Digital Twin Model for Advanced Manufacture of a Rotating Detonation Engine Injector

This project will utilize a **digital twin material model (DTMM)** for the optimum application of advanced manufacturing (AM) techniques to advance the state-of-the-art in **rotating detonation engine (RDE) injector design**

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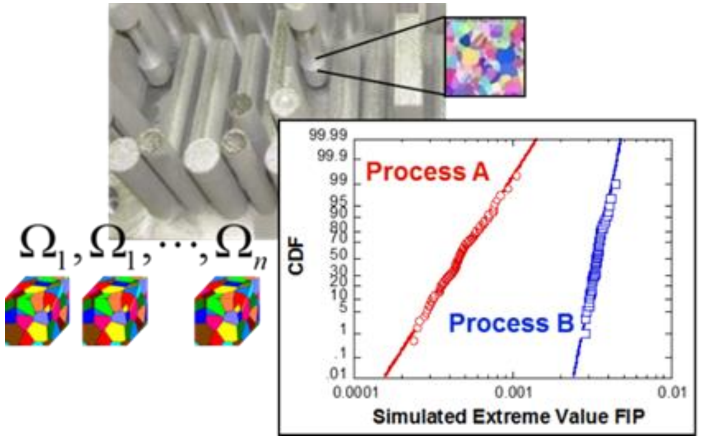
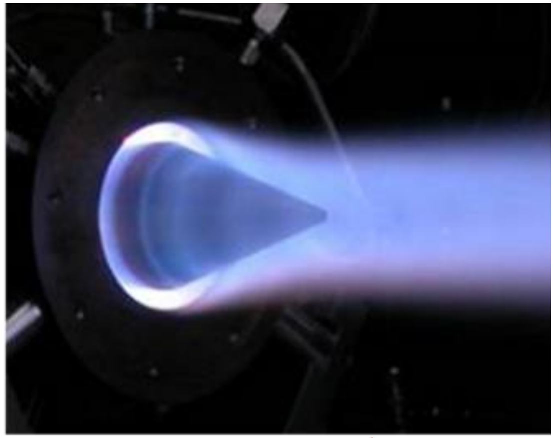
Lead Engineer

June 8, 2021

DTMM



RDE



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The 1st project objective is to demonstrate a low-loss RDE injector

*Focus of previous work by AR, SwRI, and others under an earlier NETL program

- RDE injector pressure losses must be reduced to field a commercially viable power generation system
- This project is using AM as an enabling technology to build an operable injector with reduced losses

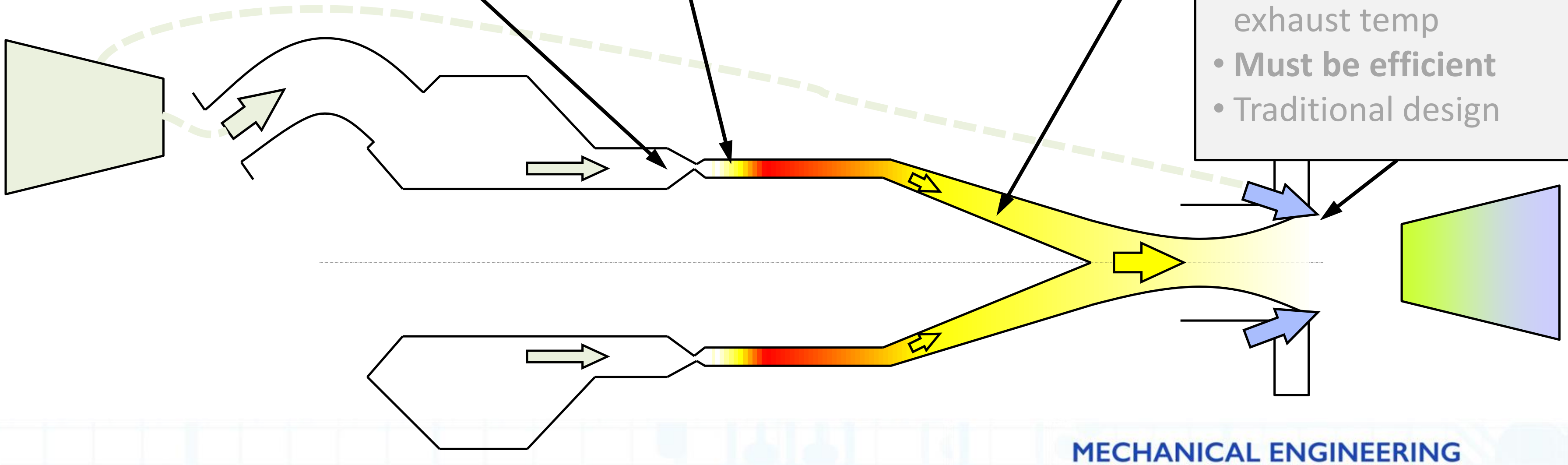
Sources of Significant Pressure Loss

ISOLATOR/INJECTOR
- Reduce upstream pressure fluctuations
- Various devices shown to be effective
- Prior program demonstrated <20% Pt loss, and peak oscillation

RDE COMBUSTOR*
- Air/NG detonation difficult due to large cell size (300mm @ STP)
- Requires large combustor
- Injection, mixing significant

DIFFUSER*
- Primary focus of Phase I, II program
- Reduce downstream pressure fluctuations
- Minimal total pressure loss

BYPASS MIXER
- May be req'd to lower exhaust temp
- **Must be efficient**
- Traditional design



The 2nd project objective is to develop a material model that predicts fatigue performance of the AM injector

