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Identifying and Controlling Factors to Improve the Production of Thin-Wall Ferrous High-Pressure Die Castings

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Emergent Metal Casting Technologies (EMCS)

AMC Technology Review

June 24-25, 2026

NADCA   COLORADO SCHOOL OF MINES EARTH • ENERGY • ENVIRONMENT   THE UNIVERSITY OF ALABAMA

Overview

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- Needs and Benefits
  - Steels of various types are widely used in weapons, vehicles, support structures, etc.
  - Die casting offers the potential to produce near-net shape, thin-walled, lightweight components at high volumes and lower costs
- Progress to-date
  - Mines is focusing on a laboratory test apparatus to quickly evaluate die life potential for a range of materials
  - Alabama is focusing on generating data on the optimum process for die casting high-quality steel
  - Both universities are working with Mercury Marine to produce a test die to produce steel die castings
- Transition
  - The team will work with Mercury (and other die casters) to transition the technology into commercial die casting operations
- Cost Share Provided: $73,254

Industrial Support

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Jacob Belke PhD, PE, Technical Associate, Mercury Marine

- “Our support of steel high pressure die casting reflects Mercury’s long-term vision to expand the boundaries of die casting by combining proven steel performance with modern manufacturing efficiency.”
- “By committing resources, expertise, and time, Mercury is driving steel die casting from concept toward an industrially viable manufacturing capability.”

Industrial Support

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<u>Caelan Kennedy</u>, Research Manager, Steel Founders’ Society of America

- “This project re-examines the potential for steel die casting, leveraging recent advances in materials, process control, and tooling to address limitations that constrained earlier research efforts.”
- “These advances position steel die castings as a viable option for high-volume applications that have traditionally been challenging by other steel manufacturing routes.”
- “The Steel Founders’ Society of America (SFSA) is contributing to this work by funding the purchase of die materials for the Mercury test tooling"

DLA Needs

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Problem

- Current production of steel shapes is typically by sand casting, investment casting, or forging
  - Both methods can produce castings with excellent quality
  - Sand casting is not especially net-shape and cannot produce thin walls
  - Investment casting is expensive
  - Forging needs extensive machining

Objective

- Extend the die casting process to steels

Technology

- Develop optimum parameters for die casting of steel components
- Identify suitable die materials/coatings/fabrication processes for dies that will survive the steel die casting process

Golden Nugget for DoW

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- Steels are used in applications such as defense systems, transportation platforms, and load-bearing structural components due to their mechanical performance
- Conventional manufacturing of steel components is dominated by cost-intensive processes
    - Machining, sand casting, forging, additive manufacturing
- High-pressure die casting offers an approach to produce steel components with near-net-shape geometries, thin sections, and reduced mass
    - At high production rates, improved material utilization, & at lower unit cost

<u>Project Objective:</u>

- Develop and validate processing methodologies for the high-volume production of steel die castings
- With competitive manufacturing costs and rapid cycle times

Milestones/Tasks - Alabama

- Completed
  - Theoretical gate velocity for steel HPDC defined
  - Gating system designed for the lever geometry
- In Progress
  - Determination of the casting-die heat transfer coefficient
  - Evaluation of die lubricants
- Planned
  - Quantification of heat losses during transfer and dosing
  - Definition of the die preheat temperature

Milestones/Tasks - Mines

- Completed
  - Testing of mechanical properties of steel die castings
  - Fabrication of laboratory die life test apparatus
- In Progress
  - Establishing automated running of laboratory die life test apparatus
- Planned
  - Use laboratory die life test apparatus to evaluate die life for a range of materials

Testing Die Life – Two Approaches

- One of the main factors that will control success of the project
  - Developing an approach to produce an economically viable die life for steel die casting
- Two concurrent testing approaches are being pursued
  - Die life testing at Mercury Marine
    - Plant-level testing using a die casting machine
    - Identify issues relating to steel die casting
  - Laboratory testing at Mines
    - A laboratory test apparatus is being fabricated
    - Rapid testing of potential die materials

Test Die at Mercury

Test Die at Mercury

- Mercury Marine is in the process of building a test die
- Inserts will be fabricated to produce two castings
  - Boat cleat (Mercury)
  - Pistol grip lever (Henry)
- The team has monthly meetings with Mercury personnel
- Cavities will be fabricated from standard H13 steel and Densimet
  - Densimet is a tungsten-based alloy
- Die should be complete by end of 2026

Boat cleat

Pistol Grip Lever

Objectives - Test Die at Mercury

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- Running the test die at Mercury will generate critical information
  - What is the main mechanism of die failure
    - Is it heat checking?
  - How important are other failure mechanisms?
    - Such as erosion
  - It will also generate process information
    - Optimize parameters for the production of high-quality steel die castings
    - Define best die lubricants
- However, the amount of information that can be generated will be limited
  - At current production rates, it will take a week to produce 500 steel die castings

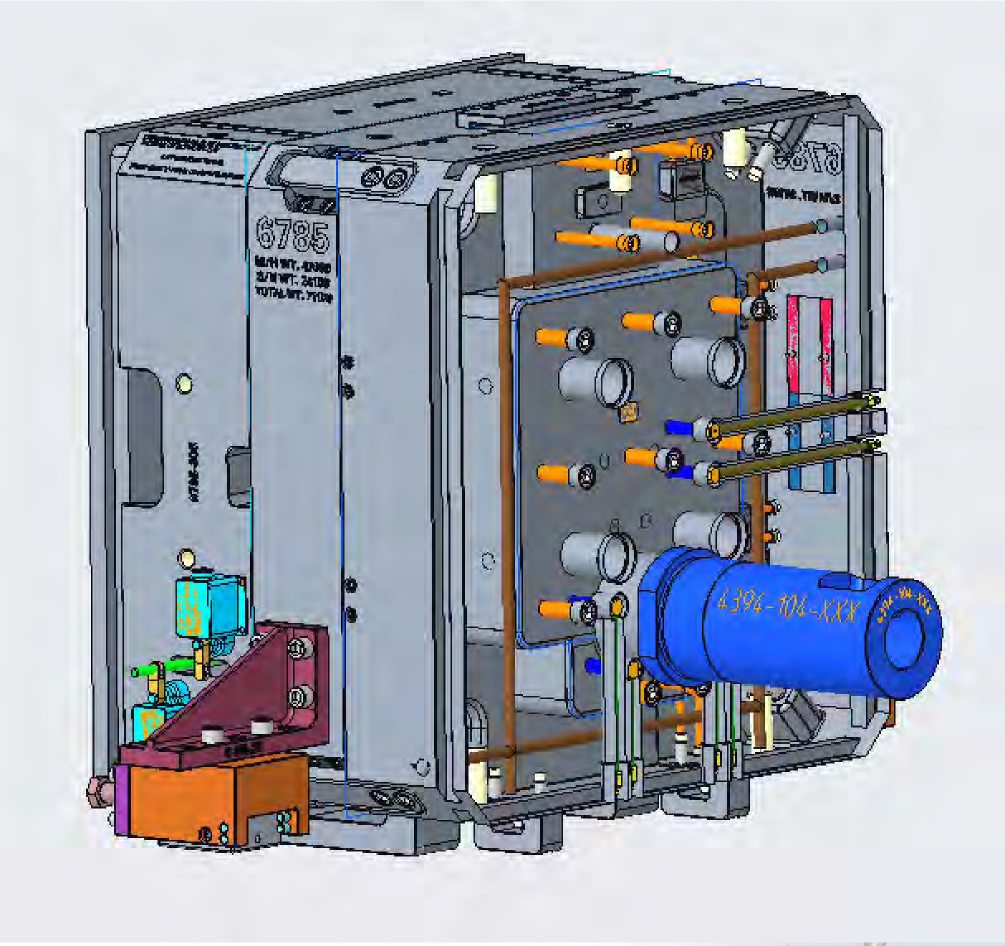
Design and Materials

- Various organizations are contributing cash towards this test die
  - NADCA is contributing $40,000 for the design and fabrication of the die
  - Steel Founders' Society of America are contributing funding towards the purchase of test materials
  - Plansee is providing Densimet (tungsten-alloys) inserts at half price
  - Mercury is covering the remaining costs of the test die design and fabrication

NADCA
NORTH AMERICAN DIE CASTING ASSOCIATION

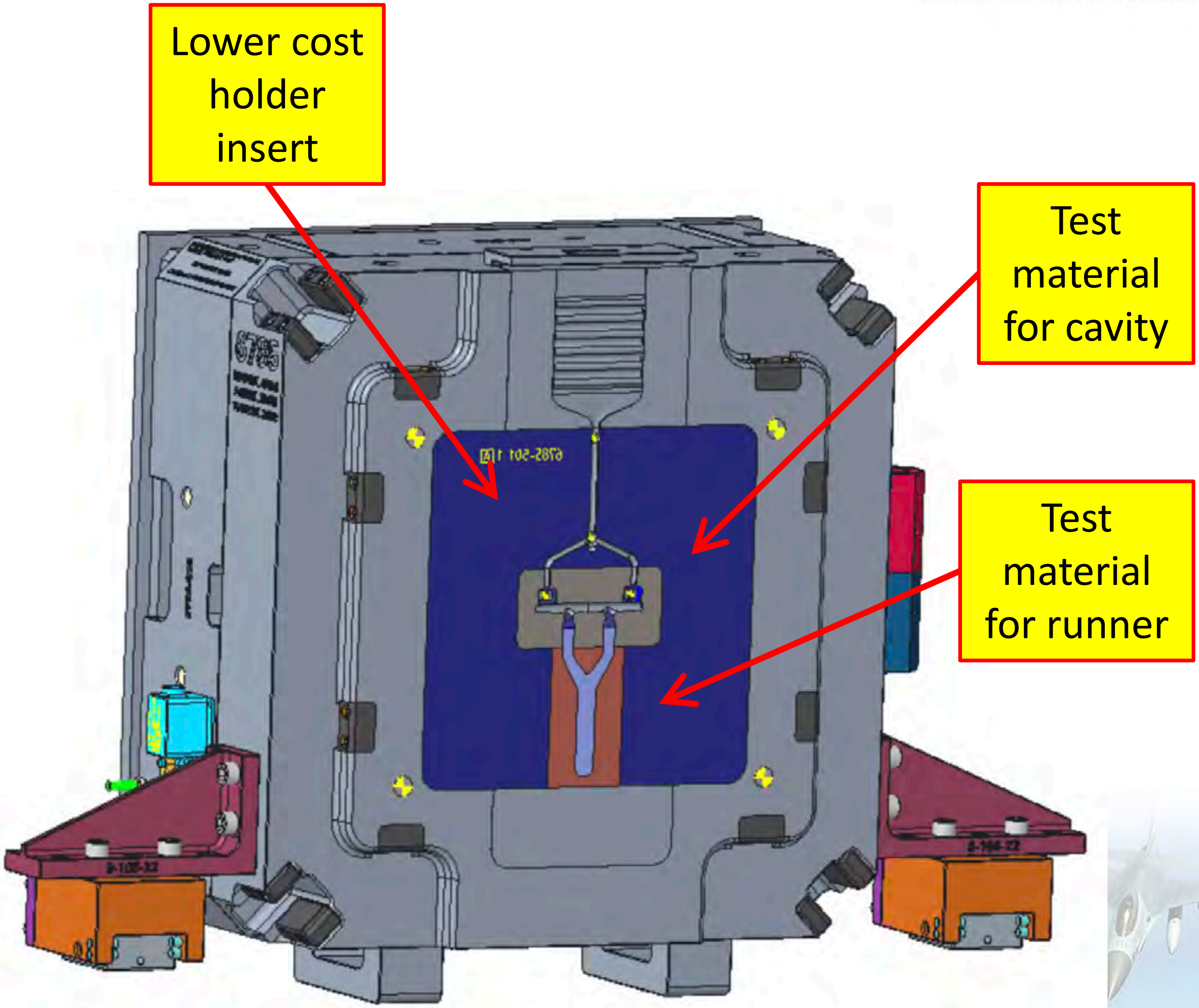
Mercury Tool Design

- 80% of tool design is done for the Boat Cleat
  - Heating and cooling lines still required
  - Clearances and thermal stack-up needs to be reviewed for different molding materials.
- Cavity design is still needed for the lever
  - This design will move quickly once the boat cleat design is complete.



