CANFSA

Center for Advanced Non-Ferrous Structural Alloys
An Industry/University Cooperative Research Center

Project 37-L: Advanced Engineered Coatings with Extended Die Life for Tooling

Semi-annual Fall Meeting
October 2021

- Student: Nelson Delfino de Campos Neto (Mines)
- Faculty: Andras Korenyi-Both, Stephen Midson, Michael Kaufman (Mines)
- Industrial Mentors: Paul Brancaleon (NADCA), Rob Mayer (Queen City Forging Co.)

COLORADO SCHOOL OF MINES   NSF   IOWA STATE UNIVERSITY

Project 37-L: Advanced Engineered Coatings with Extended Die Life for Tooling

- Student: Nelson Delfino de Campos Neto (Mines)
- Advisor(s): S. Midson, A. Korenyi-Both, M. Kaufman (Mines)

Project Duration
PhD: August 2018 to July 2023

- Problem: Molten aluminum tends to solder to die faces during the die casting process. Lubricants are applied to the die to reduce soldering and adhesion, but the lubricant reduces part quality.
- Objective: Identify PVD coatings to be applied to die casting dies to prevent soldering. Understand the mechanisms involved with adhesion.
- Benefit: Increase die casting part quality, eliminate the use of lubricants, extend die life and reduce cost-per-part.

Recent Progress

- Performed controlled laboratory die casting experiments at The Ohio State University.
- Started industry die casting trial at Stellantis.
- Characterization on tested core pins.
- Published paper: “The Use of Coatings to Minimize Soldering and Eliminate the Need for Lubrication during Aluminum High Pressure Die Casting” at Transactions of the NADCA 2021 Die Casting Congress & Exposition.

Metrics

Description	% Complete	Status
1. Literature review and development of molten aluminum tests	100%	●
2. Identification of the mechanisms that controls soldering and adhesion behavior	80%	●
3. Identification of PVD coatings to avoid molten aluminum soldering and adhesion	80%	●
4. Identification of PVD coatings durability to survive as long as the die casting dies (100,000 shots)	20%	●
5. In-plant trials. Guidelines for depositing the coating system on die components/tooling	20%	●

Industrial Relevance

- Reducing or eliminating lubricant spray will:
  - Significantly **<u>improve the quality</u>** of the die castings
    - Reduce gas porosity and scrap
    - Allow castings to be used in higher performance applications
  - **<u>Reduce costs</u>**
    - Eliminate purchase costs for lubricants
    - Reduce effluent clean-up costs
    - Significantly extend die life
  - **<u>Improve productivity</u>**
    - Faster cycle rates

Aluminum HPDC Tests

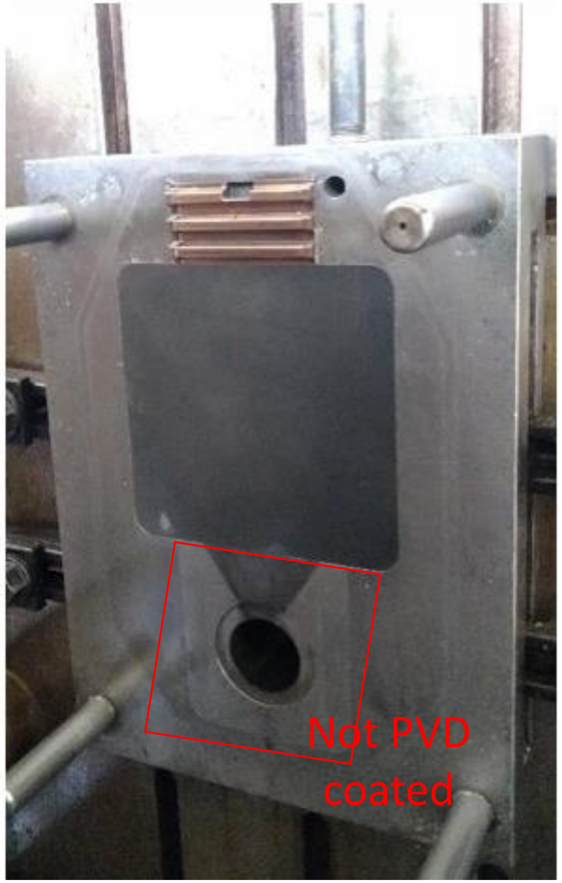
- Two sets of tests to find best PVD coatings for lube-free die casting
- Planned testing at The Ohio State University (OSU)
  - 250 ton Buhler die casting machine
  - Controlled laboratory test
  - Try to run lube-free
- Planned testing at Stellantis (Kokomo Die Casting Plant)
  - 3,000 ton commercial die casting machine
  - Run PVD coated core pins for 2,500 shots
    - Evaluate soldering of different PVD coatings
  - Evaluate soldering progression and coating life

