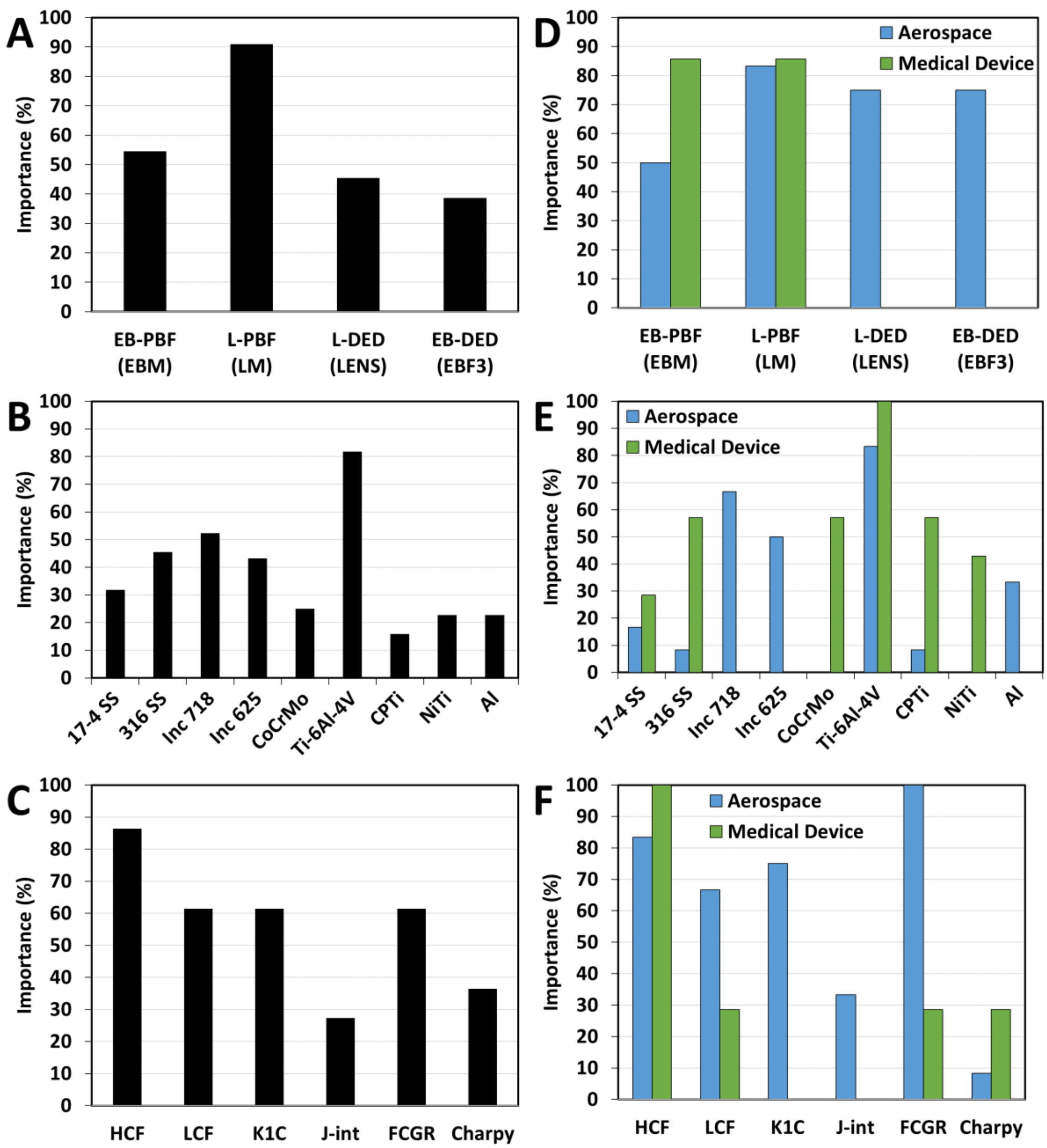

Figure 1. Preferences for AM Technique, Material, and Fatigue and Fracture Properties.
Overall results (A-C) and industry specific results for aerospace and medical device industries (D-F) are shown. Preferences for AM technique (A, D), material (B, E), and fatigue and fracture properties (C, F) are shown. EB = electron beam, L = laser, PBF = powder bed fusion, DED = directed energy deposition, HCF = high-cycle fatigue, LCF = low-cycle fatigue, K_{1C} = linear elastic fracture toughness, J-int = elastic-plastic fracture toughness, FCGR = fatigue crack growth rate, Charpy = impact toughness.

In addition to the survey results, specific areas of interest in processing, structure, and properties were also identified (Table II). As performance is application specific, and therefore a much broader topic considering the many potential applications, discussions of performance were minimal during the workshop.

Table II. Specific Areas of Interest in Processing, Structure, and Properties

processing	structure	properties
powder characteristics	chemical composition	see Figure 1
machine condition and settings	crystallographic microstructure	includes environment
post-processing	residual stress	
	internal defects	
	external defects	

For processing (Table II), powder characteristics include morphology, particle size distribution, flowability, moisture content, effects from powder recycling, and chemical composition. Machine conditions and settings include *many* variables such as energy source power, beam scan speed, scan strategy, build atmosphere, drift in energy source power over time, and build atmosphere flow dynamics. Post-processing includes heat treatment, machining, electrochemical machining, chemical-mechanical polishing, shot-peening, laser-peening, anodization, chemical conversion (for coatings), and yielding/pre-stressing (i.e. autofrettage). An example of a processing-property relationship came from one of the workshop speakers who measured an effect on mechanical properties dependent upon the number of specimens in the build [20]. The mechanism was unclear but hypothesized to be related to variations in thermal histories experienced during fabrication, resulting in different microstructures and mechanical properties.

Anisotropy was a common discussion theme for all aspects of structure (Table II). In addition to characterizing anisotropy, it is also important to understand the processing conditions that lead to the anisotropy as well as the effect of that anisotropy on fatigue and fracture properties. Crystallographic microstructure includes phase composition, grain size and shape, and dislocations. Internal defects include inclusions and porosity, and the morphology of both types of defects is important to characterize as it the magnitude of effect on fatigue and fracture properties. One of the workshop speakers stressed the importance of at least determining defect formation mechanisms and possibly determining how to prevent defect formation or eliminate defects in post-processing (e.g. hot isostatic pressing (HIP)) [21]. It seems that defect formation mechanisms have been hypothesized but are less than conclusive. Hypothesized formation mechanisms for lack-of-fusion (LOF) pores (i.e. larger pores often including partially melted powder particles) include powder packing inefficiencies and under-melting due to deviation from optimal energy beam settings (e.g. power, scan speed). Hypothesized formation mechanisms for entrapped gas porosity (i.e. smaller, spherical morphology) are retention of porosity from hollow powder feedstock (i.e. gas/plasma atomized powder) and over-melting due to deviation from optimal energy beam settings (i.e. keyholing). A suggestion was made during the workshop that if it is found that powder packing inefficiencies do contribute to LOF pore formation, powders with multi-modal particle size distribution (PSD) could help prevent these pores from forming. However, in determining the efficacy of multi-modal PSD powders for this purpose, it would also be necessary to investigate if the PSD changes during raking, sieving, and recycling. It would also be likely that changing from a uni-modal to multi-modal PSD would require re-optimization of AM machine settings. One more thought related to internal defects that came from the workshop is that near-surface defects should be distinguished from non-near surface defects due to differences in failure probability. External defects include melt flow lines, sintered particles, and loose particles trapped in tortuous surface features (e.g. internal channels). One of the speakers compared the relative effects of internal and external defects on high-cycle fatigue [22].

For properties (Table II), in addition to the preferences listed for various fatigue and fracture properties (Figure 1C and F), application environment is important to consider. Specific environments discussed included both high and low temperature as well as various corrosive environments (e.g. seawater, body fluid). One comment from the workshop was that we do not yet know all potential failure modes of AM metals. However, another comment contradicted that, explaining fatigue crack growth rate (FCGR) is microstructure controlled, while HCF and low-cycle fatigue (LCF) are defect controlled. A part size effect was also discussed as being defect controlled. This part size effect refers to differences in fatigue and fracture behavior.

There was consensus at the workshop that a curated metal AM database is necessary to build shared community knowledge of PSPP relationships in metal AM at a faster rate than the current status quo of redundant private efforts. A recent article provides a convincing argument for the need for such a database [23]. Concern was expressed at the workshop regarding hesitancy to contribute to public domain data due to intellectual property issues. However, most workshop attendees agreed that public domain data could be structured so it is pre-competitive. Two current databases (Metallic Materials Properties Development and Standardization (MMPDS) and Advanced General Aviation Transport Experiments (AGATE)) were given as examples that could be used for the framework of the proposed AM database. Desired uses of the database included identification of expected properties for design purposes as well as comparison between different AM machines and feedstock powder. In identifying expected properties, the lower-bound method was suggested. In addition to a material property database, one workshop comment recommended that effects from final part geometry (i.e. performance from PSPP) also be considered.

Multiple standardization needs related to PSPP and AM fatigue and fracture were identified during the workshop. One immediate standardization need identified is a reporting procedure that will enable trustworthy results from literature. There are some existing standards [24, 25], but more are needed especially in standardizing how processing conditions are reported. This type of reporting standardization would be necessary for an AM materials database to ensure each database entry contains sufficient information to be useful to the broader AM community.

Another identified standardization need is the evaluation of existing fatigue and fracture test methods for AM metals and possible creation of new methods if existing methods are found to be inappropriate. Some workshop attendees felt that a deeper understanding of fatigue and fracture in the unique microstructures of AM-processed metals is necessary before this evaluation can take place. Workshop attendees provided some examples of how existing methods might be inappropriate for AM: (1) assumed microstructural homogeneity, (2) test specimen size too small for AM resolution. With regards to microstructural homogeneity, it was suggested that better resolution was needed in fatigue crack test methods for AM materials to allow for characterization of local microstructure. It was recommended that the AM community look to other industries (e.g. nuclear) for previously established test methods (e.g. FCGR in scanning electron microscope (SEM)), but no specific standard test methods were cited.

Concern was expressed that current AM material standards (e.g. ASTM F2924 [26]) contain mechanical property specifications that are set inappropriately (e.g. copied from wrought specifications for the same material). The comment was made that machine-to-machine variability makes it more difficult to set specifications in the current state of AM. An AM materials database would likely facilitate setting appropriate specifications.

There was consensus at the workshop that it is important for all standards developing organizations (SDO) to communicate and work together to facilitate efficiency and harmony in new AM standards development. AMSC (jointly formed by America Makes and ANSI) has been formed to achieve this multi-SDO coordination, and all are encouraged to get involved in this volunteer effort. Within ASTM, it was specifically suggested that the various committees involved in AM standardization efforts (e.g. F42, F04, E08, and E07) co-locate meetings to facilitate harmonious AM standards development. Another important suggestion that came from the workshop is the inclusion of regulatory agencies (e.g. FDA, FAA) during standards development to ensure these agencies recognize new AM standards for use in various industries.

2.2 Mature Process and Material Models

Modeling is an integral component of comprehensive understanding of PSPP relationships (section 2.1) but is listed as a separate main topic to add emphasis to its importance. Experimental data, including fatigue and fracture data, can help validate process and material models. This combined experimental and modeling effort can conclusively identify critical processing parameters (e.g. energy density, melt pool area [21]) to help focus development of trustworthy in-process monitoring and control (section 2.3). It will also provide essential information (e.g. critical flaw sizes) to aid in development of rapid, inexpensive, and effective inspection techniques (section 2.4) as well as predictive design tools (section 2.5).

2.3 Trustworthy In-Process Monitoring and Control

There was consensus at the workshop that current commercial AM metal printers have limited in-process monitoring and control features. The ultimate goal is to be able to not just monitor but control AM processes using critical processing variables to achieve a material with desired structure and properties. There are many efforts underway to develop trustworthy in-process monitoring and control techniques. One of the workshop speakers presented work using optical pyro metry for in-process detection of defect formation [20]. Another speaker showed work controlling an AM process using melt pool area monitoring [21].

2.4 Rapid, Inexpensive, and Effective Non-Destructive Inspection Techniques

Feedback from the workshop indicated non-destructive inspection (NDI) techniques are necessary even if trustworthy in-process monitoring and control are realized, especially if post-processing (e.g. heat treatment, surface treatment) remains common in AM processes. The current lack of AM-specific NDI techniques presents a large opportunity for both research, development, and standardization. A successful NDI technique from an industrial perspective must be rapid, inexpensive, and effective at detecting critical flaw sizes. Although micro-computed x-ray tomography (µCT) is used heavily for research and validation purposes, it is too slow and expensive in its current state to be used as an everyday inspection tool. Other NDI techniques are being considered (e.g. ultrasonic [27]). The role of statistics in NDI techniques was discussed by one of the speakers in the context of the probability of detection (POD) concept [28].

2.5 Predictive Design Tools

The need for defect-based damage tolerance failure lifetime prediction tools was identified during the workshop, and there were two main approaches discussed. It is important to note that both approaches do not require complete prevention or removal of defects, only accurate characterization of the defects that are present. The first approach is to treat defects with a quality index and associated safety factor. It was suggested to look to similar standards in other industries (e.g. casting, powder metallurgy, metal injection molding (MIM)). Many at the workshop felt that more work was necessary before safety factors for AM metals could be appropriately set. This feeling is most likely related to the current state of PSPP relationship understanding and the lack of an AM materials database (section 2.1). The second approach was to use statistical inspection techniques (e.g. peaks-over-threshold (POT)) to predict defect influence on properties including fatigue and fracture [21, 29]. When discussing this approach one comment was that it would be necessary to determine critical flaw size, below which fatigue crack initiation would be dominated by microstructure instead of defects.

2.6 Rapid Qualification Framework

One of the major needs identified during the workshop was a rapid method to qualify AM processes, materials, and components. Currently, high-cost and timeintensive validation and verification practices are necessary, and many would like to see these barriers to bringing a new AM component to market decreased. It was acknowledged by many that this is a long-term goal and will require many of the previously discussed needs to be realized first. There is ongoing work toward rapid qualification for metal AM based on integrated computational materials engineering (ICME) [4, 30].

2.7 Traditional Qualification Framework

Many workshop attendees also expressed a need for a traditional qualification framework based on validation and verification. The focus seemed to be much more on standardization and many felt regulatory agencies (e.g. FDA, FAA) should lead these efforts with AM-specific qualification guides. There was discussion at the workshop regarding two aspects of traditional qualification currently used in metal AM. The first aspect was the use of witness coupons. There seemed to be many who agreed that witness coupons are not representative of other parts in the build due to geometry and location differences. However, many felt that the main purpose of witness coupons was to measure process variation across many builds, and part characterization should be conducted on finished parts in application specific testing separate from the witness coupon testing. The second aspect of traditional qualification was the concept of "locking" (i.e. freezing, holding constant) AM process variables (e.g. control software version) after part development and qualification in an effort to minimize part quality changes from build-to-build over time in a production setting. Many agreed that this is necessary with the current state of commercial AM equipment, but some expressed concern about unidentified variables that potentially are not frozen in the "locking" process and might potentially change and affect changes in part quality over time. Better in-process monitoring will hopefully address these concerns, and in the interim some workshop attendees recommended use of witness coupons as a perpetual verification tool even after part qualification.

3. Conclusions and Next Steps

Research and standardization needs necessary to achieve broader use and acceptance of metal AM in fatigue and fracture critical applications were identified during this workshop. Of the main needs identified, fatigue and fracture plays the largest role in developing comprehensive understanding of processing-structure-property-performance (PSPP) relationships. This includes both experimental and modeling efforts and must include investigations of statistical variation in metal AM processes. The benefit of an AM materials database was discussed. Specific aspects of PSPP were identified and prioritized during the workshop (Figure 1,Table II). Comprehensive PSPP understanding will contribute to three other identified needs: in-process monitoring and control, AM-specific NDI techniques, and predictive design tools. The last major need identified is frameworks for both traditional and rapid qualification.

Standardization needs were identified, but in some cases there was concern whether enough is known about metal AM processes currently to make these efforts appropriate at this time. Many workshop attendees felt AM reporting procedures need to be further standardized. Evaluation of current fatigue and fracture test methods and NDI techniques for applicability to metal AM was another identified standardization need. Also, traditional AM qualification standardization was highly desired, and many felt regulatory agencies should play a leadership role this effort.

The organizers plan to continue the metal AM fatigue and fracture discussion started at this workshop at future technical symposia. Two symposia are planned for 2017. The first is at the MS&T Conference in October 2017 (symposium title: “Additive Manufacturing of Metals: Fatigue and Fracture”, Focus: processing-structure-properties (fatigue and fracture) relationships, Abstract deadline March 15, 2017). The second is at the November 2017 ASTM Committee Week Meeting (www.astm.org/E08CFP112017, Focus: fatigue, fracture, and NDE test method evaluation and development, Abstract deadline, March 1, 2017). The organizers also plan to publish an article comparing and synthesizing the several AM roadmaps that currently exist and putting metal AM fatigue and fracture issues into context.

4. Acknowledgments

The authors would like to thank ASTM for providing the facilities for this workshop. Special thanks to Kelly Dennison (Manager, ASTM Symposia Operations) for all of her help with the logistics of the workshop. Finally, we would like to thank all of the workshop attendees (especially the speakers and expert panelists) for all of their valuable feedback.

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6. Appendix A: Workshop Agenda

ASTM INTERNATIONAL

NIST

WORKSHOP ON MECHANICAL BEHAVIOR OF ADDITIVE MANUFACTURED COMPONENTS

Sponsored by ASTM Committee E08 on Fatigue and Fracture in conjunction with the National Institute of Standards and Technology (NIST).

May 4-5, 2016
Grand Hyatt San Antonio
San Antonio, TX

Workshop Organizers: Steve Daniewicz, Mississippi State University
Nima Shamsaei, Mississippi State University
Nik Hrabe, NIST
Nick Barbosa, NIST

WEDNESDAY, MAY 4, 2016

8:00 AM
Opening Remarks
Steve Daniewicz, Mississippi State University

8:15 AM
Additive Manufacturing in the Context of Structural Integrity
Michael Gorelik, FAA

8:45 AM
Reliability of Mechanical Behavior in Metallic Additively Manufactured Parts Used in Critical Applications
Doug Wells, NASA Marshall

9:15 AM
Ti-6Al-4V for Orthopaedic Implants in Fatigue
Mukesh Kumar, Zimmer-Biomet

9:45 AM BREAK

10:15 AM
Fracture Mechanics and Nondestructive Evaluation Modeling to Support Rapid Qualification of Additively Manufactured Parts
Craig McClung, Southwest Research Institute (SWRI)

10:45 AM
Extreme value analysis of defects on AM parts
Steffano Beretta, Politecnico di Milano

11:15 AM
Fatigue Life Manipulation of SLM® Parts
Wadim Reschetnik, Paderborn University

11:45 AM LUNCH

1:15 PM
Advanced Characterization of Additively Manufactured Materials, including Synchrotron–based 3D X-rays
Anthony Rollett, Carnegie Mellon University

1:45 PM
Effects of HIP Processing on Additively Manufactured, Titanium Materials Produced Using an Electron Beam – Directed Energy Deposition Process
Hank Phelps, Lockheed Martin Aeronautics

2:15 PM
Overview of Fatigue and Damage Tolerance Performance of Powder Bed Fusion Alloy N07718
William Tilson and William Campbell, NASA Marshall

2:45 PM BREAK

3:00 PM
Presentation of Needs and Preferences Identified in Pre-Workshop Survey
Nik Hrabe, NIST

3:30 PM
Expert Panel Discussion Expanding Identified Needs
Expert Panelists:
Bob Klein, Stryker
John Slotwinski, Johns Hopkins Applied Physics Laboratory (APL)
Gautam Gupta, 3D Systems
Craig McClung, Southwest Research Institute (SWRI)

5:00 PM CLOSE 1st Day

THURSDAY, MAY 5, 2016

8:00 AM
Opening Remarks
Nik Hrabe, NIST

8:15 AM
Ongoing challenges in additive manufacturing of fatigue resistant materials
Nima Shamsaei, Mississippi State University, presented by: Jutima Simsiriwong, Mississippi State University

8:45 AM
Breakout Sessions Clarifying Identified Needs

10:00 AM BREAK

10:30 AM
Breakout Sessions prepare summaries of their discussions

11:00 AM
Breakout Sessions present summaries

11:45 AM
Closing Remarks
Steve Daniewicz, Mississippi State University

12:00 PM CLOSE Workshop

7. Appendix B: Workshop Attendee List

LAST NAME	FIRST NAME	AFFILIATION
Arnold	John	Fort Wayne Metals Res Prod
Bailey	Peter	Instron Calibration Laboratory
Bapat	Parimal	orchid
Barbosa	Nicholas	NIST
Bauer	Benjamin	
Belsick	Charlotte	Lockheed Martin
Beretta	Stefano	Politecnico Di Milano
Bills	Paul	University Of Huddersfield
Birky	Zachary	
Bonini	Julius	Lucideon M+P
Brazill	Richard	Alcoa
Briggs	Brandi	NAVAIR
Brown	Catherine	BMPC
Campbell	William	NASA Marshall
Cardinal	Joseph	Southwest Research Institute
Carroll	Siobhan	
Conley	David	Newport News Shipbuilding
Coughlin	Jessica	
Daniewicz	Steve	Mississippi State University
Deluise	Michael	Stryker Orthopaedics
Di Prima	Matthew	US FDA OMPT/CDRH/OSEL/DAM
Dodds	Robert	University Of Illinois
Dzugan	Jan	COMTES FHT
Espinoza	Alejandro	
Fang	Zhibin	Zimmer Spine
Farrell	Shannon	Defence RD Canada, Atlantic Research Centre
Floyd	Steven	
Gbur	Janet	
Gockel	Joy	Wright State University
Gonzalez	Alexander	ABS
Gorelik	Michael	FAA
Gupta	Gautam	3D Systems
Hack	Harvey	Northrop Grumman Corp
Haggerty	Ian	Battelle Memorial Institute
Hirata	Seiki	
Hrabe	Nikolas	NIST
Huang	Yong	University of Florida
Inman	Maria	Faraday Technology, Inc.

Jennings	James	Nswccd-Sses
Kapaun	Rick	Knight Mechanical Testing
Kirka	Michael	Oak Ridge National Laboratory
Klein	Robert	Stryker Orthopaedics
Kumar	Mukesh	ZimmerBiomet
LaGoy	Jane	Bodycote HIP
Lennon	Andrew	JHU APL
Li	Kejian	University of Michigan-Dearborn
Liao	Min	National Research Council Canada
LiArno	Sally	Stryker Orthopaedics
Lingenfelser	Dan	HBM - nCode
Lucon	Enrico	NIST
Mabe	James	Boeing
MacDonald	Daniel	Drexel University
Maciejewski	Kimberly	Alcoa
Maiti	Ranen	Aerojet Rocketdyne
Margheim	Susan	Rockwell Collins Inc
Marvin	Susan	FBI Laboratory
McClung	R Craig	Southwest Research Institute
McColskey	Dave	NIST
McMahon	Adrian	boston scientific
Mills	David	Rolls-Royce
Mitchell	Michael	Mechanics & Materials LLC
Narasimhachary	Santosh	Siemens Corporate Research
Neu	Richard	Georgia Inst Of Tech
Pan	Yayue	UIC
Pape	John	GE Aviation
Park	Dong-Yeob	Natural Resources Canada
Park	Chul	Boeing Commercial Airplanes
Phelps	Henry	Lockheed Martin
Prost-Domasky	Scott	A P E S
Reece	Steven	Medtronic Spine and Biologics
Reschetnik	Wadim	Paderborn University
Richey	Edward	Praxair
Ricker	Richard	NIST
Roach	Michael	
Rollett	Anthony	Carnegie Mellon University
Rosenberger	Andrew	US Air Force
Rownd	Jerome	Lockheed Martin Space
Sadayappan	Kumar	Canmet Materials
Sand	Irving	Georgia-Pacific Chemicals LLC

Scheck	Caroline	Naval Surface Warfare Center Carderock Division
Schmidt	Walter	Stryker Orthopaedics
Seifi	Mohsen	Case Western Reserve University
Shamsaei	Nima	Mississippi State University
Shao	Shuai	Center for Advanced Vehicular Systems, Mississippi
Simsiriwong	Jutima	Mississippi State Univeristy
Slotwinski	John	Johns Hopkins University Applied Physics Laboratory
Sobotka	James	Southwest Research Institute
Steffen	Bob	Raytheon Precision Manufacturing
Sylvester	Rex	Mts Systems Corporation
Tarnowski	Keith	Imperial College London
Tasan	Cemal	
Taylor	Harold	Medtronic
Taylor	Robert	University of Texas at Arlington
Thompson	Scott	Mississippi State University
Thompson	Steven	Air Force Research Lab
Thompson	Spencer	EOS of North America Inc.
Tilson	William	NASA Marshall
Walas-Maenhoudt	Agata	
Wallin	Kim	Vtt
Waterman	Jay	NAVAIR
Wells	Doug	NASA Marshall
Welsh	Greg	NAVAIR
Williamson	Scott	University Of Mississippi Medi
Young	Bruce	Battelle Memorial Institute

8. Appendix C: Speaker Presentations

Slides from presenters are included in the order listed on the agenda.

Additive Manufacturing in the Context of Structural Integrity

Presented at:

ASTM-NIST Workshop on Mechanical Behavior of Additive Manufactured Components *(sponsored by ASTM E08)*

May 4, 2016

San Antonio, TX

Presented by:

Dr. Michael Gorelik

FAA Chief Scientist and Technical Advisor
for Fatigue and Damage Tolerance

Disclaimer

The views presented in this talk are those of the author and should not be construed as representing official Federal Aviation Administration rules interpretation or policy

Outline

- State of Industry
- Challenges for AM Implementation
- Regulatory Perspective
- Lessons Learned
- Risk Mitigation

What Causes Failures?

Frequency of Failure Mechanisms *)

Failure Mechanism	% Failures *(Aircraft Components)*
Fatigue	55%
Corrosion	16%
Overload	14%
Stress Corrosion Cracking	7%
Wear / abrasion / erosion	6%
High temperature corrosion	2%

**) Source: Why Aircraft Fail, S. J. Findlay and N. D. Harrison, in Materials Today, pp. 18-25, Nov. 2002.*

- **Fatigue is the Predominant Failure Mode in Service**
- **Expect this trend to continue for metallic materials**
- **Some of the most challenging requirements *for new material systems* are related to F&DT**

State of Industry - ***Today***

- **Field experience for certified metal AM parts in Civil Aviation** (*in 10,000 hours*) → **zero** *)
- **Full-scale production experience for metal AM parts in Civil Aviation** (*in 10,000 parts*) → **zero** *)

***) approximate as of the end of 2015 (based on information available to presenter)**

Are New "Lessons Learned" Likely..?

State of Industry (cont.)

"Additive manufacturing is the new frontier. It has taken the shackles off the engineering community, and gives them a clean canvas…"

Mr. David Joyce, GE Aviation President and CEO

"Metal parts from <u>some</u> AM systems are *already on par with their cast or wrought counterparts*. As organizations qualify and certify these and other materials and processes, the industry will grow very large…

<u>Source</u>: Wohlers Report 2012

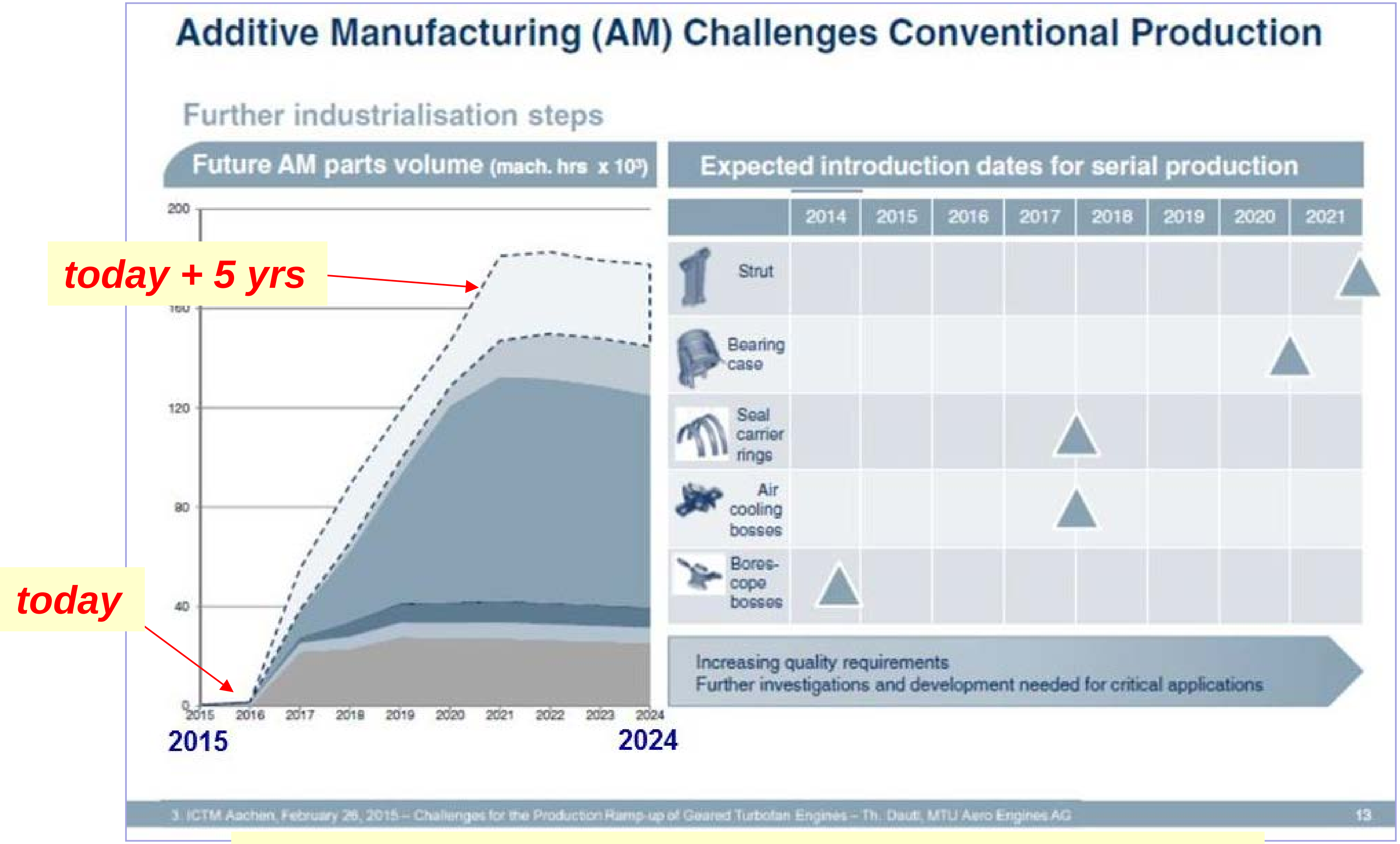
"We are on the cusp of a step-change in weight reduction and efficiency – producing aircraft parts which weight 30 to 55 %, while reducing raw material used by 90 % …"

Mr. Peter Sander, Airbus

"3D printing opens up new possibilities, new design space… Through the 3D printing process, you're not constrained [by] having to get a tool in to create a shape. You can create any shape you like."

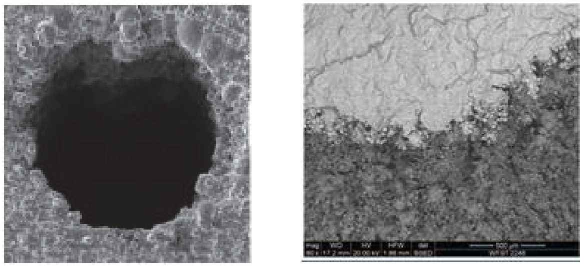
Dr. Henner Wapenhans, Rolls-Royce Head of Technology Strategy

State of Industry (cont.)

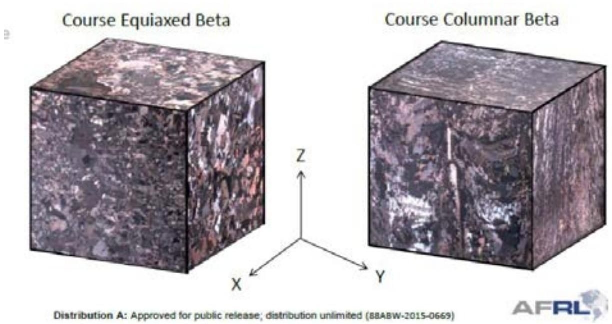


We are on the Cusp of a Significant Increase in the Use of Metal AM Parts in Commercial Aviation…

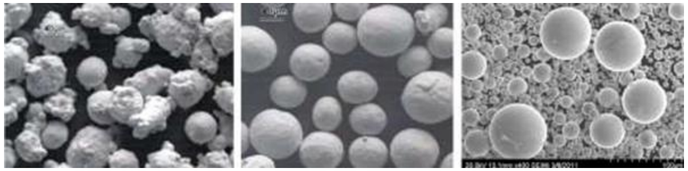
Examples of Risk Factors for AM - *Materials*



Surface Quality



Microstructure Variability

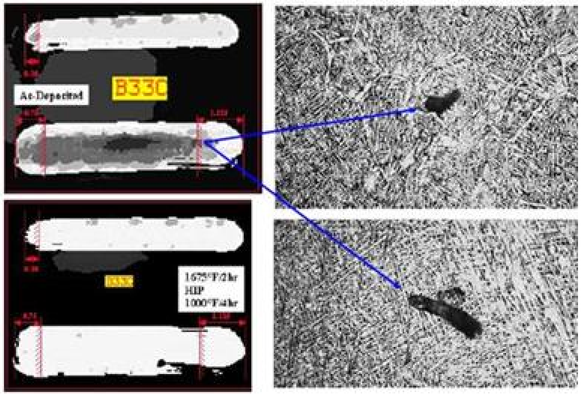


Powder Control

Powder feed rate (g/min)
Laser Power (W)
Scan speed (in/min)
Laser spot size (in)
Substrate temp (°F)
Hatch spacing (% of calculated)

over 100 process parameters identified

Process Controls

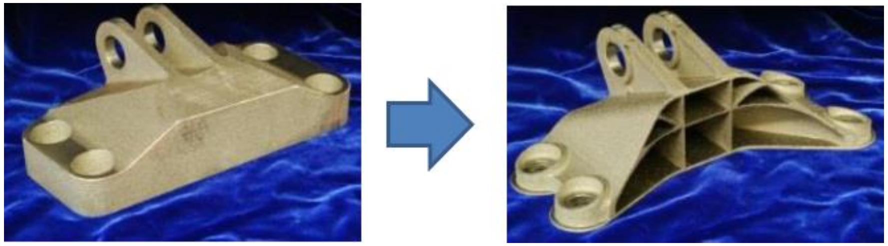


HIP Effectiveness

Many More Identified by Experts…

Example of Risk Factors for AM - ***Design*** (Topological Optimization)

"***Complexity is Free with AM…***"



- ***… But is it really?***
  - **High number of Kt features**
  - **Inspectability challenges**
  - **Location-specific properties**
  - **Surface quality of hard-to-access areas**
    - **may need to live with as-produced surface**

Need a Realistic Assessment of Technical Challenges / Risks

AM Challenges To Be Addressed

“top five”

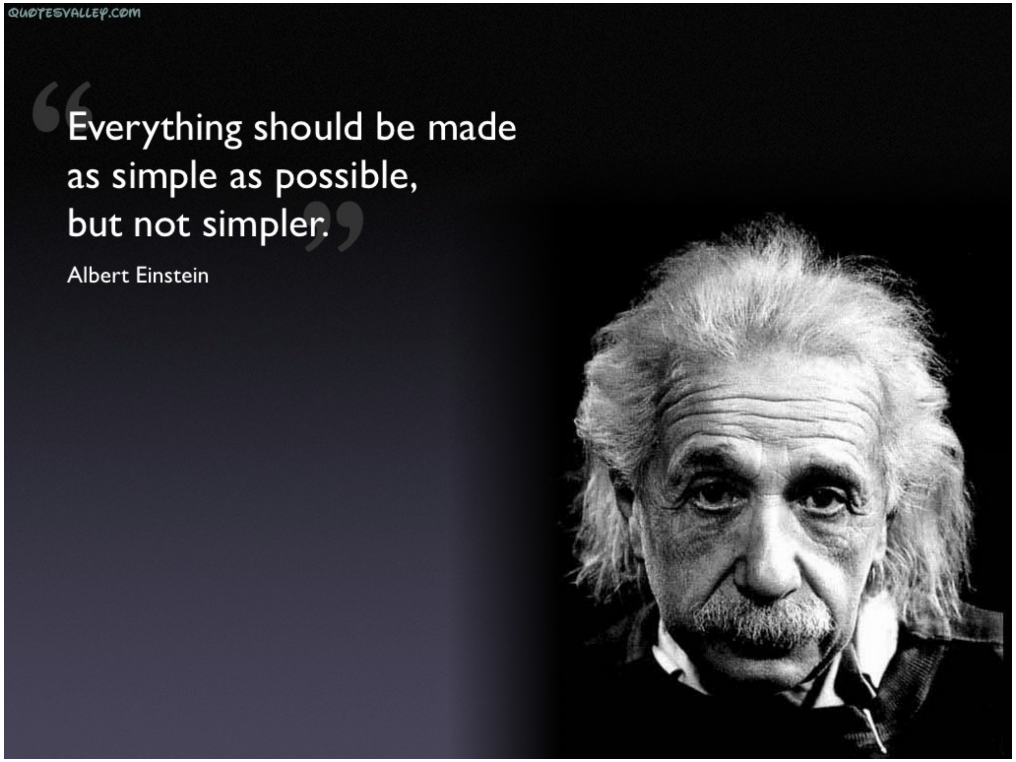
- Limited understanding of acceptable ranges of variation for key manufacturing parameters
- Limited understanding of key failure mechanisms and material anomalies
- Lack of industry databases / allowables
- Development of capable NDI methods
- Lack of industry specs and standards

Additional level of complexity – these areas are not independent…

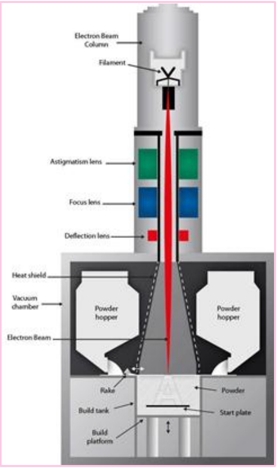
Other considerations

- *Lack of robust powder supply base*
- *OEM-proprietary vs. commodity type technology path*
- *Low barrier to entry for new (inexperienced?) suppliers*

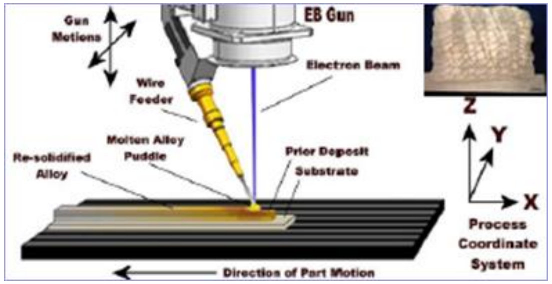
Some Regulatory Considerations for AM



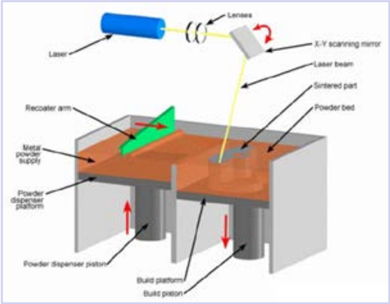
Diversity of AM Processes and Certification Domains



By Source of Material:
Powder vs. Wire



By Source of Energy:
Laser vs. E-Beam



New Type and Production Certificates	Repair and Overhaul (MROs)	Aftermarket Parts (PMAs)

Two Types of FAA Certificates for New Products *(14 CFR Part 21)*

- **Type Certificate**
  - An applicant is issued a *Type Certificate* once they have demonstrated ***through test and analysis*** that the type design data (drawings, specifications and other documents needed to describe a design) meets all relevant regulatory requirements
- **Production Certificate**
  - An applicant is issued a *Production Certificate* once their manufacturing facilities are capable of ***repeatably*** producing product *per the approved Type Certificate*

Diverse Regulatory Environment

(driven by different product types)

Transport Airplane Directorate

(14 CFR Part 25)

Small Airplane Directorate

(14 CFR Part 23)

Engine and Propeller Directorate

(14 CFR Parts 33, 35)

Rotorcraft Directorate

(14 CFR Parts 27, 29)

- 4 Directorates
- Multiple Cert office

Part Rules Comparison for Material Requirements - *General Observations*

- **Detailed material related requirements are Part rule dependent**
- **Various levels of requirement details by Part**
- ***Some of the most critical material requirements (Fatigue / Damage Tolerance) are closely linked to OEMs design / analysis system, and typically approved on OEM-specific basis***

From Non-Critical to Critical

- **Typical new aerospace alloy development and introduction timeline – *10 to 15 years***

➢ **However**

TABLE 2.2 Typical Development Times for New Materials

Development Phase	Development Time
Modification of an existing material for a noncritical component	2 to 3 years
Modification of an existing material for a critical structural components	Up to 4 years
New material within a system for which there is experience	Up to 10 years. Includes time to define the material's composition and processing parameters.
New material class	20 to 30 years. Includes time to develop design practices that fully exploit the performance of the material and establish a viable industrial base (two or more sources and a viable cost).

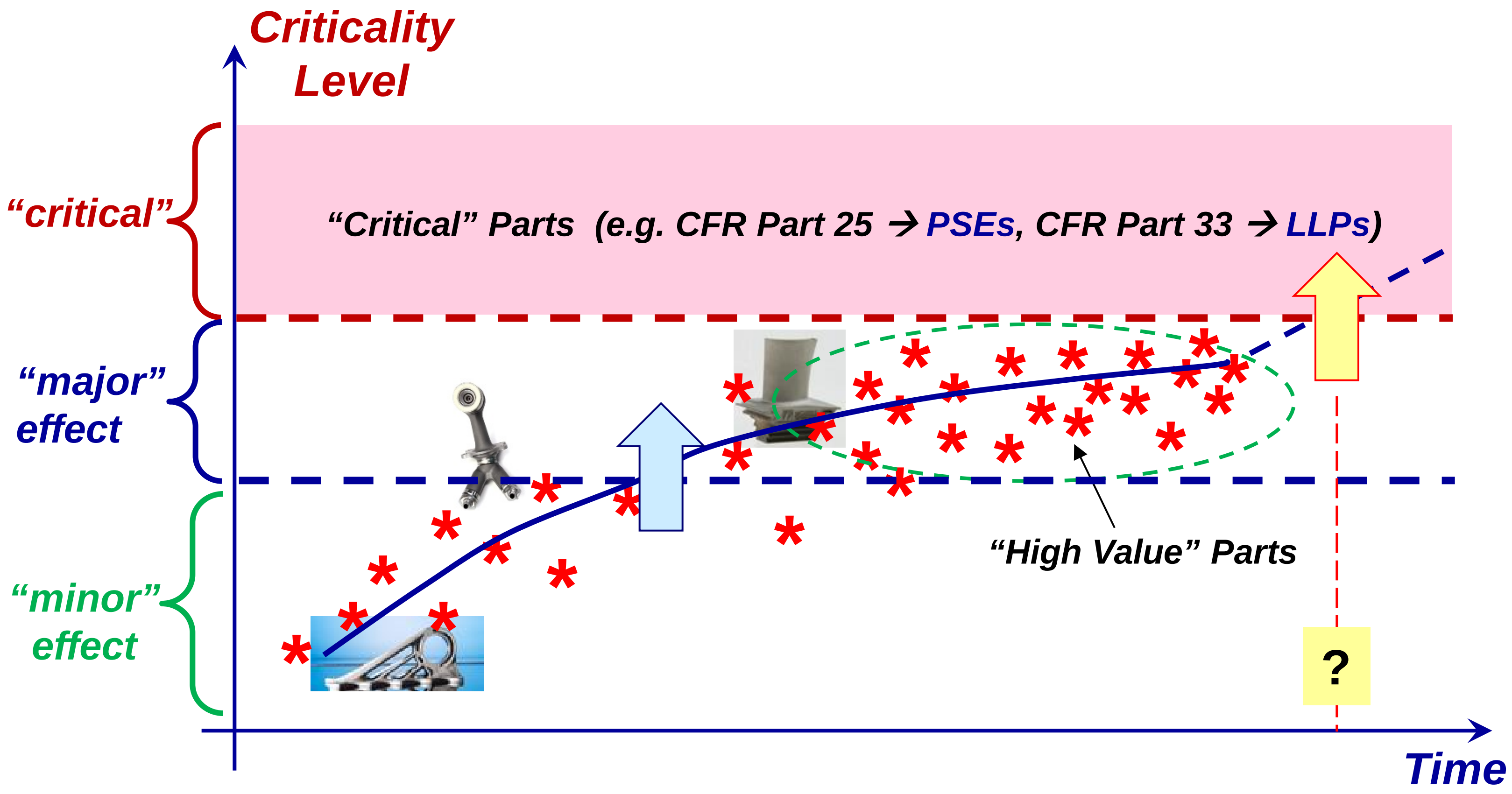
SOURCE: R Schafrik, GE Aircraft Engines, briefing presented at the National Research Council Workshop on Accelerating Technology Transition, Washington, D.C., November 24, 2003.

Example

"The *outcome* of Rawfeed (*an R&D program*) will be a *specification for a process to additively manufacture Class 1 titanium structures*, such as engine hangers, wing spars and gear ribs… expensive, critical parts…"

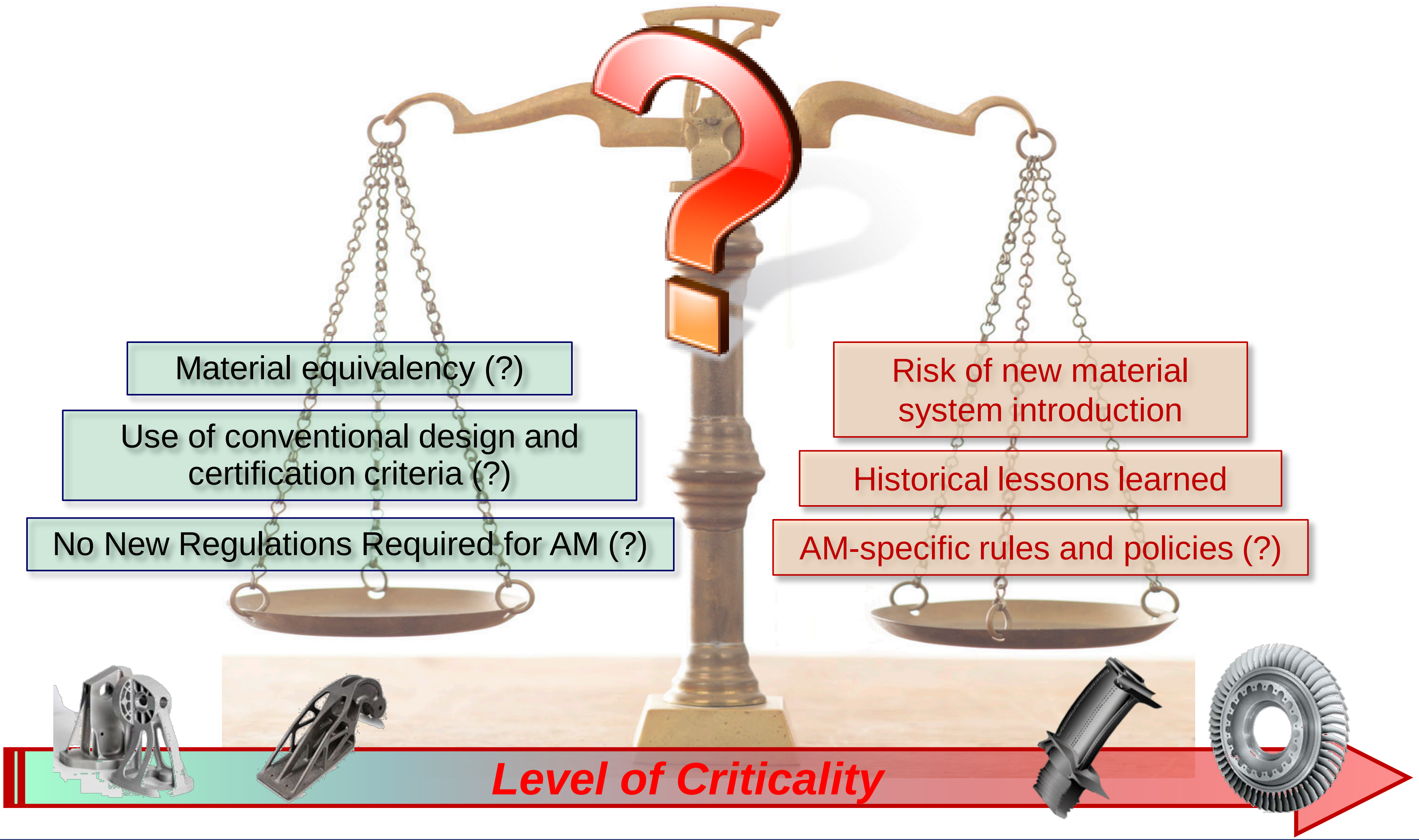
Reference: ***Rolling Key To Additive-Manufacture Of Critical Structures*, Aviation Week & Space Technology, Nov 10, 2014.**

Evolution of Criticality of AM Parts



Aggregation of parts at "sub-critical" levels may result in non-trivial *cumulative* risk impact at fleet level

Finding The Right Balance…

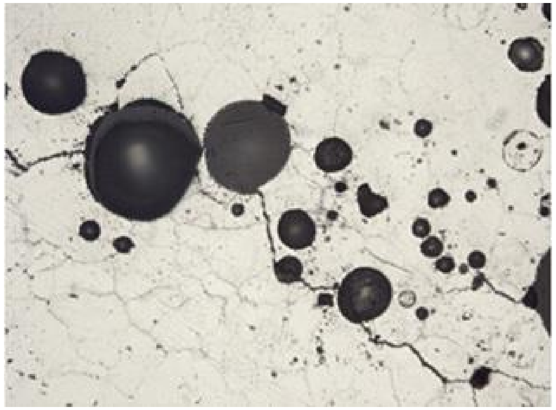


“History is a Vast Early Warning System”

Norman Cousins

Lessons Learned – Structural Castings

- **Prone to manufacturing variability, material anomalies and resulting variation in material properties, including fatigue**
- **Range of material anomalies intrinsic to castings, including gas and shrinkage porosity, inclusions, micro-cracking etc.**



Examples of Material Anomalies in Cast Alloys

Effect on debit in material properties is well documented …*but not necessarily well quantified*

Lessons Learned – Structural Castings (cont.)

- **Historically, and in part due to the *lack of modeling capabilities*, an *empirical framework* was developed to mitigate the risk of the above factors**
- **It consists of the following key elements:**
  - **Class of Casting (1 through 4) - determined by application criticality**
  - **Casting Grade (A through D) - defines acceptable levels of NDI indications, either for the entire part or for a specified area (zone)**
  - **Casting Factor - a safety factor originating from uncertainties in material properties**

5.2.1 "… The application of factors of safety to castings is based on the fact that the casting process can be inconsistent …"

5.2.2 "… Since the mechanical properties of a casting depend on the casting design, the design values established … for one casting might not be applicable to another casting made to the same specification."

Reference: FAA Advisory Circular 25.621-1 "Casting Factors", Oct. 2014.

Lessons Learned – Structural Castings (cont.)

Challenges

- **Empirical – effects of material anomalies are not well understood or quantified → *no explicit feedback loop to process controls and QA***
- **No means to assess / quantify risk**
- **May be too conservative in a number of cases**

"…by taking every deleterious variable imaginable, it was found that average strengths were still well above minimum requirements…"

Reference: "Modern Castings", D. McLellan, ISSN: 0026-7562, May 1994.

Lessons Learned – Powder Metallurgy (PM)

- “The early years of P/M superalloys were ones of great expectations
  - For example, in 1971 it was suggested that in 5 years, 20 to 25 % of the weight of advanced engines would be P/M superalloys…
- The application of powder metallurgy (P/M) to superalloys was initiated in order to overcome difficulty encountered during forging and heat treating of advanced, highly alloyed, nickel-base superalloys.
- Several major OEMs were developing this technology for 10-15 years, prior to initial applications

Reference: “P/M Superalloys – A Troubled Adolescent?”, R. L. Dreshfield and H. R. Gray, NASA Technical Memorandum 83623, 1984.

Lessons Learned – Powder Metallurgy (PM)

FLIGHT INTERNATIONAL, 11 October, 1980, pg 1413

… The US Navy grounded its 13 F-18s following the crash of a TF-18 in England on September 8 (see Flight, September 20, page 1177), following an inflight failure of one General Electric F404 engine. The cause of the accident was the disintegration of the low-pressure turbine (LPT) disc in the right-hand (No 2) engine.

- **An event which strongly influenced the direction of P/M superalloy technology, especially as-HIP, was the loss of an F/A-18 aircraft in September 1980.**
- **The crash was attributed to the failure of a P/M superalloy low pressure turbine disk.**
  - **The cause of the disk failure has not been conclusively established as portions of the failed disk critical to the failure analysis were not recovered.**
- **A plausible explanation for the failure of that turbine disk is that it contained a *large undetected flaw* which propagated due to low cycle fatigue until it became critical and fracture occurred**

Effect on Early PM Production Rates

- **Shortly after the F/A 18 crash, the production of as-HIP P/M superalloys decreased dramatically.**

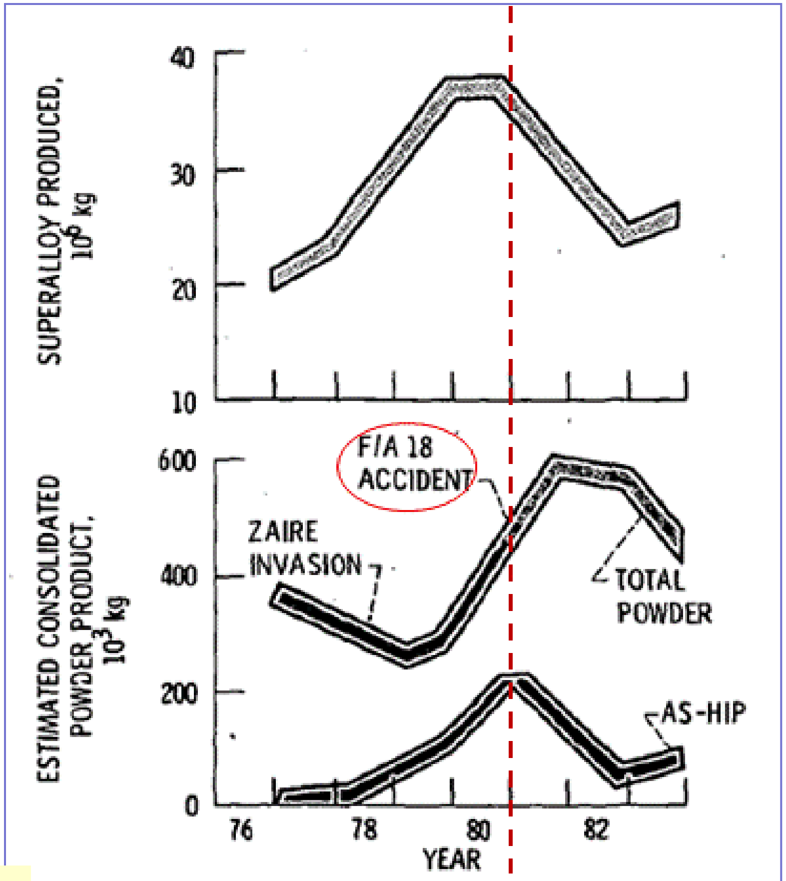


Figure 2. - Superalloy production.

<u>Reference</u>: "P/M Superalloys – A Troubled Adolescent?", R. L. Dreshfield and H. R. Gray, NASA Technical Memorandum 83623, 1984.

Inherent Anomalies *Specific to PM Alloys*

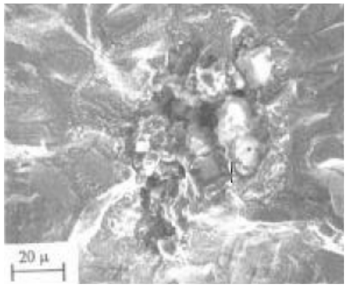
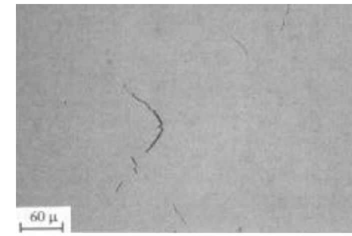


Table I. Major Types of Defects in HIP Rene' 95

Type	Description	Typical Elements	Size, Mils^2(*) Avg.	Max.
1	Discrete chunky ceramic	Al, Mg, Zr, Ca, O	8	50
2	Ceramic agglomerates	Al, Si, Mg, Ca, O	10	110
3	Reactive agglomerates forming PPB	Al, Zr, Cr, Ca, O C, Ca, Fe	15	250
4	Voids	Ar	<2	--



Inherent Anomalies in AM Alloys…

- **Lack of fusion..?**
- **Micro-cracking due to residual stresses..?**
- **Porosity..?**
- **Other..? ("known unknowns")**

…Need to be Understood, Characterized and Managed

Lessons Learned Summary

- **Early failures in high-criticality applications have a major impact on new technology**
- **Scale-up challenges – transitioning from well-controlled development environment to full-scale production**
- **Good understanding of the key failure modes and material anomalies is crucial**
  - **And needs to be connected to manufacturing process controls and NDI methods**
- **Initially believed to be an innocuous material system change, subject to conventional design criteria…**
  - **… Ended up giving rise to a new *probabilistic* lifing framework used for both military and commercial certification**
  - **Highlights importance of managing uncertainty and variation**

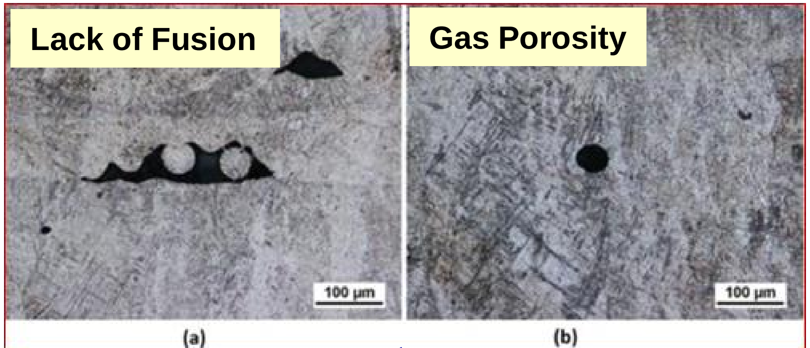
What Did Historically Work Well to Address “Known Unknowns”?

- **Effective manufacturing process controls**
- ***Damage tolerance (DT) framework***
- **QA / NDI methods**
- **Sharing of lessons learned across the industry**

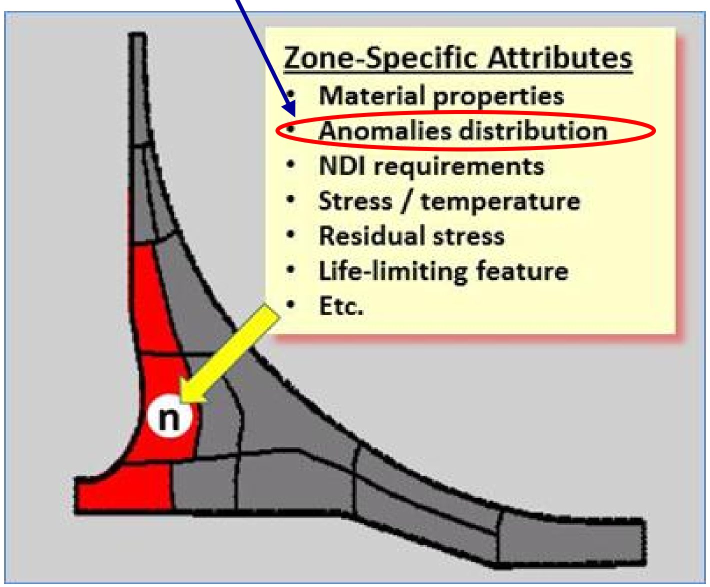
Success story – rotor-grade Titanium alloys

(Reference: proceedings of AIA RISC Working Group)

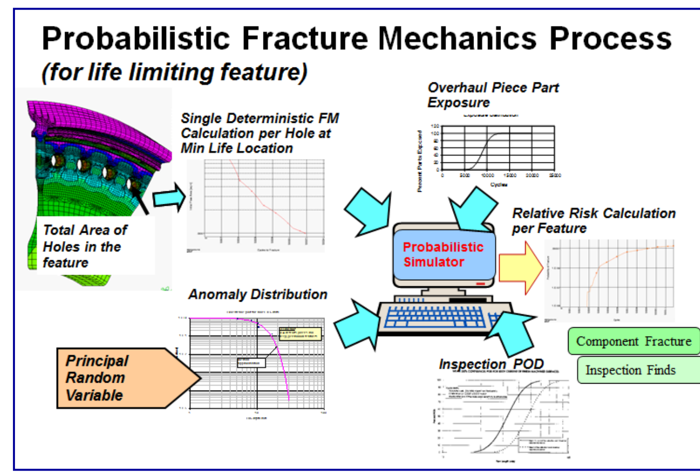
Part Zoning Considerations



- AM parts are uniquely suited for *zone-based evaluation*
- Concept is similar to zoning considerations for castings…
- … however, modeling represents a viable alternative to empirical "casting factors"



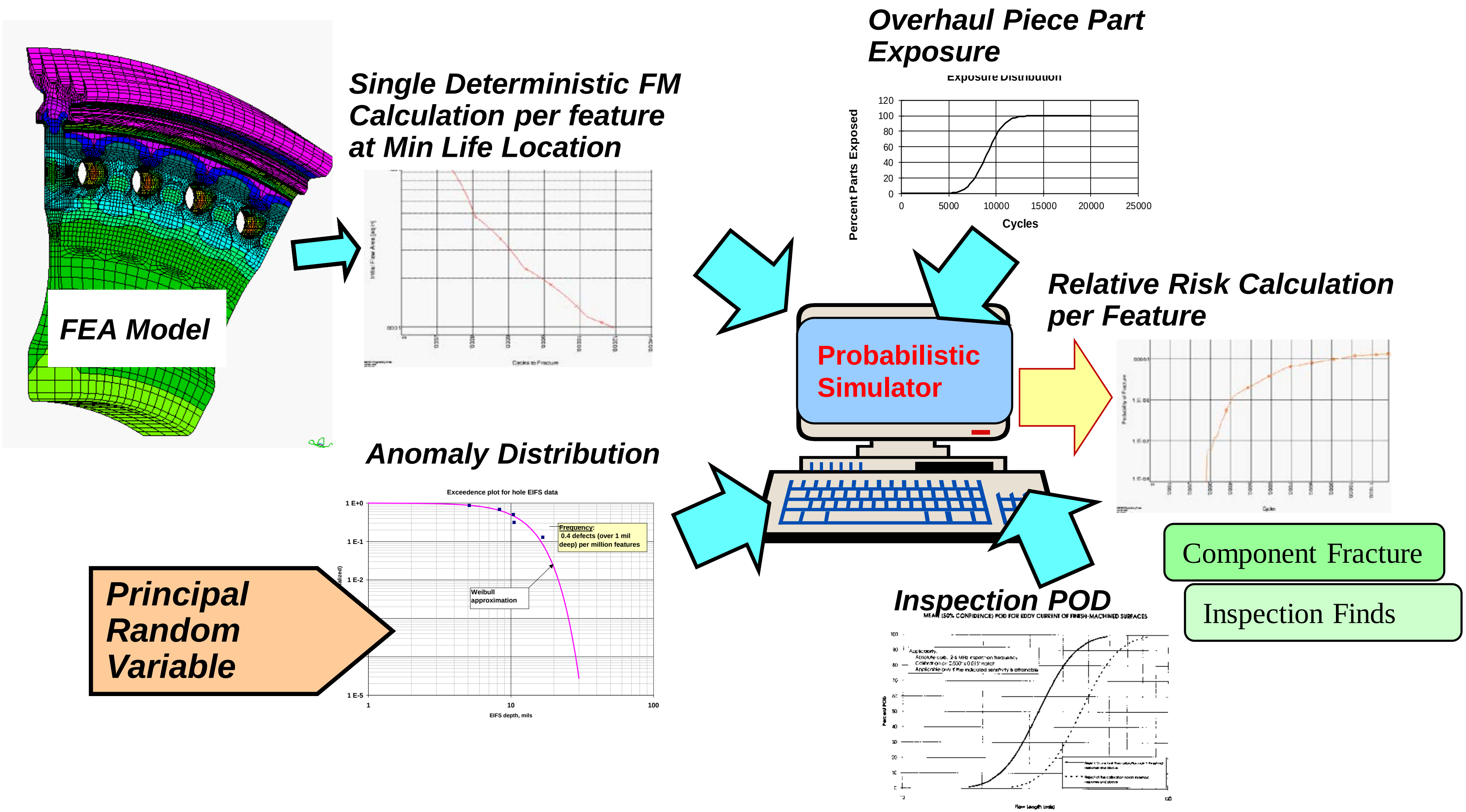
*One Assessment Option – PFM *)*



***) PFM - Probabilistic Fracture Mechanics**

(see next page)

Example: PFM Process *(for a life limiting feature)*



Summary

- **Expected (rapid) expansion of AM in Aviation, and increase in the levels of AM parts criticality**
- ***Development of industry standards and specs are key enablers***
- **Most OEMs and agencies support *risk-based approach*, including *"system-level" considerations,* including:**
  - Manufacturing process controls, specs development
  - Characterization of key failure modes and anomalies
  - Lifing system and certification criteria
  - QA, Process Monitoring and NDI methods
- **Need to leverage historical "lessons learned" and risk mitigation strategies … *including appropriate use of DT principles for more critical applications***

Discussion

Dr. Michael Gorelik, PMP

Chief Scientist, *Fatigue and Damage Tolerance*

Aviation Safety

Federal Aviation Administration

michael.gorelik@faa.gov

(480) 419-0330, x.258

National Aeronautics and Space Administration
Marshall Space Flight Center

Reliability of Mechanical Behavior in Metallic Additively Manufactured Parts for Critical Applications

Doug Wells
NASA MSFC
Huntsville AL

ASTM/NIST Workshop on
Mechanical Behavior in
Additive Manufactured parts

May 4, 2016

AM Reliability Challenges

There is more to AM than manufacturing

AM machines create a unique material product form – typically purview of the foundry or mill

Subtractive Forging Process

1. Ingot Making
2. Cutting
3. Heating
4. Forging
5. Heat Treating
6. Machining
7. Inspection
8. Delivery with CoC

Additive SLM Process

1. Powder Making
2. Printing
3. HIPing
4. Heat Treating
5. Machining
6. Inspection
7. Final Part

As the 'mill', the AM process must assure manufacturing compliance throughout the build process and material integrity throughout the volume of the final part.

AM Reliability Challenges

- AM responsibility serving as the material mill gives rise to additional reliability concerns
  - Low entry cost compared to typical material producers
  - New players in AM, unfamiliar with the scope of AM, lacking experience
  - Fabrication shops not previously responsible for metallurgical processes
  - Research labs converting to production

Concept Laser X-line Material Mill in a Box

- **AM machines operate with limited process feedback!**
  - **Reliability depends upon the quality and care taken in every step of AM operations => rigorous and meticulous controls**

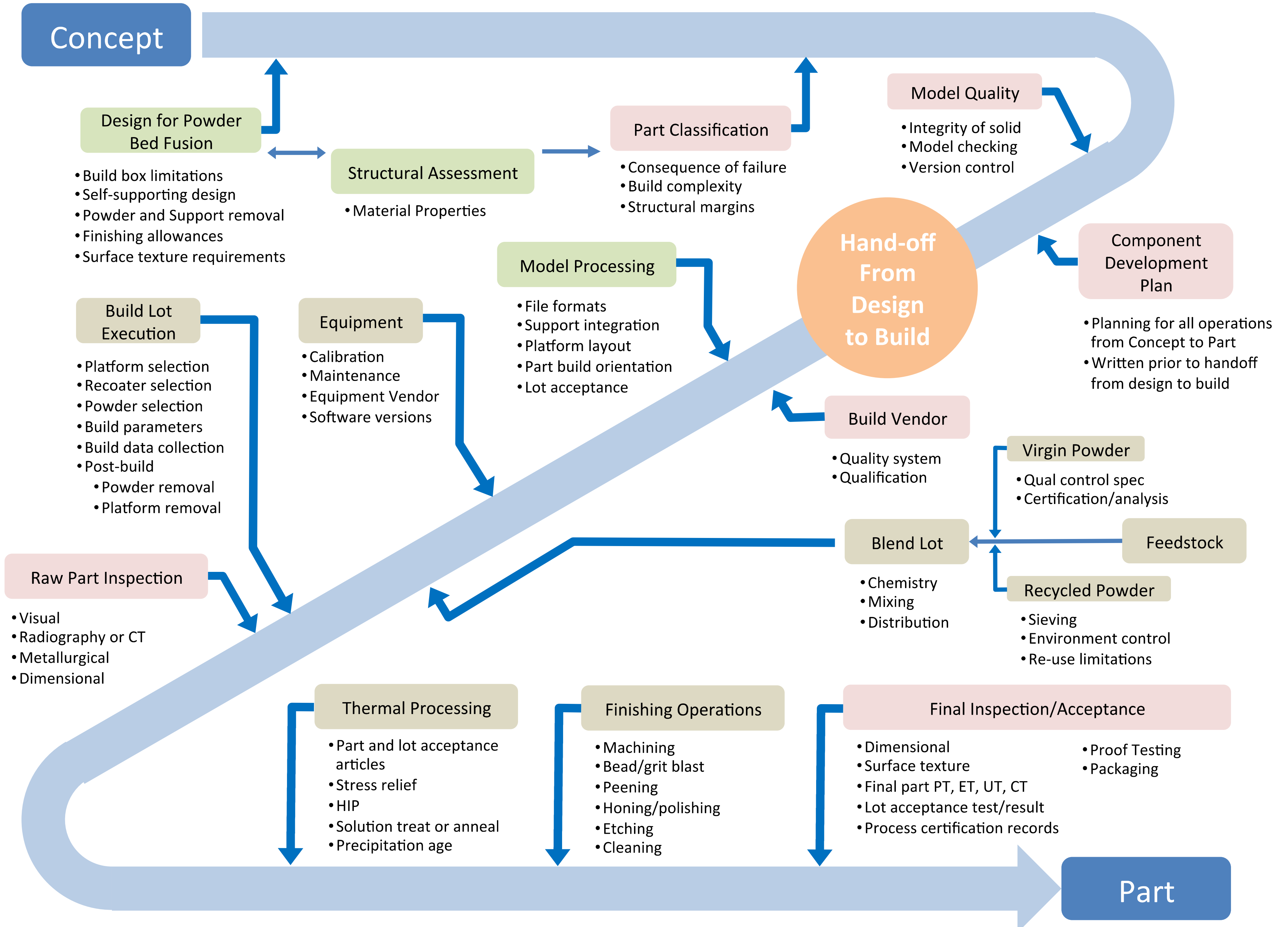
Opportunities to Secure AM Reliability

Two primary opportunities to ensure AM reliability

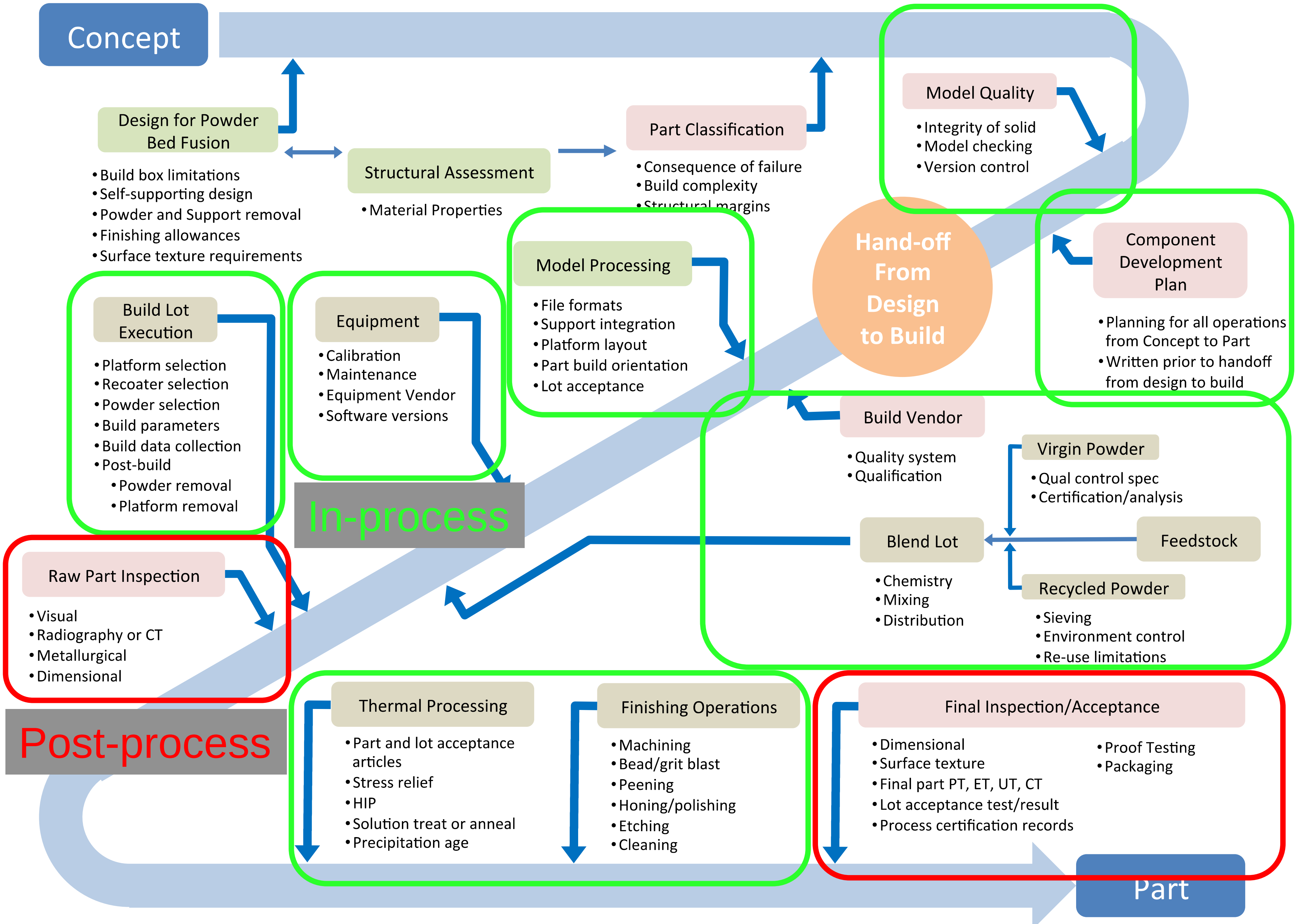
1. In-Process Controls, (Control what you do)
   - Understanding fundamentals of the process
   - Knowing the process failure modes (pFMEA)
   - Identifying observable metrics and witness capabilities
   - Meticulous process scrutiny
   - *Future to provide detailed process feedback for post-process evaluation, eventually closed-loop controls.*
2. Post-Process Evaluation (Evaluate what you get, NDE)
   - Extensive subject, ASTM E07 and many partners involved
   - Not covered in this discussion

Part reliability rationale comes from sum of both in-process and post-process controls, weakness in one must be compensated in the other

The AM Process: Concept to Part



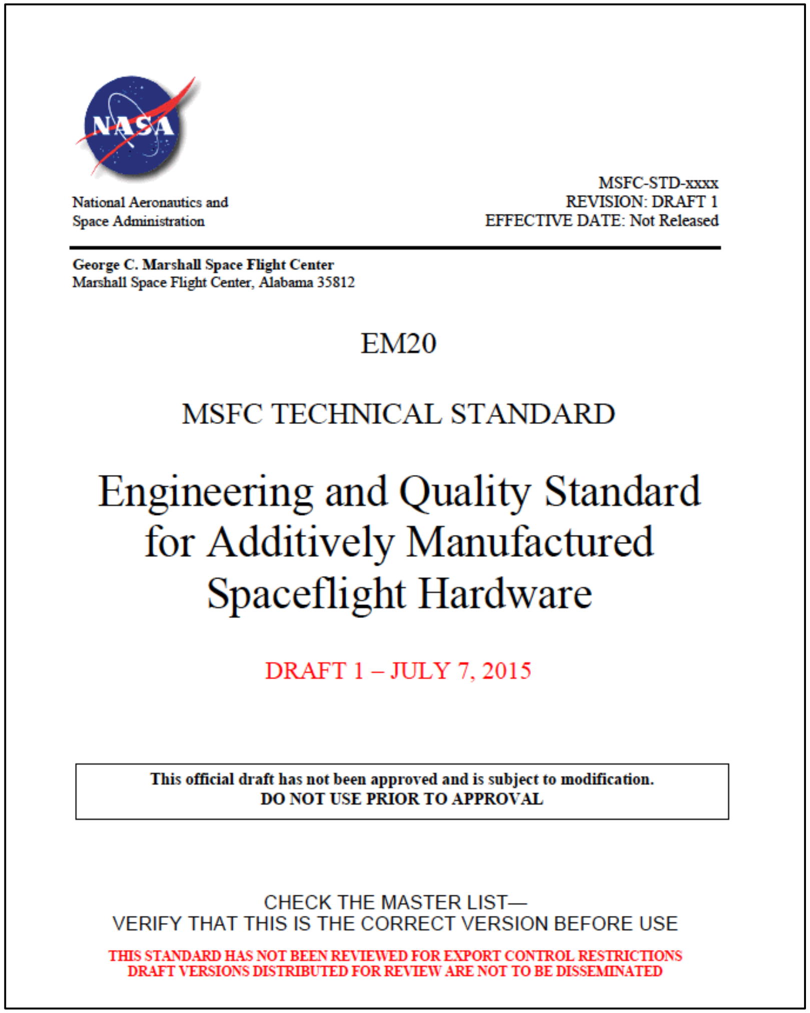
The AM Process: Concept to Part



Standardization for AM Mechanical Reliability

- Systematic and controlled execution of AM processes is required to achieve requisite mechanical reliability
- Standardization of AM processes is actively pursued by private industry, government organizations, and standards development organizations worldwide.
  - ASTM F42, ISO collaboration
    - Only SDO with open, published AM standards
  - SAE AMS-AM
  - AWS
- NASA works with SDOs to bring open industry standards to AM
- Currently available open industry standards do not levy sufficient controls for spaceflight applications

Standardization for AM Mechanical Reliability



National Aeronautics and Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

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DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

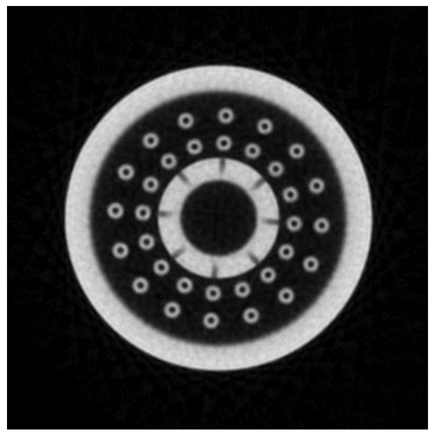
- Draft NASA MSFC Standard
- Current methodology for AM reliability for critical applications
  – Space Launch System
  – Commercial Crew Program

Aerojet Rocketdyne RS-25

SpaceX SuperDraco

Aspects of Process Control

Draft NASA MSFC Standard implements four fundamental aspects of process control for AM:

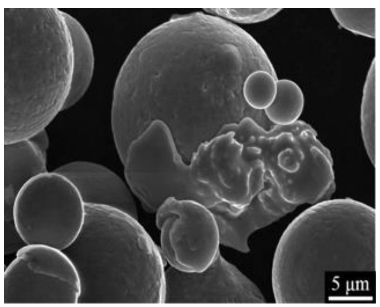


Metallurgical Process Control	Part Process Control	Equipment Process Control	Build Vendor Process Control

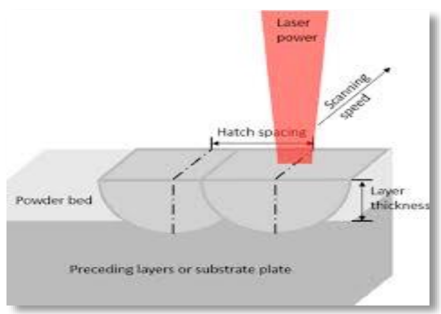
- Each aspect of process control is essential to the production of critical AM parts with reliable mechanical behavior
- Discussion here focuses on process control fundamentals for production of mechanically reliable AM materials

Foundation: Qualified Metallurgical Process

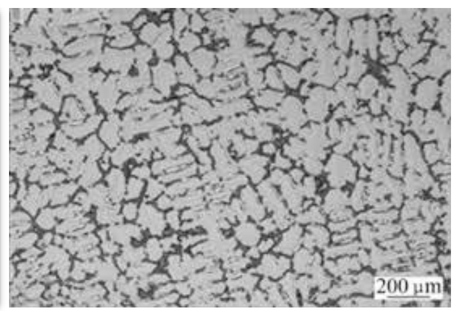
- Draft NASA MSFC Standard identifies AM as a unique material product form and requires the metallurgical process to be qualified on ***every*** individual AM machine
- While aspects of this foundation are present in, for example, ASTM F3055 (IN718 AM spec), rigor, qualification, and traceability are currently lacking.