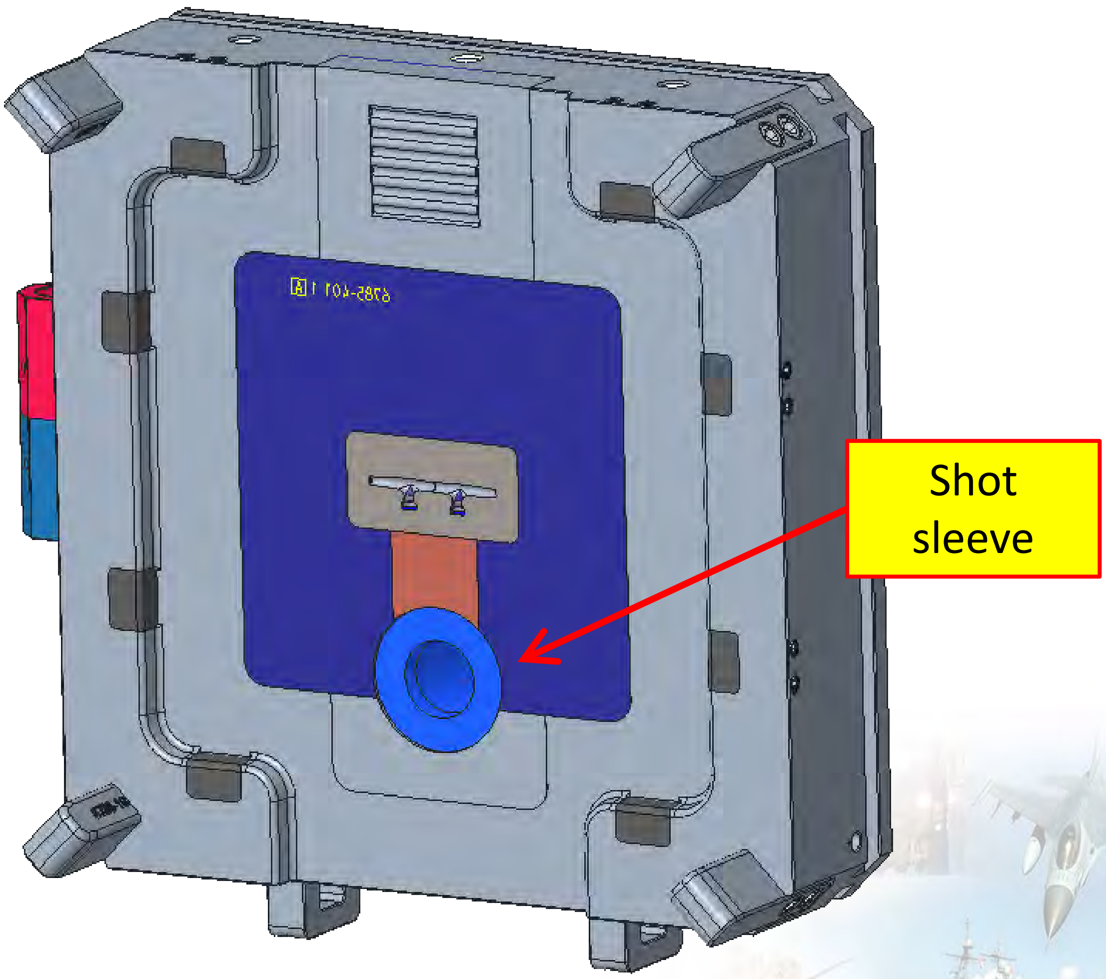
Ejector Side of the Die

- Segmented cavities to reduce material cost for trials
- Design still needs cooling passages and heater installation holes.



Cover/Fixed Side of the Die

- Same insert approach will be used



Activities Related to the New Die

Review of the Design Rules

The literature identifies the following variables as the starting point for design:

- **Flow time**

$$t_{f_s} = \frac{d_w \rho C_P}{2h}\left[-\ln\left(\frac{T_{liq} - T_{die} - f_s\left(T_{liq} - T_{sol}\right)}{T_{gate} - T_{die}}\right) - \frac{L_f}{C_P\left(T_{liq} - T_{sol}\right)} \ln\left(\frac{T_{liq} - T_{die} - f_s\left(T_{liq} - T_{sol}\right)}{T_e - T_{die}}\right)\right]$$

- **Gate velocity**

$$D \rho v_g^{1.71} > J$$

- **Gate area**

$$X_{f_s} = v_g . t_{f_s} \qquad A_g = \frac{V_{cav}}{v_g . t_{f_s}} = \frac{V_{cav}}{X_{f_s}}$$

The First Variable to Define is the Gate Velocity

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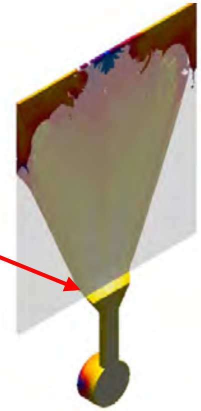
- Metal velocity entering the casting cavity



Example geometry illustrating typical metal flow behavior at HPDC velocities

- There are recommended gate velocities for different alloys, but not for steel

Typical gate speeds and values for the J factor (NADCA PQ^2 & Gating Manual)

Alloy	Typical Gate Speed		Gate Speed Range		Atomization Constant	
	v_g				J	
	in/s	m/s	in/s	m/s	$(lb/in^2)(in/s)^{1.71}$	$(kg/m^2)(m/s)^{1.71}$
Mg	1675	42.0			275	362
Al 360, 380, 384	1550	38.7	1000-1600	25.4-40.6	400	526
Al 390	1550	38.7	1000-1600	25.4-40.6	400	526
Zn 12, 27	1150	29.0	1000-2000	25.4-50.8	475	625
Zn 3, 5, 7	1000	25.0	1000-2000	25.4-50.8	475	625
Cu 60/40	900	22.5			750	987
Cu 8-5-5-5-5	880	22.0			750	987
Pb	775	20.0			300	395

- The minimum gate velocity is based on the atomization condition

$$D \rho v_g^{1.71} > J$$

$$D = \frac{ab}{(a+b)}$$

Gate cross-section area representation

J is three times larger for steels than for Al alloys

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- The expression for J is

$$J = \frac{10^{\left(\frac{K}{0.7}\right)}}{2\mu^{0.29}\sigma^{1.71}}$$

where

μ = liquid metal viscosity [kg/m.s]

σ = liquid metal surface tension [kg/s^2]

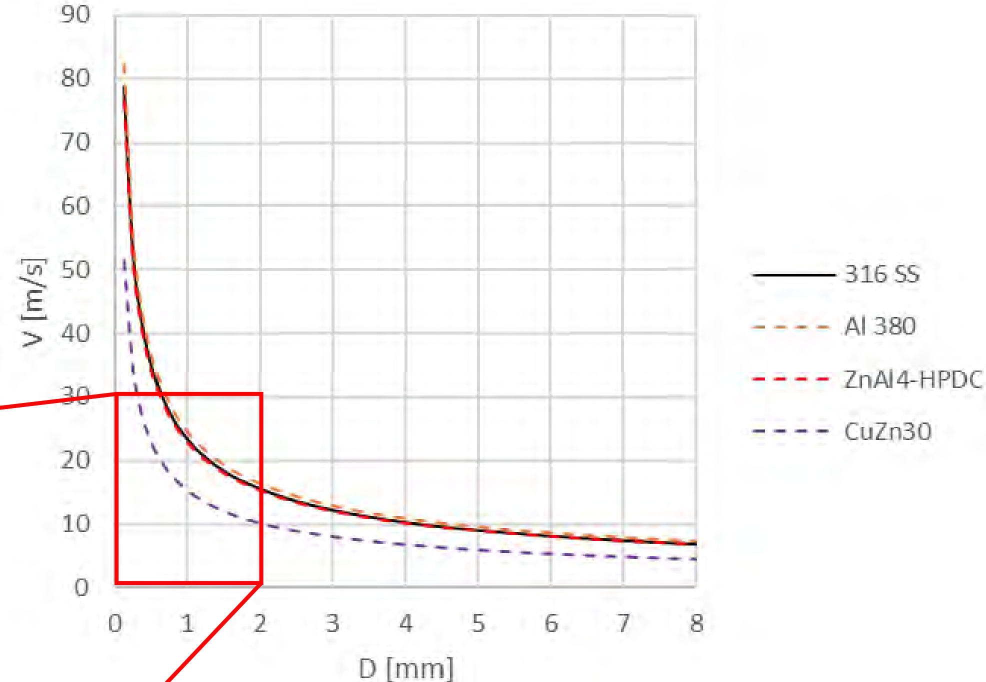
K = 2.8

- Atomization constant J for steel (316 SS)

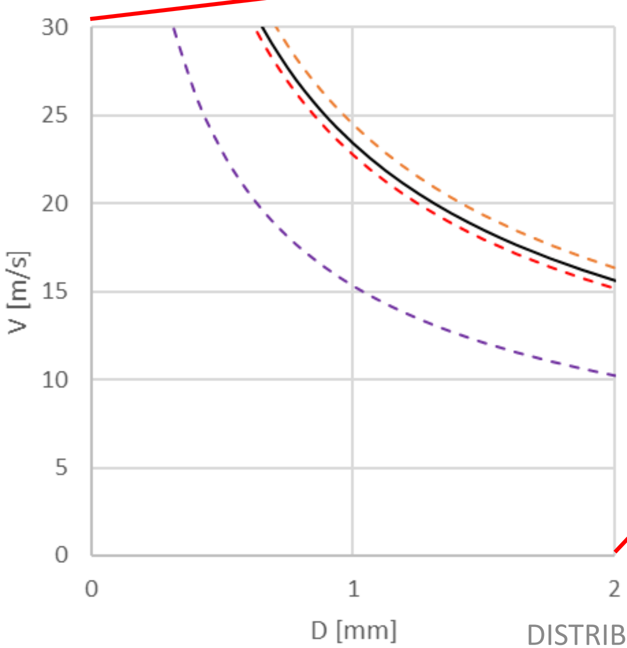
$$J = 1505\ kg/m^{0.29}s^{1.71}$$
$$1143\ lb/in^{0.29}s^{1.71}$$