Lube-free die casting trial at The Ohio State University

New Die Inserts (AlCrN PVD Coated)

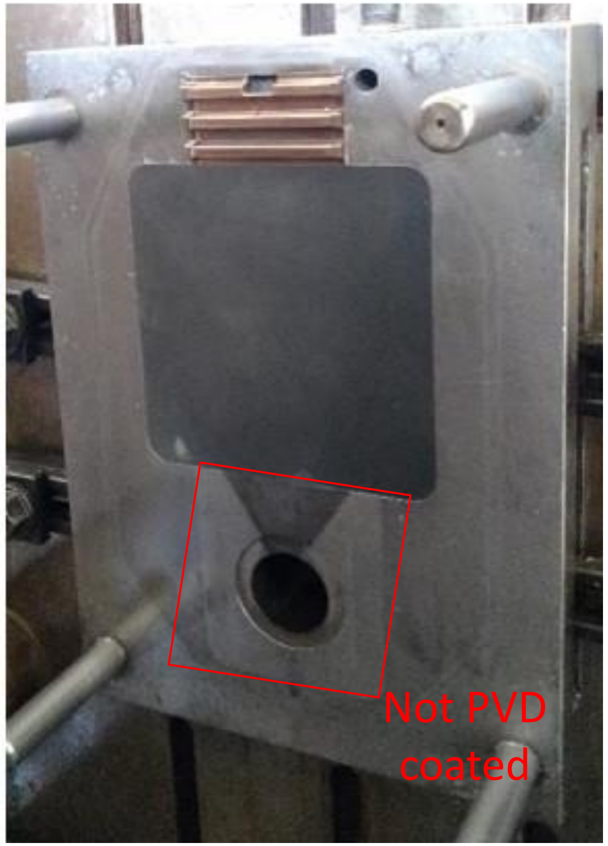
Ejector side

Cover side



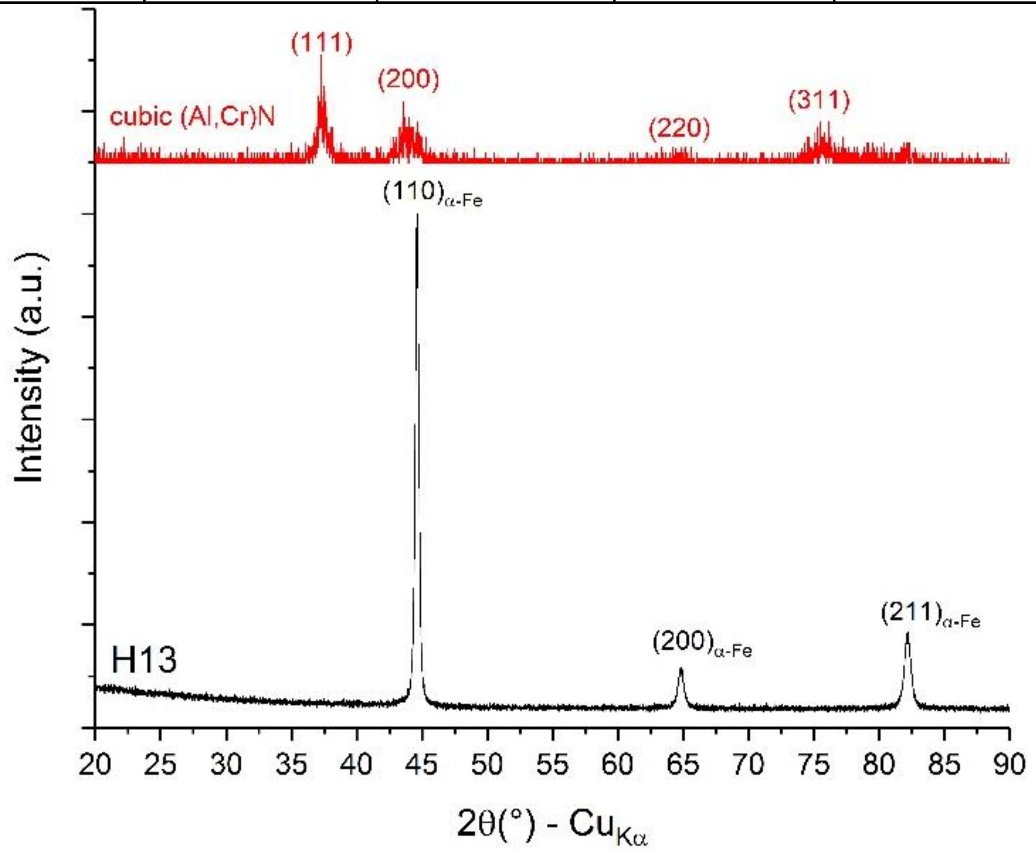
Ejector side

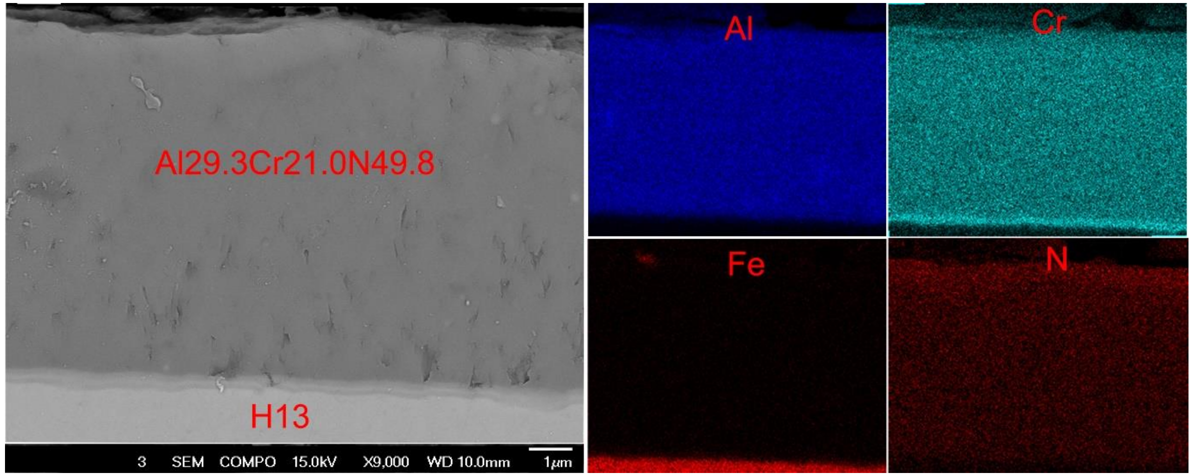
Cover side