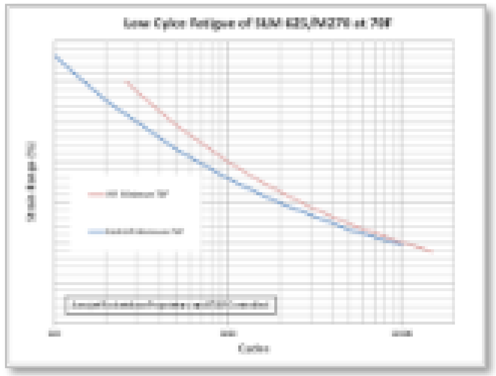
Machine Parameters

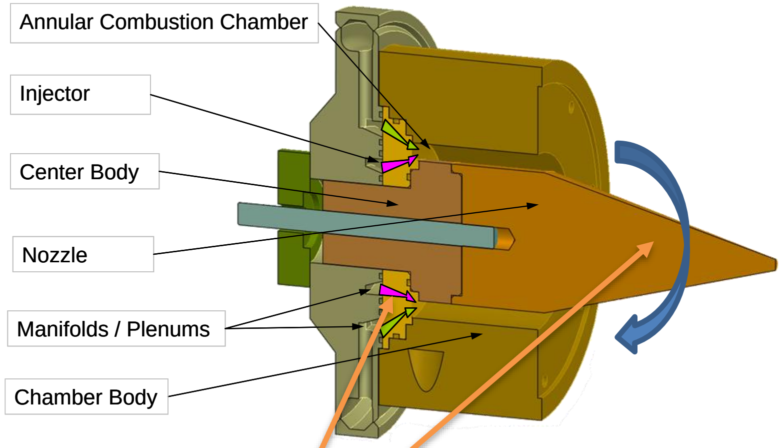
Material Properties

Part Performance

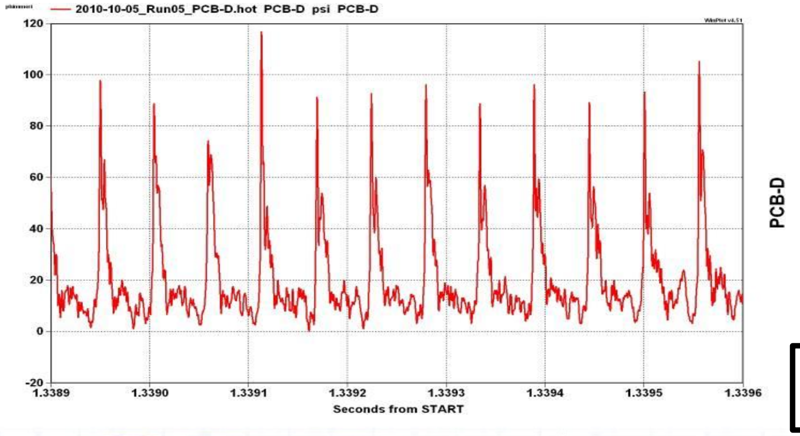
Modeling here…

…reduces iteration here





Dynamic pressure environment of an RDE
~5 kHz pressure oscillations

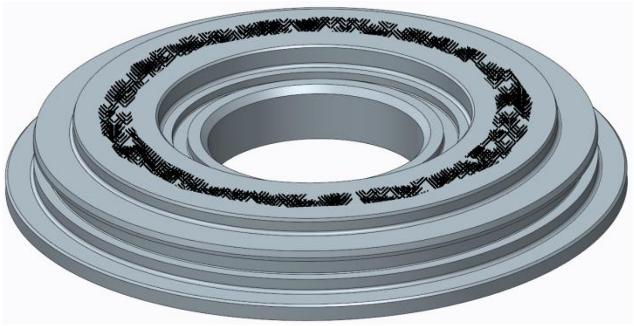


Pressure oscillations create a high frequency wobbling motion that transmits loads to the injector

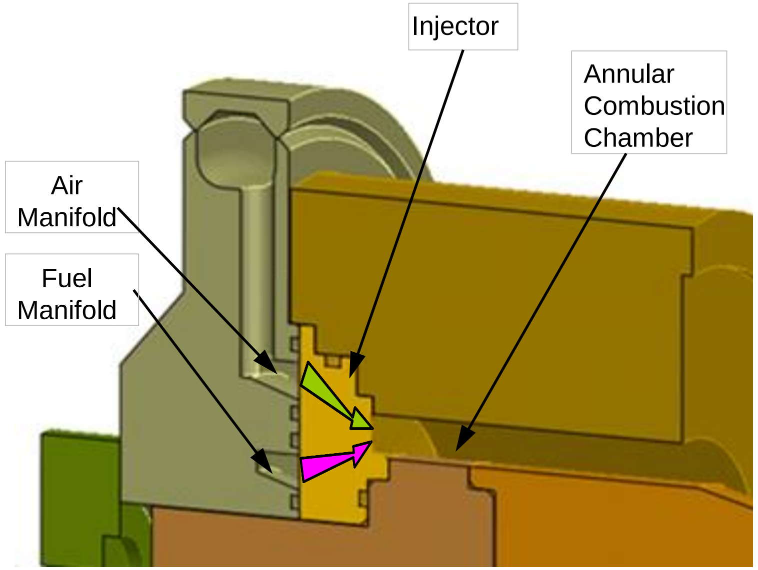
The injector is potentially subject to high cycle fatigue, particularly in the context of a commercial power generation application

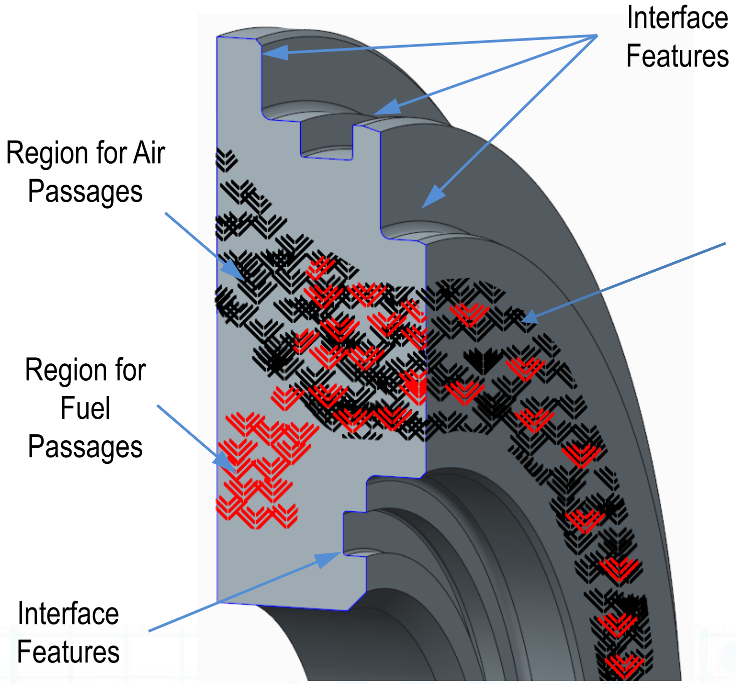
AM process settings must be selected to maximize injector fatigue strength

Two injectors have been designed to address the project objectives



- Injector #1
  - Opens the oxidizer flow path
  - Low pressure losses
  - Fired a few times to assess operability and pressure losses (project objective #1)
- Injector #2
  - Constricts the oxidizer flow path
  - Has more pressure losses
  - Lower risk of operability issues
  - Will be repeatedly fired to develop high cycle fatigue for comparison to model predictions (project objective #2)