- Recommended gate velocity for steels is 26.2 m/s or 1031 in/s

Al 380, ZnAl4, and SS 316 have the same velocity requirements



Minimum gate velocity as a function of gate parameter for various metals

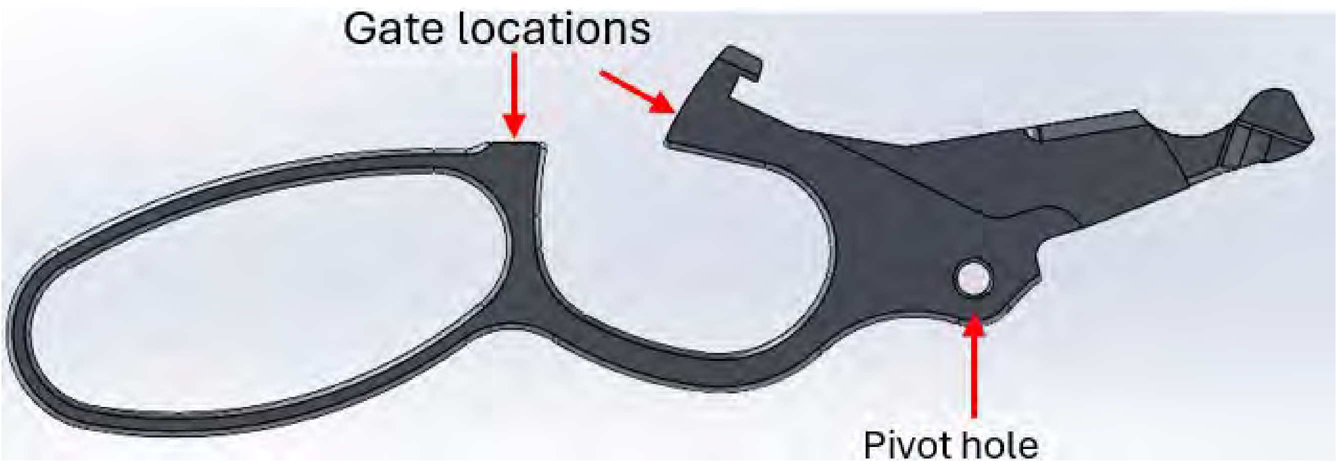


Casting and Gate Locations

- Casting is a pistol rifle lever
- Small casting, different thickness sections
- Once assembled in the final product, part of the casting is visible, and part is hidden in the assembly
- The areas less visible in the casting were selected as a tentative location for the gates

Casting characteristics

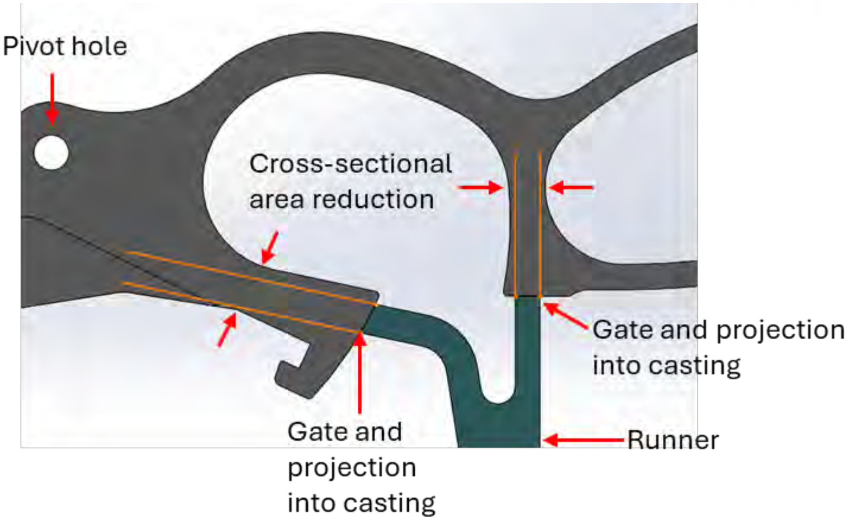
Mass:	0.19	kg	0.42	lb
Volume:	24.12	cm^3	1.47	in^3
Surface area:	128.89	cm^2	19.98	in^2
Length:	223.94	mm	8.82	in
Max. thickness:	9.35	mm	0.37	in
Min. thickness:	1.40	mm	0.06	in
Avg. thickness (d_w):	6.93	mm	0.27	in



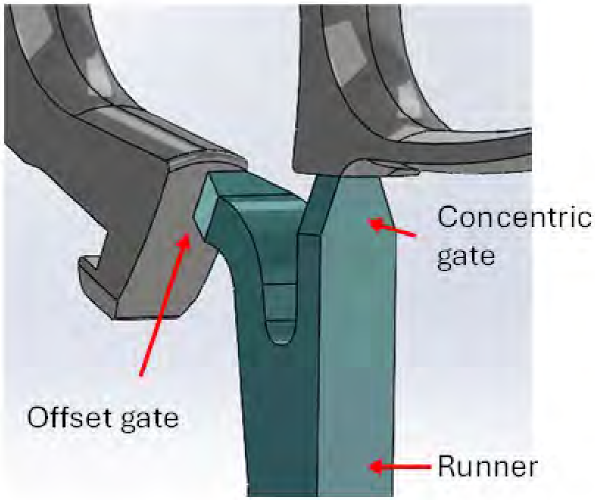
Lever geometry

Gating System

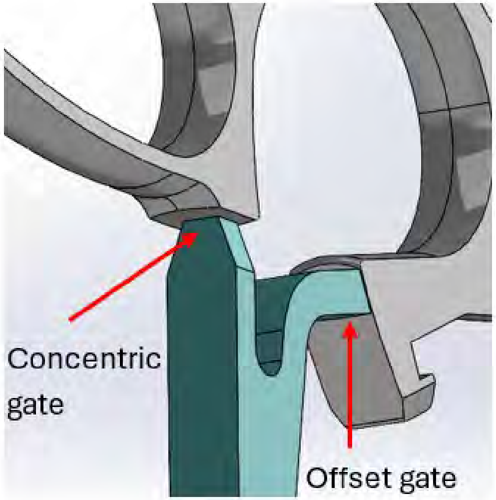
- Five iterations of the runner and gate were considered and simulated
- Flow direction is important – chisel-type gates were used
- There is a reduction in the cross-sectional area in the casting (becoming this reduction the effective area).
- An offset gate is used to help direct the flow deeper into the casting



Projection of the gates into the casting



(a) *Front view*

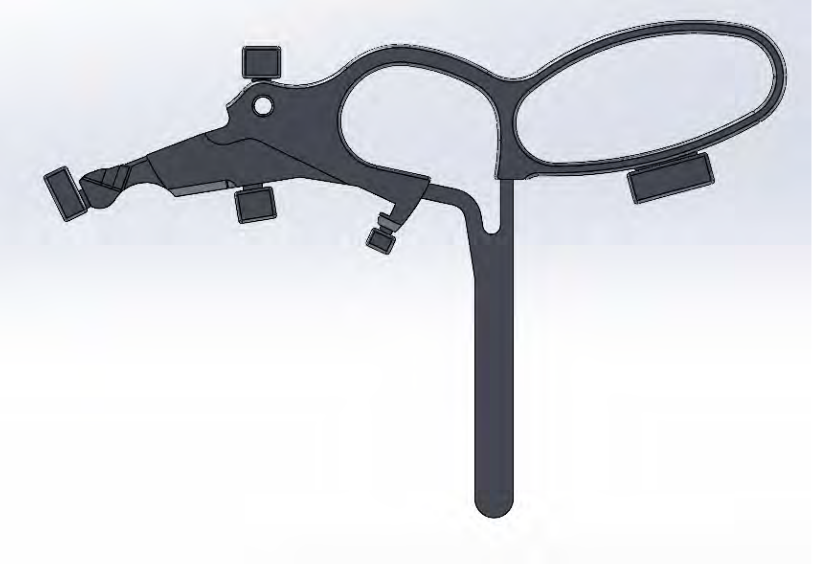


(b) *Rear view*

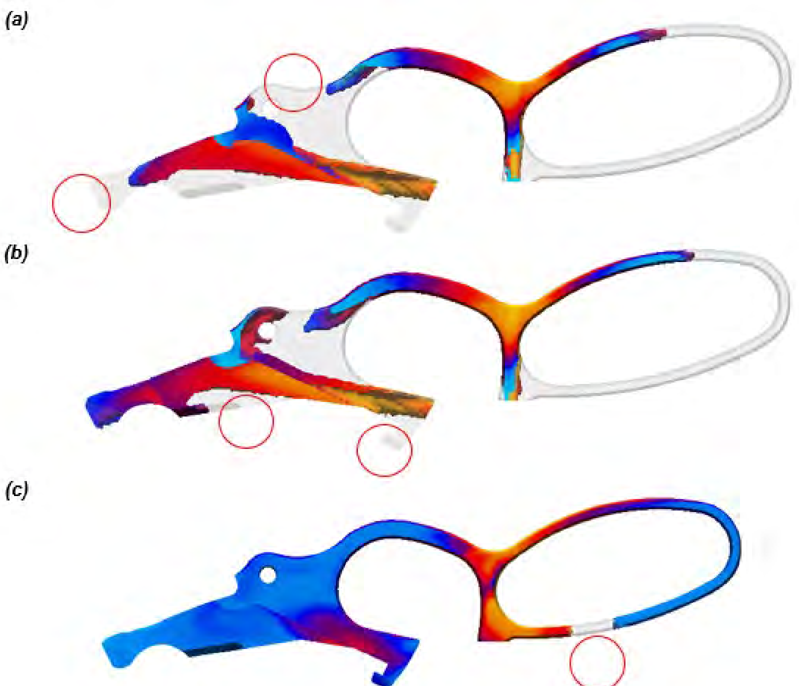
Front and rear views of part of the runner, gates, and casting

Final Design

- Simulation of filling was used to identify the overflow locations
- The next configuration will serve as a base for the die design
- This version is currently under review by Mercury



