Project ID: mat233

Light Metals Core Program Thrust 2 – Selective Processing of Al Castings

Glenn Grant (Thrust Lead), Saumyadeep Jana, Aashish Rohatgi, Arun Devaraj
Pacific Northwest National Laboratory

Zhili Feng, Alex Plotkowski
Oak Ridge National Laboratory

Dileep Singh, Jeff Spangenberger
Argonne National Laboratory

2021 DOE Vehicle Technologies Office Annual Merit Review
June 24, 2021

LMCP OVERVIEW

LMCP overview

Timeline

- Lab Call Award – September 2020
- Kickoff – November 2020
- End – September 2023
- 5% Percent complete

Budget

- Total project funding $15M/3 years
- Funding for FY 2021 - $5M

Lightweight Metals Core Program Overview			
	Title	**# of Projects**	**FY21**
Thrust 1	Selective Processing of Aluminum Sheet Materials	3	$1,300,000
Thrust 2	Selective Processing of Aluminum Castings	3	$1,450,000
Thrust 3	Selective Processing of Magnesium Castings	2	$1,100,000
Thrust 4	Crosscutting Thrust - Characterization, Modeling and Lifecycle	7	$1,150,000

Barriers and Technical Targets

- **Materials Performance and Cost** limit the penetration of lightweight Al and Mg alloys into the entire range of vehicle
- **New Alloy** development is slow and costly
- **Recyclability** is complex due to large number of different alloys

Partners

- Program Lead
  - Pacific Northwest National Laboratory
- Partner Laboratories
  - Oak Ridge National Laboratory
  - Argonne National Laboratory
- Industry Engagement
  - Informal support and guidance from OEMS and Tier 1 suppliers
  - CRADAs planned for future years

THRUST 2 OVERVIEW

LMCP Thrust 2 Overview

Selective Processing of Al Castings

Timeline/Budget

- Project start: Oct 2020
- Project end: Sep 2023
- Percent complete: 5%
- **Thrust 2 Budget**
  - **FY21: $1.45m**

Barriers and Technical Targets

- Large aluminum cast parts offer excellent opportunities for vehicle lightweighting, reduced part and alloy count, and lowered assembly costs.
- Science and engineering challenges inherent to cast materials: low ductility, low fatigue performance in stressed members, and low strength in high fluidity alloys needed for complex and large castings.
- In many cases, the challenge occurs only very locally on one part of the casting.

- **Technical Target: a suite of low-cost, advanced manufacturing processes that can improve the local properties of castings and allow higher performance, lighter weight and potentially enable lower cost and fewer alloys in the glider to simplify the supply chain and recycle path.**

Thrust 2. Localized Property Enhancements for Cast Structural Aluminum Applications

Project	Title	FY21
2A1	Local thermomechanical processing of die-cast aluminum alloys for improved fatigue and fracture toughness behavior (PNNL)	$400k
2A2	Power Ultrasonic Surface Processing of Die Cast Al Alloys (ORNL)	$200k
2B	High-intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Al Castings (PNNL)	$400k
2C	Cast and Print (ORNL)	$450k
	Thrust Totals	$1.45m

Partners

- Program Lead Lab
  - Pacific Northwest National Lab (PNNL)
- Thrust 2 Participating Labs
  - Pacific Northwest National Lab (PNNL)
  - Oak Ridge National Laboratory (ORNL)
  - Argonne National Laboratory (ANL)
- Thrust 2 Collaborators
  - Ford Motor Company
  - General Motors

Relevance

Thrust 2
Localized Property Enhancements for Cast Structural Aluminum Applications

- Large thin-walled aluminum cast parts offer excellent opportunities for vehicle lightweighting, reduced part count and lowered assembly costs

- However, there are science and engineering challenges with the integration of castings into the BIW including:
  - low ductility
  - fatigue in stressed members
  - Low strength of high fluidity alloys

- Often, due to the casting process, these problems can be unpredictable in their severity and can be very localized on a part.

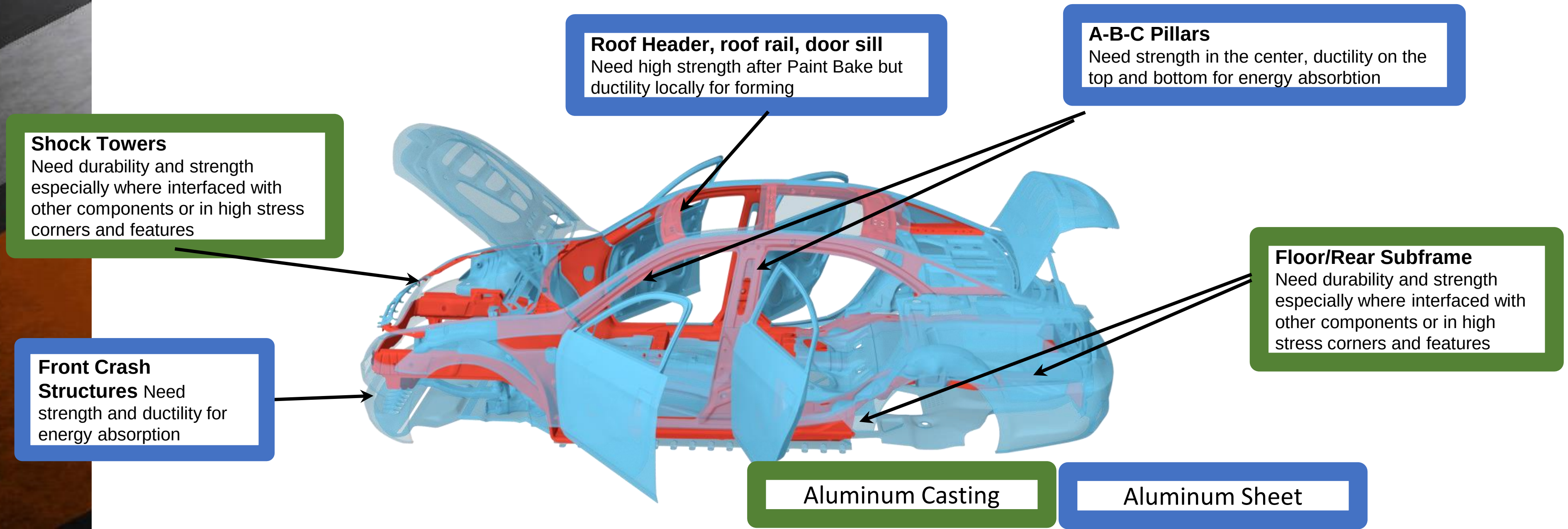
- Failure in these areas can drive global section thickness or strength requirements.

- If we could “fix” or improve just those areas, material, cost and structural efficiencies could be achieved.

Relevance

Motivation

- Can we develop manufacturing approaches to <u>locally</u> customize, optimize and/or repair microstructures in the component to meet specific application performance requirements?
- In addition, if local microstructures are modified for a better heat treatment response, cast parts can be strengthened and downgaged enabling an even greater insertion of thin wall castings into glider components.
- **Impact of success - There is potential weight saving and reduced part count if we could substitute thin-walled aluminum casting throughout the glider**



Cast Aluminum B pillar ?

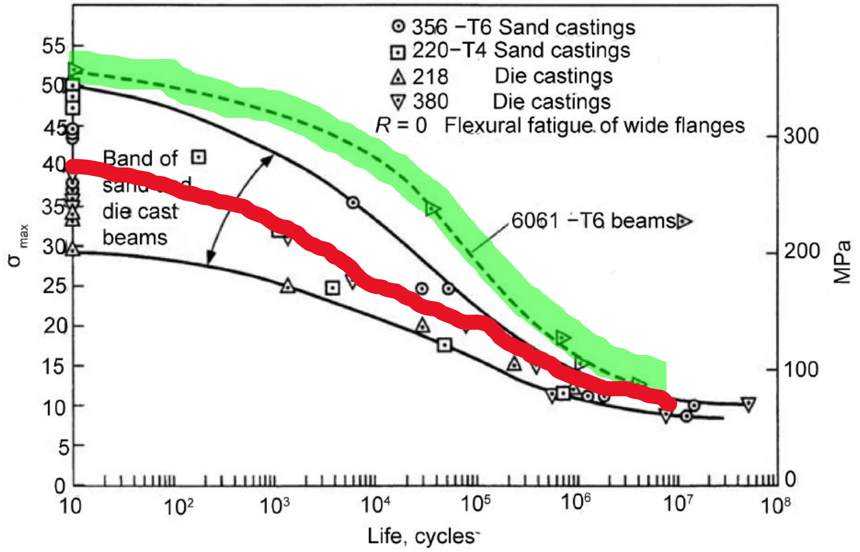
…But can we do it in a way that makes sense: Low Cost, Fast, Recyclable

Relevance

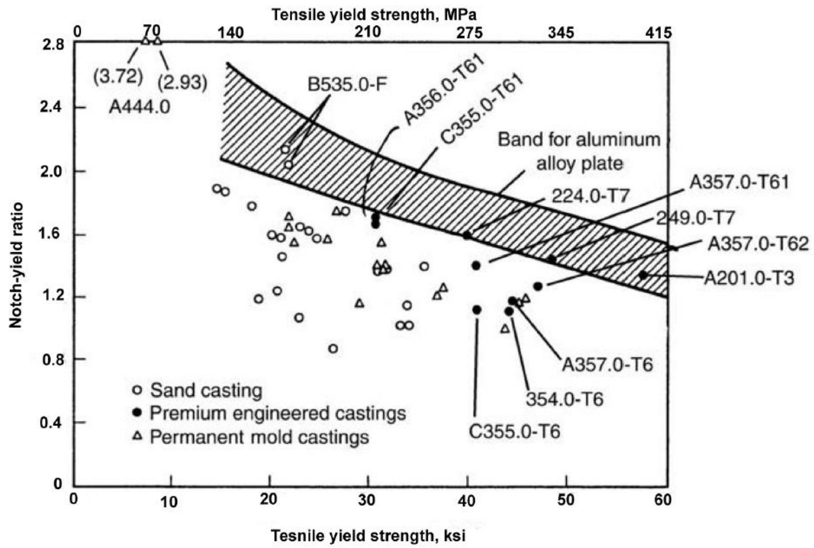
Thrust 2 Scientific and Engineering Challenges