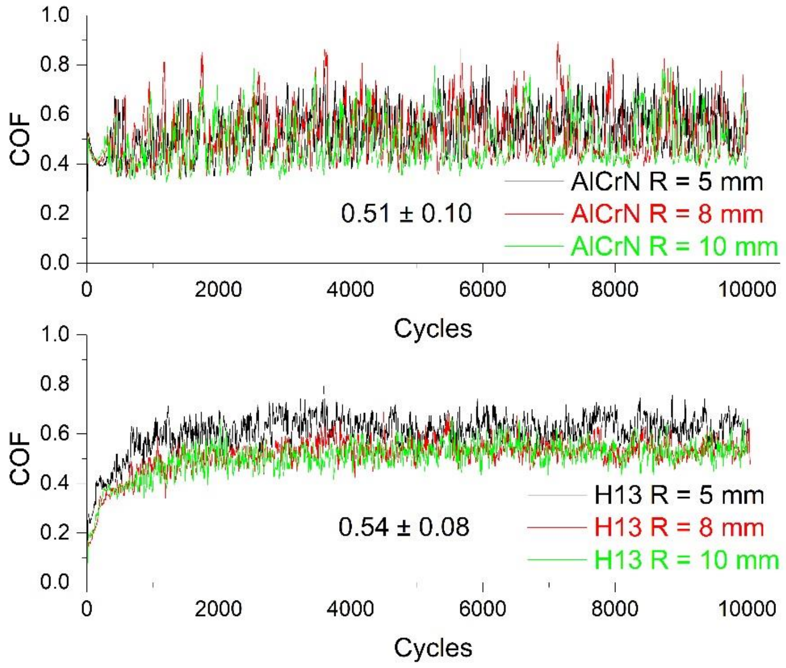


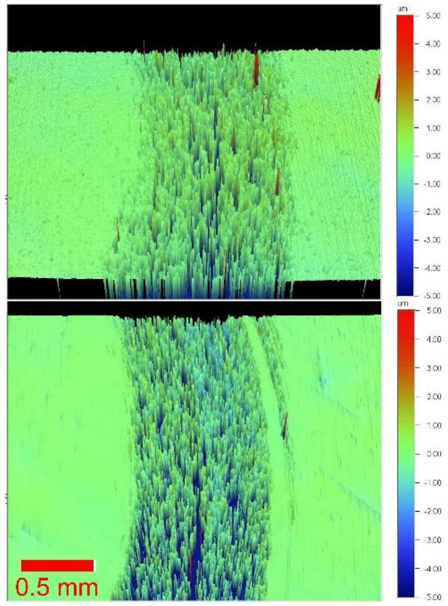
PVD AlCrN Coating Characterization

Composition by XPS (at. %)	Thickness (μm)	Roughness Ra (nm)	Cohesion Lc1 (N)	Adhesion Lc2 (N)	VDI 3198
$Al_{29.3}Cr_{21.0}N_{49.8}$	8.6 ± 0.2	100 ± 13	8.7 ± 2.0	23.0 ± 6.1	HF 1