Lever with runner and overflows



Lever filling sequence with candidate overflow locations

The Challenge of Steel HPDC

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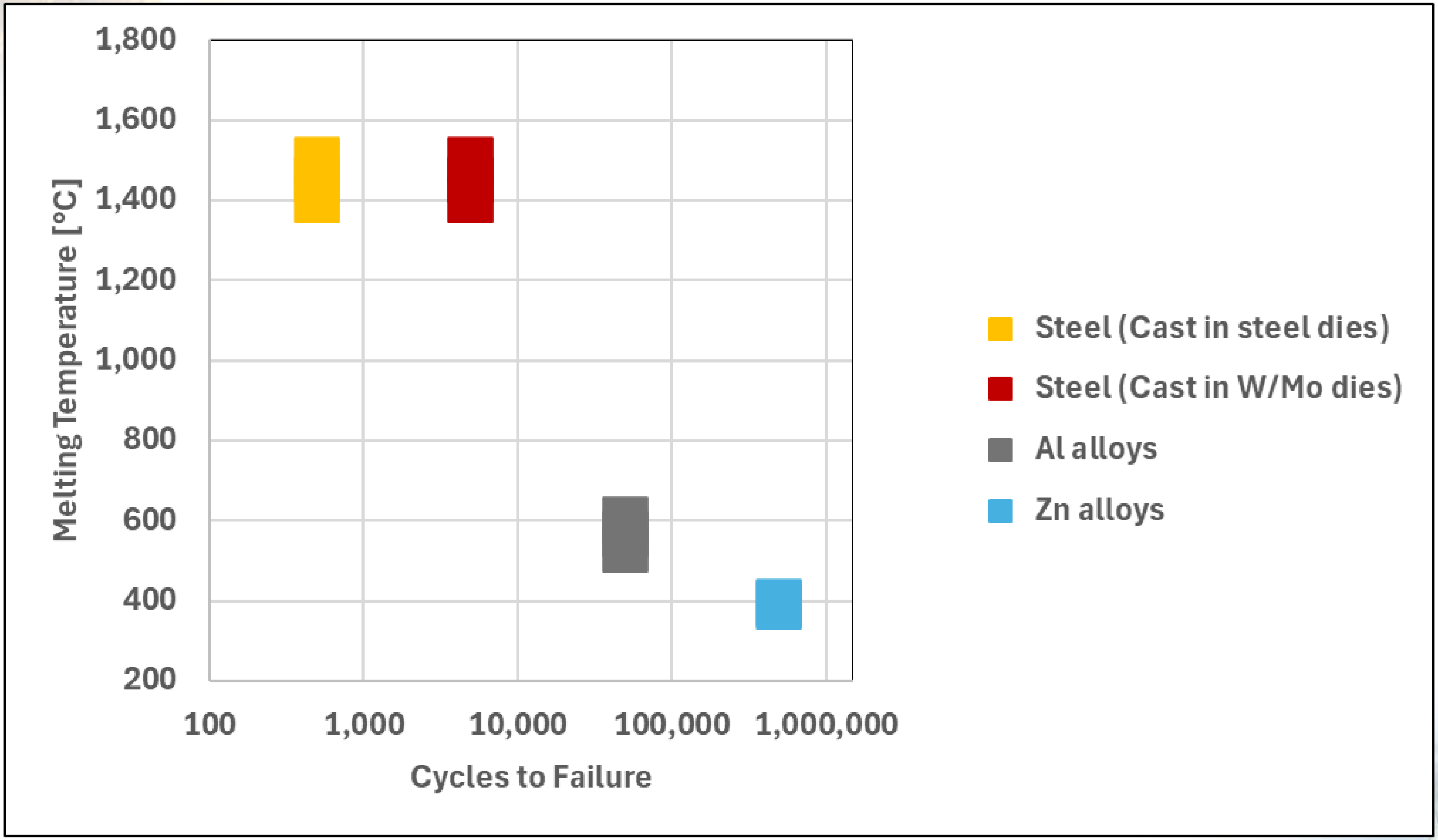

Estimated die life for various cast metals based on Sellors (1970s), Cross (1980), and Kaye (1982)

Heat Transfer Coefficient (HTC) Determination – In progress

The Thermal Load in the Die is Affected by the HTC

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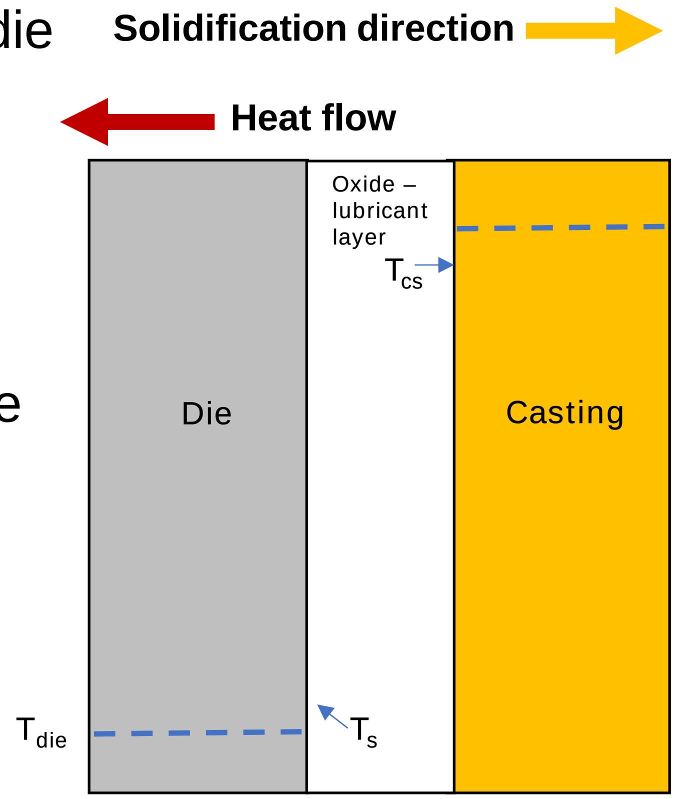
- The heat exchange between the casting and the die is what defines the casting microstructure and thermal load on the die
- The heat exchange is controlled by the physical properties of the casting, die, and the HTC
  - HTC quantifies the rate of heat flow across the metal-mold interface
- Mercury coaster die will be instrumented to obtain the transient temperatures within the die



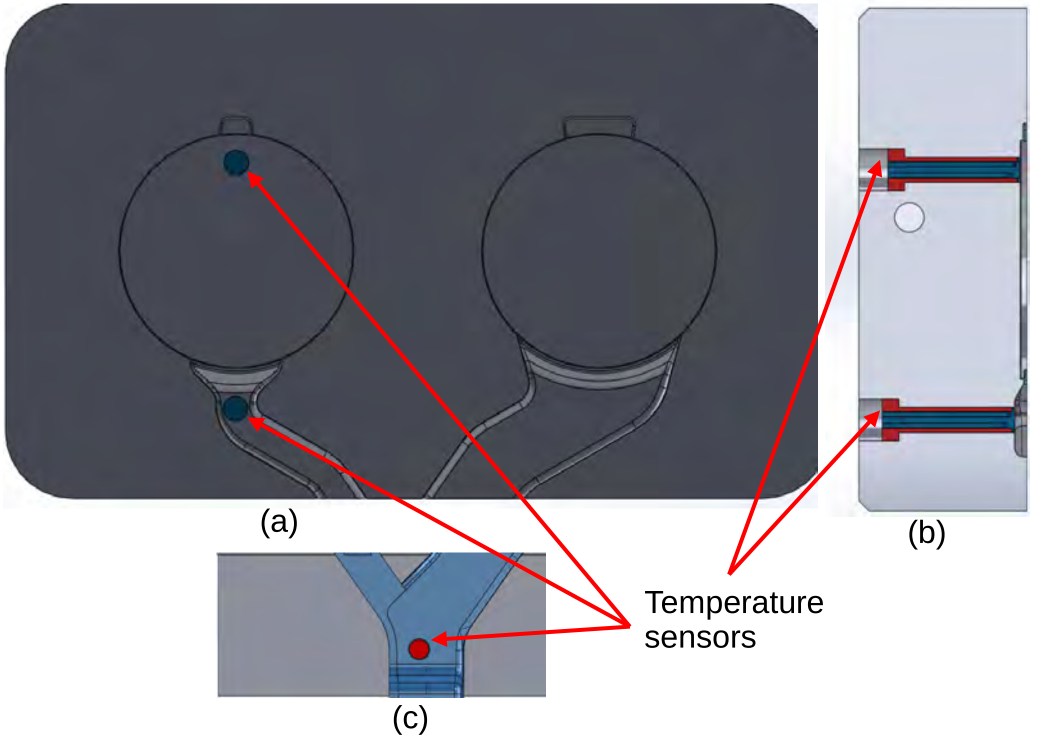
Temperature distribution in the casting and die (Adapted from Lindsey, 1968)

$$HTC = \frac{q}{(T_{cs} - T_s)}$$

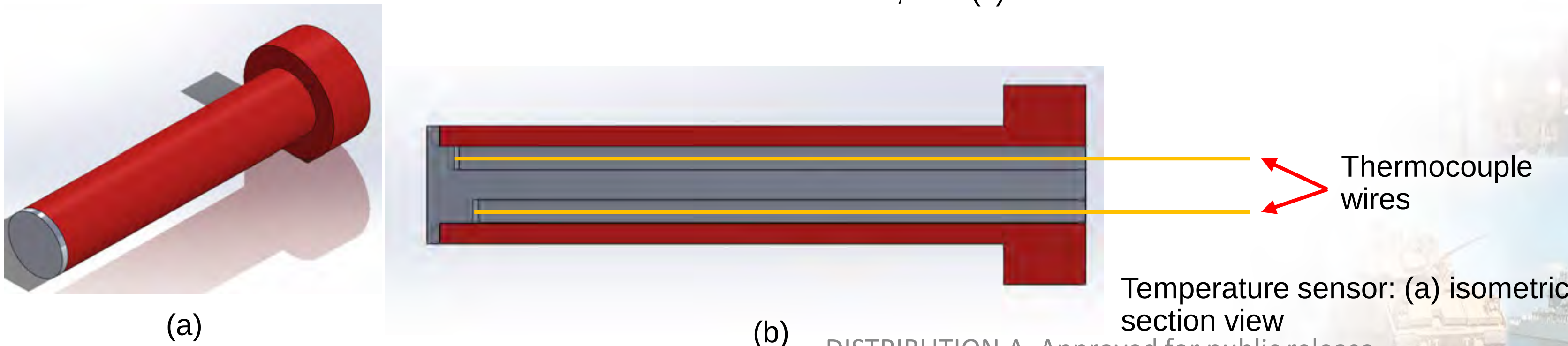

Coaster die on the fixed half of the HPDC machine

Temperature Sensors

- Three sensors, two in the runner and one in the coaster cavity
- Data will be collected at 1.5 mm and 3 mm beneath the die surface
- Sensor will be tested at UA before planning the trip to Mercury Marine



Temperature sensor location in the dies: (a) front view, (b) section view, and (c) runner die front view



Temperature sensor: (a) isometric view, (b) section view

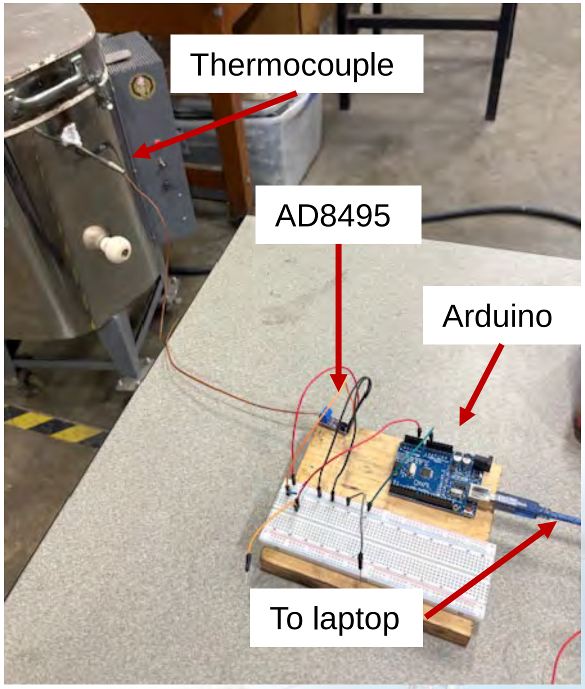
High-speed data sampling requires a customized solution

Figure XX. AD 8495 thermocouple amplifier module

- Based on previous trials, the cavity filling time is about 30 ms
- Thermocouple readers available range from 4 Hz/250 ms to 25 Hz/40 ms
- A thermocouple module, in conjunction with a microcontroller, offers the option of increasing the sampling rate to 1 kHz

Thermocouple —μV→ **AD8495** —V→ Arduino → Laptop

AD8495
- Amplification
- Cold-junction compensation
- Outputs an analog voltage proportional to temperature, approximately 5 mV/°C