Powder



Process Variables



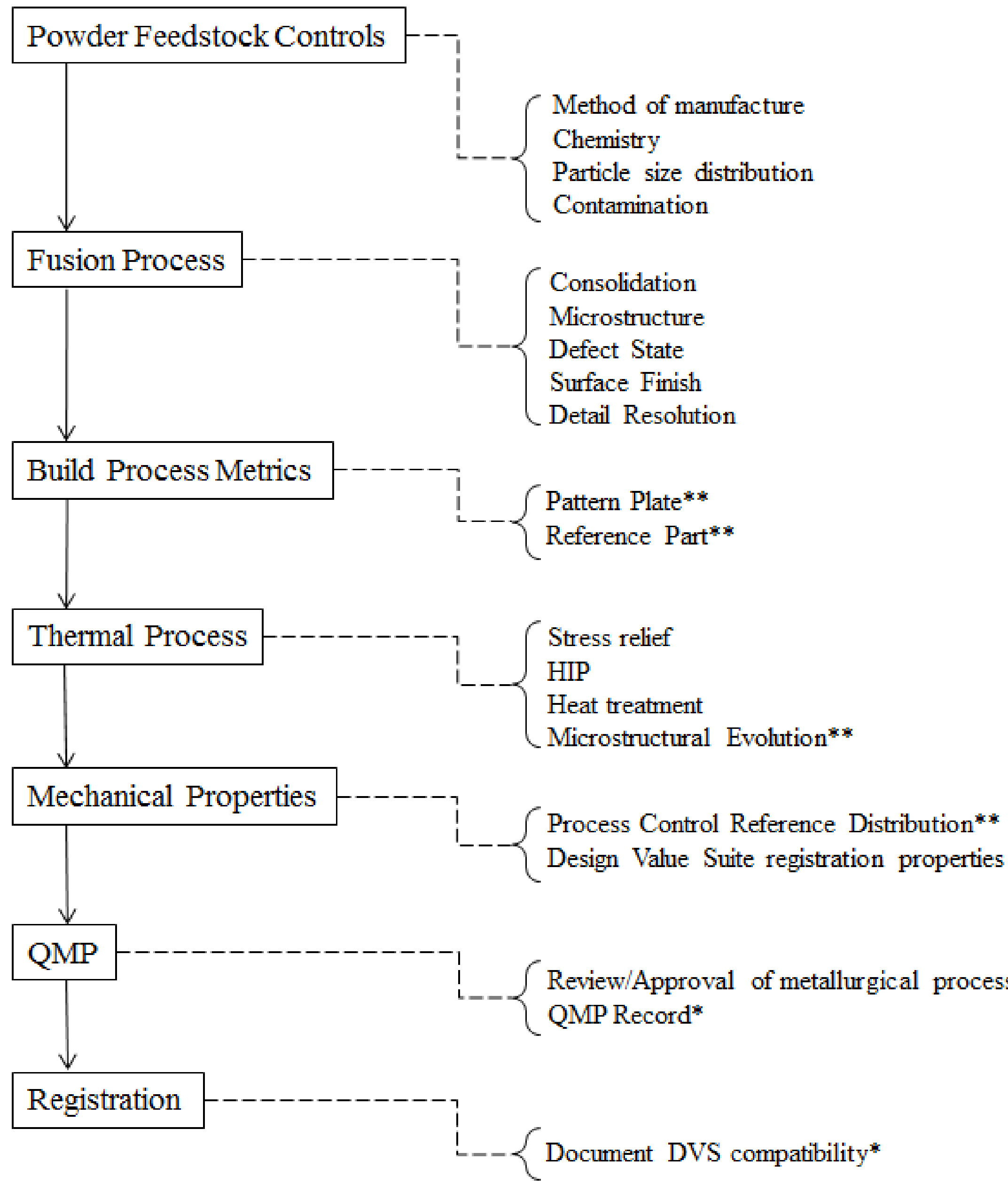
Microstructure

Properties

Foundation: Qualified Metallurgical Process

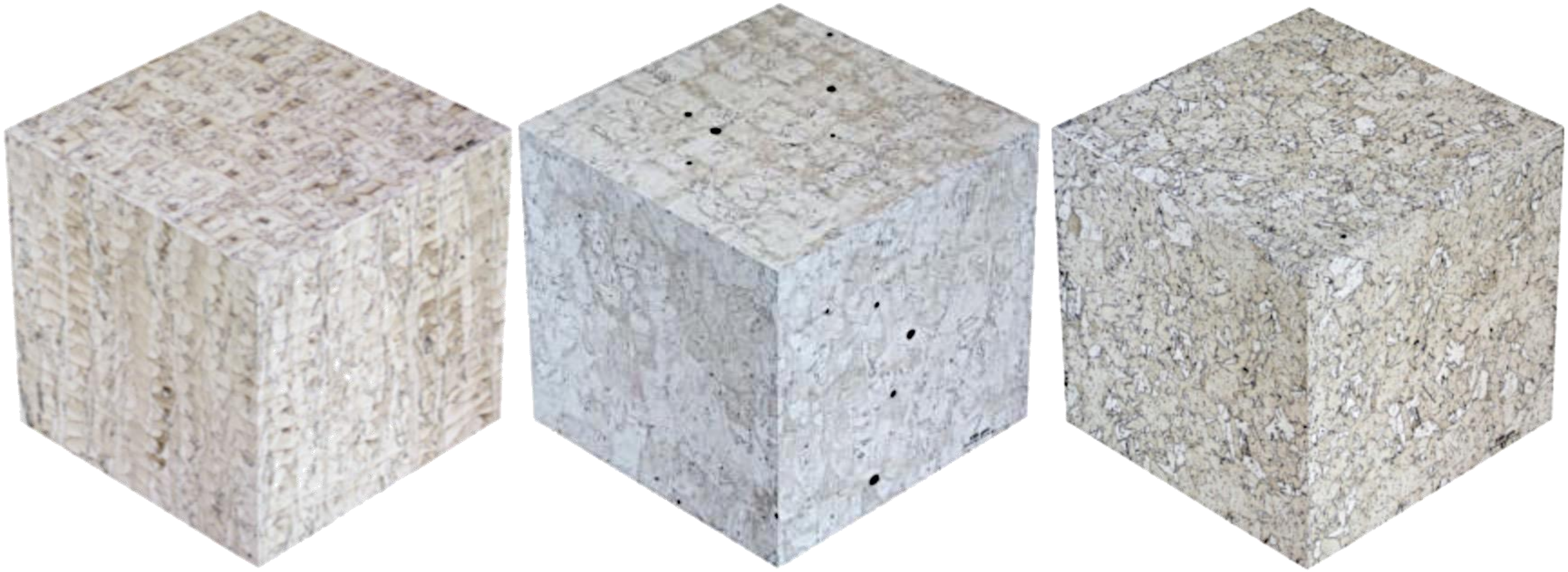
Qualified Metallurgical Process (QMP)

- Feedstock control or specification
- AM machine parameters, configuration, environment
- As-built densification, microstructure, and defect state
- Control of surface finish and detail rendering
- Thermal process for controlled microstructural evolution
- Mechanical behavior reference data
  - Strength, ductility, fatigue performance



*Quality management system record
**Acceptance criteria metric

Foundation: Qualified Metallurgical Process

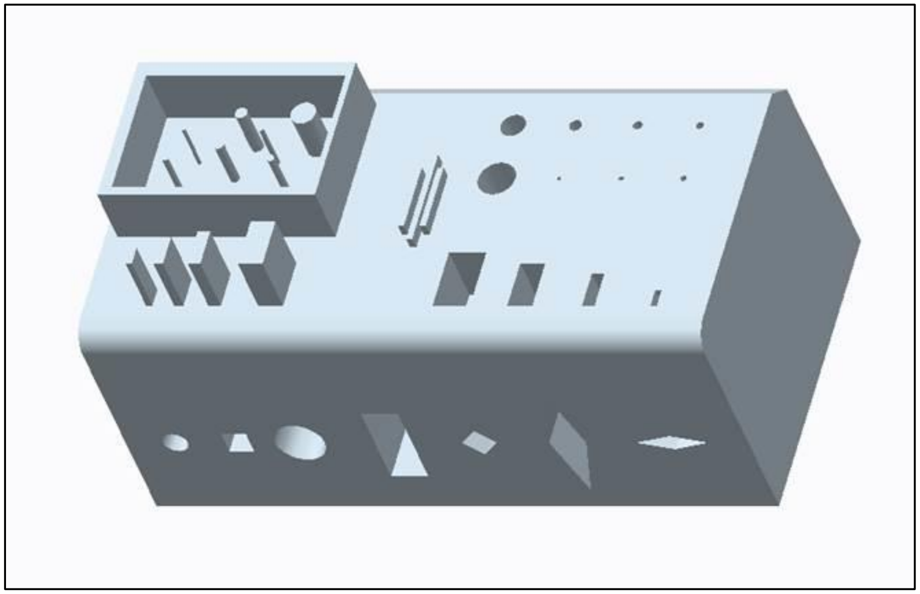


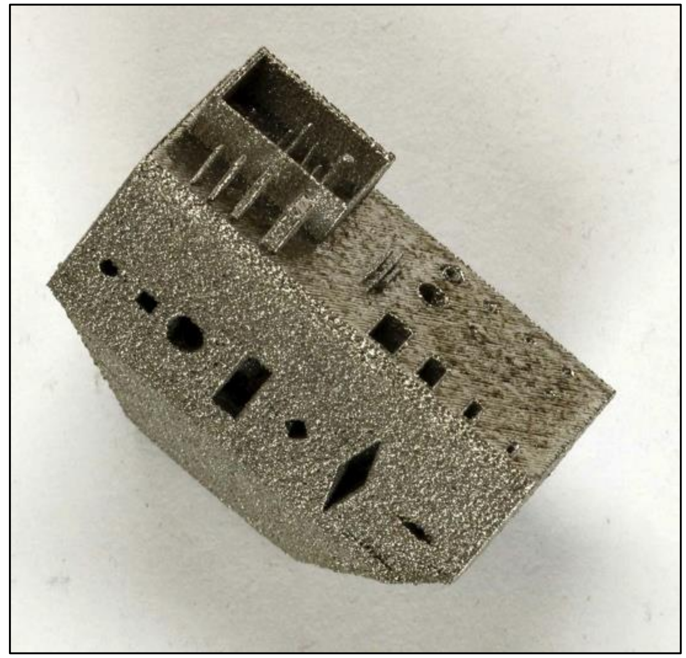
As Built | Stress Relieved | HIP & Final

Qualified Metallurgical Process (QMP)

- As-built densification, microstructure, and defect state
- Thermal process for controlled microstructural evolution

Foundation: Qualified Metallurgical Process





Reference parts:

Metrics for surface texture quality and detail rendering

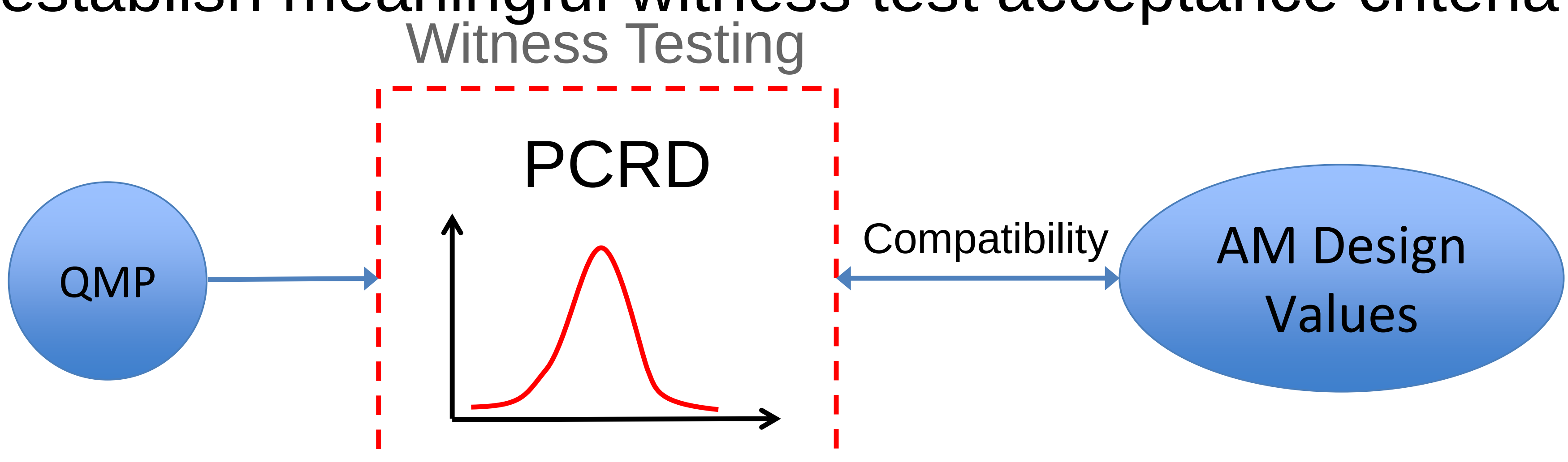
Overhanging, vertical and horizontal surface texture, acuity of feature size and shape

Qualified Metallurgical Process (QMP)

- Reference Parts
- Control of surface finish and detail rendering
- Critical for consistent fatigue performance if as-built surfaces remain in part

Foundation: Qualified Metallurgical Process

- Mechanical behavior reference data
  - Strength, ductility, fatigue performance
  - Process Control Reference Distributions (PCRD)
- Establish and document estimates of mean value and variation associated with mechanical performance of the AM process per the QMP
  - Will evolve with lot variability, etc.
- Utilize knowledge of process performance to establish meaningful witness test acceptance criteria



Foundation: Qualified Metallurgical Process

Types of AM build witness specimens

- Metallurgical
- Tensile (strengths and ductility)
- Fatigue
- Low-margin, governing properties

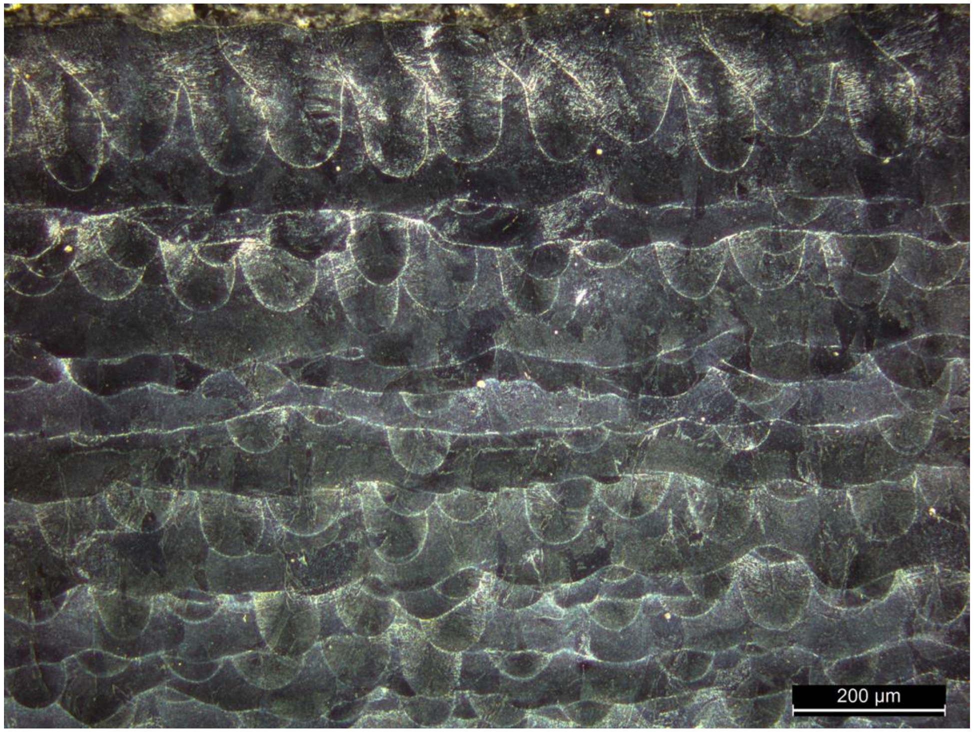
What is witnessed?

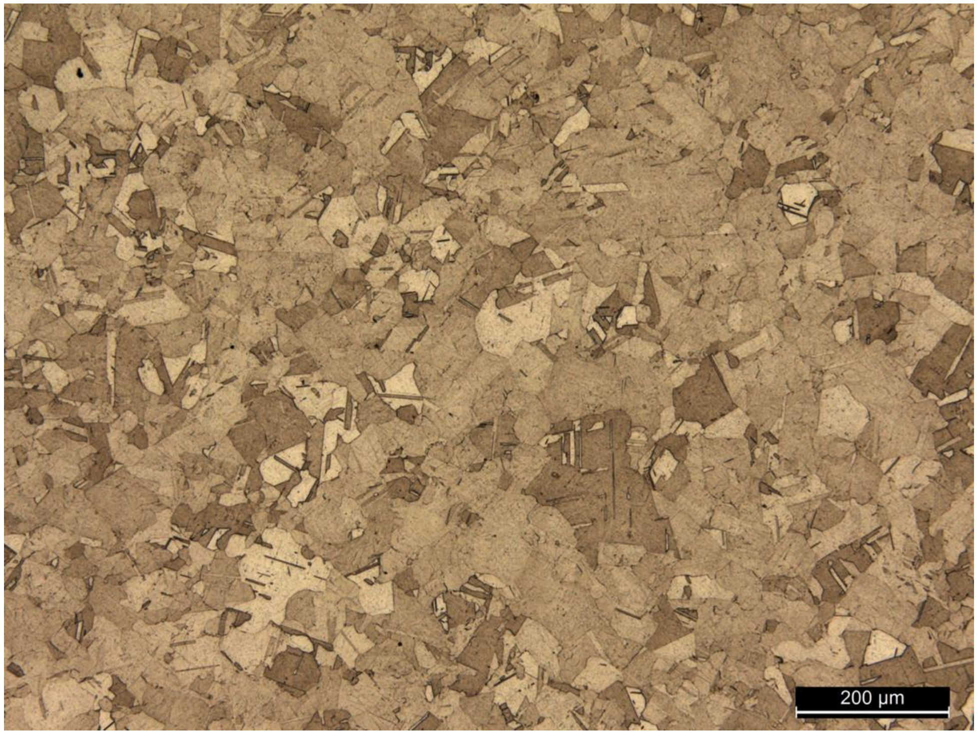
- Witness specimens provide direct evidence only for the systemic health of the AM process during the witnessed build
- Witness specimens are only an in-direct indicator of AM part quality through inference.

Foundation: Qualified Metallurgical Process

Types of AM build witness specimens

- Metallurgical





Example acceptance criteria - as-built state:
- Weld penetration depth and shape
- Grain nucleation patterns
- Porosity
- Lack of fusion / Cracks

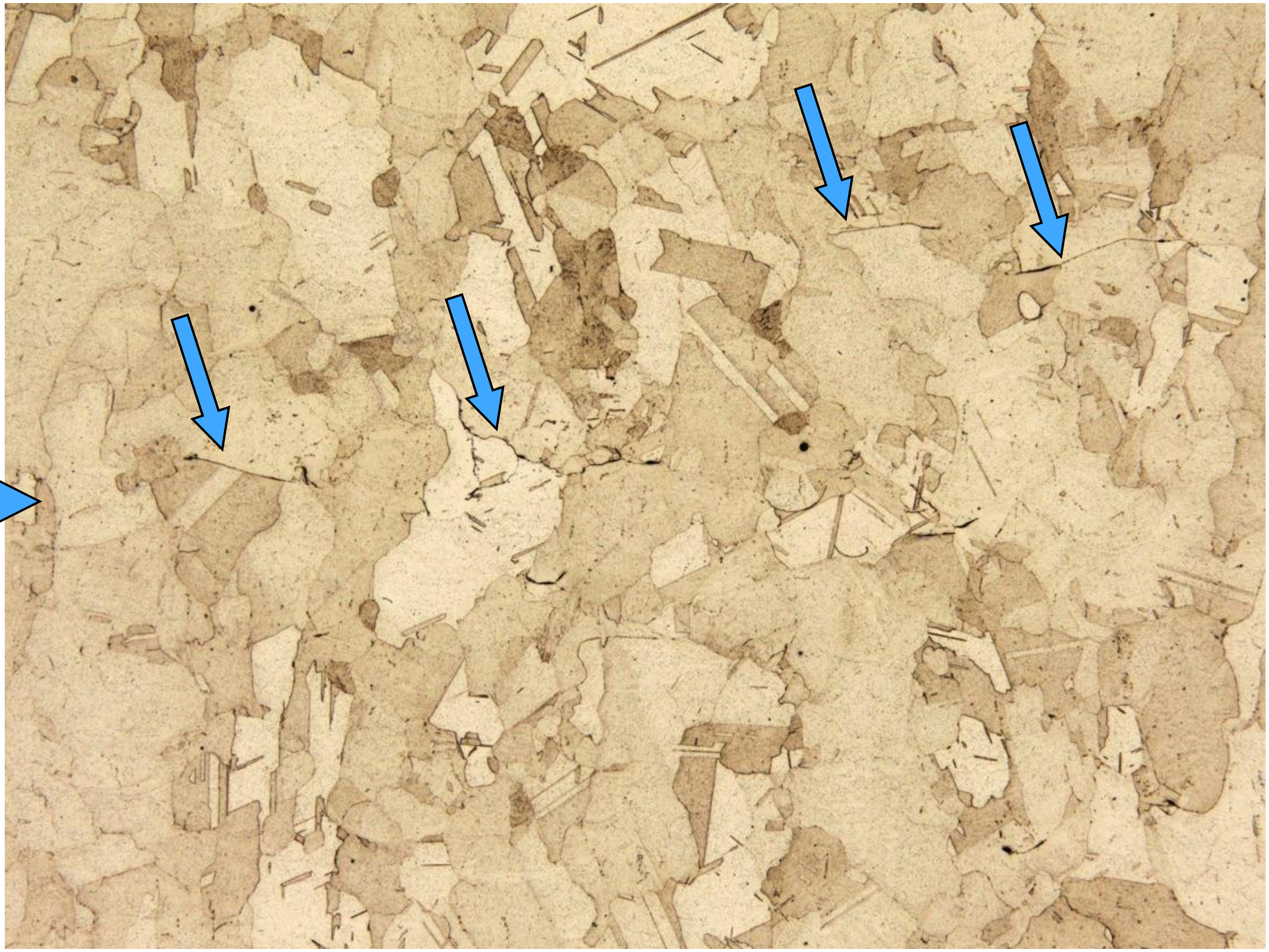
Example acceptance criteria - final state:
- Grain size
- Expected phases or carbide sizes
- Grain boundary cleanliness
- Porosity
- Lack of fusion / Cracks

Types of AM build witness specimens

- Metallurgical

Example acceptance criteria - final state:

- Grain size
- Expected phases or carbide sizes
- Grain boundary cleanliness
- Porosity
- Lack of fusion / Cracks



Foundation: Qualified Metallurgical Process

Types of AM build witness specimens

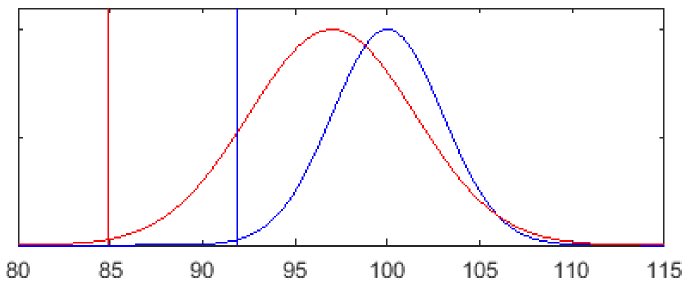
- Mechanical
  - Move away from spot testing for acceptance against 99/95 design values or specification minimums
  - Evaluate with sufficient tests to determine if the AM build is within family
  - Compromise with reasonable engineering assurance
  - Proposed
    - Six tensile
    - Two fatigue

Evaluate against the PCRD of the QMP

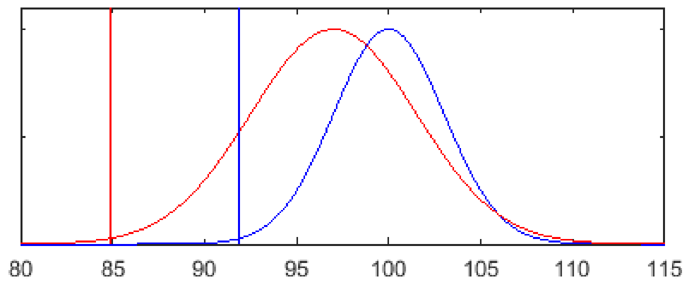
- **Ongoing evaluation of material quality substantiates the design allowable**
- **Only plausible way to maintain design values**

Example of AM build witness specimen evaluations

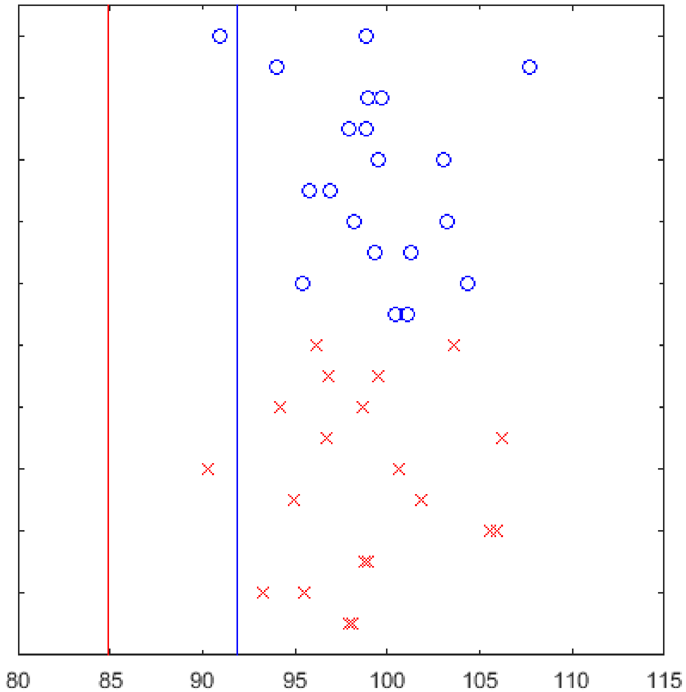
Nominal process is blue, off nominal in red



Two (2) witness tests per build

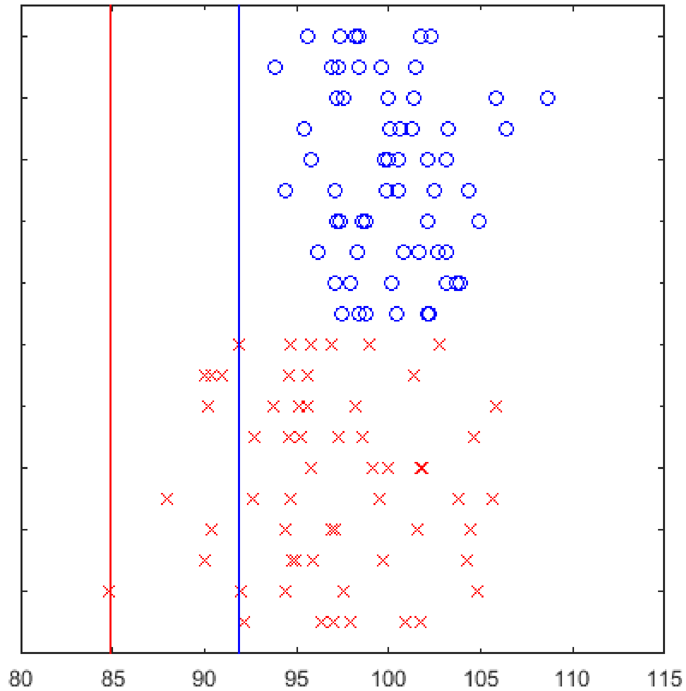


Six (6) witness tests per build



Random draw from nominal process 10 times

Random draw from off-nominal process, 10 times



Process shift hard to discern

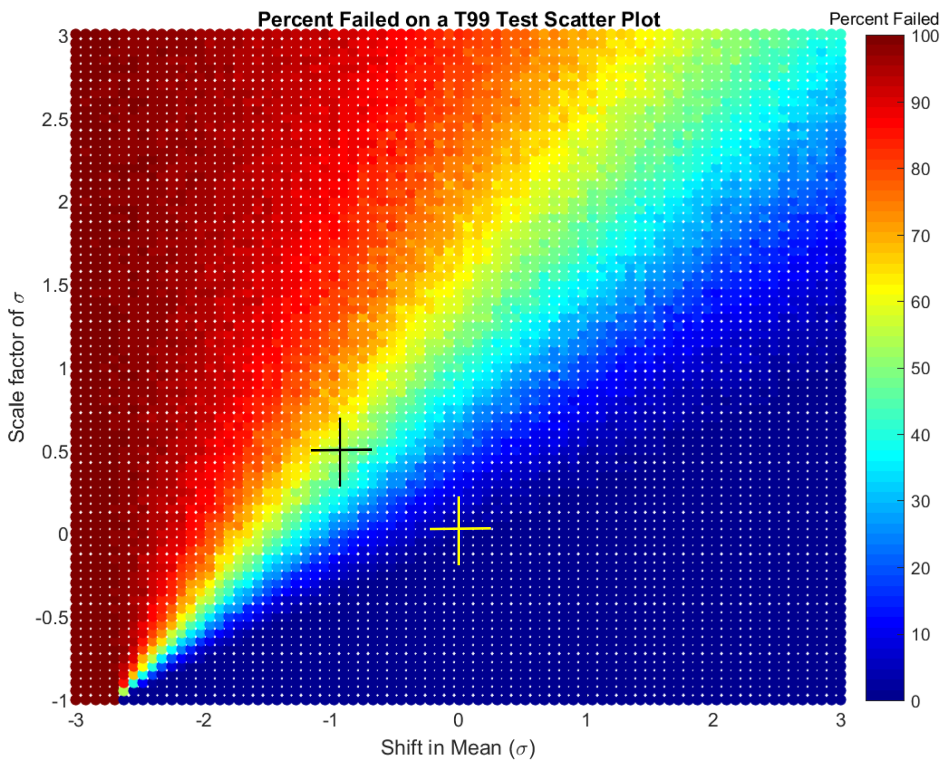
Process shift discernable with analysis of mean and variation

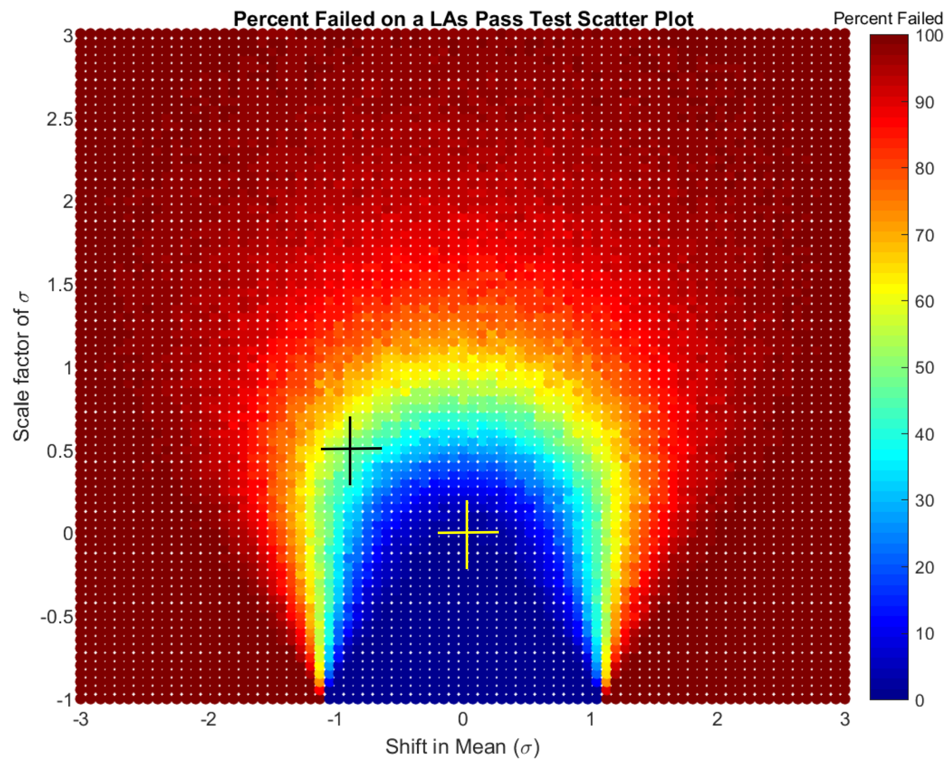
Witness for Statistical Process Control

Simulation is used to evaluate small sample statistical methods for witness specimen acceptance

Design acceptance criteria for the following:

- Keep process in family
- Minimize false negative acceptance results
- Protect the design values witnessed
- Protect the inferred design values





Role of Quality Management System

AM process controls cannot be meaningfully implemented without oversight and integration with strong Quality Management System

- Example, SAE AS9100

Mechanical reliability in AM cannot be established until:

- Process is defined and understood – Concept to Part
- Failure modes identified
- QMS engaged to monitor process and defeat failure modes

Standardization is key to developing a consistent approach

Summary of Points

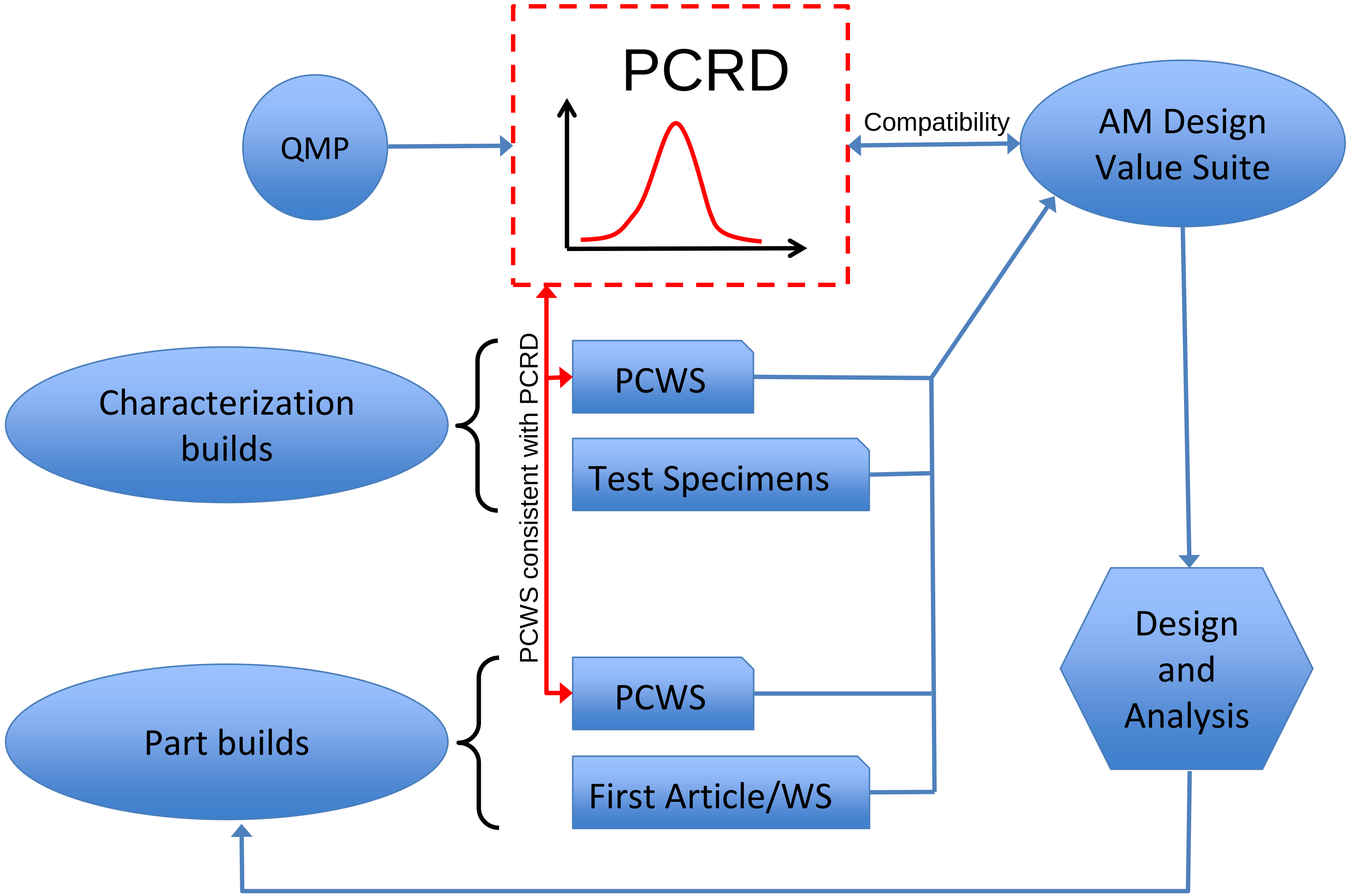
To ensure mechanical reliability in AM:

- Requires thorough understanding and control of the process - Just as would be expected from a mill, foundry, or manufacturing house
- Requires sufficient process standardization to produce reliable parts in a routine fashion
- Requires quality management systems be in place
- Requires In-Process controls
  - Start with a solid foundation
    - Qualified metallurgical Process
  - Ensure mechanical reliability
    - Process witnessing, statistical evaluations
- Requires Post-Process controls
  - NDE
  - Proof testing
  - Etc.

Thank You

Additive Manufacturing at MSFC

Witness for Statistical Process Control



Ti-6Al-4V for Orthopedic Implants in Fatigue

Mukesh Kumar
Zimmer-Biomet

WORKSHOP ON MECHANICAL BEHAVIOR OF ADDITIVE MANUFACTURED COMPONENTS

Sponsored by ASTM Committee E08 on Fatigue and Fracture in conjunction with the National Institute of Standards and Technology (NIST).

May 4-5, 2016
Grand Hyatt San Antonio
San Antonio, TX

What does the Orthopedic Industry do

In the business of restoring mobility by replacing damaged bone / cartilage with metallic implants that

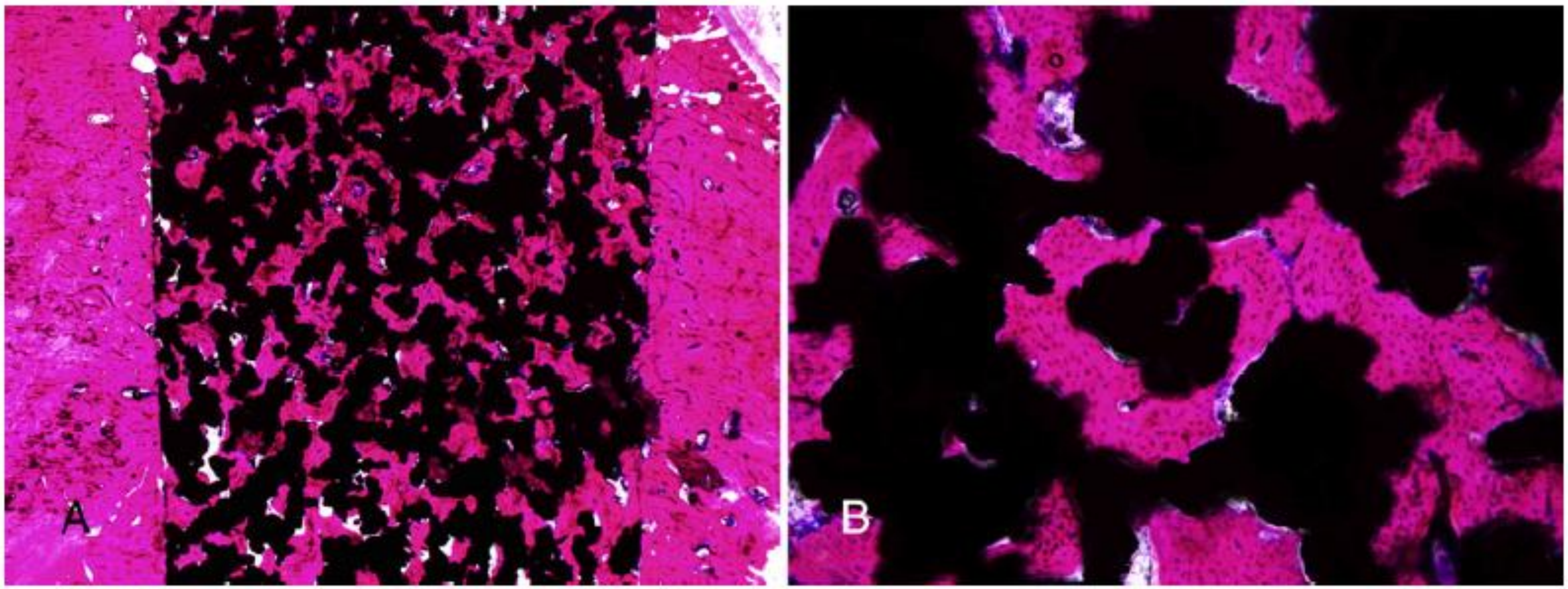
- Must survive years
- In a hostile (corrosive) environment
- (osseo) integrate with the surrounding bone to transmit 5-8 X body weight
- Under fatigue conditions

Titanium and Porous Structure

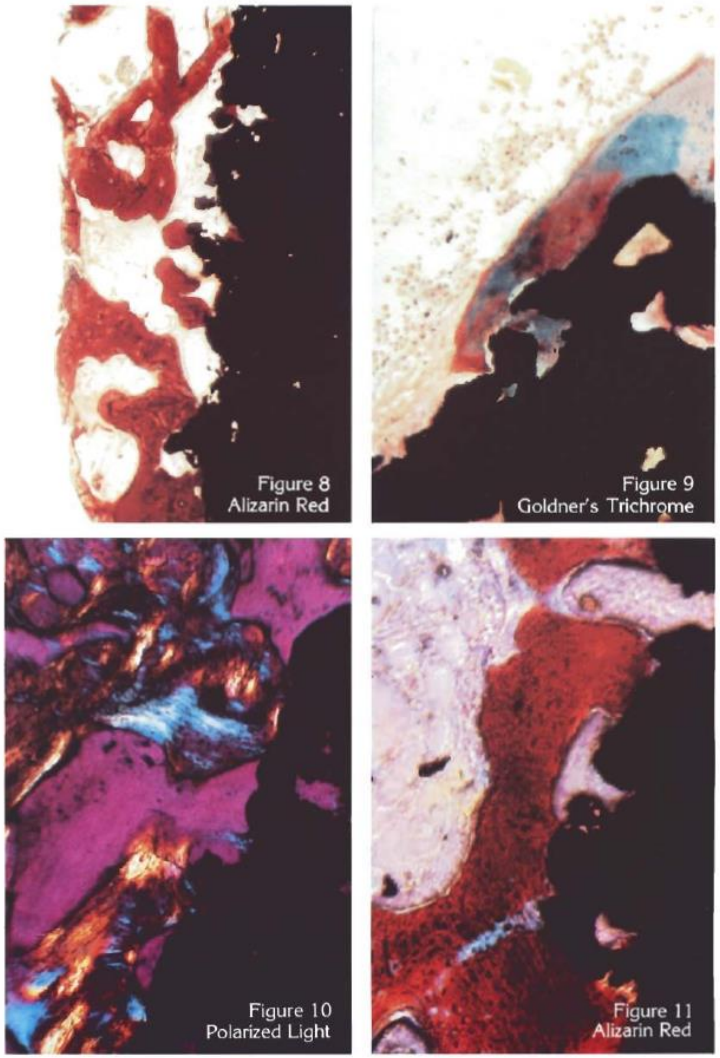
- Why do we need this porous structure
  - Bone – Implant Interface
    - Transmit load

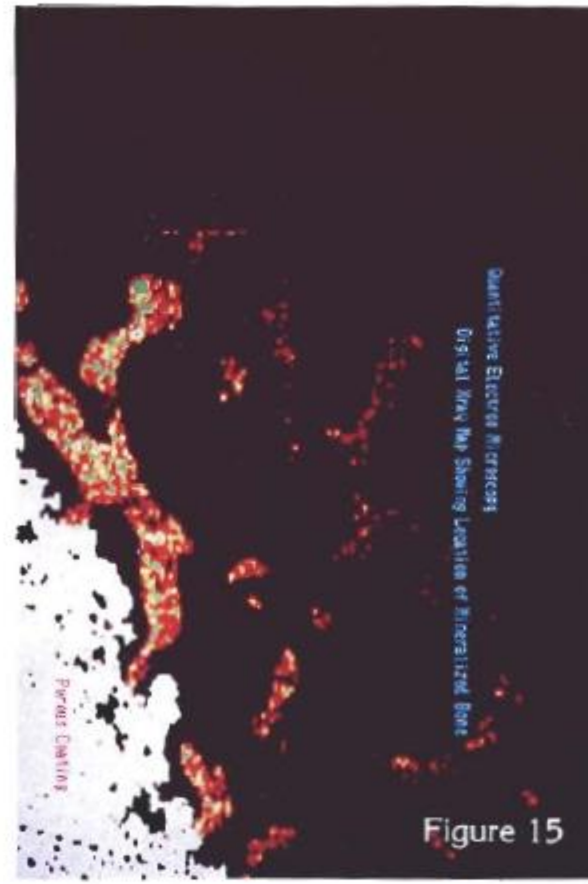
- Animal
- Human

Animal Studies

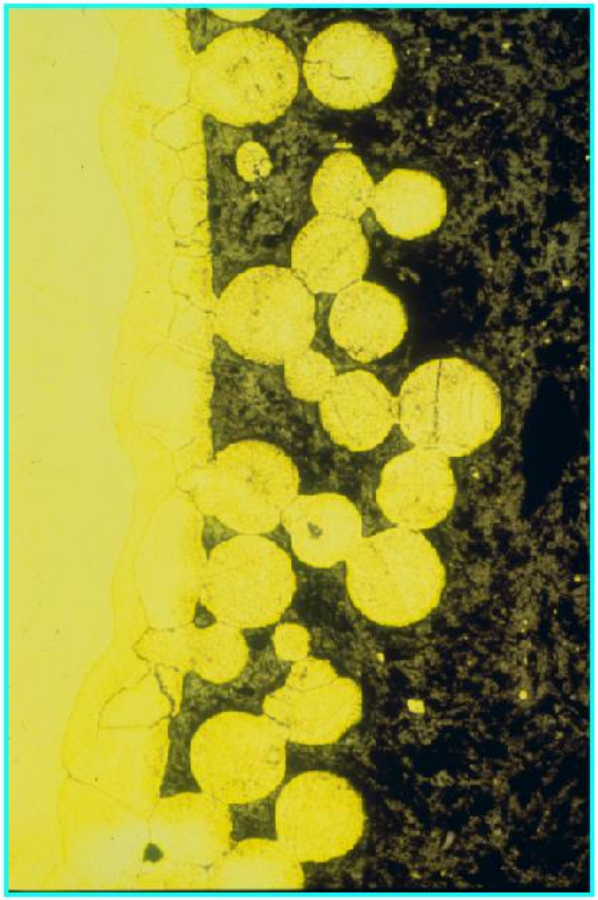


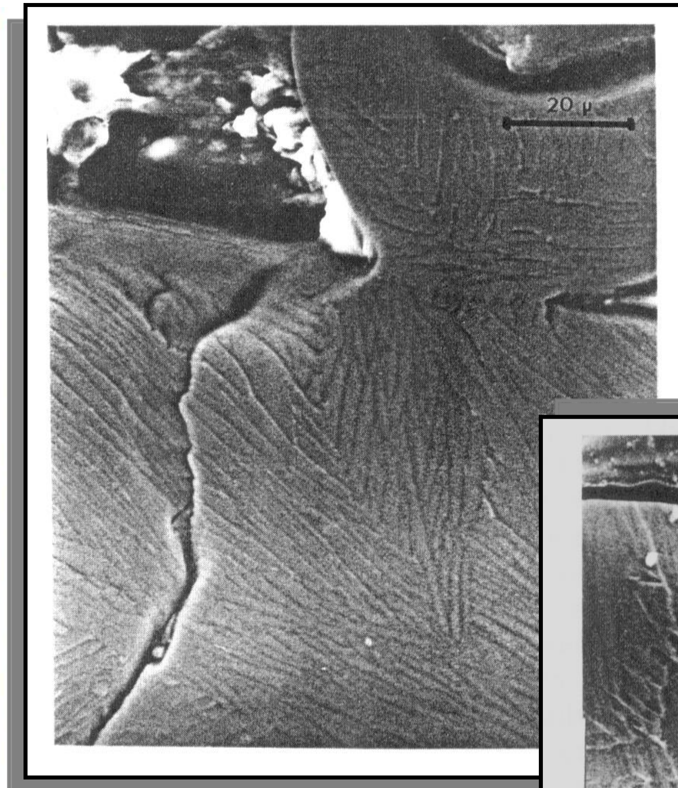
Human – Retrieval Analysis



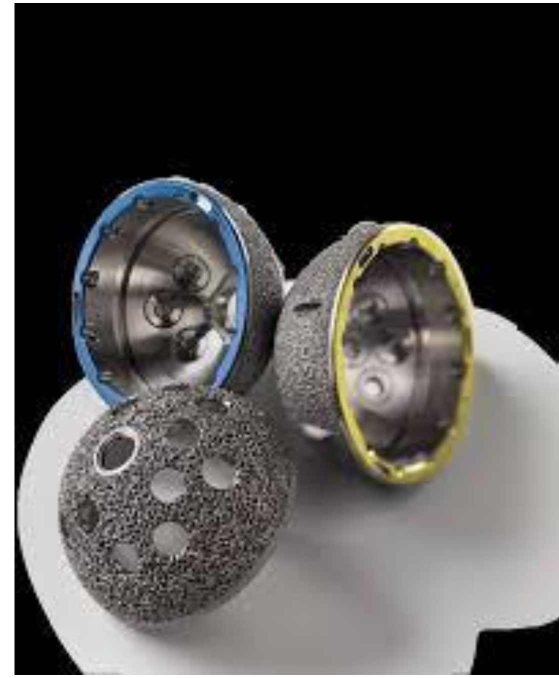


Porous Beaded Structure - Notch





Orthopedic Industry and Additive Manufacturing



Additive Manufactured Implants now available

- Acetabular shells
- Spinal Implants

Low fatigue environment

Some Surgical Cases

Some clinical cases ….

- To get an idea of loads involved
    - Imagine your own anatomy

Why Additive Manufacturing makes perfect sense

Imagine the following work flow

Image (sometimes the contralateral side)

Create CAD

Make Implant / Bone Model / Fixtures and Guide

In many cases - Time is of the essence

18 year old patient

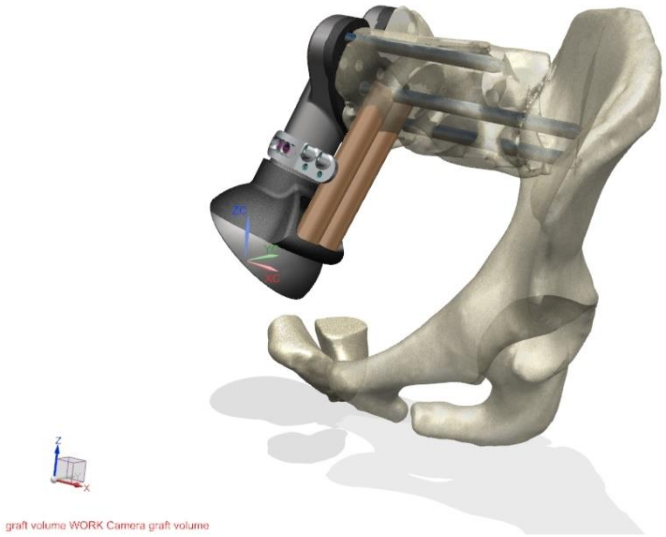
osteosarcoma of the proximal humerus

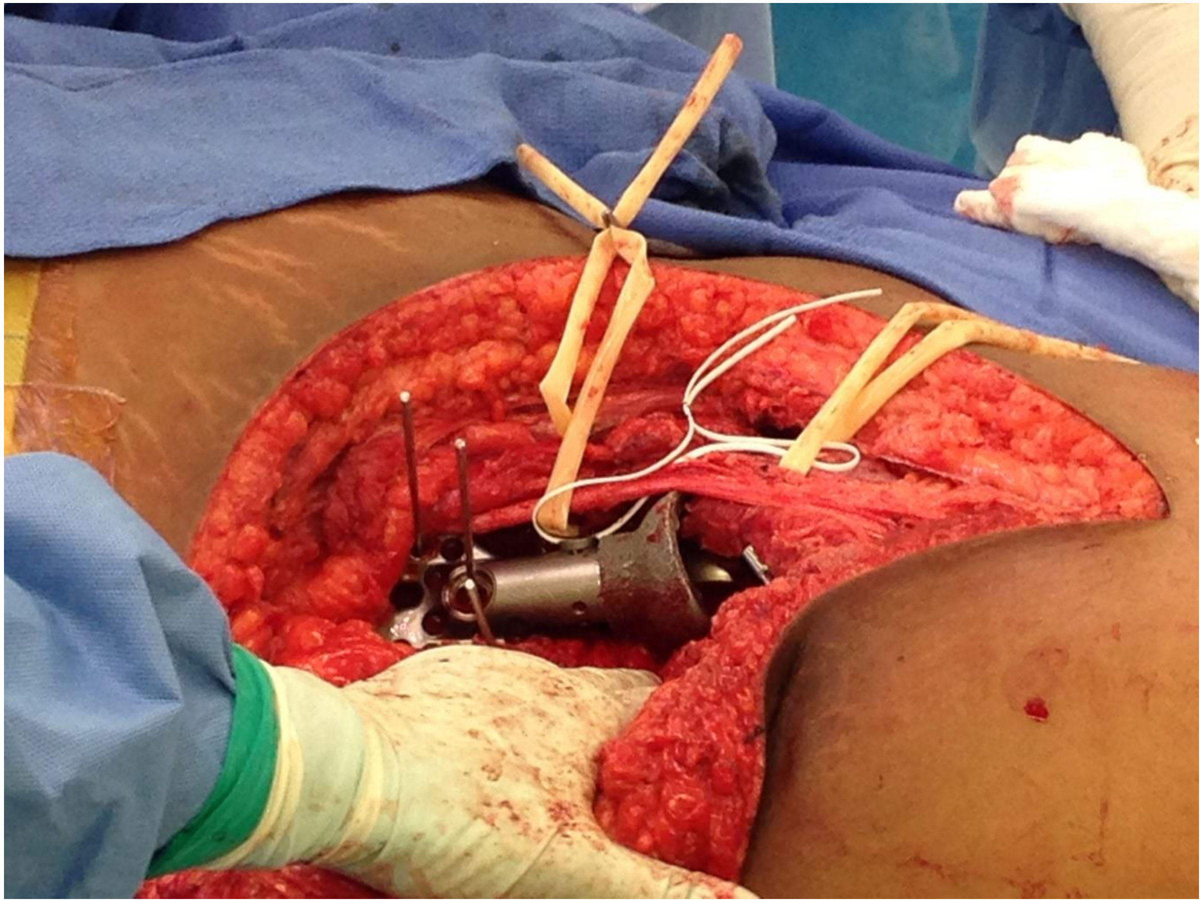
Expandable proximal humeral implant with a Compress stem

IMPLANT NOT FDA CLEARED

- Bilateral Triflanges

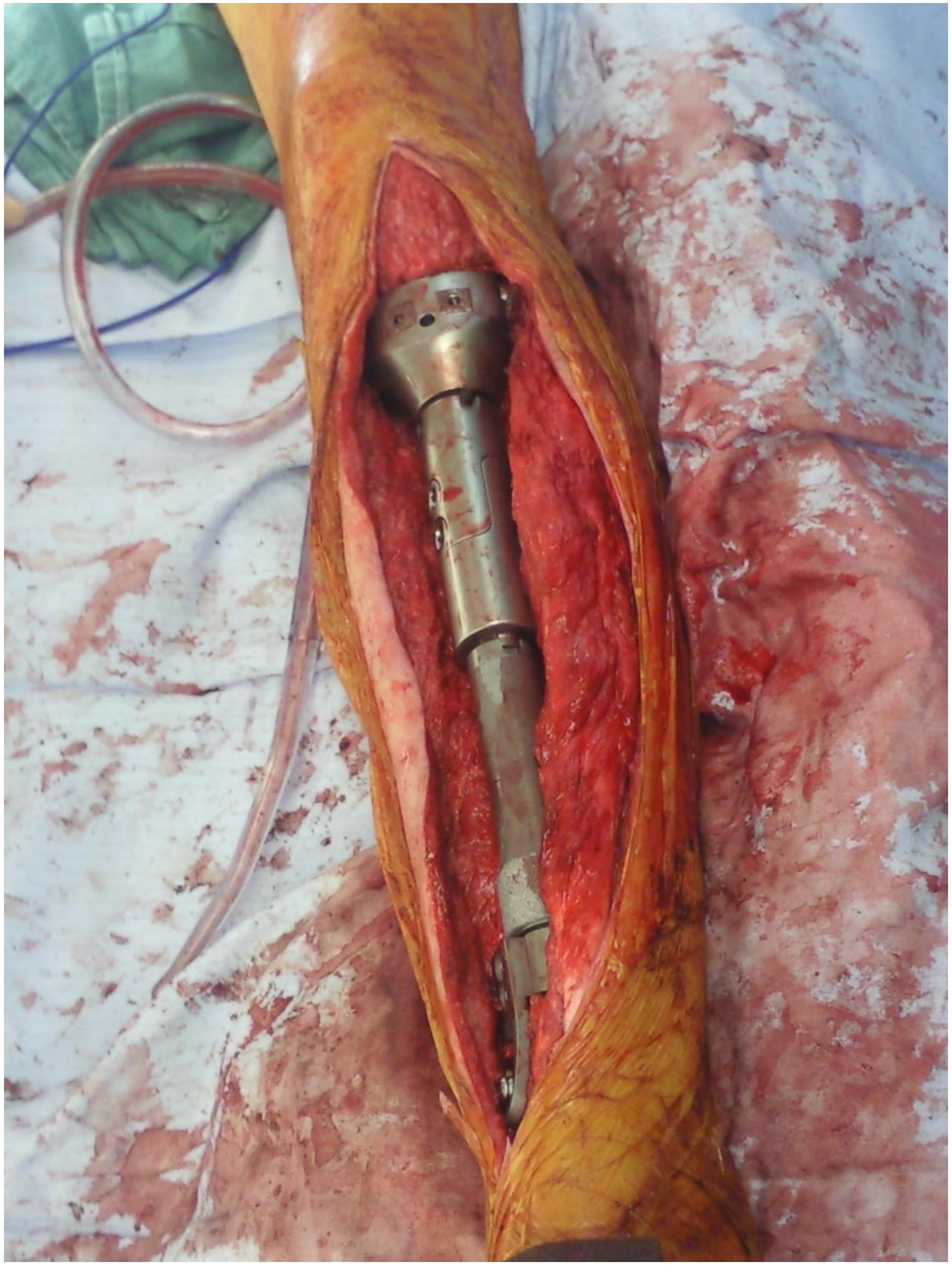
IMPLANT NOT FDA CLEARED





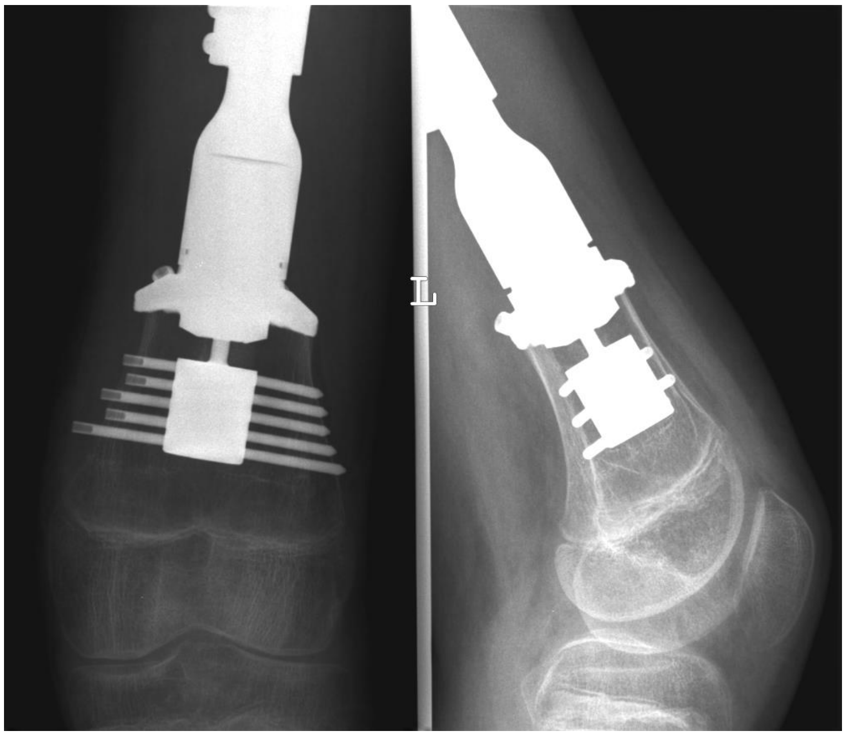
IMPLANT NOT FDA CLEARED

- Mid shaft Tibia



IMPLANT NOT FDA CLEARED

- Mid shaft femur



IMPLANT NOT FDA CLEARED

Work flow

What do we do today

- Scan of bone
- Evaluate contralateral side if available
- Design implant with surgeon (truly one of – so surgeon prescription)
- Surgeon approval
- Machine implant from bar stock
- Coat implant with porous structure
- Clean / passivate / package / sterilize

What we want to do

- Based on scan
  - 3D Print
  - Can print the porous structure
  - No need to program CNC machines
  - No issues of tolerance match ups
- Clean / passivate / package / sterilize

Can we define what we need to get Additive Manufactured Implant more main stream

Some Functional Requirements
The Patient

- All age groups
  - Young and Old

- Activity level
  - Sedentary and Active
    - And this can change with time
- Body Mass
  - And this definitely changes

Some Functional Requirements

Must be similar to ASTM F136

- Why?
  - We know ASTM F136 works
    - Maybe unnecessarily high
  - Surgeons have a comfort

What are we looking for …

- What heat treatment regimen can provide fatigue properties in excess of wrought material?
- How does the fatigue property change if there is semi-sintered loose powder on the "as built" surface?
  - Is there a way to simulate the decrease in fatigue from the presence of such semi-sintered surface particle clusters and thus help define acceptance criteria for such clusters?
- Design rules - recognizing that porous structures are essential features in orthopedic implants, but the presence of porous structures create stress risers and reduce fatigue properties, what design rules could be followed to help create a higher fatigue strength implant

Questions?

Fracture Mechanics and Nondestructive Evaluation Modeling to Support Rapid Qualification of Additively Manufactured Parts

ASTM Workshop on Mechanical Behavior of Additive Manufactured Components
May 4, 2016
San Antonio, Texas

Craig McClung, Michael Enright, John McFarland, Jonathan Moody
Southwest Research Institute

Irving Gray, Joe Gray
NDE Technologies, Inc.