Barriers to address

- Die Cast microstructures are inherently less homogeneous than wrought materials
- Their properties (e.g., fatigue, fracture performance, ductility) are usually defined by local microstructural characteristics, such as porosity, 2nd phase distribution and morphology, and dendrite size and morphology.
- Castings are especially prone to durability challenges due to near surface microstructural inhomogeneities esp hot cracking, micro-segregation, shrinkage porosity
- Strength is driven by alloy chemistry and microstructure and is often a compromise with fluidity and die filling, strength is generally low for Al Si alloys
- Very high integrity castings can be obtained with vacuum high pressure die casting but costs are high, especially when complex designs are needed to avoid hot short and cold shut defects



M.L. Sharp, G.E. Nordmark, and C.C. Menzemer, Fatigue Design of Aluminum Components and Structures, John Wiley & Sons



ASM Handbook, Volume 2B, Properties and Selection of Aluminum Alloys
Kevin Anderson, John Weritz, and J. Gilbert Kaufman, editors
DOI 10.31399/asm.hb.v02b.a0006548

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Overall Project Approach

Thrust 2 will seek to overcome the barriers to greater integration of castings through a collection of projects aimed at solutions to the science and engineering challenges

To enable further integration of lightweight castings into the Body-In-White (BIW), Thrust 2 proposes to develop processes to locally modify cast parts so that single castings can satisfy the varying property requirements at different locations of the component.

Thrust 2 will develop methods to attain higher strengths and higher elongations in cast alloys from high volume, low-cost casting processes (non vacuum HPDC)

Thrust 2 will develop methods to enhance the local properties in cast aluminum components through three projects aimed at creating wrought-like or high performance microstructures and properties in local regions of aluminum-silicon castings.

Success is defined by demonstrating improvement at the prototype or full-scale level in the mechanical performance and durability of targeted components

Project Approach

Approach Thrust 2 Projects

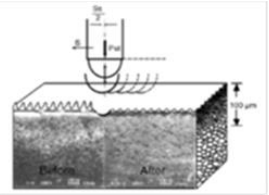
Project 2A1,2A2

Local thermomechanical processing of die-cast aluminum alloys for improved fatigue and fracture toughness behavior

Approach 1: Friction Stir Processing (PNNL)

Saumyadeep Jana

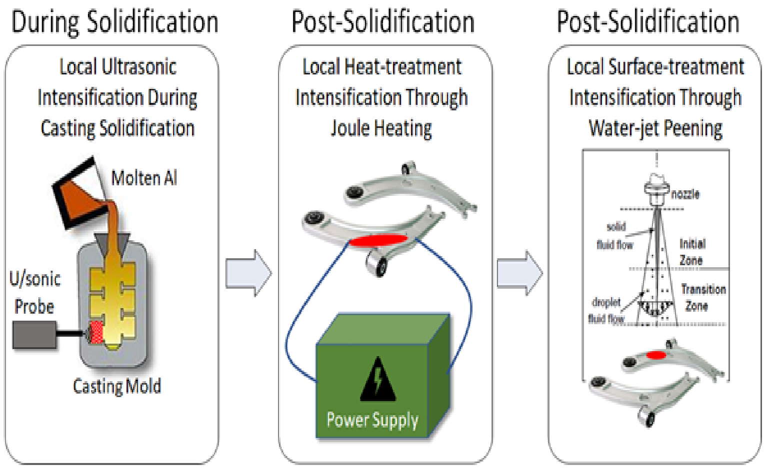
Approach 2: Power Ultrasonic Surface Processing of Die Cast Al Alloys (ORNL)



Zhili Feng

Project 2B

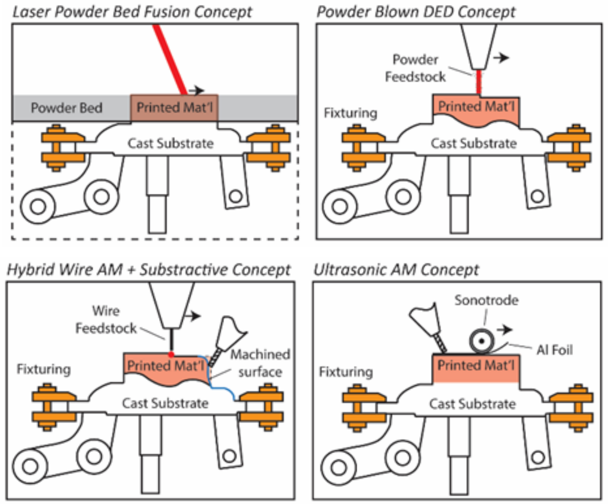
High-intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Al Castings



Aashish Rohatgi

Project 2C

Cast-and-Print – Additive Manufacturing for Localized Property Enhancement of Cast Al Alloys



Alex Plotkowski

Milestones

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Milestones

- All 1st and 2nd quarter milestones have been met

Project	Milestone Name/Description	Criteria	End Date
All	Thrust 2 Planning and Kickoff: PNNL will host a planning and kickoff meeting between all members of the LMCP and VTO stakeholders, to review scope, schedule, budget, management structure, and expectations.	Completed and documented revised scope and task planning for year 1 based on LMCP kickoff meeting discussions and decisions made between principal investigators.	12/31/2020
2A2 (ORNL)	Initial USM processing on flat geometry cast Al alloys.	Determining USM process conditions on flat geometry cast aluminum for robotic/flexible operation readiness.	3/31/2021
2B (PNNL)	Mold Design for Locally Sonicated Casting: Design a mold for Al casting that allows for cooling rates with sufficient time for external ultrasonic excitation during solidification.	Simulations that show the casting cooling rates in the range of 10-50 deg. C/min.	3/31/2021
2C (ORNL)	Down-select cast alloys in Al-Si and/or Al-Mg system for highest impact on structural automotive components based on consultation with automotive OEMs.		3/31/2021
2A1 (PNNL)	Solid Phase Processing or Aluminum Castings: Demonstrate that FSP can modify the local microstructures of a thin-walled high pressure die-cast (HPDC) aluminum alloy of interest to the program (Al-Si) such that the relevant mechanical properties can be improved.	(i) Reduction of total porosity content to less than 0.5% by volume, (ii) refinement of second-phase constituent particles to an aspect ratio ~1, (iii) refinement of Si particles to an aspect ratio ~1 and uniform redistribution such that Si-Si interparticle distance is less than the secondary dendrite arm spacing.	6/30/2021
2A2 (ORNL)	Complete baseline mechanical property and microstructure characterization of USM processed materials	Evaluation of mechanical property (tensile strength, ductility, and fatigue life) and characterization of microstructure.	6/30/2021
2A2 (ORNL)	Complete initial development of USM process on lab scale samples	Review results from both processes and develop strategy for process improvement and integration with robotic systems for next fiscal year	9/30/2021
2B (PNNL)	Determine the effectiveness of using an ultrasonic field applied locally through an external ultrasonic probe to refine the microstructure of an Al casting during solidification.	Targeted microstructural size refinement of 25% relative to the microstructure produced without ultrasonic excitation.	9/30/2021
2C (ORNL)	Use Cast-and-Print approach to demonstrate surface deposits with adequate adhesion.	Deposit substrates with greater than 100 MPa adhesion strength by ASTM testing	9/30/2021

Approach Project 2A1 – 2A2

Local thermomechanical processing of die-cast aluminum alloys for improved fatigue and fracture toughness behavior

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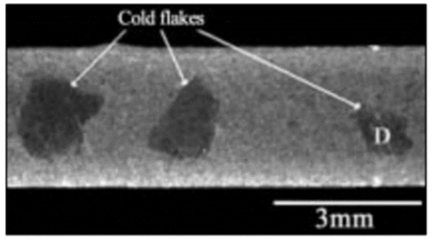
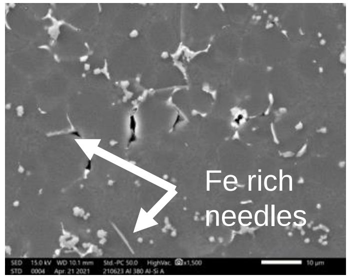
Castings are especially prone to microstructural and performance variability because of common process defects



Cold Shots

Porosity



Intermetallics in higher strength alloys

- If these inhomogeneities are located in an area of stress concentration, early and sometimes unpredictable failure can occur
- This leads to local performance uncertainty, which leads to structural / material inefficiency (thicker part sections, pad ups, heavier parts)
- If local areas could be made to have different tradeoffs between ductility and strength in the same part it is possible to reduce alloy count, part count and cost

Selective Processing methods can locally fix these issues and improve part level efficiency

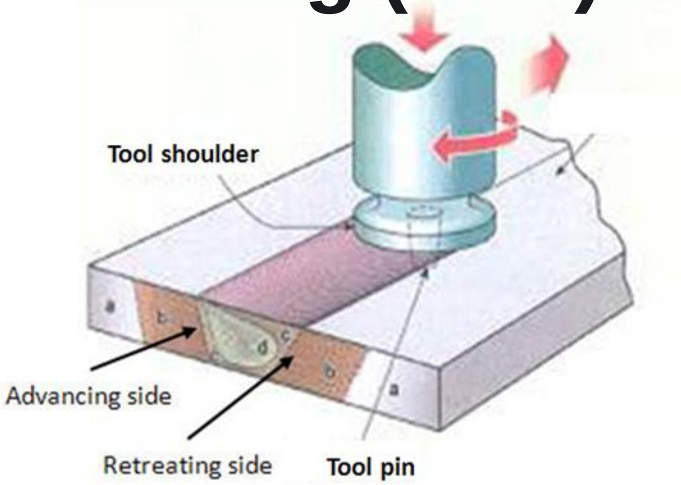
Gantry Friction Stir Processing, 8 ft by 4 ft working envelope (PNNL)