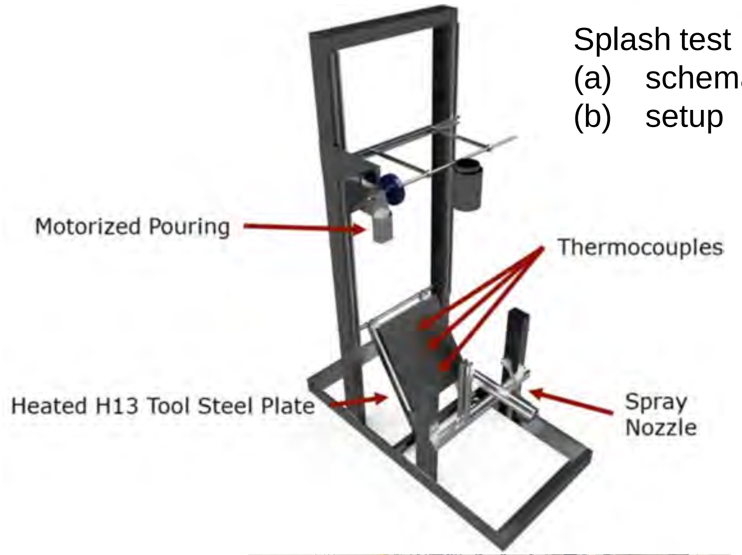
Temperature recording setup

Die Lubricant Evaluation – In progress

ASTM-Based Test Setup

- The rig has been used to study the thermal response of the plate (die) under cycling conditions
- The splashes of molten metal can be done in a controlled and consistent way
- Temperature on the plate can be controlled (Preheat temperature)
- Uses a spray system similar to the one used in the HPDC industry
- Temperature response beneath the plate surface is recorded after each splash

Splash test rig:
(a) schematic,
(b) setup



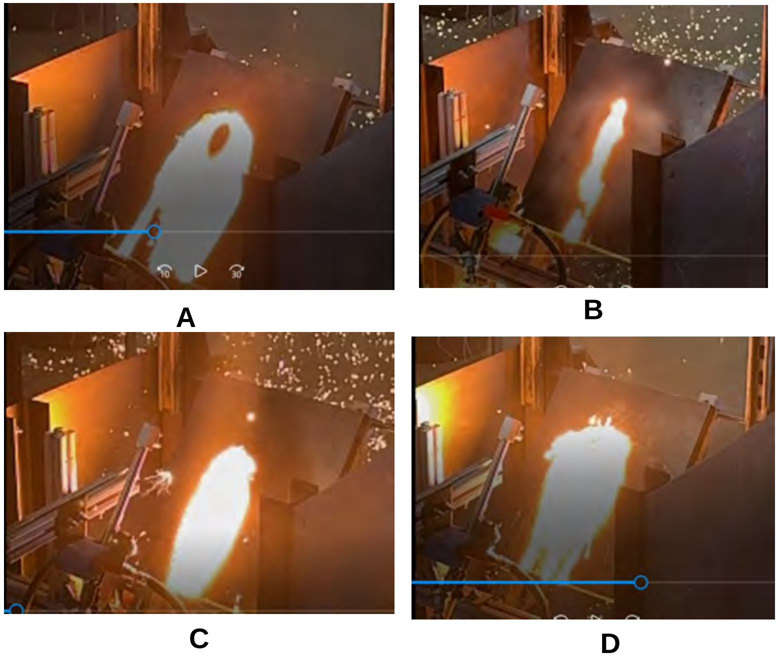
(a)

(b)

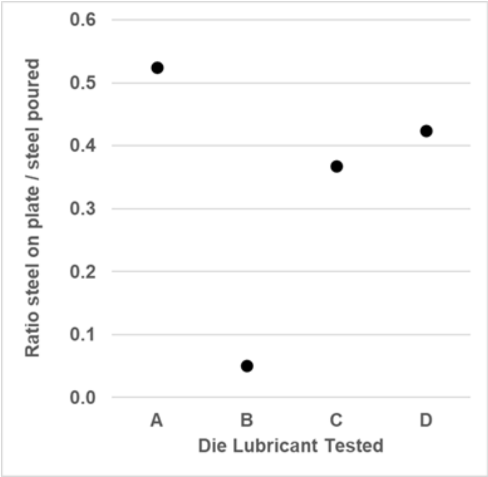
Preliminary Test Video

Preliminary Test

- The goal was to verify that the rig functioned properly
- Four die lubricant conditions were tested. A: No die lubricant, B: Boron nitride, C: Graphite, and D: Inorganic die lubricant
- Temperature data from the plate was obtained
- The spray of the die lubricant was irregular – needs improvement
- The steel-on-plate to steel-poured ratio could be used as another indicator of die lubricant performance



Steel plate after splashes for conditions A, B, C, and D.

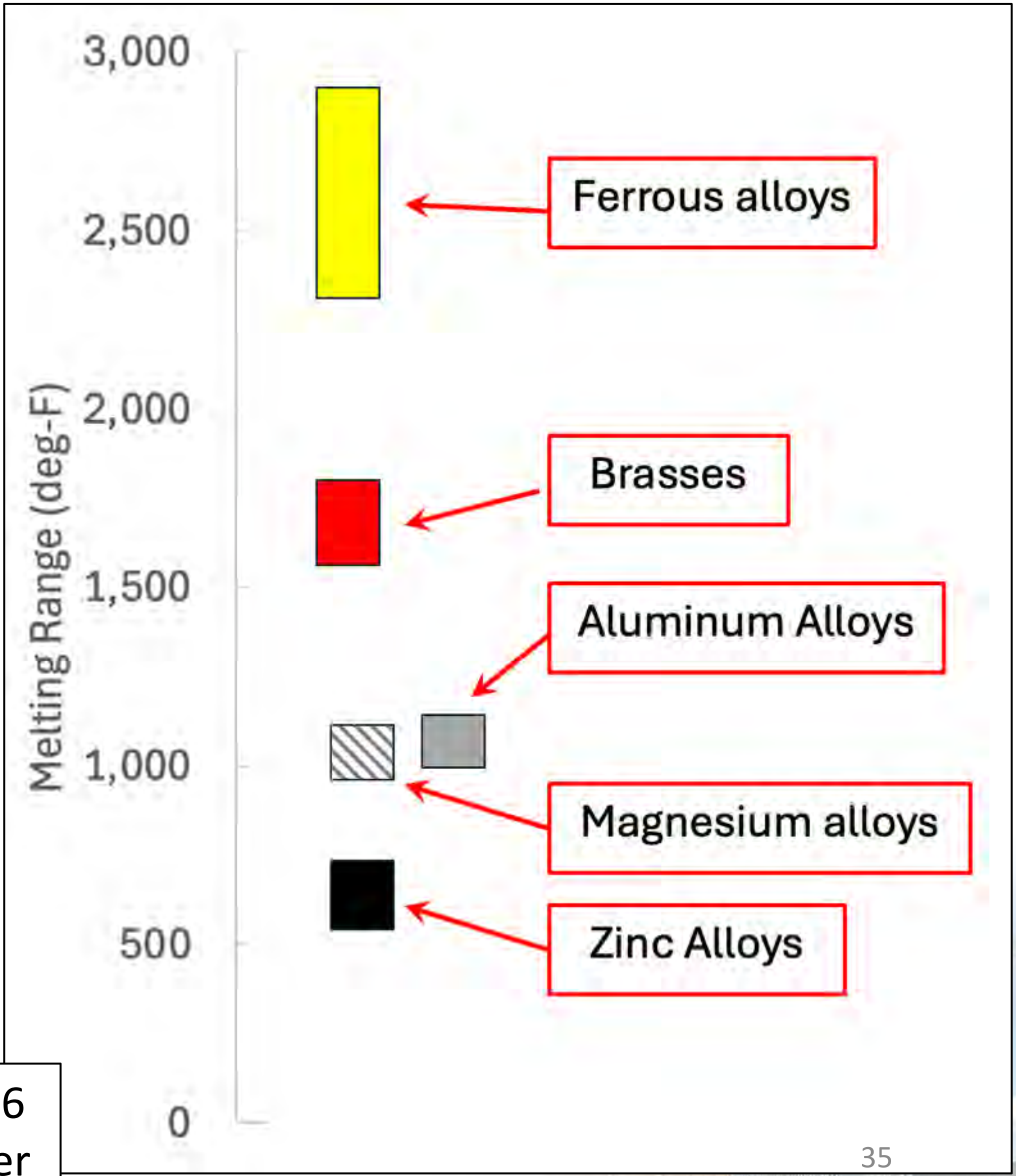


Ratio of adhered mass to poured mass for different die lubricant conditions

Die Life Testing at Mines

Background

- Steels are currently not die cast
  - Due to their high melting temperatures
- Need to identify die materials and coatings that will survive at these high injection temperatures

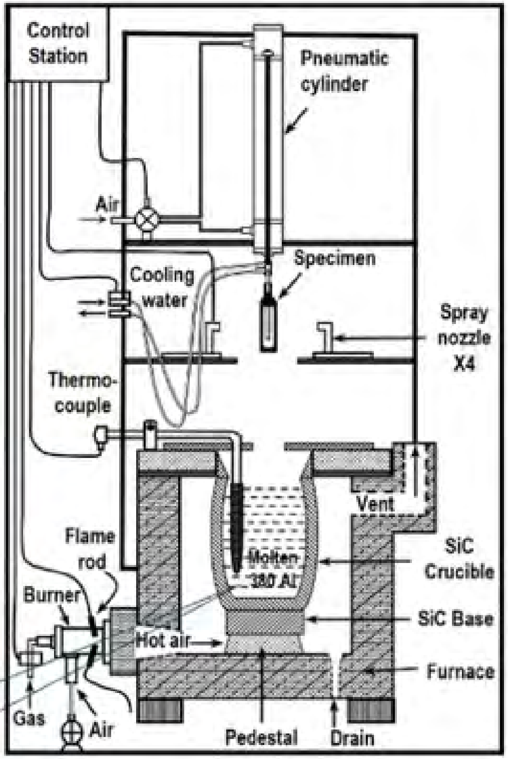


Modified from a 1976 steel die casting paper

Die Life Testing Apparatus

- Mines has built a laboratory test apparatus
  - Similar to the Case Western dunk test
  - But utilizing induction to heat the steel die material
    - Rather than a liquid metal
  - This will allow the evaluation of heat checking resistance
    - Of a wide range of materials and process conditions