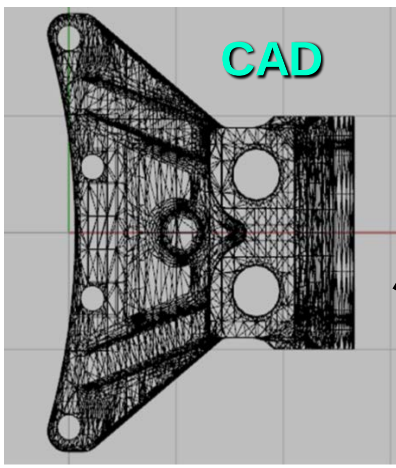
Acknowledgments

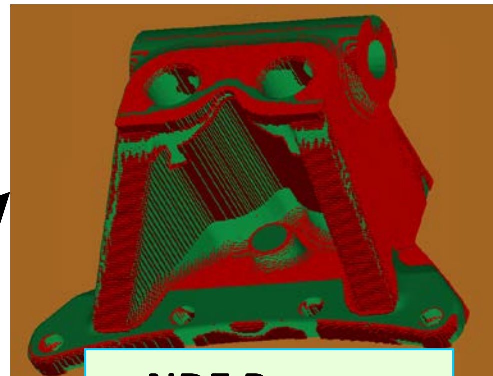
- Funding for this SBIR effort provided by the US Air Force Research Laboratory
  - Andrew Nauss, AFRL Program Monitor for Phase I
  - Bill Musinski, AFRL Program Monitor for Phase II

Motivation

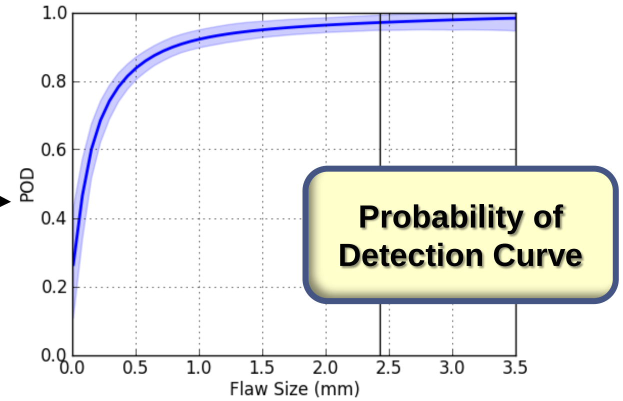
- Additive Manufacturing methods can produce defects
- NDE may be required to ensure structural integrity
- Key questions:
  - What size defects can be found in a complex part?
  - What size defects matter to structural integrity?
- Simulation modeling can be used to answer these questions without expensive physical testing
  - NDE simulation can determine what size defects can be found
  - Fracture mechanics simulation can determine what size defects matter to structural integrity
  - Coupled simulations can determine the impact of NDE reliability on fracture risk

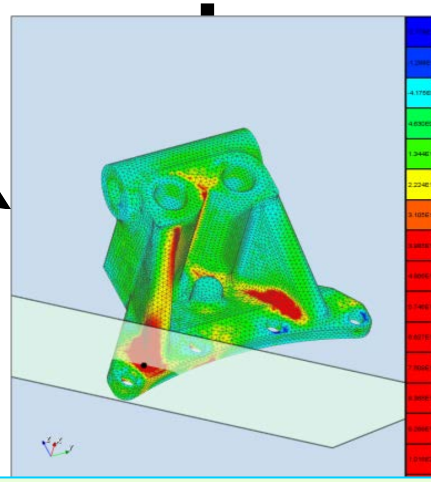
Method: Integrated NDE and Fracture Risk Models



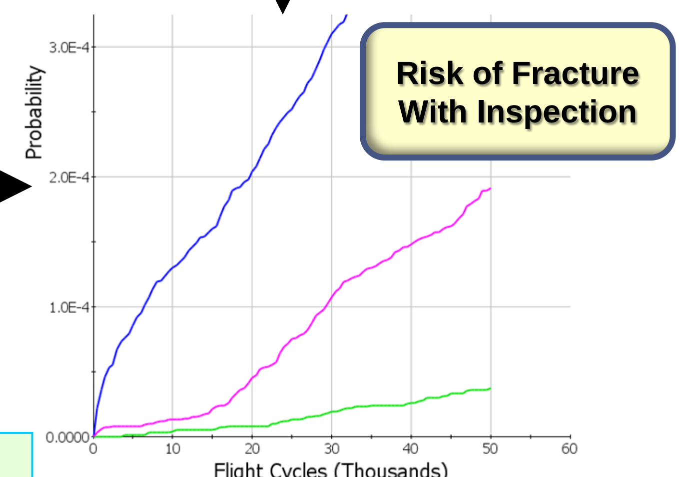


NDE Process Simulation





Stress and Fracture Mechanics Analysis

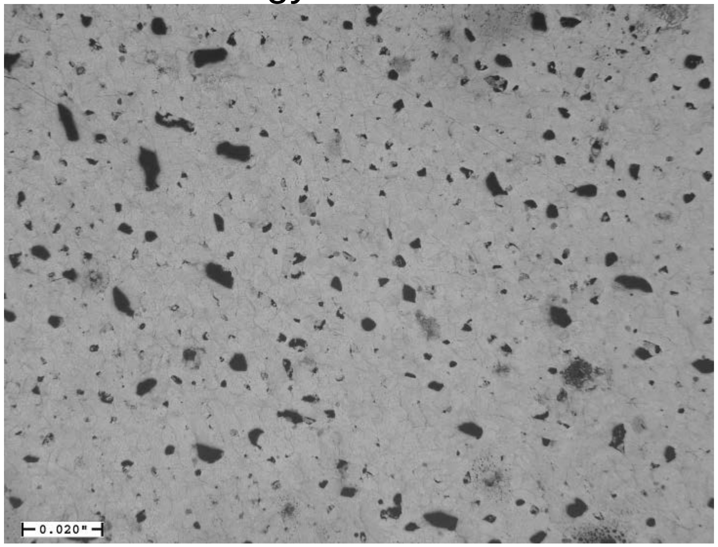


Overview

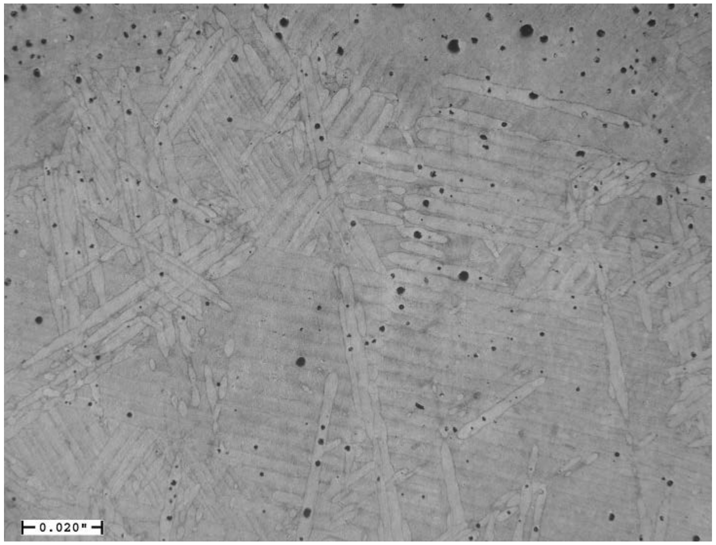
- Defect Morphology
  - Identify anomaly types associated with DMLS additive manufacturing processes
- POD Curve Simulation
  - Link NESSUS with XRSIM to generate location-specific POD curves
- Fracture Risk Simulation
  - Link NESSUS/XRSIM-generated POD curves with DARWIN to predict risk of fracture with inspection
- Application Example
  - Illustrate generation of location-specific POD curves and fracture risk assessment for actual component (engine mount)

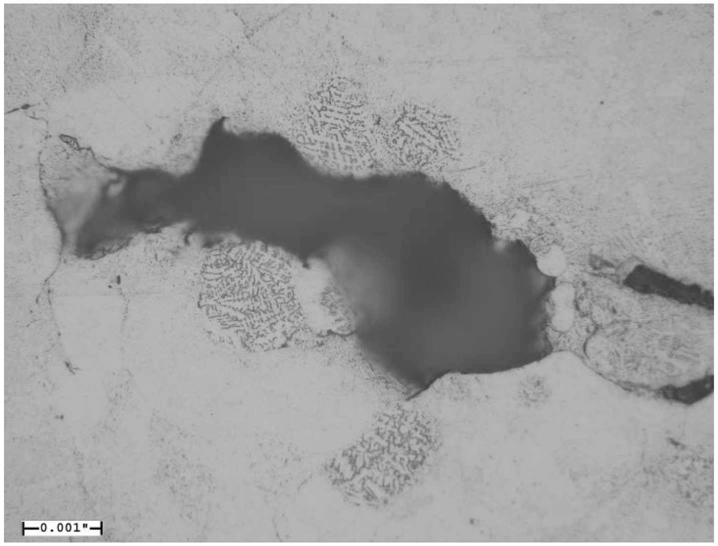
Representative AM Defects

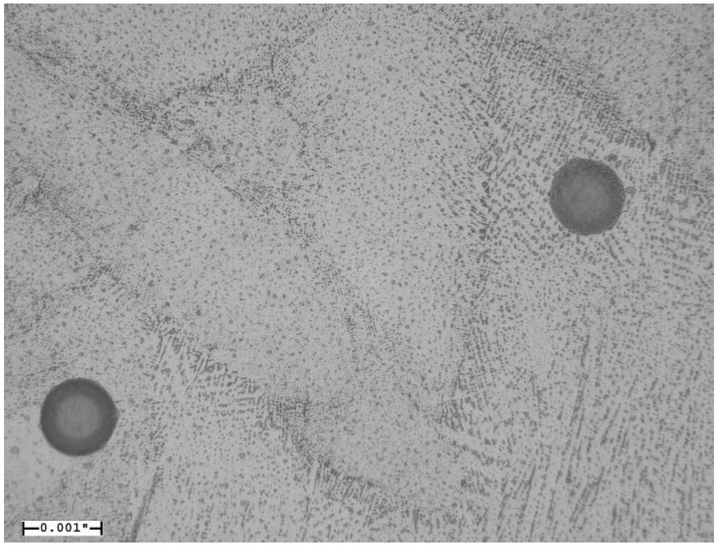
Low Energy- Lack Of Fusion



High Energy- Keyhole Porosity





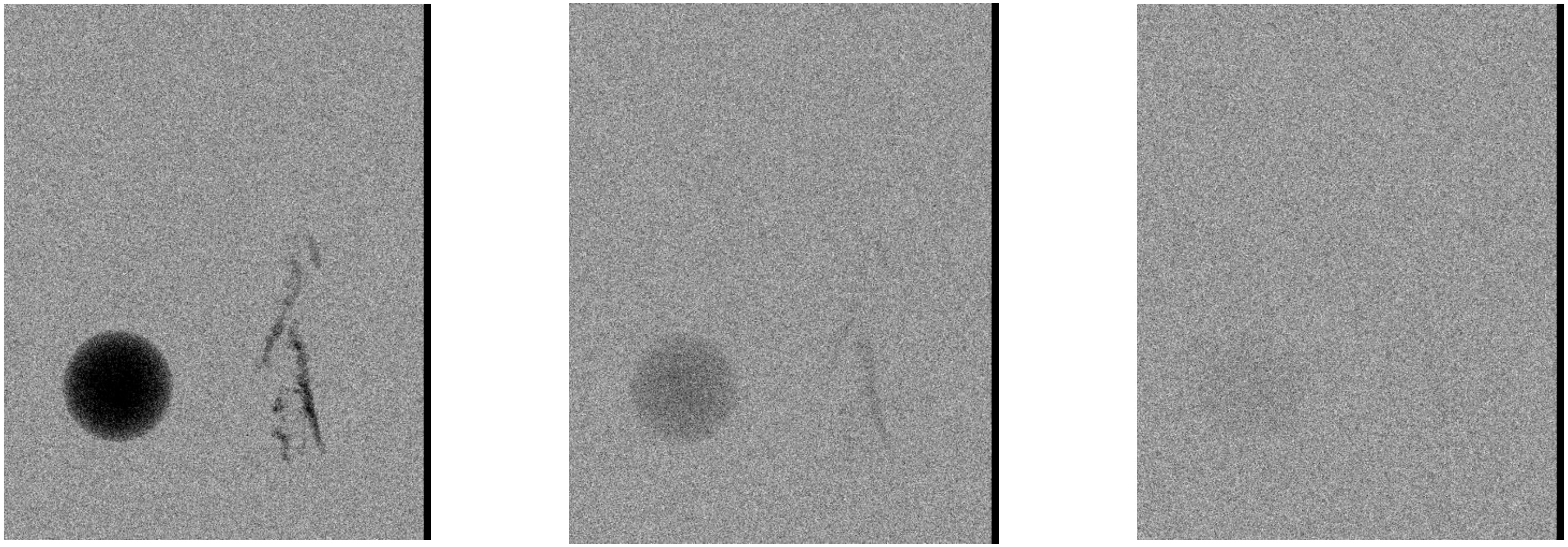


Simulating Non-Destructive Inspections Using XRSIM

- XRSIM simulates the application of X-Rays to a component to identify defects
- The intensity of the simulated X-Ray images is dependent on a number of factors
  - Equipment
    - Inherent filtration of x-ray tube, eddy current lift off and coil tilt, broad band center frequency
  - Setup
    - Placement of the central axis of the x-ray tube, orientation of the UT probe, scan variation in lift off and probe tilt
  - Signal Noise
  - Flaw morphology
    - Size, shape, position & orientation in the part

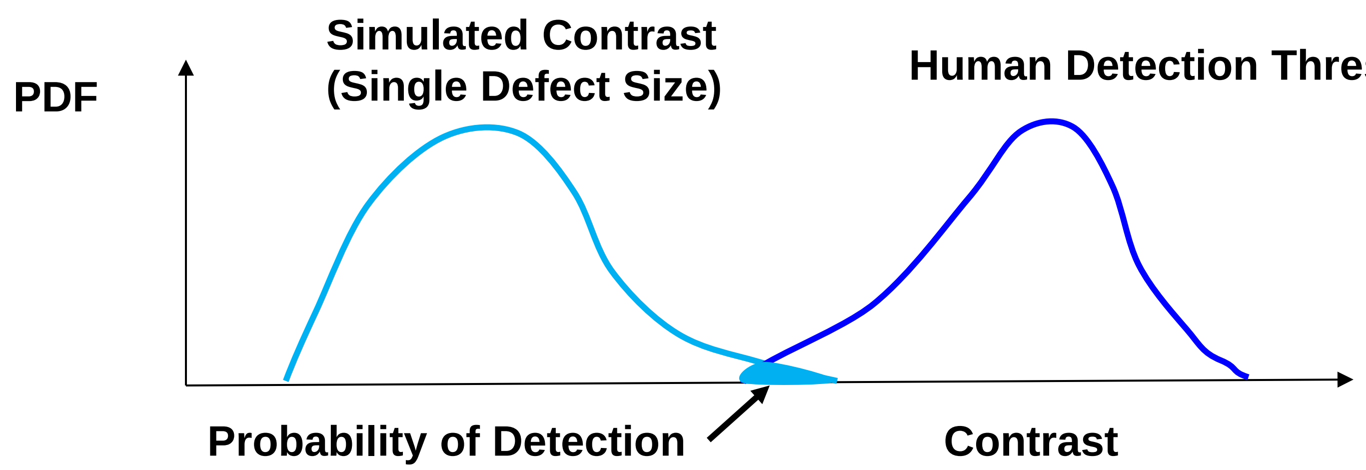
XRSIM Defect Detection Based on Contrast Values

- XRSIM provides virtual images that simulate the X-Ray NDE method
- Human detection of a defect is dependent on contrast values
  - Contrast is based on the image intensity at a defect versus the intensity of the surrounding image



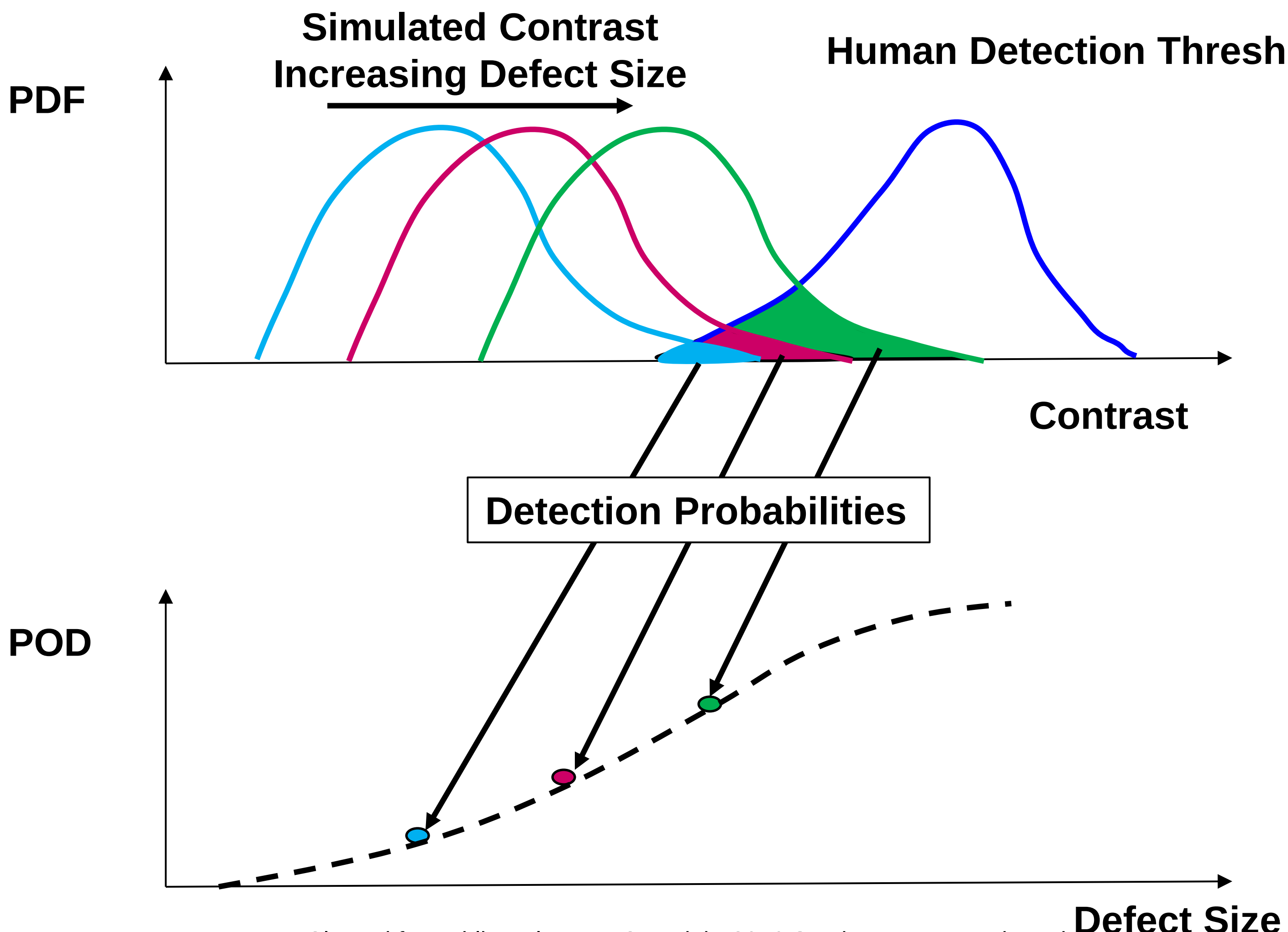
Simulating POD Curves Using Probabilistic Analysis

- The contrast value associated with a single defect size is modeled as a random variable
- The threshold contrast value at which a defect can be detected by a human is also modeled as a random variable



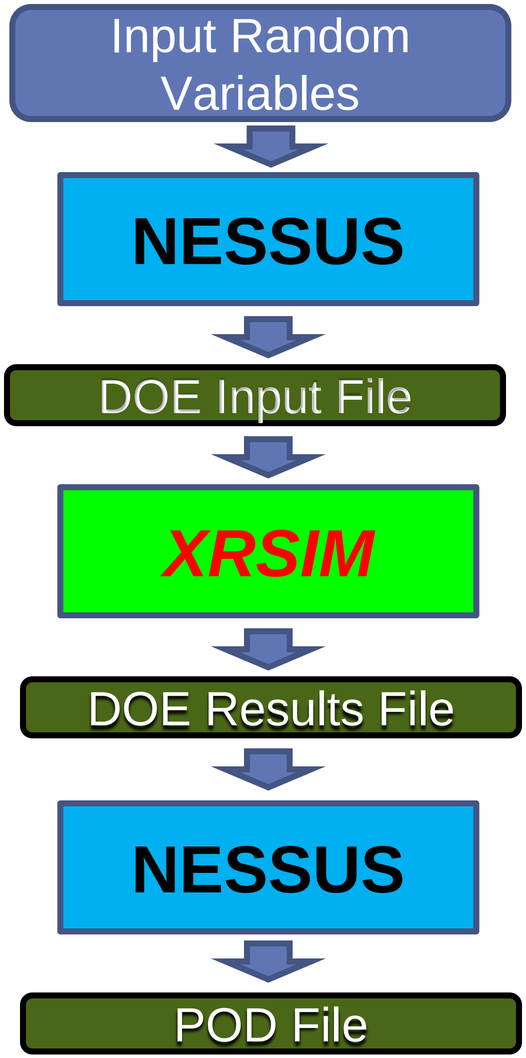
Simulating POD Curves Using Probabilistic Analysis (cont.)

- The POD values for each anomaly size can be used to construct the full POD curve



POD Curve Simulation Using NESSUS and XRSIM

- Create a response surface model
  - Relates contrast values with XRSIM input variables
- Propagate NDI random variables through response surface
  - Result: PDF of contrast values
- Create a probabilistic model (PDF) of human contrast detection threshold
  - Based on detect/no detect data
- Obtain POD curve
  - Achieved by comparing contrast PDF with contrast threshold PDF at each anomaly size

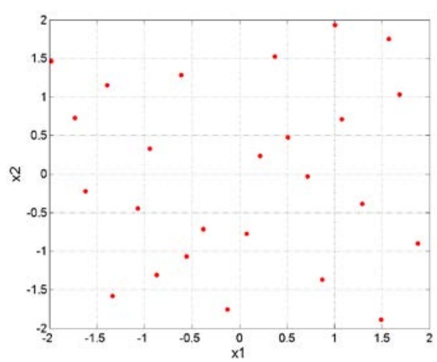


Process for Constructing Contrast Response Surface

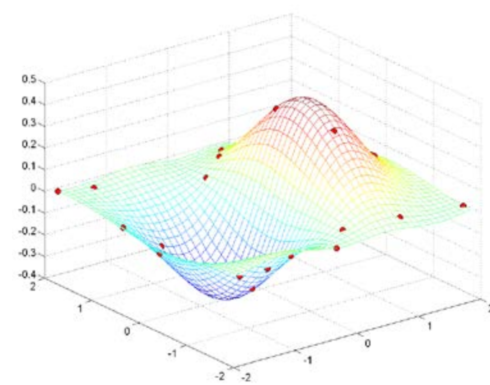
- Identify ranges of XRSIM input variables
- Generate a table of XRSIM input data using design of experiments (DOE) approach in NESSUS
- Generate training data for each set in DOE table using XRSIM
- Construct a Gaussian Process response surface fit to the contrast training data using NESSUS

Variable	Units	Lower	Upper
Part orientation	deg	-2	2
Detector signal w/ grain diffraction	gs	1825	3175
Detector signal w/o grain diffraction	gs	2305	2695
Spherical porosity	µm	20	200

Input Variable Ranges



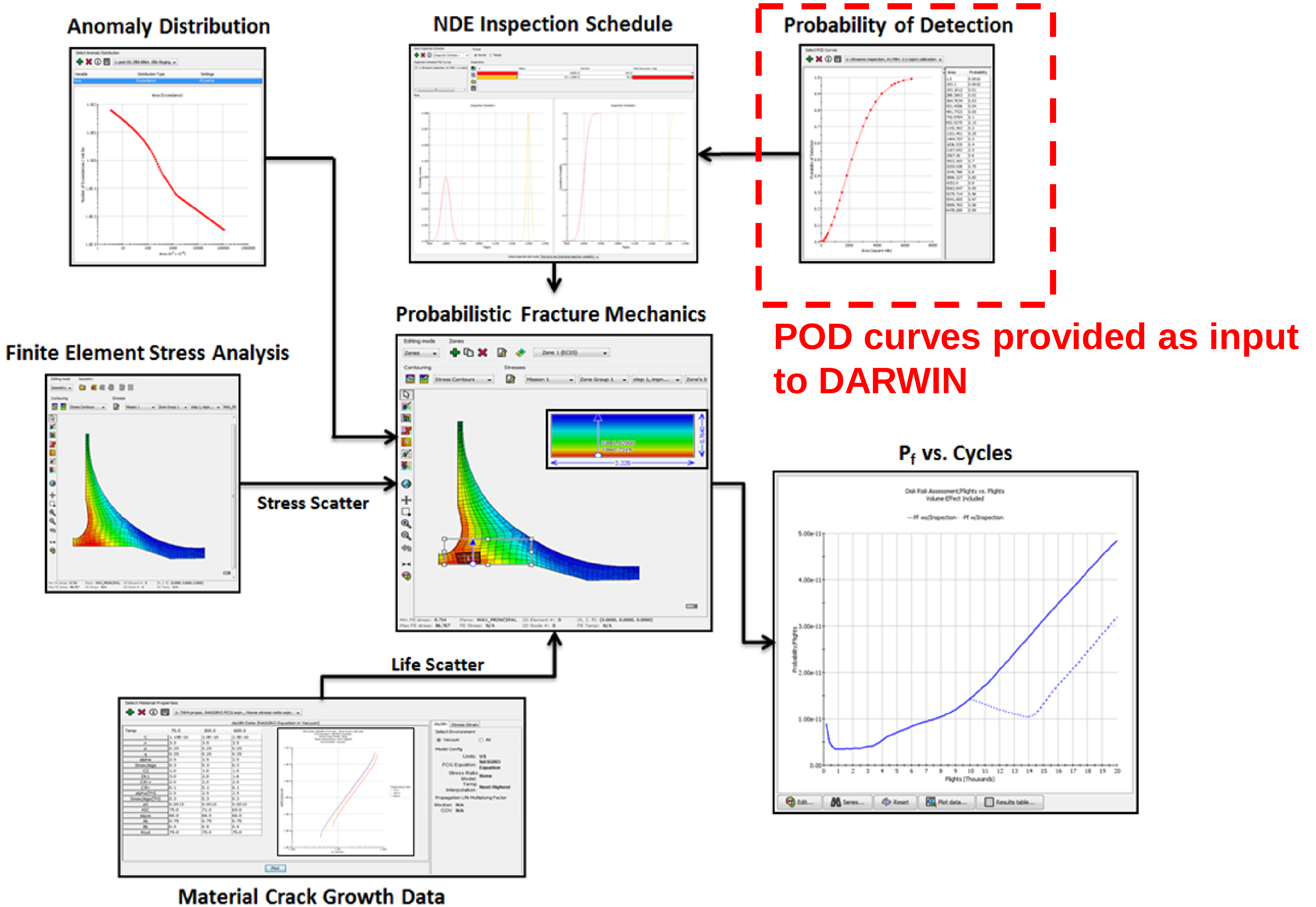
Design of Experiments



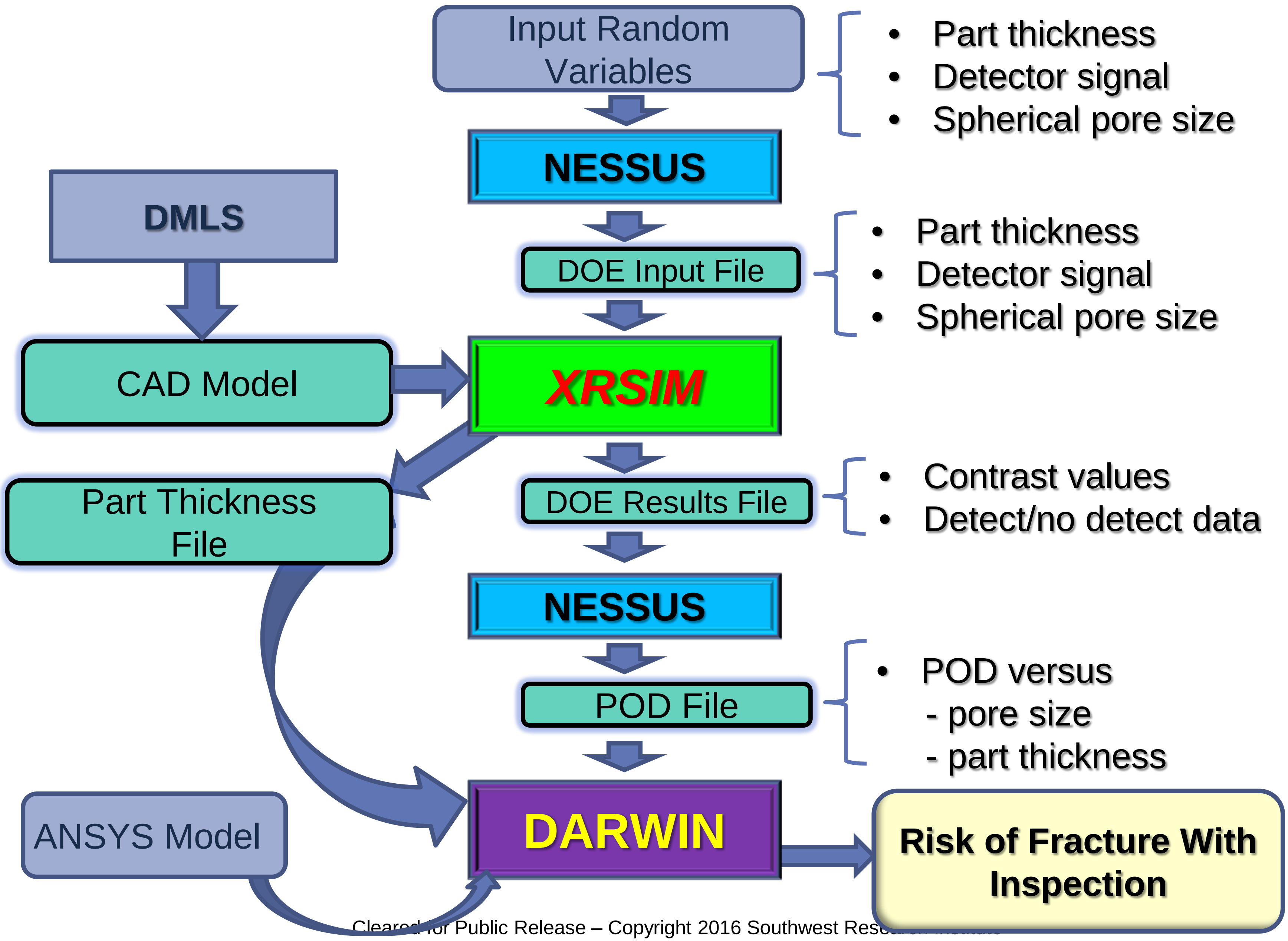
Response Surface

DARWIN GUI Overview

Design Assessment of Reliability With INspection

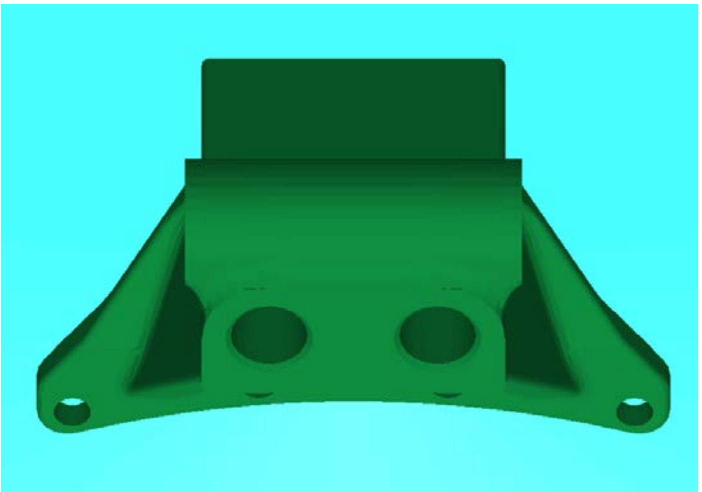


Linking XRSIM/NESSUS with DARWIN

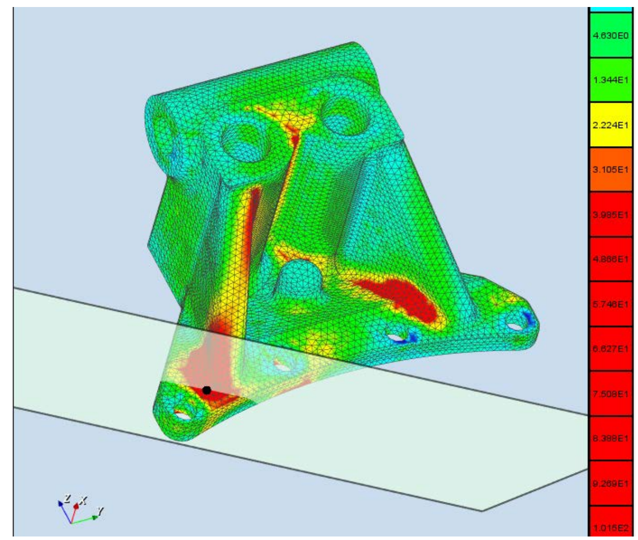


Application Example: Additive Manufacturing

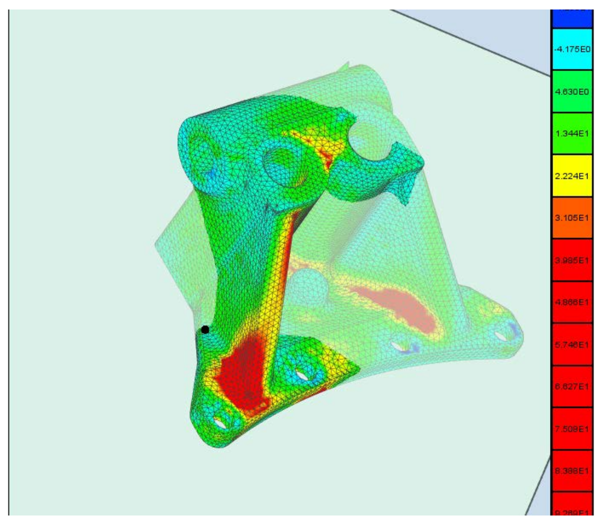
- Actual engine mount developed under DARPA project (DMLS AM process, Ni 718 Alloy)



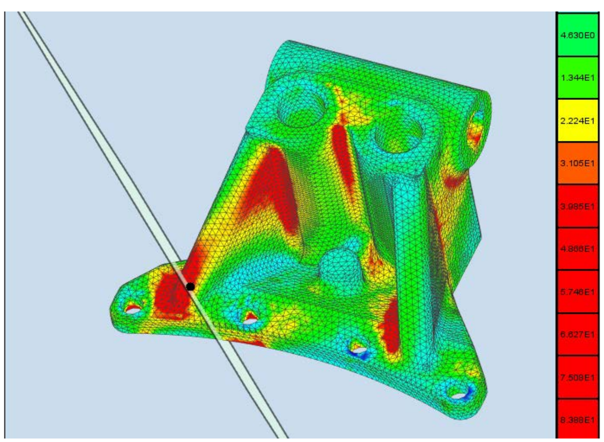
CAE Model



Location 3



Location 2



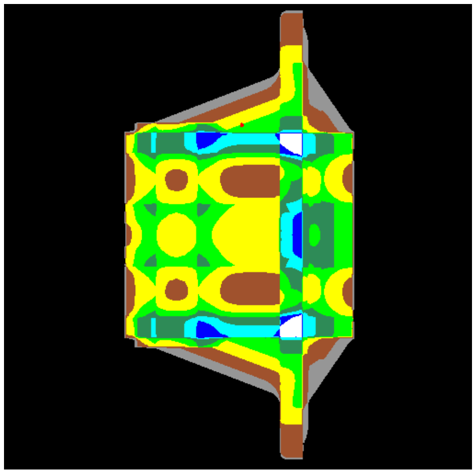
Location 1

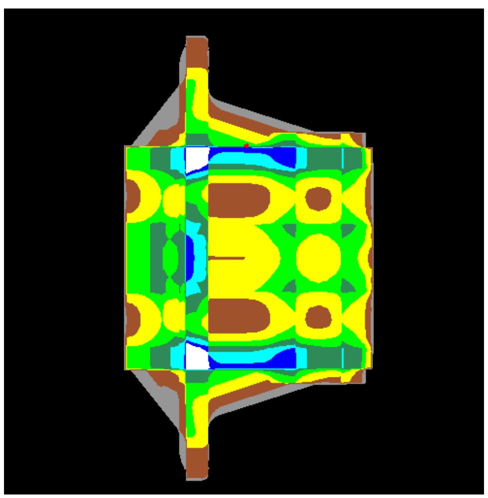
XRSIM Input Variables

- Geometry complexity implies
  - Multiple orientations of the part
  - Several kilovoltage settings
- POD data assumes application of an inspection protocol where kilovoltage and orientations are fixed
- Key parameters controlling contrast
  - Part thickness
  - Pore size
  - Detector signal (grey scale)
  - Contrast noise

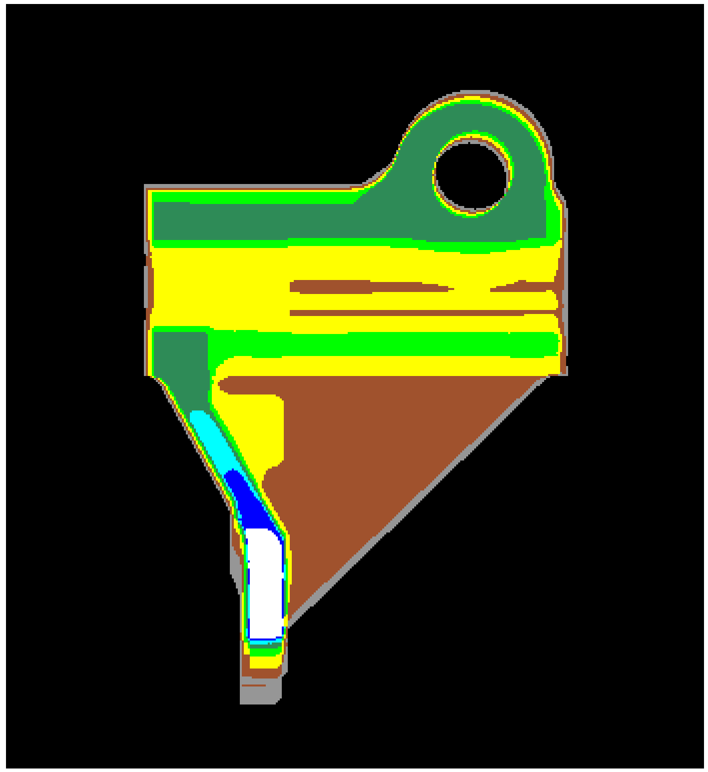
XRSIM Thickness Maps

Front View





Back View

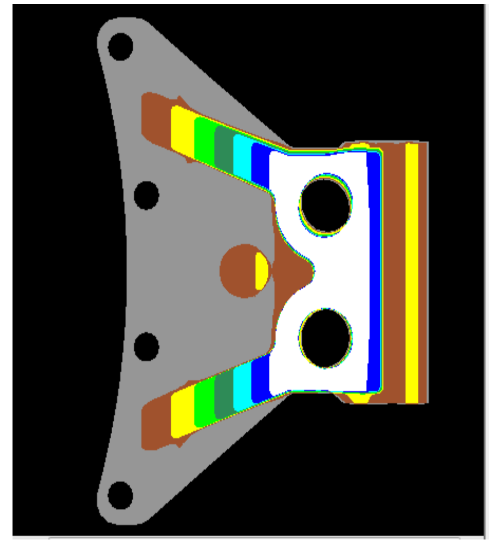


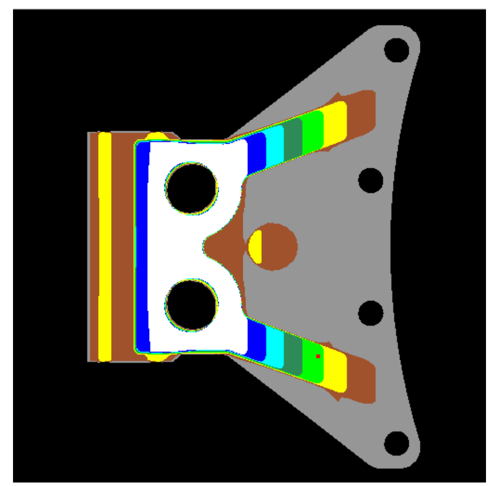
Top View

0.000 - 0.000 cm	
0.000 - 0.634 cm	0.634 - 1.269 cm
1.269 - 1.903 cm	1.903 - 2.537 cm
2.537 - 3.171 cm	3.171 - 3.806 cm
3.806 - 4.440 cm	4.440 - 5.074 cm

Thickness Legend

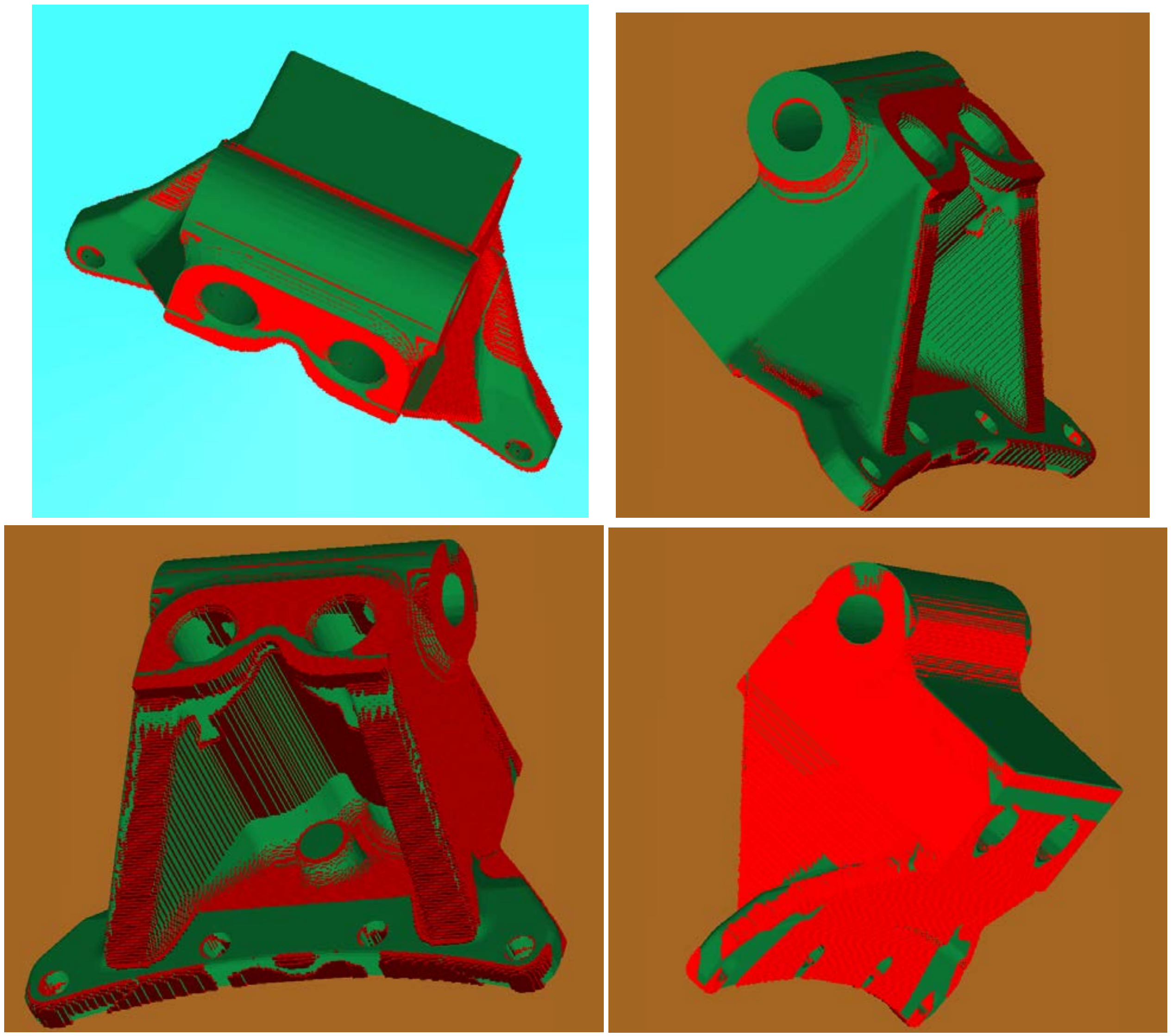
Right View





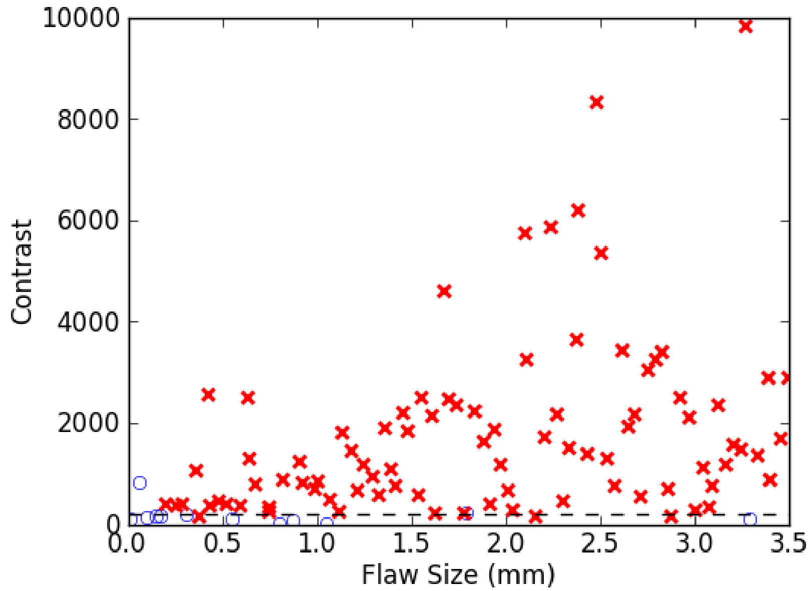
Left View

Detectability Maps from XRSIM at Several Orientations

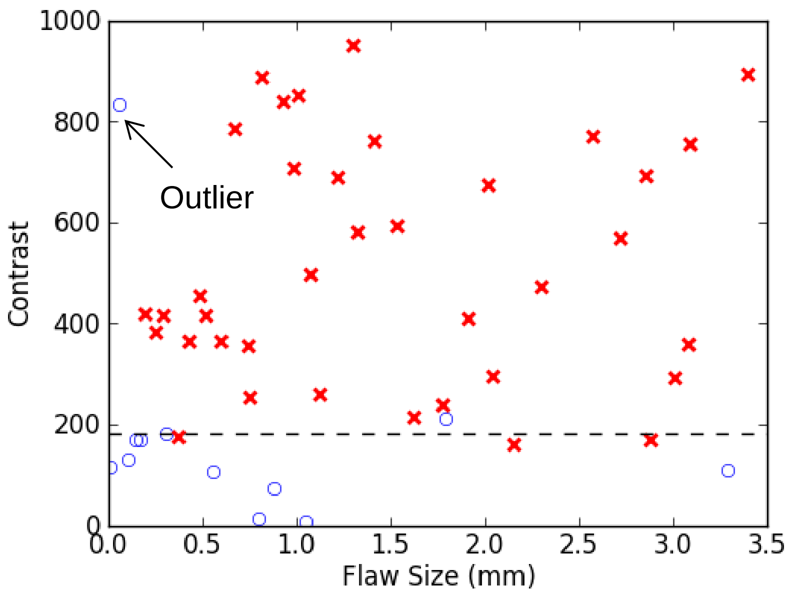


Probabilistic Model of Human Detectability Contrast Threshold

Detect/no detect results



Zoomed in to show detail near threshold



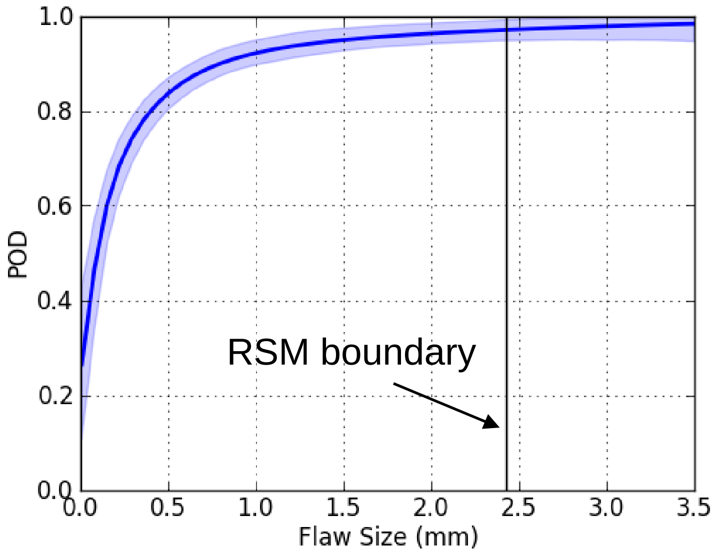
- Threshold value estimated based on 100 XRSIM results and corresponding detect/no detect data from NDE Technologies
- Detection does not follow a strict rule based on a single threshold value, so threshold modeled as a random variable
- Maximum likelihood used to estimate threshold mean and standard deviation, assuming normal distribution: Mean=183, Stdev=41

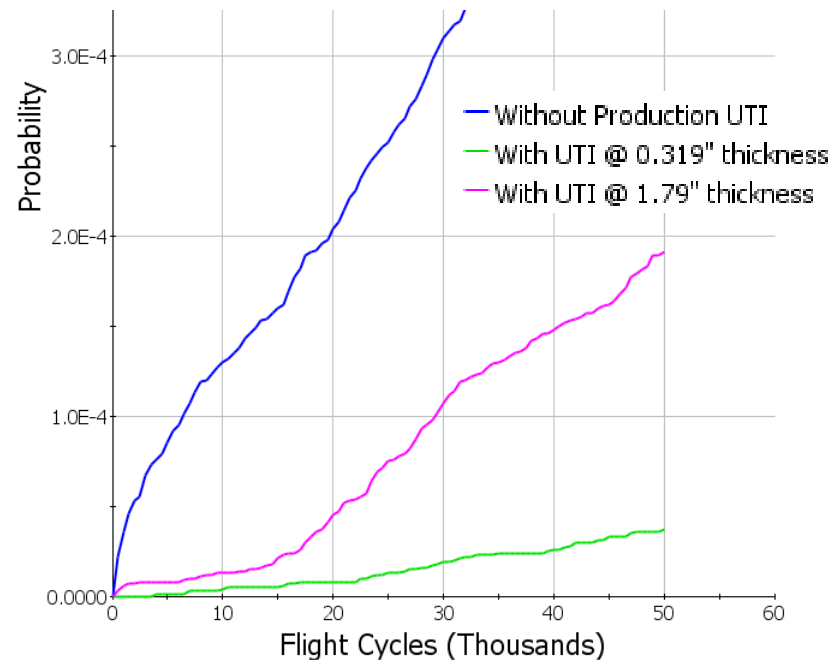
Probability of Detection Curves

- Deterministic input variables:
  - Part thickness
  - Pore size
- Random input variables:
  - Detector signal: Uniform (10,14000)
  - Contrast noise: Normal (0,79)
  - Contrast threshold: Normal (183,41)
- POD curves were computed using Monte Carlo simulation combined with conditional expectation
  - POD = Probability [Contrast > Contrast threshold]

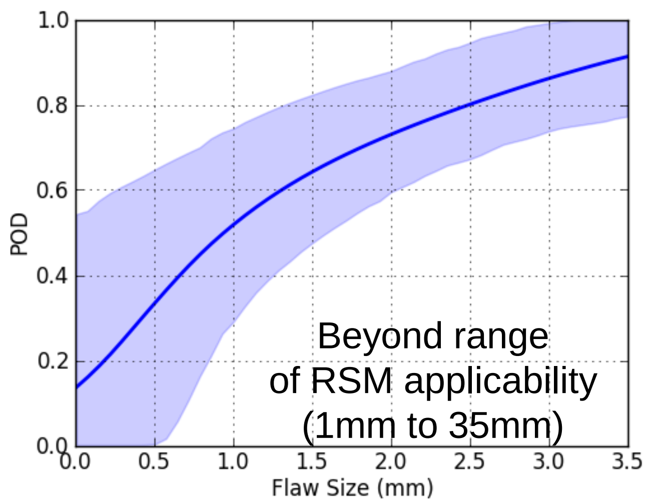
Location 1 Results

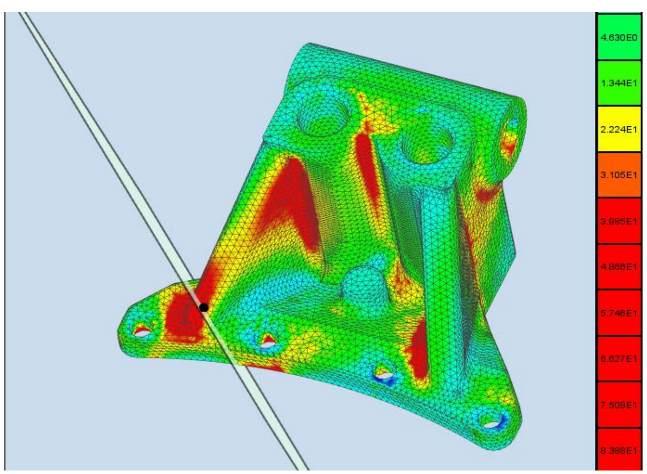
Orientation 1 Thickness = 8.1 mm (0.319 in)



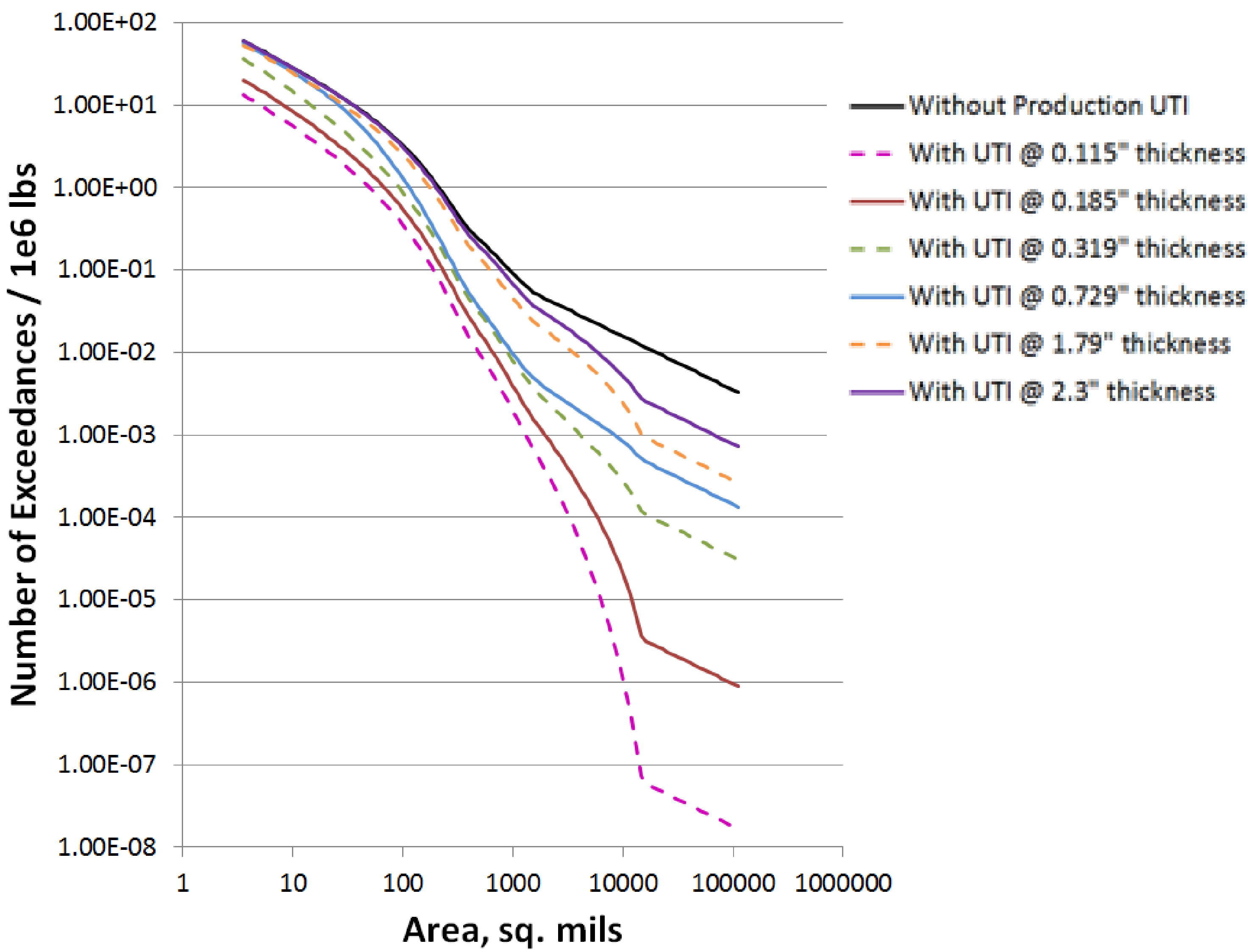


Orientation 2 Thickness = 45.45 mm (1.79 in)

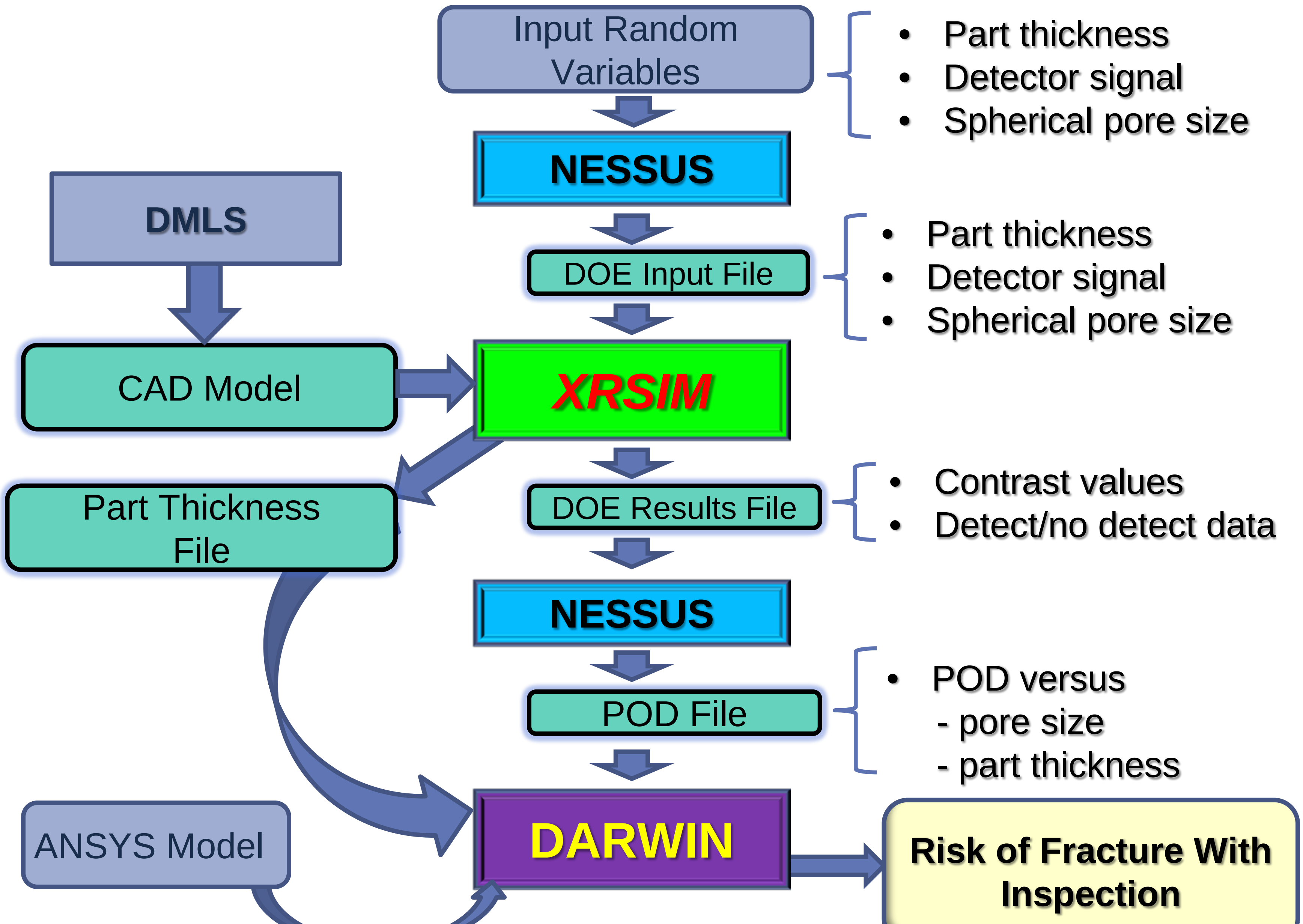




Influence of NDI on Manufacturing Anomaly Distribution



Summary



Input Random Variables
Part thickness
Detector signal
Spherical pore size
NESSUS
DMLS
DOE Input File
Part thickness
Detector signal
Spherical pore size
CAD Model
XRSIM
Part Thickness File
DOE Results File
Contrast values
Detect/no detect data
NESSUS
POD File
POD versus
- pore size
- part thickness
ANSYS Model
DARWIN
Risk of Fracture With Inspection

Continuing Tasks

- Automate POD curve creation in XRSIM
- Automate transfer of location-specific POD curves from XRSIM to DARWIN
- Implement inverse calculation of critical initial crack size in DARWIN and transfer to XRSIM
- Verification and validation

Potential Future Extensions

- Use the integrated XRSIM-DARWIN modeling system to optimize NDE scan plans
- Combine with ICME models of the AM process (including models of microstructure and defect formation) to optimize the AM process itself

Role of Material Properties

- The fracture risk simulations also depend on known/assumed values of material properties (e.g., FCG)
- The uncertainties in these properties could be included as another random variable in the fracture risk simulations
- The material properties will be functions of the local microstructure, which will depend on the manufacturing process and the location/orientation within the part

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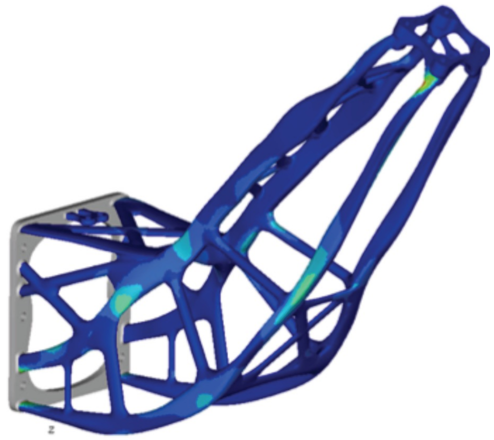
EXTREME VALUE ANALYSIS OF DEFECTS ON AM PARTS

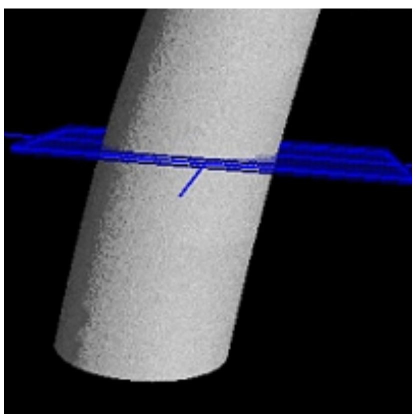
S. Beretta, S. Romano – Politecnico di Milano, Dept. Mechanical Eng., IT

A. Brandao, J. Gumpinger – European Space Agency, Noordwijck, NL

A research with the support of RUAG Space, Product Unit Structures

Summary of the presentation



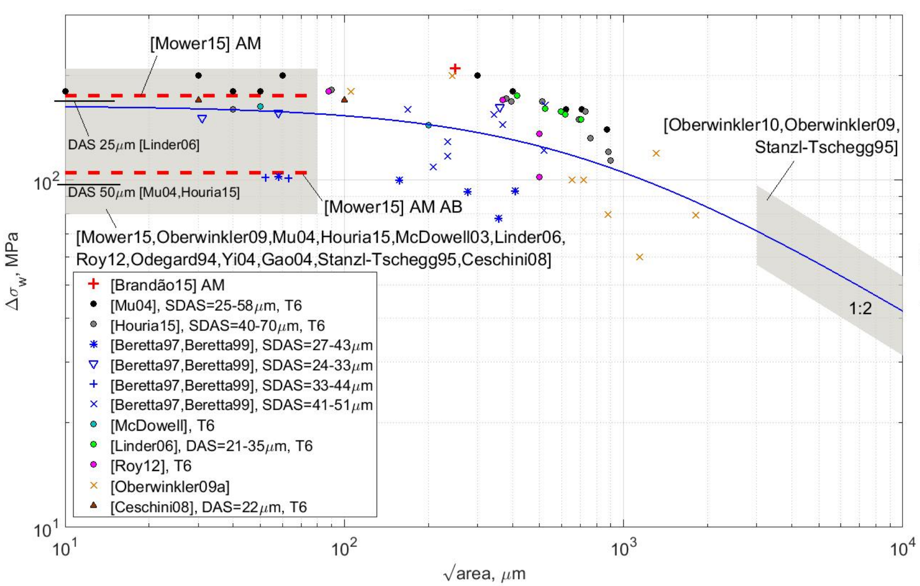


- **Introduction & motivation**
- **Extreme value analysis for CT scans**
  1. Sampling strategies;
  2. Analysis in terms of volumes;
  3. Geometric features of extreme defects;
- **How to reduce CT scan effort**
  5. Choice of the threshold;
  6. Minimum material volume to be scanned;
- **Application to component**
  7. prospective application onto a component;
  8. Fatigue assessment.
- **Conclusions**

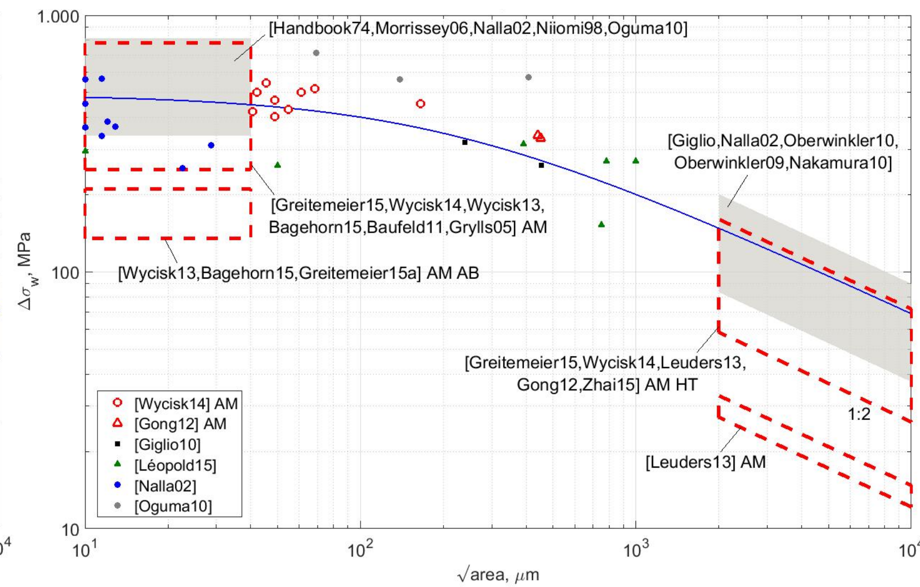
Literature review

Defects have a large influence on the fatigue limit. They can be treated as short cracks according to Murakami's projected root area and described by the **Kitagawa diagram**.

AlSi10Mg, R = -1

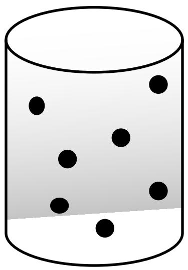


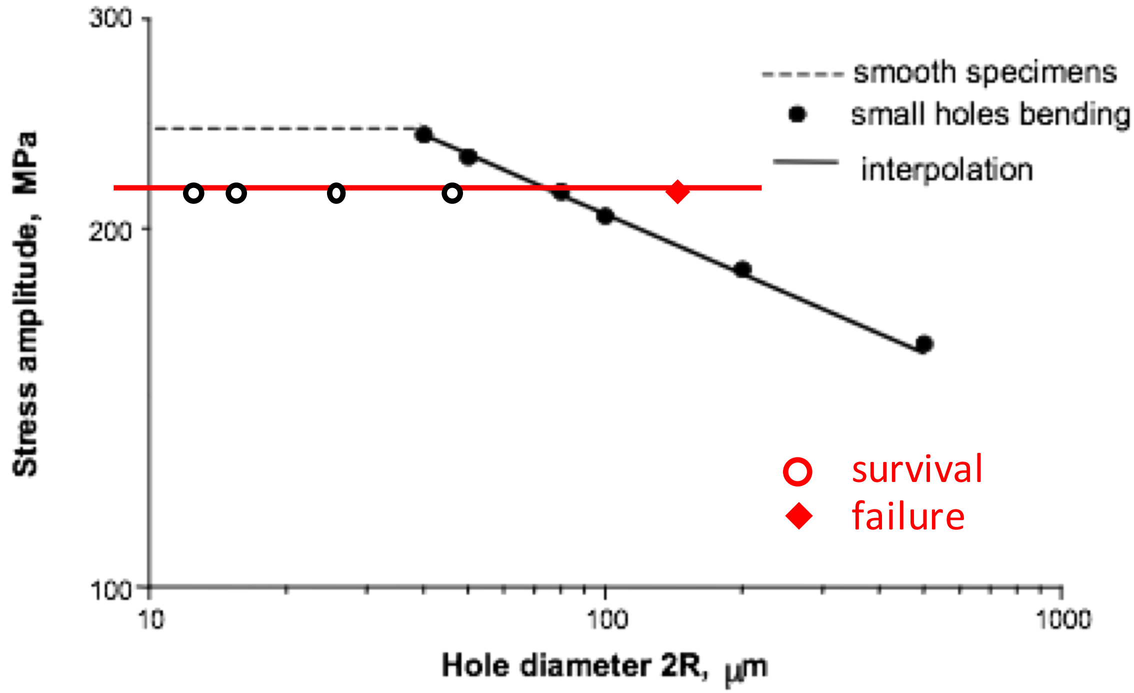
Ti6Al4V, R = 0



- Fatigue properties of AM are very similar to those of standard processes;
- Large reduction of fatigue resistance for as-built samples (they can be modeled as equivalent surface defects);
- Intrinsic variability of the fatigue limit due to several factors (process/microstructure).

Extreme value statistics for defects





the fatigue is controlled by the **extreme values** of the population of defects **not** by the average dimension

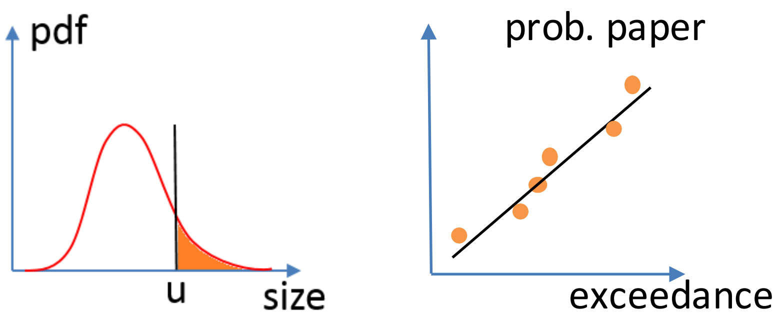
analysis of extremes based on **extreme value sampling** at the end of the 90's

ESIS P11-02
ASTM E2283-03

Statistics of extremes strategies

Peaks-over-threshold

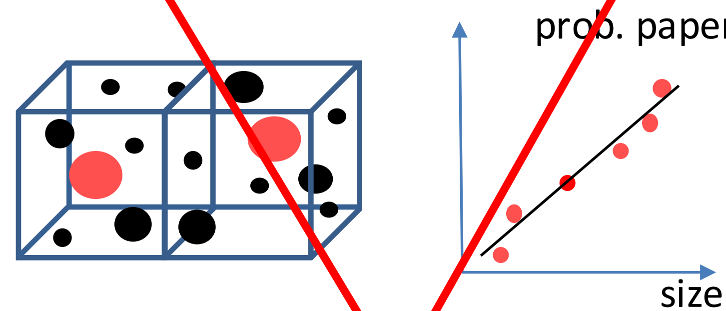
In a given volume, all the defects over a certain threshold are considered.



- no standard (but good books);
- all the measurements above *u* are treated;
- **Exponential distribution** (d →∞);
- Extrapolated distribution for the maximum defect in a given volume is the **Gumbel distribution**

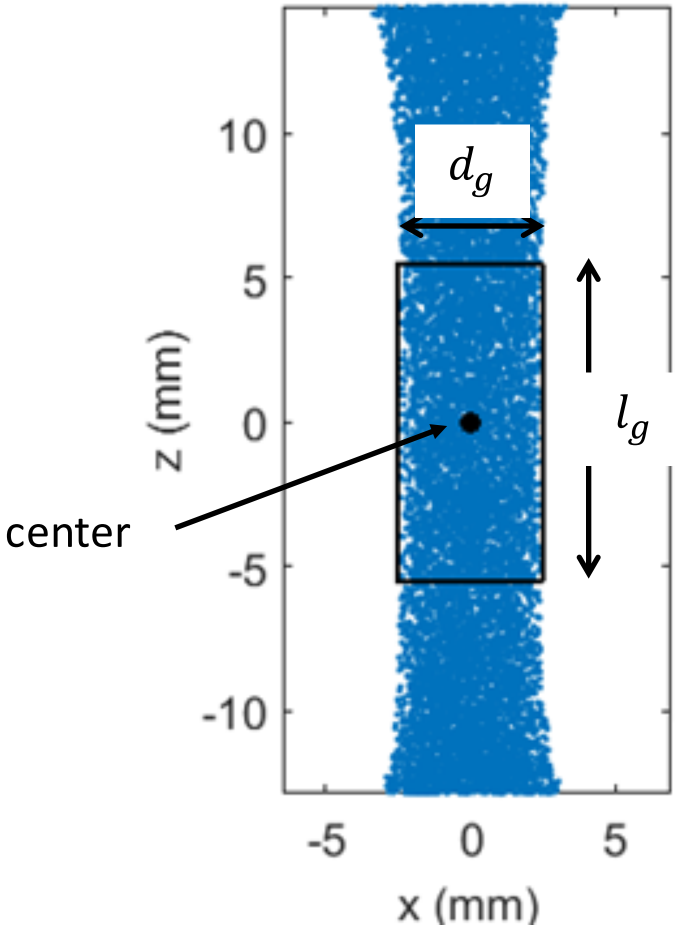
Block maxima

In a given volume, only the largest defect is considered.



- considered in ASTM E2283-03;
- it is applied very naturally with polished sections;
- a bit 'innatural' to pick up the maximum defect in a given sub-volume.
- **Gumbel distribution** (d →∞)

Activity



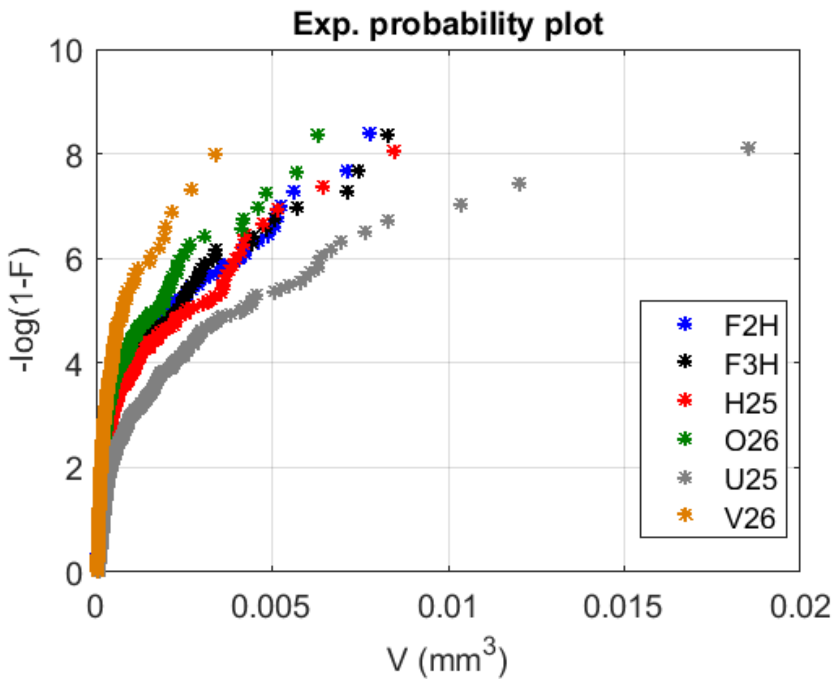
At the beginning only the data in the gage length were considered

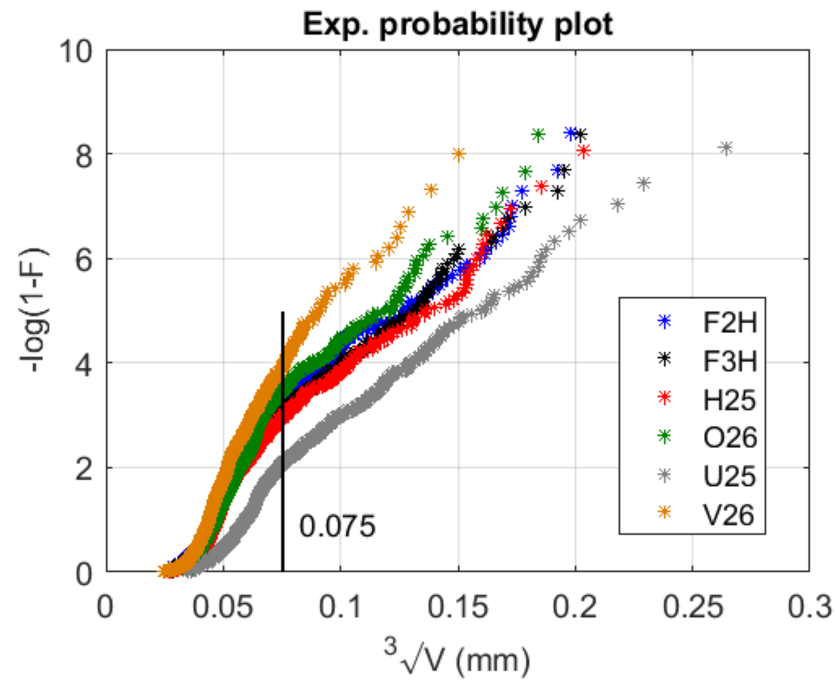
- CT scans for a series of specimens that were provided by RUAG Space, Product Unit Structures,
- together with a component were analyzed with CT scans at ESA;
- Analysis with the statistics of extremes with POT method.

Name	Print direction	N	V_{max}
F2H	horizontal	12740	0.0119
F3H	horizontal	15851	0.0142
H25	horizontal	22345	0.0121
O26	vertical	6600	0.0107
U25	vertical	10880	0.0222
V26	vertical	20871	0.0038

Volume distribution

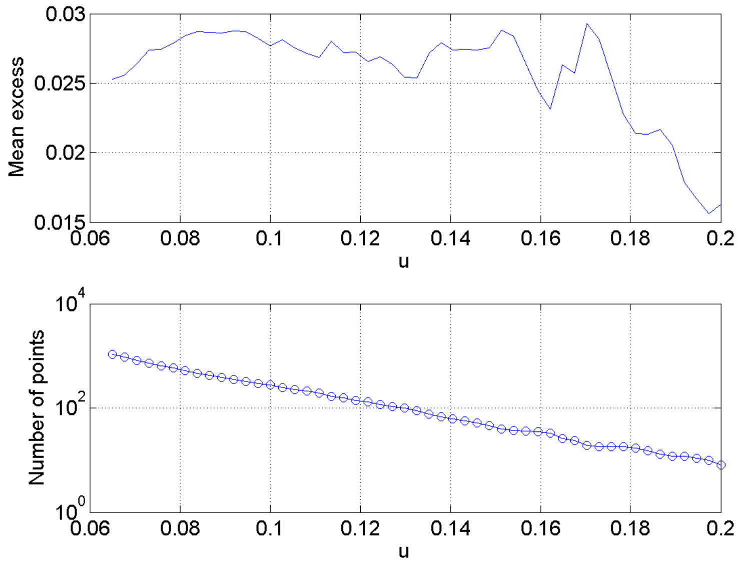
A comparison on defect size V and $\sqrt[3]{V}$ is done considering only the gage volume. Some difference among the specimens.