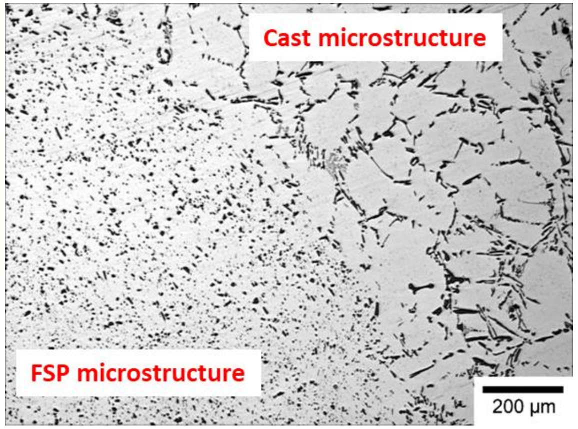
High Load Robotic Friction Stir Processing (IRB7600) (PNNL)

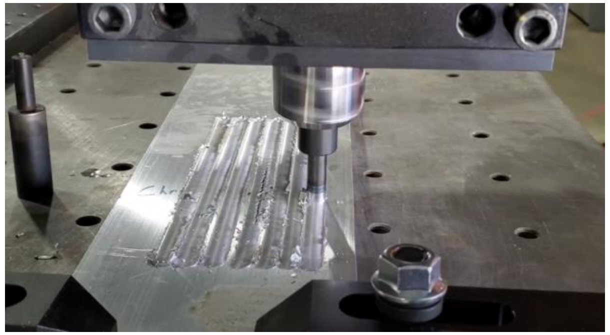
Power Ultrasonic Processing Equipment (ORNL)

Approach 2A1

Project 2A1 Approach: Friction Stir Processing (FSP)

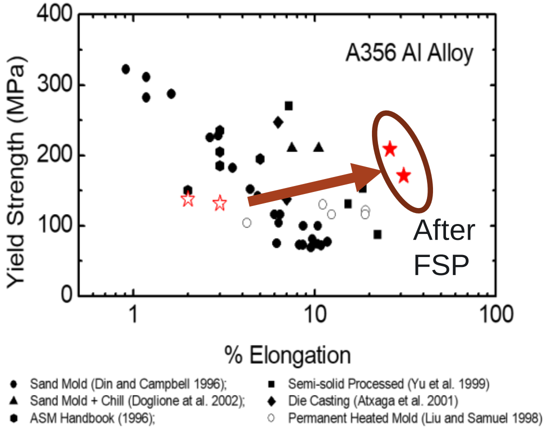




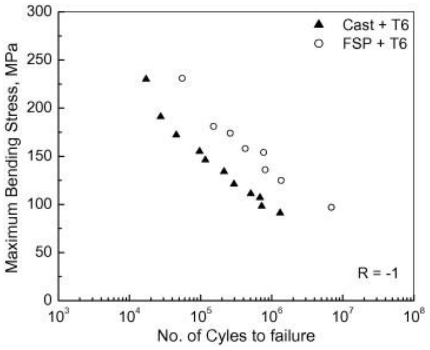


What is FSP?

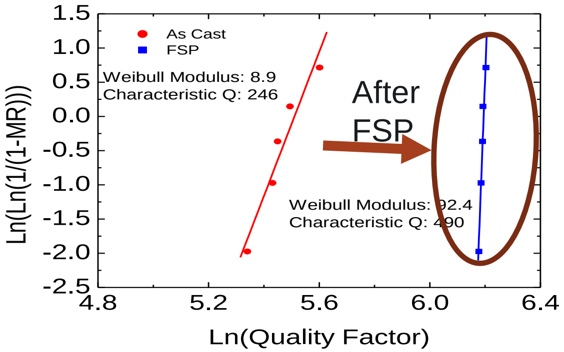
- Spinning, non-consumable tool is plunged into the surface of a material.
- Friction and plastic work energy heats the material sufficiently to lower the flow stress.
- When material softens, the tool is then translated along the surface creating a fine-grained, wrought microstructure, healing porosity and solutionizing or refining second phase, or other particles
- The process region can be just on the surface or be completely through-wall depending on the tool design and geometric conditions



- **30% improvement in strength**
- **Almost 10x improvement in ductility**



5x enhancement in fatigue life after FSP in an *investment cast F357 alloy*



Dramatic improvement in Weibull modulus and Quality Index

$$Q = \sigma_{UTS} + 150 \log E$$

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Project 2A1 Technical Accomplishments

Down selection of experimental alloys complete and initial quantities purchase and or received

1. Alloy A380 General purpose die casting alloy

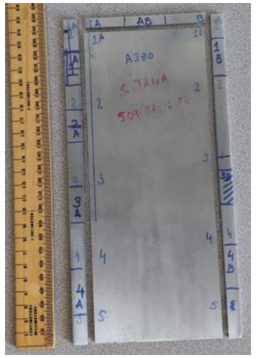
Composition: Al-(7.5-9.5Si)-3Cu-1.3Fe-3Zn

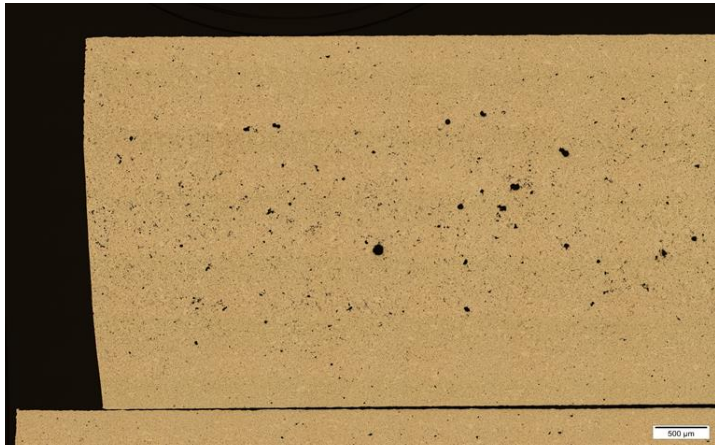
2. Aural-5 and Aural-2 (From Ford) Premium die casting alloy

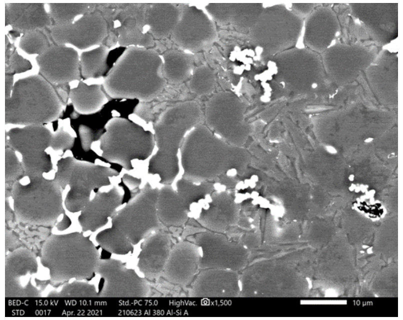
Composition: Al-(9.5-11.5Si)-0.03Cu-0.22Fe-0.03Zn-0.6Mg-0.55Mn (Aural-2)

These materials have been shared across labs and will form a common set of base materials for all projects in Thrust 2

Completed microscopy evaluations of HPDC 3.5mm cast plates





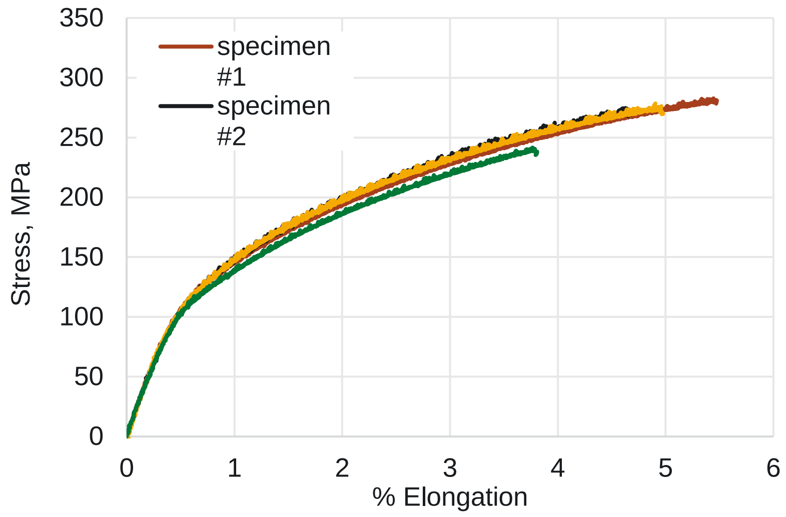


- Total porosity vol. fraction % ~ 0.6-0.9
- SDAS ~ 10-15 µm
- Lots of second phase particles, mostly Cu-Fe rich phase, vol. fraction % ~ 5.0

Inhomogeneous cast microstructure, presence of defects – in short, perfect for selective processing

Project 2A1 Technical Accomplishments

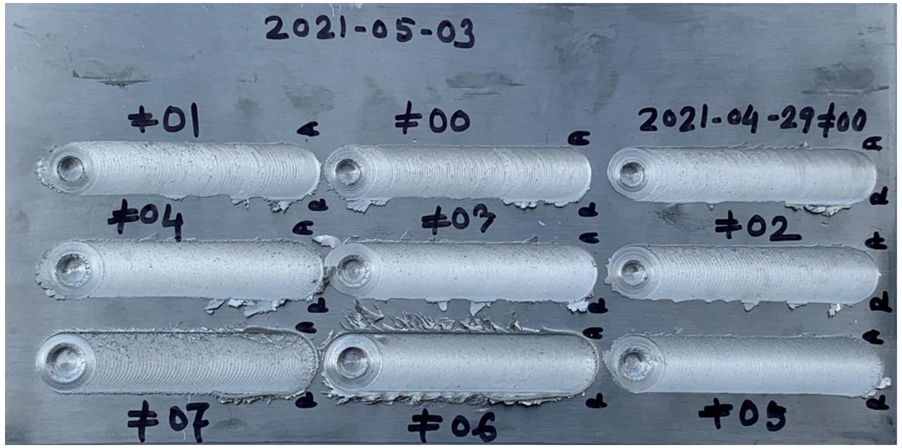
Mechanical properties of HPDC A380 cast plates



As cast A380 HPDC Plates

- % elongation to failure ~ 2-4%
- YS is low, ~ 120 MPa
- TS varies between 225-275 MPa
- Limited ductility in HPDC A380 alloy is evident from the lack of localized necking.