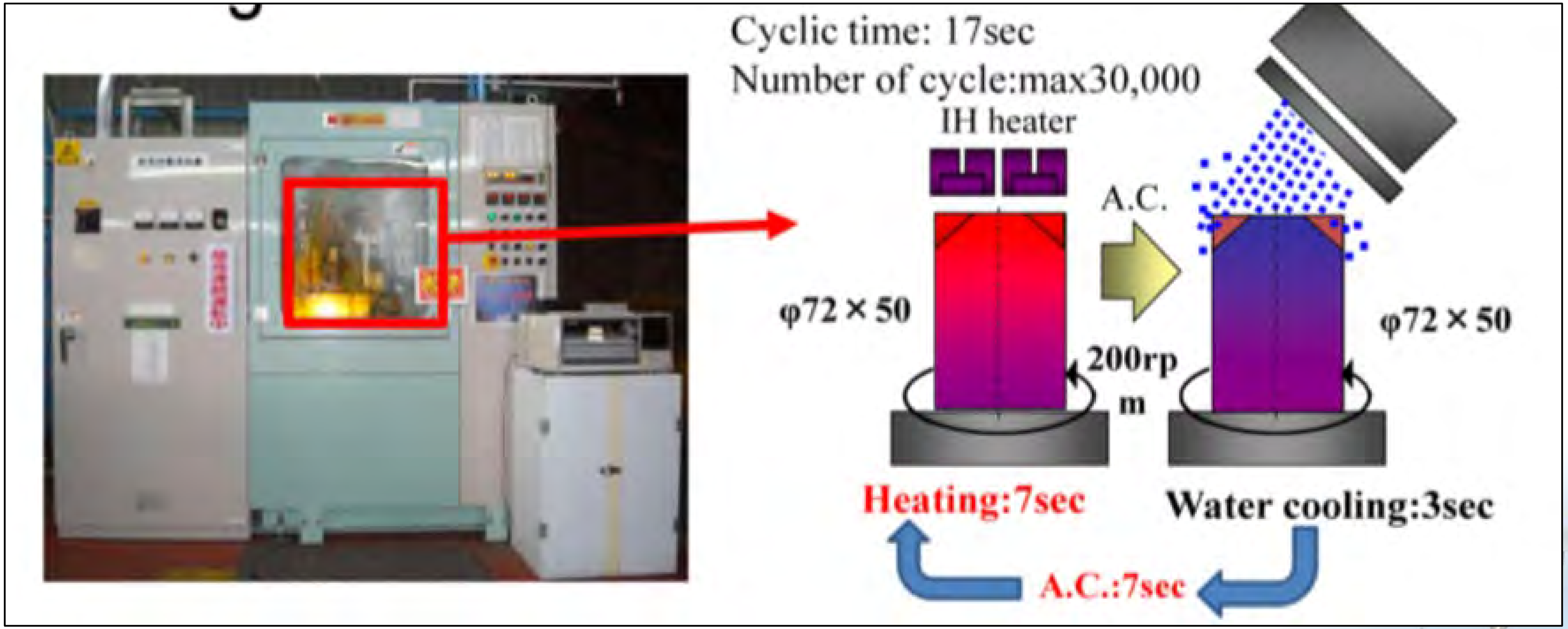
Case Western Reserve University Dunk Tester



- Has been used for more than 50 years
  - To examine die life for aluminum die casting

Daido (Japan)

- Also used to examine die life for aluminum die casting
- Uses induction to heat the sample of die material
  - Rather than liquid aluminum



Mines Test Rig Design

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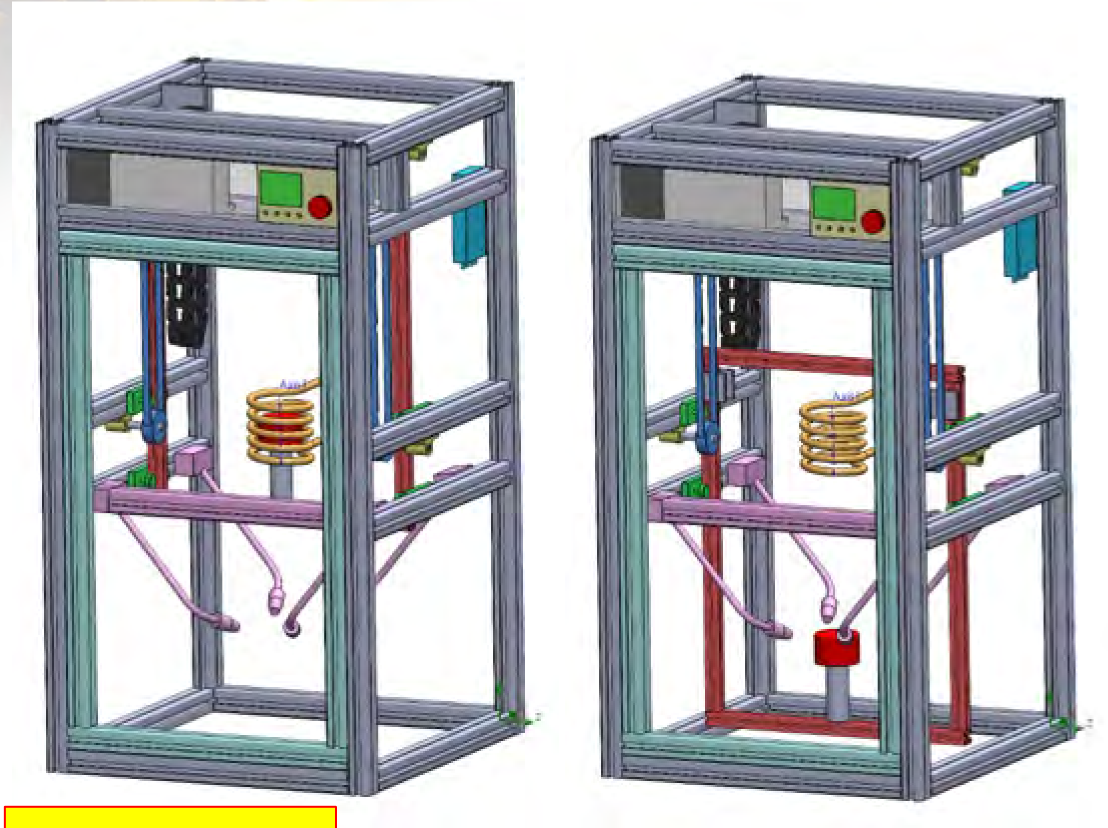


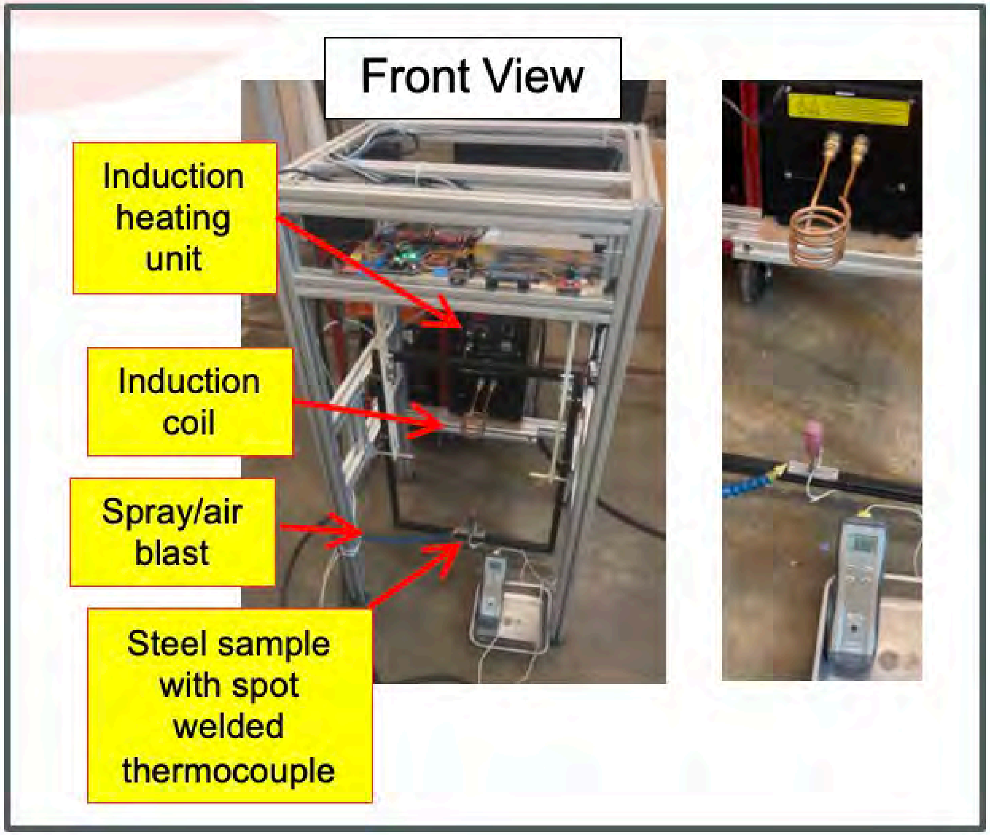
Sample in upper position - heating

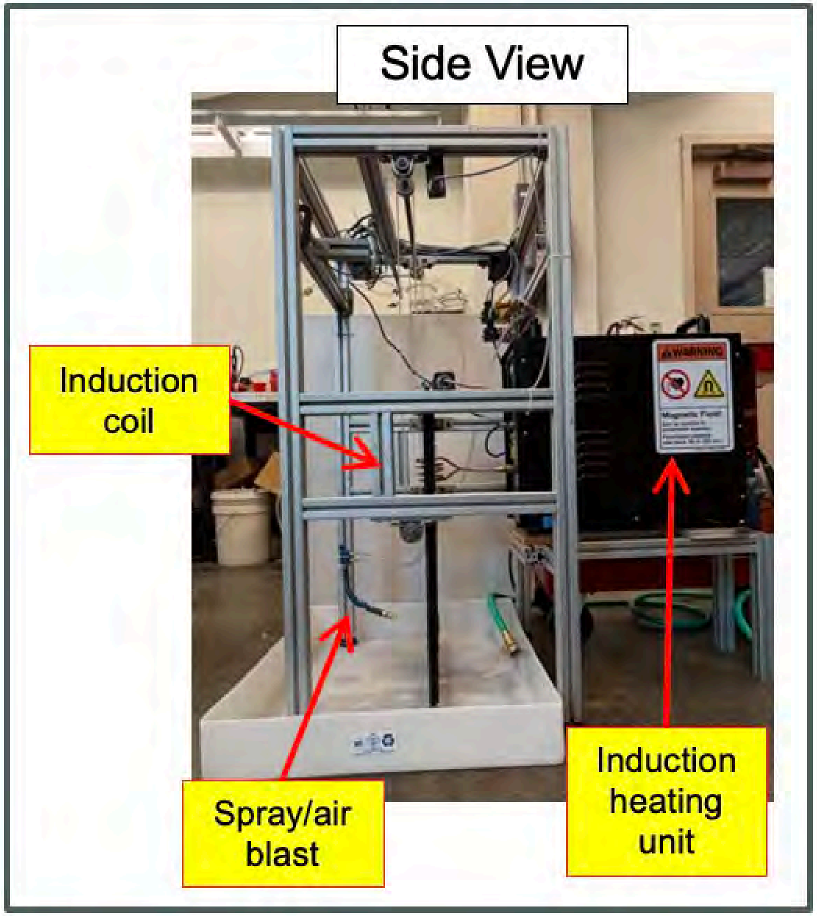
Sample in lower position - spraying

- Thermocouple is spot welded to the surface of the sample
  - So that the heating can be controlled
- Test sample can also be pre-heated or cooled

Test Rig Status

- Test rig has been fabricated
- Heating/cooling trials have been run





Typical Test Conditions

- Heating a steel slug (1.0" diameter by 2.0" tall) with a thermocouple spot welded to its surface
  - Sample does not have internal cooling
- Approx. 20-to-30 seconds overall cycle (open loop)
  - Raise slug into induction coil: 2-3 secs
  - Heating in induction coil: 6-10 secs
  - Lower slug into spray position: 2-3 secs
  - Air blast: 3 secs
  - Air cooling: 7 secs