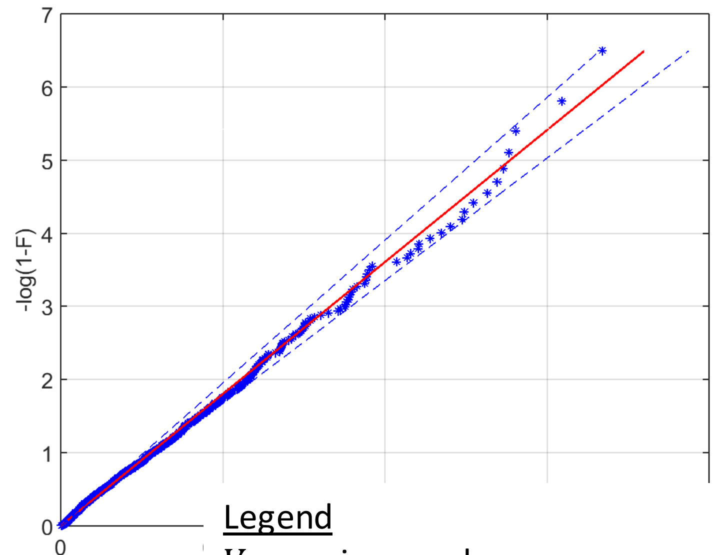




- Above a threshold of 0.075 mm, the flaw distribution of the exceedances is an exponential;
- this corresponds to the well established results for inclusions in steels (√area is a Gumbel)

Example of analysis





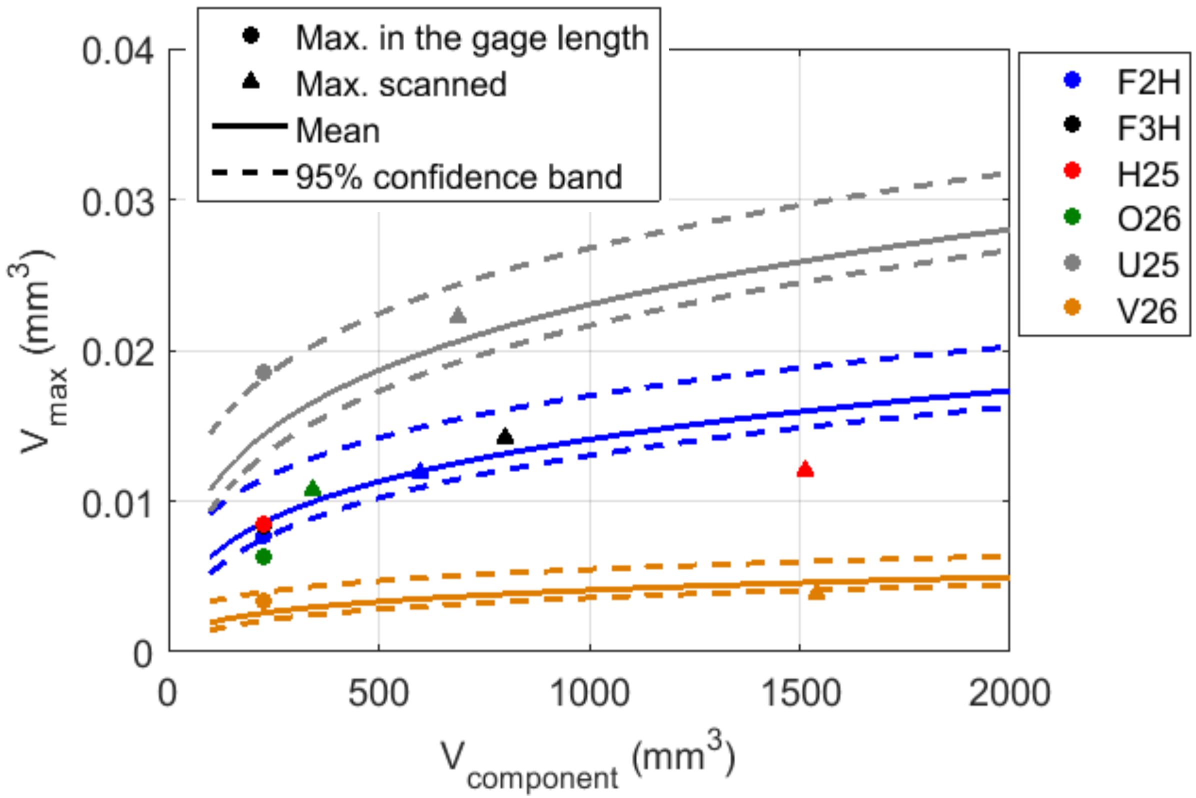
Legend
V_c: specimen volume
V_s: scanned volume
n: number of defects exceeding *u*
T: return period of the max. defect

1. Fix a threshold for the volume: $u = 0.075$
2. Calculate the mean excess: $\mu = mean(\sqrt[3]{V} - u)$
3. Return period of the defect exceeding *u* in a bigger volume: $T = \frac{V_c}{V_s} \cdot n_u$
4. Define the maximum defect with return period T in terms of diameter and volume:

$$d_{max,T} = \mu \cdot \log T + u \qquad d_{max} \in LEVD \begin{Bmatrix} \lambda = d_{max} \\ \delta = \mu \end{Bmatrix}$$

Estimation of extreme defects

Predictions of maximum defects have been compared with maximum defect detected on the entire specimen (not only the gage lenght).

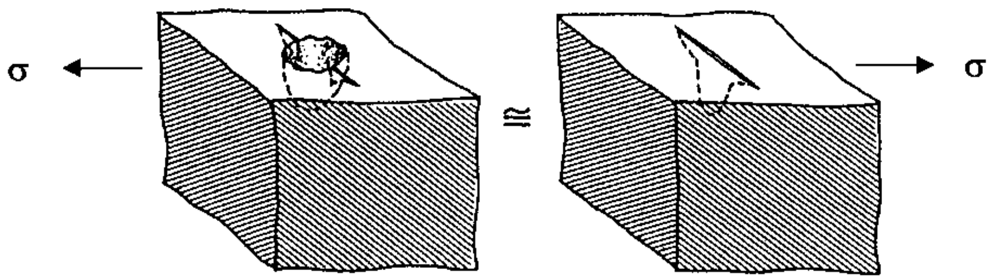


Considering the low number of defects used in the estimation of maxima (only those in V_g), the prevision is quite good.

Defects → fatigue

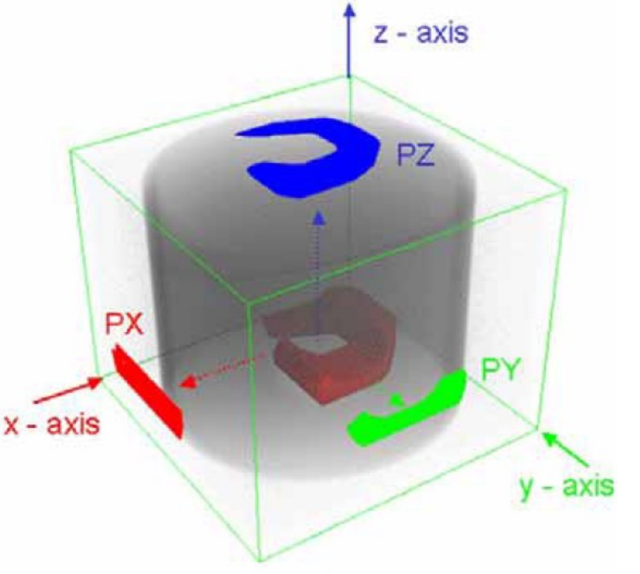
From Murakami we know that:

$$\Delta K = 0.65 \cdot \Delta S \cdot \sqrt{\pi\sqrt{area}}$$



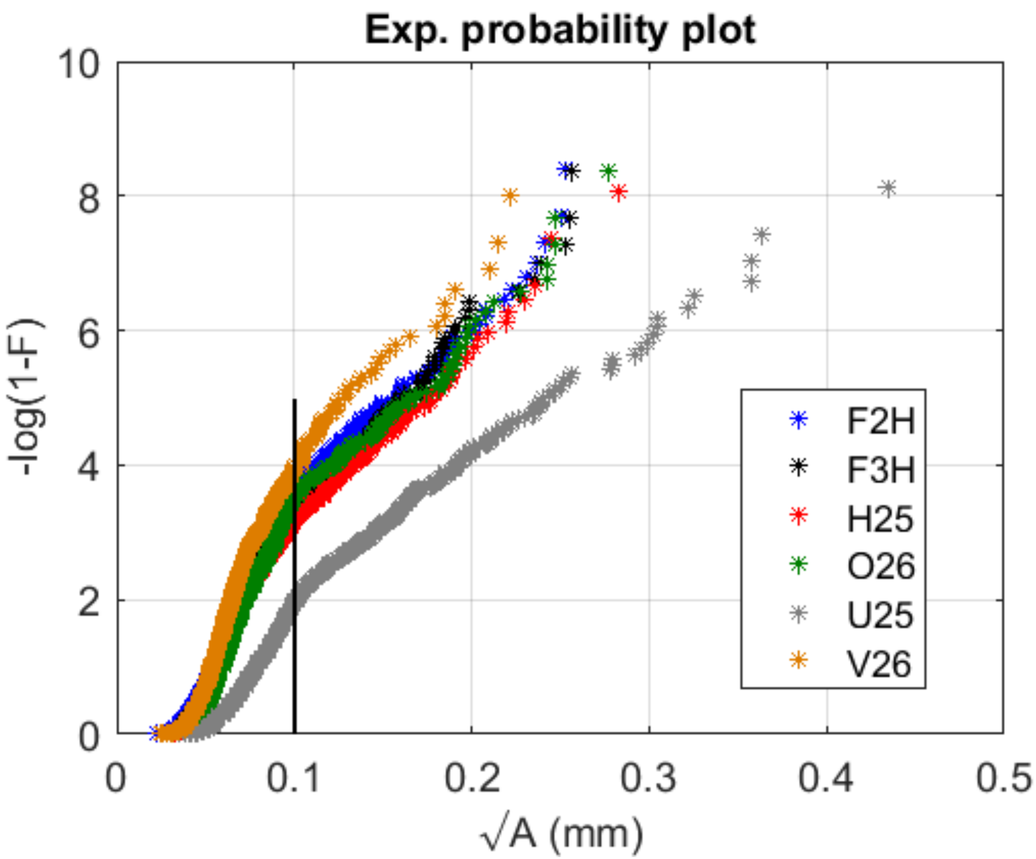
The projection along the stress direction (PZ) can then be used to define the $\sqrt{Area}$ parameter, essential for the Kitagawa diagram.

In order to perform good estimations of the fatigue life, the extreme value analyses have to be carried out on the $\sqrt{Area}$ parameter.



POT on $\sqrt{A}$

Even considering $\sqrt{A}$, distributions are very similar, except for U25 and V26.
Once again, only the defects in the gage volume are taken into account.

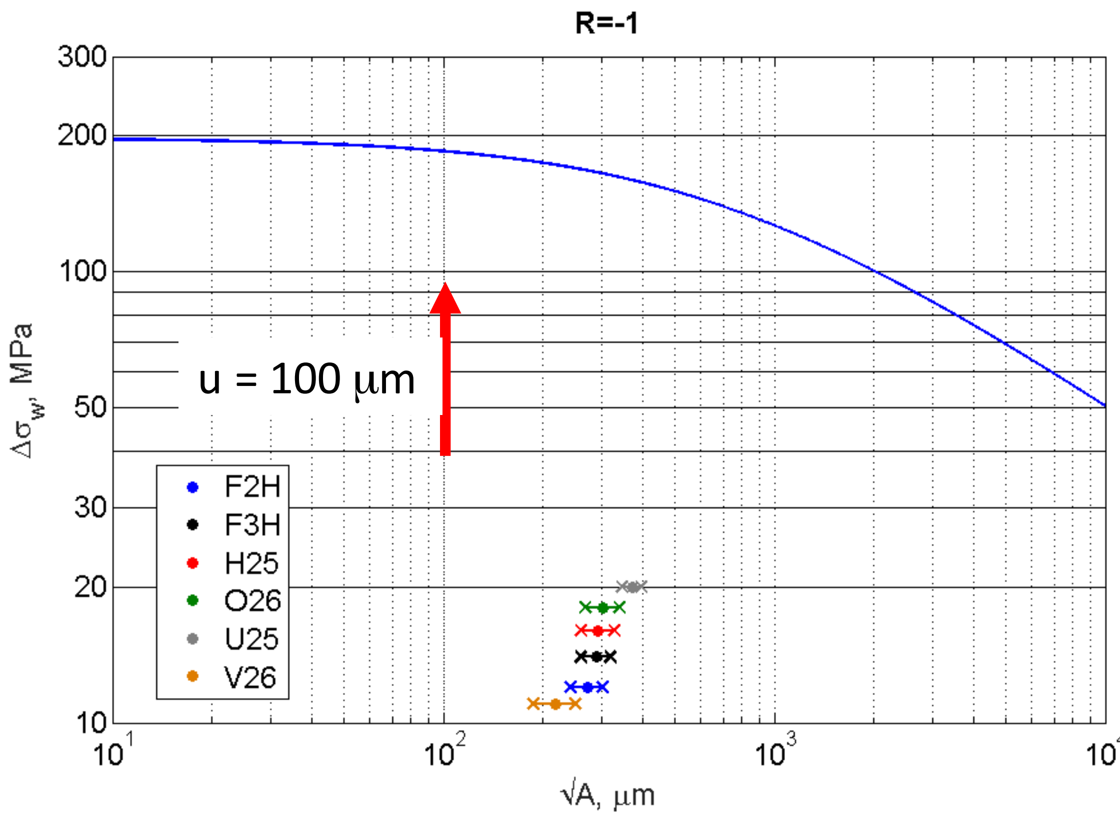


POT threshold:
$\sqrt{A_{th}} = 100\mu m$

The analysis of √area confirms that the exponential fit can be adequate

Summary of the application

- Comparison of the specimens considering the √area of defects perpendicular to specimen axis;
- Important defects have $\sqrt{A} > 100\mu m$ (final flat part of Kitagawa diagram);



threshold *u* has a meaning also from the point of view of Kitagawa diagram (only defects exceeding 100 μm are detrimental)

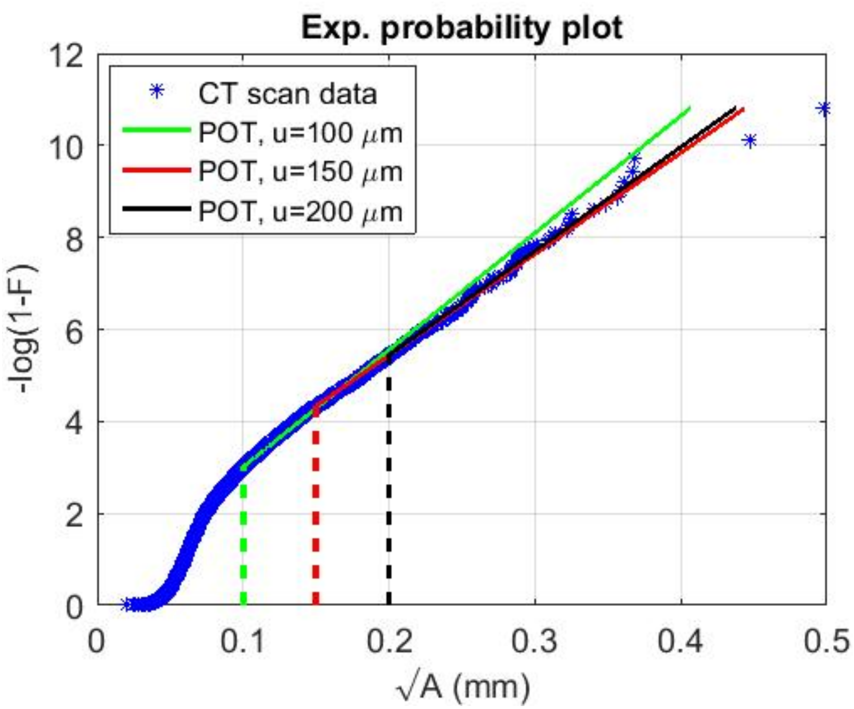
1) Our estimates of maximum defects from a small material volume are really precise ?

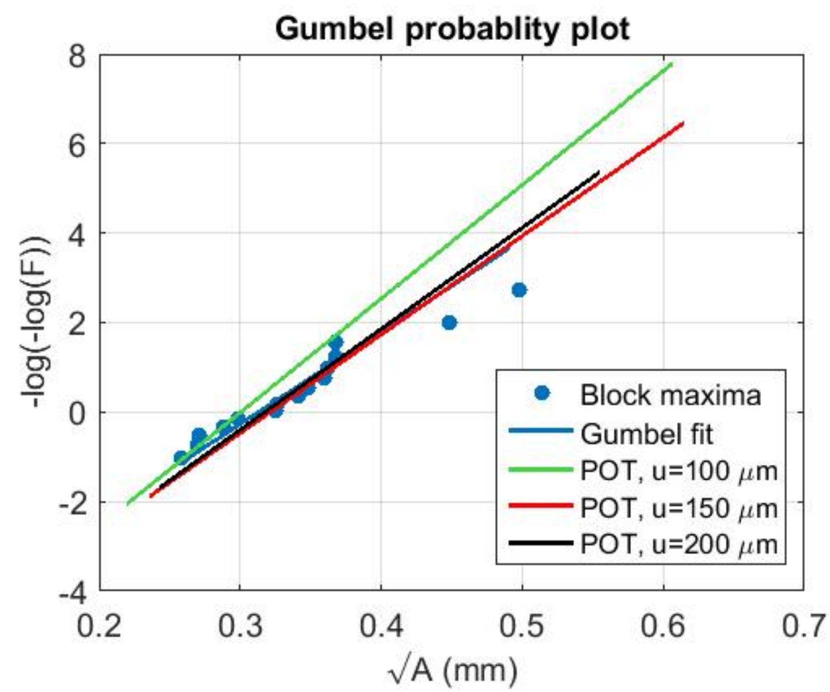
2) How much effort do we have to spend (scanning time, material volume) for obtaining good estimates if we had to estimate the maximum defect on a big component ?

Block Maxima on defect area

The reference distribution obtained by 'Block maxima' sampling a much larger material volume has been estimated through the POT by taking different values of u.

The threshold varies from u=100 µm to u=150 µm and 200 µm.





The estimations based on the two POTs described are in line with the maxima found, and in particular the estimation is very accurate fixing u=150 µm, while using u=100 µm we underestimate the real maxima. No further improvement for 200 µm.

Low resolution scan

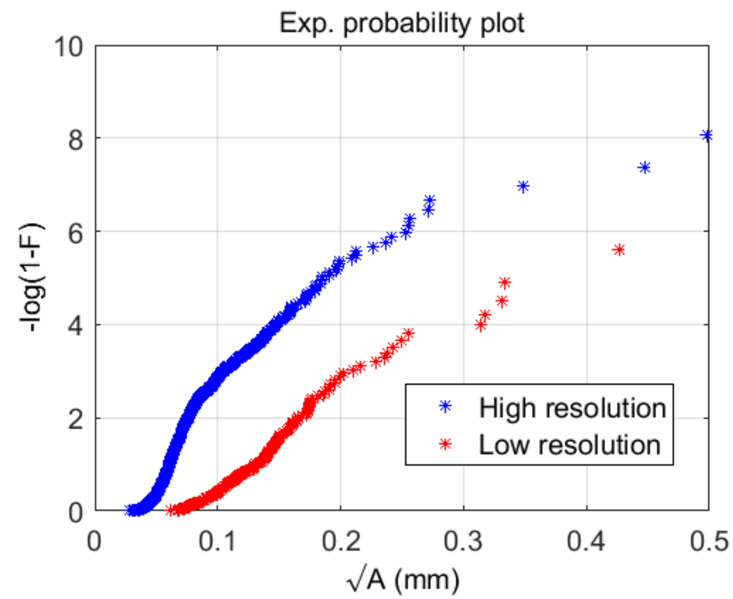
We are analyzing defects above 100-150 mm
→ it would be worth reducing resolution ?

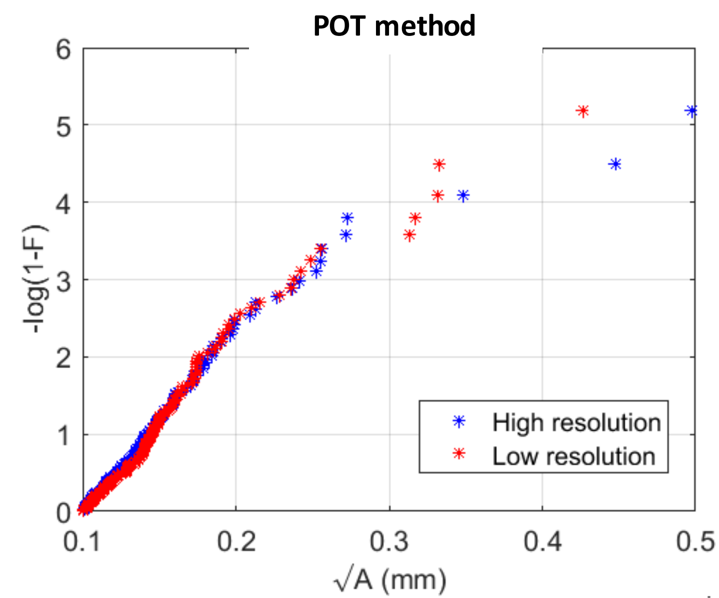
Specimen F3H was tested considering two CT resolutions:

- High resolution: pixel size 15 µm;
- Low resolution: pixel size 30 µm.

The goal is to verify if decreasing the resolution some time needed for CT could be saved, without loosing in accuracy when describing the extreme defect distribution.

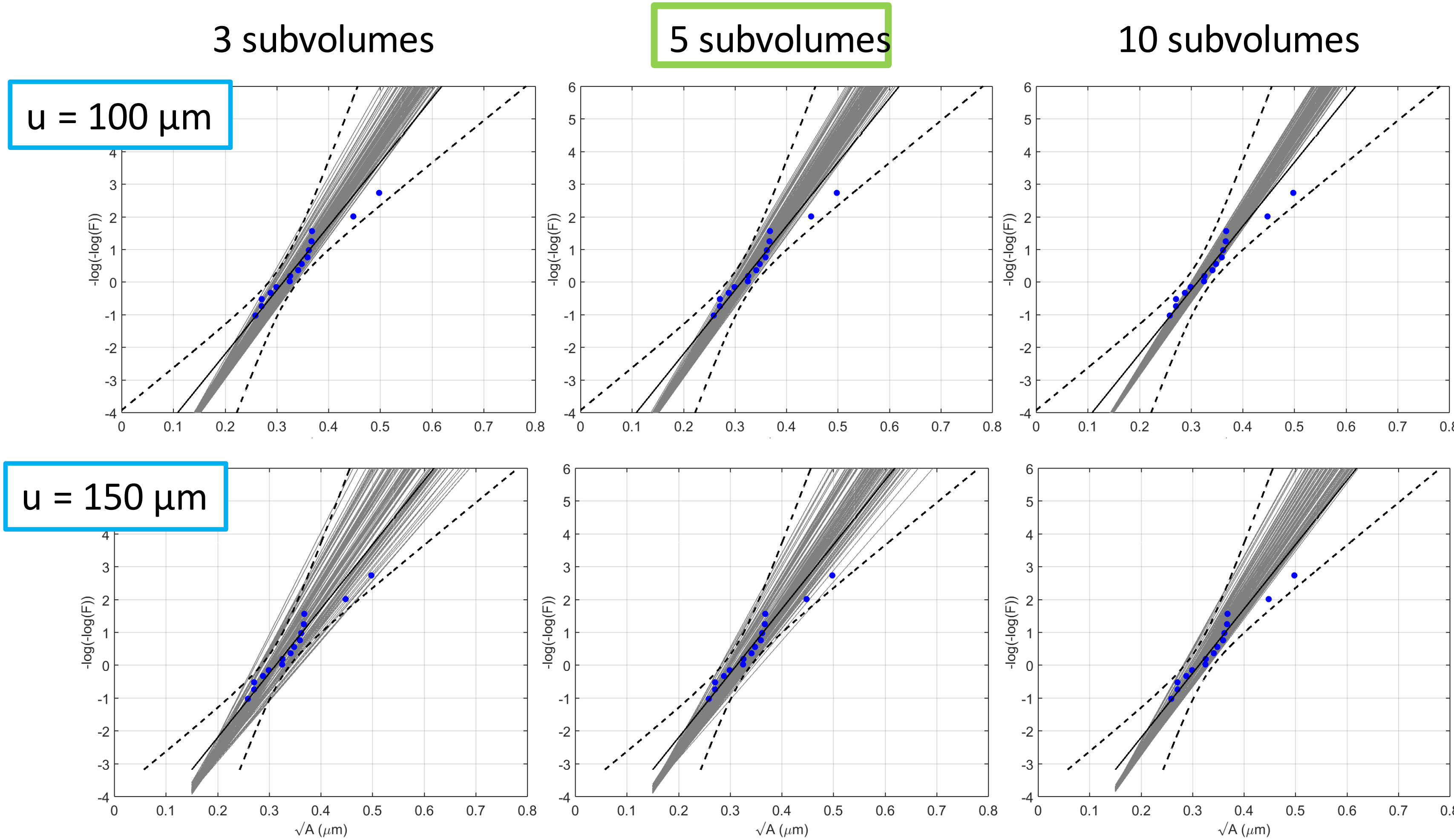
- Distribution of POT is almost the same!
- Significant time saving from 7.5 h to 2.3h !





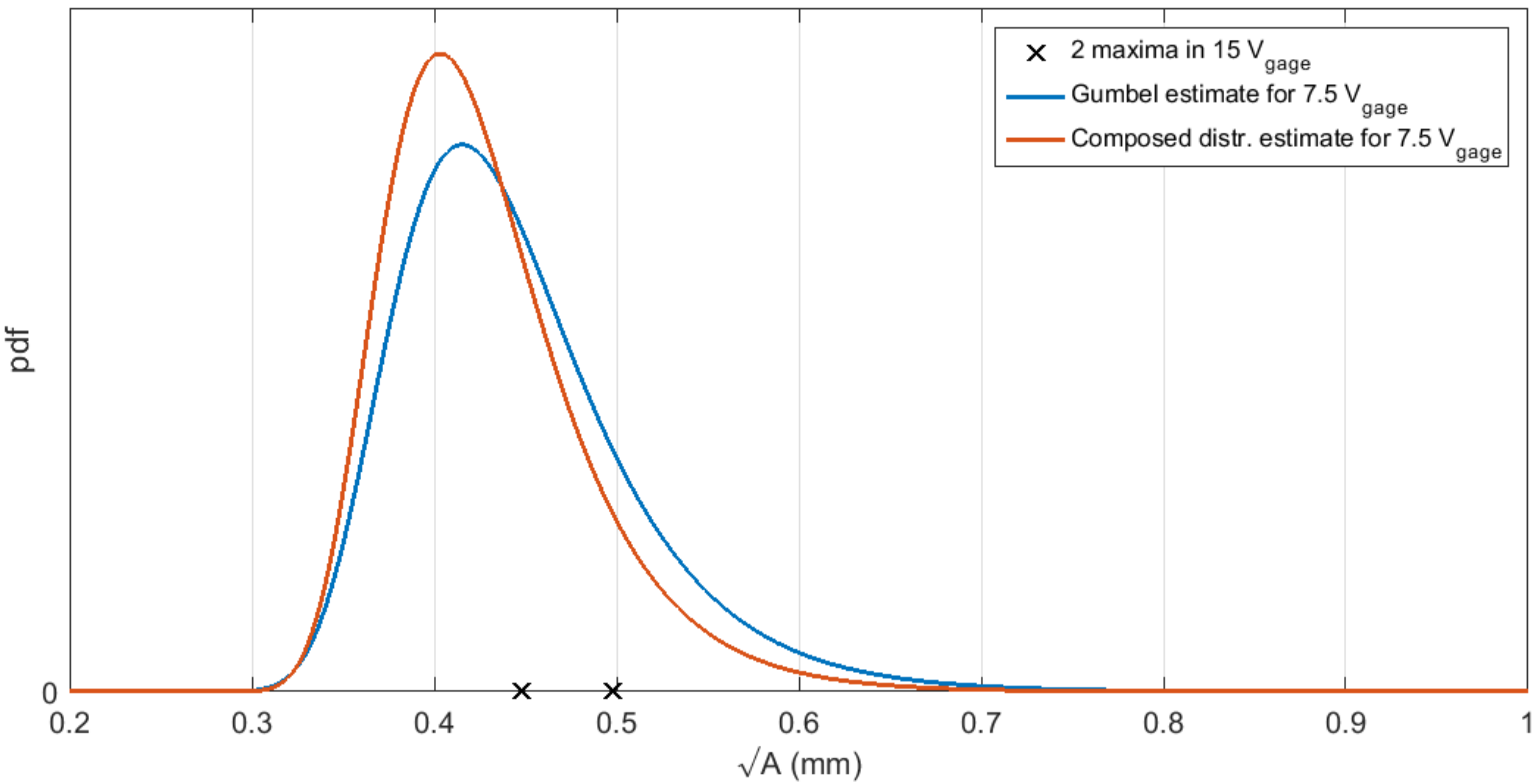
Minimum material volume

Monte Carlo simulations have been performed in order to understand the influence of this variability, sampling 3, 5 or 10 subvolumes of the 15 ones and fitting the exponential distribution on the exceedances over the threshold *u*.

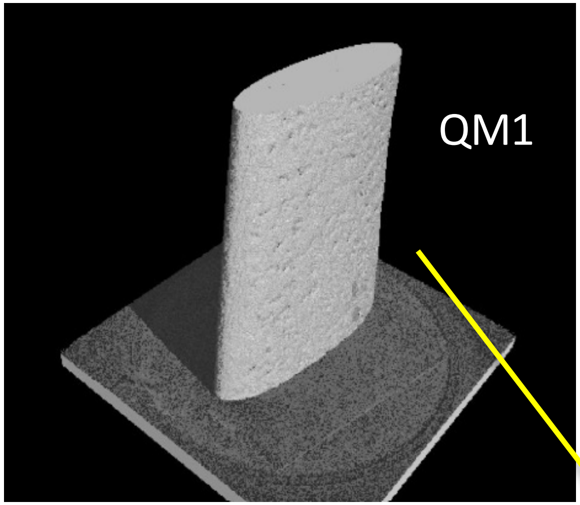


The distribution matters !

Even if the two maxima are not perfectly in line with the estimation, both the LEVD and the composed distribution found by statistic of extremes on a volume equal to 7,5 V_{gage} (the whole volume divided by 2, the return period of these points) yields a good prevision.



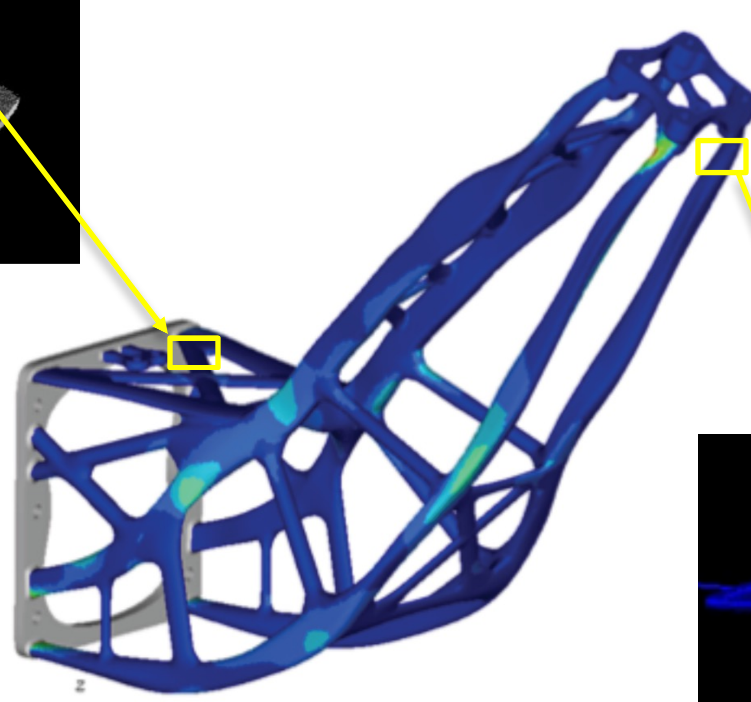
Bracket parts

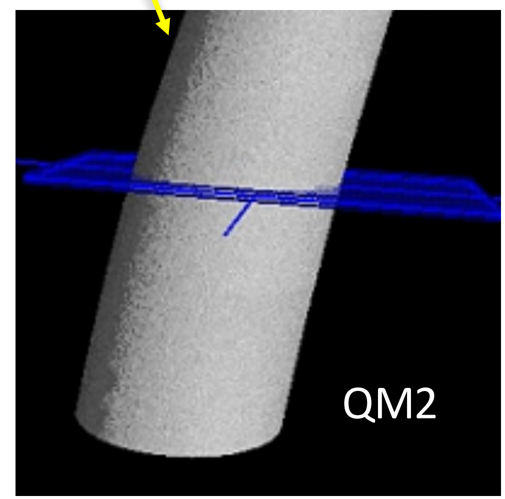


Two small parts of the component were analyzed by CT: QM1 and QM2.

Their volumes are:

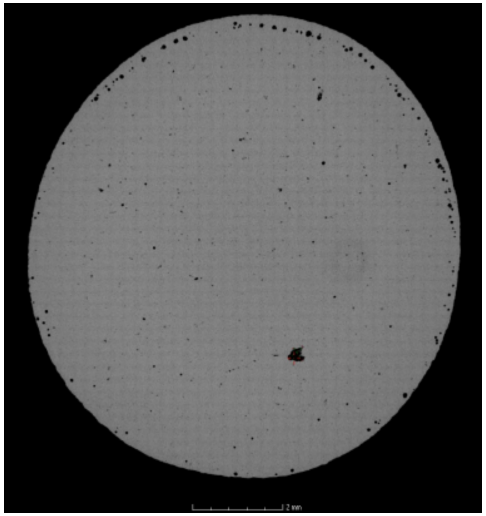
- V_{QM1} = 15500 mm^3
- V_{QM2} = 3870 mm^3



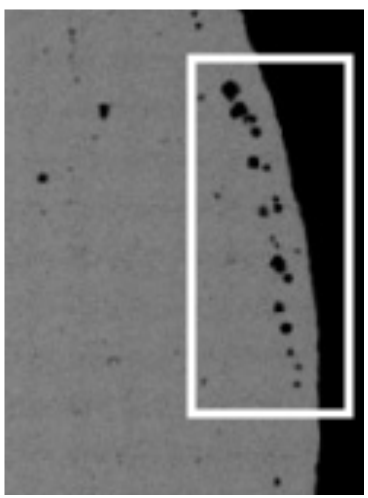


Application of the previous ‘rules’ was successfull

Prospective fatigue strength - 1



CT scans of the component reveal that, apart internal volumetric defects, there are regions of sub-surface pores

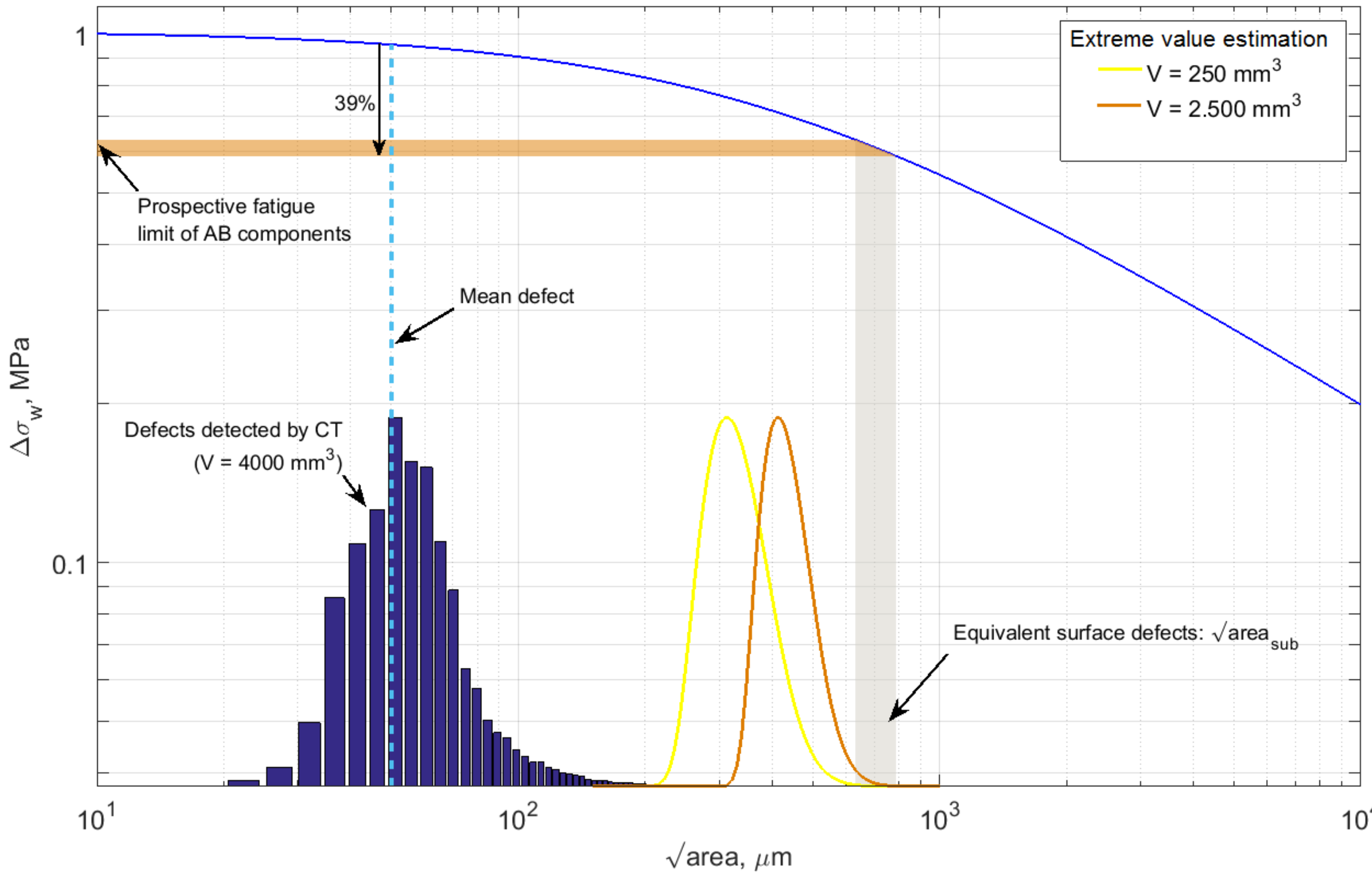


If we treat them as a 2-D crack:

$$\sqrt{area}_{sup} = 650 - 790 \ [\mu m]$$

Prospective fatigue strength - 2

Prospectively, this is the scenario for fatigue assessment considering average strength of AlSi10Mg



The sub-surface defects appear to be more detrimental than the internal ones

Conclusions

In this presentation I have discussed some applications of the statistics of extremes to AM parts:

- it has to be used because fatigue strength is controlled by the maximum defect in a given volume;
- features and methods developed in the '90's for inclusions are still valid and it is worth adopting that wide background (e.g. ASTM E2283-03);
- It looks that the 'Peak Over Threshold approach' is the most simple to apply for CT scan measurements;
- It is possible to determine the minimum requirements for the scan of a component (threshold, minimum volume) that also allow to reduce the effort of defect sampling;
- prospective application to fatigue is very simple through the Kitagawa diagram.

Essential references

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[8] Beretta, Stefano, Clive Anderson, and Yukitaka Murakami. "Extreme value models for the assessment of steels containing multiple types of inclusion." *Acta materialia* 54.8 (2006): 2277-2289.
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ASTM E08 Fatigue and Fracture - Workshop on Mechanical Behavior of Additive Manufactured Components

Fatigue Life Manipulation of SLM® Parts

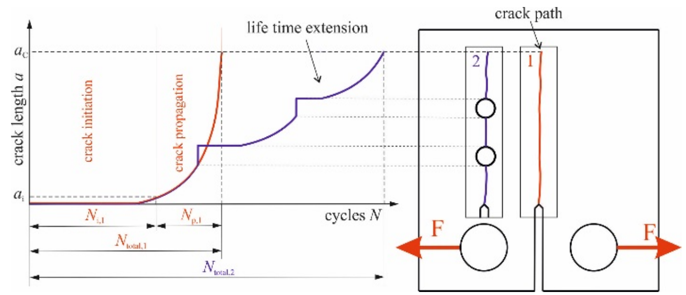
Wadim Reschetnik,
Richard Grylls, Benjamin Bauer,
Hans Albert Richard, Gunter Kullmer

Direct Manufacturing Research Center
Paderborn University – Germany
SLM Solutions NA, Inc.

Agenda

1. Additive Manufacturing – Selective Laser Melting - SLM®
    - SLM Solutions NA, Inc.
    - Selective Laser Melting System SLM® 280^{HL} and 500^{HL}
    - Qualified Materials

2. Project Fatigue Life Manipulation
    - Direct Manufacturing Research Center – DMRC
    - Motivation and Aims of the Project



3. Experimental Investigation
    - Setup and Testing Methods
    - Fatigue properties of SLM® materials
    - Fatigue Life Manipulation by Notches

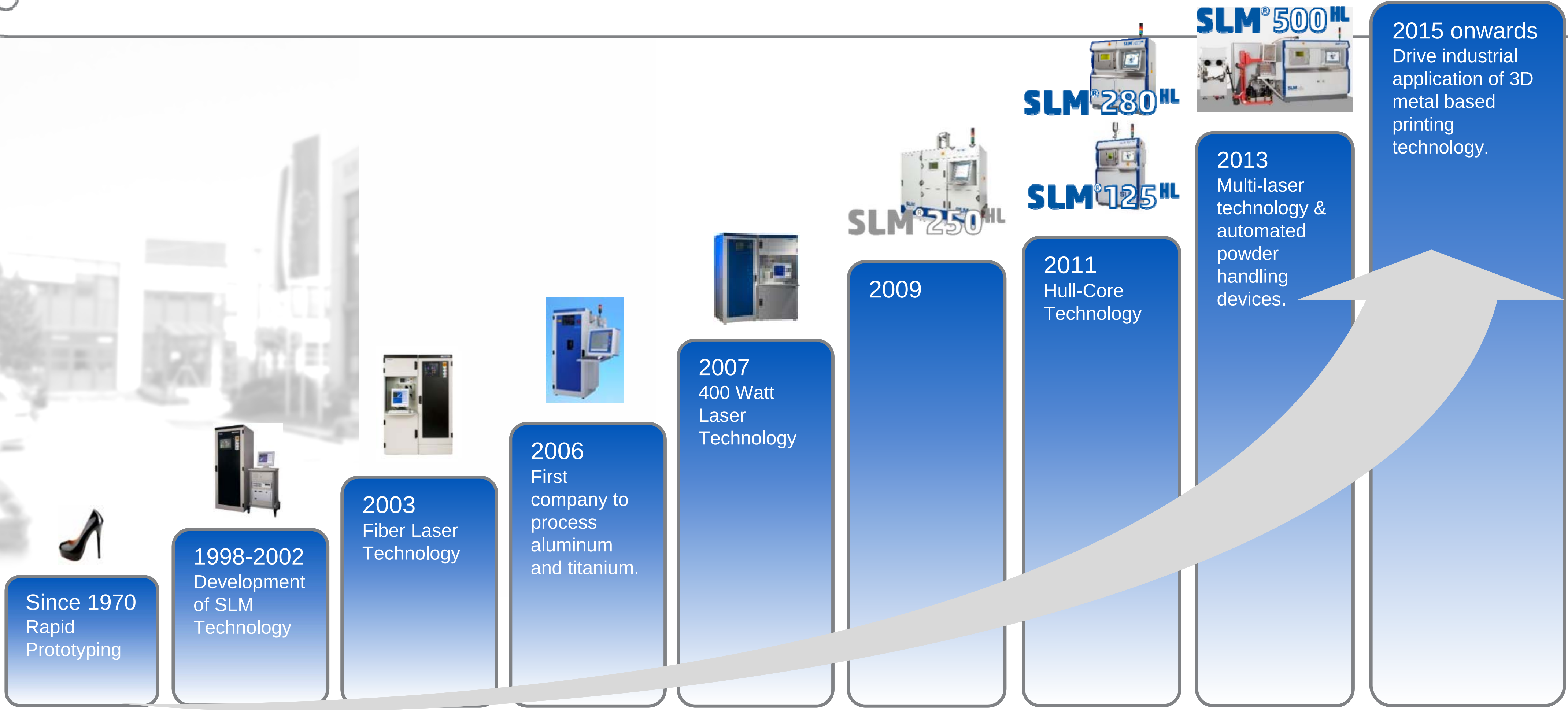
4. Conclusion

SLM Solutions NA, Inc.

Formerly: **HEK GmbH** • **MCP HEK Tooling GmbH** • **MTT Technologies GmbH**

SLM Solutions NA, Inc. | 28350 Cabot Drive, Suite #100, Novi, MI 48377 | 248.243.5400 | info@slm-solutions.us | www.slm-solutions.us

SLM Solutions Group AG – a deep rooted 3D printing heritage



Note: History of SLM Solutions Group and its predecessors
Source: Company information

SLM®280HL

35% faster than the competition with twin-laser technology

- 280 x 280 x 350 mm build envelope
- Built-in 400 W laser
- Option to add 1 additional 400 W (twin) or 1000 W (duo) laser
- Ideal for medium to high volume part production
- Closed-loop powder handling
- Patented bi-directional powder recoater movement
- Upgraded process control
- Open software architecture and system parameters
- Optimized gas flow and recirculation

Build Speed	**20 – 45 ccm/h**
Layer Thickness	**20 – 75 / 100 µm**
Operational Beam Focus	**80 – 120 / 700 µm**
Dimensions in mm (B x H x T)	**1800 x 1900 (2400) x 1020**
Weight	**approx. 1000 kg**

SLM® 500HL

The flagship system for larger complex metal parts.

- 500 x 280 x 365 mm build envelope
- 2 standard 400 W lasers
- Option to equip 4x 400 W (Quad Laser Technology)
- Lasers may be used independently or parallel in the build process
- Closed-loop powder handling
- Patented bi-directional powder recoater movement
- Adapter for higher platform temperatures
- Open software controls
- Optimized gas flow and recirculation

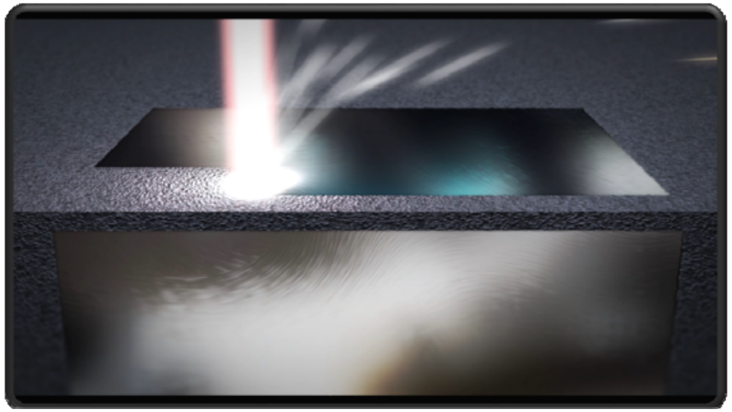
Build Speed	**55 | 105 ccm/h Twin | Quad**
Layer Thickness	**20 – 75 µm**
Operational Beam Focus	**80 – 150 µm**
Dimensions in mm (B x H x T)	**5200 x 2700 x 2800 (incl. PRS & PSX)**
Weight	**approx. 3100 kg**

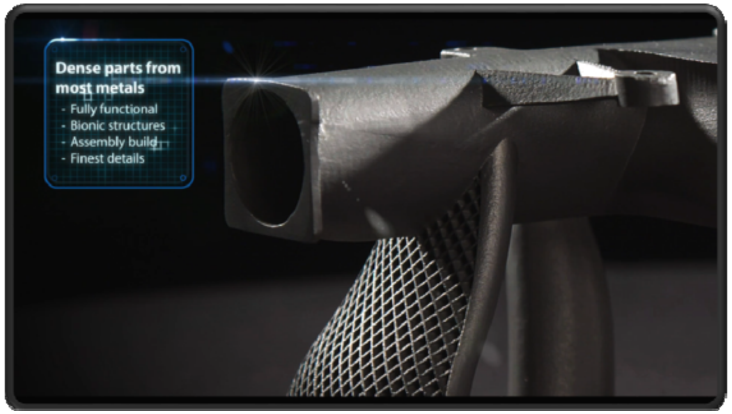
1. Additive Manufacturing - Selective Laser Melting - SLM®

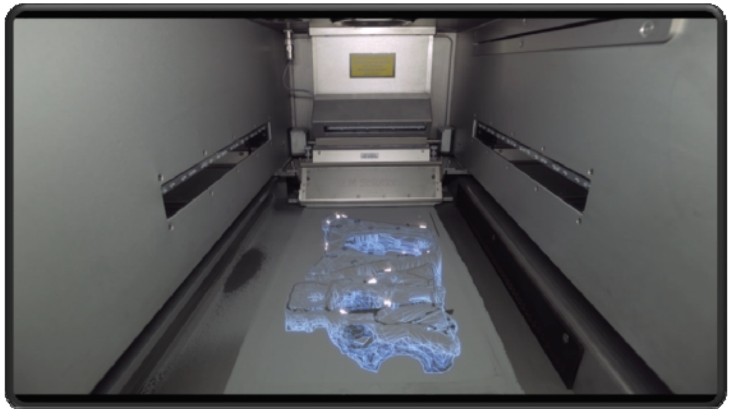
SLM SOLUTIONS

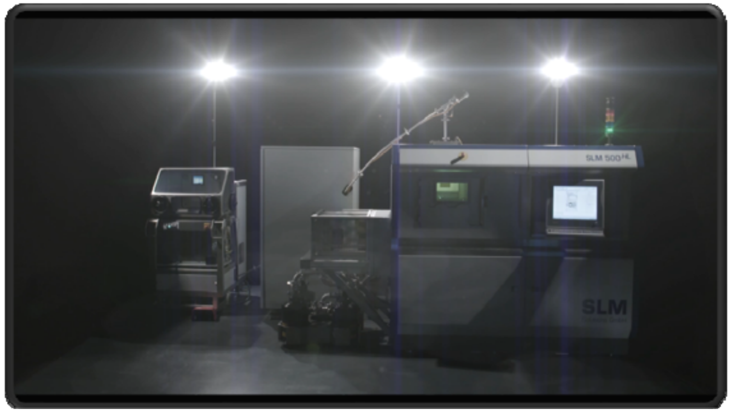
PADERBORN UNIVERSITY
The University for the Information Society

SLM® 500HL









SLM SOLUTIONS

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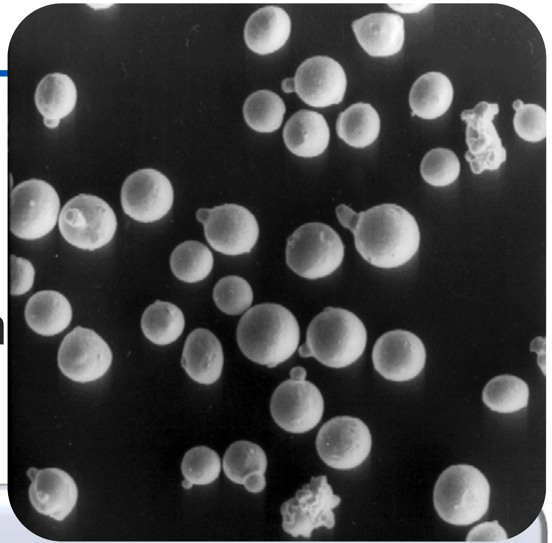
Qualified Materials

SLM Solutions

- **Continuous development of different materials. Certification due to customers needs and requirement.**

- Material data is available on a separate attachment. System parameters are available for the following materials:



Stainless Steel:	316L (1.4404)	17-4 (1.4542)	
Tool Steel:	Maraging (1.2709)	H13 (1.2344)	
Titanium:	Ti Al6 V4	Ti Al6 Nb7	Ti (grade 1)
Aluminum:	AlSi10Mg	AlSi12	
Cobalt Chrome:	CoCr28Mo6 (ASTM F75)		
Inconel:	625	718	738

Direct Manufacturing Research Center – DMRC

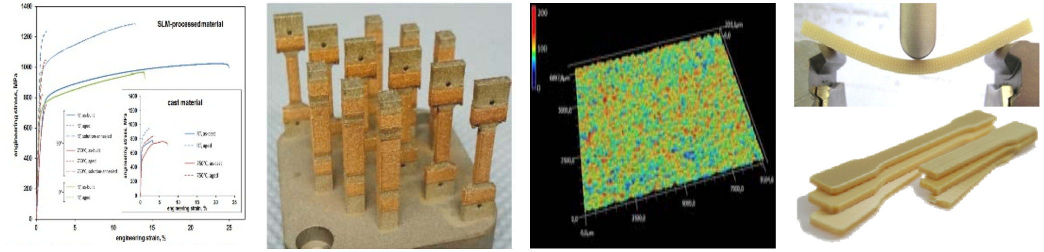
- Institution of the faculty of mechanical engineering at the Paderborn University
- Flexible and very interdisciplinary structure
- Collaboration of 9 different chairs and a large number of industrial partners
- Funded by the State Government of North Rhine-Westphalia, industrial partners and public sources
- All project topics are guided by industry partners

Research → Materials → Machines → Service providers and end-users

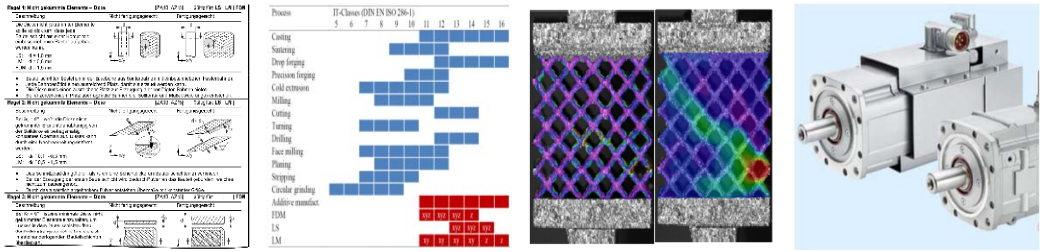
★ = Founding member

Direct Manufacturing Research Center – DMRC

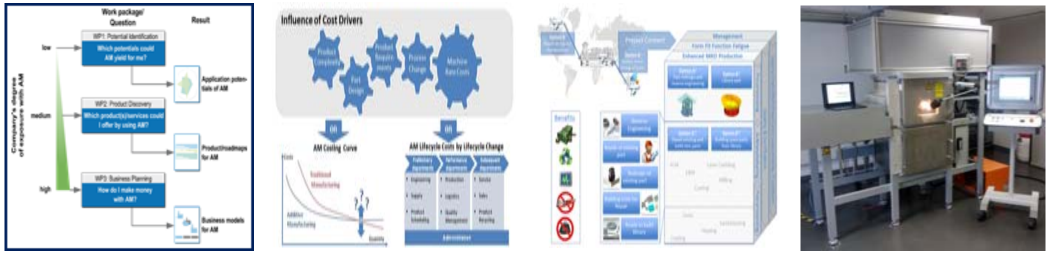
- Research fields in Laser Sintering, Fused Layer Modeling & Laser Melting



- **Material and process qualification:** LM.fatigue, LM, LS, FLM



- **Design for AM:** Design Rules, Tolerances, Light weight design



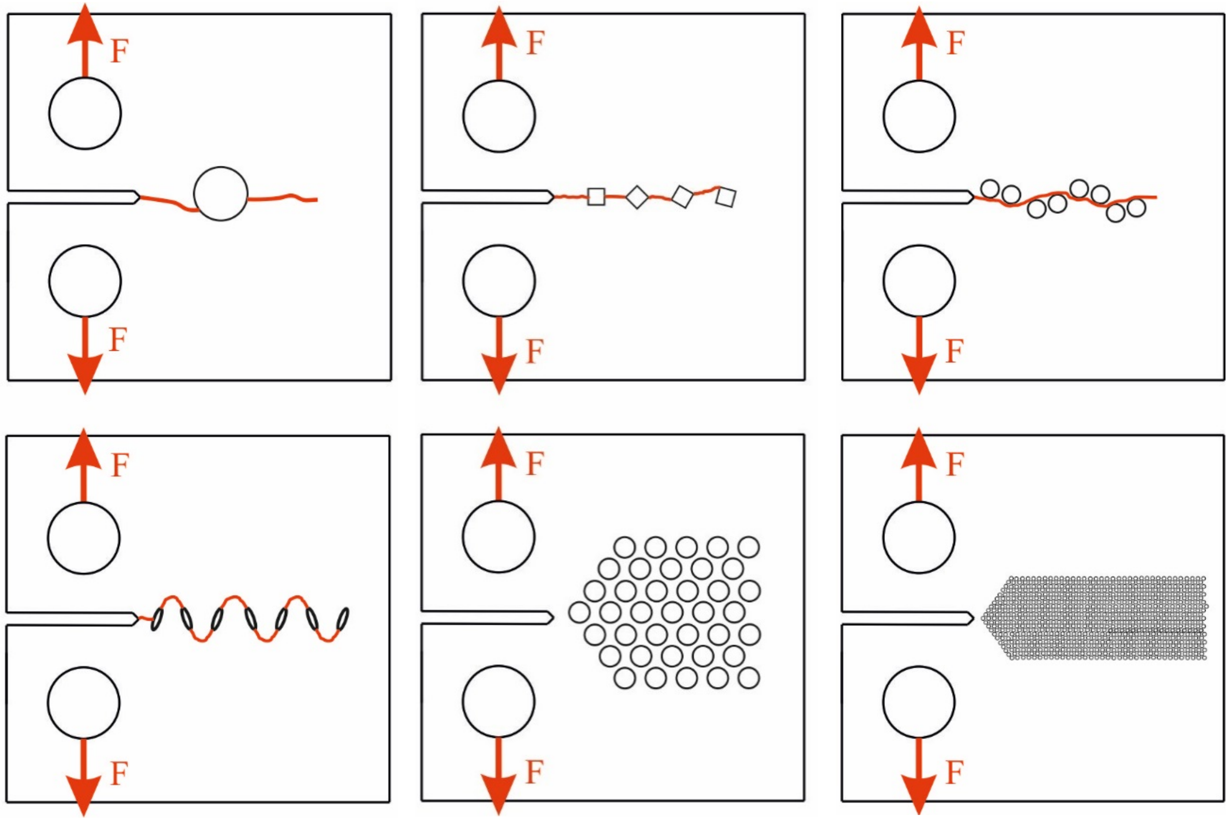
- Business development, Costs, Applications, Function Integration, Machine development

Motivation

- Technical components are subjected to various stresses
- Responsible for the limited service life

Main Goal

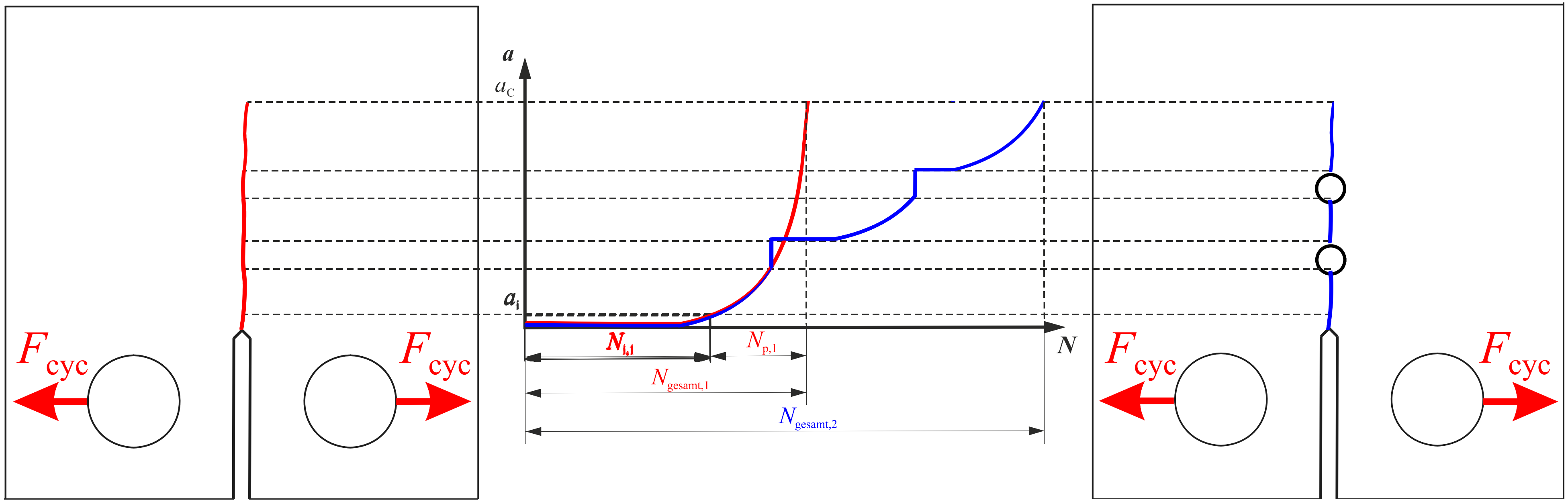
- **Extending the total life time of components**
- Using advantages of additive manufacturing
- Ingenious configuration of
  - Notch form
  - Notch position
  - Notch orientation



Schematic illustration of notch form, notch position and notch orientation for lifetime manipulation

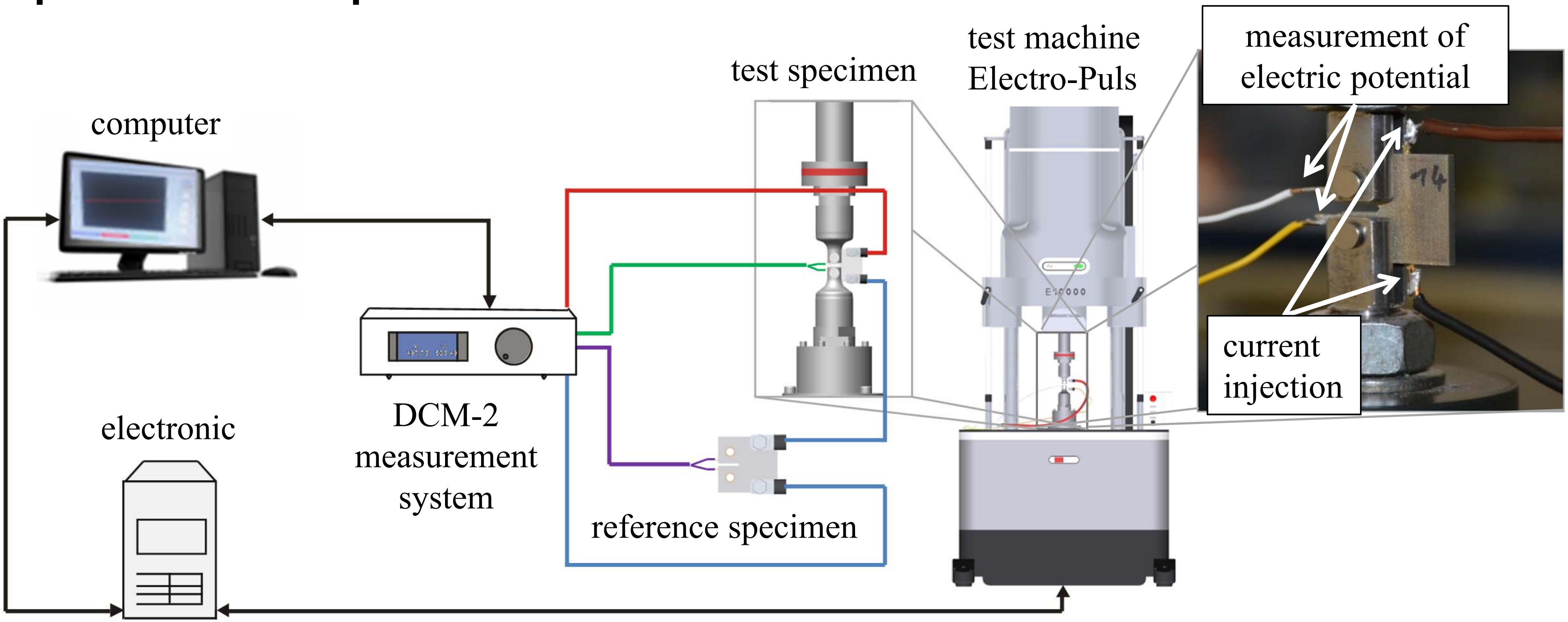
Major measure for lifetime modification

- Lifetime under fatigue loading is divided into crack initiation and fatigue crack propagation
- “Jump” in a-N-diagram and shorten the lifetime
- Switching between fatigue crack propagation and crack initiation phase
- Initiating effect at each notch



Schematic illustration of lifetime manipulation caused by notches

Experimental setup for fracture mechanics



$$U = R_{\Omega} \cdot I_0 = \rho \cdot \frac{l}{A} \cdot I_0$$

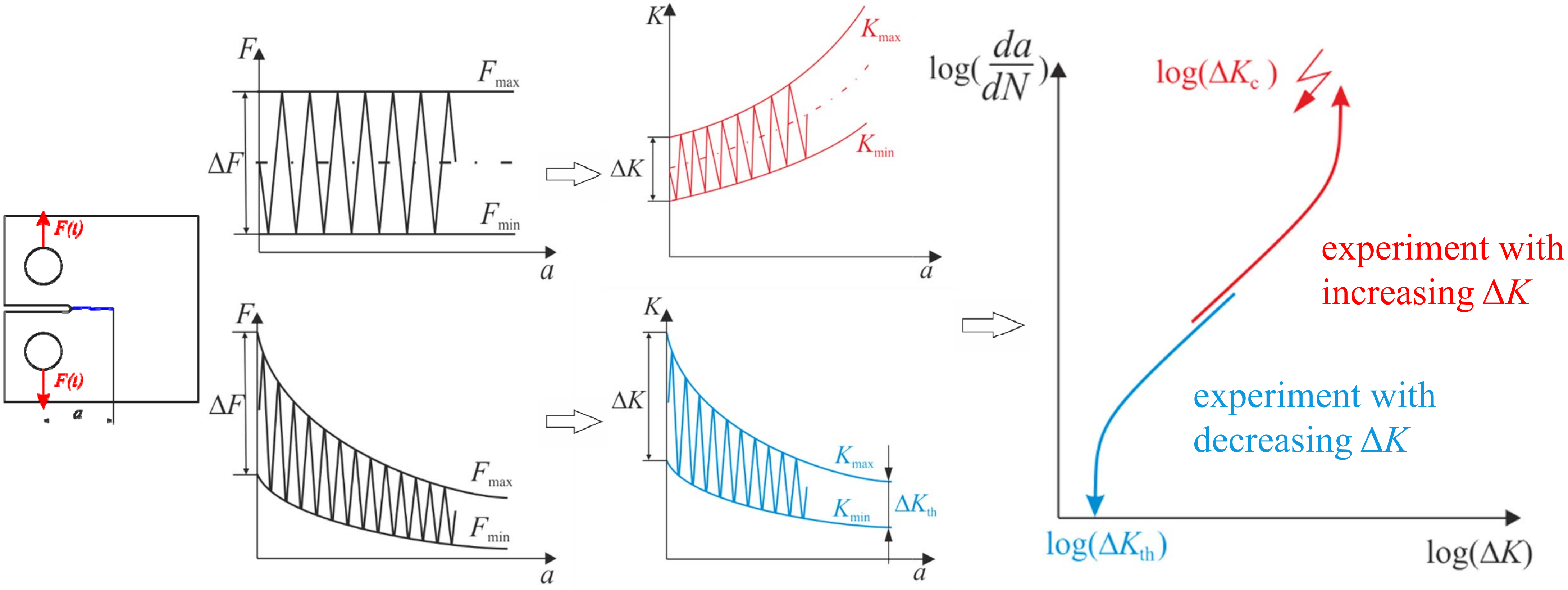
U = voltage
R_{Ω} = resistance
I_0 = supply current

ρ = specific material resistance
l = length of specimen
A = cross sectional area

Testing Methods

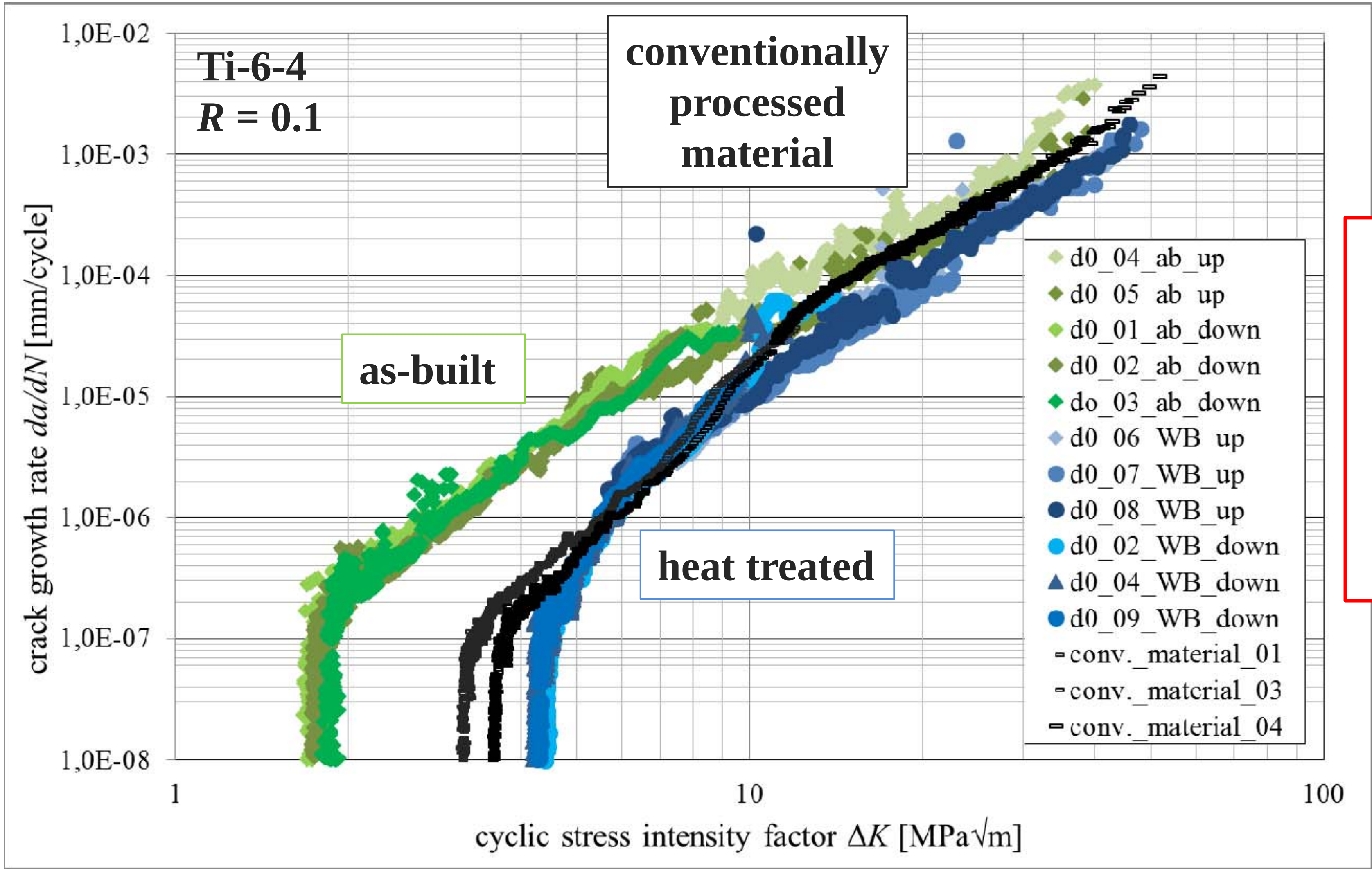
mechanical load

cyclic stress intensity factor at the crack



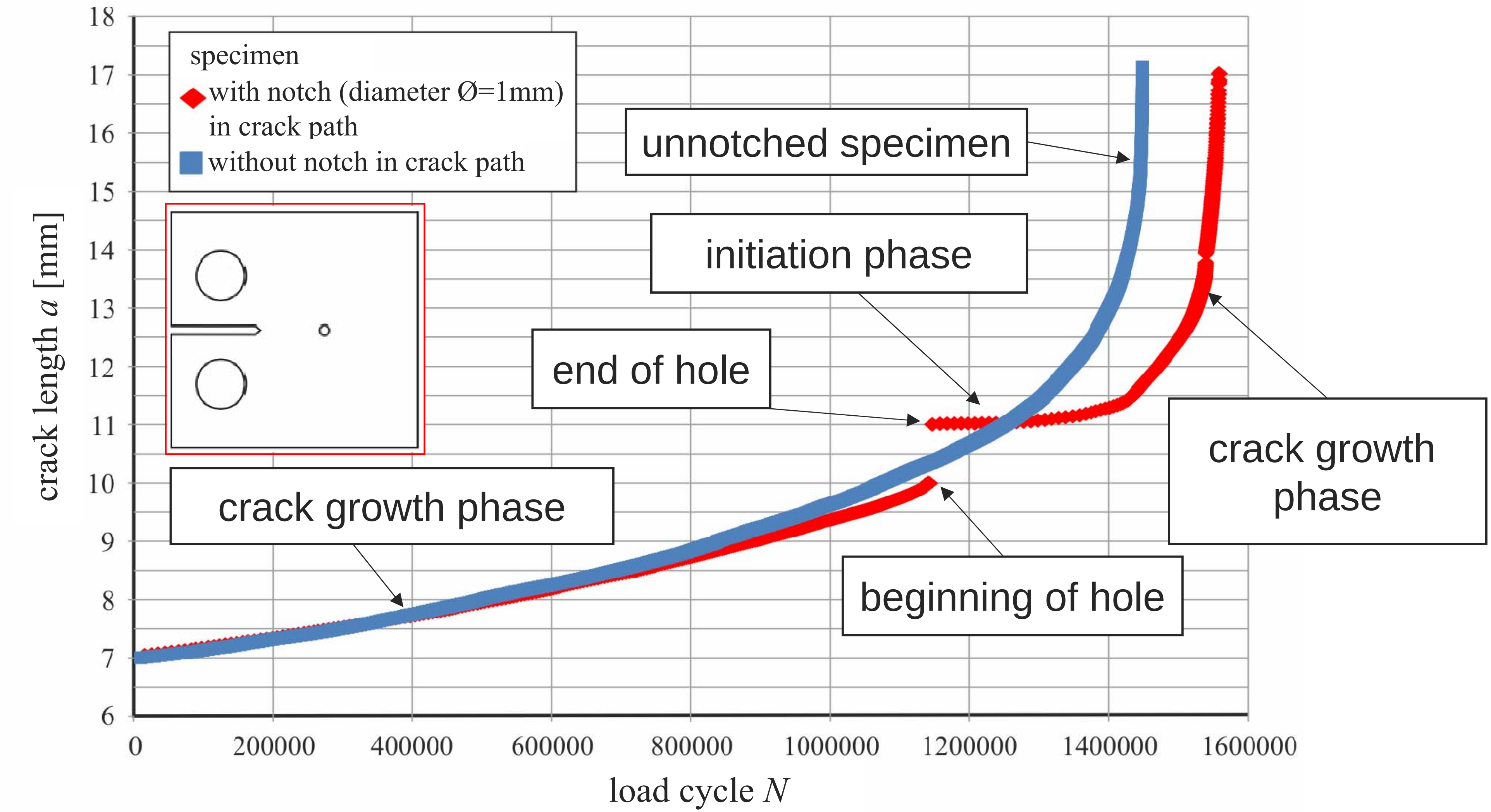
$\Delta K_{\mathrm{I}} = \Delta\sigma \cdot \sqrt{\pi \cdot a} \cdot Y_{\mathrm{I}}$ $\Delta\sigma =$ cyclic loading stress $a =$ crack length $Y_I =$ geometry factor