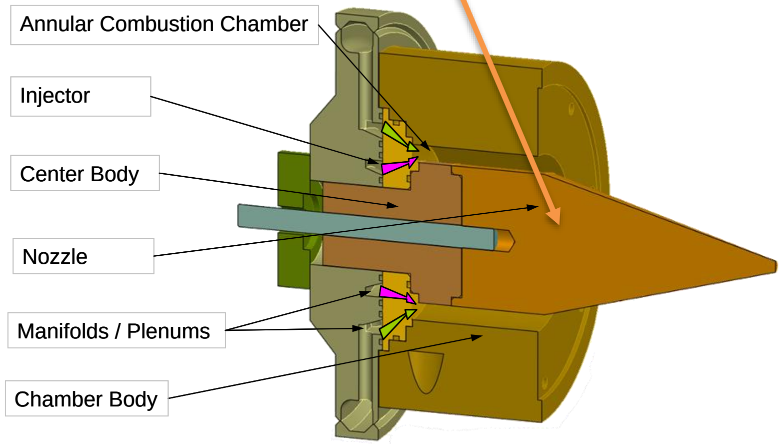




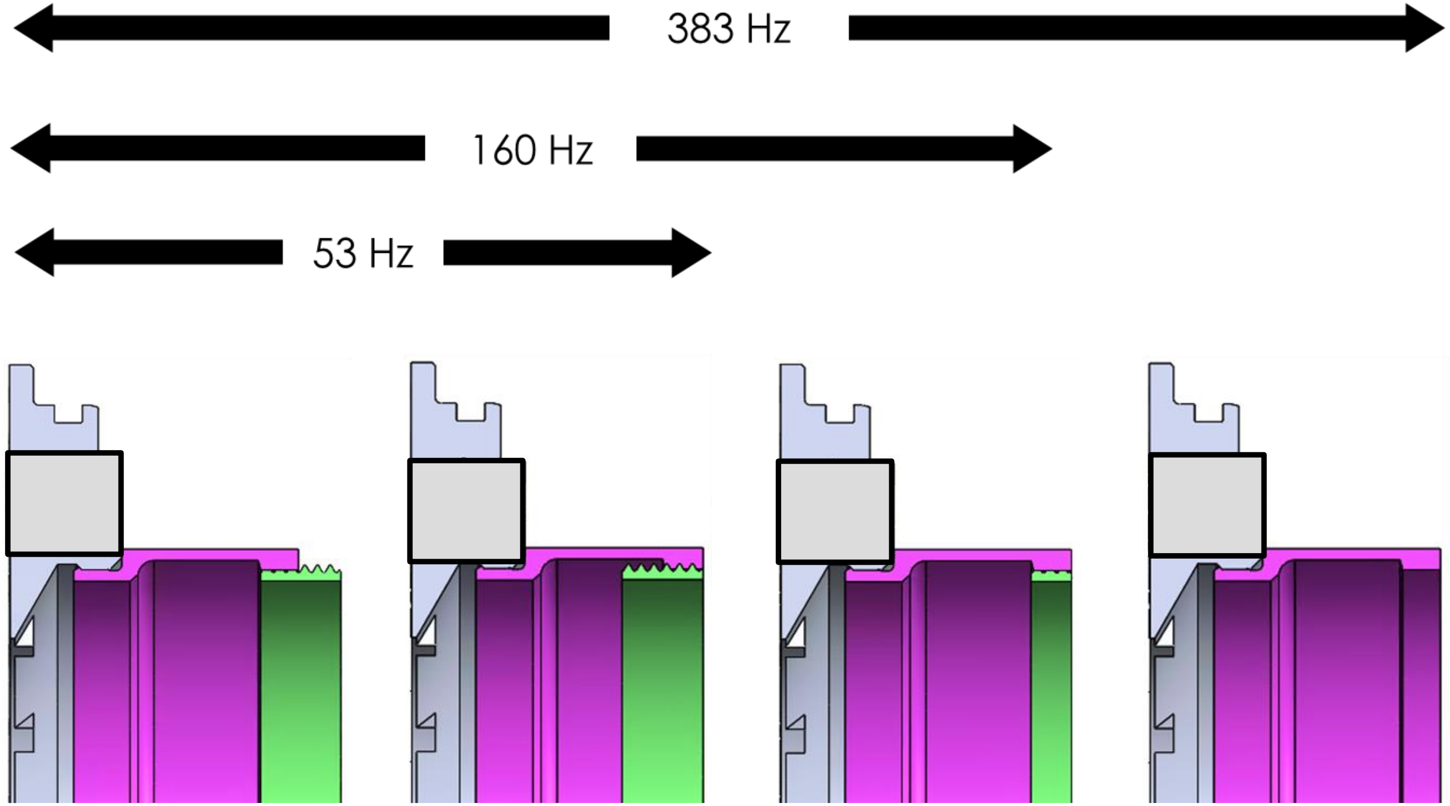
Location of aggressive mixing geometry that is enabled by additive manufacturing

A high cycle fatigue condition is designed into the RDE system to test material model predictions

Typical development hardware uses a massive center body that filters high frequency excitation



This project uses a lightweight center body with adjustment features to align the mechanical natural frequency with the RDE detonation frequency



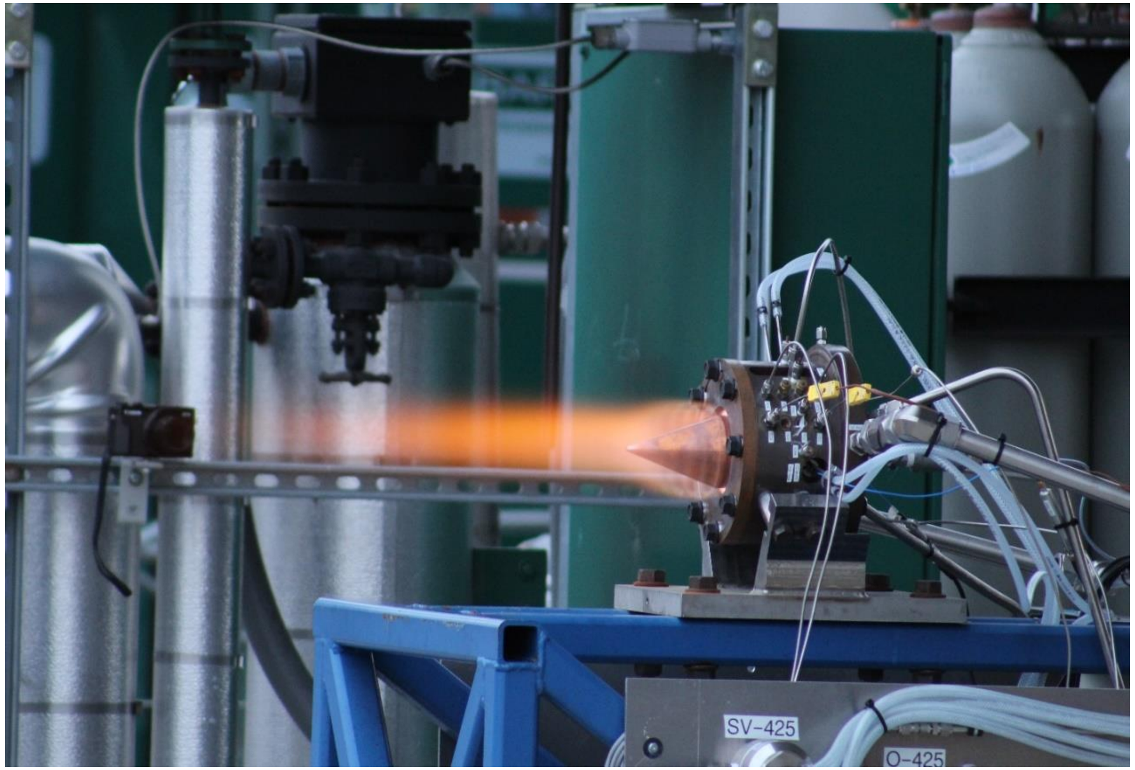
Additively manufactured injectors achieve key internal dimensions in as-built condition, but some challenges must be mitigated

- The injector is used primarily in an as-is condition, with clean-up machining only applied to mating surfaces
- The as-built dimensions of key internal features were achieved in Injector #1
  - Fillet radius that defines the expected fatigue location is within 0.002 inches of target
  - Internal fuel passage diameter is also within 0.002 inches of target
- Injector #1 shrank considerably in the hot-isostatic-pressing (HIP) treatment
  - Global shrinkage between 7% and 9%
  - Mating features must be oversized in the AM build so that sufficient material remains for clean-up machining
- While AM enables more complex internal geometries, the removal of AM build supports is a challenge
  - The part design must carefully consider build support locations to avoid labor-intensive clean-up operations
  - Build support approach is being revised for Injector #2

Exceptional pressure-loss performance has been demonstrated in the hot-fire testing of Injector #1

- Injector #1 was tested 64 times over 3.5 days in March 2021
  - Up to 28 tests performed per day
- Tests explored a variety of operating conditions in terms of mass flux, equivalence ratio, and oxygen concentration
  - 58 tests achieved combustion
  - 36 tests exhibited sustained detonation
  - 26 tests operated with a single detonation wave
- Static-to-static injector pressure loss varied with configuration, but it was as low as 3.6% for cases with detonation
  - Much less than the 30% or more value for a choked RDE injector

The AR & SwRI 10-cm RDE firing with Injector #1



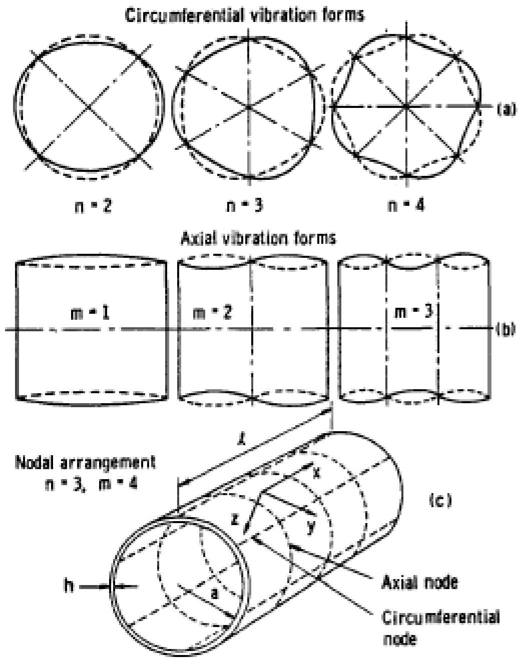
1st Objective Complete: Additive manufacturing enables RDE injectors with pressure loss characteristics similar to conventional gas turbine injectors