Test Apparatus

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Test Apparatus

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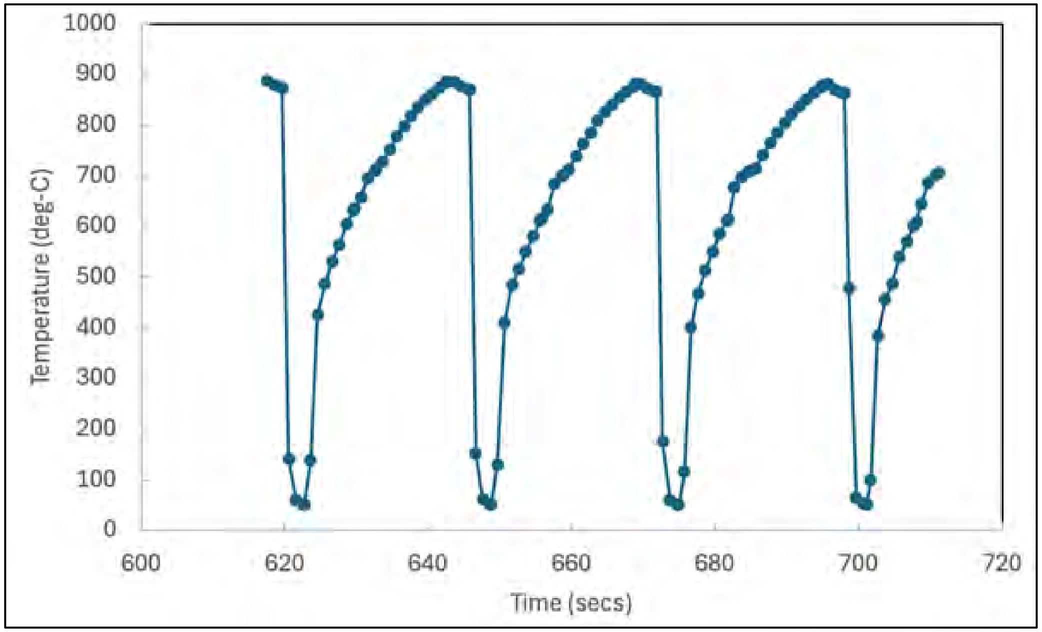
Die Life Testing at Mines - Status

- A series of trials and modifications have been performed
  - Open loop heating versus closed loop heating
  - Run 1,000 cycles
  - Modify sample shape to promote heat checking
  - Up-grade spray system

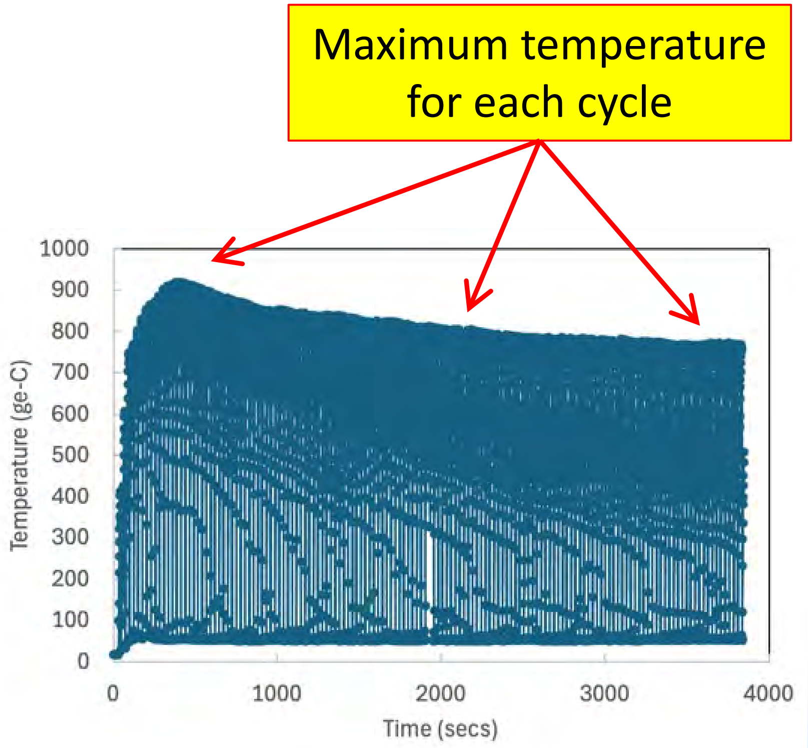
Background – Temperature Measurement

- The sample being heated/cooled is a cylinder (2" tall by 1" diameter)
  - Hardened H13 steel
- A thermocouple is spot welded to its surface
- Temperature data is recorded every 0.3 seconds



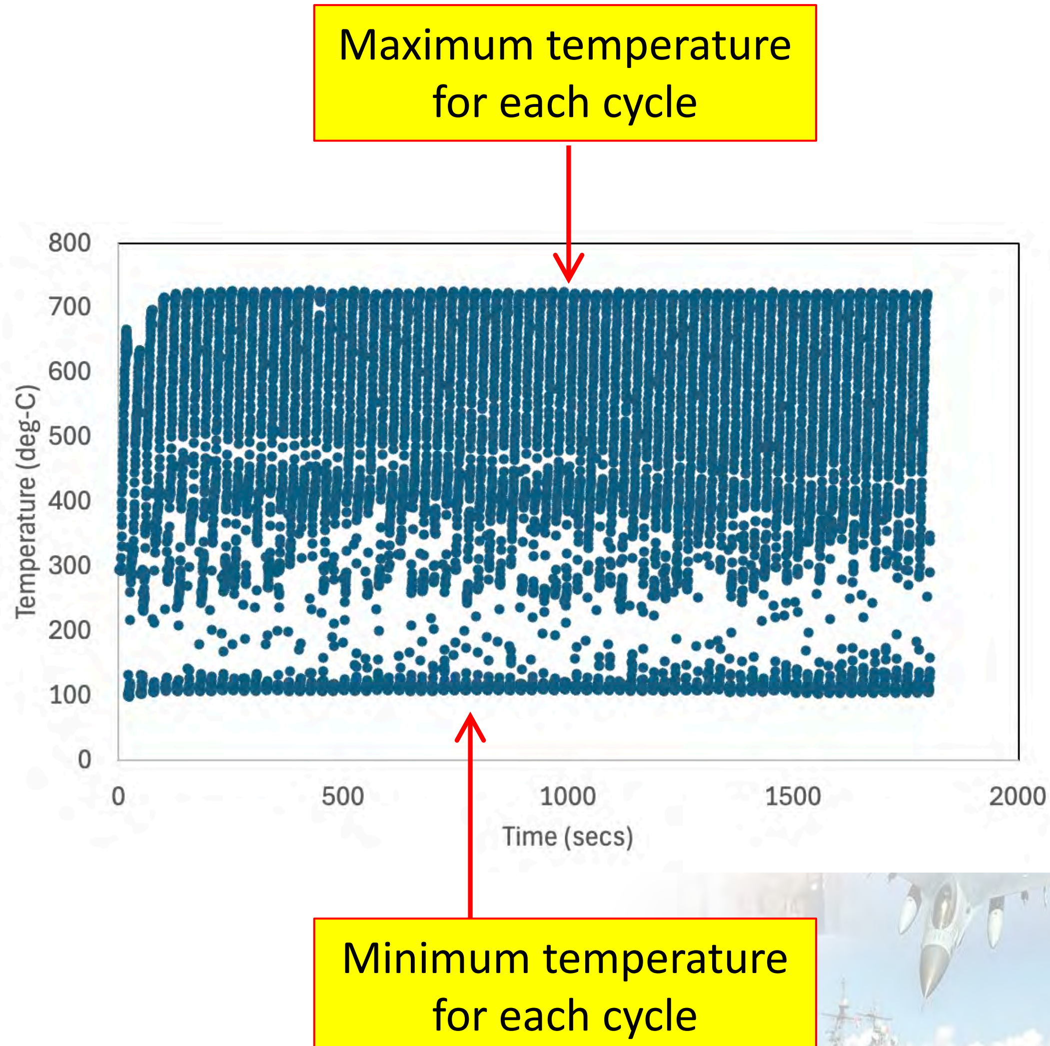
Open Loop vs. Closed Loop Control

- Shows a 100-cycle run
  - Run using open loop control
    - Heating for ten seconds
  - For an H13 steel slug
- Maximum temperature decreased during the run
  - By more than 100°C
  - Possible reasons
    - Changes in surface emissivity as the slug oxidizes, resulting in higher radiation losses
    - Changes in the electrical conductivity of the steel slug, changing the energy input to the slug each cycle
    - Changes in the induction heater power source during the run



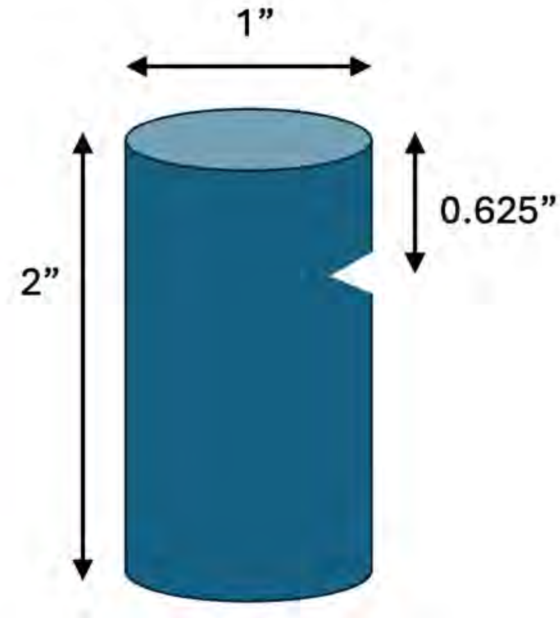
Closed Loop Control

- Data from approx. 50-cycle run
- Both the maximum and minimum temperatures each cycle are extremely consistent
- The maximum temperature was set to 700ºC
    - Held to this maximum temperature extremely closely
- This is extremely important
    - ΔT ($T_{max} - T_{min}$) is very important for heat checking



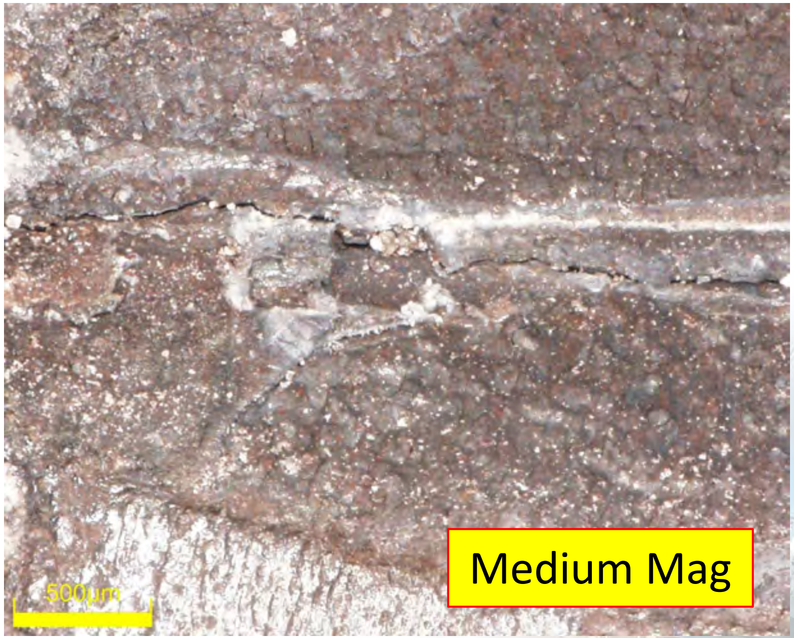
Notched Sample

- A change has been made to the shape of the sample being heated and cooled
- To-date, the sample has been a simple cylinder
- Now machining a sharp notch in one side of the sample
  - Induce a significant stress riser at the root of the notch
  - Objective is to induce a heat check fatigue crack at the notch root