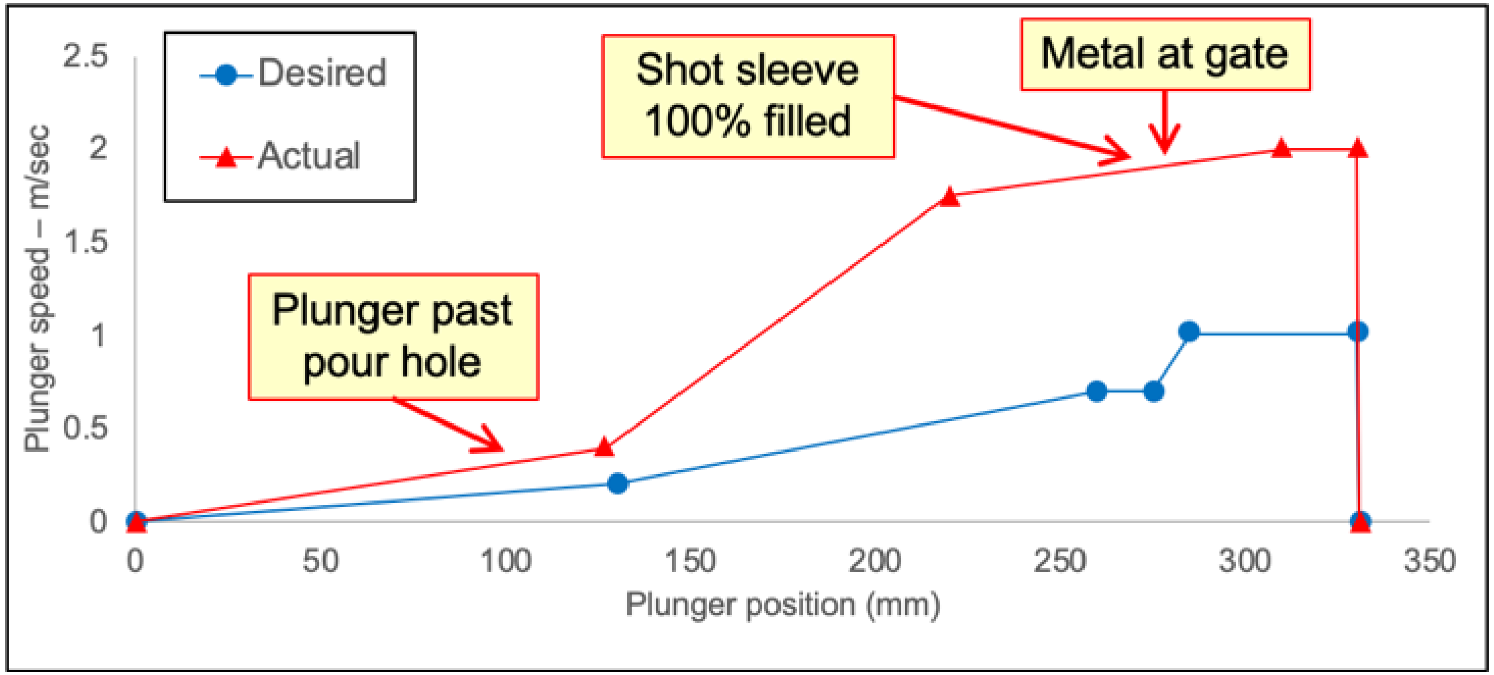




Casting Conditions

- A380 alloy (300 lbs)
  - Degassing prior to use (15 minutes N_2 gas)
  - Sample taken for composition measurement
- Thermal camera used to measure die temperature between shots
- Machine issues prevented use of optimized shot profiles*
- Molten A380 temperature was varied between 680-720 °C
- Heating oil temperature was varied between 200-290 °C
- Lube-free attempts
  - Start trial with normal lube, then decrease until lube-free
  - Attempt to run lube-free for a number of castings

Die Casting Operation – Shot Profile

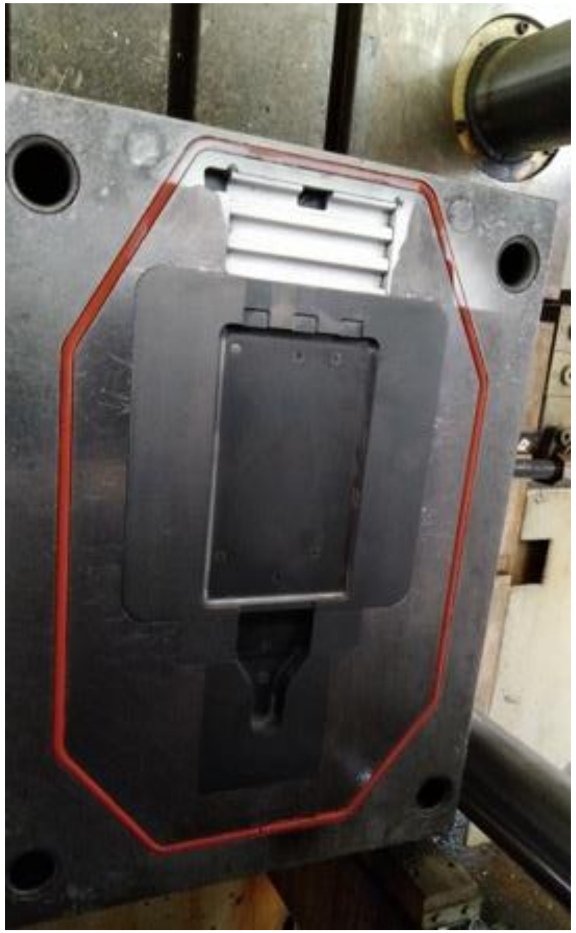


A380	Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
Day 1	85.90	8.29	0.98	3.12	0.20	0.20	0.034	0.049	1.02	0.061
	85.70	8.45	0.95	3.15	0.20	0.21	0.035	0.048	1.06	0.062
Day 2	86.00	8.00	0.95	3.11	0.19	0.22	0.034	0.046	1.22	0.059
	85.80	8.12	0.94	3.20	0.19	0.22	0.034	0.047	1.23	0.058
Day 3	86.00	9.14	0.94	3.13	0.19	0.18	0.034	0.047	1.16	0.059

- Planned to run the desired plunger profile
  - Desired gate speed of 1,400 in/sec
  - Unable to adjust machine parameters
- Actual shot profile was inappropriate for these casting geometries
  - Gate speed of 2,665 in/sec (~2X desired)
  - High gate speed expected to exacerbate soldering

1st Trial at The Ohio State University
May 12th, 2021
Thin plate die (Die #1)

First OSU Trial – Die #1 – (May 12th)