Tensile testing confirms low ductility in as cast HPDC A380 alloy



Friction Stir Processing Trials are underway to establish the relationship between process and properties

45#4

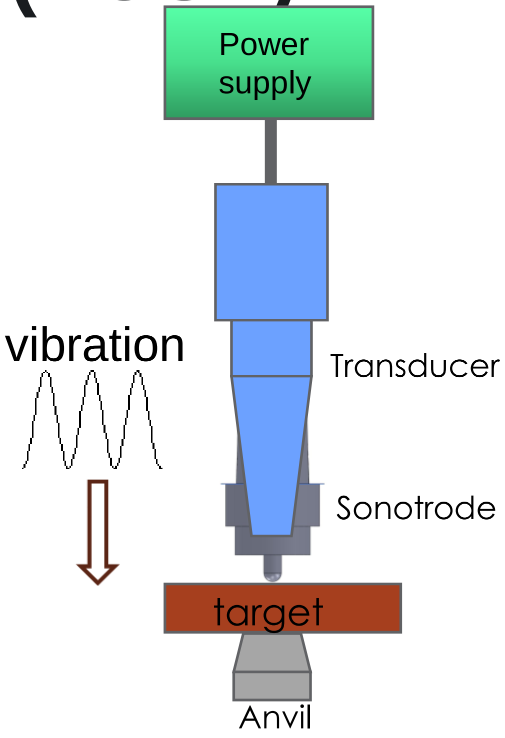
43#1

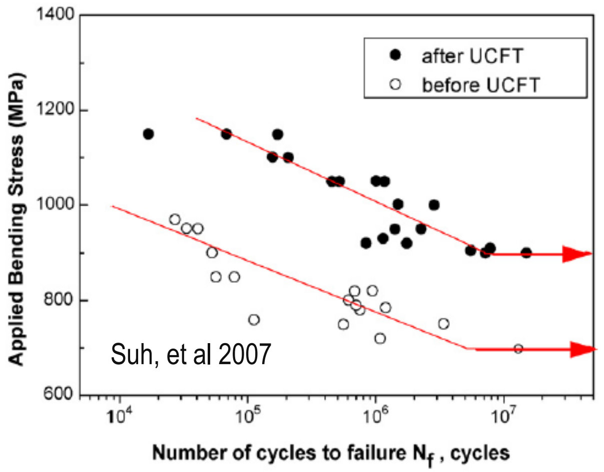
S

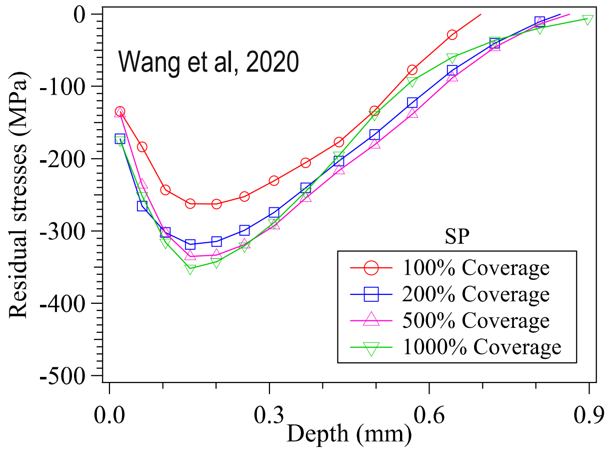
Preliminary work is showing wide process windows for defect free processed zones. This offers potential for a wide range of properties.

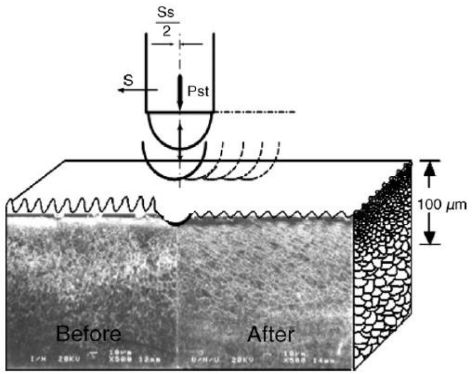
Project 2A2 Approach - Power Ultrasonic Surface Processing (PUSP)

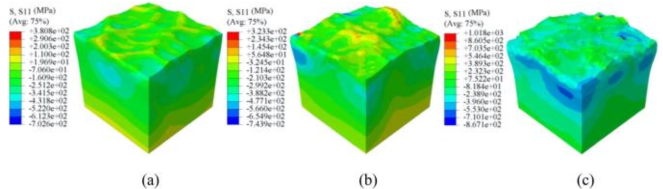
- Physics Principles
  - Local heating and severe plastic deformation
  - Promote recrystallization and phase transformation
  - Refine grains to nano-size near the surface
  - Close cast porosity
  - **Generate compressive residual stresses**
  - Acoustic plastic softening (APS)
- Benefits
  - Fatigue life improvement
  - Strength and ductility increase
  - Formability enhancement
- Technology Gaps
  - Effect of process parameters on properties improvements
    - Power level, duration and tool design, vibration mode etc
  - Processing large area
  - Processing complex geometry (robotic system)











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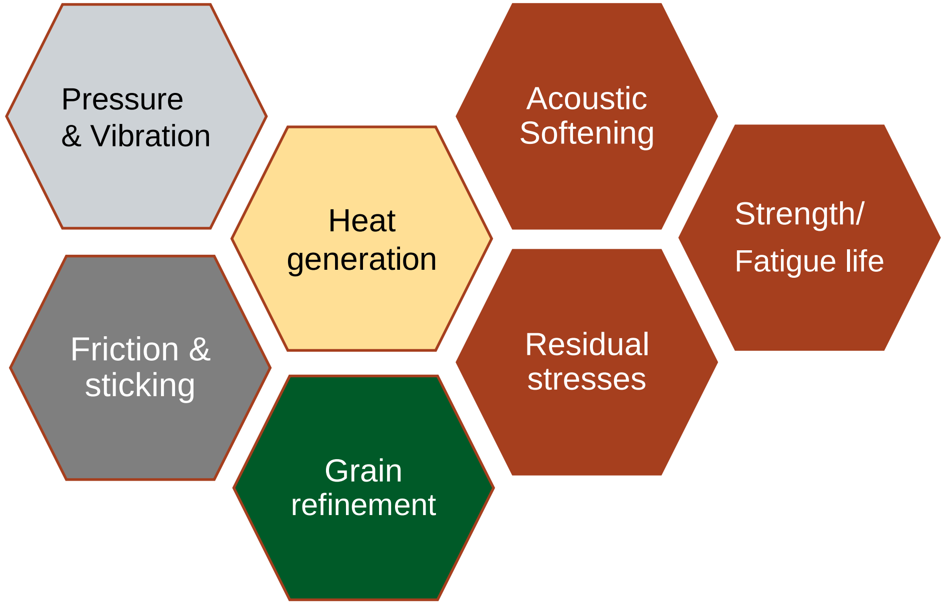
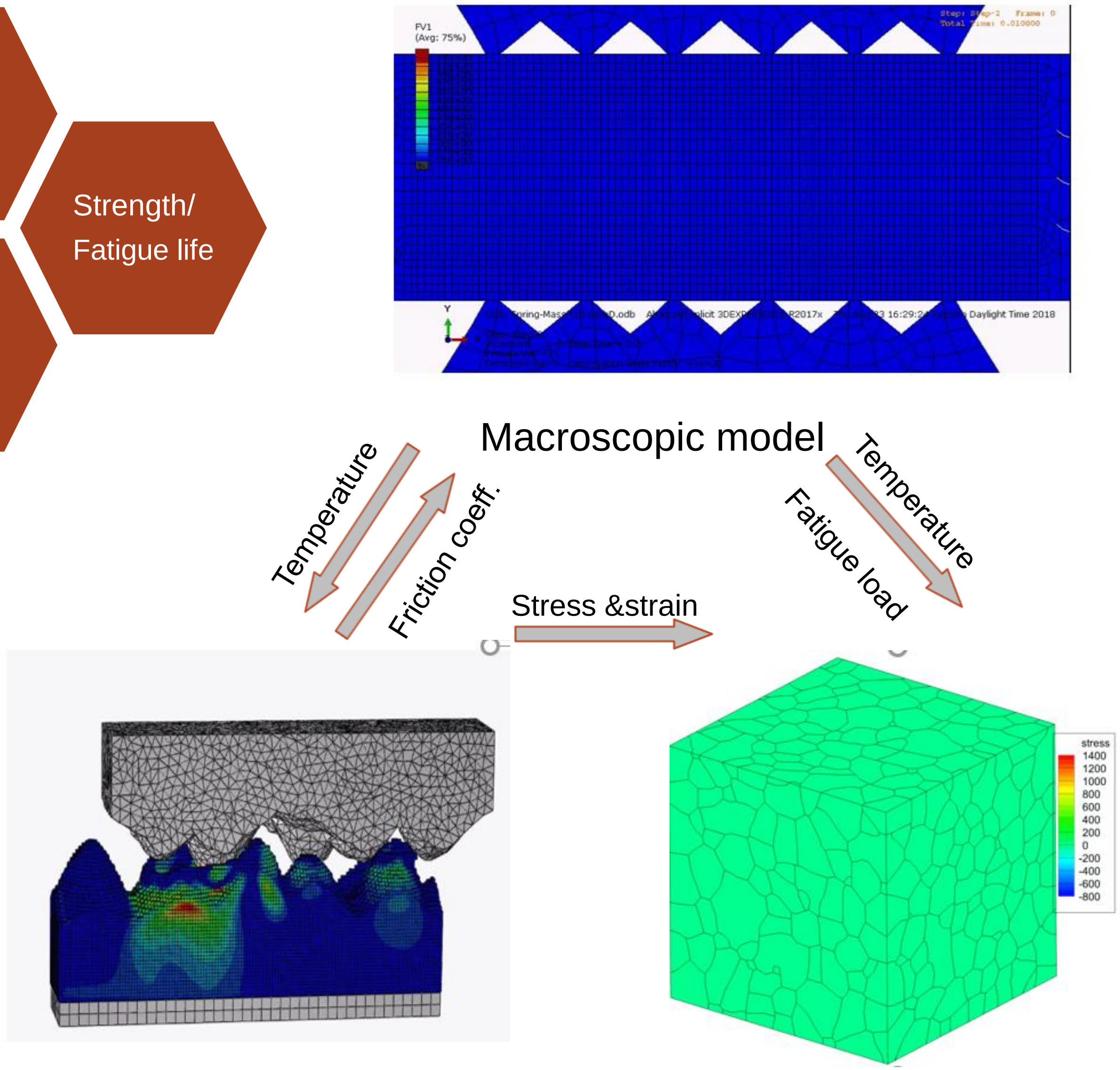
Technical Accomplishments Project 2A2