Vibration of the injector was <u>not</u> demonstrated in the hot-fire testing of Injector #1

- The operable detonation frequencies were lower than expected based on historical performance of choked RDE injectors
  - Suggests that there is room to improve the mixing properties of the injector

- As a result, the Injector #1 testing did not excite the wobble mode
  - The testing did subharmonically excite a centerbody shell mode at 4x the detonation frequency, but this does not transfer motion to the injector
- Additional tuning rings are being made for testing Injector #2 to ensure that we can operate at the wobble mode while avoiding the shell modes

Breathing Modes of a Thin Cylindrical Shell

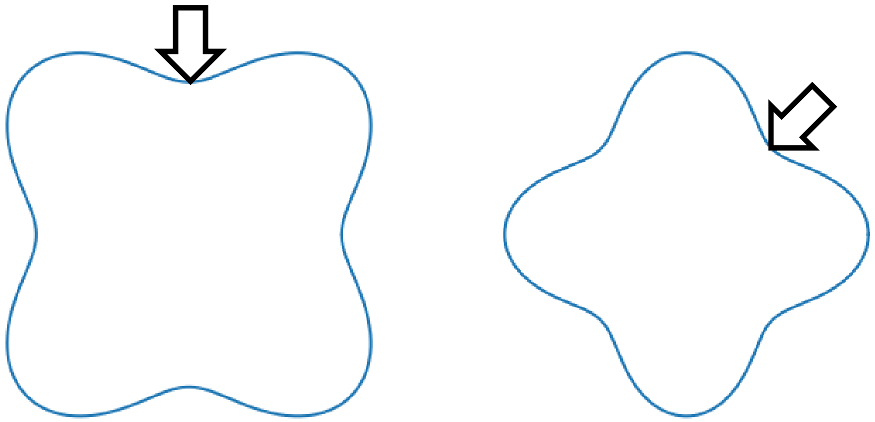


¼ Subharmonic Forcing of a 4-Lobe Mode

Positive Interference

Pressure pulse location at

$\phi = 0$ $\phi = \pi$



RDEs can excite shell modes well above their operating frequency

The material model is developed from statistical analysis of sample build microstructures and property tests

Processing

DofE Builds

Collect all processing history for each discretized digital volumes

SwRI, AR

Structure

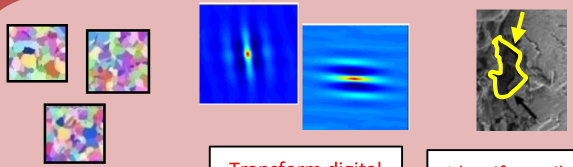


Image each built volume to resolve critical attributes of the structure

Transform digital images to a statistical quantification of the structure

Identify attributes controlling HCF from characterizing fracture surfaces

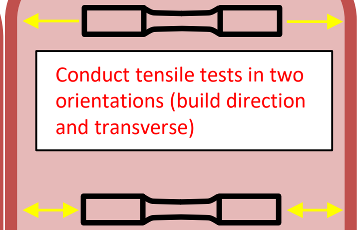
Compute low-dimensional description of microstructure

Establish the P-S relationship via regression

Establish the S-P relationship via regression

GT

Properties

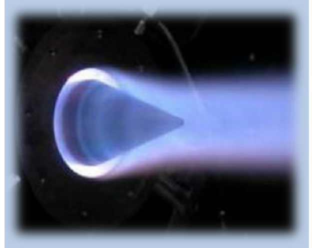


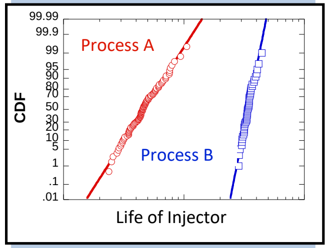
Conduct tensile tests in two orientations (build direction and transverse)

Determine HCF behavior under reference condition in two orientations (build direction and transverse)

GT, SwRI

Performance





Injector Builds

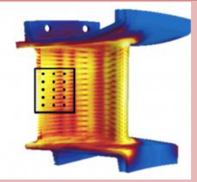
Collect all processing history and loading from FEA for each discretized digital volumes

AR, SwRI

Predict the low-dimensional descriptor of microstructure of each discretized volume

GT

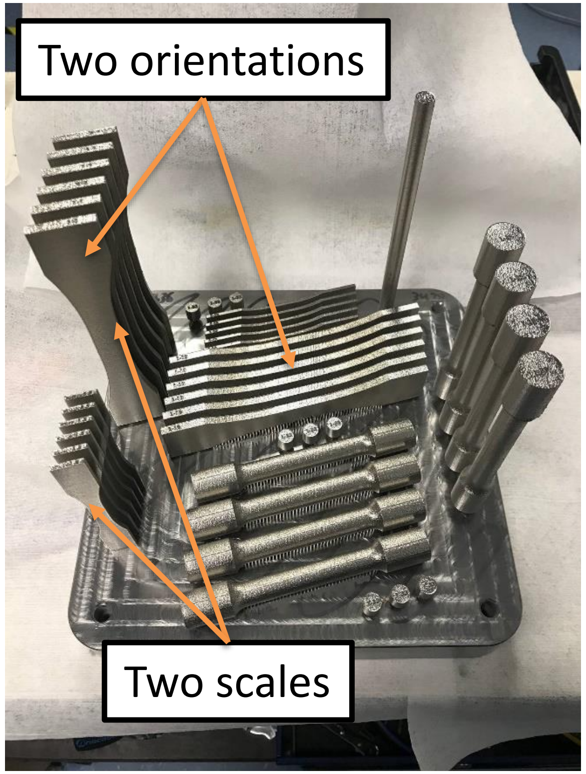
Impose macroscopic stress and thermal FEA of injector to each discretized volume in the digital twin to predict properties and state of each volume



Prognose performance of each volume in the digital twin; validate predictions of microstructure and properties

GT, SwRI

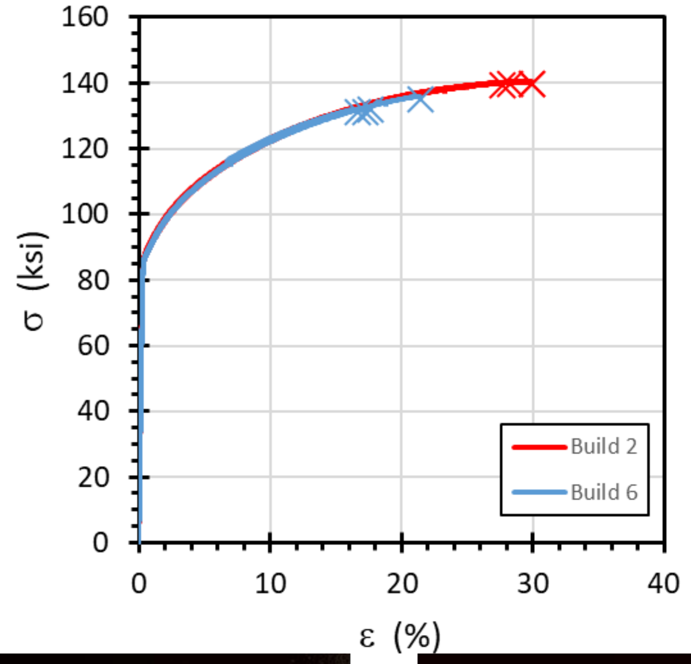
1 of 11 sample builds manufactured to create data for the material model