Ejector side

Cover side

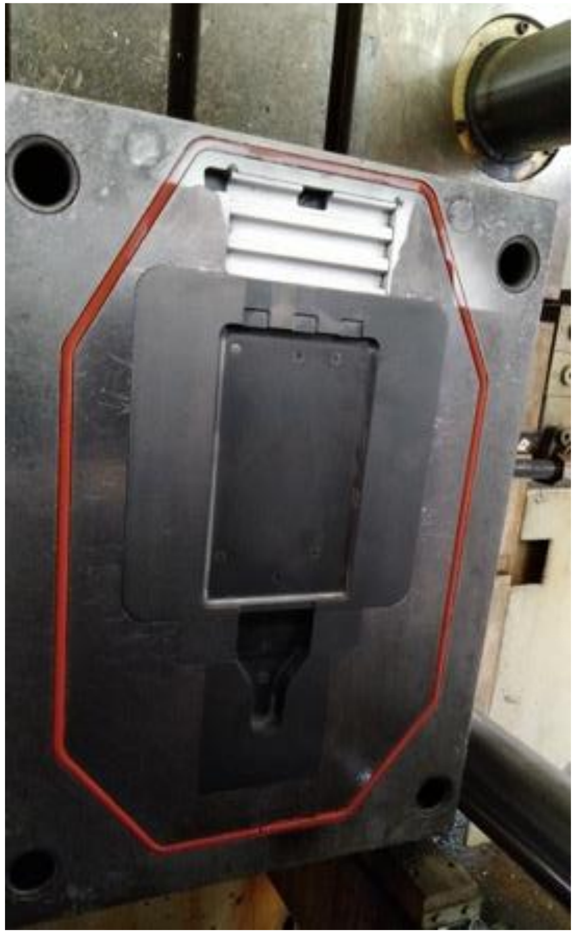
- A380 alloy temperature at 680 °C
- Die pre-heating/cooling temperature at 200 °C

Castings		# of die lube spray			
#	**Quantity**	**cavity**	**runner**	**cover**	**shot block**
1 to 6	6	BN			
7 to 11	5	3	3	3	3
12 to 14	3	2	2	2	2
15 to 17	3	1	1	1	1
18 to 57	**40**	**Lube-Free**			

- Successfully produced 40 lube-free castings

2nd Trial at The Ohio State University
June 11th, 2021
Thin plate die (Die #1)

Second OSU Trial – Die #1 – (June 11th)



Ejector side

Cover side

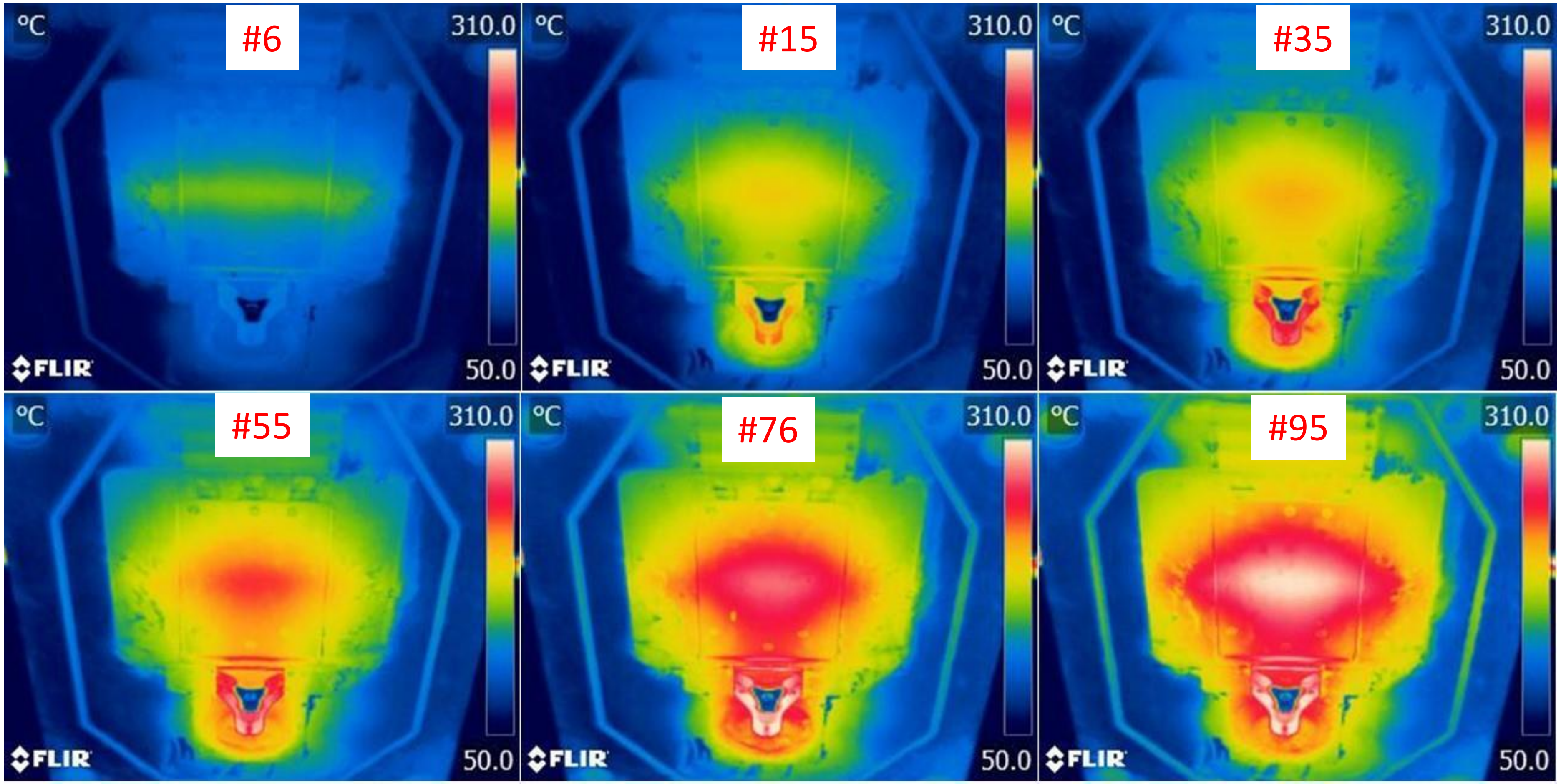
- Mapping processing conditions for lube-free