Multiscale Modeling for Ultrasonic Surface Process –

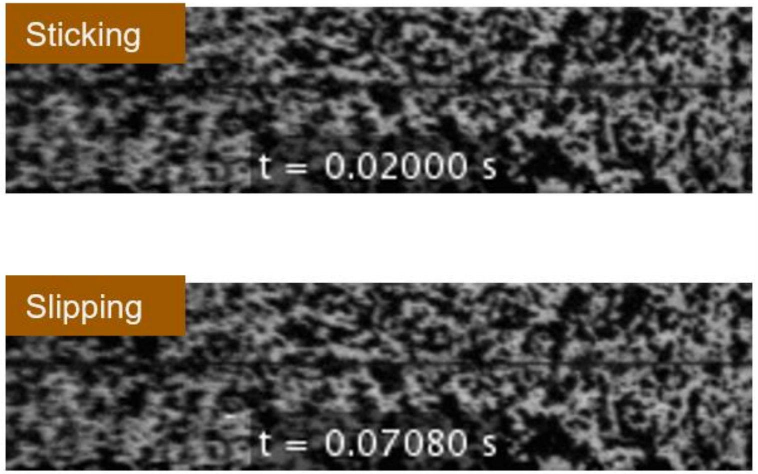




Mesoscale model

Microstructure model

In-situ high-speed imaging



Technical Accomplishments 2A2

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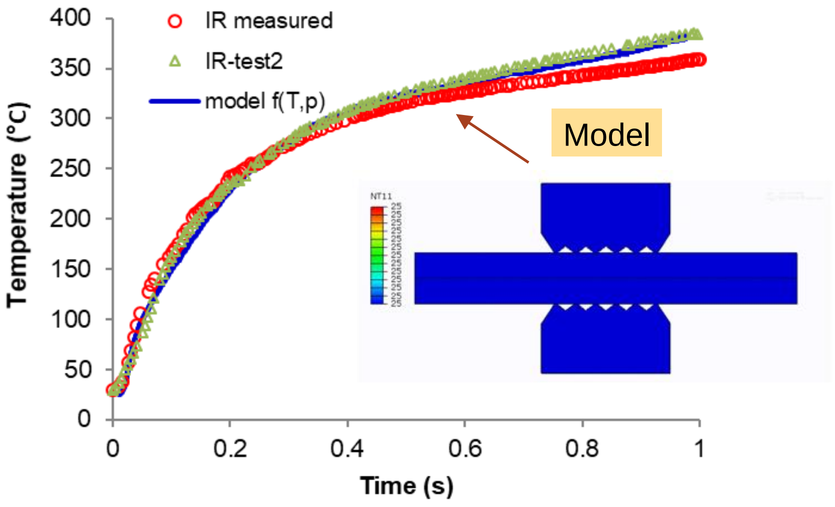
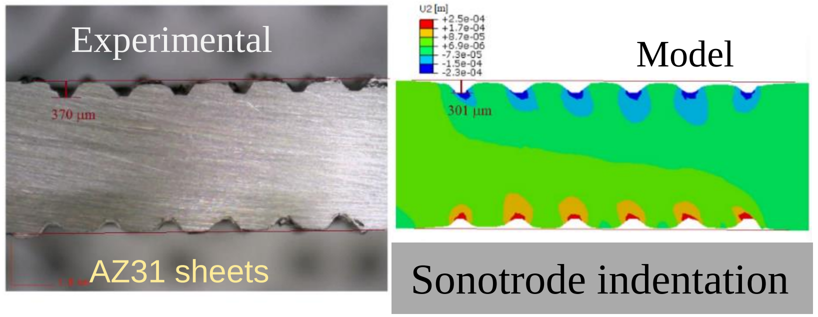
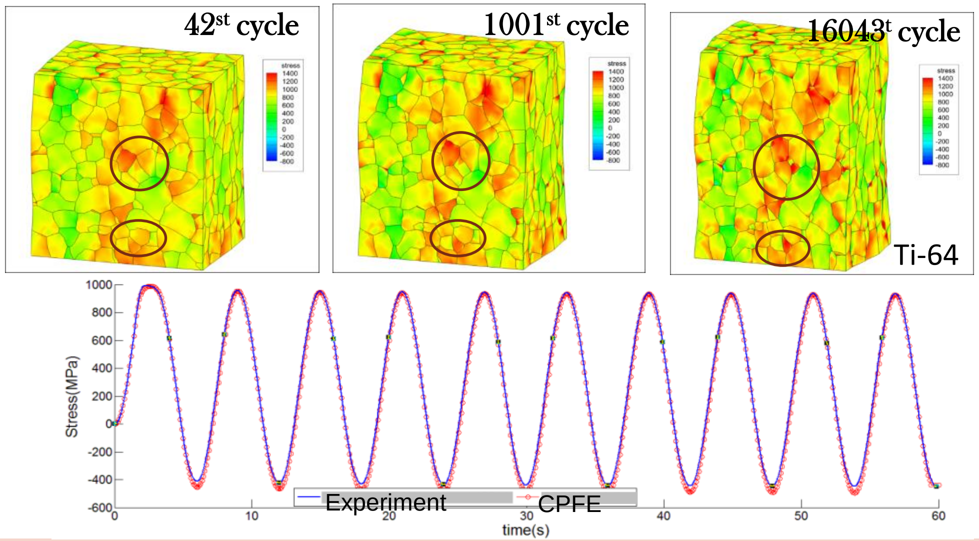
Technical Accomplishments Project 2A2

Heat Generation and Deformation Modeling for USP







- Process model captures essential physical features (heat generation, deformation) in ultrasonic joining/processing of alloys.
- Performance model using crystal plasticity finite element (CPFE) can predict stress localization and evolution in microstructure under large fatigue load cycles.
- New development on crack modeling can capture influence of microstructure grain size/shape and orientation on crack propagation rate and tortuous crack path.

Integrated model can help to investigate USP performance on fatigue property under various processing condition (ultrasonic power, clamping load, surface roughness etc.)

Approach 2B

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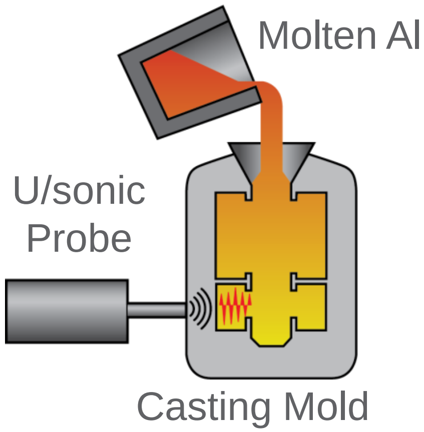
Approach Project 2B

High-intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Al Castings

FY2021

During Solidification

Local Ultrasonic Intensification During Casting Solidification

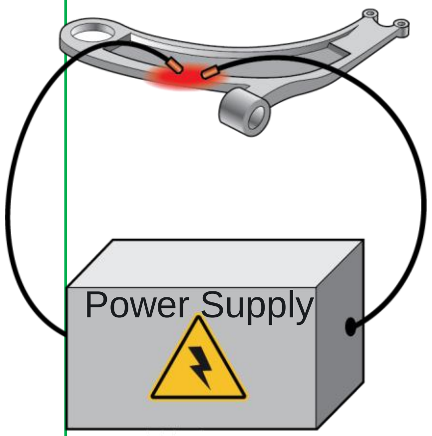


Microstructural refinement by heterogeneous nucleation, fracture of dendrites and intermetallics