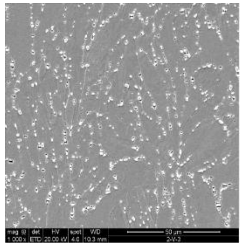
Sample build variables include AM machine type, scan speed, hatch spacing, and post-build annealing

Untracked process variations are found to be a limiting factor in the modeling of AM materials

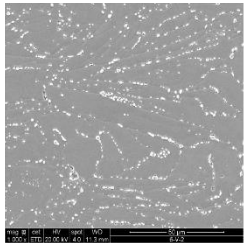
Identical builds exhibit notably different ductility (Built on same machine according to the same settings, but on different days)



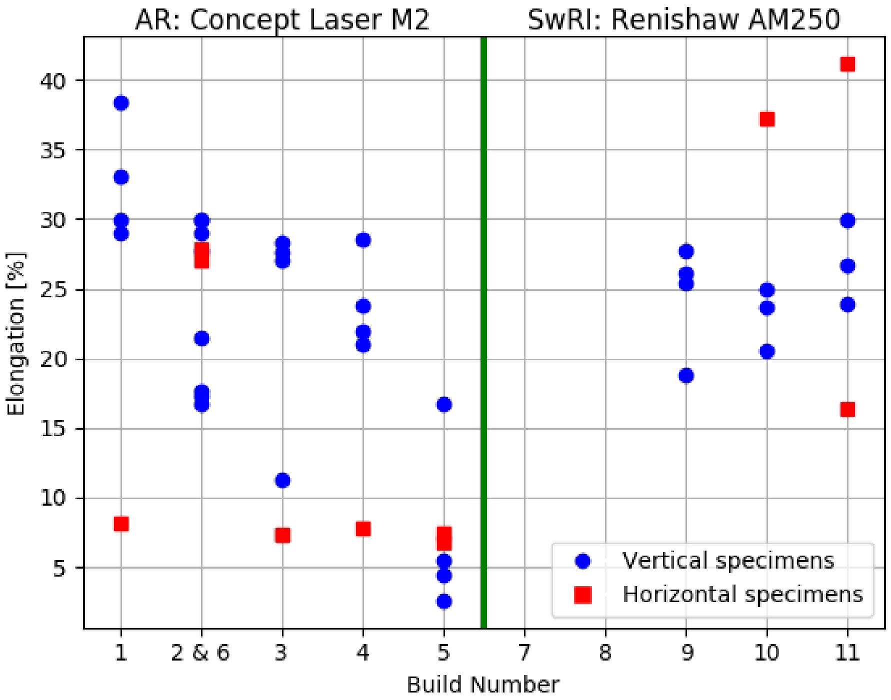
Build 2 microstructure

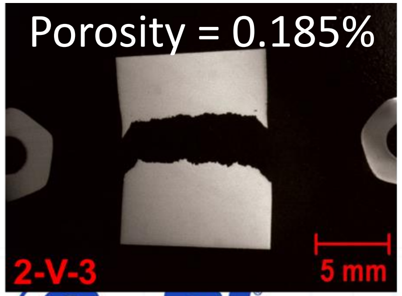


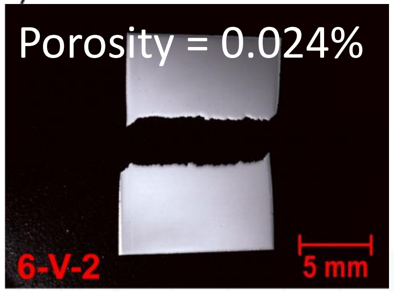
Build 6 microstructure



Significant property variations also exist in specimens within a single build



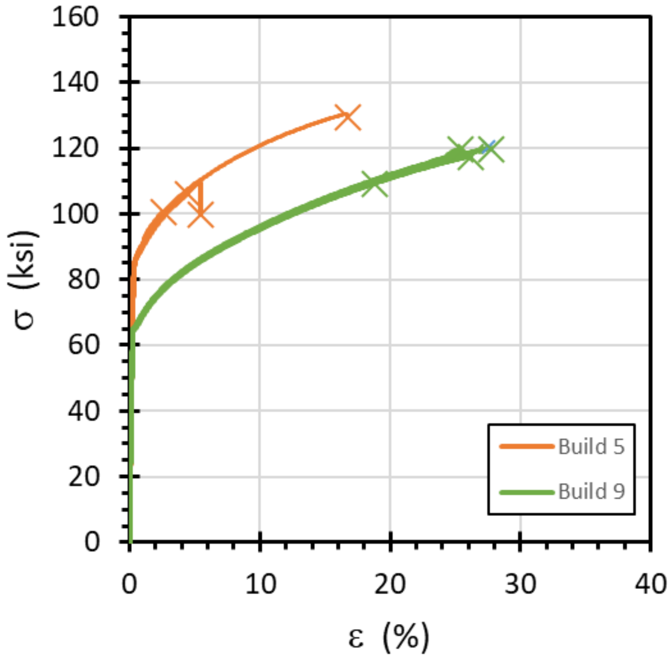




Property difference occurs despite the builds having identical microstructures and similar porosities (the lower ductility build actually has less porosity). Difference may be related to small differences in the prevalence of surface defects.

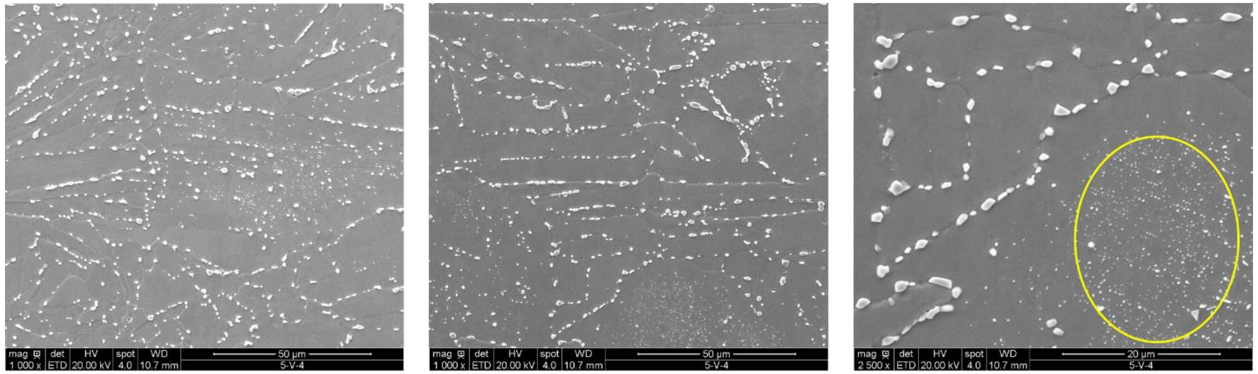
Parts from additive manufacturing machines of different makes and models are notably different even when the same settings are used

Builds 5 and 9 use equivalent settings
Build 5: AR's Concept M2
Build 9: SwRI's Renishaw 250