Castings		Temperature (°C)		Condition
#	**Quantity**	**A380**	**Oil**	**Lube**
1 to 5	5	680	200	BN, spray
6 to 25	20	680	200	**Lube-Free**
26 to 45	20	720	200	
46 to 65	20	720	230	
66 to 85	20	720	260	
86 to 122	37	720	290	

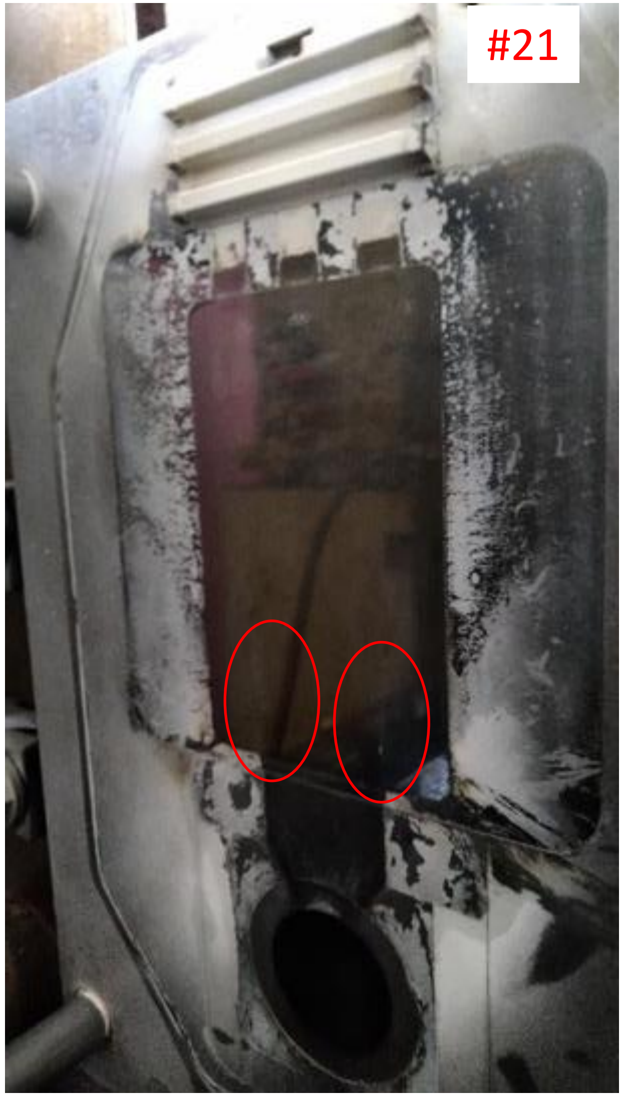
- Successfully produced 117 lube-free castings

Die #1 – Temperature Track

- Thermal camera was used to track die surface temperature between castings
- Die temperature increased and temperature better distributed during trial



Sticking Phenomena (Build-up)