Modeling for vibrational analysis

Post-Solidification

Local Heat-treatment Intensification Through Joule Heating

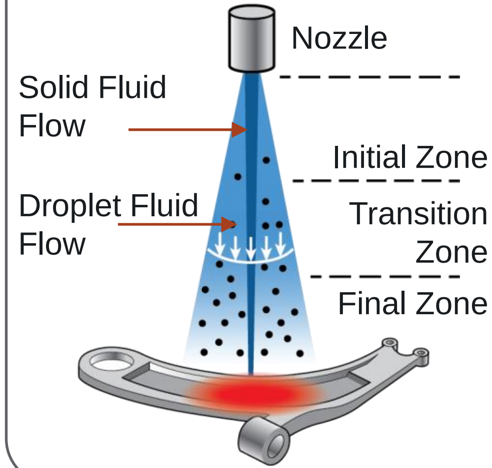


Acceleration of atomic scale diffusion processes

Modeling for coupled electrical-thermal heat distribution

Post-Heat-treatment

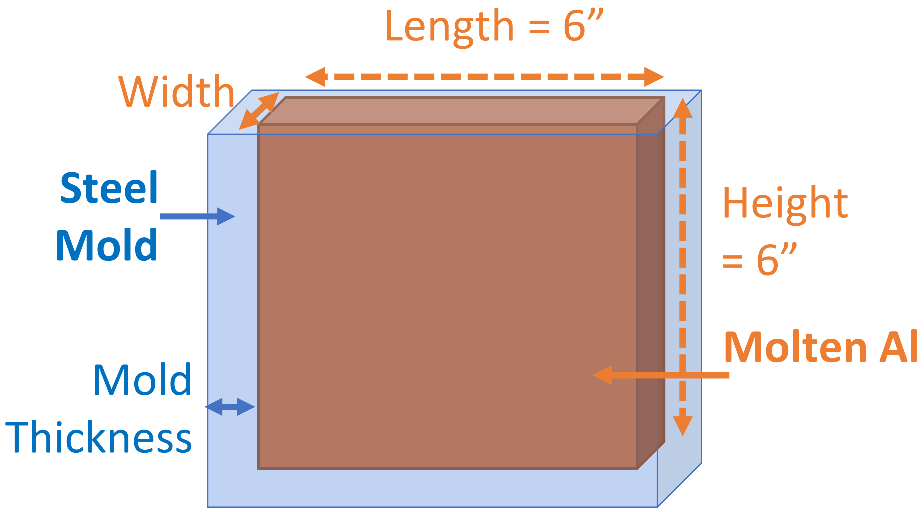
Local Surface-treatment Intensification by Water-jet Peening



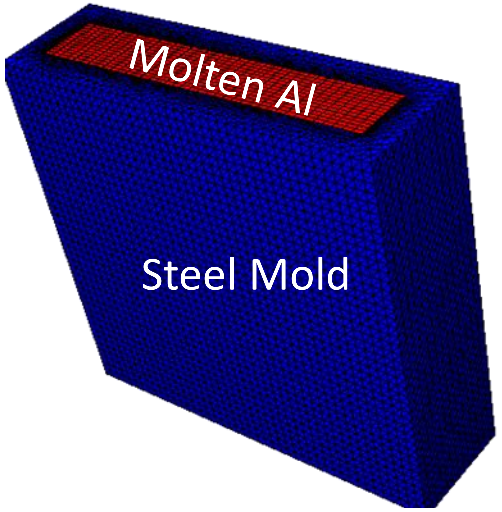
Deep residual stresses by high-pressure water-jet peening

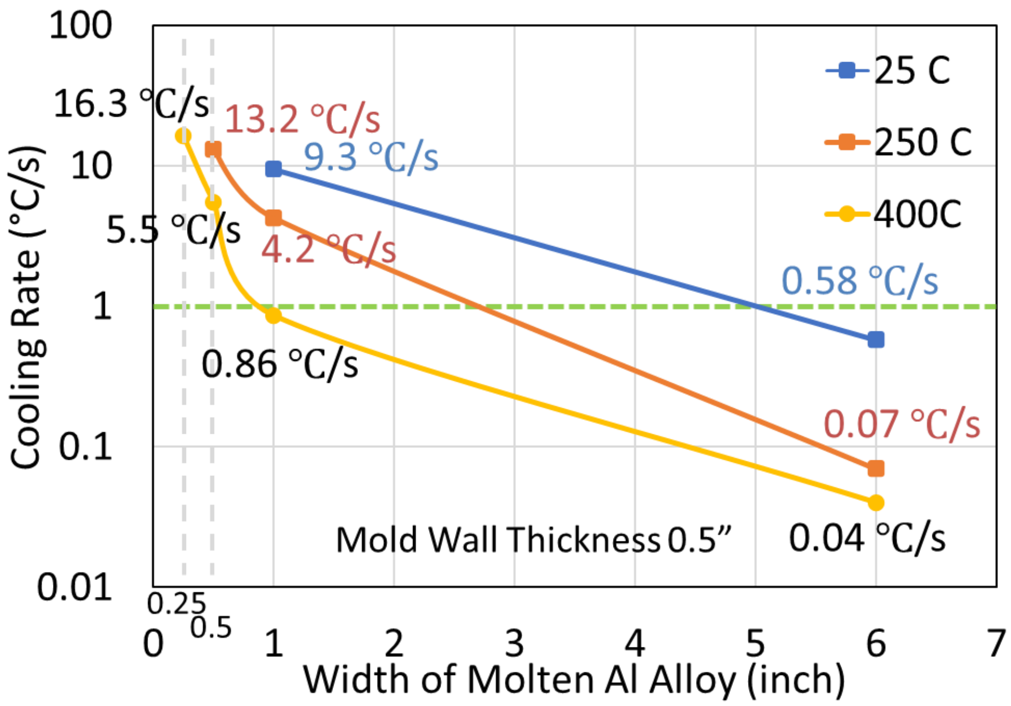
Modeling of residual stress depth and distribution

Technical Accomplishments 2B – Thermal Modeling



Finite Element Model





- Developed an Abaqus model of a steel mold for thermal simulations of cooling rates during solidification of an Al alloy
- Cooling rate of 1°C/s between liquidus and solidus would allow ultrasonication time of ~60s and ~100s for A356 and A206 Al alloys, respectively
- Model predicts that cooling rates ~1°C/s or lower can be achieved using a combination of preheated mold, molten Al width and mold thickness

Approach Project 2C

Cast-and-Print – Additive Manufacturing for Localized Property Enhancement of Cast Al Alloys

Barriers

- **Additive manufacturing using complex cast Al components as substrates**
- **Processing to locally control microstructure and properties for complex shapes**
- **Understanding the influence of process conditions and filler chemistry on microstructure and properties**

Alloy Selection → Process Optimization → Materials Characterization → Initial Component Demonstration

Alloy Selection

- Identify relevant sheet alloys for automotive applications
- Consult with OEMs
- Select suitable filler metals

Process Optimization

- Utilize process modeling and computational thermodynamics
- Design of experiments
- Control process conditions to achieve spatially controlled poperties

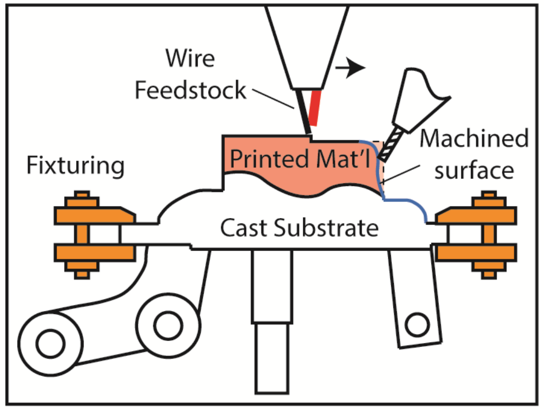
Materials Characterization

- Minimize defects
- Characterize microstructure with respect to process conditions
- Validate computational models
- Mechanical performance

Initial Component Demonstration

- Demonstrate properties of hybrid Cast+AM component

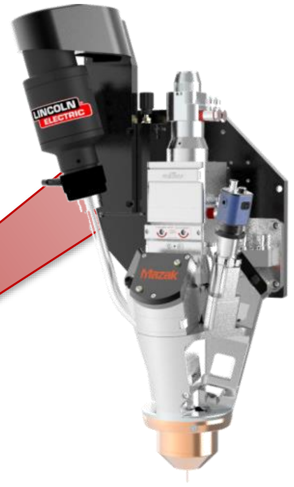
Hybrid Wire AM + Substractive Concept



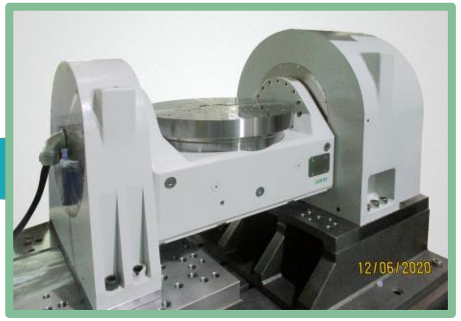
Technical Accomplishments 2C – Alloy and Process Selection

- Alloy selection
  - A356 and A380 selected as model cast alloy systems
  - Ingots of each received and undergoing initial characterization
  - 4xxx and 5xxx filler metals received
- Process selection
  - Hybrid Mazak system outfitted with a Lincoln Electric Laser Hot-Wire DED system
  - Large build volume suitable for automotive components
  - Machining capabilities for surface preparation and finishing
  - Delivery: early June
  - Preliminary processing at Mazak