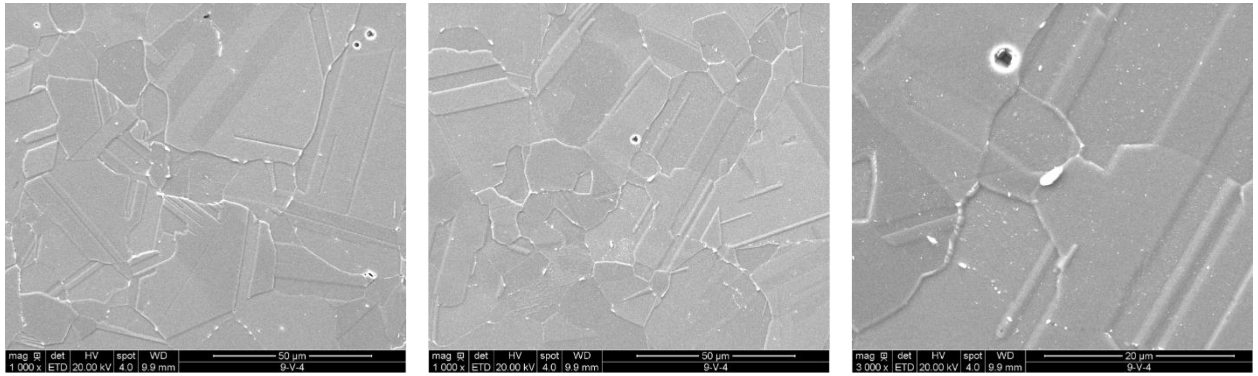


The two AM machines generate completely different microstructures

Build 5 microstructure



Build 9 microstructure



The build parameters are related to microstructure using three different machine learning methods

- Regression methods that are trained against the principal component reduction of the surface roughness and porosity statistics
  - Parametric Linear Multiple Regression (MR)
  - Support Vector Regression (SVR)
- Regression methods that are trained directly against the full statistics
  - Multiple Tensor-on-Tensor Regression (MTOTR)
- The MTOTR method performs the best for this small dataset, but is more computationally demanding

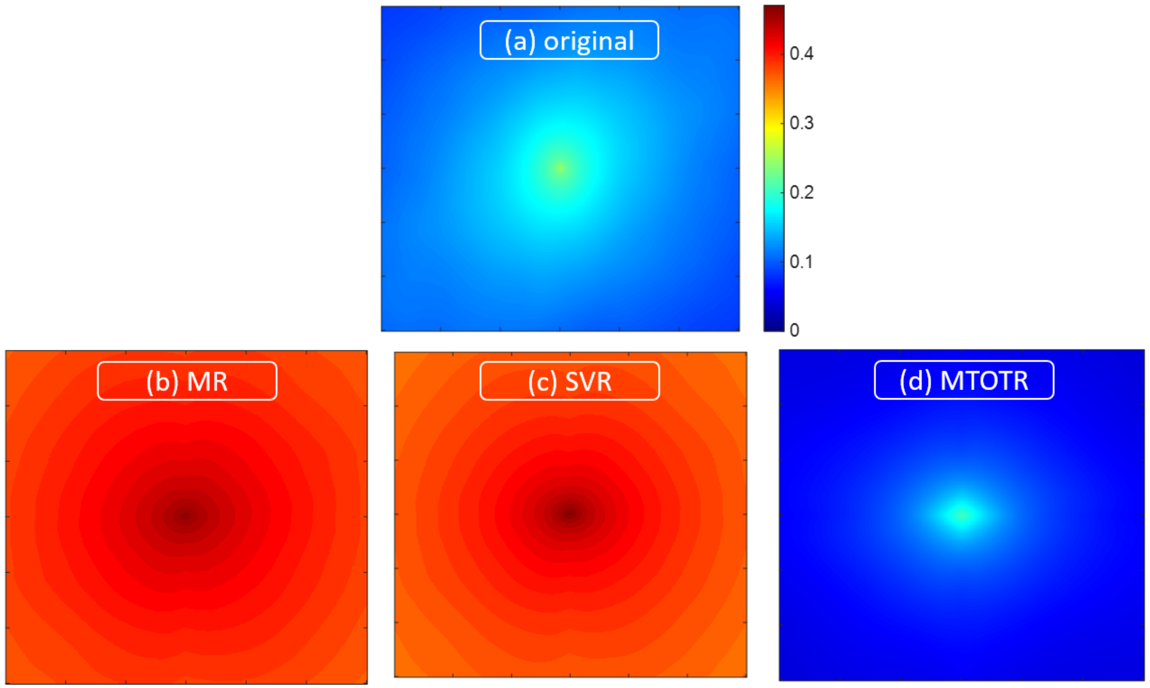
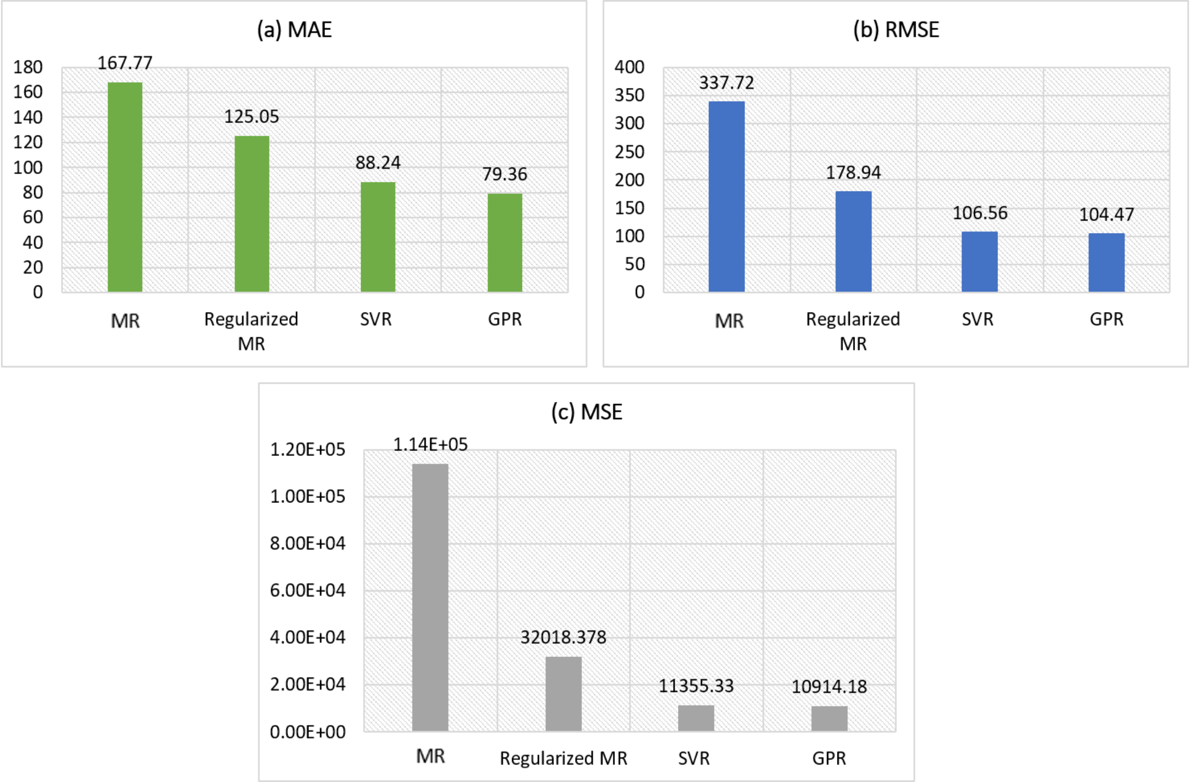


Illustration of an (a) an original 2-point correlation representation of a sample surface roughness and the estimation of the same image using the models developed by the (b) MR, (c) SVR, and (d) MTOTR algorithms. Color scale is the same for all images.