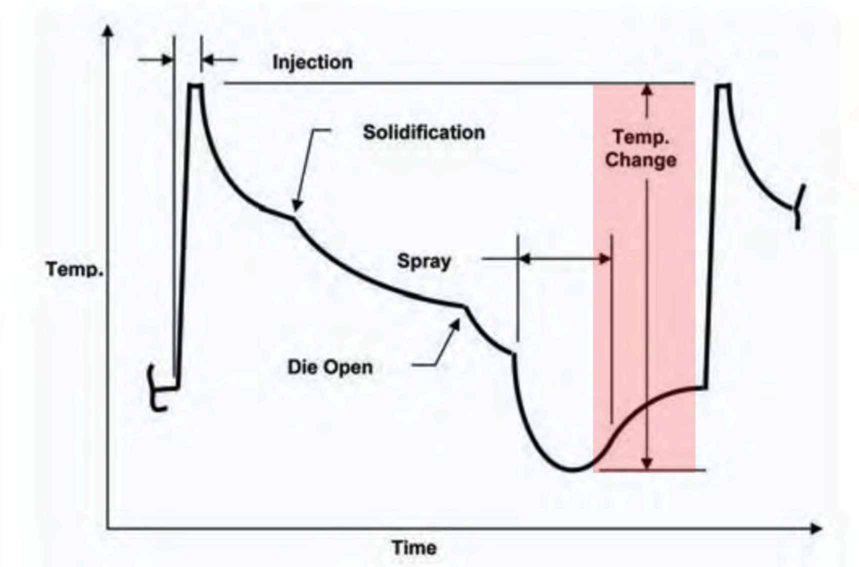
Crack in Notched Sample

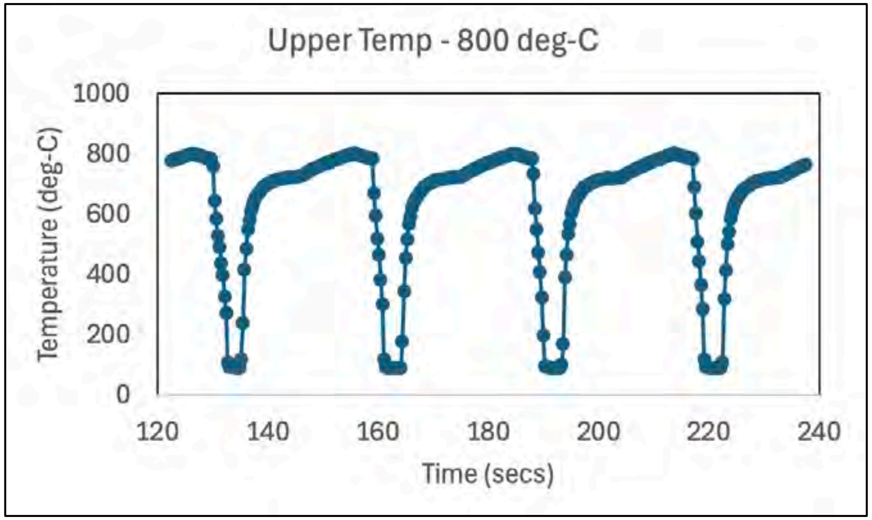
- Sample ran 2,250 cycles
- Upper temperature – 700^{o}C
- Lower temperature – ~120^{o}C

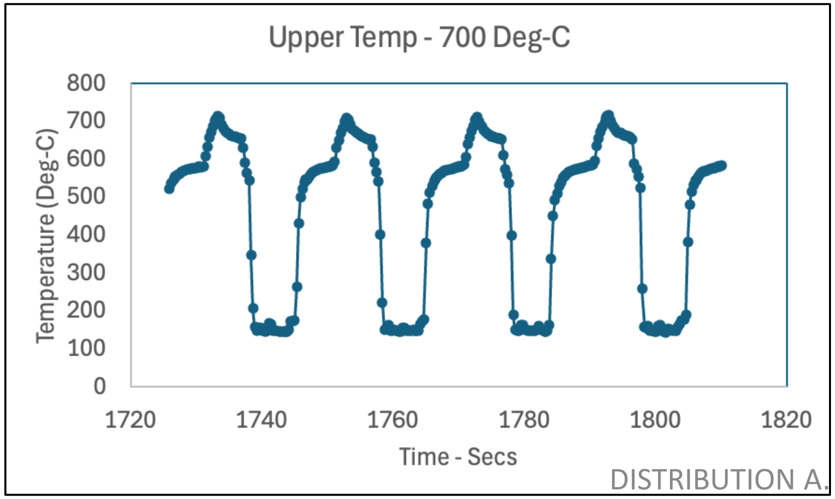


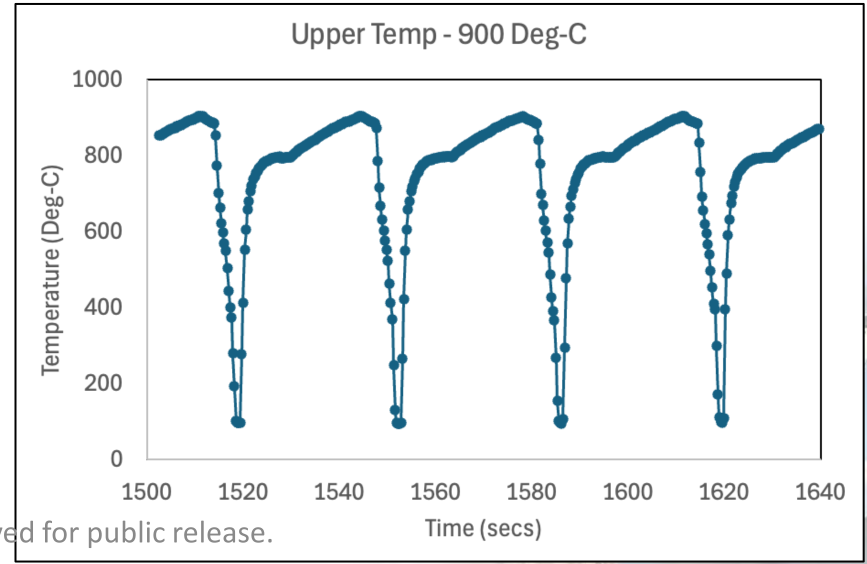
Changing Process Parameters

- Die life is controlled by temperature change of die surface during casting cycle









Project Plans – Short Term (Mines)

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1. Characterize effect of process conditions on crack formation and size
   - Run under different conditions
   - Measure size of cracks formed
2. Establish automated running of equipment
   - At present, each run is being observed
     - Generally, by two people (for safety)
   - Goal is to allow the equipment to run automatically
     - Unsupervised
   - Before this can be achieved
     - Have to ensure that the equipment runs consistently and safely

Project Plans – Longer term (Mines)

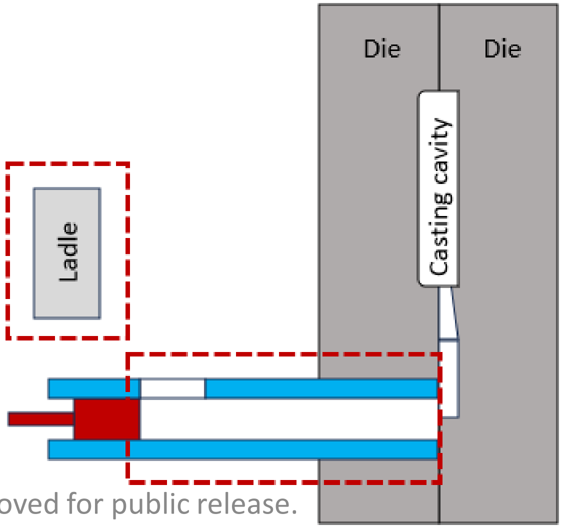
- Test a range of materials
  - H13 steel, with & without internal conformal cooling
  - Advanced hot work die steels such as H21
  - Water cooled copper dies
  - Refractory alloys, such as Densimet and TZM, pre-heated to different temperatures
  - The effect of advanced manufacturing processes, such as 3D printing and coatings, on die life

For example, extreme water cooling associated with lattice structures

Project Plans (Alabama)

- Short Term:
  - Complete HTC determination under HPDC conditions
  - Complete die lubricant evaluation

- Long Term:
  - Characterize heat losses during transfer and dosing
  - Define values for process variables: die preheat temperature and furnace temperature



HPDC machine schematic

Transition Plan

- Several leading die casting organizations have expressed interest in advancing steel die casting technology
- Project updates will continue to be communicated to industry stakeholders through future North American Die Casting Association Congresses and technical committee meetings
- Mercury Marine has shown particular engagement in this effort, their plan to fabricate a test die
- The project is currently progressing through the die design stage, targeting the production of a firearm component for Henry Repeating Arms

Producing test steel die castings at Mercury's plant in Fond du Lac, WI

Leveraging

- The project plans to leverage several previous efforts on die casting of high melting temperature alloys
  - 1960's GE project
  - 1970s copper-alloy die casting project funded by the International Copper Research Association
  - 1990s effort to die cast pure copper led by the Copper Development Association
  - European Union-funded COST Consortium from the 2000s, focusing on semi-solid casting of steel
  - DLA-funded project on high-temperature die casting under AMC's Innovative Casting Technologies program

Project Metrics

Description	Baseline	Threshold	Goal	How Measured	Target Date	Progress	How Demonstrated
Filling distance for steel high pressure die casting	0.15 m flow length for 6 mm wall thickness casting	0.30 m flow length for 6 mm wall thickness casting	0.60 m flow length for 6 mm wall thickness casting	Production of steel die castings	2029	N/A	N/A
Define recommended steel HPDC process variables	No recommended process window established	Gate velocity defined; remaining variables identified	Recommended values for velocity, pressure, die preheat temp., dosing temp., and lubricant type	Number of variables with recommended values identified	2029	1/5	Documented process supported by casting evaluation
Mechanical properties	Yield strength values at least 50% of sand castings produced from the same alloy	Yield strength values at least 75% of sand castings produced from same alloy	Yield strength values equivalent or better than sand castings produced from same alloy	Mechanical property testing	2029	Achieved with 316 stainless	Mechanical property testing of die castings
Die life	1,000 shot minimum	1,500 shot minimum	2,000 shot minimum	Casting trial	2029	Test rig and test die are being fabricated	N/A

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This research is sponsored by the Defense Logistics Agency Information Operations, J68, Research & Development, Ft. Belvoir, VA and DLA Troop Support, Philadelphia, PA.

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Identifying and Controlling Factors to Improve the Production of Thin-Wall Ferrous High-Pressure Die Castings

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AMC AMERICAN METALCASTING CONSORTIUM

Problem:

- Steel components are currently produced using relatively expensive manufacturing processes (sand casting, forging, machining). Utilizing high pressure die casting (HPDC) would reduce cost, expand the supply base, and enable the production of steel castings with thin wall sections.

Objectives:

- Filling distance of 0.6 m for a 6 mm thick wall for steel in HPDC, have a yield strength equivalent or better than sand castings produced from the same alloy, and have a minimum die life of 2,000 shots.

Benefits to Warfighter:

- Use of HPDC for steel alloys will result in improved availability, enhanced quality, and decreased cost of steel die castings for DLA.

Description of Project:

The project will identify and control quality and cost factors to extend the high pressure die casting process to produce higher melting temperature steel alloys, improving the availability, enhancing the quality, and decreasing the cost of steel die castings for DLA

Team: North American Die Casting Association, ATI, Colorado School of Mines, University of Alabama

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Milestones / Deliverables:

- Identify cold chamber die casting machines and complete initial die casting trials
- Determine best approach for induction melting of steel
- Identify approach for transferring liquid steel from melting furnace to the die casting machine
- Finalize characterization of factors that affect and control the quality of the castings and complete evaluation of die life
- Production of commercial steel die castings