LE Tri-beam Laser Hot-Wire System

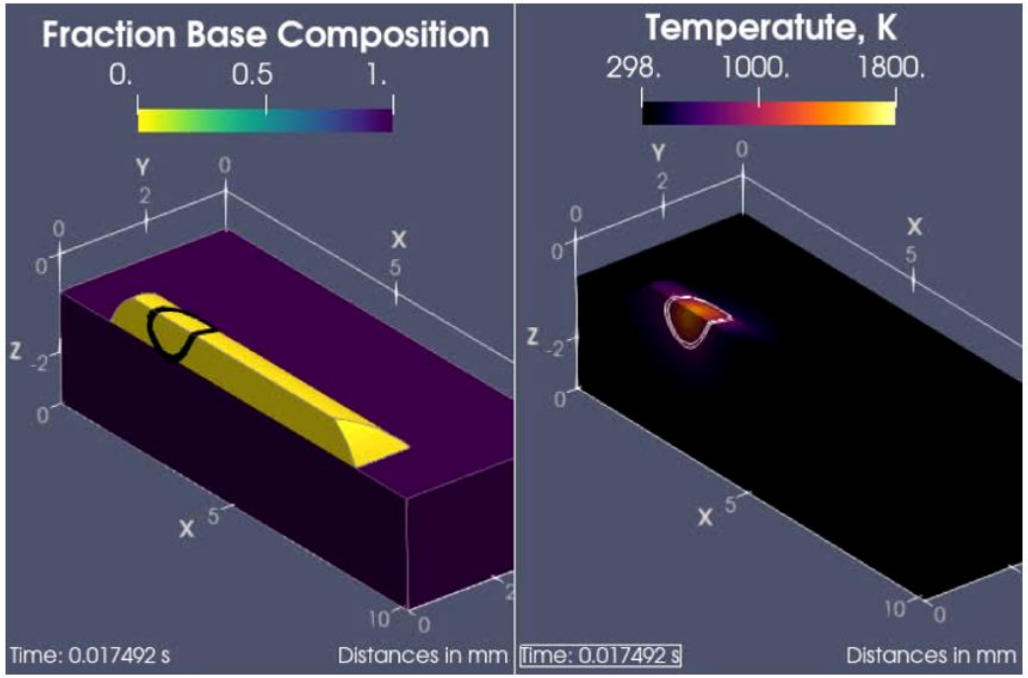


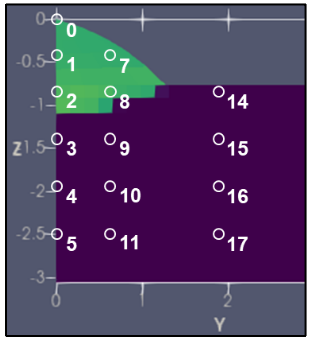
5-Axis Table

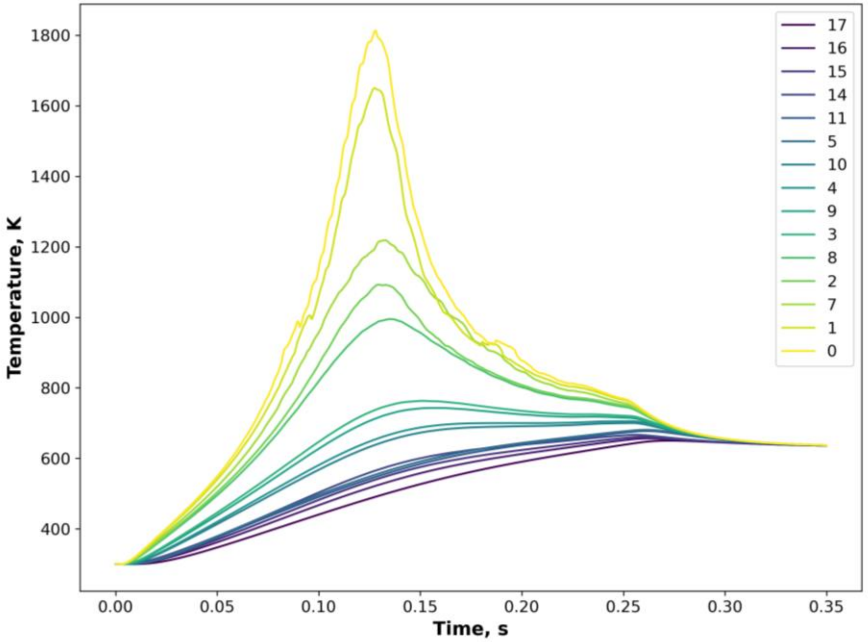


Technical Accomplishments 2C – Computation (Cost share with P1B)

- Developing computational fluid dynamics model for predicting deposit chemistry and thermal conditions during processing
- Extract thermal conditions at each point to evaluate with respect to microstructure evolution







Time temperature history at each probe point shown in the cross-section to the left.

Collaborations and coordination with other Institutions

- This thrust brings together PNNL, ORNL, and ANL teams to develop scalable and cost-effective processing methods to locally enhance the properties of cast aluminum through integrated projects and leverages each national lab expertise and capabilities
- Materials sourced externally are shared between the labs so that experimental trials are using the same base materials and discoveries about the effects of selective processing techniques are easily shared
- Projects, through a user proposal process, are leveraging advanced characterization and computational resources at all three labs through Thrust 4, the crosscutting thrust.
  - Specifically, beamline work at Argonne National Lab (Advanced Photon Source)(Dileep Singh, Jonova Thomas); Solidification modeling at ORNL(Adrian Sabau);Thermal modeling at PNNL(Kranthi Balasu, Ayoub Soulami)
- External Collaborators:
  - Ford Research is providing premium cast materials Aural 2 and Aural 5 and participating in additive efforts at the MDF
  - Mazak providing additive/subtractive equipment (to the ORNL MDF) and providing preliminary processing data
  - Computherm is a collaborator on model development

Response to previous years reviewer comments

- This is the first year that the project has been reviewed

Remaining Challenges and Barriers

- **We need to define a part demonstrator in order to define the practical concerns of using selective processing**
  - What is the manufacturing time adder, the cost adder etc, relative to current practice and relative to material savings)
- **Selective processing creates a microstructural and therefore, a property gradient. Are there issues with stress concentrations or residual stress because of this ?**
  - Heat affected zones in alloys that have precipitation hardening characteristics, etc.?
  - Need to determine if by making one area good, have we made a different area bad.
- **Solid Phase Processing (both FSP and PUSP) of curved surfaces (3D parts) will be challenging and requires designing an appropriate processing tool and robotic implementation**

Proposed Future Work

Proposed Future Research

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Project 2A1-2A2 Local thermomechanical processing of die-cast aluminum alloys for improved fatigue and fracture toughness behavior

- Demonstration of local property improvements to cast materials
  - FSP coupon development and mechanical property characterization - A380
  - Casting quality improvement demonstration
  - Establish the anticipated benefit of local FSP on global fatigue and fracture toughness behavior of HPDC A380 alloy
- Develop FSP method for processing of 3-D profiles. Use of robotic heads for component level processing. Use of bobbin-type tools for through-thickness processing.
- PUSP process development
  - Establish process, microstructure-property relations, Tool/horn design, vibration mode etc, specific for surface modification
  - Considerations of system integration on robotics

Project 2B High-intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Al Castings

- Solidification under ultrasonic field
  - Transducer coupling with steel mold, Pre-heating steel mold while protecting the transducer, Microstructural analysis
  - In-situ solidification experiments in ANL-APS beamline (1-ID-E)
- Heat-treatment process development

Project 2C High-intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Al Castings

- Mazak Equipment Center to be placed at the MDF in early summer when primary experimental work will begin
- Modeling activities are helping to define critical parameters to validate including predictions of temperature generation, chemistry and dilution of the melt pool

"Any proposed future work is subject to change based on funding levels."

Summary

Summary

Project 2A1-2A2 **Local thermomechanical processing of die-cast aluminum alloys for improved fatigue and fracture toughness behavior**

- Preliminary Friction Stir Processing trials are showing wide processing windows in A380, opening the possibility for a wide range of different local microstructures and properties
- Multiscale heat generation and deformation modeling is showing great promise for capturing the physics of the Ultrasonic processing methods

Project 2B **High-intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Al Castings**

- Thermal modeling has defined the parameters of the experimental book mold so that cooling rates will allow enough time in a molten state for sonication during solidification

Project 2C **High-intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Al Castings**

- Computational fluid dynamics models have been constructed for predicting deposit chemistry and thermal conditions during processing.
- Alloy and wire selected and procured for experimental trials in late June

Impact Toward VTO Objectives

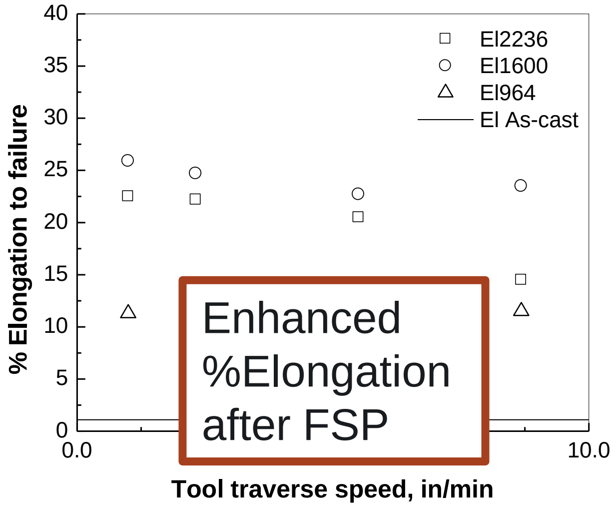
Improved local performance and reliability of castings will enable greater insertion of large thin-walled cast structural parts in the glider, leading to lower weight, lower alloy and part count and greater recyclability.