Fatigue properties of SLM® materials

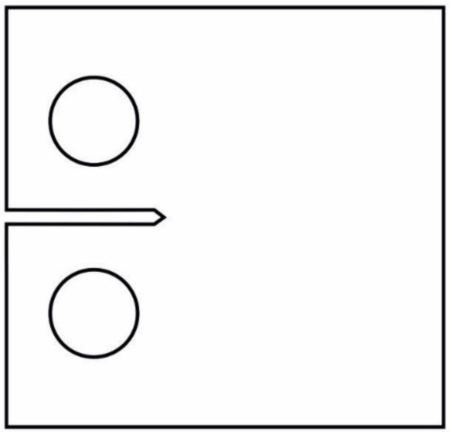


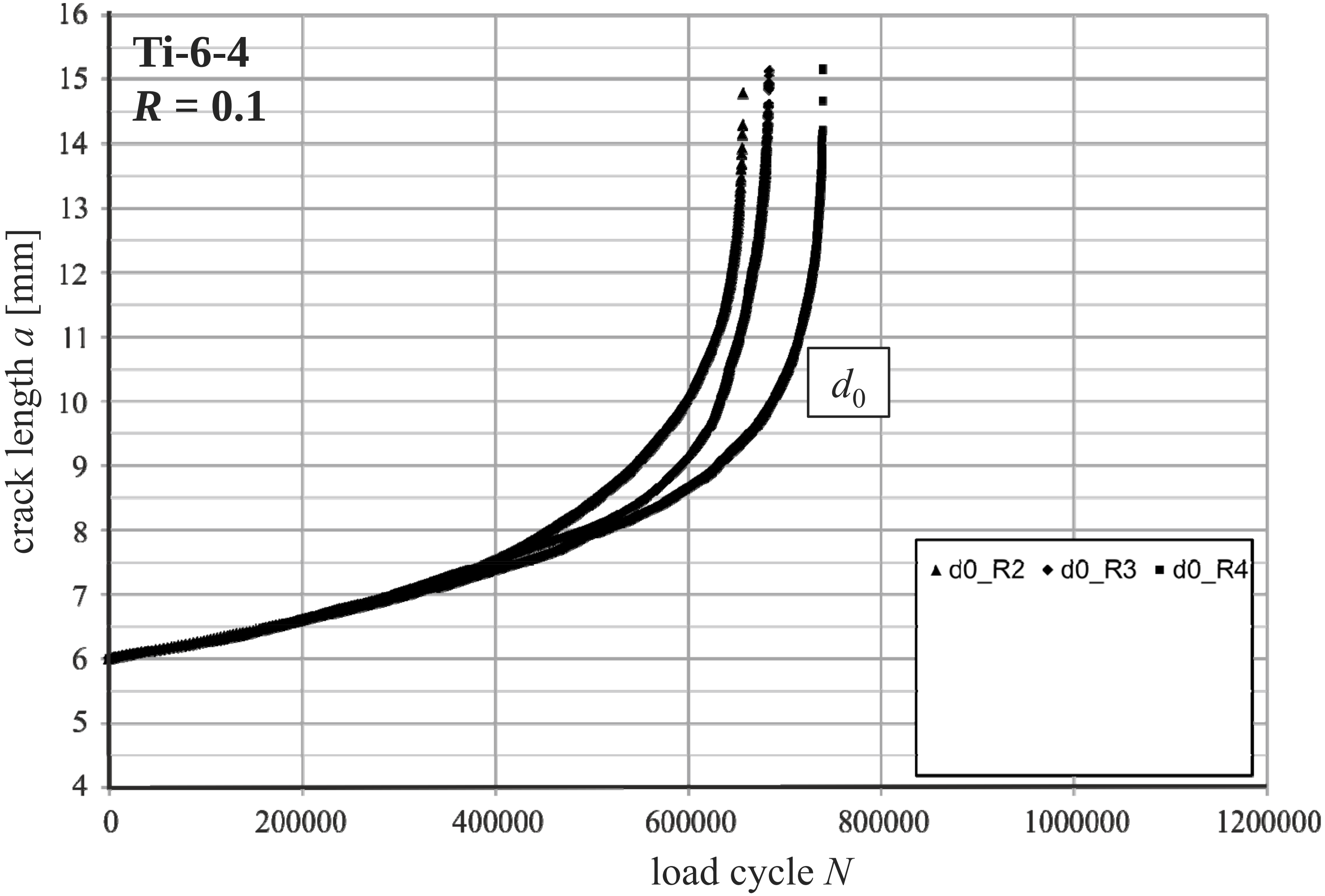
Heat treatment significantly improves the fatigue crack growth performance

Fatigue Life Manipulation by Notches – Lifetime Phases

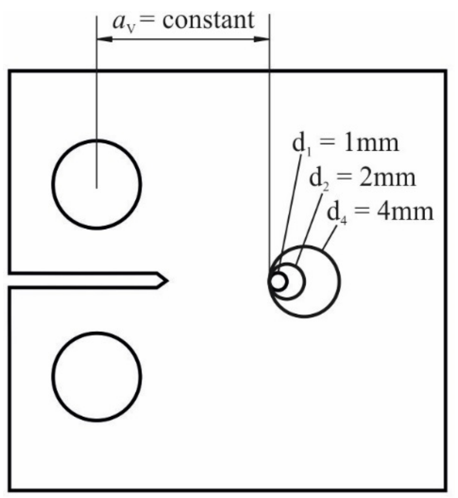


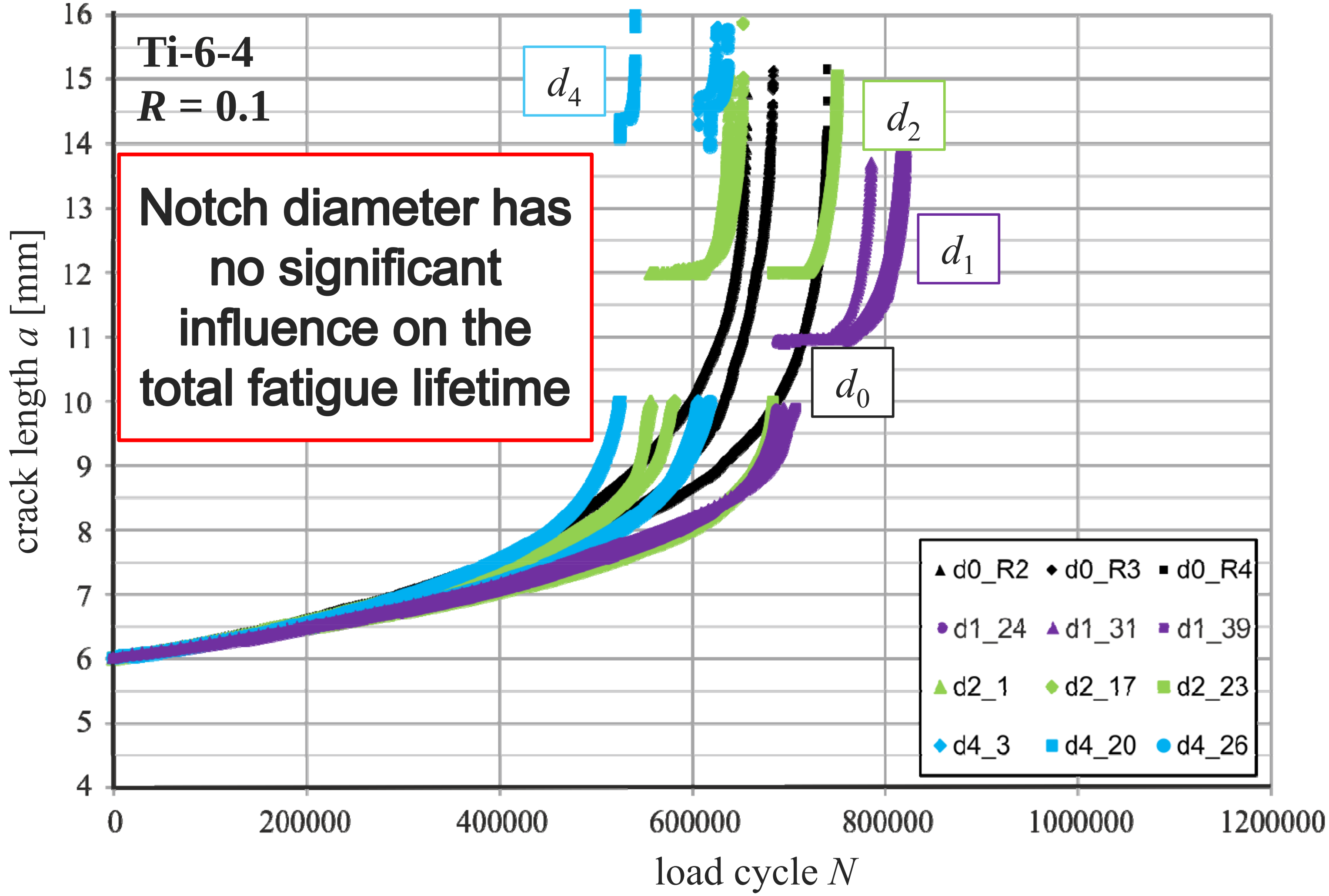
Fatigue Life Manipulation by Notches – Unnotched Specimen





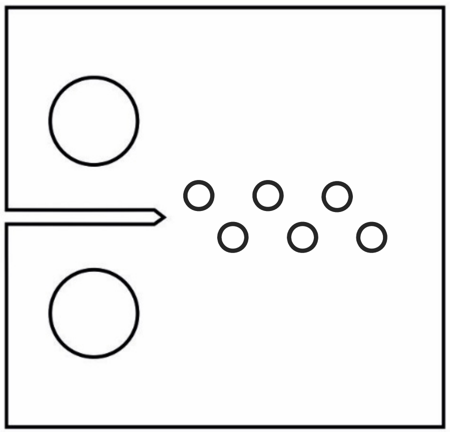
Fatigue Life Manipulation by Notches – One Hole with different Diameter



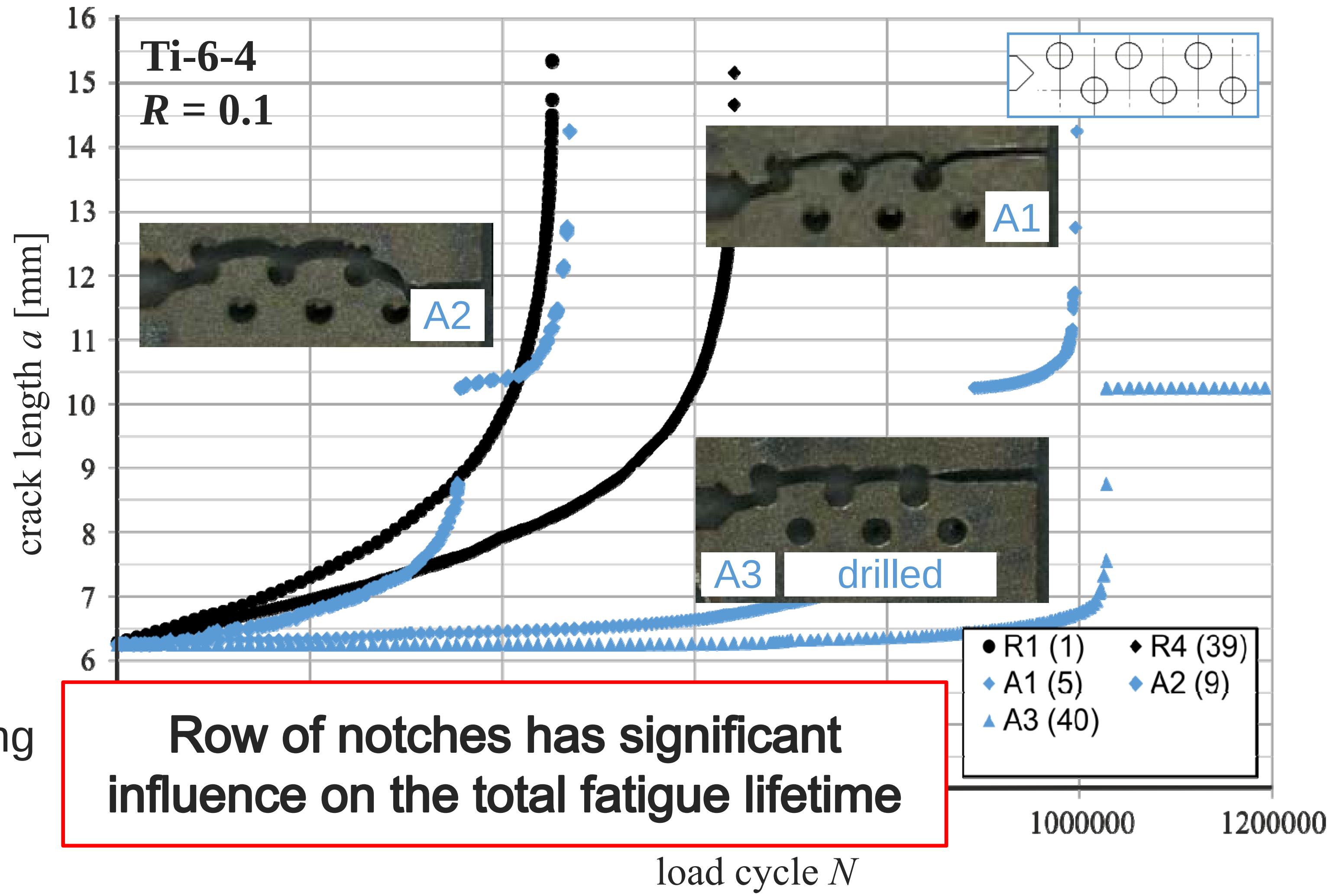


Fatigue Life Manipulation by Notches – Row of Holes

- No re-initiation after growing at the first hole
- force increasing



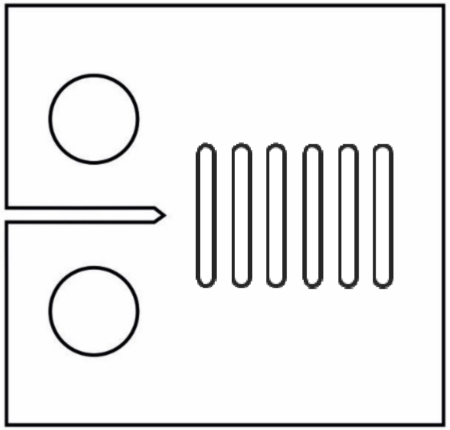
- deformed notches due to manufacturing process

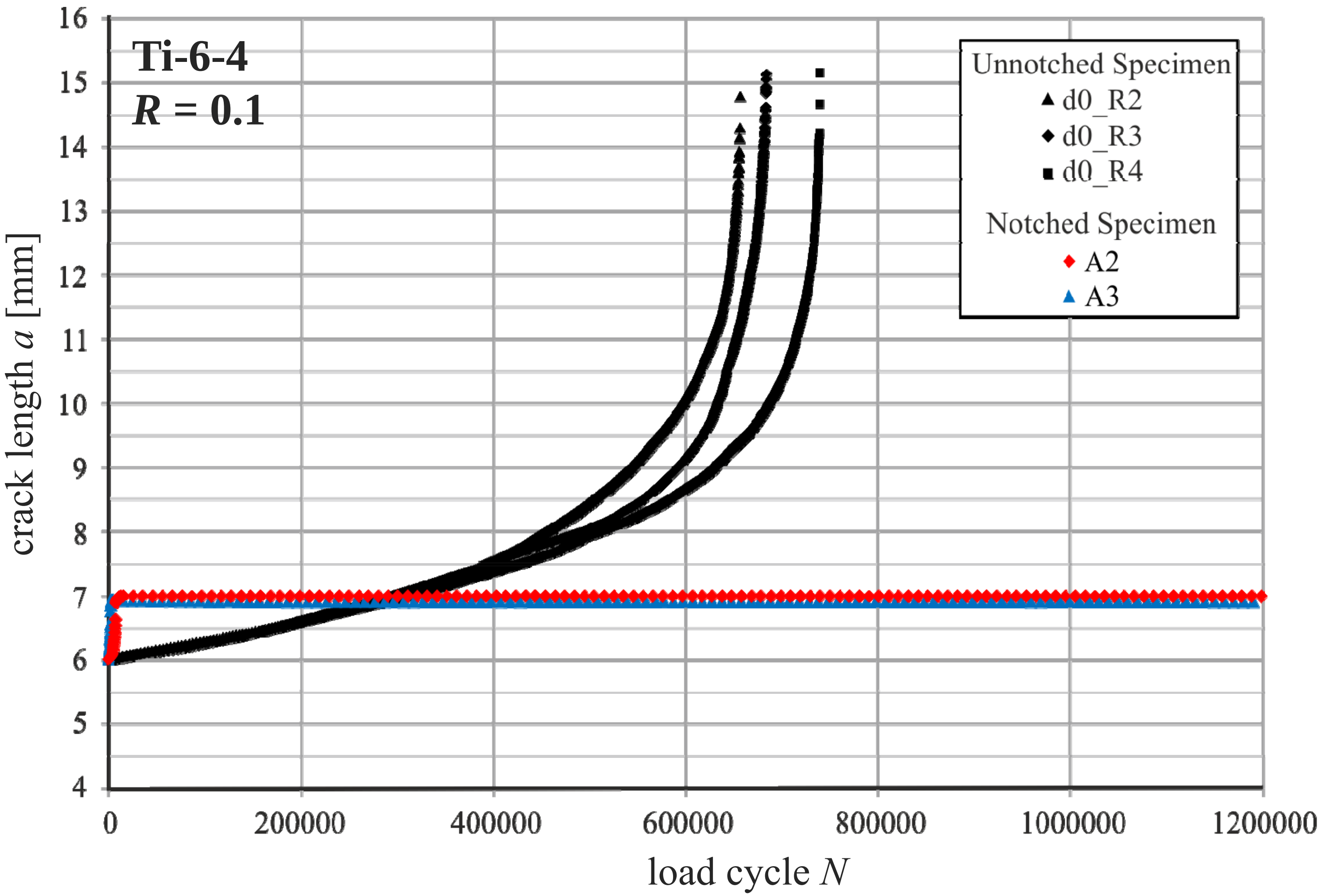


Row of notches has significant influence on the total fatigue lifetime

Fatigue Life Manipulation by Notches – Elongated Notches

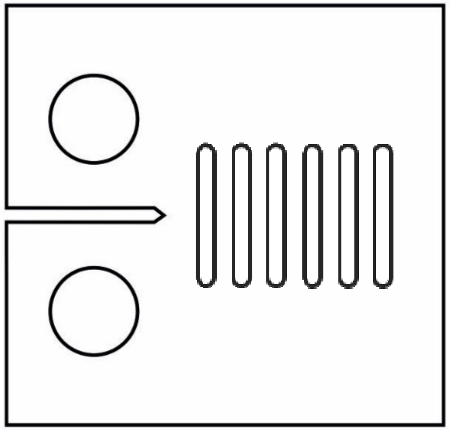
- No re-initiation after growing at the first elongated notch

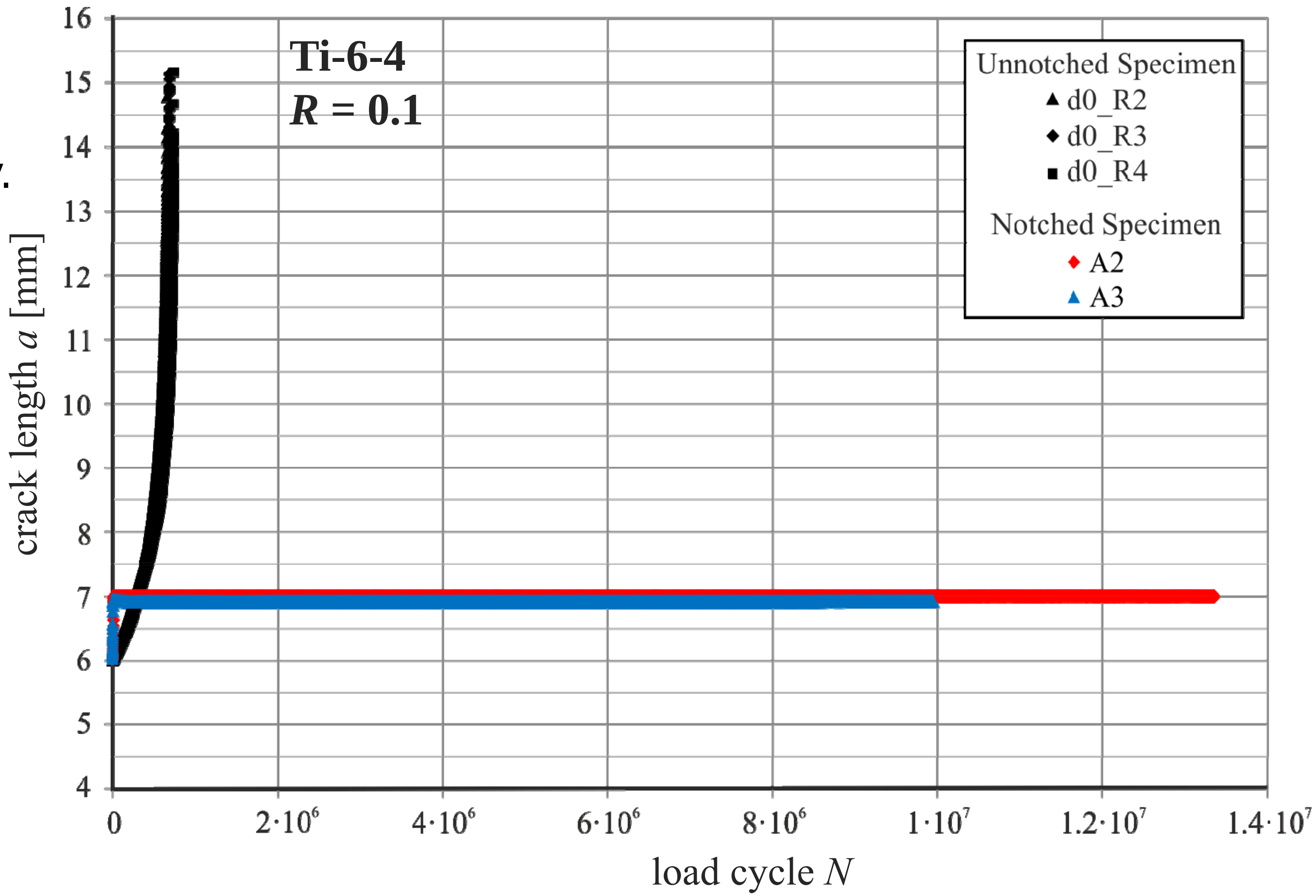




Fatigue Life Manipulation by Notches – Elongated Notches

- No re-initiation after growing at the first elongated notch
- Even after 10mil. cy.





Fatigue Life Manipulation by Notches – Elongated Notches

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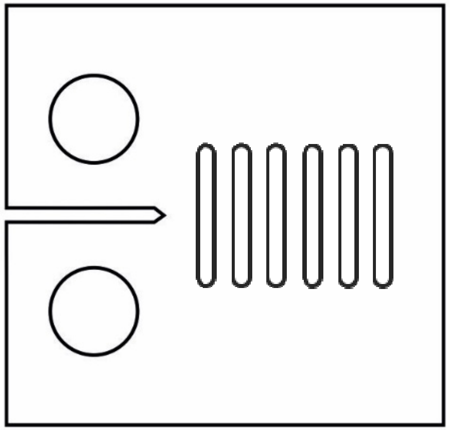
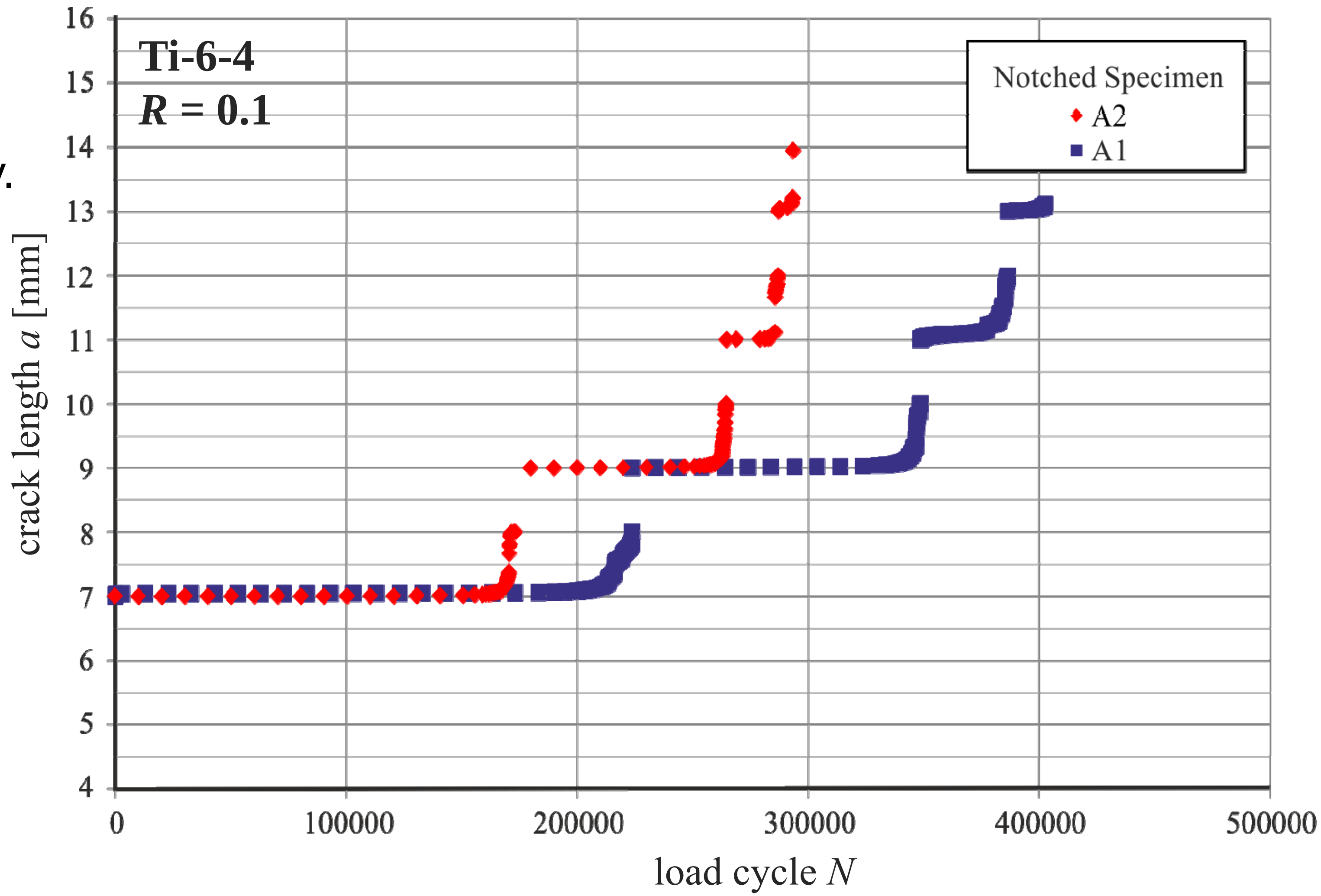
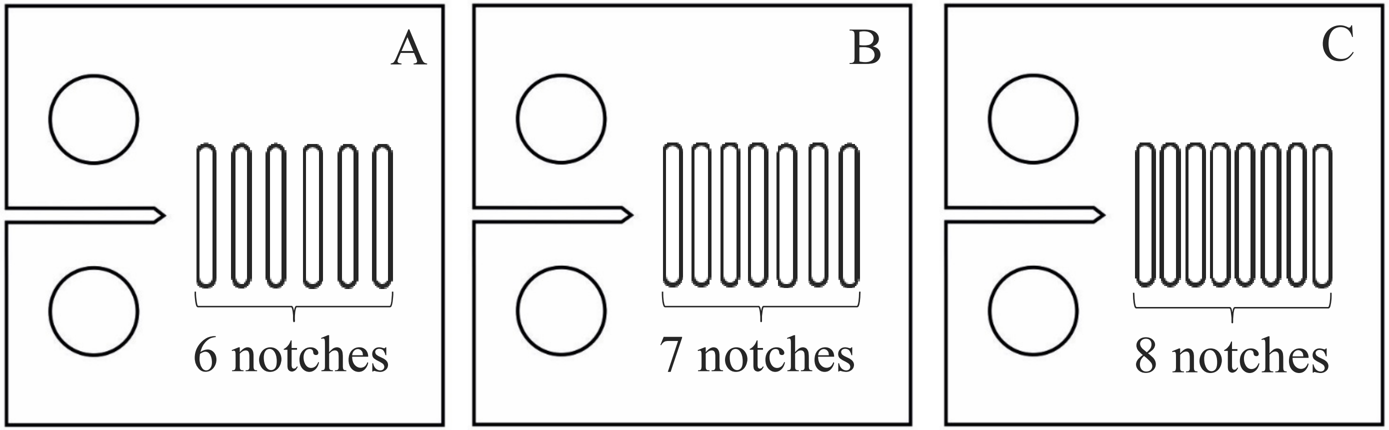


- force increasing

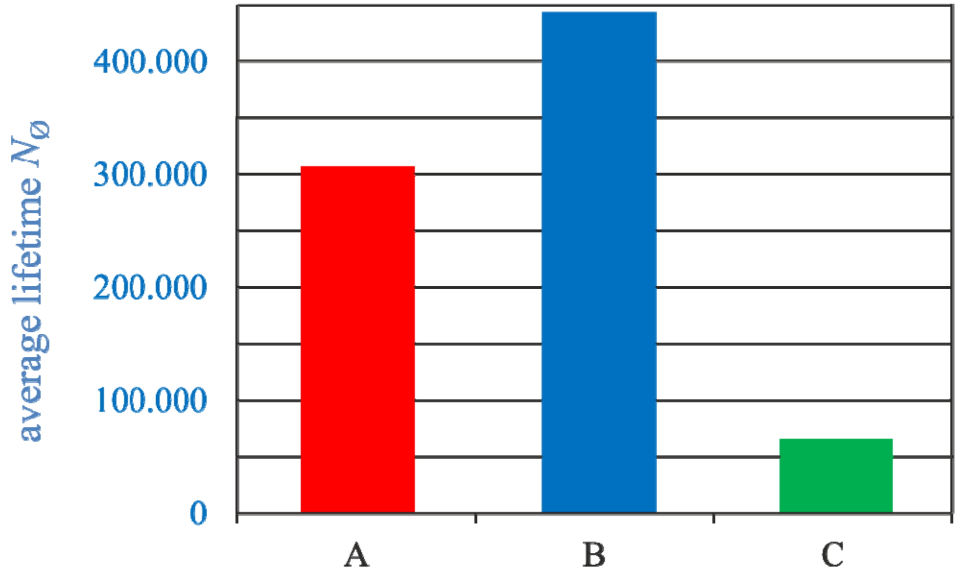


Fatigue Life Manipulation by Notches – Elongated Notches

- Comparison of different specimens with elongated notches – width 1 mm
- Notches lead to initiation effect
- This initiation effect increases with the number of notches
- But this effect is limited by the residual cross-section area of the specimen

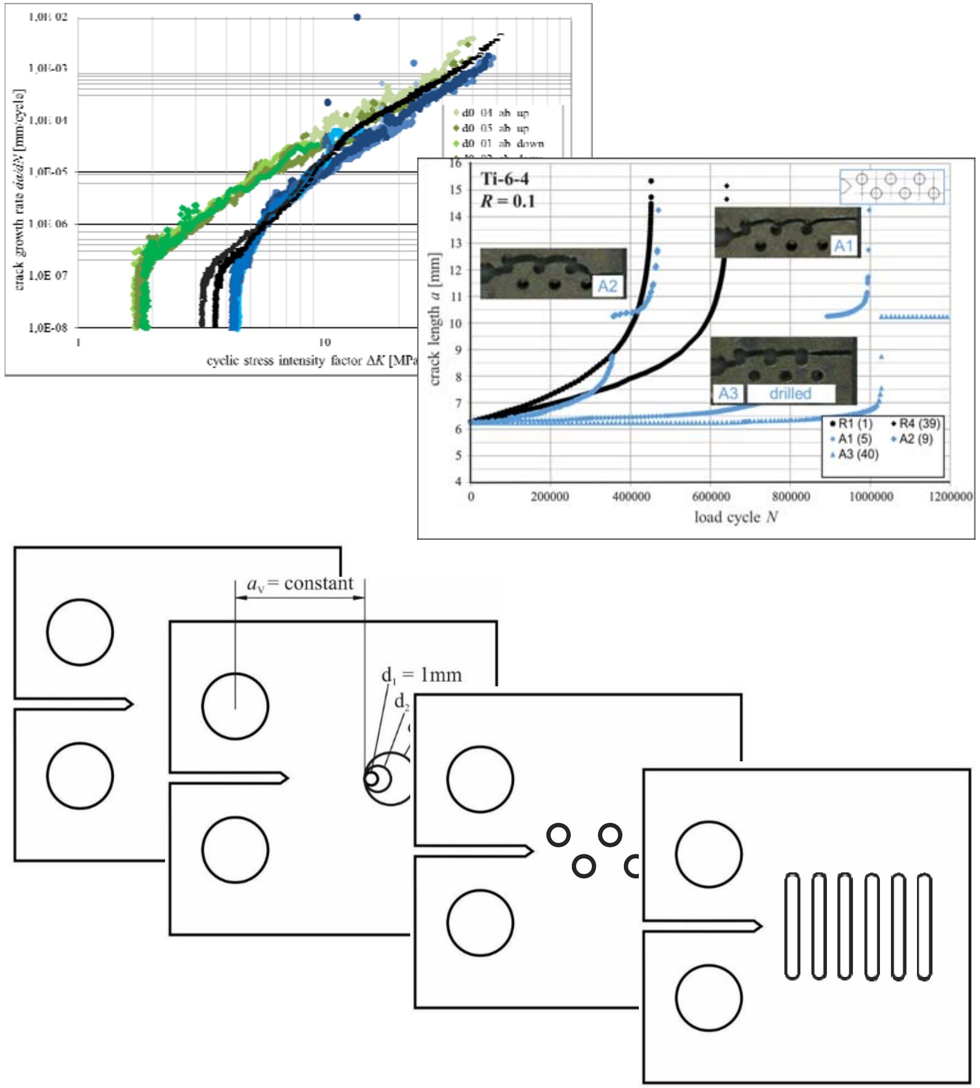


→ **The fatigue lifetime manipulation is possible and influenced by the number, size, form and position of the notches**



4. Conclusion

- Numerous experimental investigations were conducted on different SLM®-processed materials like titanium alloy and stainless steel
- Only a part of the results was presented
- Results show that the fatigue life (decrease or increase) can be manipulated by notches
- Significant crack growth retardation occurs if the crack initiation phase, caused by notches, plays a significant role in the total lifetime
- Taking the titanium alloy as an example, a significant lifetime extension can be achieved by using a row of notches
- Additive manufacturing offers the possibility to produce structures that have a longer fatigue lifetime



Fatigue Life Manipulation of SLM® Parts

THANK YOU FOR YOUR ATTENTION

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W. Reschetnik, A. Riemer, H.A. Richard. Optimization of SLM structures with respect to crack growth and lifetime. Proceedings of ASPE Spring Topical Meeting, Dimensional Accuracy and Surface Finish in Additive Manufacturing, American Society for Precision Engineering, Berkeley, USA, 2014, S.190-195.

A. Riemer, W. Reschetnik, H.A. Richard. Fatigue Crack Growth in TiAl6V4 and 316L Manufactured by Selective Laser Melting – Influencing Factors and Measures for Lifetime Optimisation. ESA - Workshop on Additive Manufacturing for Space Application, 28.10.-29.10.2014, ESTEC, Noordwijk, Niederlande.

A. Riemer, S. Leuders, M. Thöne, H. A. Richard, T. Tröster and T. Niendorf. On the fatigue crack growth behavior in 316L stainless steel manufactured by selective laser melting. Engineering Fracture Mechanics, 120 (2014) 15-25.

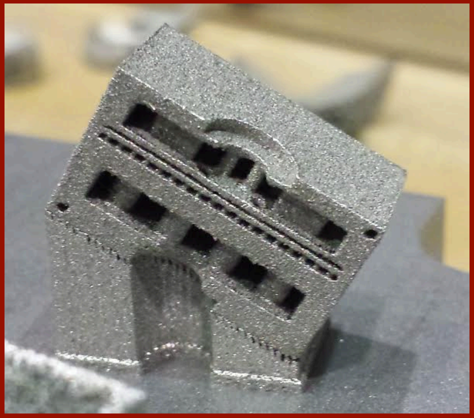
S. Leuders, M. Thöne, A. Riemer, T. Niendorf, T. Tröster, H. A. Richard, H. J. Maier. On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: Fatigue resistance and crack growth performance, International Journal of Fatigue, 48 (2013) 300-307.

Advanced Characterization of Additively Manufactured Materials, including Synchrotron–based 3D X-rays

A.D. (Tony) Rollett, Ross Cunningham, Sneha Narra, Tugce Ozturk, Brian De Cost, Suraj Rao, Samikshya Subedi, Harshvadhan Jain, Ming Tang, Luke Scime, Paul Chao, Shuchen Cong, Jake Vries, Bryan Webler, Chris Pistorius, Jack Beuth, David Menasche, Liz Holm, Bob Suter.

With help from many others, especially John Siemon, Yanar Cagatay, Jaakko Suni (Alcoa Tech. Center) & Xianghui Xiao (APS)

Support:
America Makes
NSF
PA-RAMP
Adv. Photon Source
DOE
NIST
NASA
DOE-NNSA



Prototype Heat Exchanger

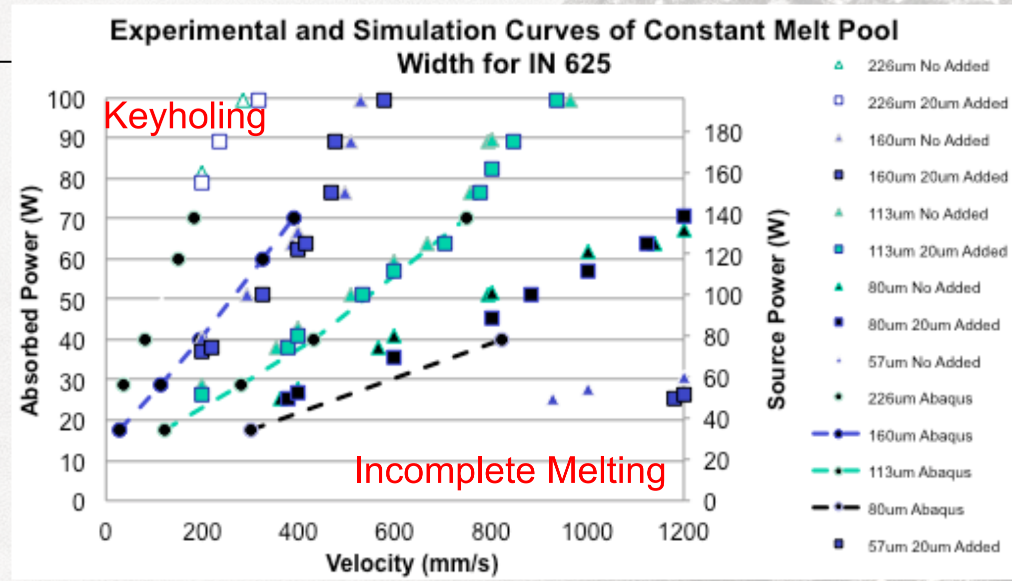
GE Engine Brackets

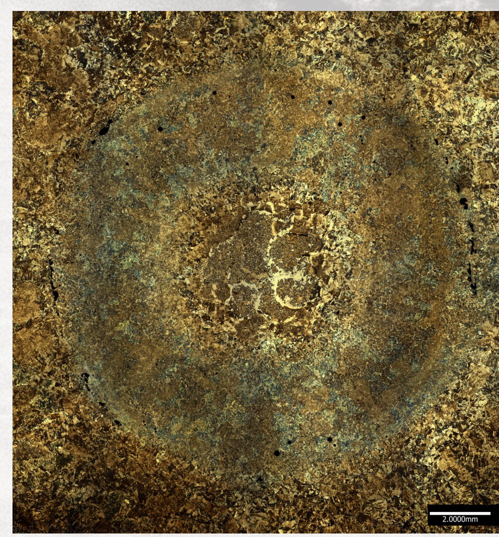
Outline

- NextManufacturing Center at CMU; process model
- Quantitative prediction of microstructure: reduced order model to predict porosity
- Advanced characterization, e.g., 3D tomo (CT), HEDM
  - 3D High Energy x-ray Diffraction Microscopy (HEDM)
  - Pore size distributions, powder particle sizes, statistical presentation of data.
- Machine vision for microstructure
- Summary

Metals AM

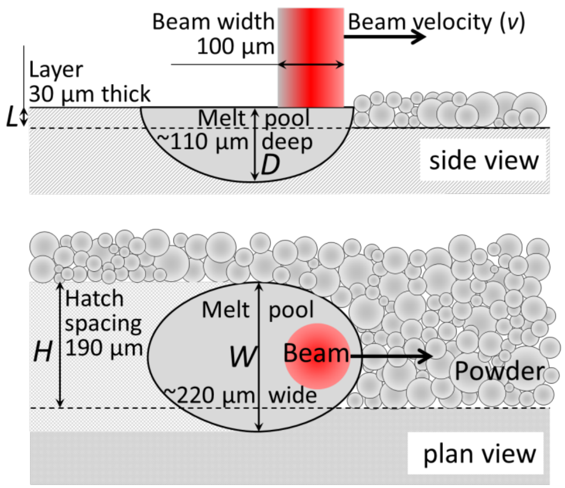
- CMU NextManufacturing Center
  - Broad AM group at Carnegie Mellon
  - Many inter-related projects with significant contributions
  - Strong emphasis on genomic approach
  - Brings together the AM ecosystem in the region
- Process Mapping Overview
  - Broad approach to process understanding
- Within 5 years AM users will be able to:
  - Vary microstructure spatially within parts
  - Monitor and control the process
  - Choose from a wide variety of powders
  - Eliminate or design for porosity
  - Design the process as they design a part (including cost estimates)



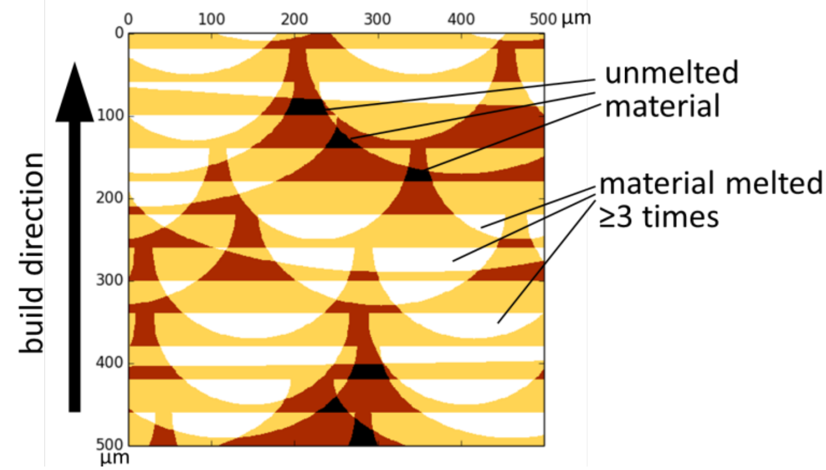


Work by Tang, Pistorius, Beuth

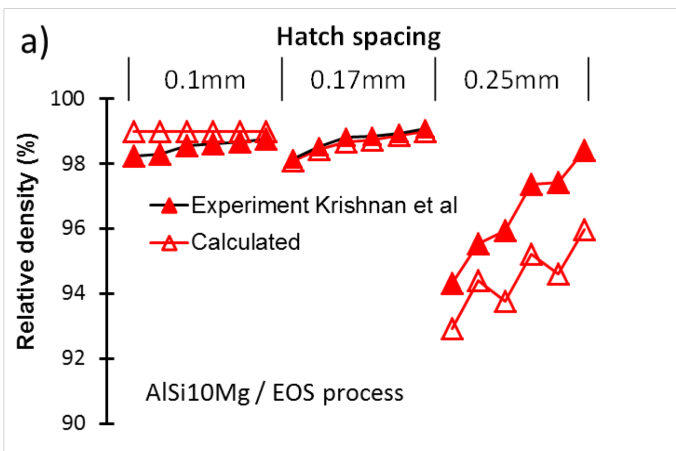
Porosity/Density Prediction



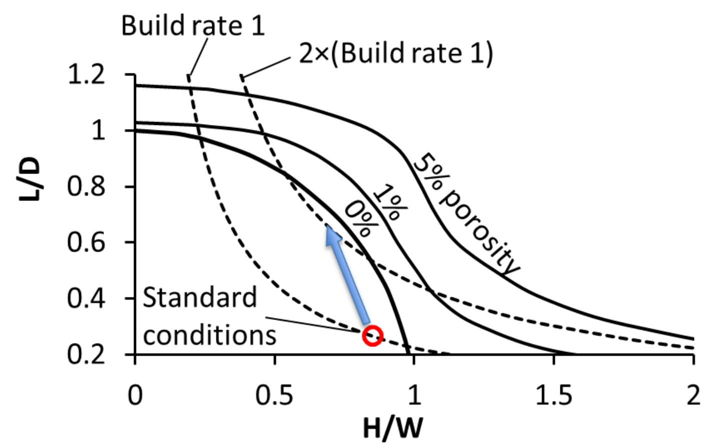
Melt pool geometry



Melt pool overlap across layers



Comparison of model with literature data



Comparison with standard operating point

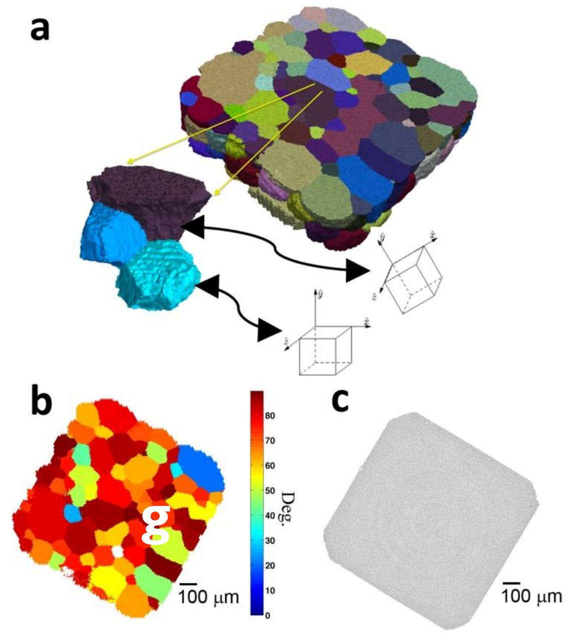
Synchrotron Computed Tomography

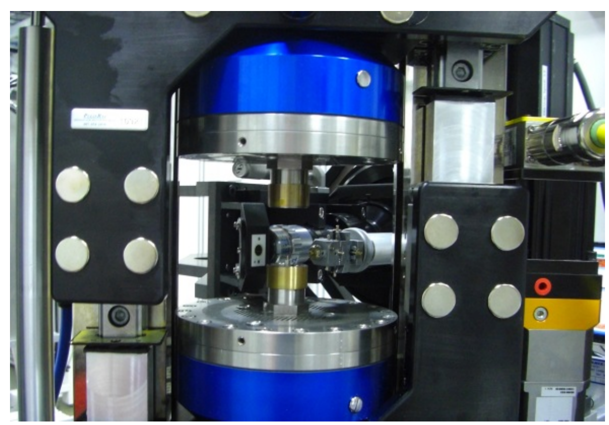
- The Advanced Photon Source (APS) at Argonne National Laboratory provides high energy x-rays with **high brilliance (flux)**
- Synchrotron source is useful for computed tomography (CT):
  - Sample size (up to 2 mm diameter at 2BM)
  - Resolution (0.65 µm)
  - **Short scan times** (2-6 mins)
  - Terabytes of data; **long times** required to a) reconstruct each 3D image and b) analyze the results (e.g., segmentation)

Advanced Photon Source,
Argonne National Lab, Chicago

Advanced Synchrotron Capabilities: CT+HEDM

- Recently NF- & FF-High Energy Diffraction Microscopy (HEDM) experiment at 1-ID on AM Ti-6-4
- 3D microstructure and orientation information with Near-Field mode
- 3D residual stress distribution via Far-Field mode
- Capability for in situ loading during CT, NF and FF; RAMS loading system developed by AFRL
- Schuren *et al.* (2015), 'New opportunities for quantitative tracking of polycrystal responses in three dimensions', COSSMS, **19** 235.





Porosity Measurement via CT

- "Evaluating the Effect of Processing Parameters on Porosity in Electron Beam Melted Ti-6Al-4V via Synchrotron X-ray Microtomography", R. Cunningham, S.P. Narra, J. Beuth, and A.D. Rollett, *JOM*, **68** 1 (2016)
- Aim was to characterize porosity size and shape distributions as a function of processing conditions
- Used computed tomography at the Advanced Photon Source at the Argonne Natl. Lab. In Chicago
- High energy x-rays permit rapid measurement (a few minutes per mm^3 sample volume) at high resolution (minimum pore size ~ 1 µm), which is suitable for pores ranging up to 100 µm.
- About 100 sample volumes can be measured per 24 hours of beamtime at 2BM (at APS), which uses "pink" radiation (parallel beam, limited range of energies, very high intensities). Each volume is of order 1 mm^3 with a resolution of approx. 1 µm. Substantial help from Xianghui Xiao (APS) is gratefully acknowledged.
- The void content of any material is particularly important with respect to fatigue resistance. Fatigue cracks typically start from voids in preference to other microstructural features (after manufacturing defects and corrosion pits).

CT on Beamline 2BM at APS

About XMI ▾ | Science and Research ▾ | Beamlines ▾ | Highlights ▾ | Software & Tools ▾ | Internal ▾ | Search APS...

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Beamlines and Facilities: Beamline:2-BM

Introduction

The 2-BM beamline offers measurement capabilities for x-ray microtomography, x-ray topography and x-ray microdiffraction. X-ray microtomography and x-ray diffraction instruments are installed on separate optical tables for independent operation with fast switch over time. Optically-coupled high-resolution CCD system is used for microtomography and topography with up to 1 micron spatial resolution. X-ray microdiffraction setup consists of KB microfocussing mirrors (~3 micron minimum spot), four-circle Huber diffractometer, high-precision translation sample stage, two orthogonally-mounted video cameras for viewing sample, fluorescence detector (Si-drift diode) and diffraction detector (a scintillation detector or a CCD).

Three different levels of monochromaticity are available. Conventional monochromatic x-rays from a double-bounced Si (111) crystal monochromator (DCM, D E/E=1E-4), wide band-pass monochromatic x-rays from a double multilayer monochromator (DMM, D E/E=1~4E-2) and pink beam. The available x-ray range is from 5 keV to 30 keV. The lower limit is due to the x-ray windows and the upper limit is due to the critical angle of the x-ray mirror. Two different coatings (Cr and Pt) for the x-ray mirror allow either 20 keV or 30 keV energy cutoff.

Beamline Scientist:

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Beamline post-doc:

Yongshen Pan: pany@aps.anl.gov , (630) 252-5939

Techniques

- X-ray Tomography

Optical Components

Component	Distance from Source	Description	Installed
Filter assembly	23.2 m	8 filters on 2 carriers	05/1996
Hor. and vert. slits	23.5 m	25 µm reproducibility	05/1996
Vert. deflecting mirror	24.9 m	0.15 deg. plane w/ 2 coatings (Cr, Pt)	12/1997
Double multilayer mono.	27.4 m	Unfocussed	05/2000
Hor. and vert. slits	48.3 m	25 µm reproducibility	02/1997

Beamline Configurations

White Beam: (2-BM-A)	Beam at sample: 50 x 3 mm 2 (hor x vert), uncollimated
Pink Beam: (2-BM-B)	Beam at sample: 50 x 3 mm 2 (hor x vert), uncollimated
Monochromatic (multilayer): (2-BM-B)	Beam at sample: 25 x 4 mm 2 (hor x vert), E= 0.5-33 keV, dE/E= 10 -2

Detectors

Detector	Manufacturer	Description
Vortex	Radiant technologies	Energy dispersive solid state detector
Coolsnap HQ	Roper, Photometrics	Peltier cooled CCD camera
PCO Edge	PCO	sCMOS
PCO Dimax	PCO	CMOS
Bicron		Scintillator Point Detector
Ion Chambers		

2-BM-B X-ray Optics

KB-Mirrors, University of Chicago design

Parabolic refractive x-ray Be lenses

Ancillary Equipment

Micropositioning system

Time used: 3-5 minutes per volume

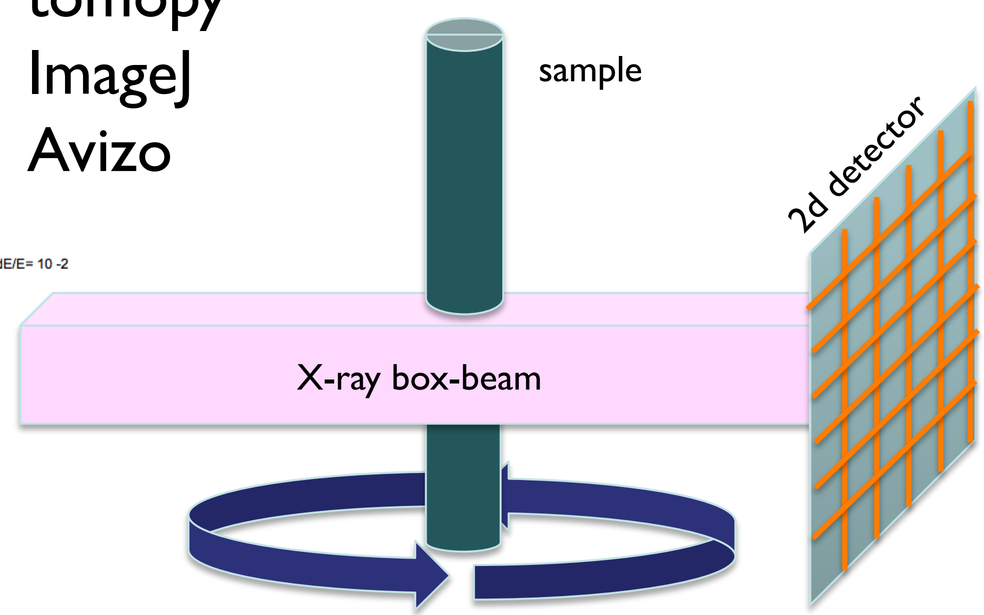
Data: approx. 0.2 Tbytes per volume

Software used for analysis:

tomopy

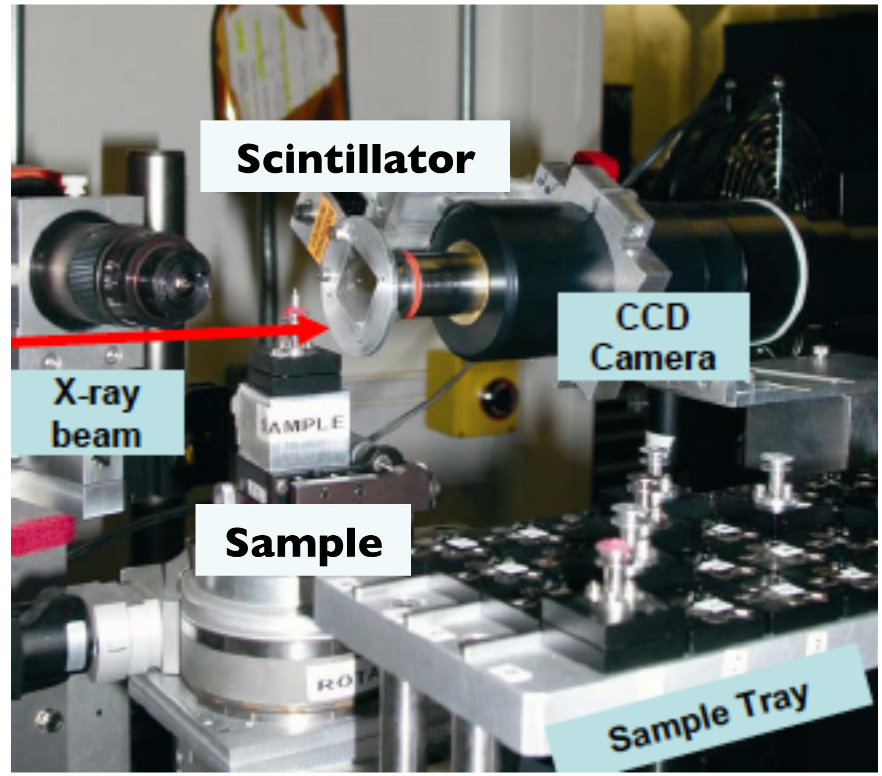
ImageJ

Avizo



X-ray Computed Tomography (XCT)

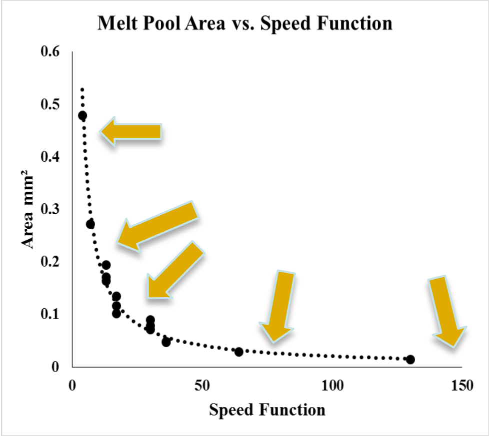
- Conventional methods for porosity analysis inadequate
  - Archimedes
  - Metallographic analysis
- XCT: Constructs 3D model from a series of 2D radiographs
  - Contrast generated by difference in X-ray absorption as they travel through a material
- Provides information on size, morphology, and spatial distribution in 3D
- Most lab-scale XCT instruments have limited resolution (~25 μm)
- **Synchrotron source offers significantly better resolution (~1 μm), scan time**



XCT setup at APS Beamline

https://www1.aps.anl.gov/files/download/Committees/InterCAT_Technical_Workgroup/2010/20100318decarlo.pdf

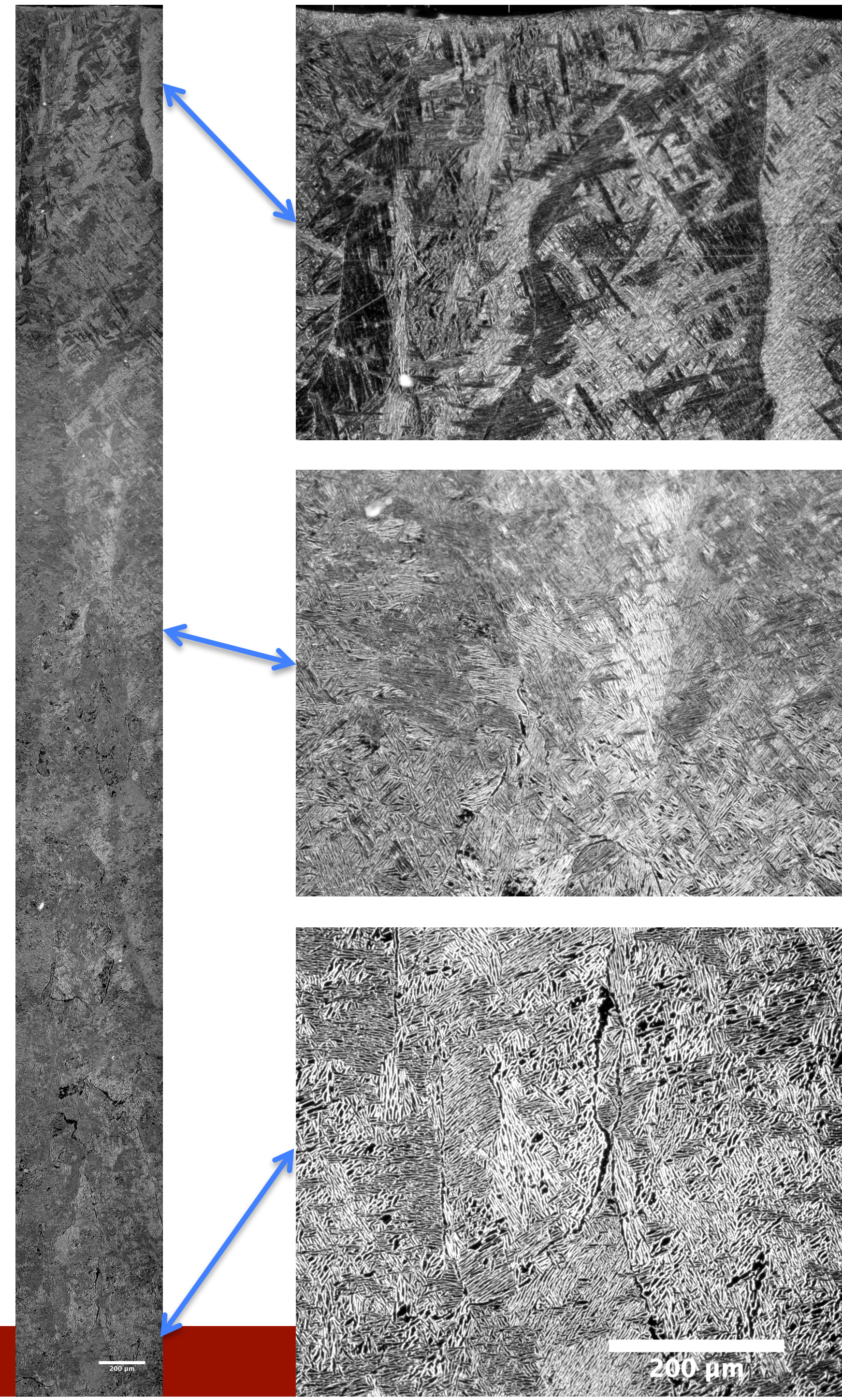
Microstructure in Ti-6Al-4V



- Illustrate lamellar microstructures observed.
- **Five Ti-6Al-4V samples** (3 cm diameter, 1.5 cm height cylinders) were fabricated on Arcam EMB System at NC State
- **Beam velocity was varied to create melt pool areas corresponding to 1X, 2X, 4X, 1/2X, 1/4X of the "nominal" melt pool area**
- 1 x 1 x 15 mm imaging samples were cut from the bulk, and contour-bulk interface. CT-scans were taken from top ~ 8 mm of each sample
- CT on 2-BM beamline with 100 keV pink beam (parallel box beam), absorption mode; help from Xianghui Xiao (APS) acknowledged.
- Objective was to **characterize different types of porosity observed in AM metals**, and begin to **supplement process maps with intrinsic defect properties**

Ti-6Al-4V microstructure

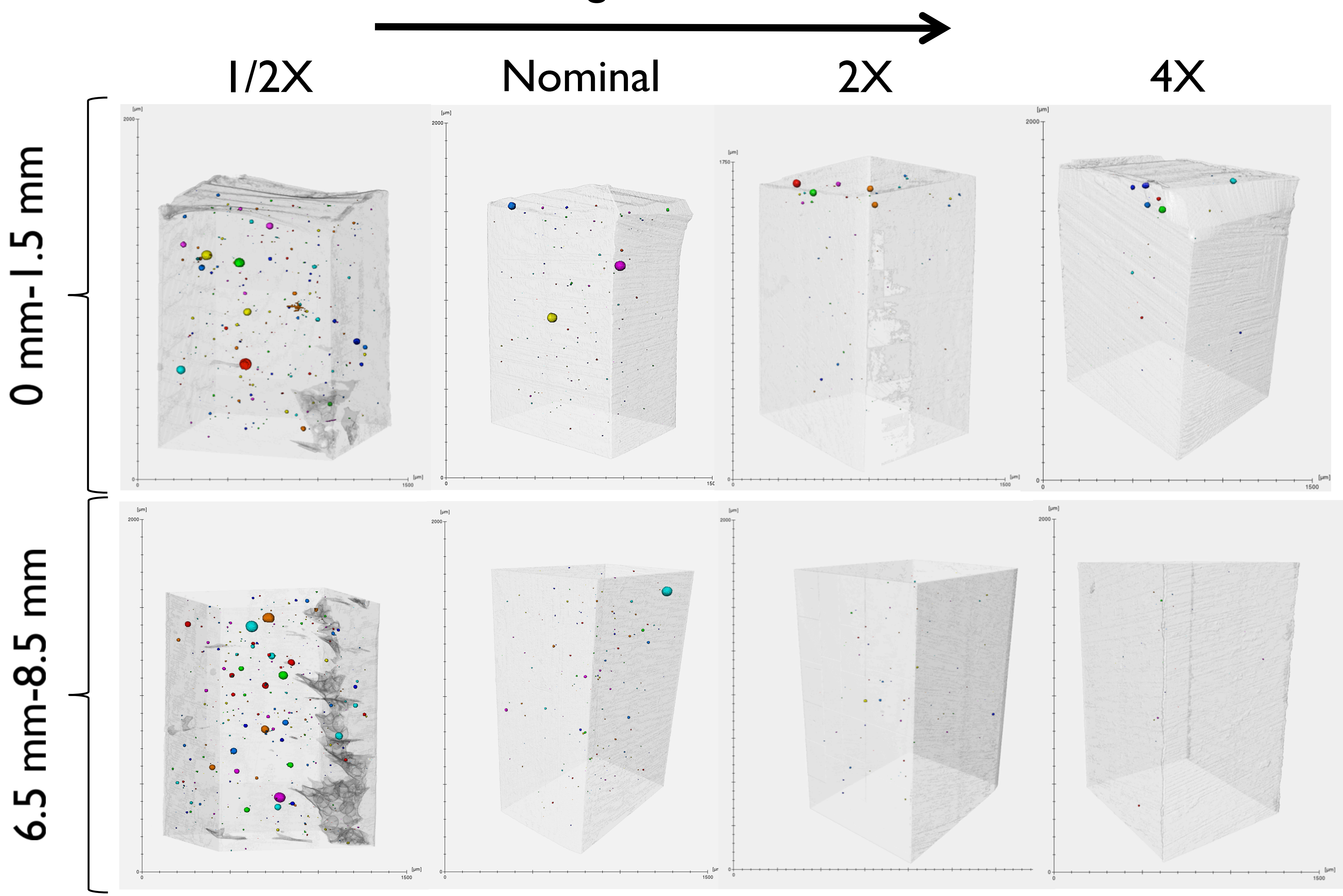
- Standard microstructures are based on heat treatment in the two-phase range; this gives a mix of primary α and Widmanstätten $\alpha+\beta$.
- Despite the high cooling rate ($\sim 10^6$ /s), the β structure is columnar and the transformation gives either martensite or acicular α.
- Variations in thermal history can give rise to significant transitions in microstructure. This example documents the variation in a Ti-6Al-4V build, which shows a martensitic microstructure near the top and a basketweave microstructure (or tempered martensite) towards the base.