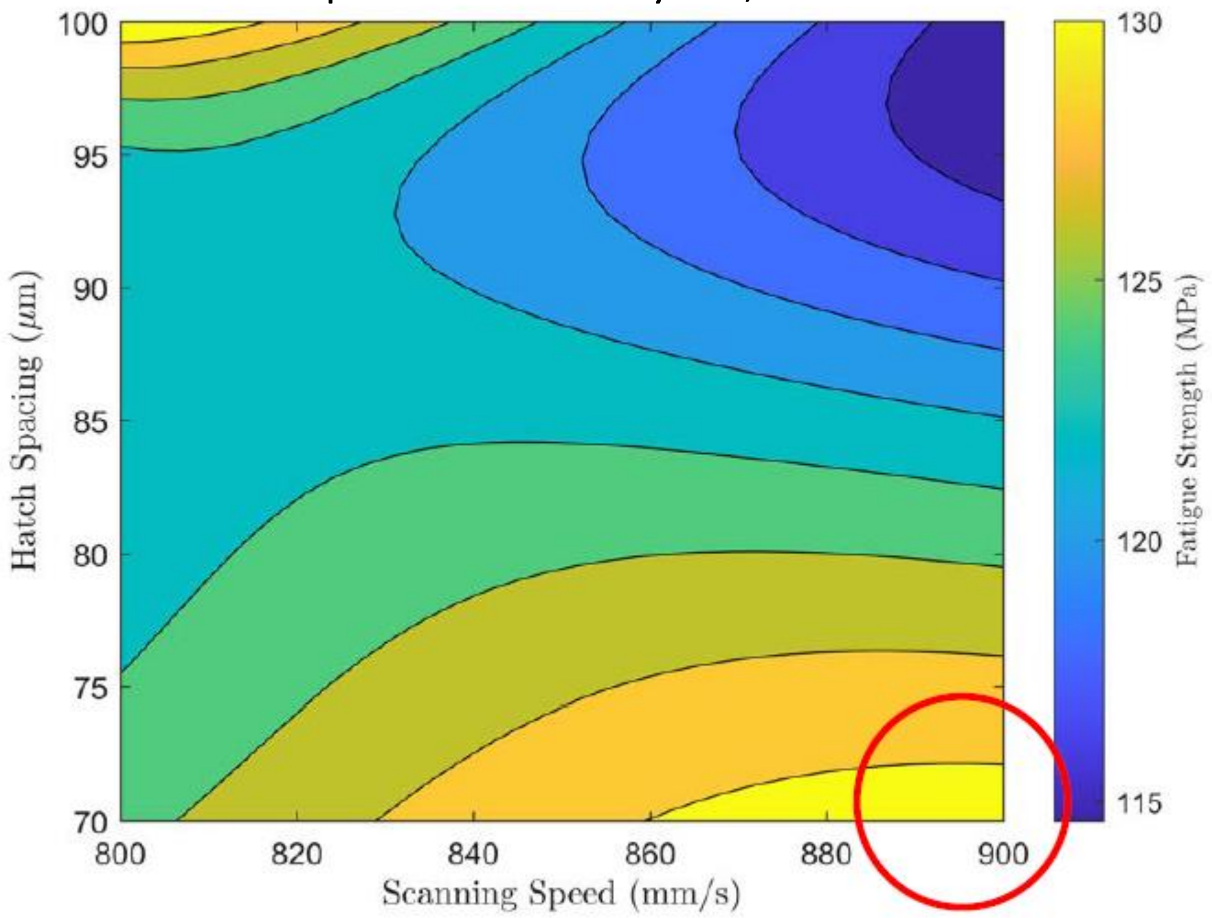
The microstructure is related to fatigue strength using four different machine learning methods



- MR and SVR are the same methods as used in the parameter-structure model
  - MTOTR was not applied in this linkage because it is not as useful when predicting a scalar quantity
  - Regularized MR used ridge regression to improve upon the base MR method
- Gaussian Process Regression (GPR), a prevalent surrogate modeling technique that supports uncertainty quantification
- GPR performs the best

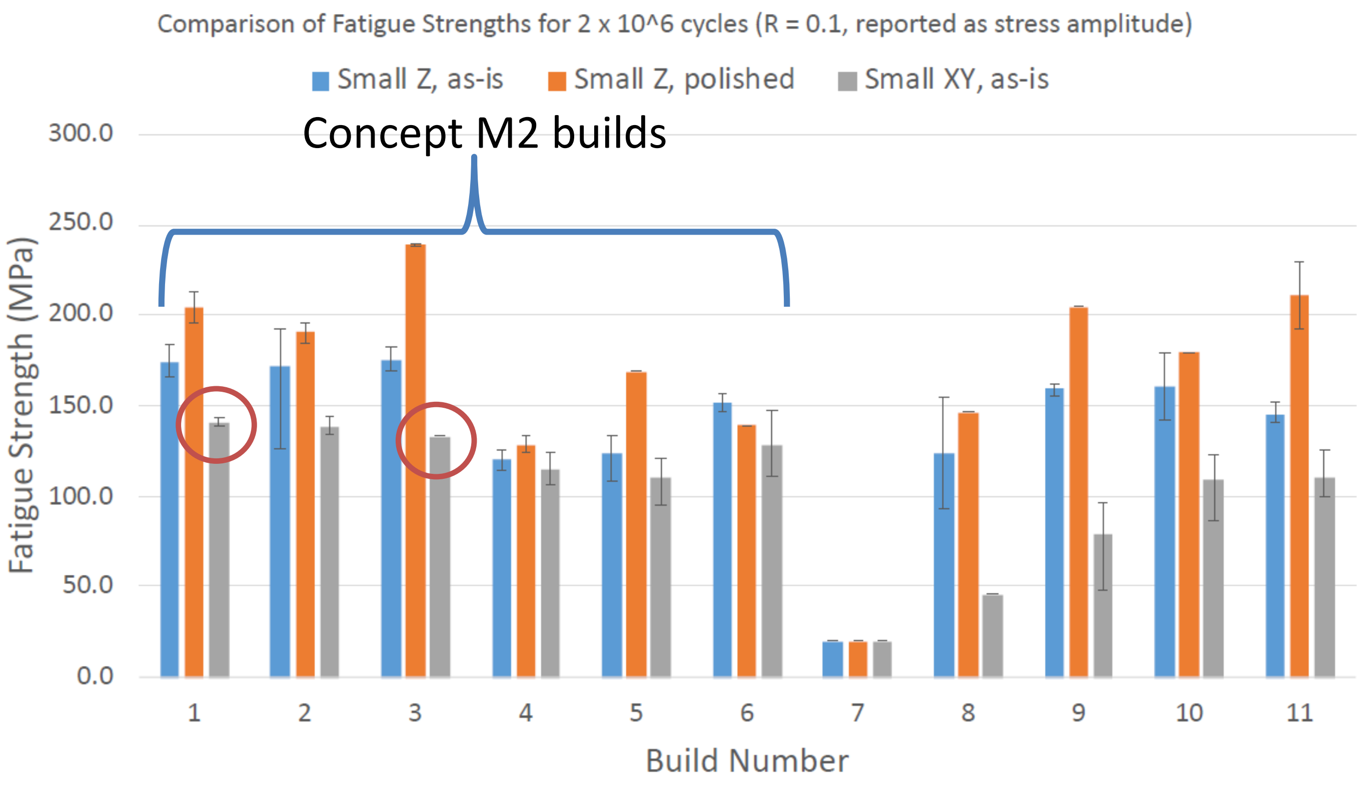
Optimal build parameters for Injector #2 are selected using the DTMM

Fatigue Strength for Small As-Built Specimens in the As-Built Condition, Reported as Stress Amplitude for 2e6 Cycles, R = 0.1



- The predictions use the GPR Structure-Property model
- The model predicts a primary dependence on hatch spacing and a secondary dependence on scanning speed
- The model predicts no dependence on post-build annealing (the universally applied HIP wipes out any differences from the annealing)
- The optimal settings correspond to Build #3 from the sample build matrix