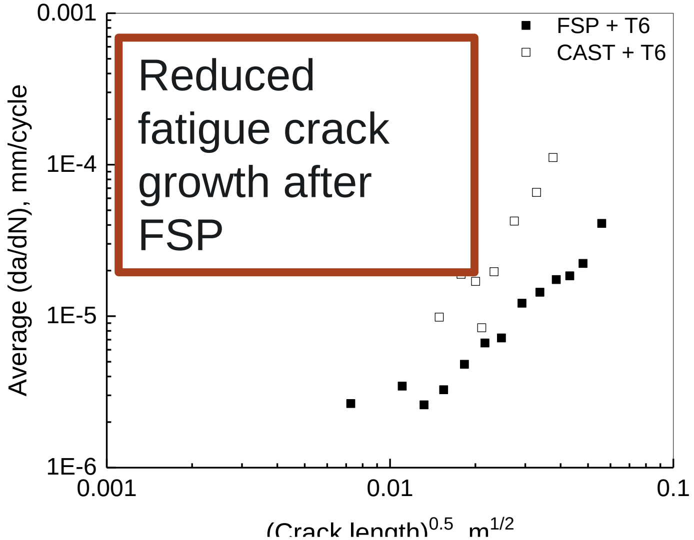
Technical Backup Slides

Project 2A1 Approach

1. FSP to improve fatigue properties in thin-walled HPDC parts

Modification of cast microstructure, removal of casting defects





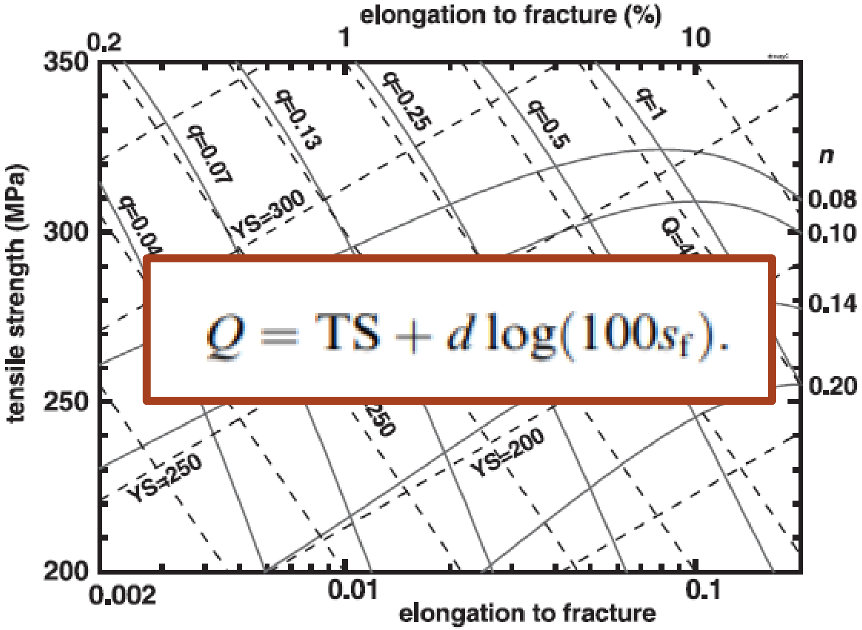
Selective area FSP vs. global effect on fatigue?

- FSP of HPDC Al-castings at selective locations
- Use of flat die-cast plates at coupon level to try the concept

- Fatigue model for the hybrid structure
- Residual stress

2. Local alloying by FSP for overall strengthening of a HPDC Al-alloy casting

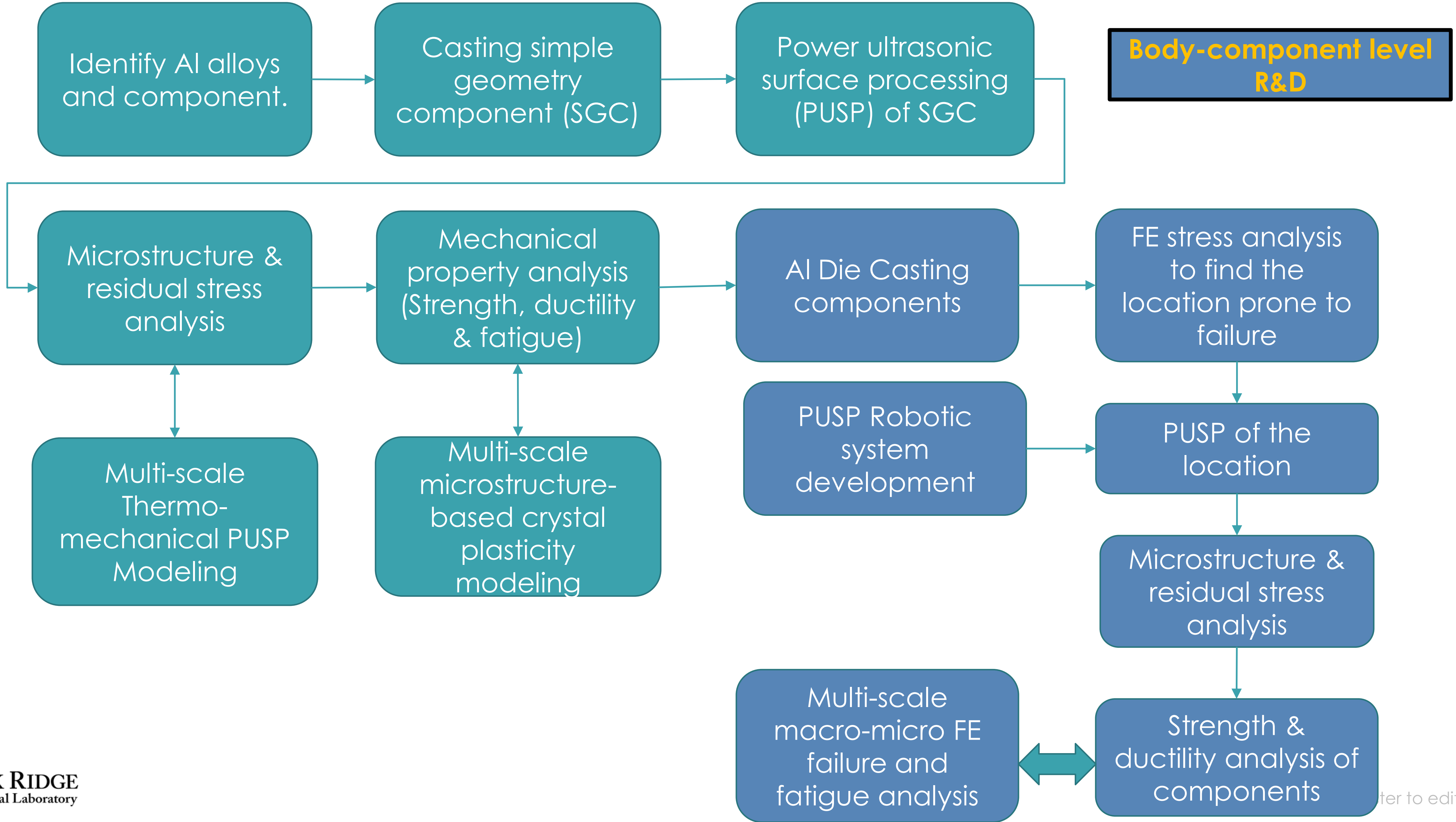
- FSP of castings at selective locations that need higher strength
- Addition of alloying elements (Cu, Mg) through FSP/increased cooling
- Grain refinement to promote ductility
- Possibility of using FSP as a post-process value-addition method for die-cast components



$$Q = \mathrm{TS} + d\log(100 s_{\mathrm{f}}).$$

FSP to improve Quality index of HPDC Al-castings

Project 2A2 Detailed approach



Backup

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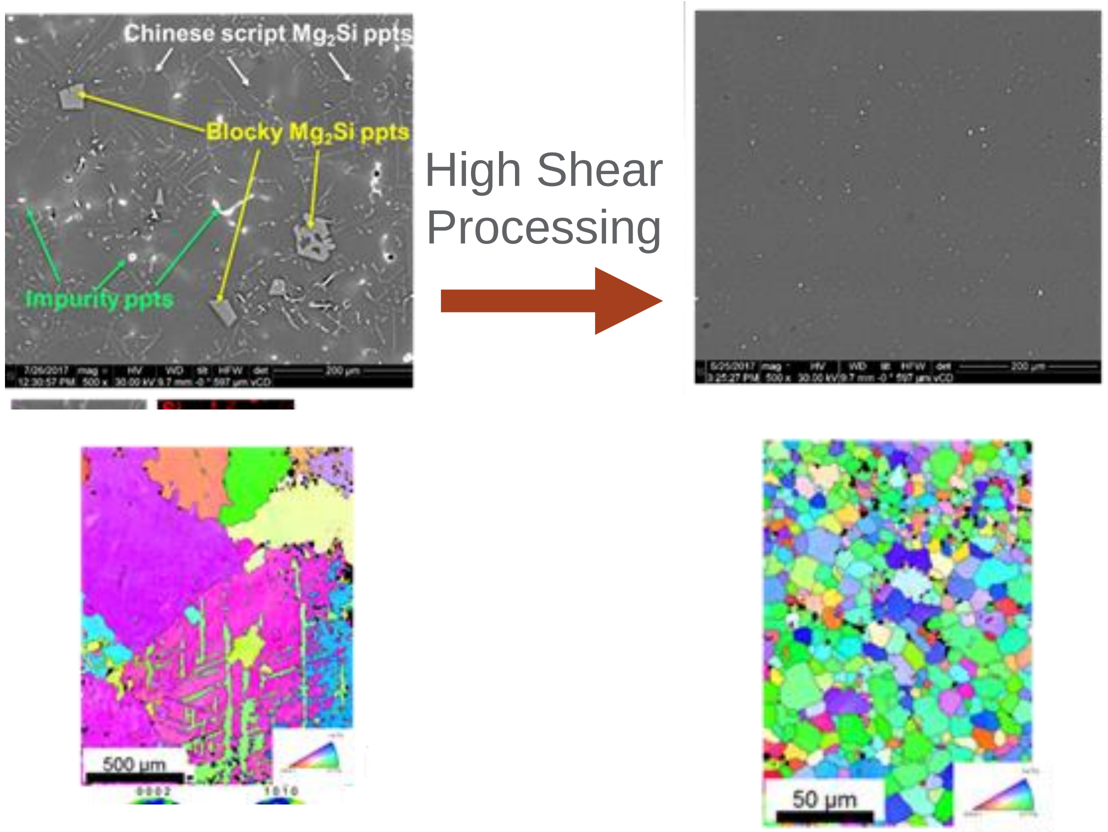
Advantages of FSP materials in corrosive environments

- Example - Alternative Fuels:
  - Highly refined microstructures have superior performance in generalized and localized corrosion, and in resistance to hydrogen diffusion and embrittlement.
  - For example, Magnesium alloys have been demonstrated to have reduced galvanic reaction between matrix and second phase particles through refinement and dissolution of intermetallics during applications of extreme plastic shearing.
  - In these alloys, resistance to mixed-chloride corrosion is improved



May be opportunity to improve the performance of body structures exposed to abrasive and corrosive environments (vehicle underbody)