Ross Cunningham, Sneha Narra

Cunningham *et al*. (2016) *JOM*, **68** 1-7

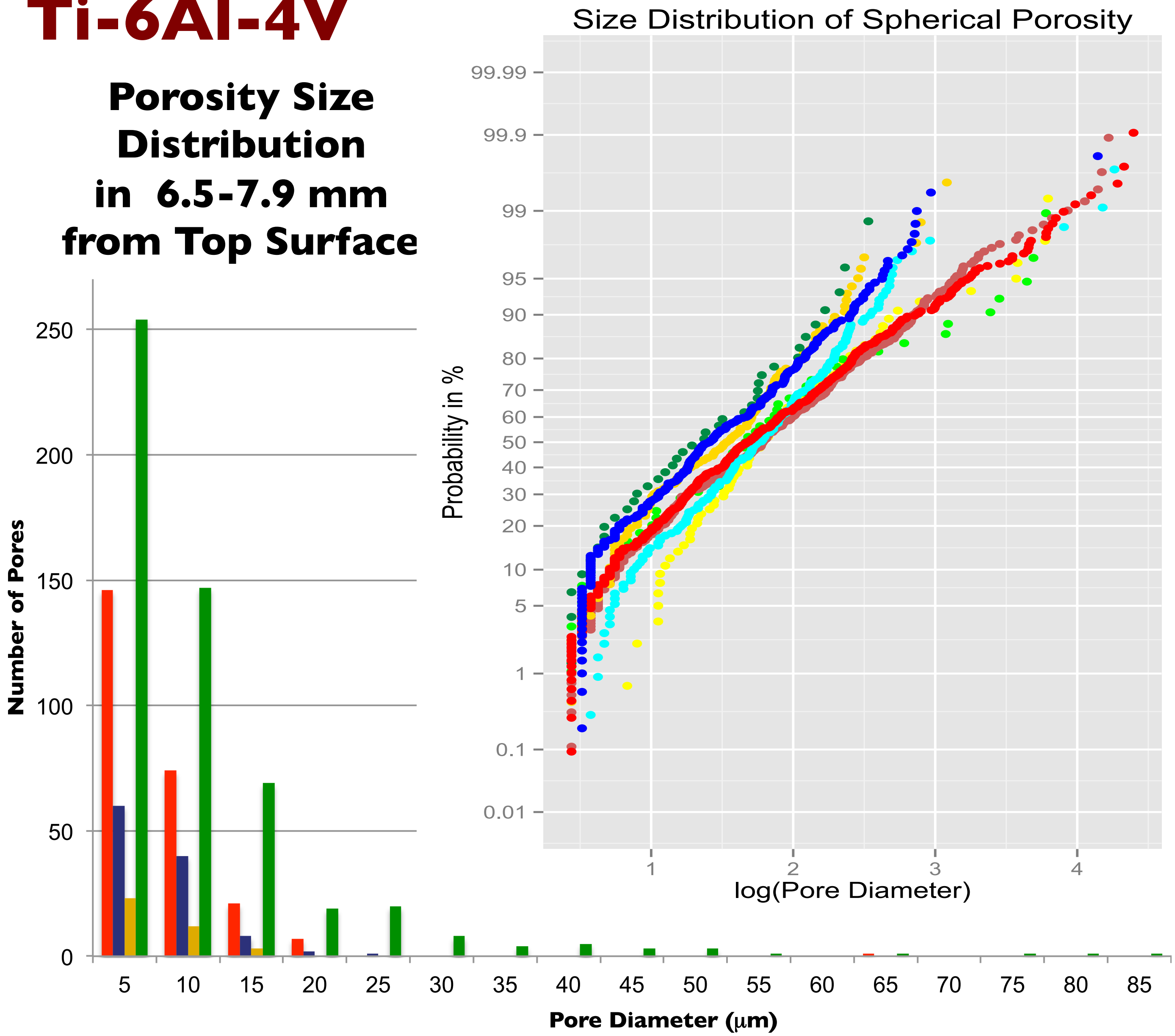
Ti-6Al-4V



Cunningham *et al*. (2016) *JOM*, **68** 1-7

Ti-6Al-4V

Porosity Size Distribution in 6.5-7.9 mm from Top Surface

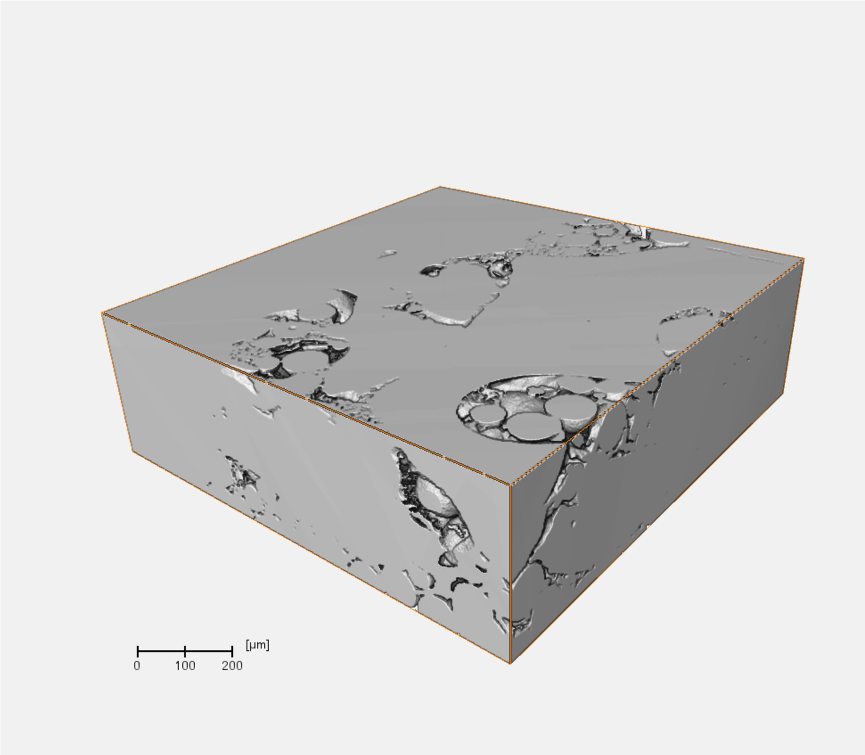


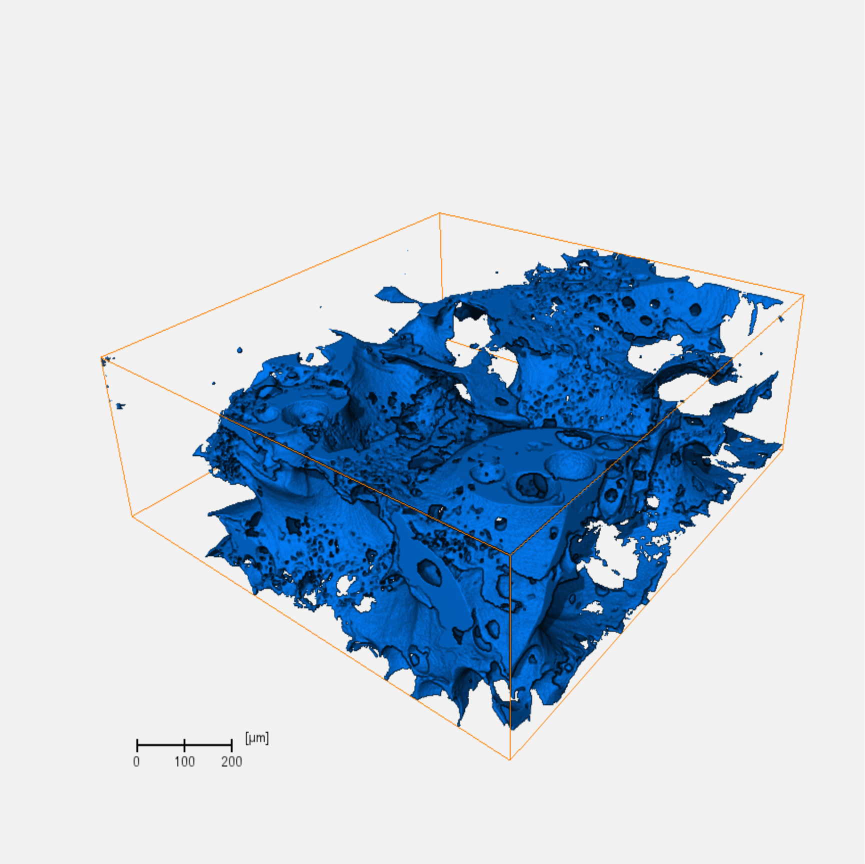
Tutorial: probability plots show straight line for normal distr. Plots made with R package, open source, **www.r-project.org**

Quantifying the pore size distribution enables understanding of how it varies with conditions, and eventually control. Crucial for fatigue resistance

Donegan *et al*. (2013) *Acta mater*. **61** 5595; application of peaks-over-threshold for quantifying tails

Ti-6-4 Sample 5B, contour-bulk interface: Intentionally porous

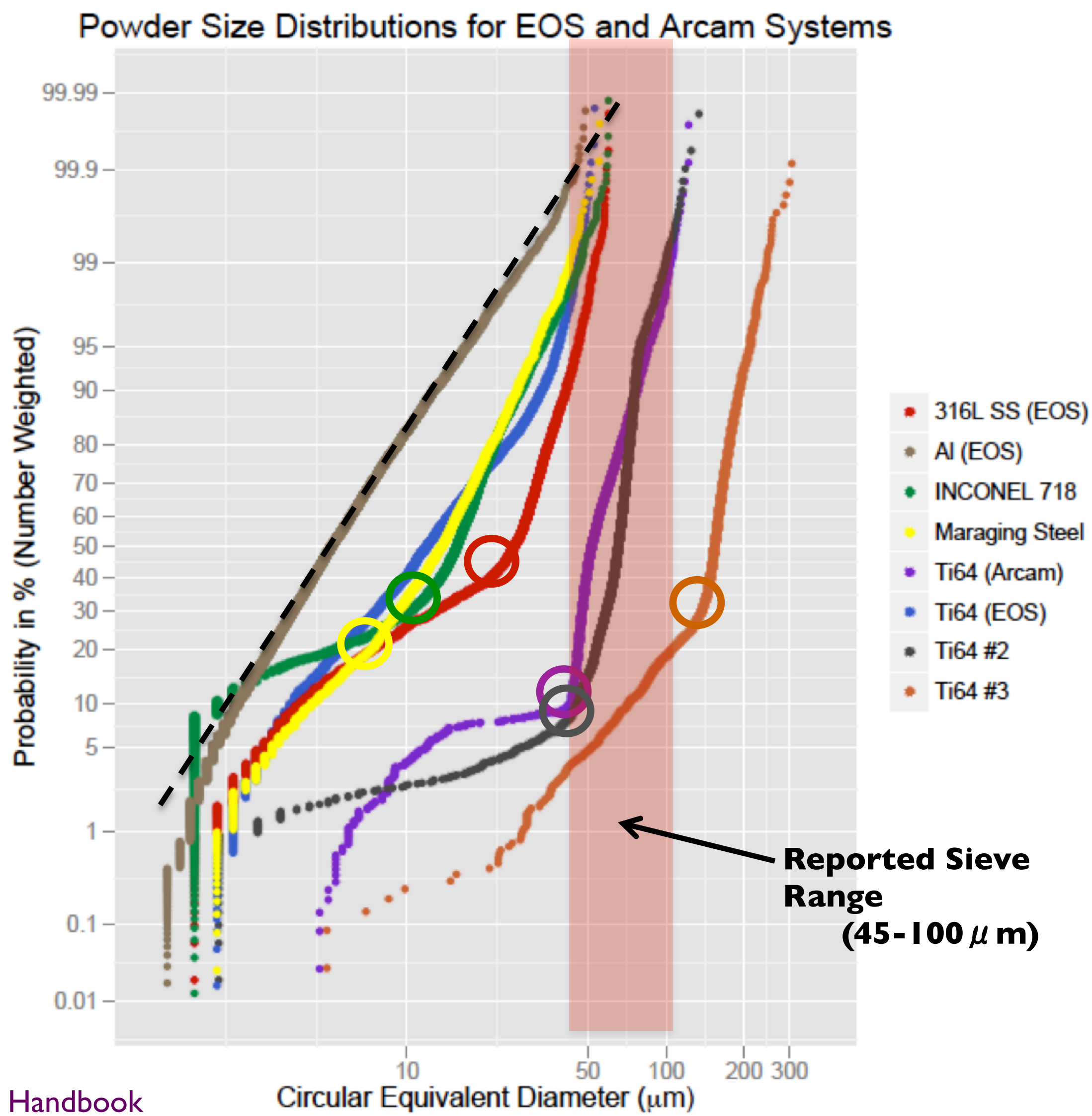




Powder Characteristics vs. Flow Behavior

- Gas-atomized powder generally display a log-normal size distribution[1]
- Log-normal distribution will appear linear on adjusted cumulative probability plot

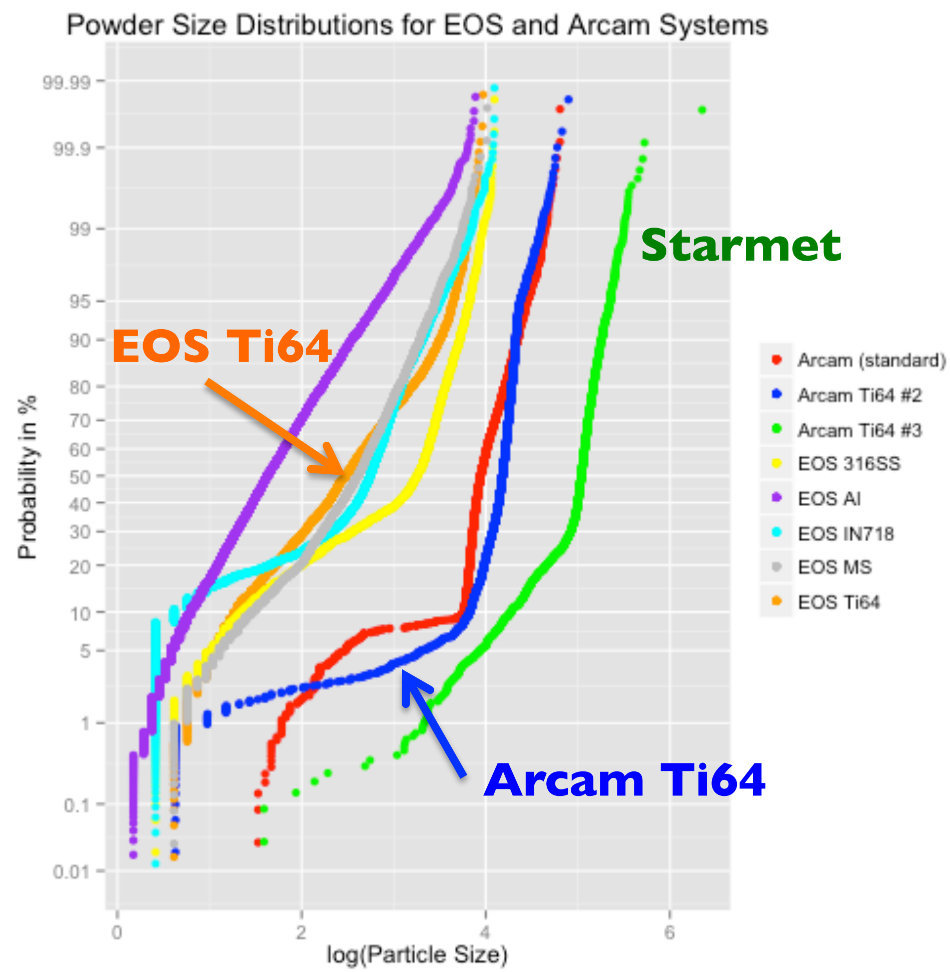
- **Deviation from log-normal suggests sudden change in distribution (sieving)**
- **AlSi10Mg powder does not deviate from log normal**
- **EOS Ti-6Al-4V does not follow this trend**



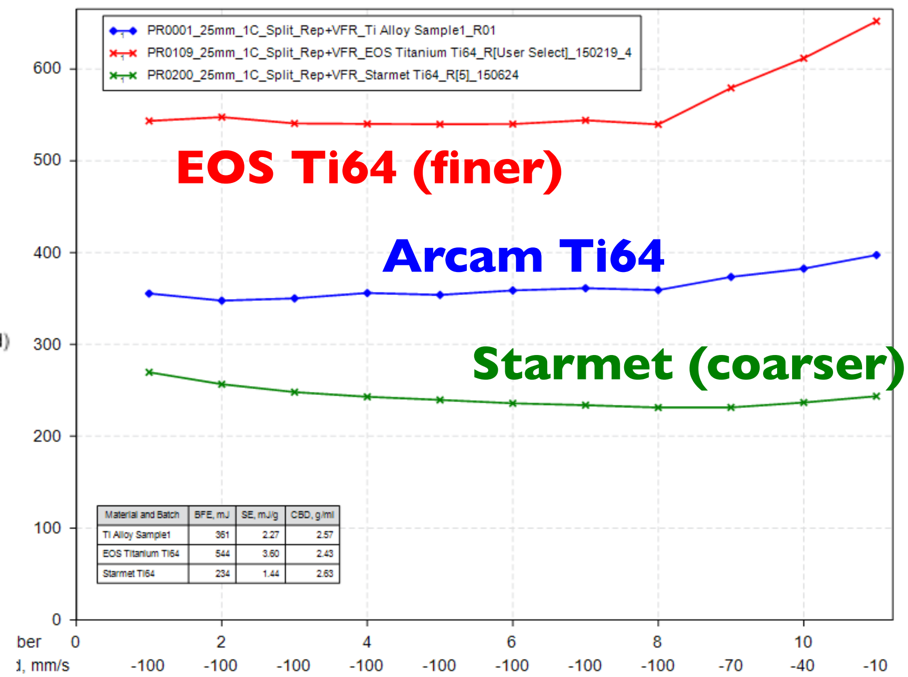
[1] O.D. Neikov, Chapter 5 - Atomization and Granulation, In Handbook of Non-Ferrous Metal Powders, edited by Neikov et al., Elsevier, Oxford, 2009, Pages 102-142

Powder Distribution vs. Flow

Distributions



Flow



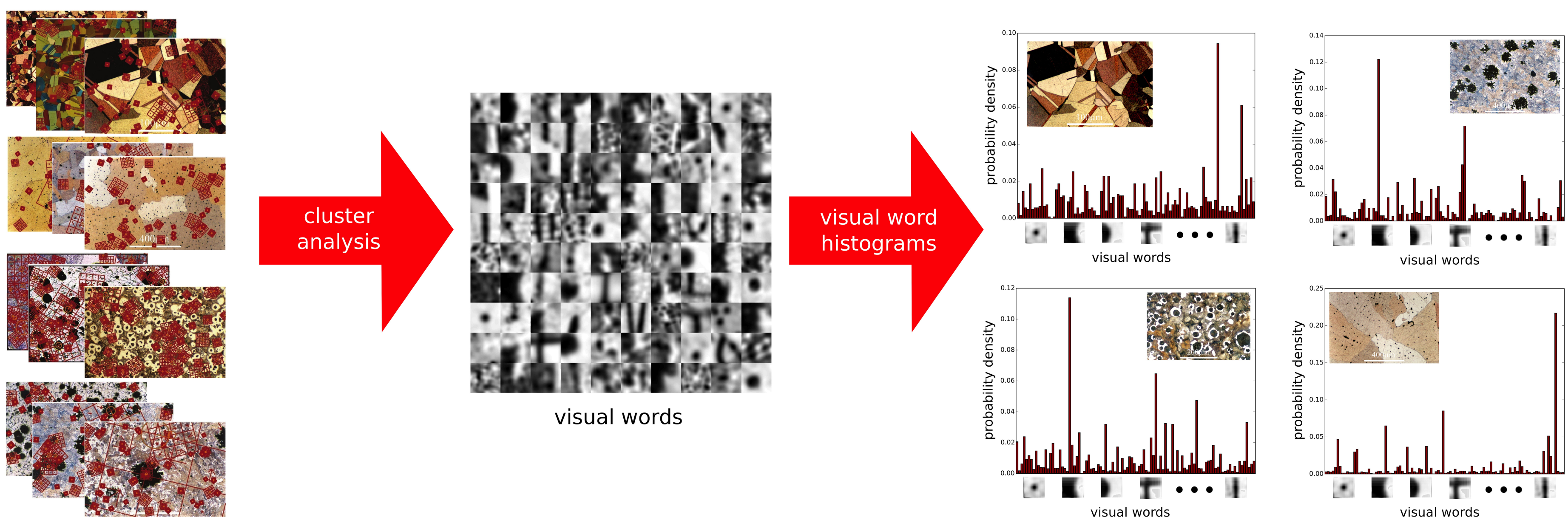
Material and Batch	BFE, mJ	SE, mJ/g	CBD, g/ml
Ti Alloy Sample1	361	2.27	2.57
EOS Titanium Ti64	544	3.60	2.43
Starmet Ti64	234	1.44	2.63

Flow measurements on a Freeman Rheometer
Propeller driven into a beaker full of powder
Confined flow effectively measured
Contrast with free flow with a Hall Cup

An automatic and objective system for finding relationships between microstructures

- Using machine vision and machine learning techniques, we automatically harvest, store, and compare microstructural image data.

Bag of visual features microstructure representation



1: Extract keypoint descriptors

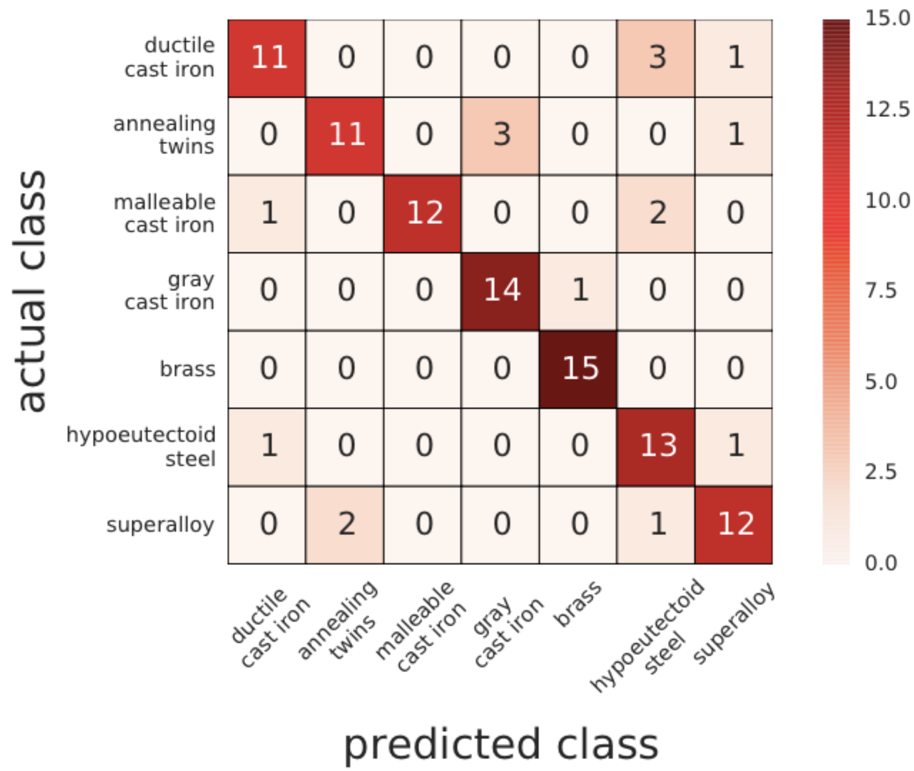
2: Obtain visual dictionary

3: Create microstructural signatures

DeCost and Holm, *Computational Materials Science* **110** (2015) 126–133

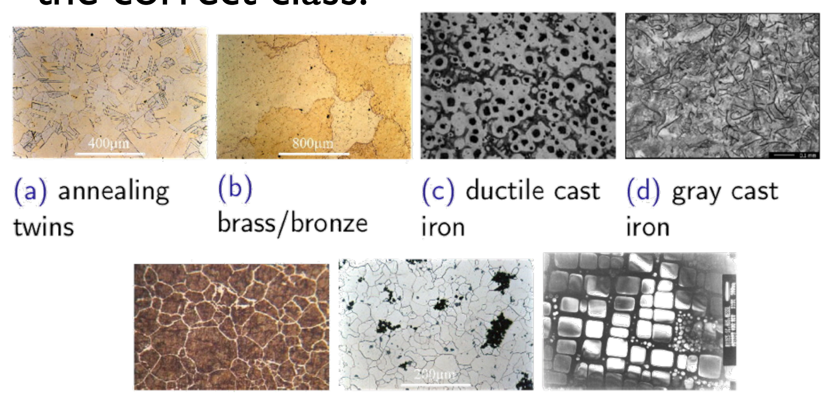
Outcome: A microstructure classifier

- Given "training" micrographs divided into classes, we can classify new micrographs automatically and with high accuracy.



- 5-fold cross-validation on 15 microstructures per class (105 total)

∴ A score of '15' indicates perfect classification of validation images into the correct class:



(a) annealing twins (b) brass/bronze (c) ductile cast iron (d) gray cast iron (e) hypoeutectoid steel (f) malleable cast iron (g) superalloy

- **Applications:** Process analysis, control and qualification; archiving; statistical analysis; finding correlations between structure and processing.

DeCost and Holm, *Computational Materials Science* **110** (2015) 126–133

Summary

- Understanding microstructure is important during every step in the additive manufacturing process. If you do not understand the details of the process, it is entirely possible to have a problem because of defects such as voids.
- Location of the voids relative to the surface is very important.
- This challenge can be addressing by combining
  - Measurement of powders and defects, especially pores: analysis with extreme value statistics, link to powder flow
  - Advanced characterization 3D microscopy with high energy synchrotron x-rays e.g. tomography of voids
  - Demonstrated ability to predict incomplete melting (and keyholing)
  - Development of micro-mechanical models for materials

Effects of HIP Processing on EB-DED Additively Manufactured Ti-64 Materials

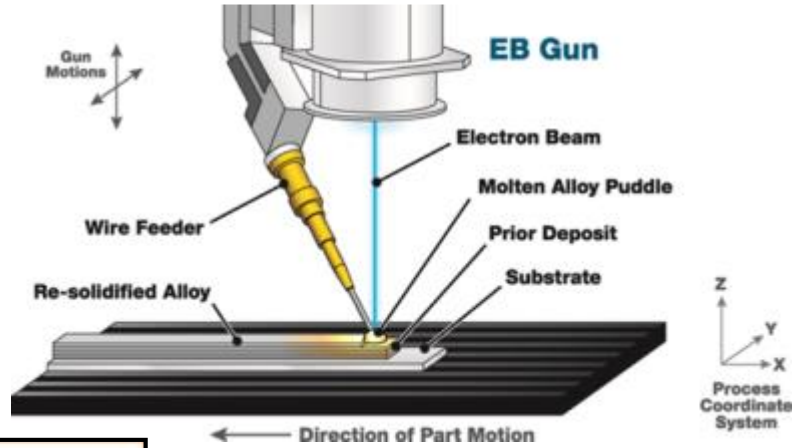
LOCKHEED MARTIN

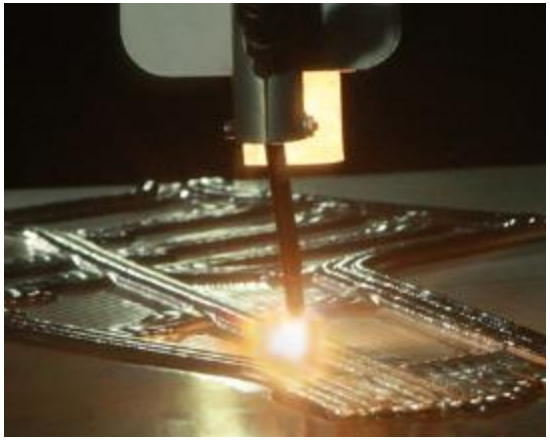
Hank Phelps
Jeff Langevin
Adam Sutton

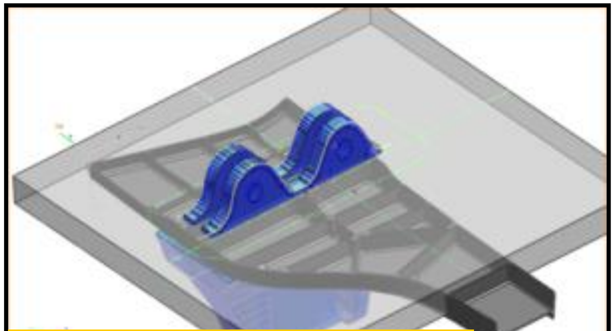
Outline

- Background on EB-DED
  - Process
  - Flaw Types
  - Potential Applications
- Hot Isostatic Press Process
  - Why Considered
  - Benefits
- Impacts on Mechanical Properties
- Summary
- Conclusions

EB-DED Process





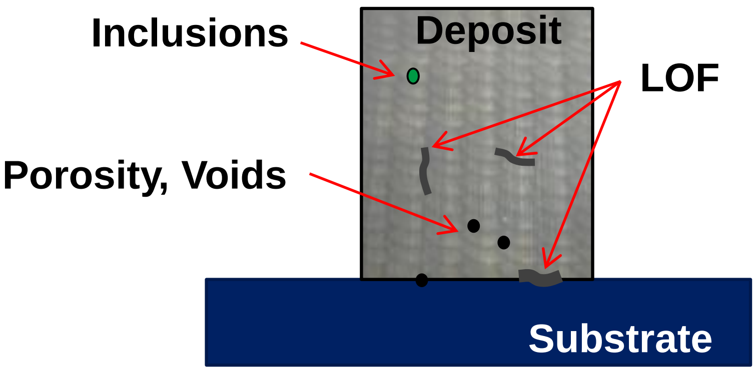


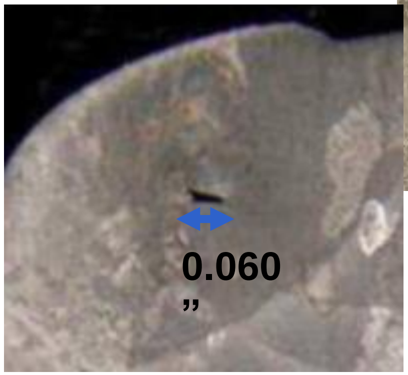
NC Path Planning and Deposition

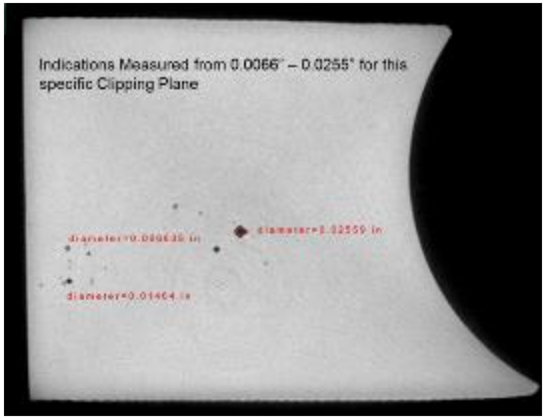
Near-shape Article

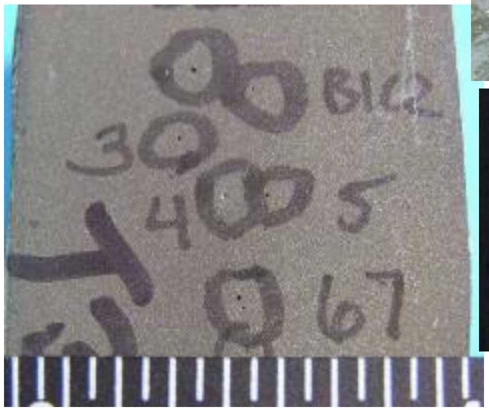
Machine Part

Examples of Discontinuities

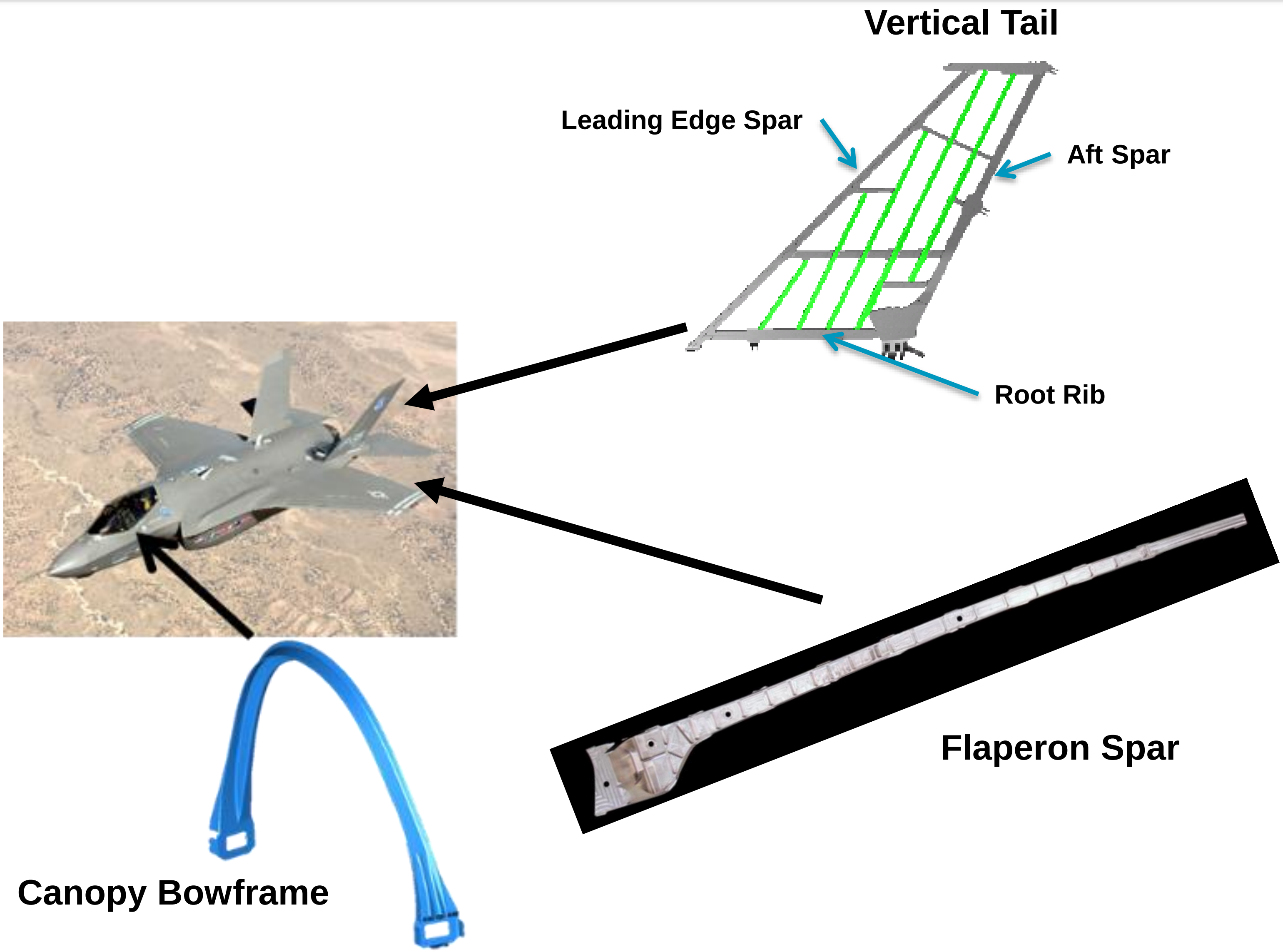




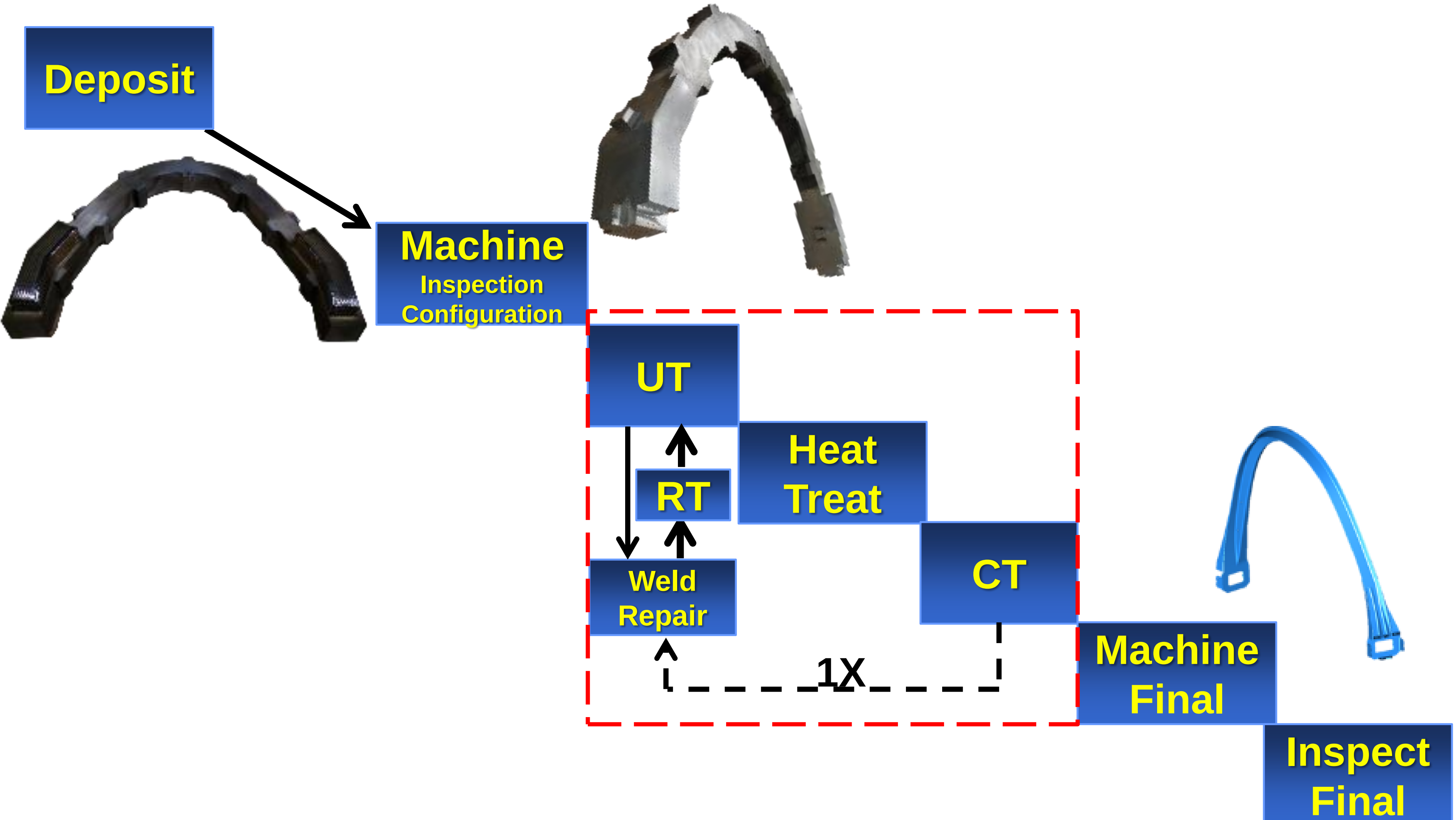




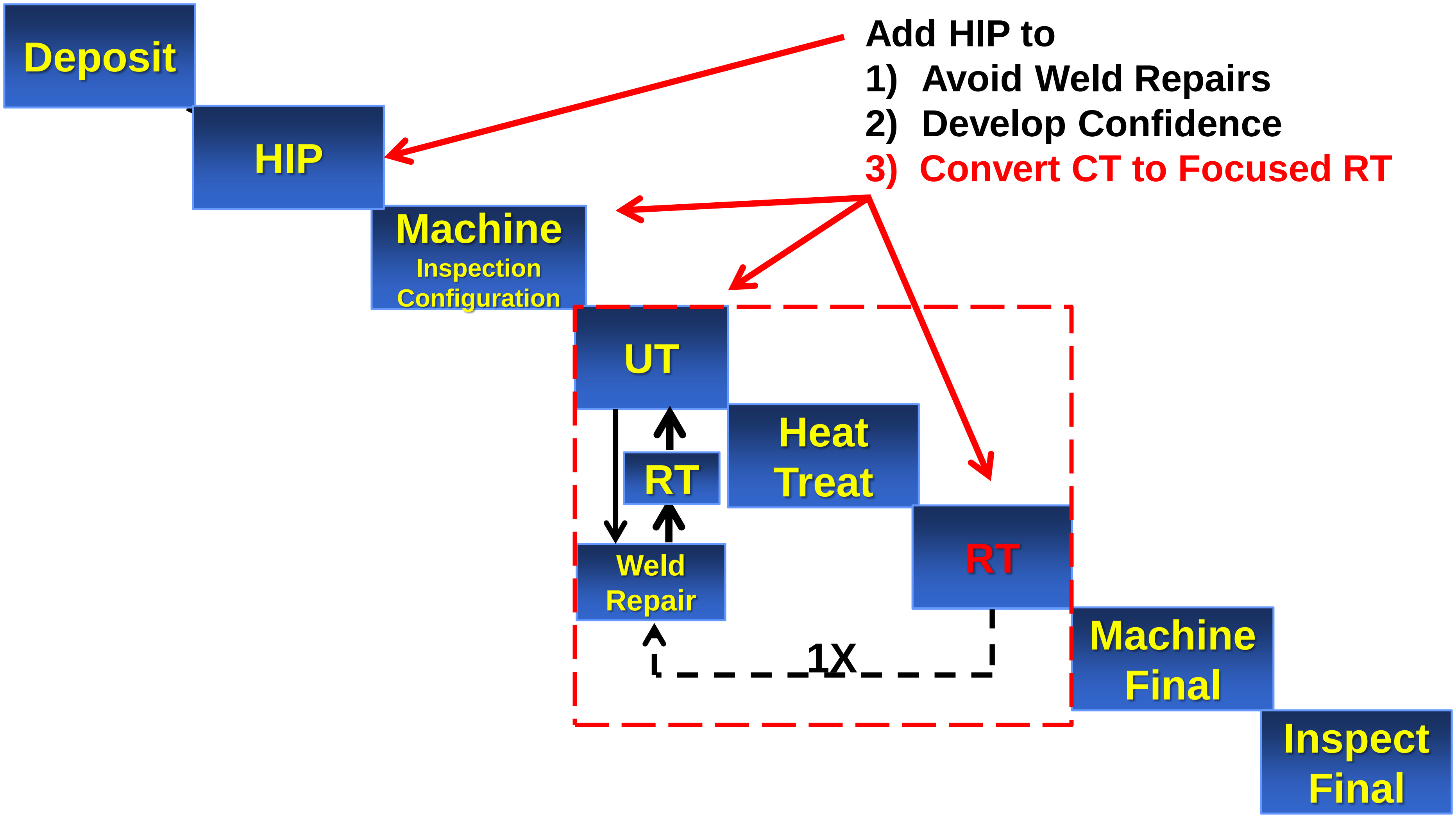
Potential Applications



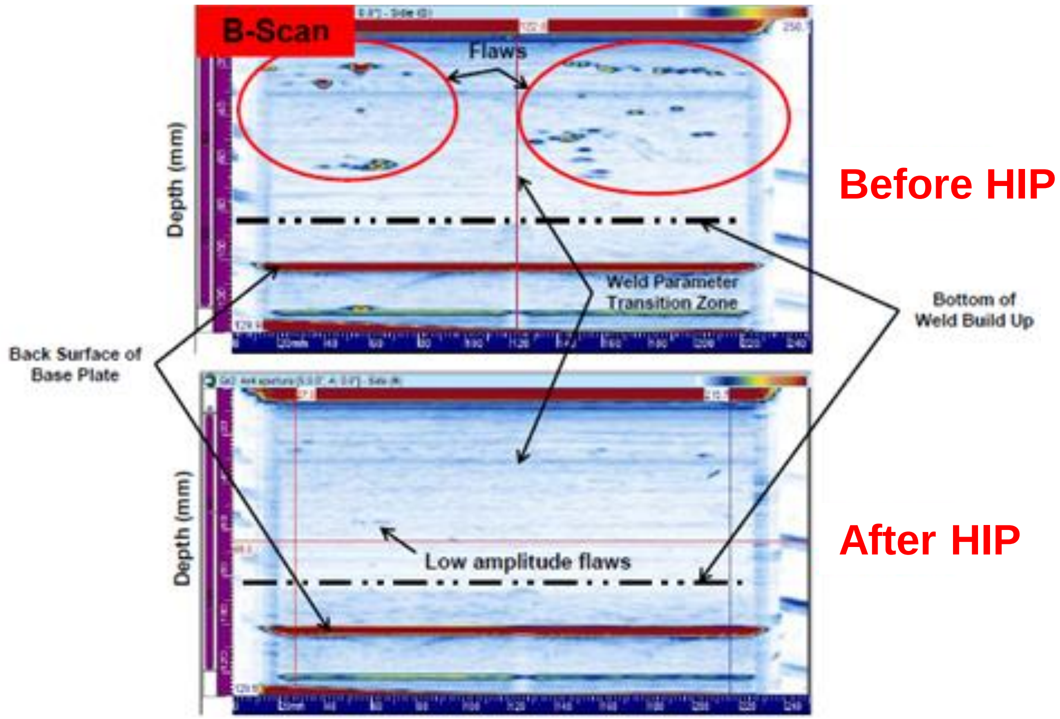
Planned EB-DED Process Flow



Alternative Process Flow



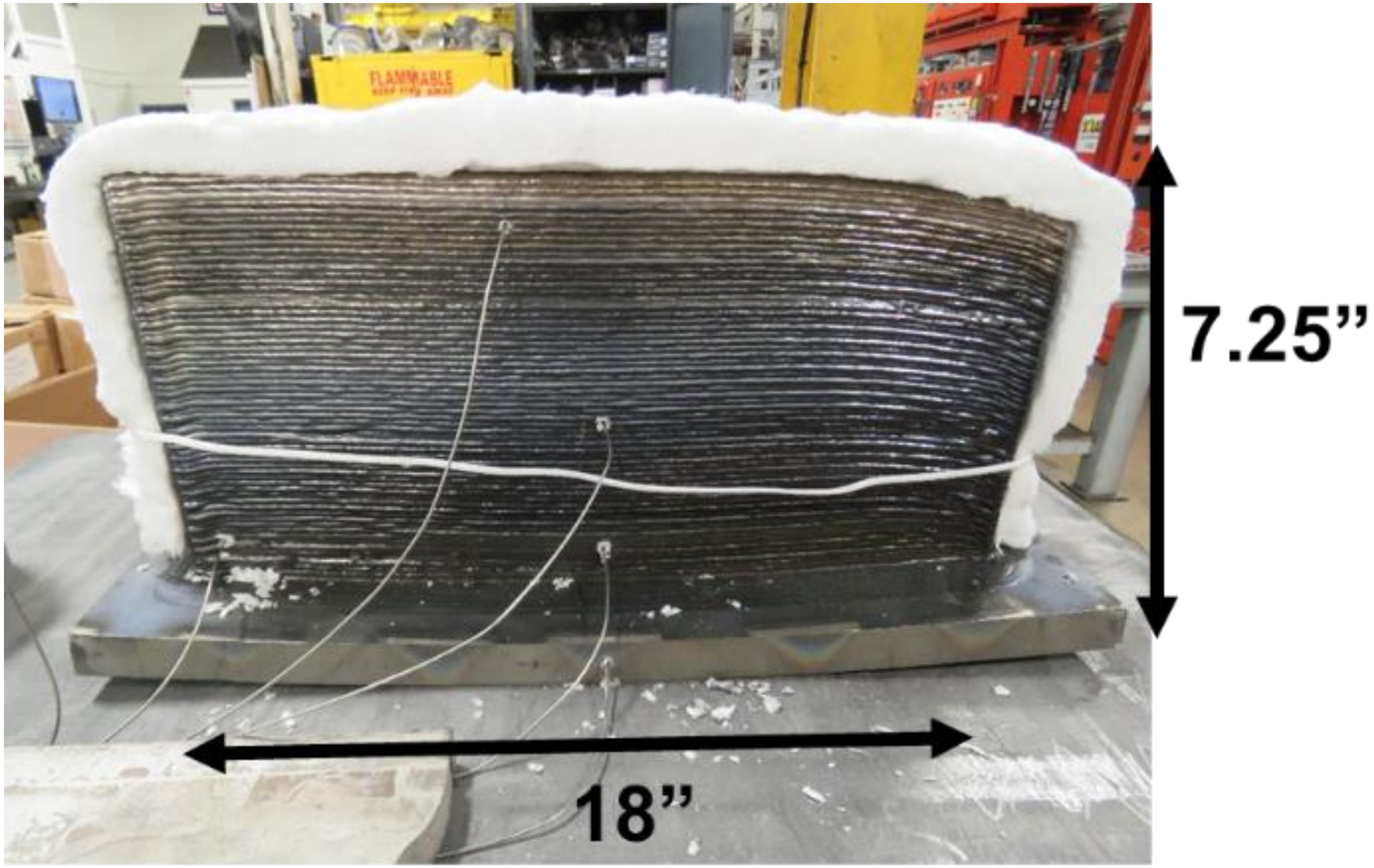
HIP Mitigation of Internal Flaws



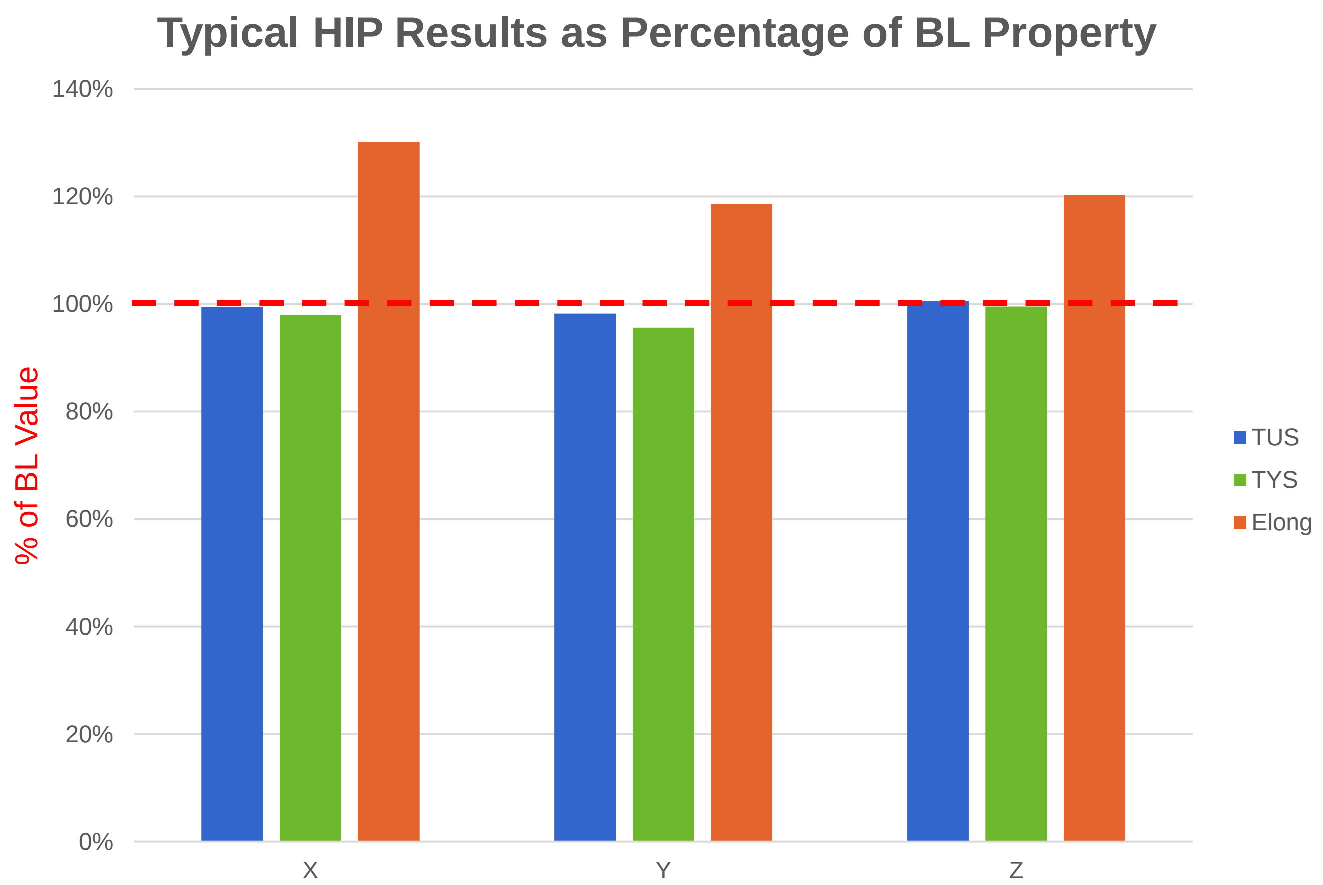
Refining Microstructure of Additive Manufacturing Materials to Improve Non-Destructive Inspections (NDI)(4034.001)

EB-DED Preforms

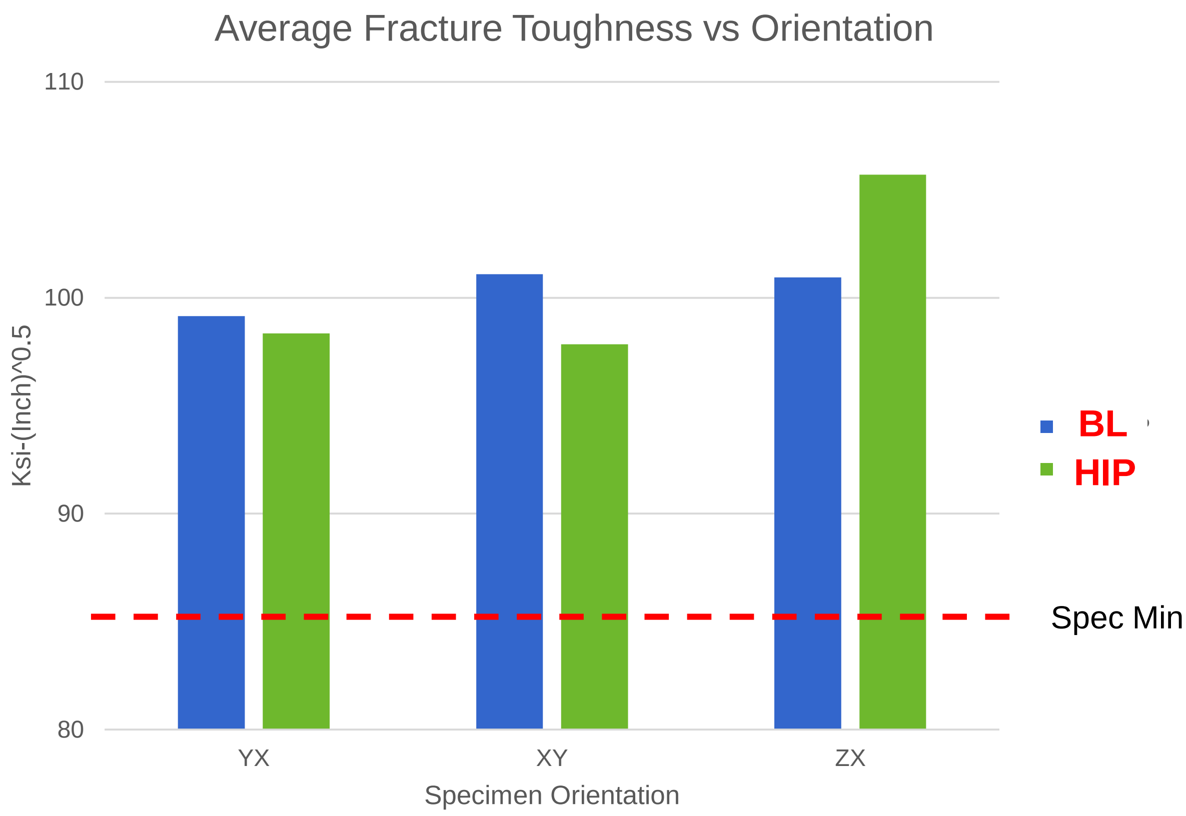
Condition	Process
Baseline	EB-DED + BA
HIP	EB-DED + HIP + BA



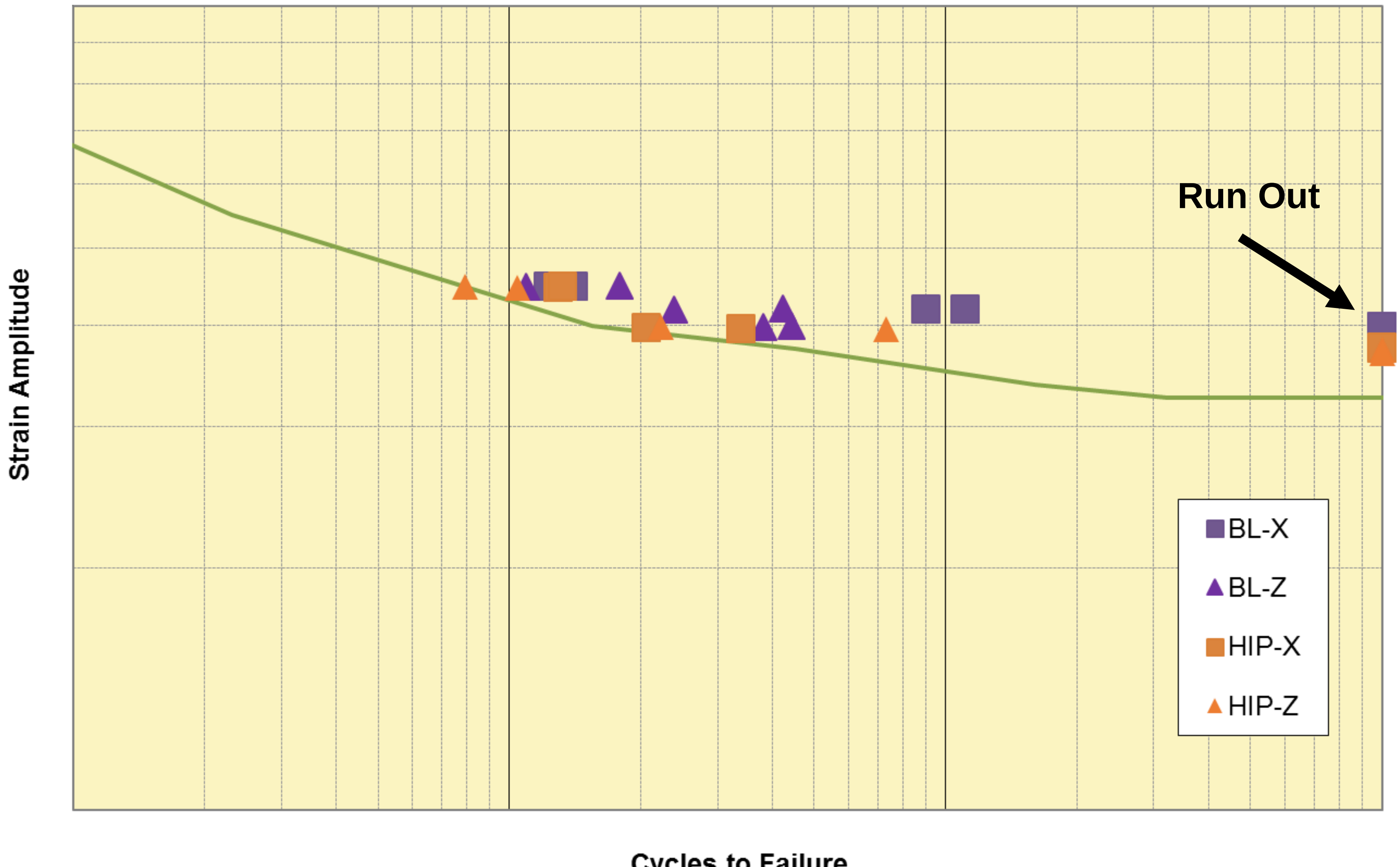
Tensile Results



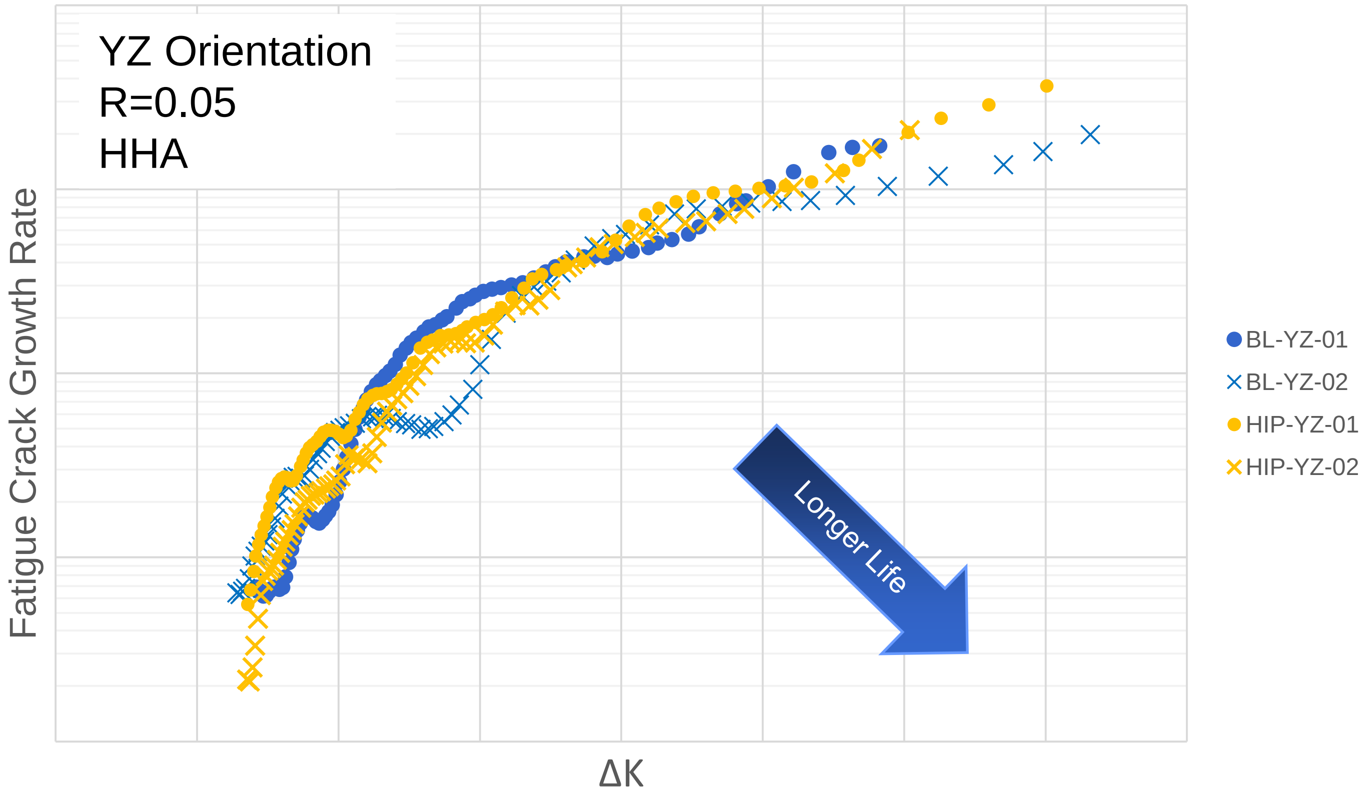
Fracture Toughness



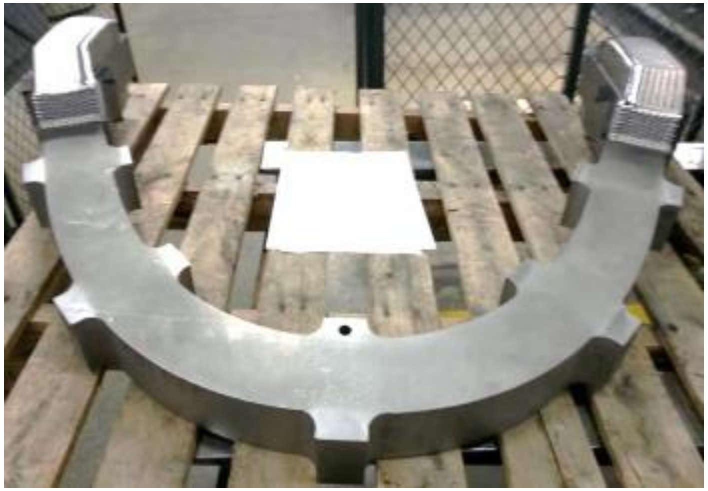
Strain Life Results (R=-1.0)

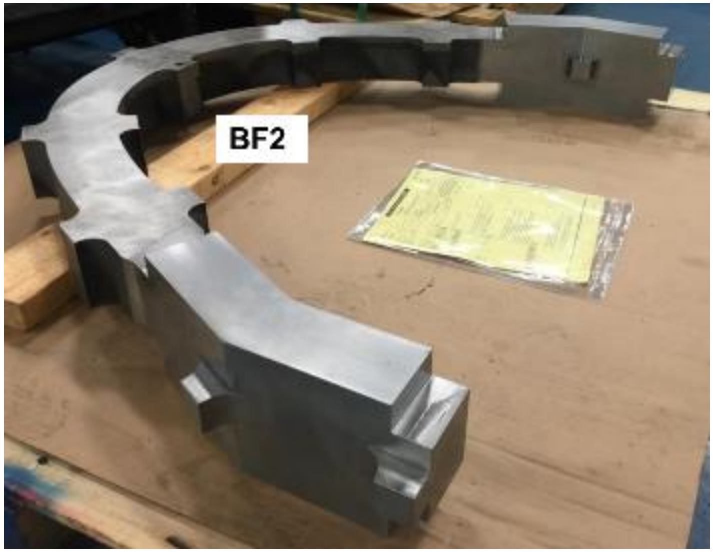


Fatigue Crack Growth Results



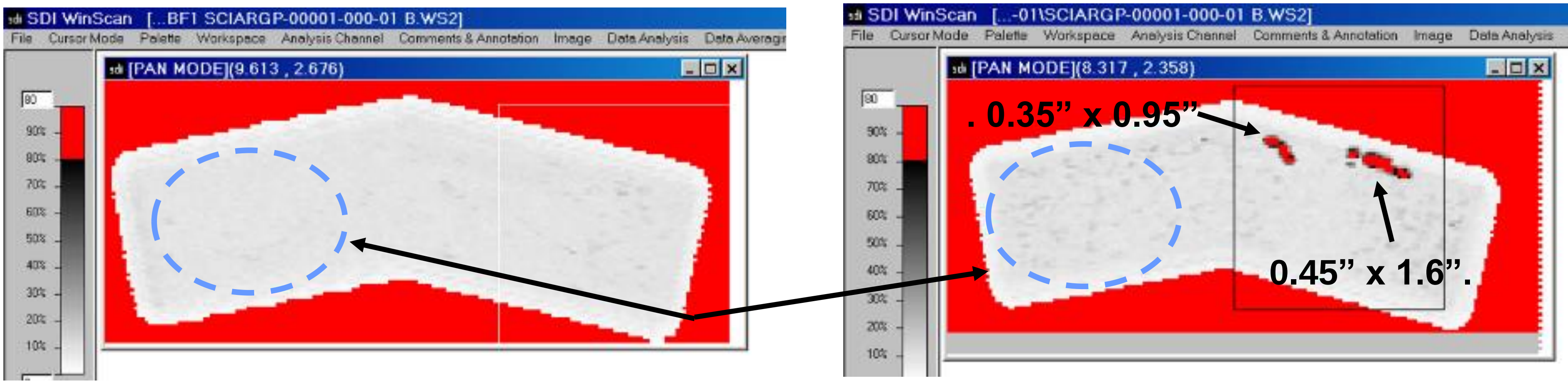
UT Inspection Results





HIP

BL



Transducer: 0.75" Diameter, 5 MHz, 6" Focus Immersion

Note – Lg LOF Result of Process Breakdown

Summary

Property	Effect of HIP	Note
Tensile UTS Yield Elongation	• X/Y < 2% Z Equivalent • X/Y < 5% Z < 1% • Increased 11 to 22%	Reduced Scatter
Fracture Toughness	• No Impact	
Strain Life	• Supports Existing Design Curve	
Fatigue Crack Growth	• Supports Existing Design Curve	
Ultrasonic Inspection	• Improved Inspectability • No Rejectable Indications	

Conclusions

- EB-DED Process Capable of Producing Large Aerospace Components
  - High Build Rates
  - Internal Material Quality Still an Issue
- Hot Isostatic Pressing
  - Capable of Closing & Healing Internal Flaws
  - Minimal In-Plane Strength Reduction Offset by Lower Scatter
  - Improves Out of Plan (Z Direction) Strength
  - No Other Significant Property Impacts
  - Recommended for Inclusion for Critical Components

Acknowledgements

- Mike Mesick – LM NDI Level III
- Scott Stecker – Sciaky
- Andy Mugnaini – Sciaky

National Aeronautics and Space Administration
Marshall Space Flight Center

Overview of Fatigue and Damage Tolerance Performance of Powder Bed Fusion Alloy N07718

William Campbell
NASA MSFC
Huntsville AL

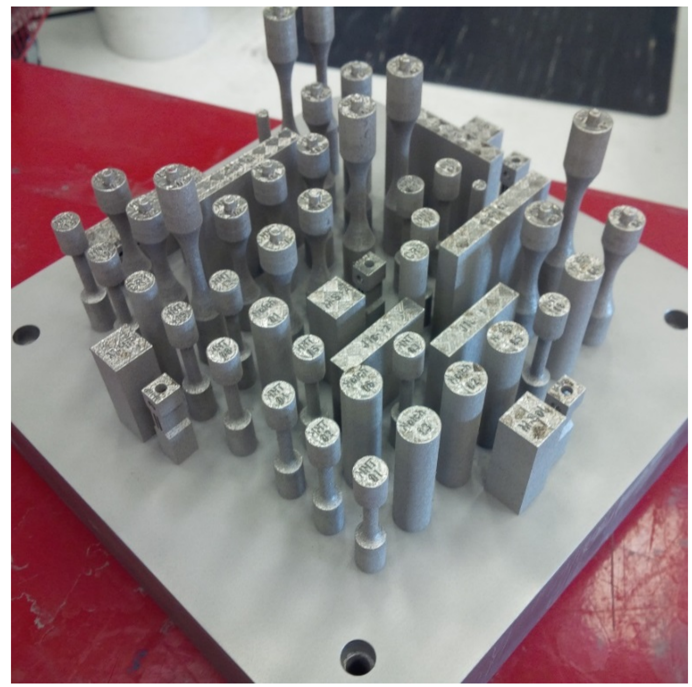
William Tilson
Jacobs ESSSA Group
Huntsville AL

ASTM/NIST Workshop on Mechanical Behavior in Additive Manufactured parts

May 4, 2016

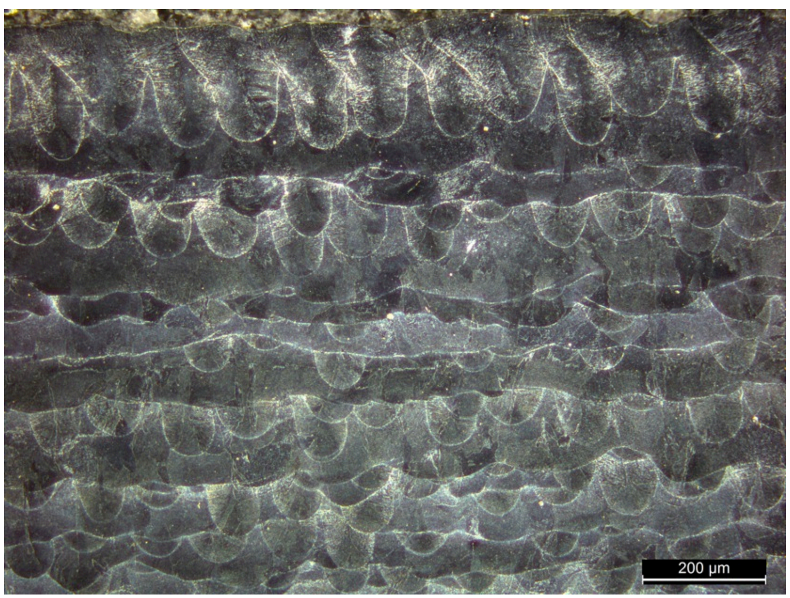
MSFC PBF Capability

- Selective Laser Melting (SLM)
  - Heat source is a 200 W laser
- Concept Laser M1 Cusing SLM machine
  - 250 x 250 x 250 mm^3 build volume

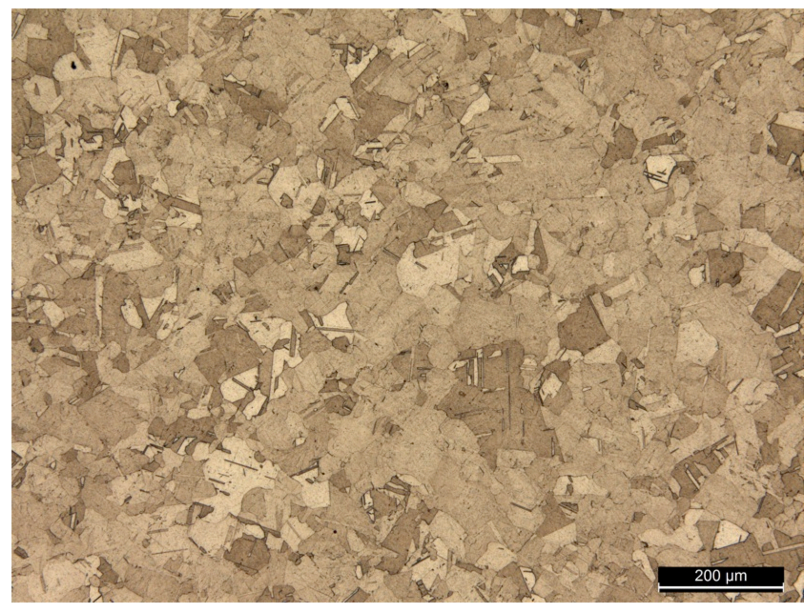


SLM 718 Post-Processing

- Stress Relief: 1065°C for 1.5 hours; furnace cool.
- HIP: 1165°C, 100 MPa, 3-4 hours
- Solution (AMS 5664): 1066°C for 1 hour; air cool.
- Age (AMS 5664): 760°C for 10 hours; furnace cool to 650°C; treat for total of 20 hours.



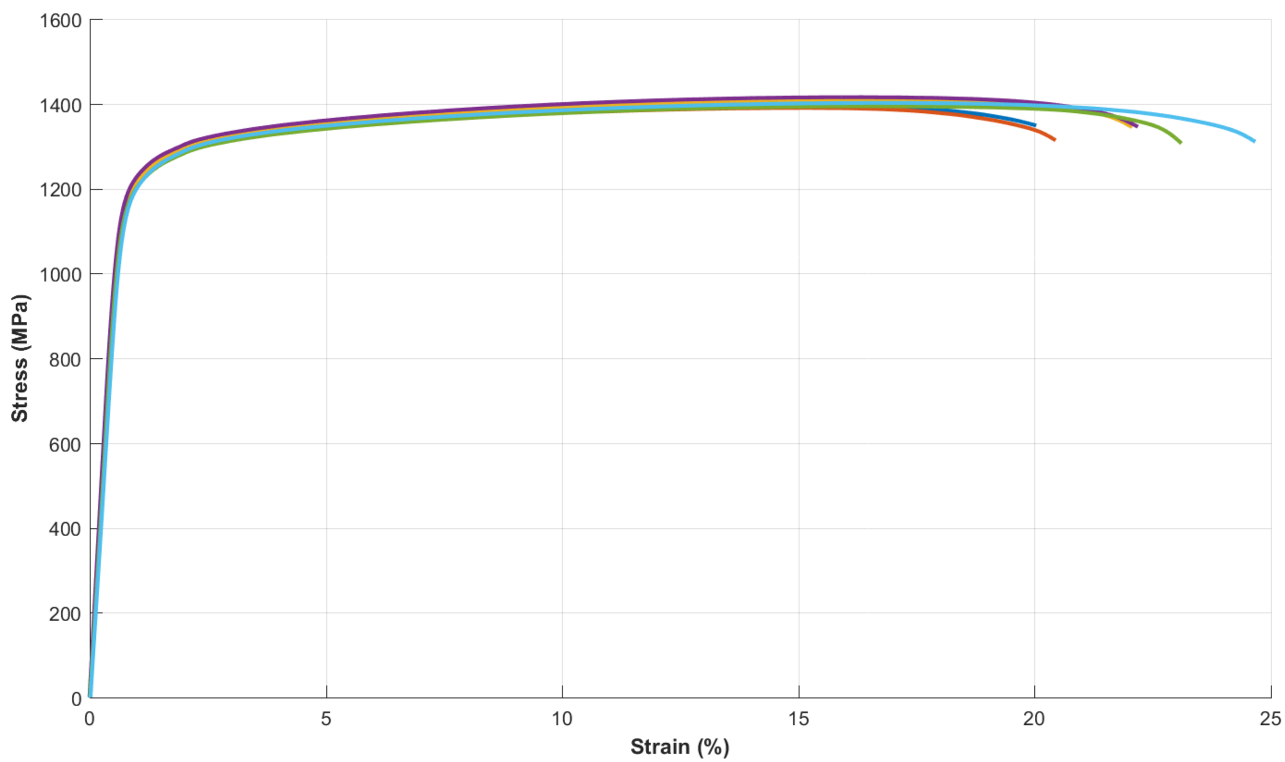
As-built microstructure



Heat treated microstructure

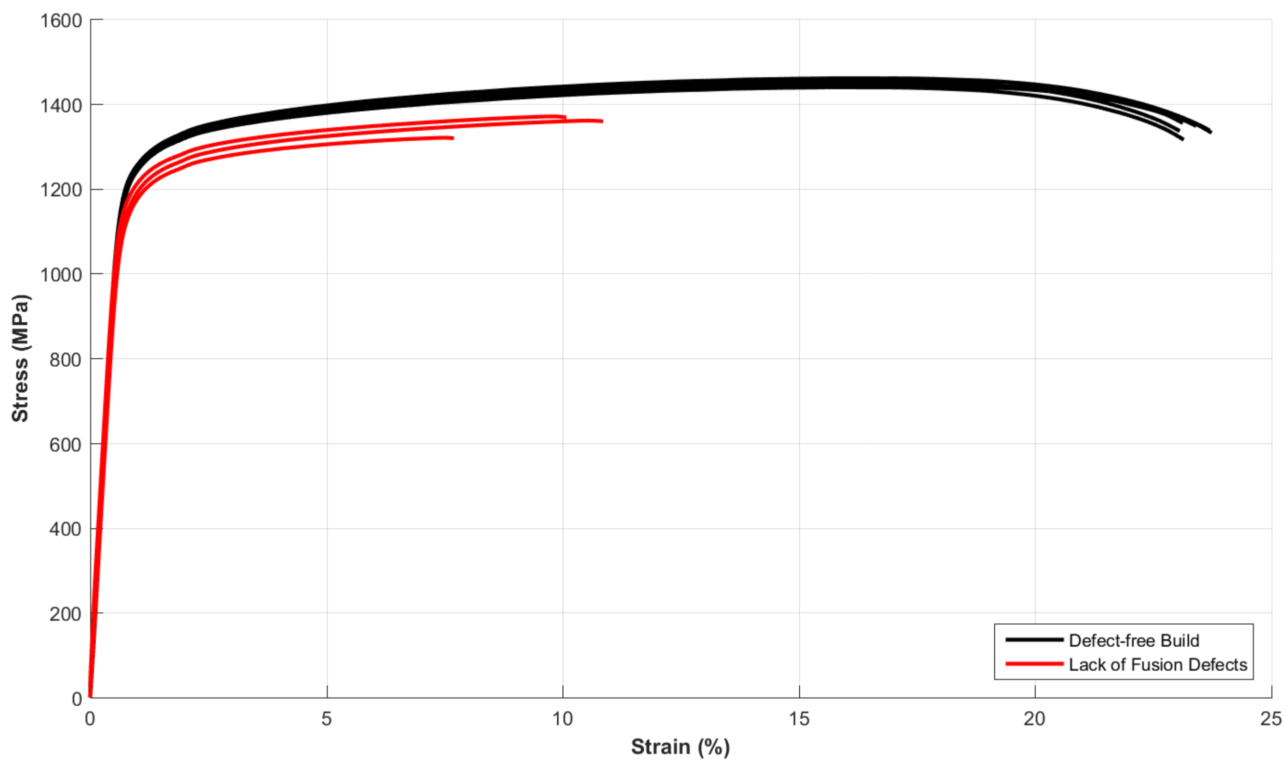
Typical Build Properties

- Typical tensile witness test curve for SLM 718.
  - Ultimate Tensile Strength: ~ 1380 MPa
  - Yield Strength: ~ 1170 MPa
  - Fracture Elongation: > 20%



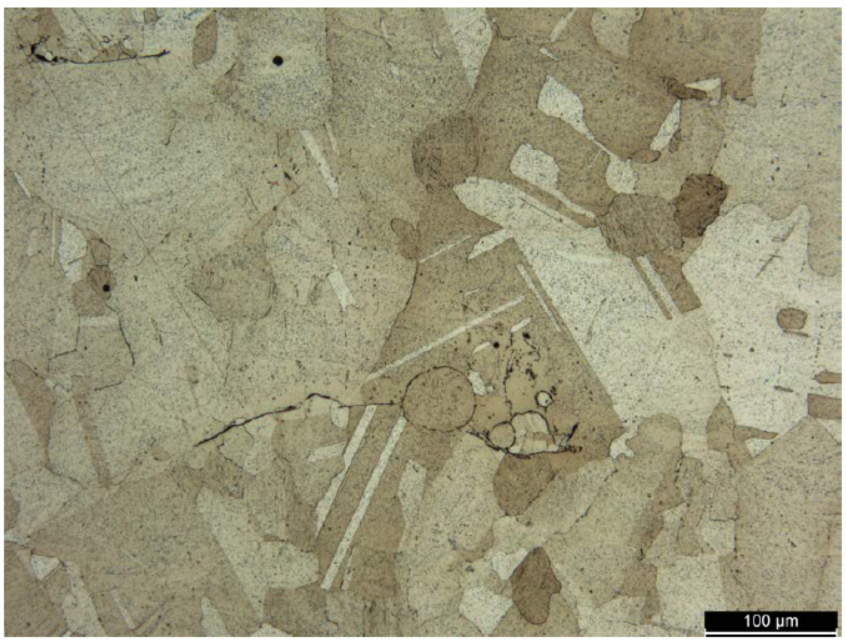
Defective Build

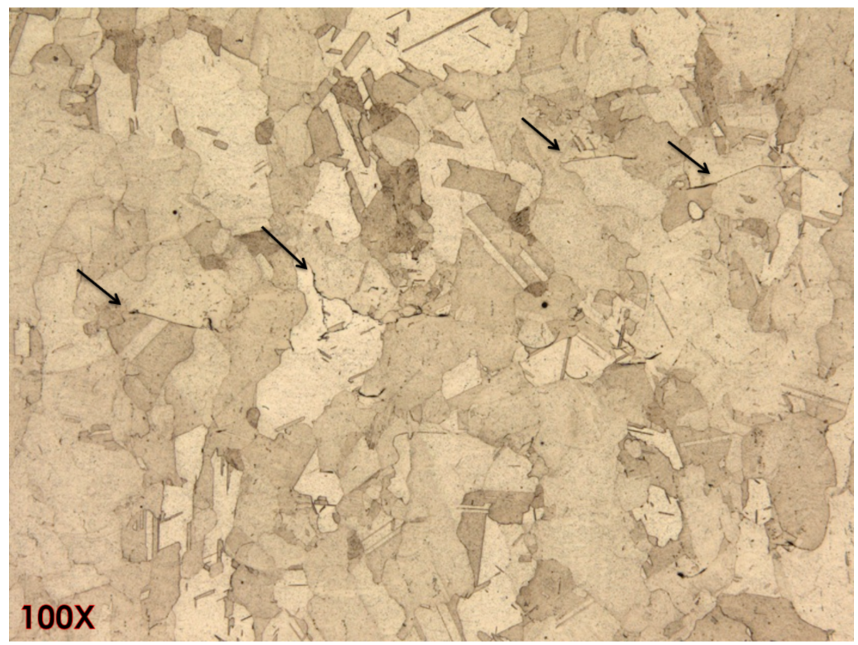
- A build of test specimens was produced; all indications were that the build was successful.
- Witness tensile testing revealed lower than expected material properties.