The model's selection of build #3 as an optimal point is a non-trivial result that would not be apparent in a simple data review

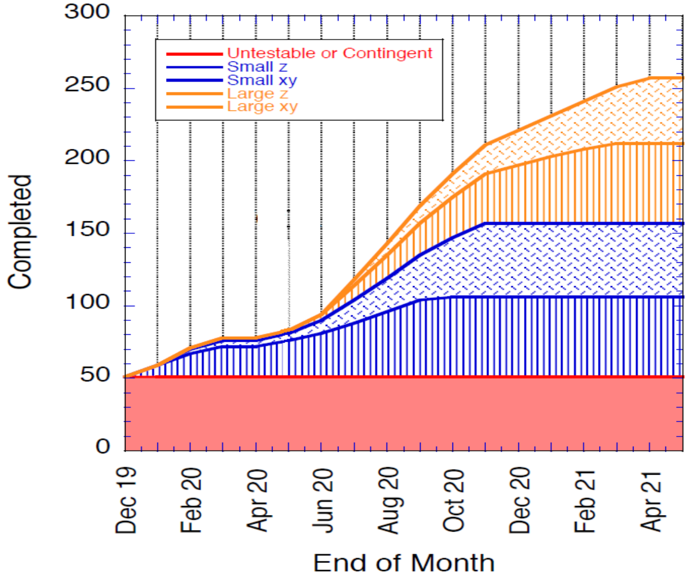


- The build #3 data point is below the build #1 average, and only limited data could be obtained for the build #3 X-Y specimens because of flaws related to build supports
- As shown on previous slides, there is considerable variation in the data
- By considering all of the data in a holistic manner, the model points us to the build parameters that are **most likely** to result in the best performance
- This can be different than the build parameters that happened to have the best performing specimens in the small data set

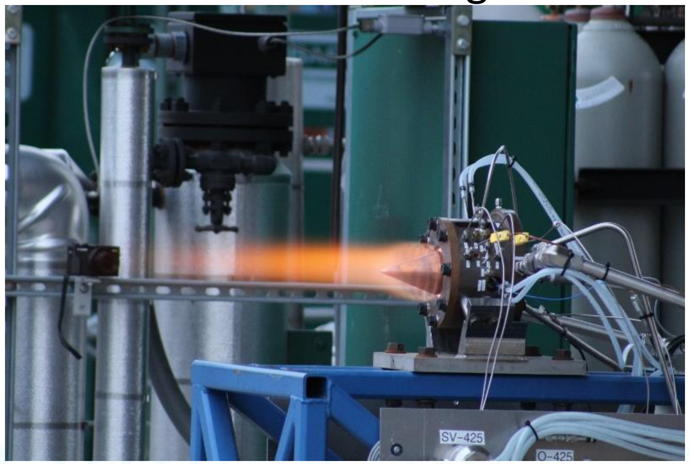
The project is on track for a September 2021 completion

- Injector design, manufacture, and test
  - Injector #1 testing is complete and low-loss operation was demonstrated
  - Injector #2 is in manufacturing
  - Hot-fire testing concludes in July 2021
- Material modeling
  - The first version of the material model was completed in January 2021
  - The material model was used to select the optimal build parameters for Injector #2
  - Model predictions will be compared to actual performance of Injector #2
    - Both microstructure and fatigue performance
  - Additional fatigue tests are underway and the material model will be updated at the end of project

Fatigue specimen testing schedule

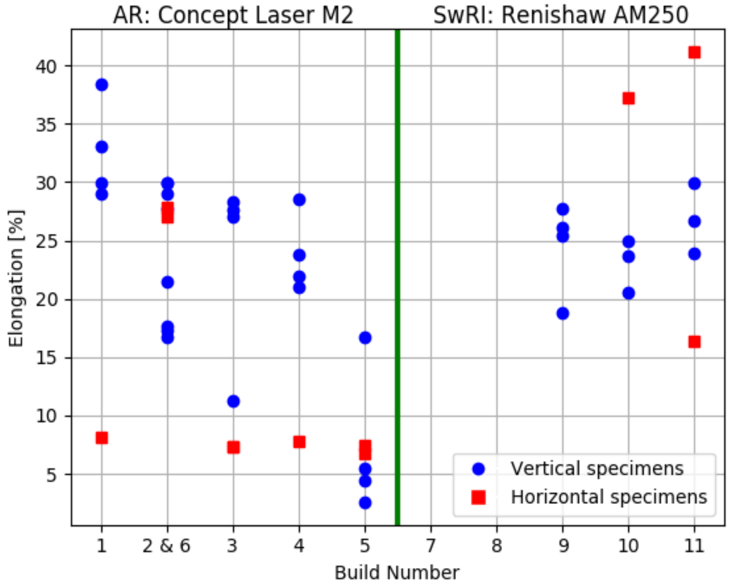


Hot-fire test rig

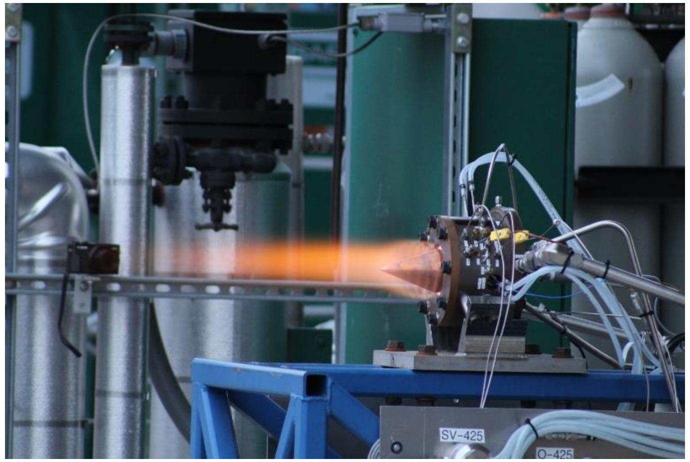


There are several takeaways from the work completed to date

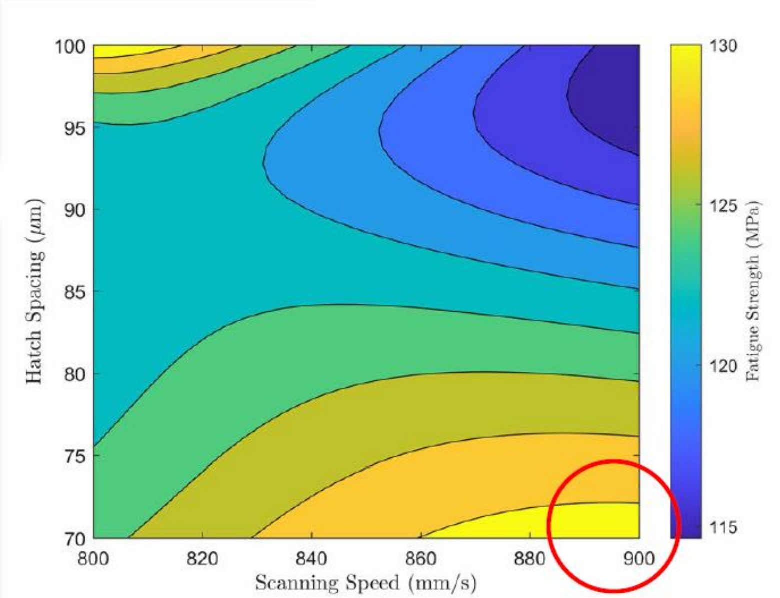
A large quantity of repeat builds are needed to accurately assess any AM build process, and more specific in-situ measurements are needed



AM enables low-loss RDE injectors that operate with sustained detonation



The Process-Structure-Property DTMM points to optimal build properties that would not be obvious from a simple data review



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