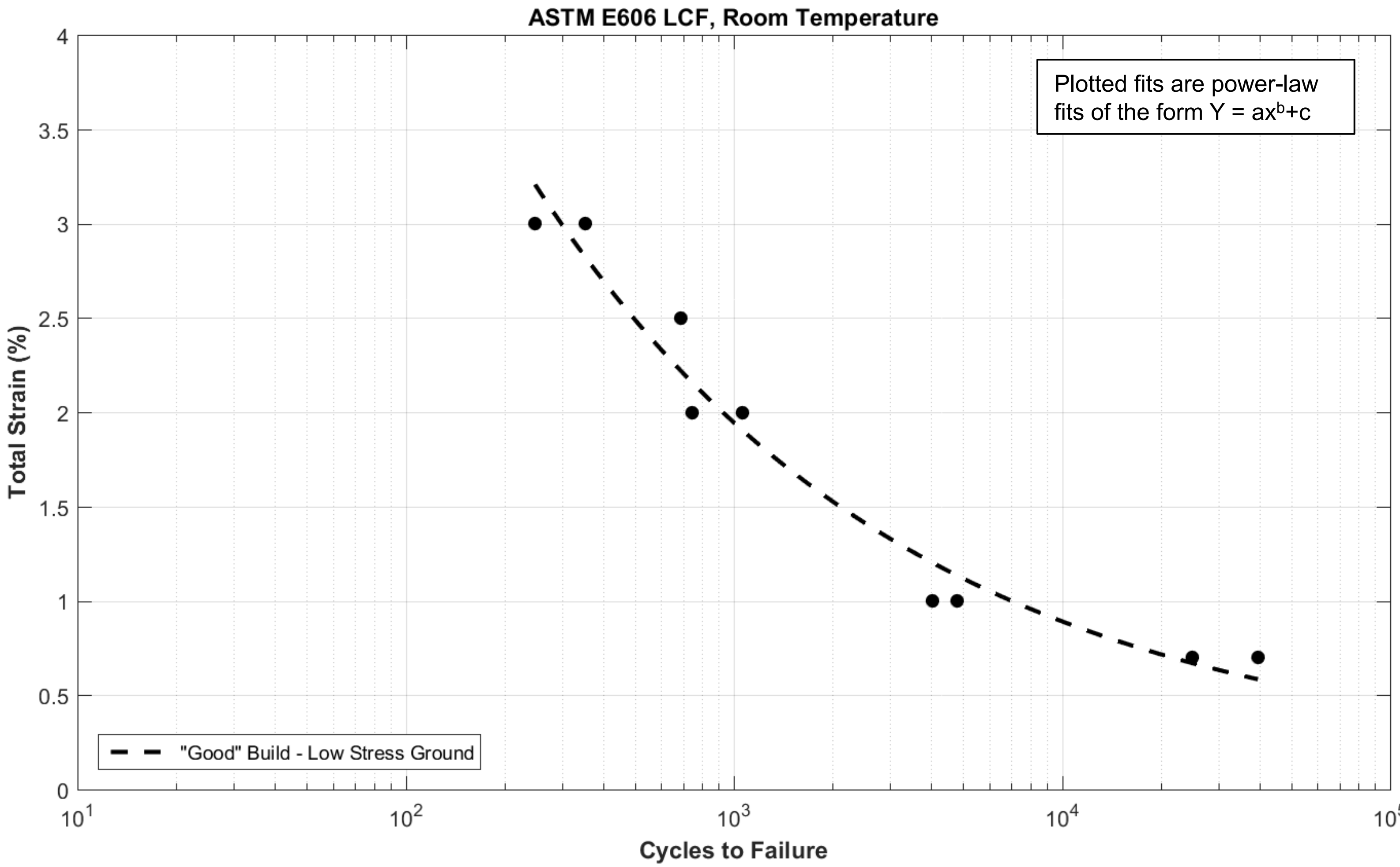
Defective Build

- Metallographic examination revealed lack of fusion defects in the material.
- Source was eventually determined to be a clogged ventilation duct that was allowing combustion by-products to settle on the powder bed.



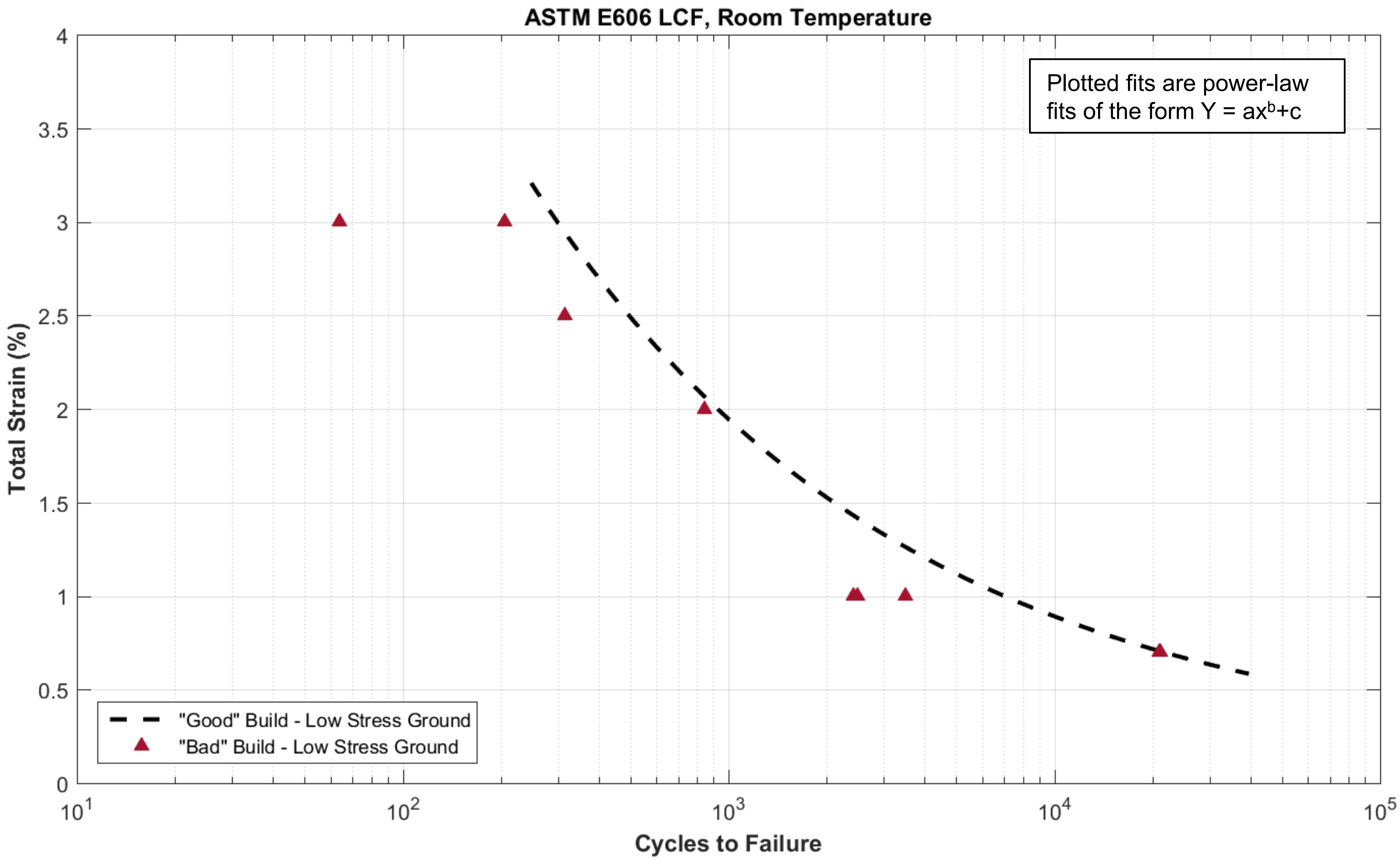


Low Cycle Fatigue of SLM 718



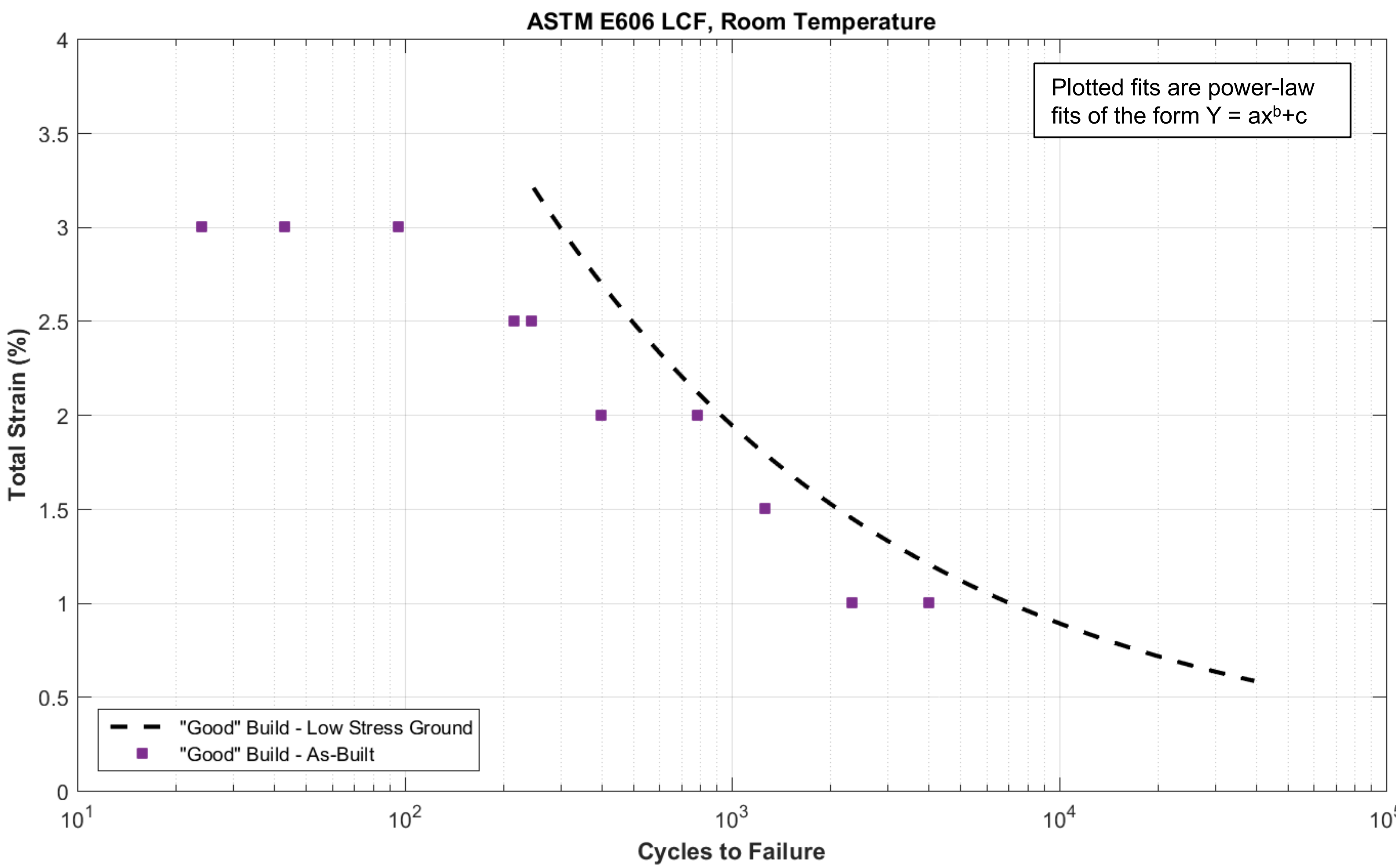
- “Reference” data – Low Stress Ground, R = -1, Defect-free build

Low Cycle Fatigue of SLM 718



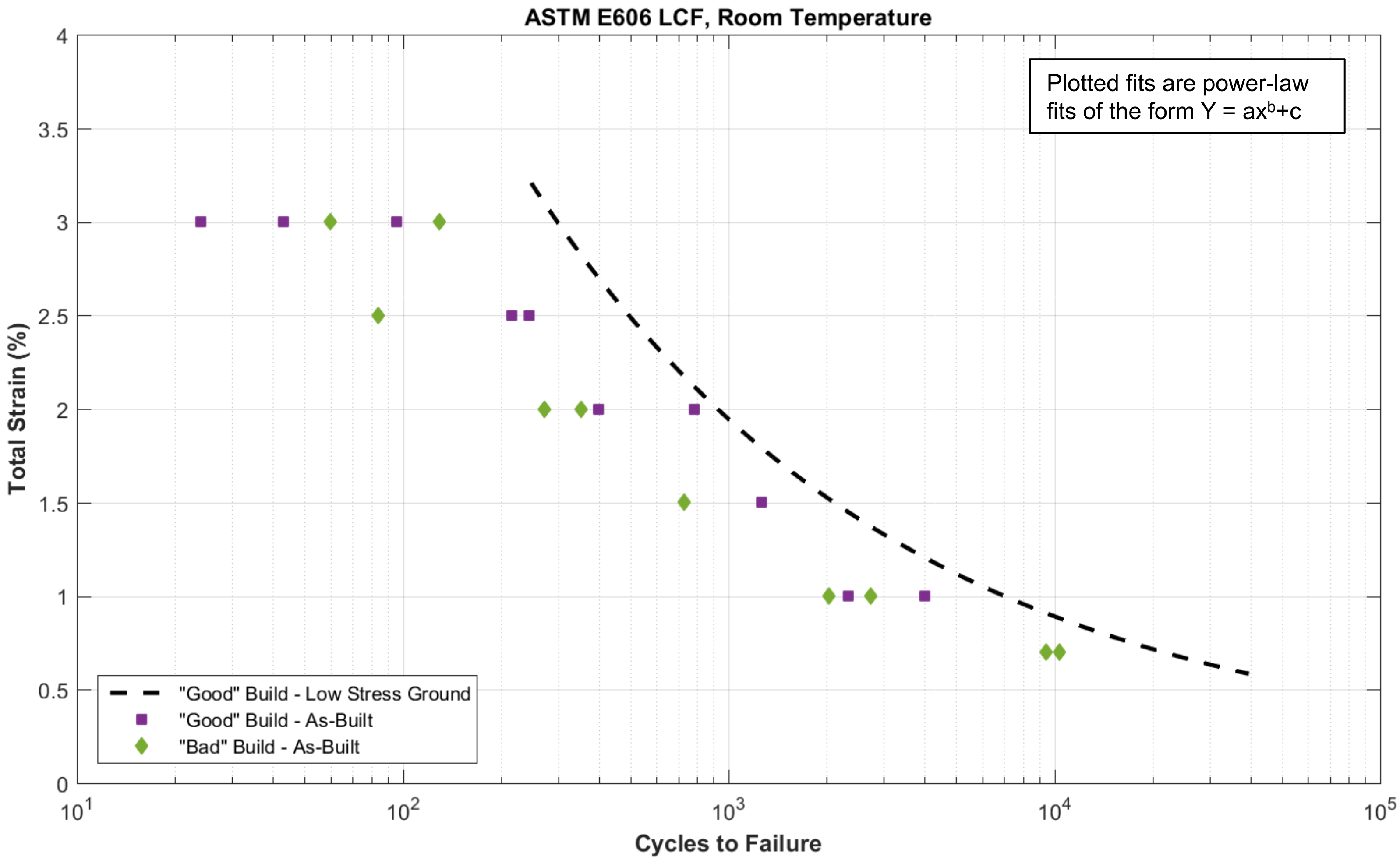
- Compare to build with defects – slightly lower fatigue life

Low Cycle Fatigue of SLM 718



- Defect-free build with as-built surface finish; fatigue life even lower

Low Cycle Fatigue of SLM 718

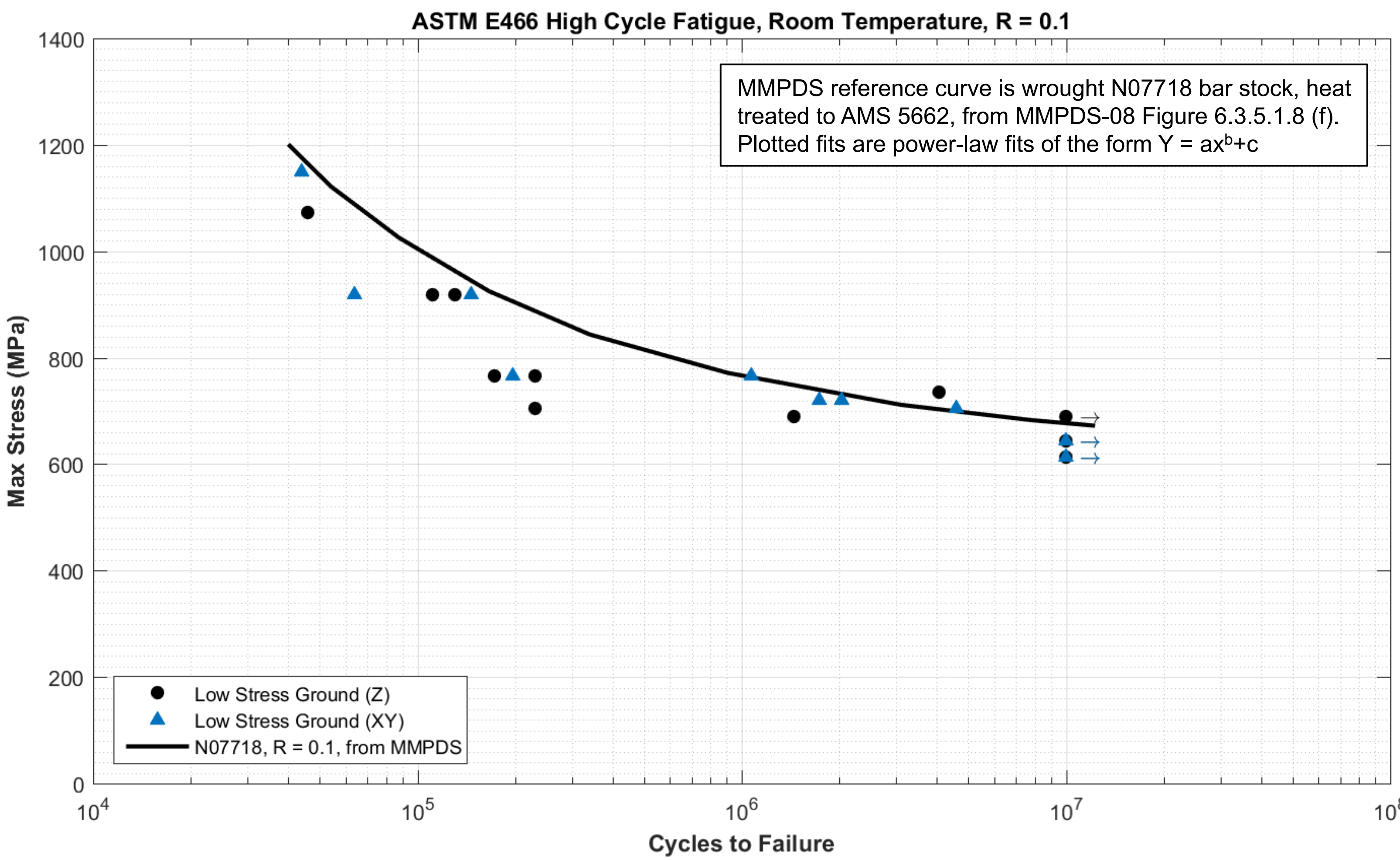


- As-built surface finish, with defects; surface finish has more effect than internal defects.

High Cycle Fatigue of SLM 718

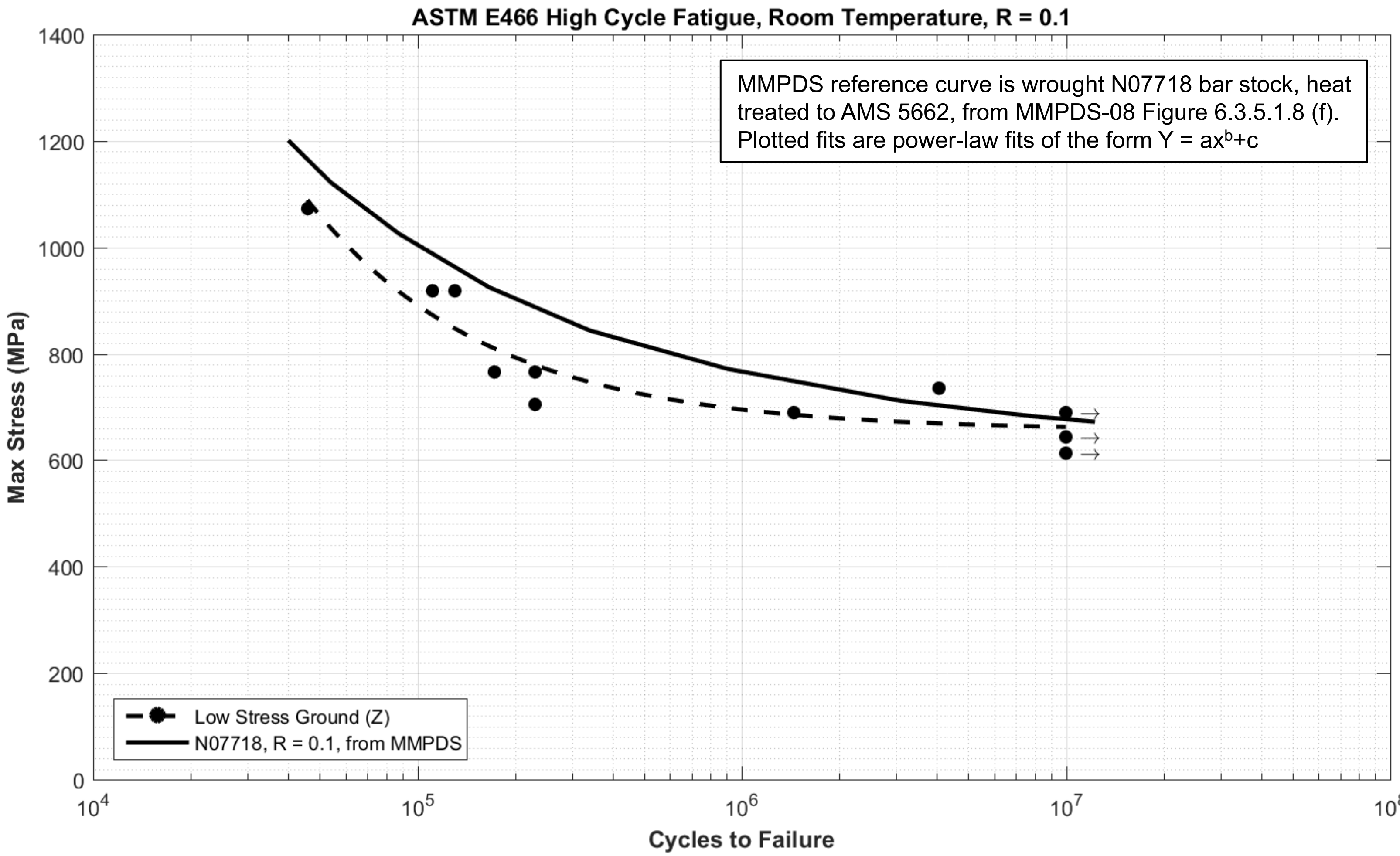
- Key Variables
  - Orientation
    - Z – loading axis perpendicular to powder bed plane.
    - XY – loading axis parallel to powder bed plane.
    - 45° – loading axis 45° from powder bed plane.
  - Surface Finish
    - Low Stress Ground – ASTM E466 finishing procedure
    - As-Built – Surface finish from the SLM machine
  - Temperature
    - Room Temperature (RT) – nominal lab conditions, 70-75°F
    - Liquid Nitrogen (-320°F)

High Cycle Fatigue of SLM 718



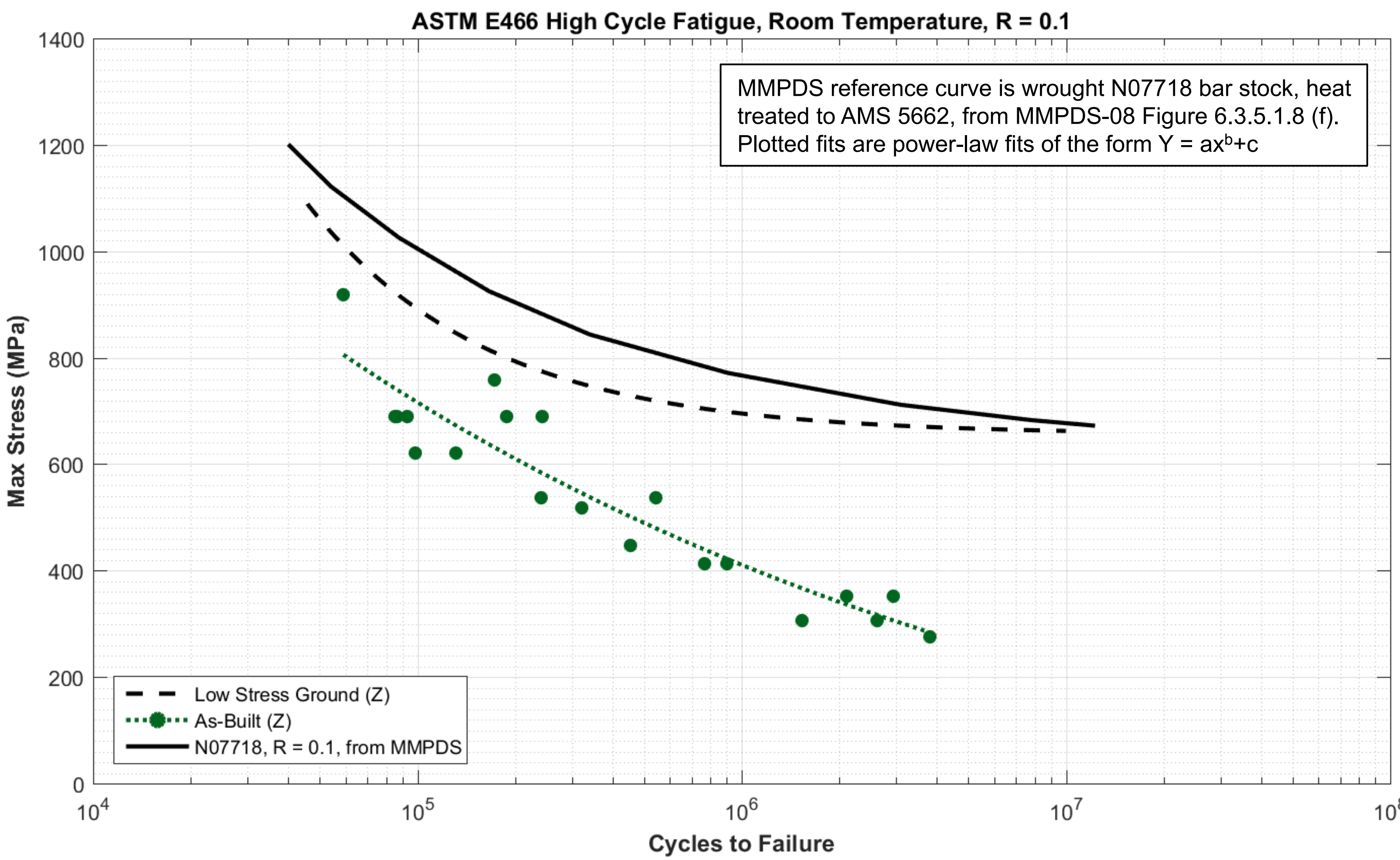
- Low stress ground; minimal effect from orientation

High Cycle Fatigue of SLM 718



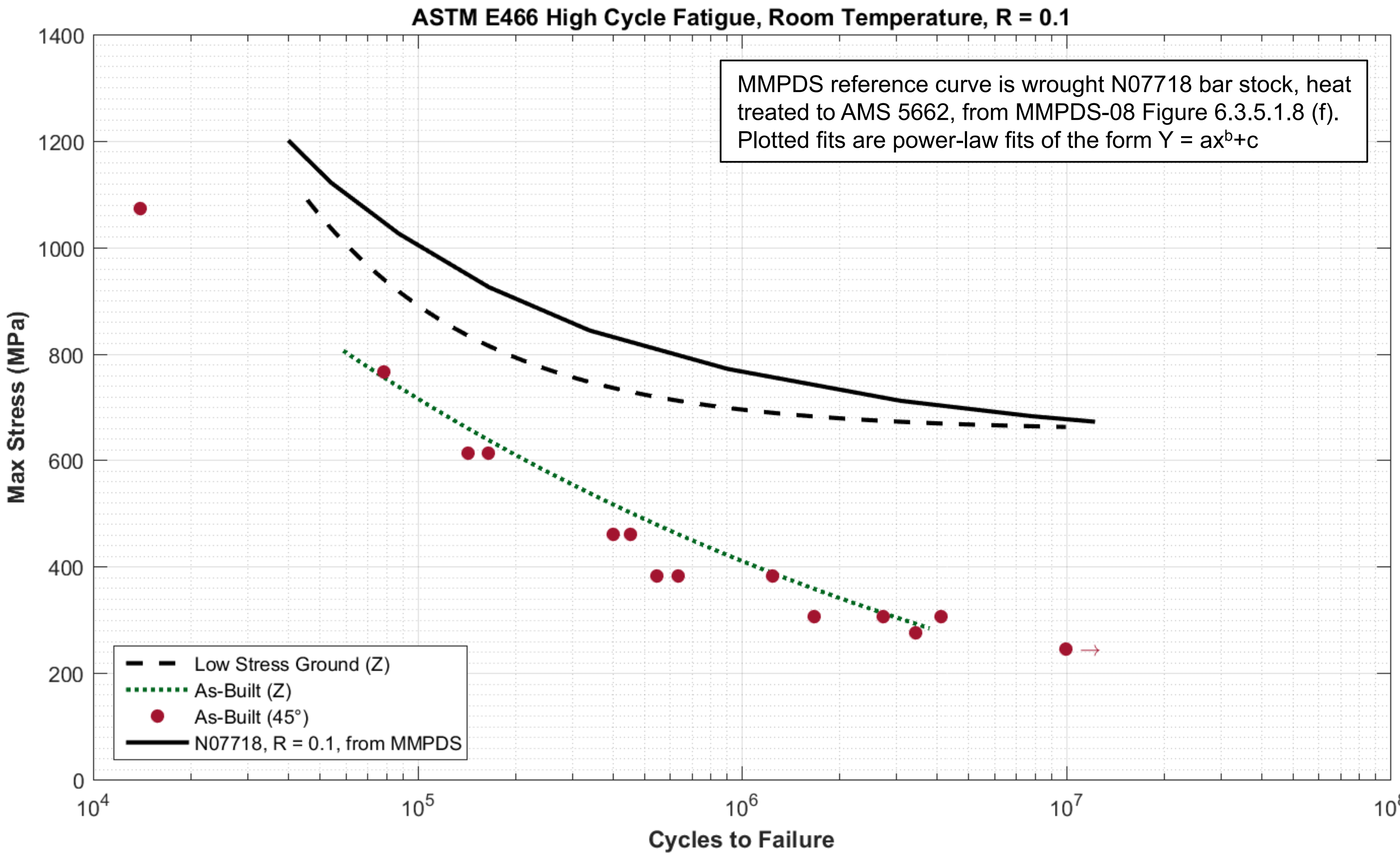
- “Reference” data – Low Stress Ground, Room Temperature, R = 0.1

High Cycle Fatigue of SLM 718



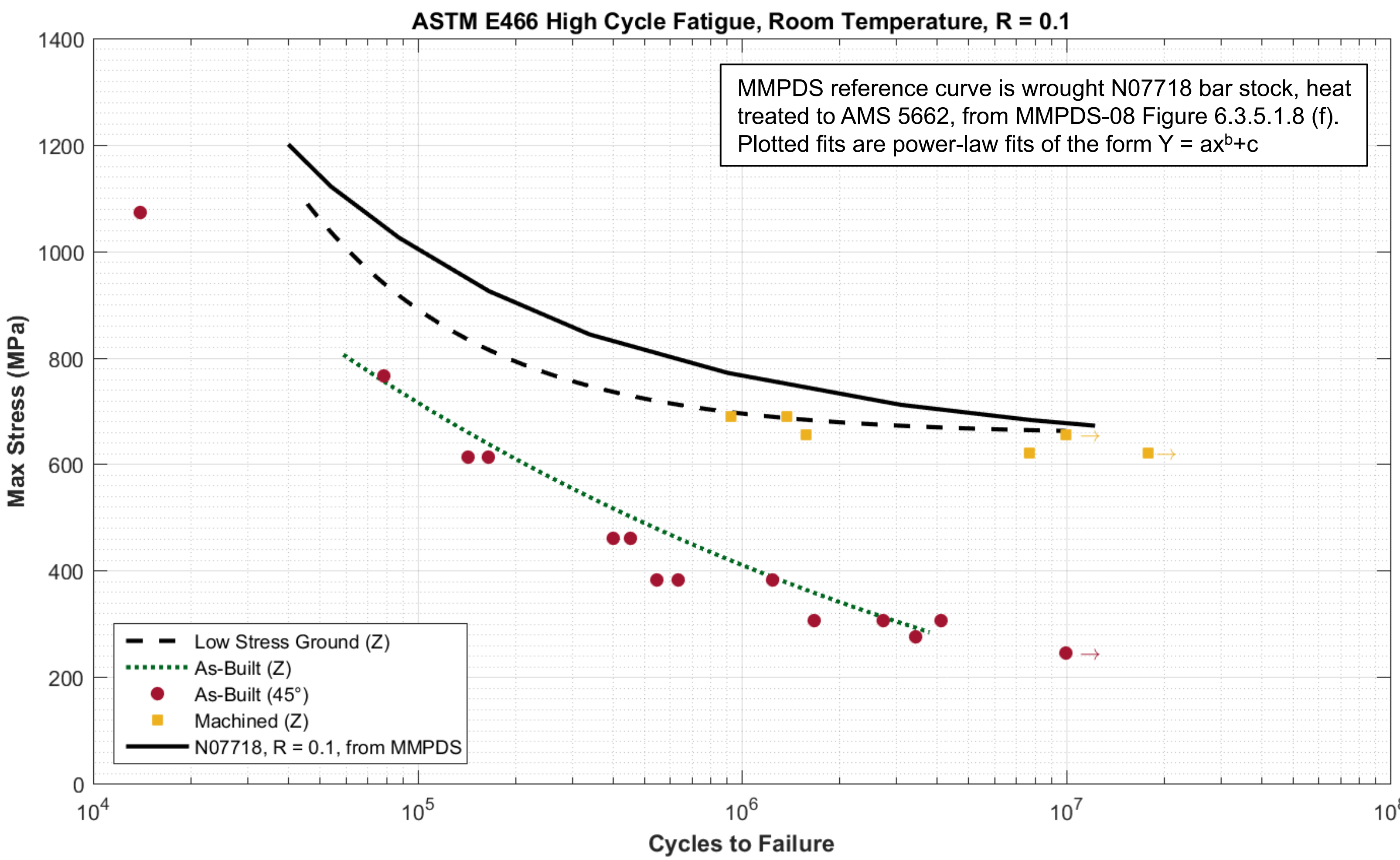
- Z-oriented, As-built surface finish; decreased fatigue life

High Cycle Fatigue of SLM 718



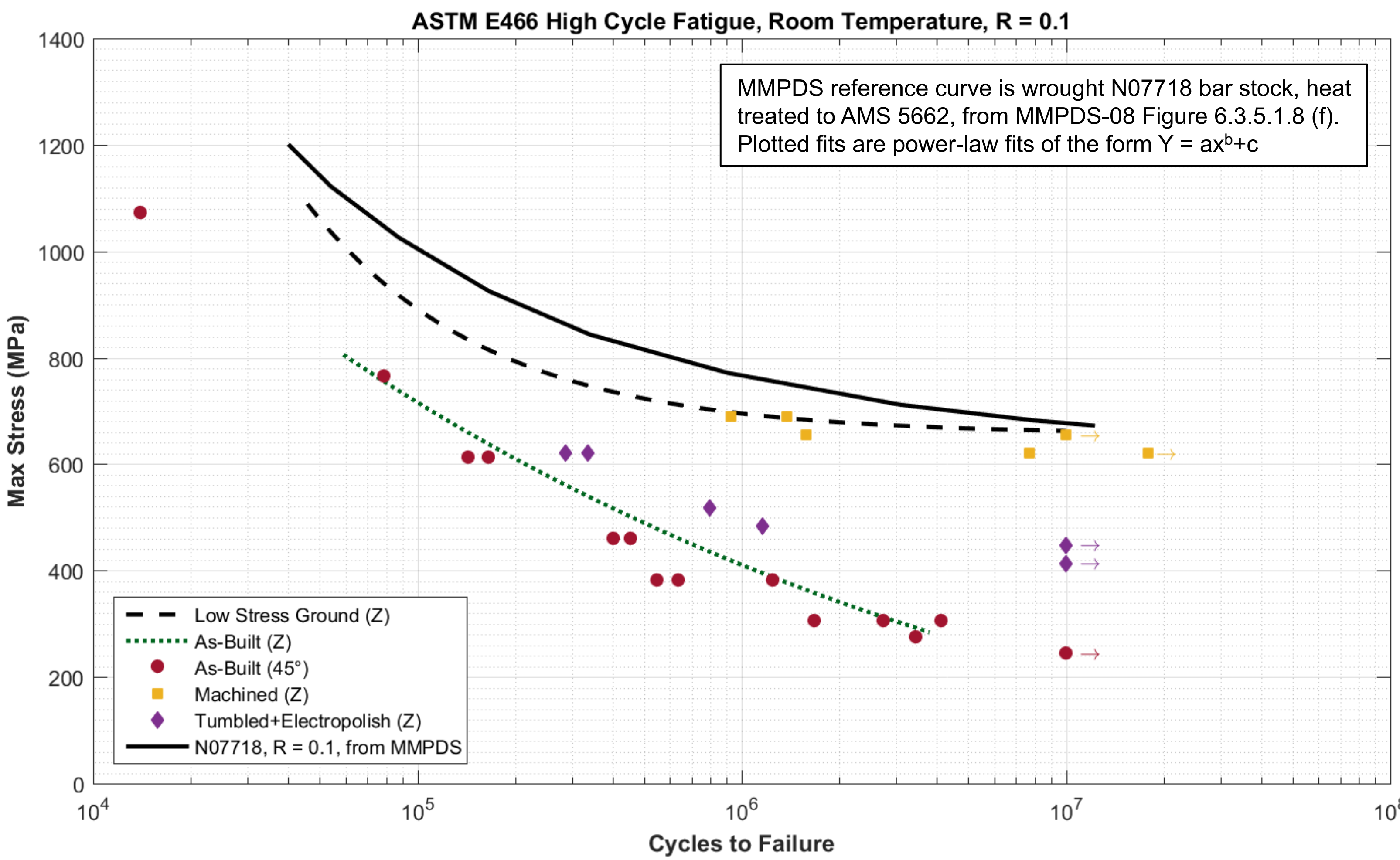
- 45°-oriented, As-built surface finish; similar fatigue life, 45° tend to be rougher than Z

High Cycle Fatigue of SLM 718



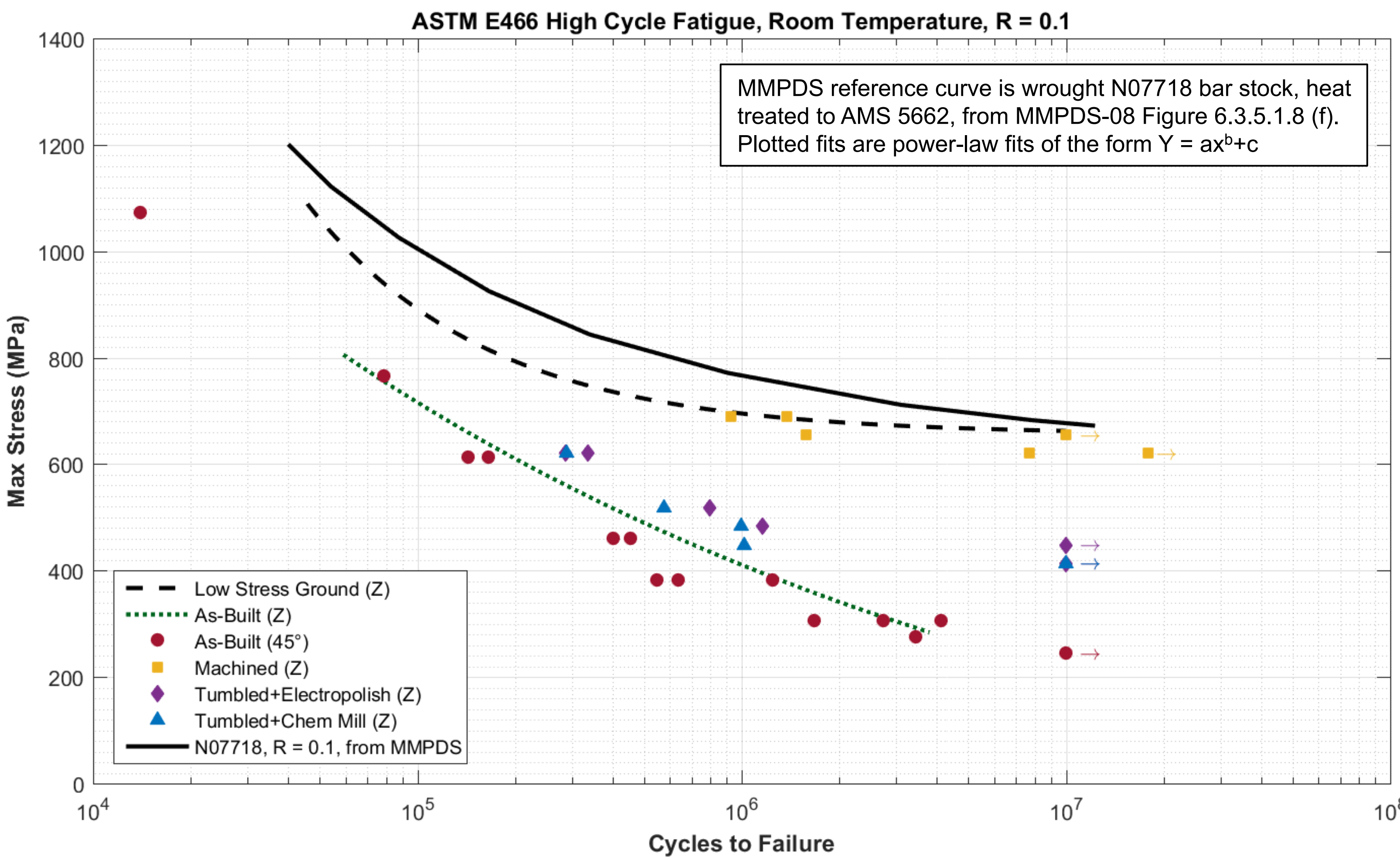
- Z-oriented, lathe-turned surface finish; quicker machining turnaround, slight decrease in life from low stress ground.

High Cycle Fatigue of SLM 718



- Z-oriented, Tumbled then Electropolished; investigated for part finishing.

High Cycle Fatigue of SLM 718

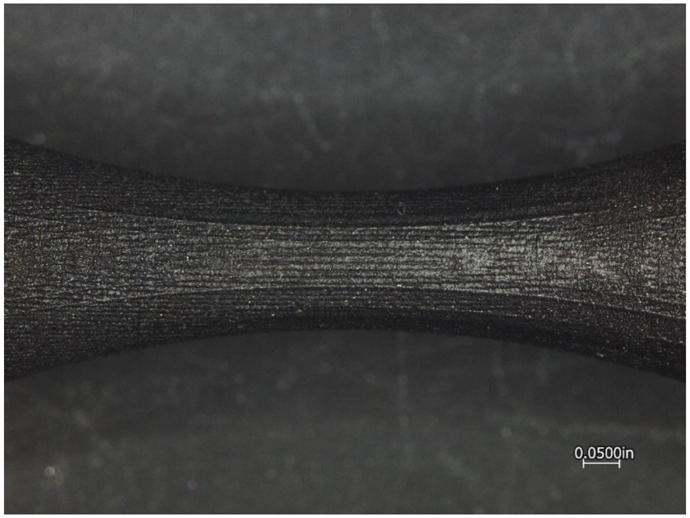


- Z Oriented, Tumbled then Chem Milled; investigated for part finishing.

High Cycle Fatigue of SLM 718

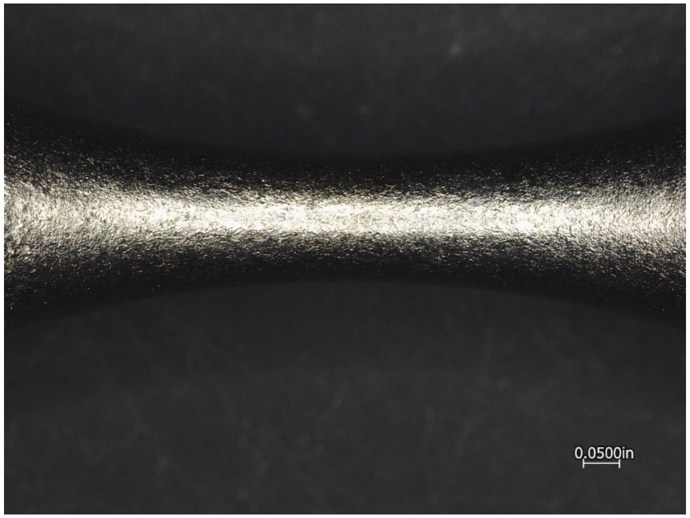
- Fatigue life decreases with increasing surface roughness.

Low stress ground



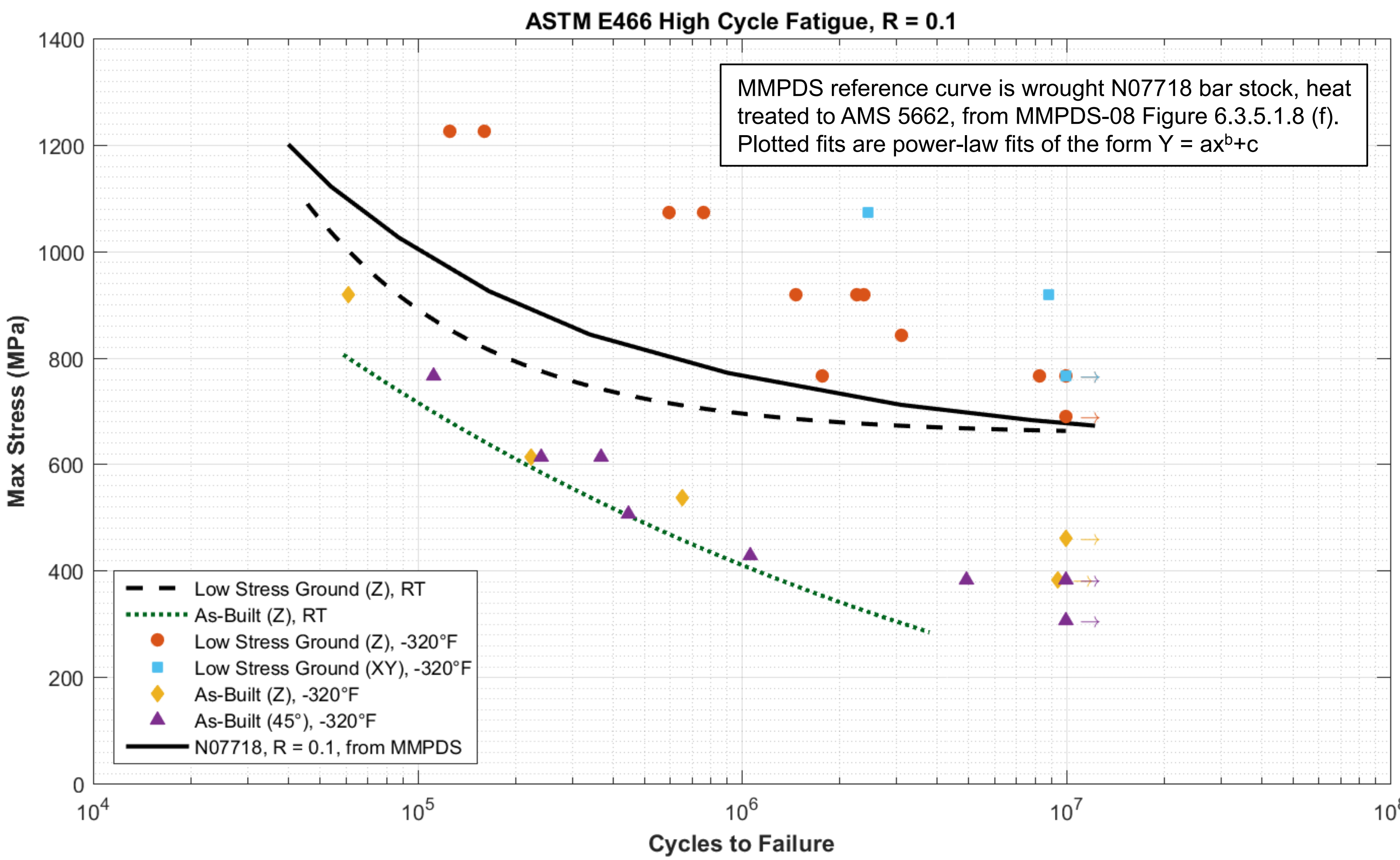
As-built

Tumbled & Electropolish



Tumbled & Chem Mill

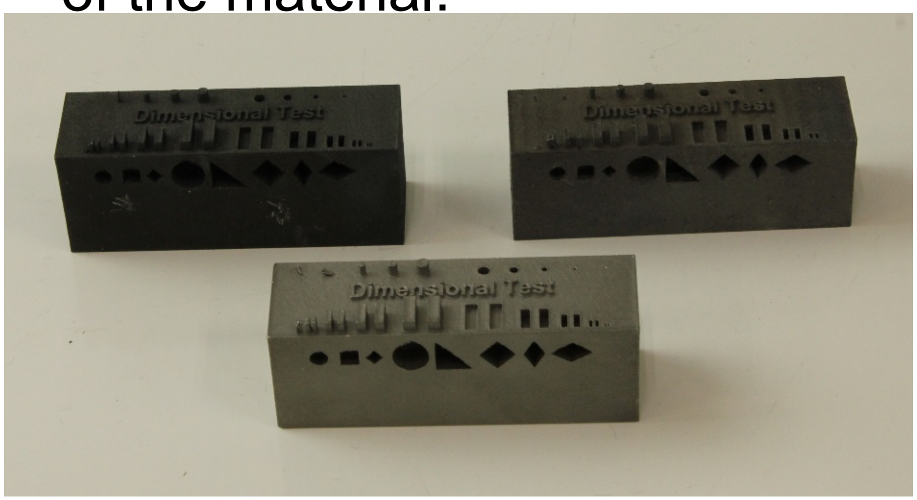
High Cycle Fatigue of SLM 718

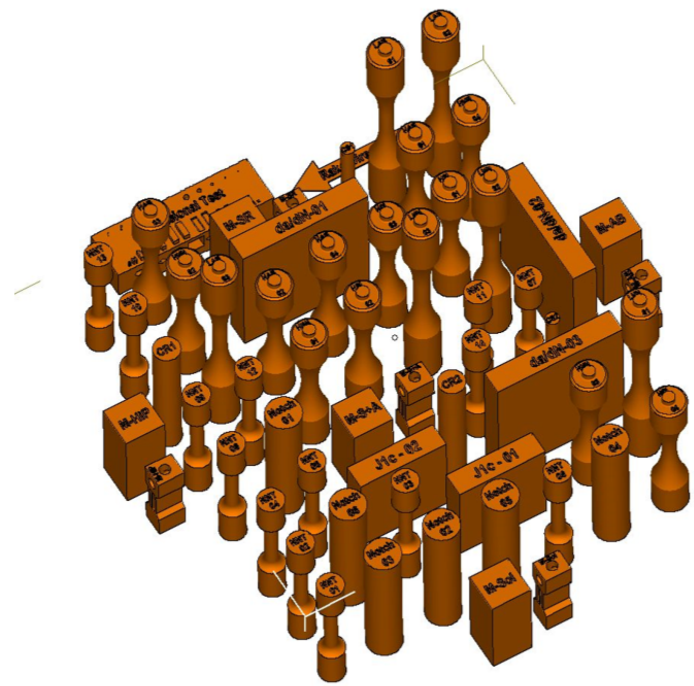


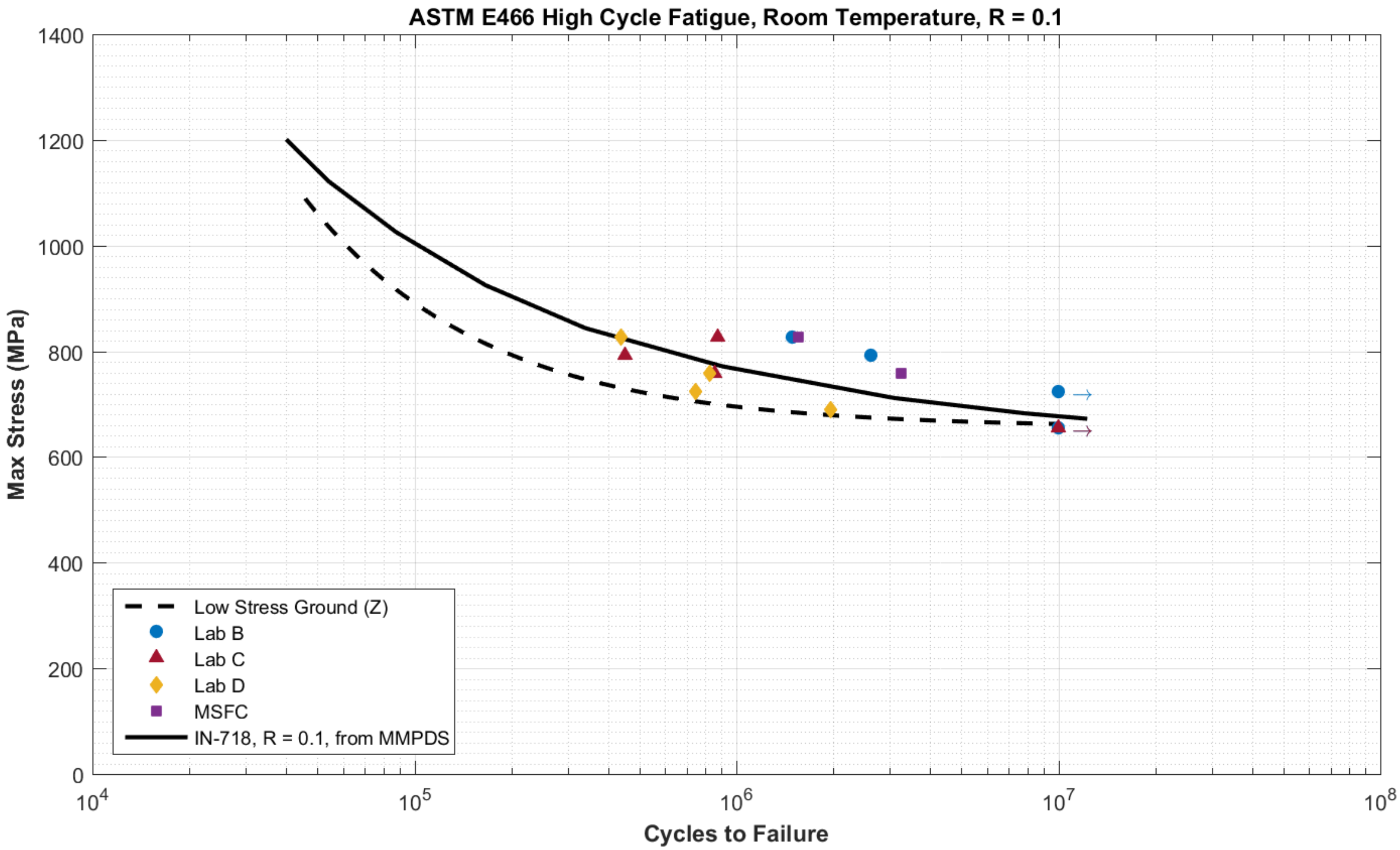
- Tests in LN_2 (-320°). Some increase in life for as-built surfaces; more increase for low stress ground.

Vendor Round Robin

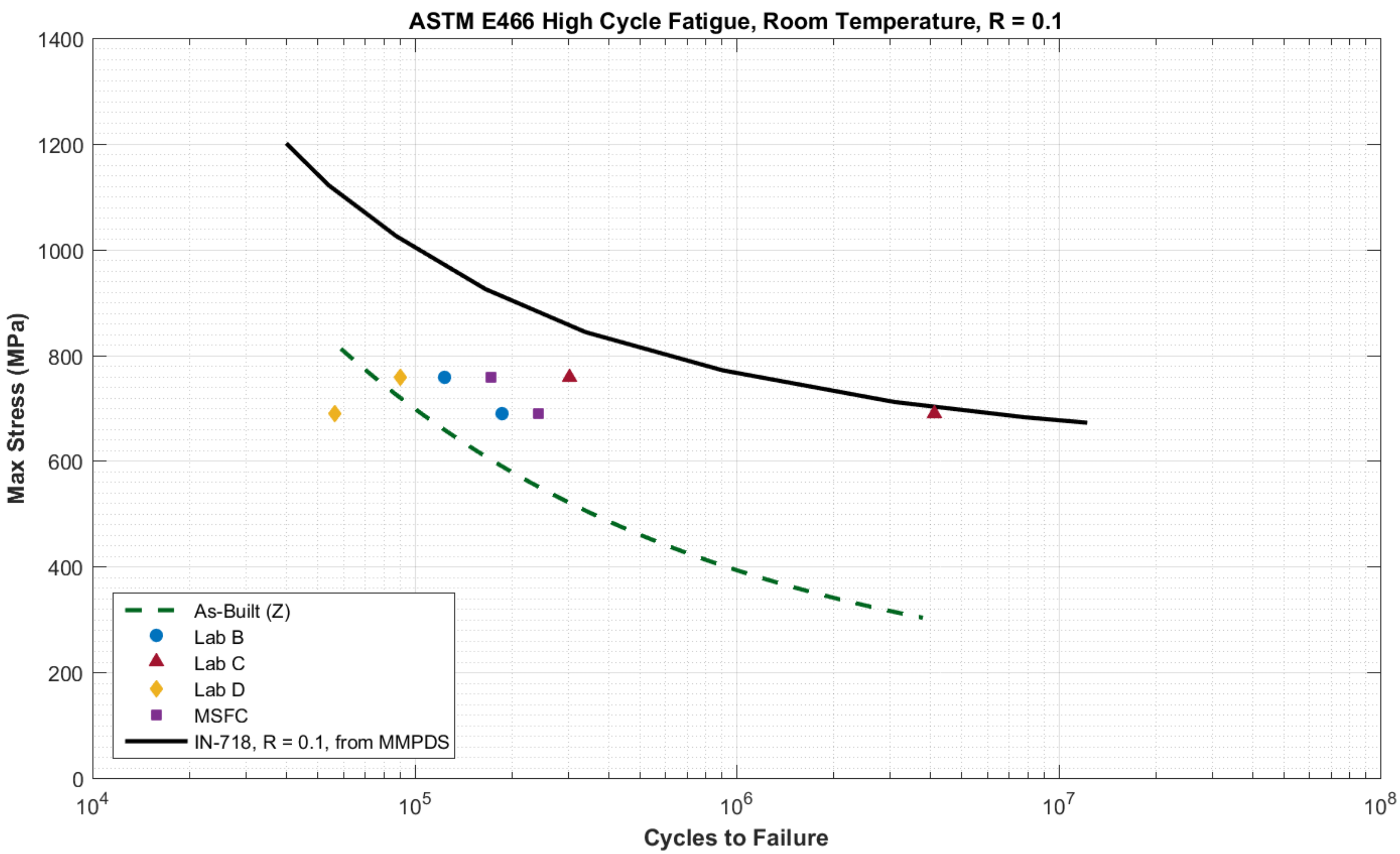
- Identical builds were procured from three third-party SLM vendors; one build was provided by MSFC.
- The specimens were heat treated per MSFC guidance, although allowances were made for vendors with existing mature processes.
- A series of comparison testing was
  of the material.







- Z-oriented, low stress ground surface finish; compared to M1 and wrought reference curves



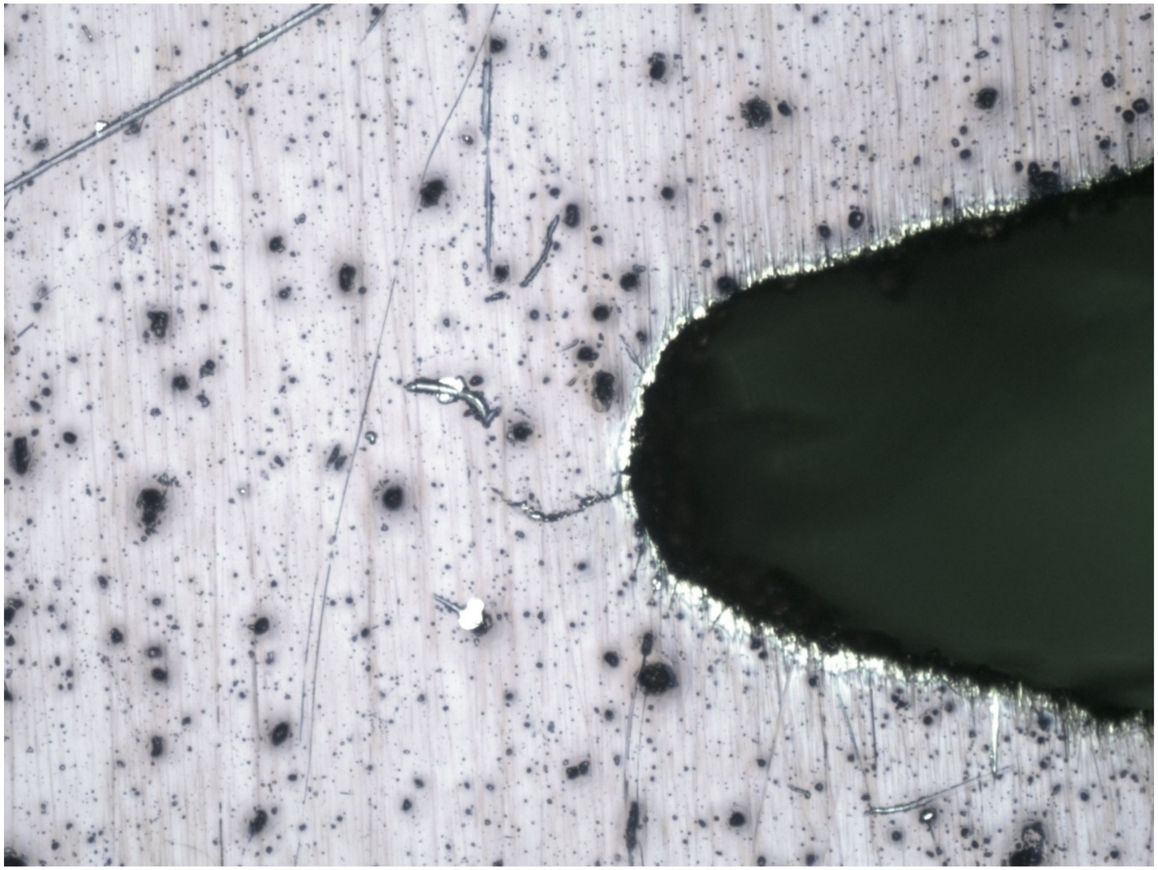
- Z-oriented, “as-provided” surface finish; compared to M1 and wrought reference curves

Fatigue Crack Growth Results

- Round Robin Results
  - 3 specimens from each build
  - Z-XY test orientation
  - Post-processing same as fatigue specimens
- Testing Methodology
  - Tested according to ASTM E647
    - "Standard Test Method for Measurement of Fatigue Crack Growth Rates"
  - R = 0.1 and R = 0.7 data shown
  - Compression pre-cracking procedure (CPC)

Compression Pre-Cracking

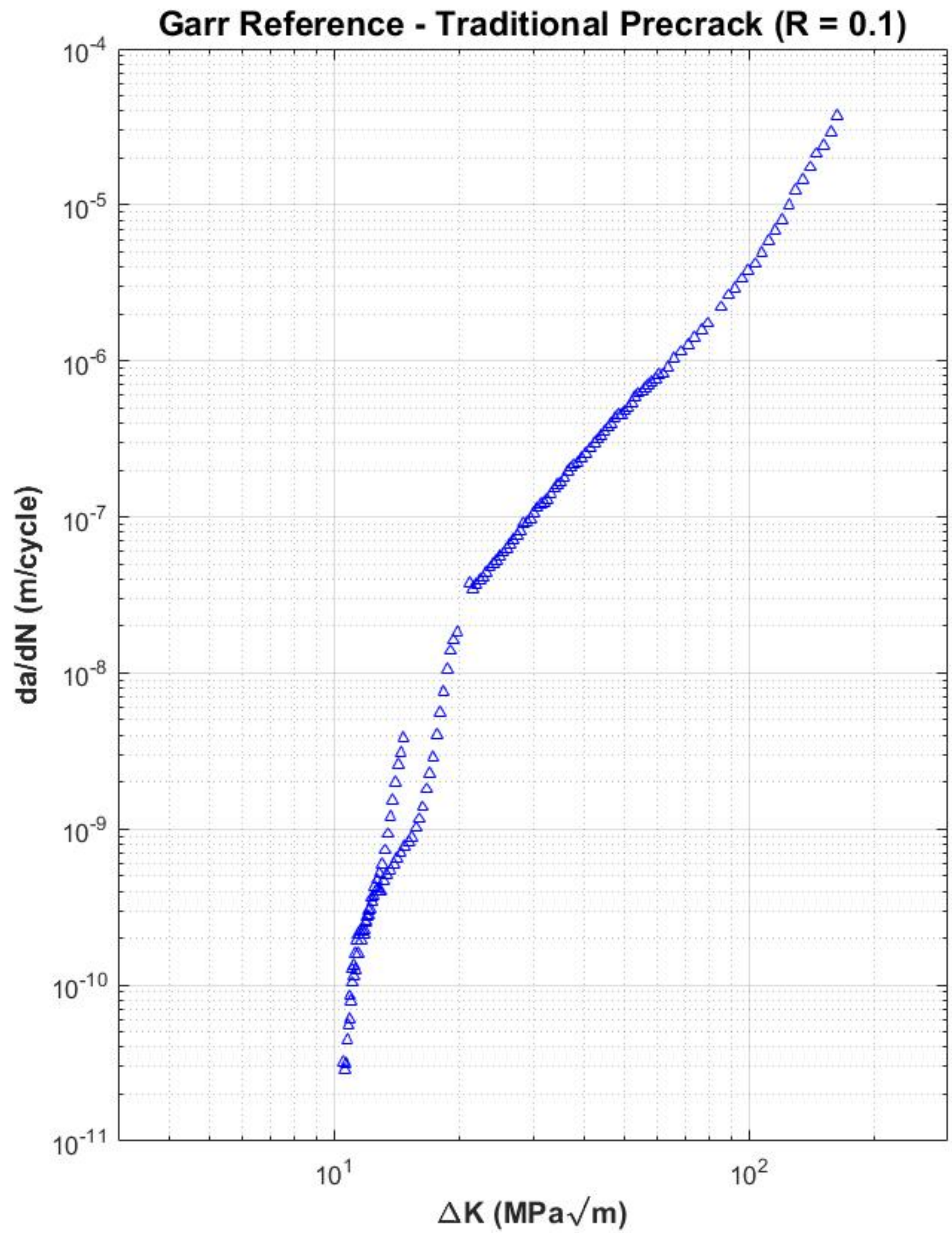
- Compression-compression loading used to generate a crack at the notch root of a c(T) specimen.
- May produce more conservative threshold and near-threshold crack growth rates.
- Following CPC procedure detailed by Newman and Yamada.



Fatigue Crack Growth

- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the ASTM LR test method and CA loading.

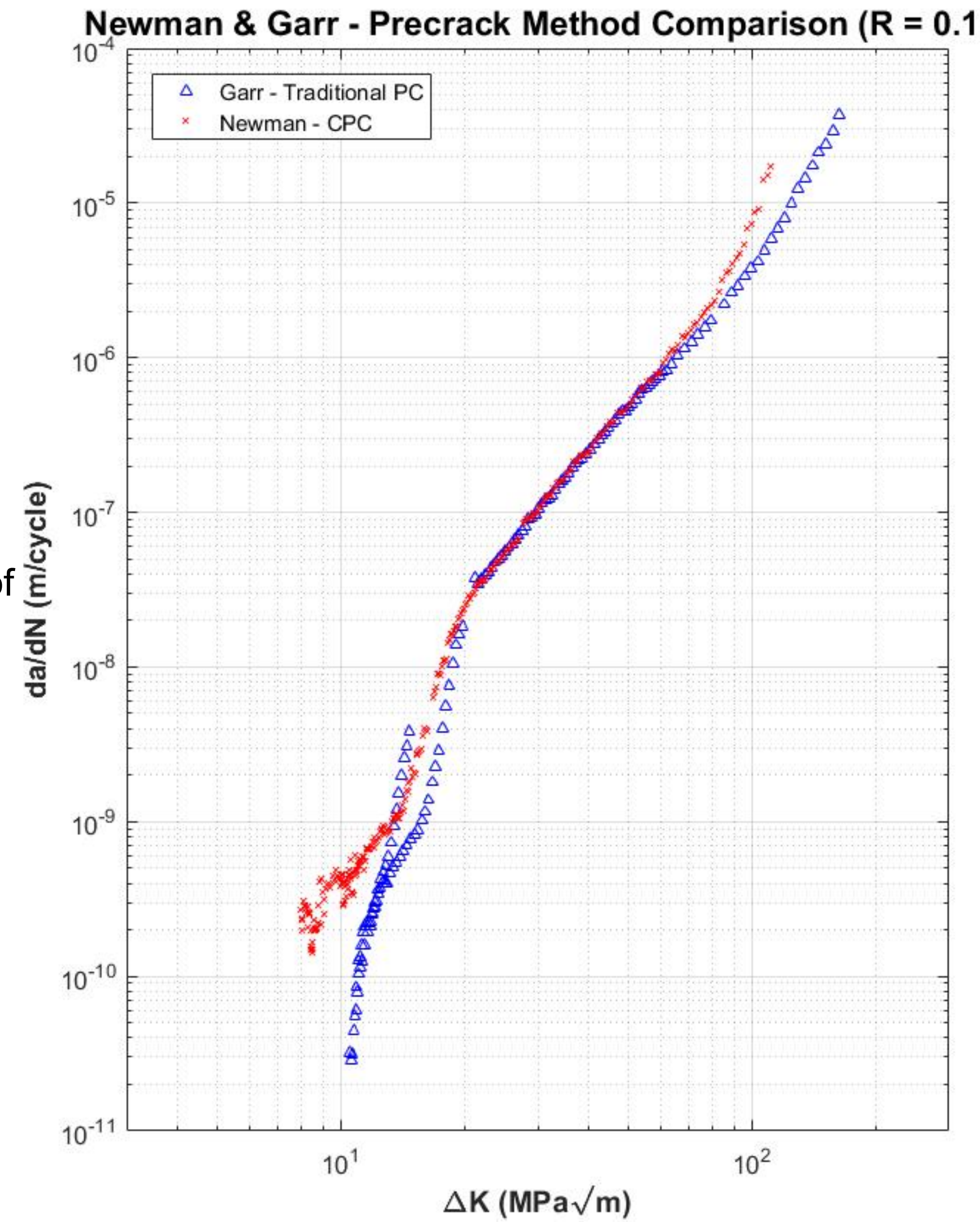
- Garr KR, Boeing-Rocketdyne Propulsion and Power Company, private communication; 2004.



Fatigue Crack Growth

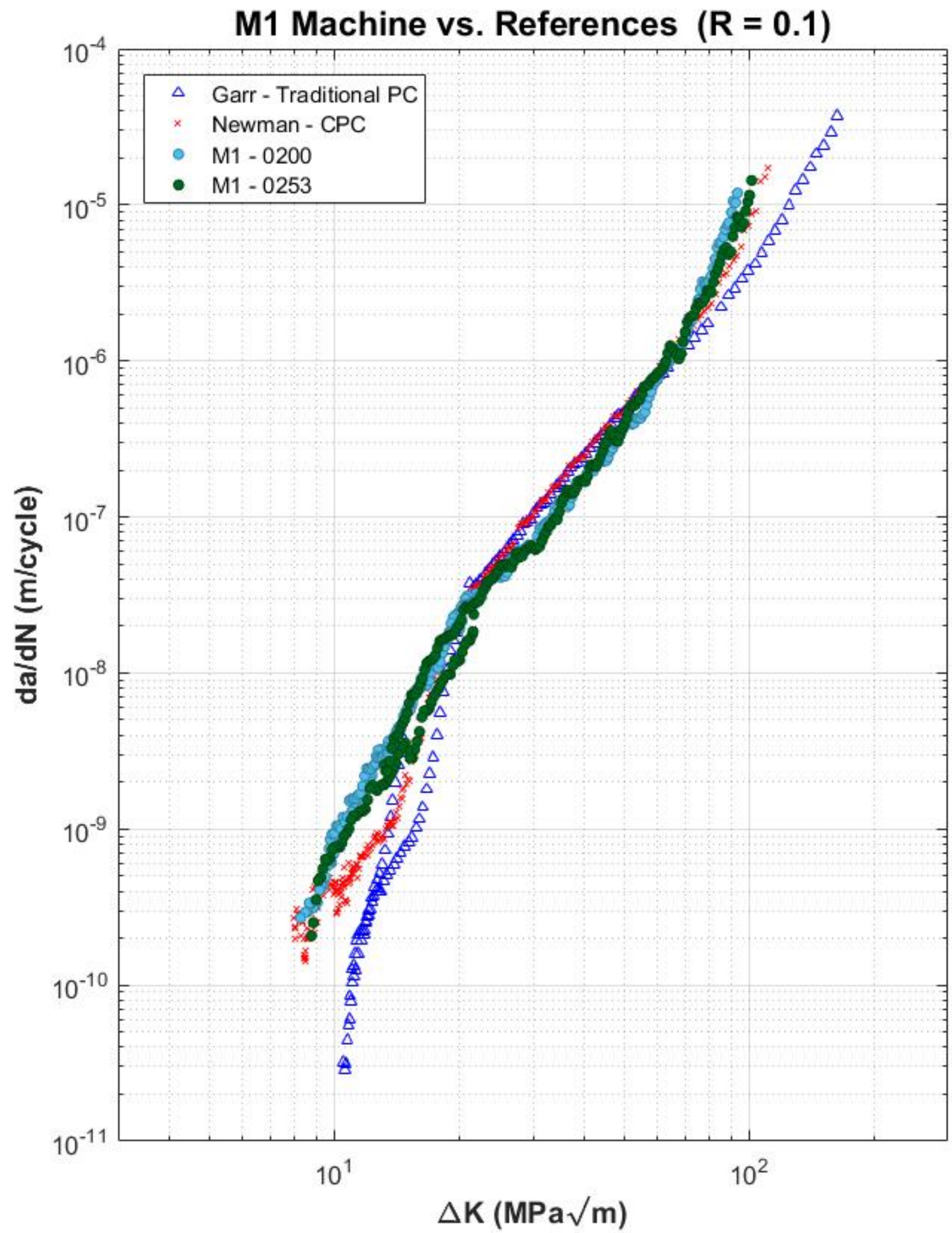
- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the CPLR test method and CA loading.

- Newman, J.C., Jr. and Yamada, Y., "Compression Precracking Methods to Generate Near-Threshold Fatigue-Crack-Growth-Rate Data", International Journal of Fatigue, Vol. 32, 2010, p.879-885.



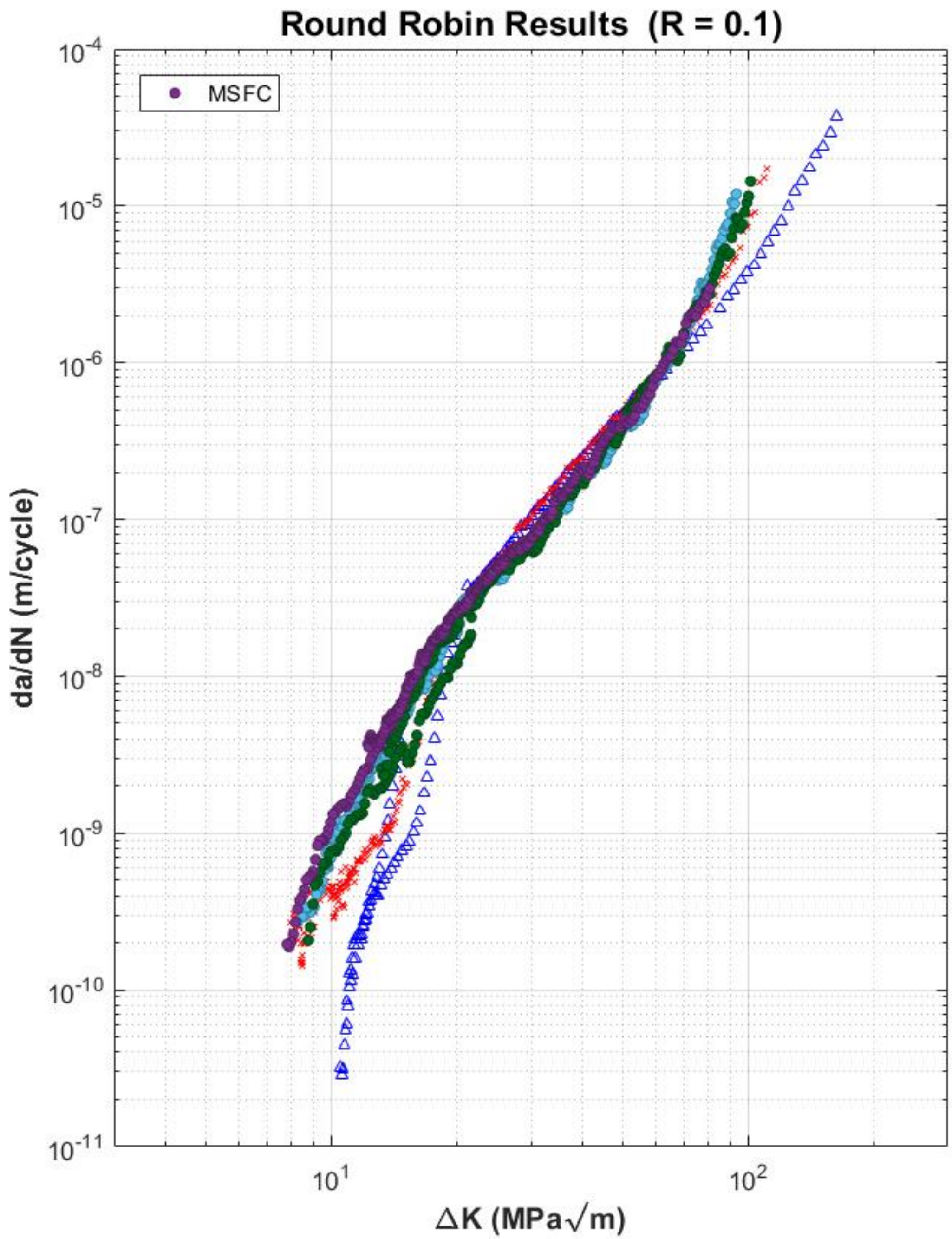
Fatigue Crack Growth

- SLM 718 M1 Machine included as a reference. This data is not part of the Round-Robin.
- Produced using ASTM LR and CA loading.



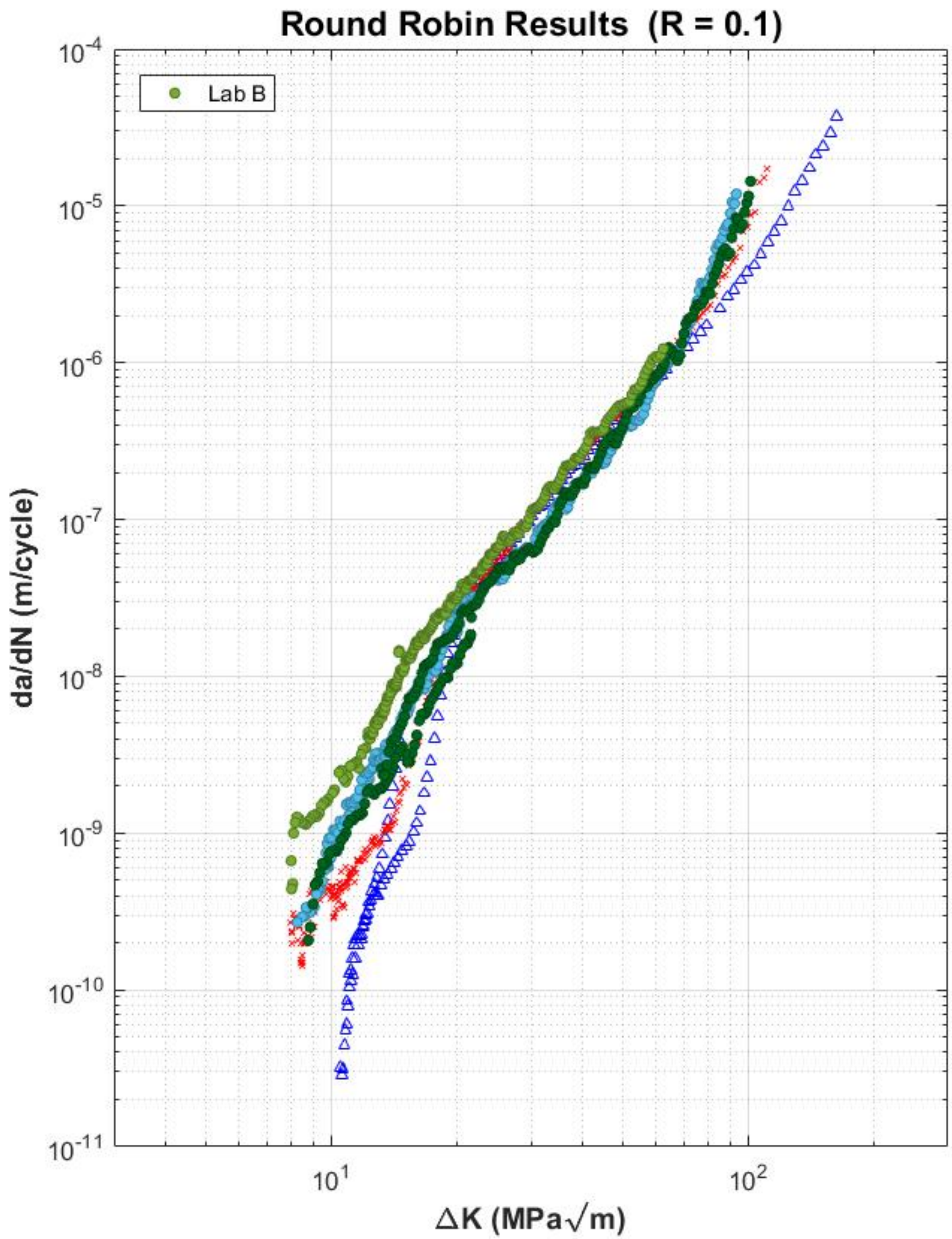
Fatigue Crack Growth

- MSFC Round-Robin data. Consistent with M1 data.



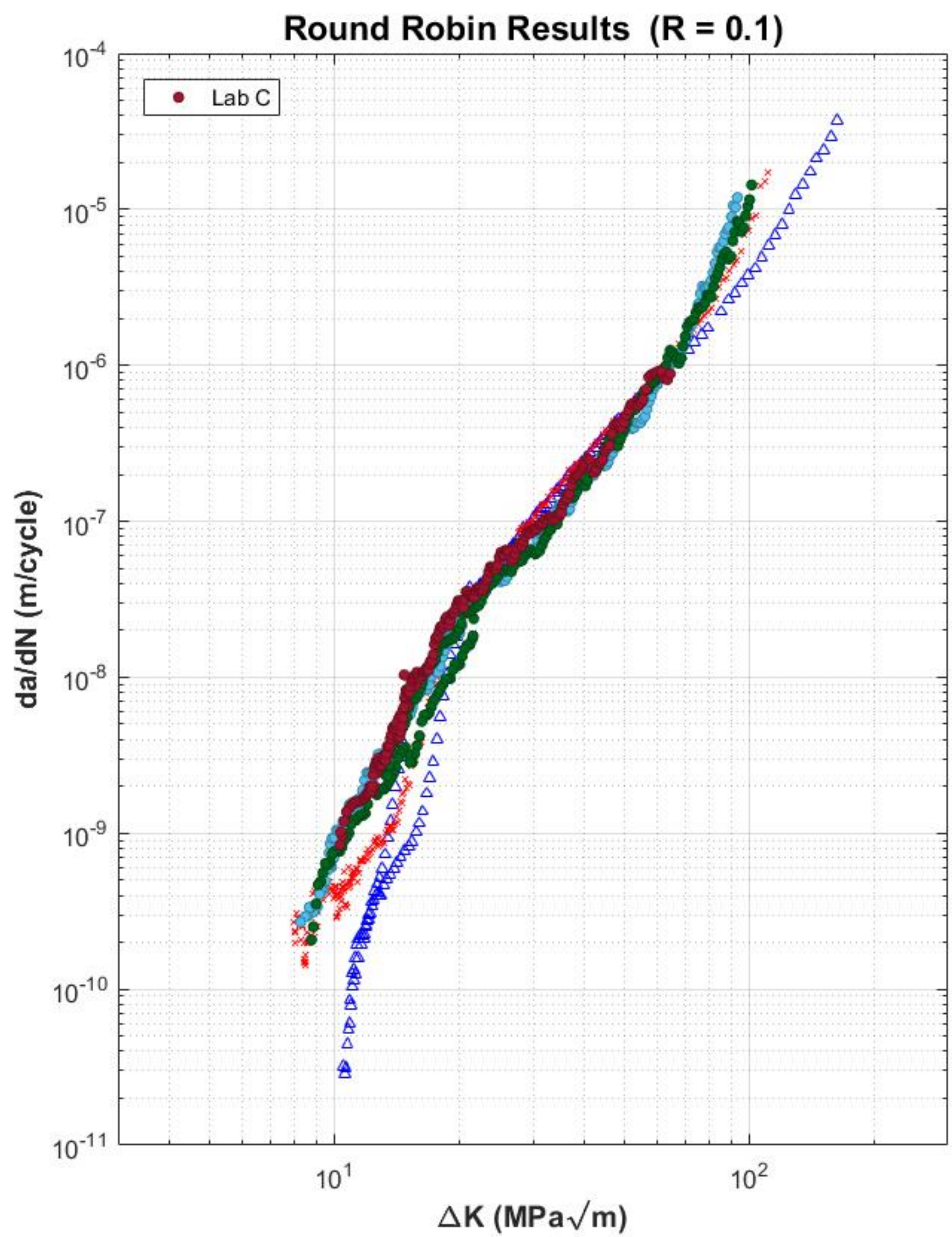
Fatigue Crack Growth

- Lab B - Higher observed growth rates than M1 data.



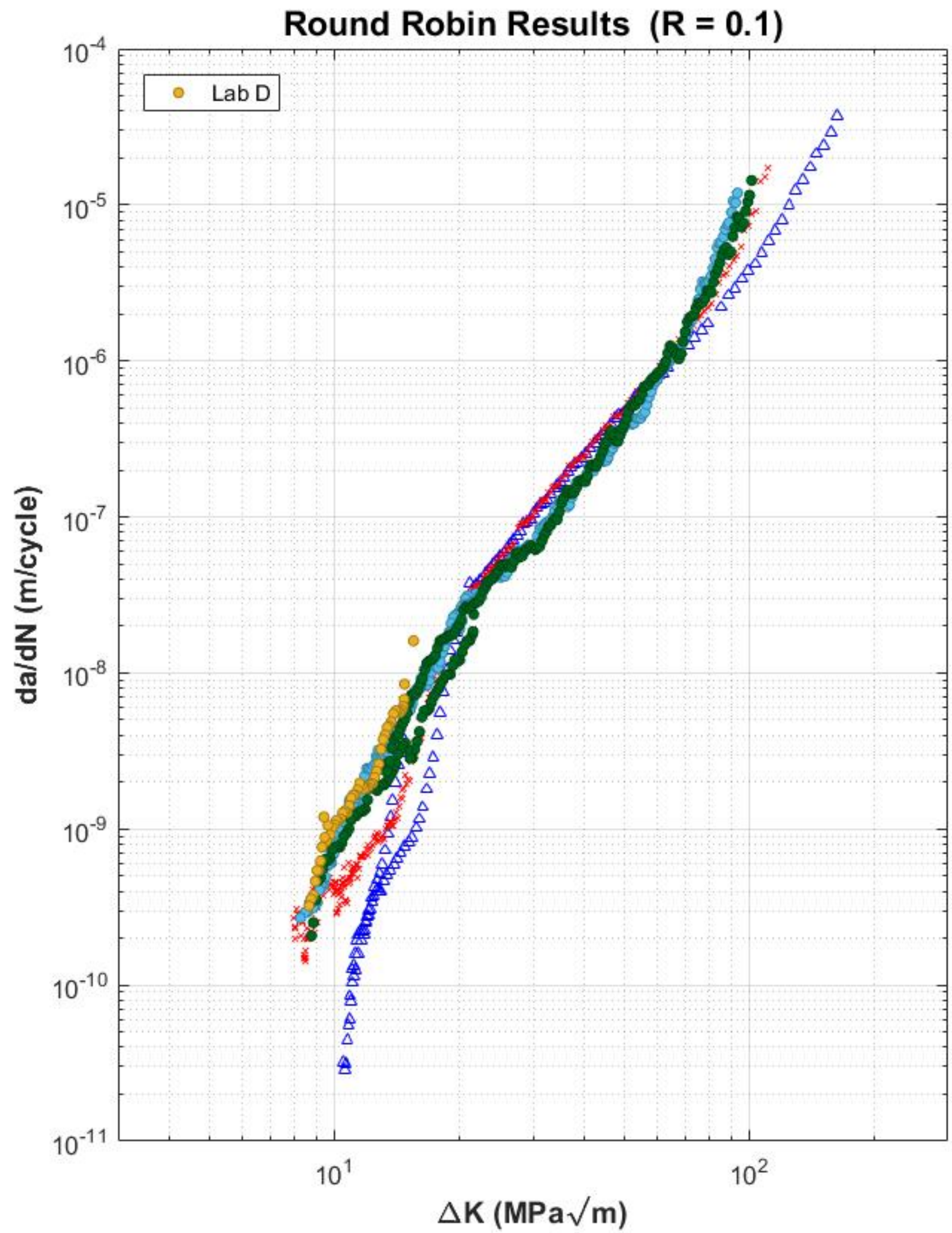
Fatigue Crack Growth

- Lab C - Consistent with M1 data.



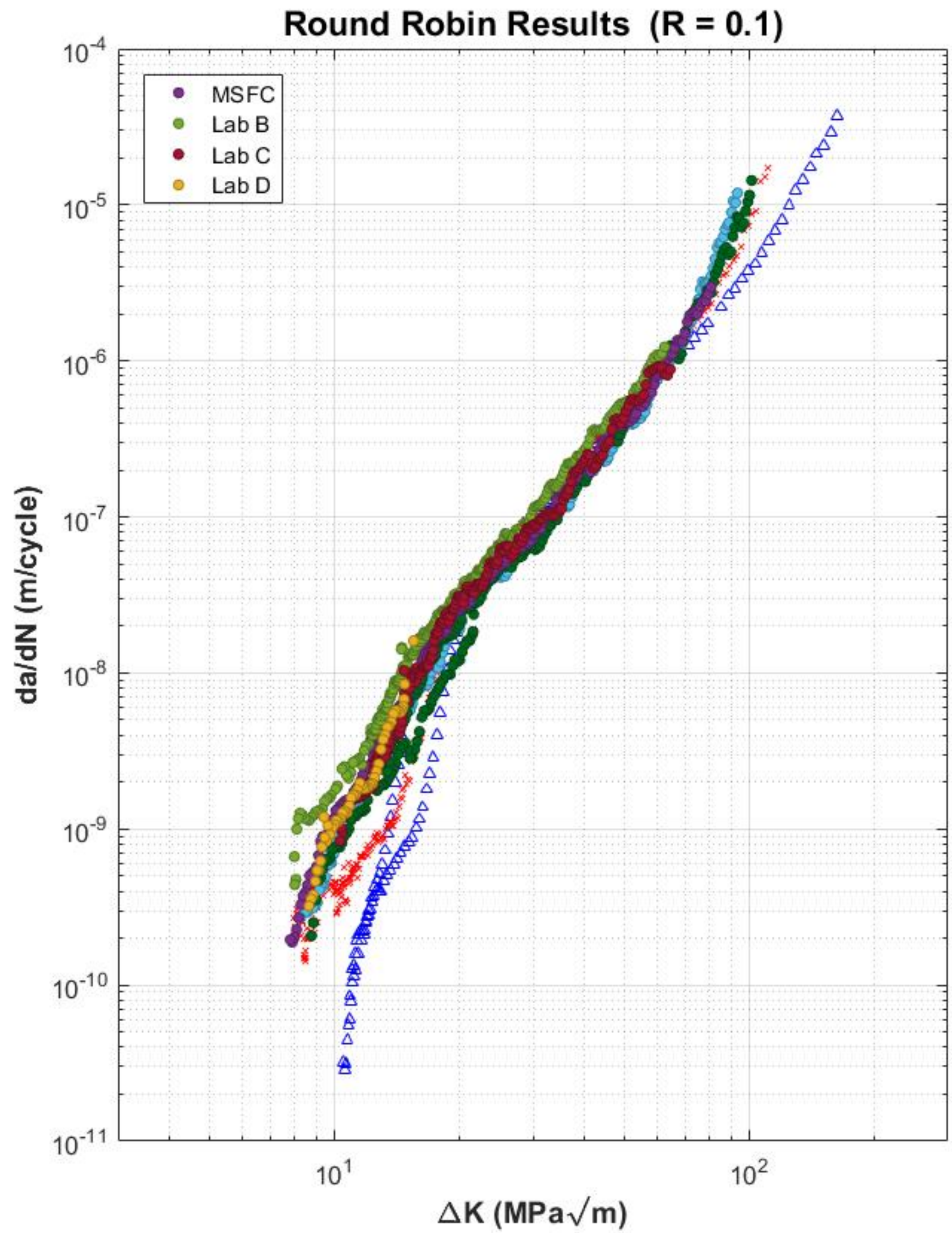
Fatigue Crack Growth

- Lab D - Consistent with M1 data. CPLR only.



Fatigue Crack Growth

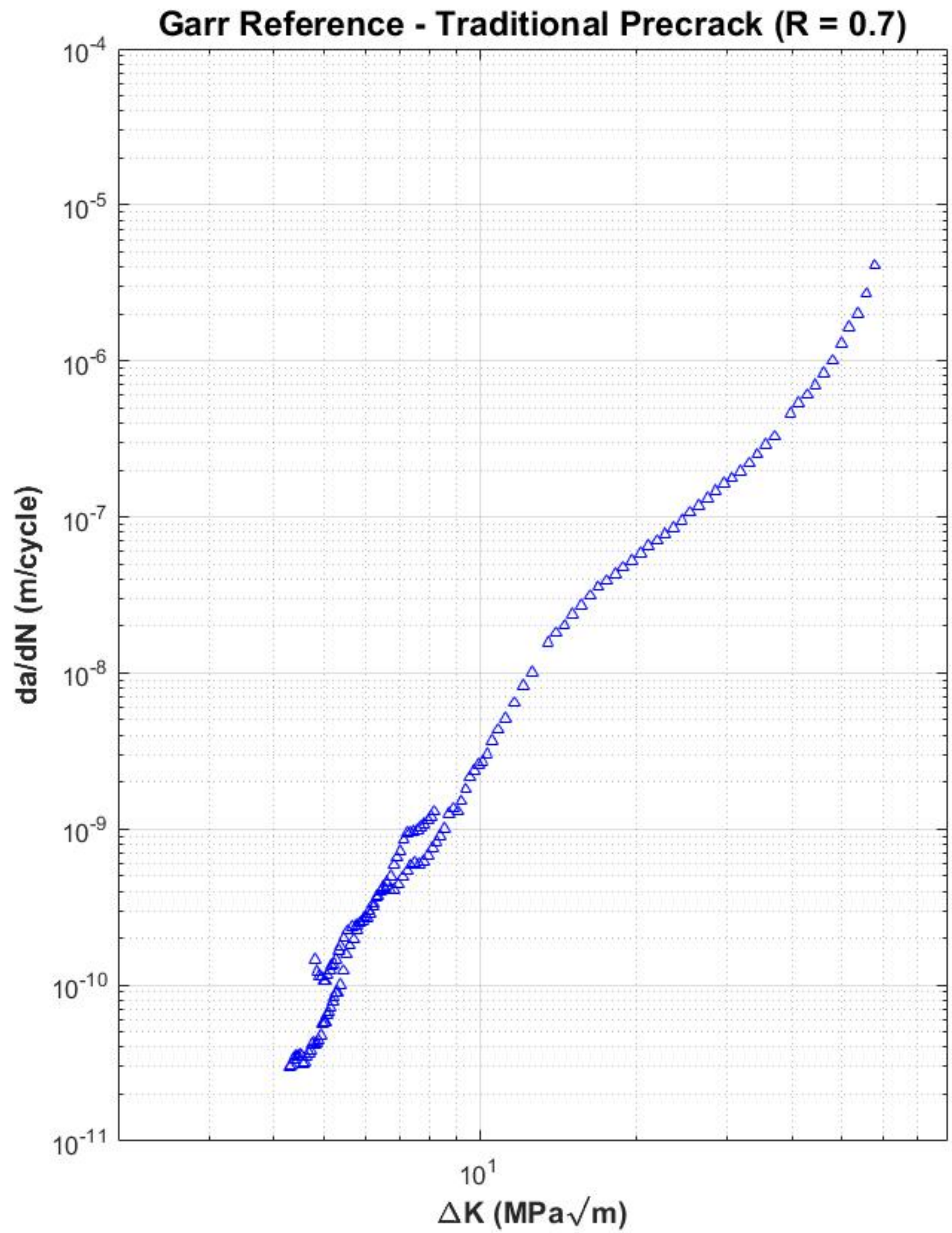
- Only Lab B had any distinction from the M1 data.



Fatigue Crack Growth

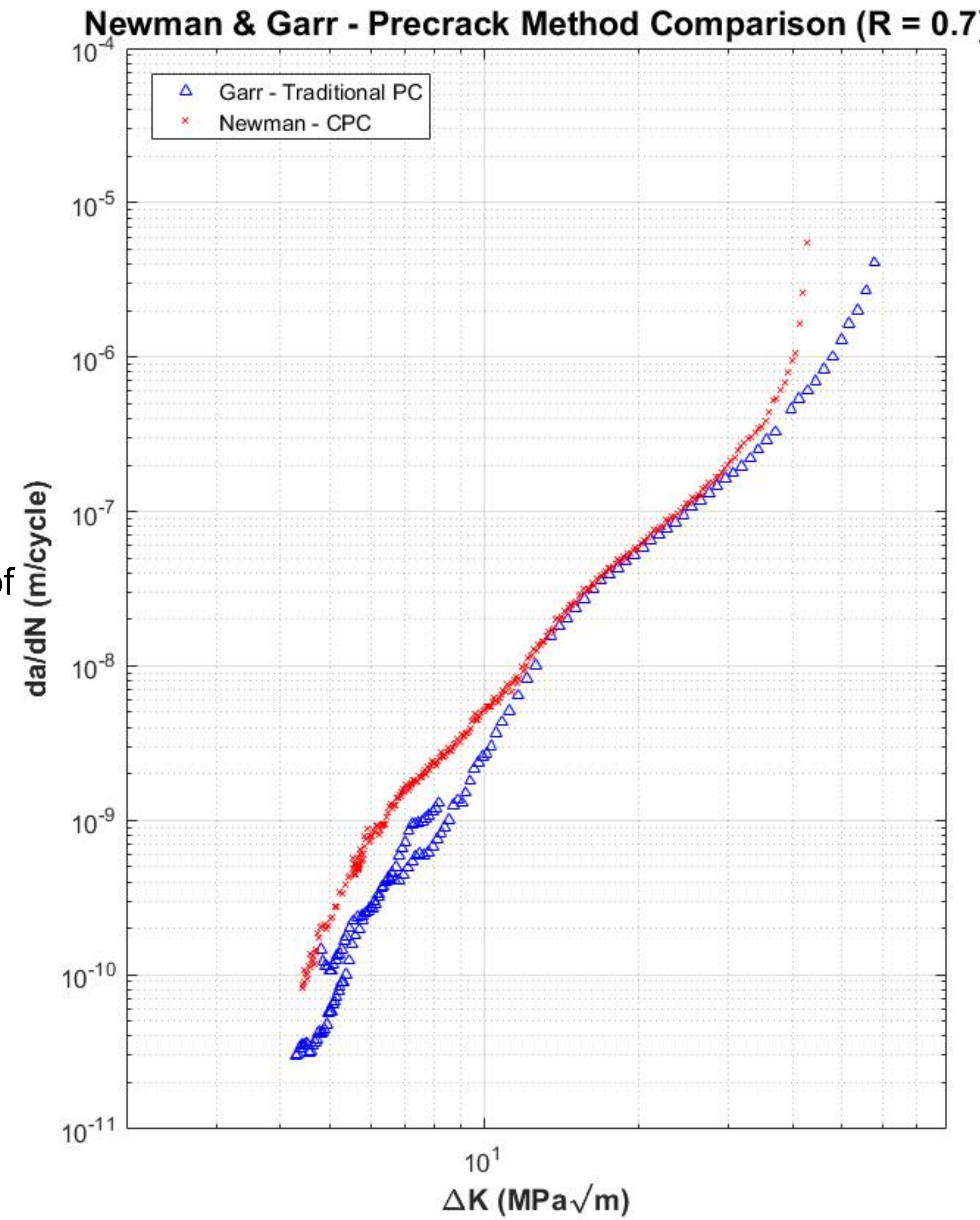
- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the ASTM LR test method and CA loading.

- Garr KR, Boeing-Rocketdyne Propulsion and Power Company, private communication; 2004.



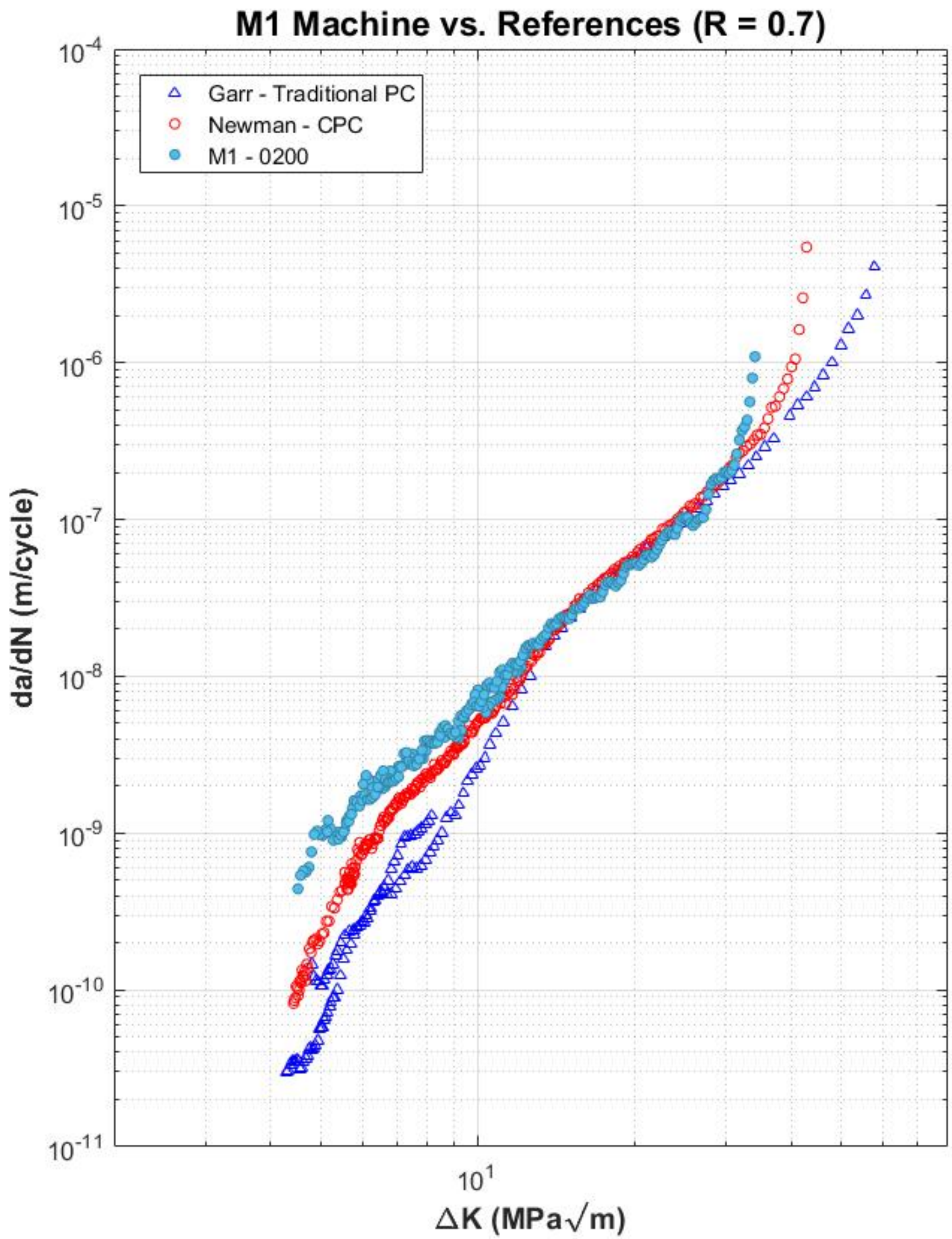
Fatigue Crack Growth

- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the CPLR test method and CA loading.
- Newman, J.C., Jr. and Yamada, Y., “Compression Precracking Methods to Generate Near-Threshold Fatigue-Crack-Growth-Rate Data”, International Journal of Fatigue, Vol. 32, 2010, p.879-885.



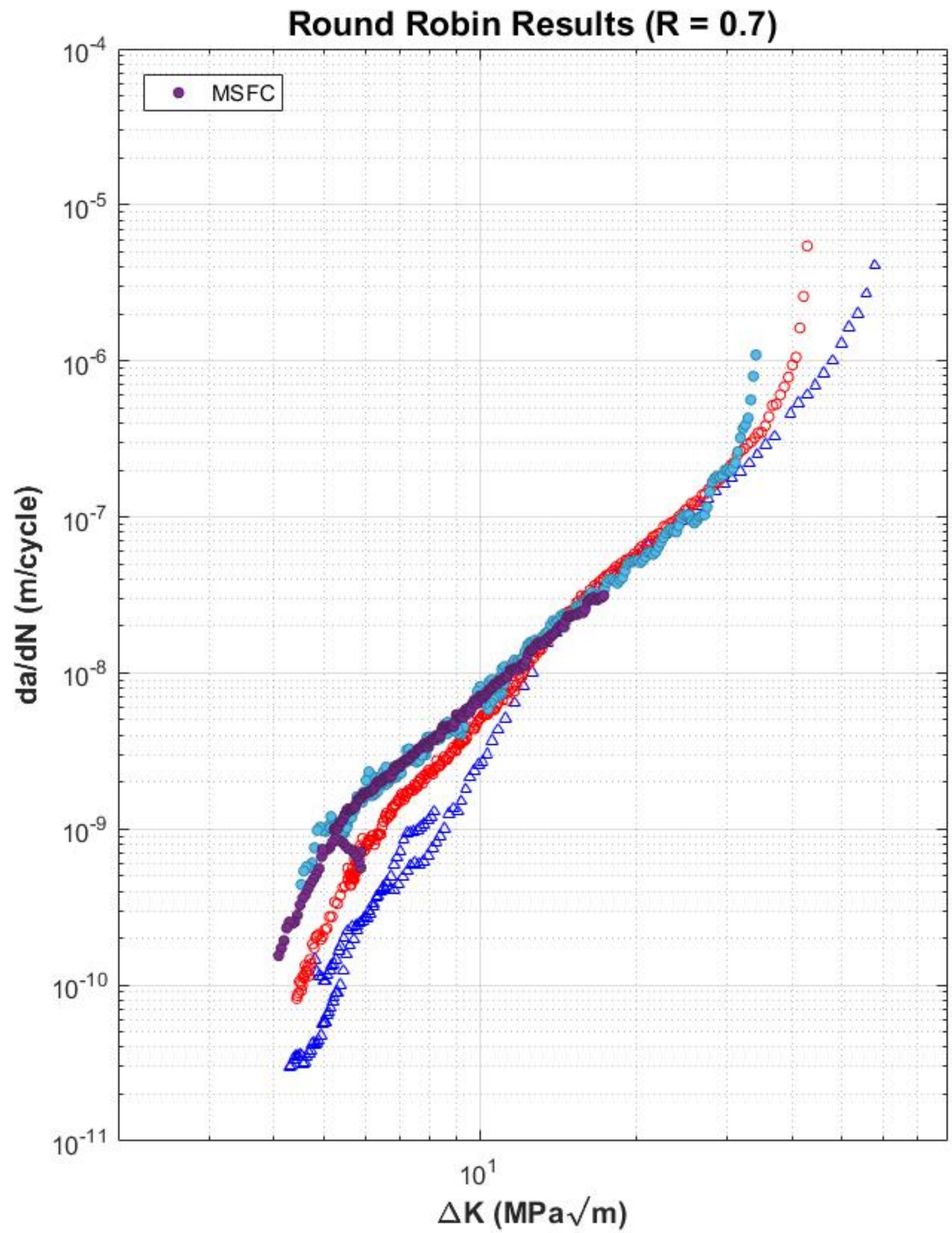
Fatigue Crack Growth

- Higher observed growth rates compared to wrought 718 near-threshold.



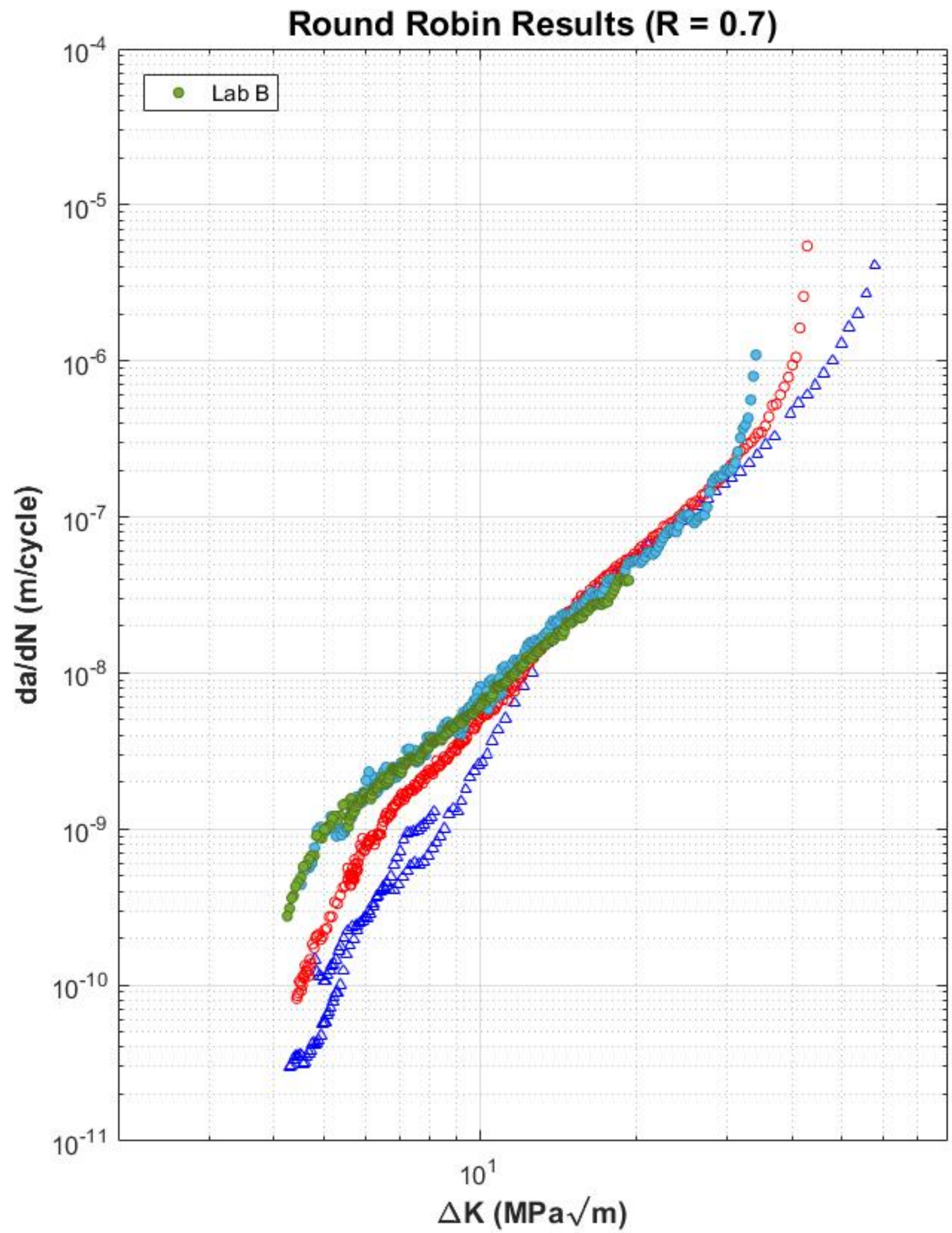
Fatigue Crack Growth

- MSFC - Consistent with M1 data.



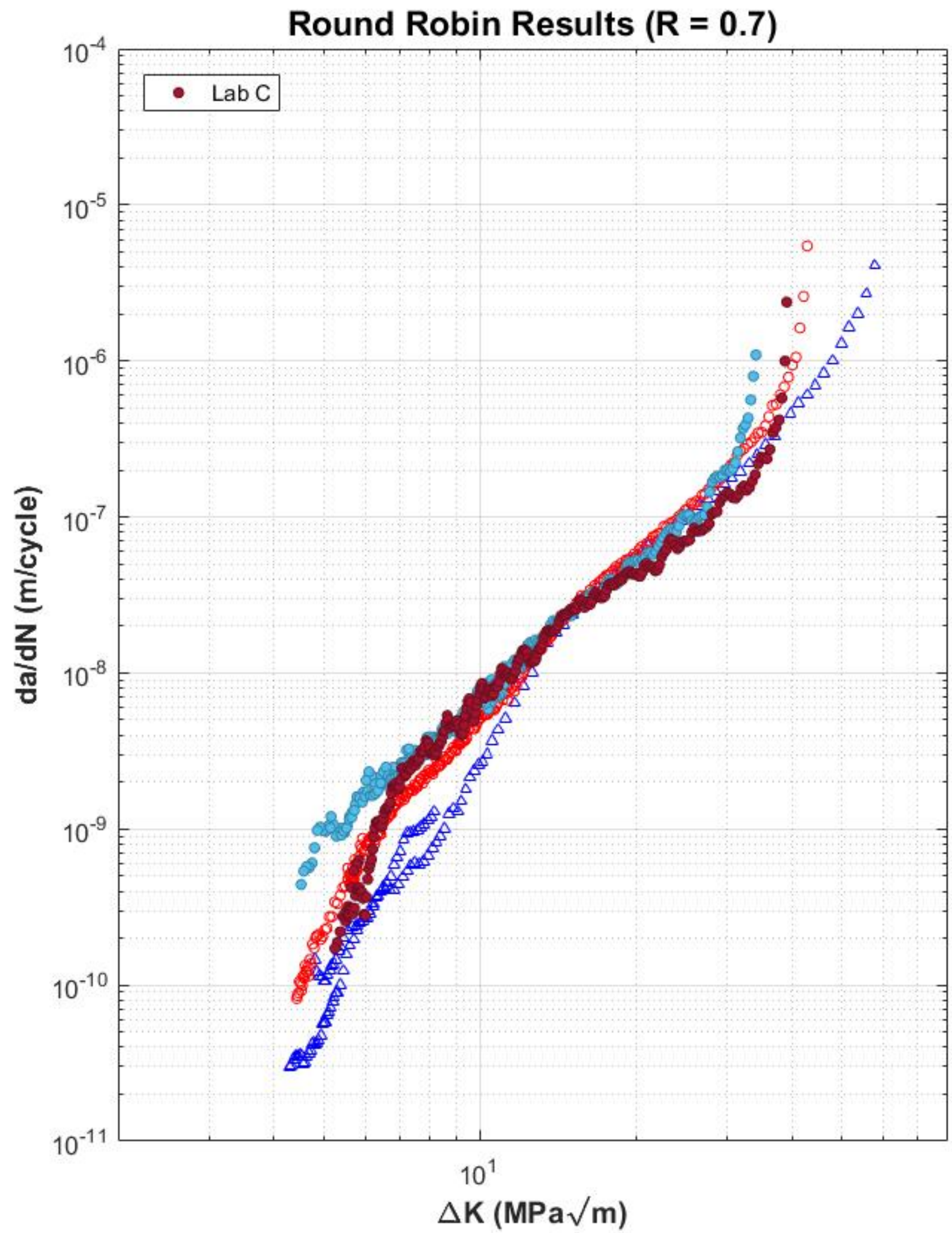
Fatigue Crack Growth

- Lab B - Consistent with M1 data.



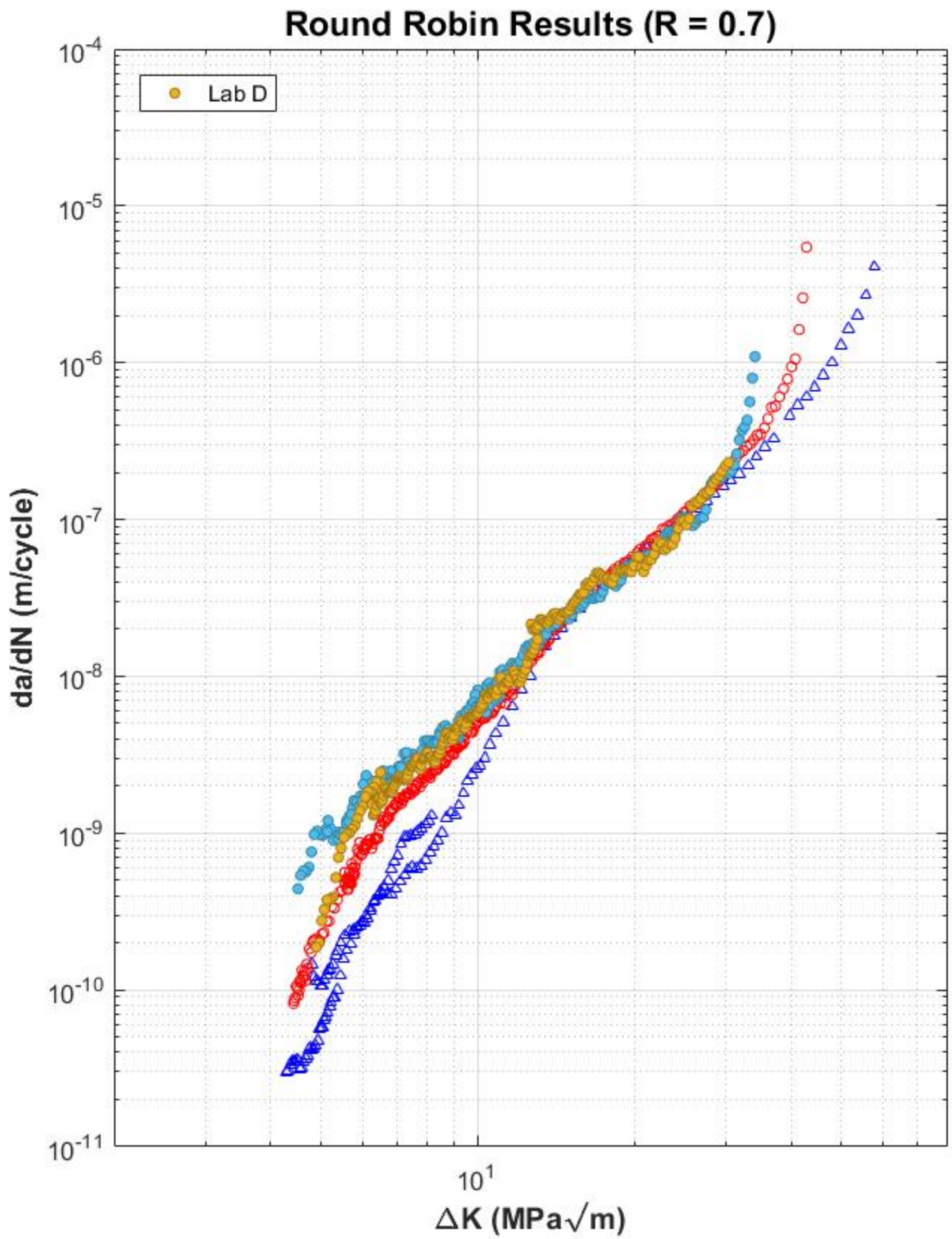
Fatigue Crack Growth

- Lab C - Lower crack growth rates near-threshold compared to M1 data. More closely follows Newman data.



Fatigue Crack Growth

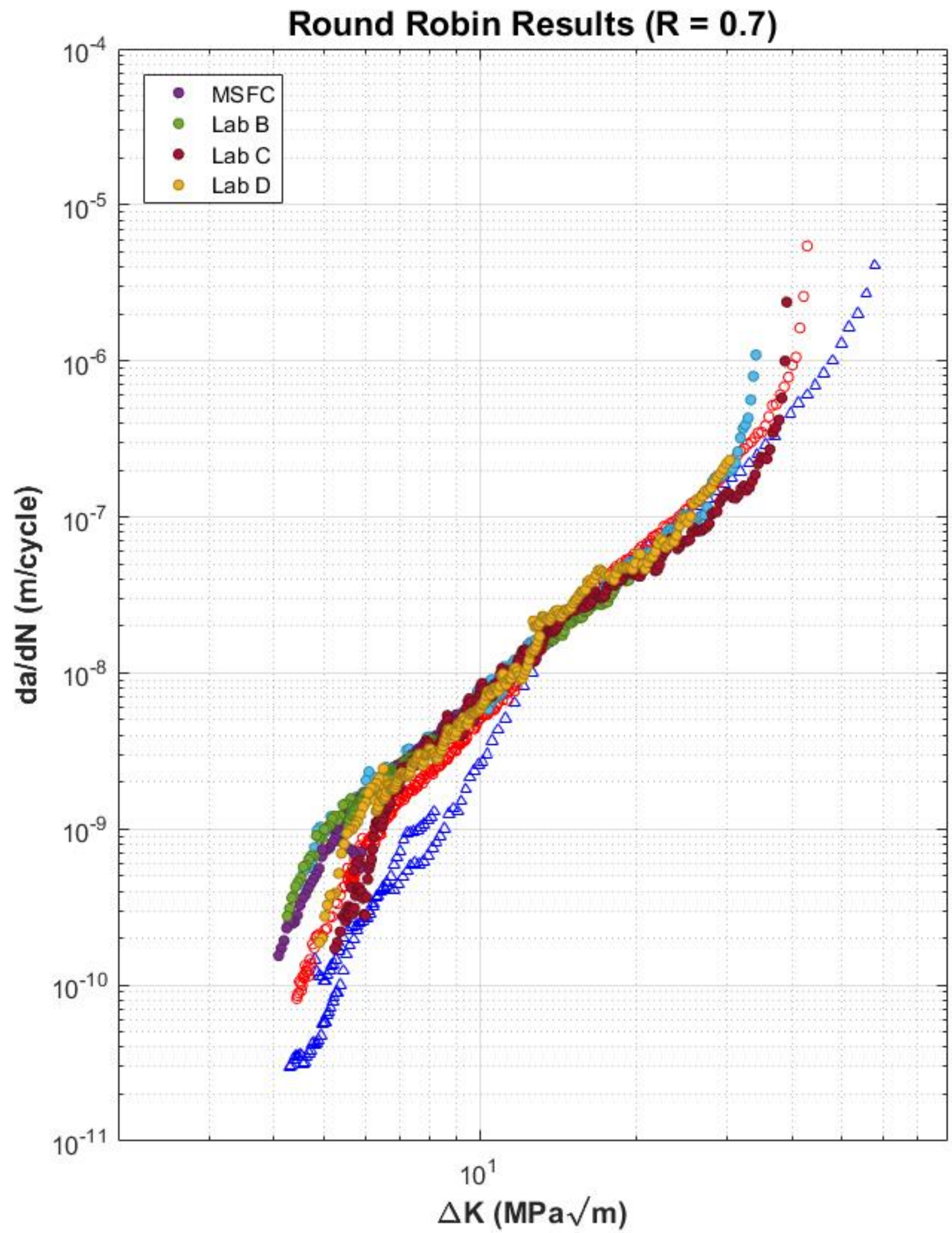
- Lab D - Lower crack growth rates near-threshold compared to M1 data. More closely follows Newman data.



Fatigue Crack Growth

- MSFC & Lab B: Consistent with M1 data

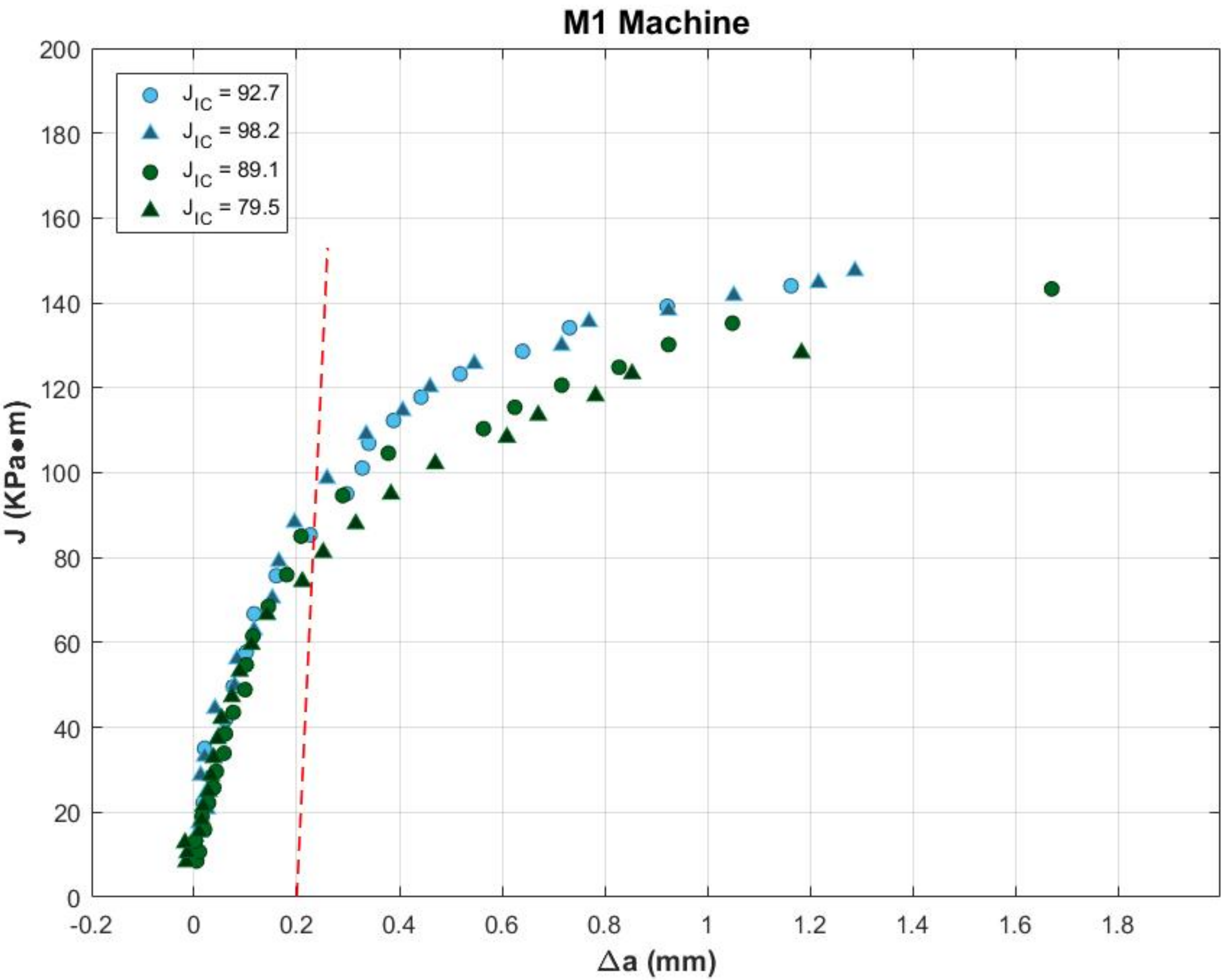
- Lab C & Lab D: Consistent with Newman data



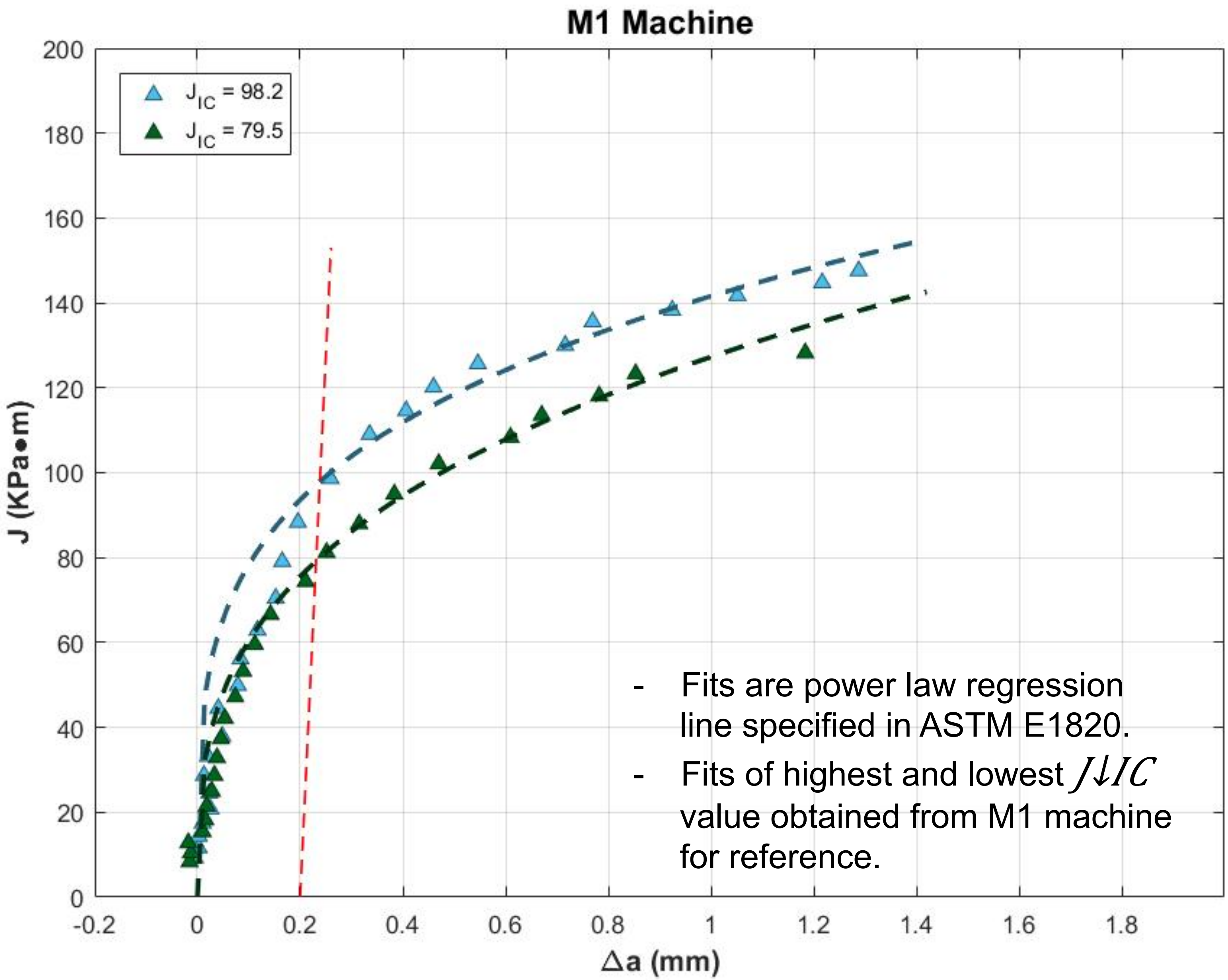
Fracture Toughness Results

- Round Robin
- SLM 718
  - Stress relief, HIP, ASM 5664 Heat Treatment
- ASTM E1820
  - J-R vs Δa
  - Legend lists J_{IC} value obtained from ASTM E1820

Fracture Toughness Results

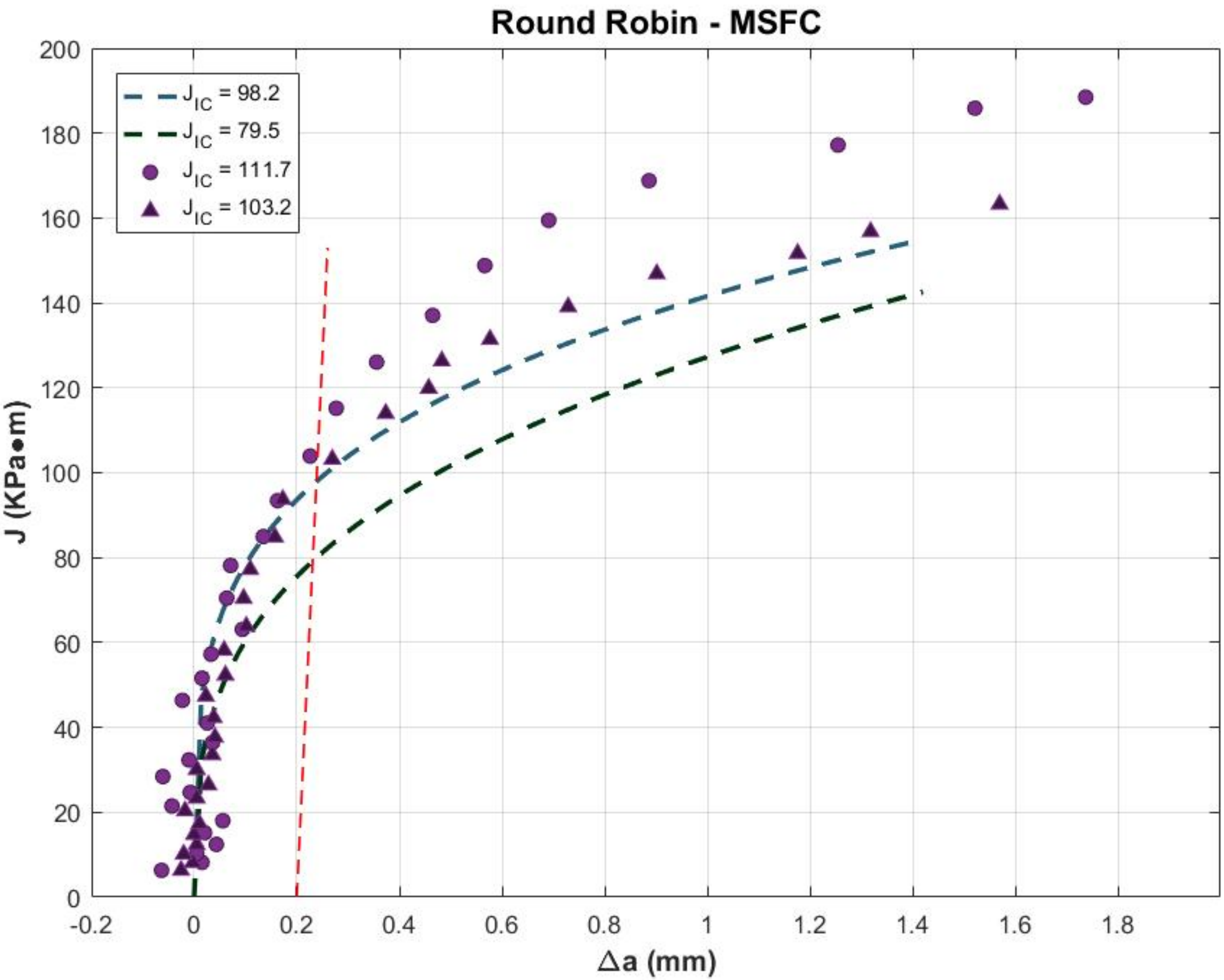


Fracture Toughness Results

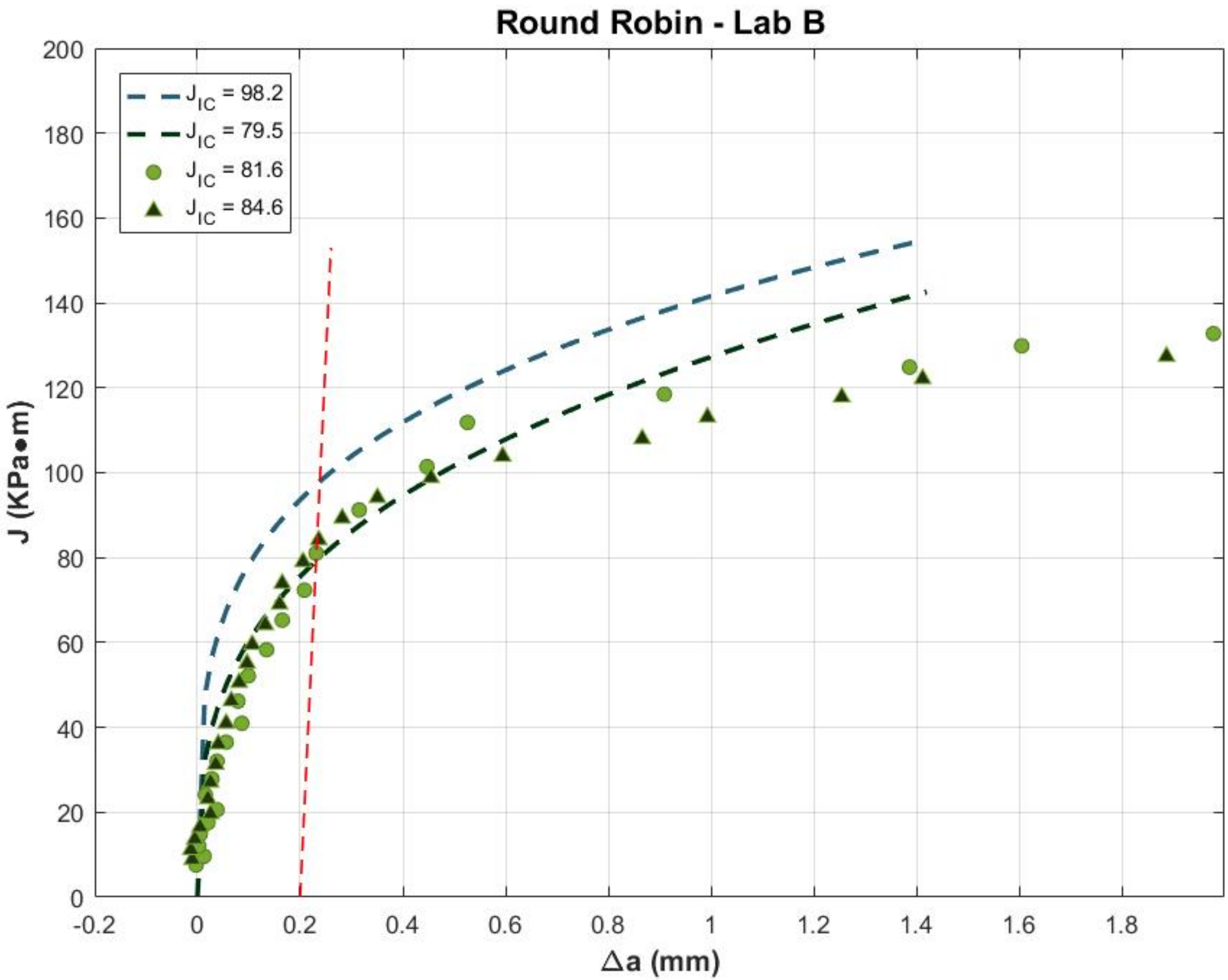


- Fits are power law regression line specified in ASTM E1820.
- Fits of highest and lowest J_{IC} value obtained from M1 machine for reference.

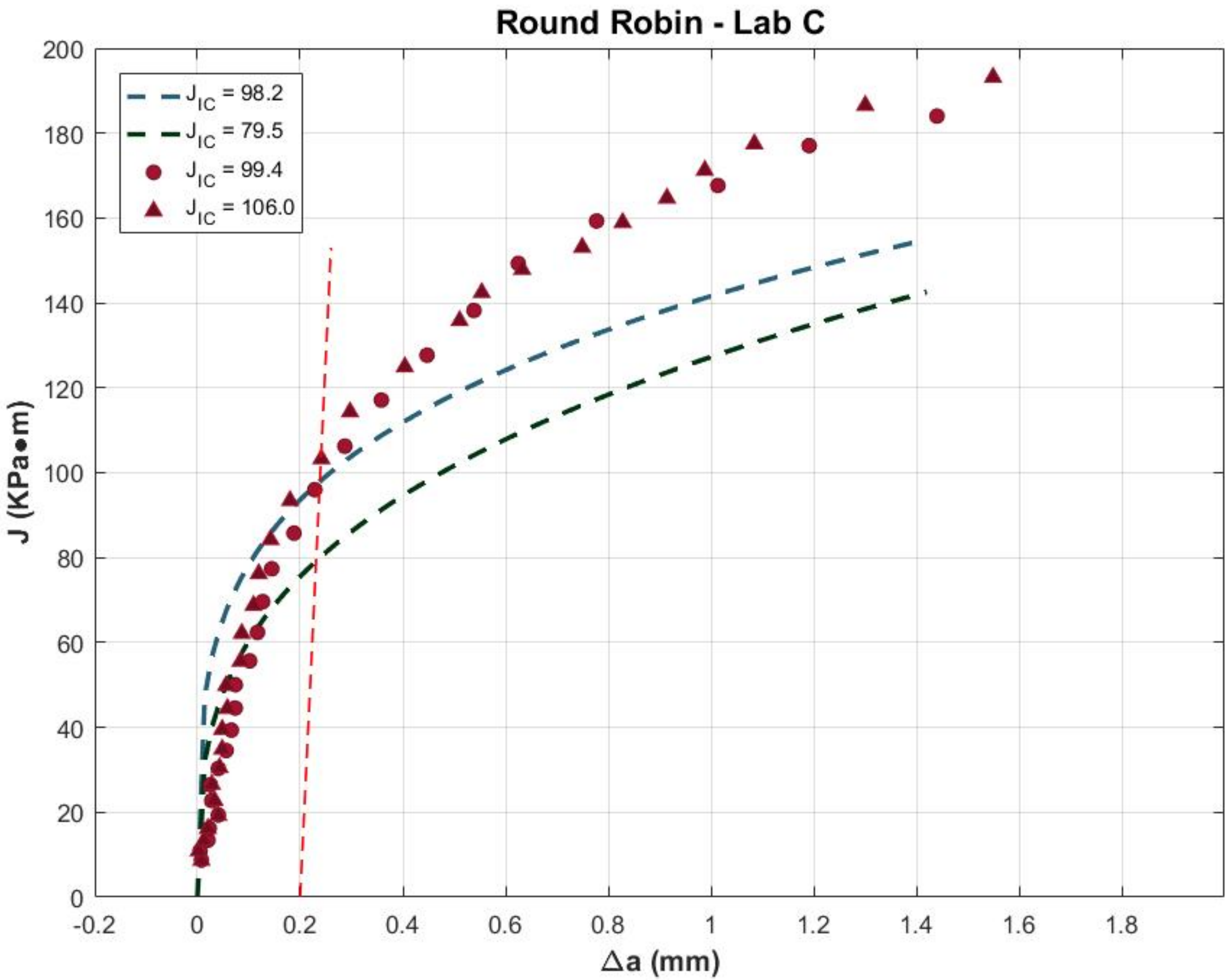
Fracture Toughness Results



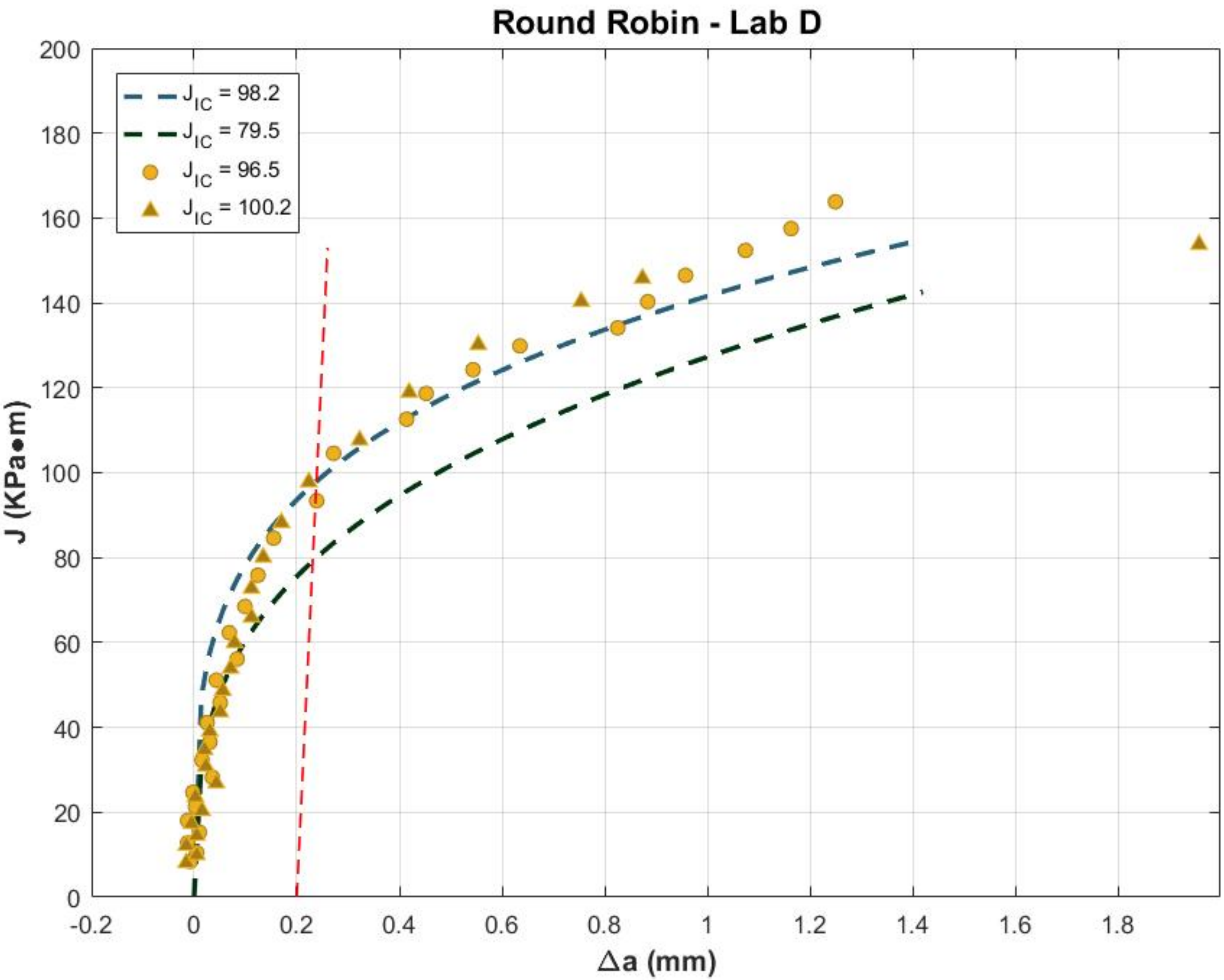
Fracture Toughness Results



Fracture Toughness Results



Fracture Toughness Results



Fracture Toughness Results