- A few times casting ended up stuck to the tip of ejector pins
  - Flat tips of ejector pins are not well coated
- Build-up continuously appeared and disappeared after a few castings during the lube-free trial
- No evidence of build up developing to soldering was found in the coated inserts

3rd Trial at The Ohio State University
June 22nd, 2021
Thicker plate die (Die #2)

Third OSU Trial – Die #2 – (June 22nd)

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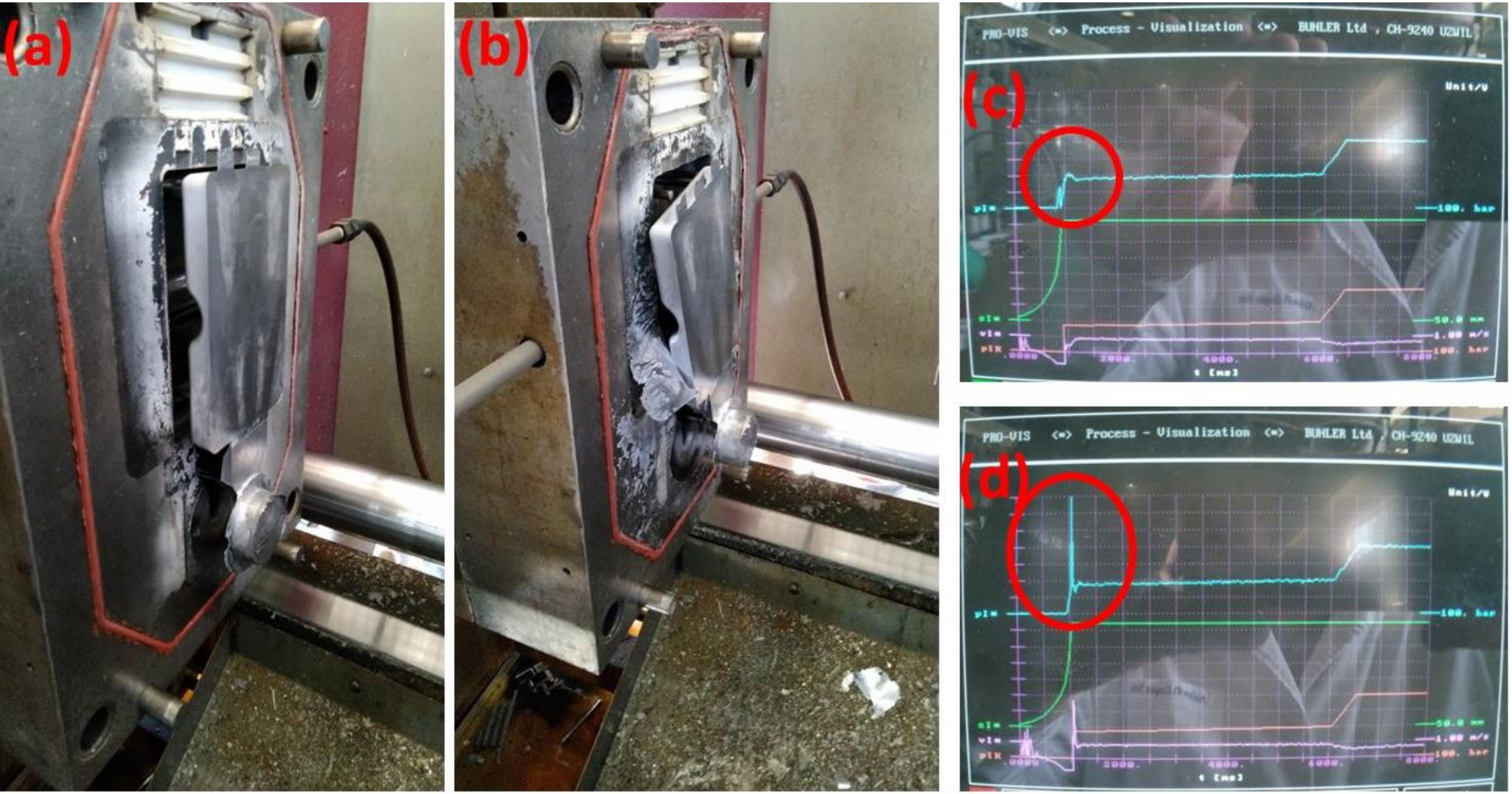
Ejector side

Cover side

- Mapping processing conditions for lube-free
- Successfully produced 56 lube-free castings
- Stopped due to machine malfunction

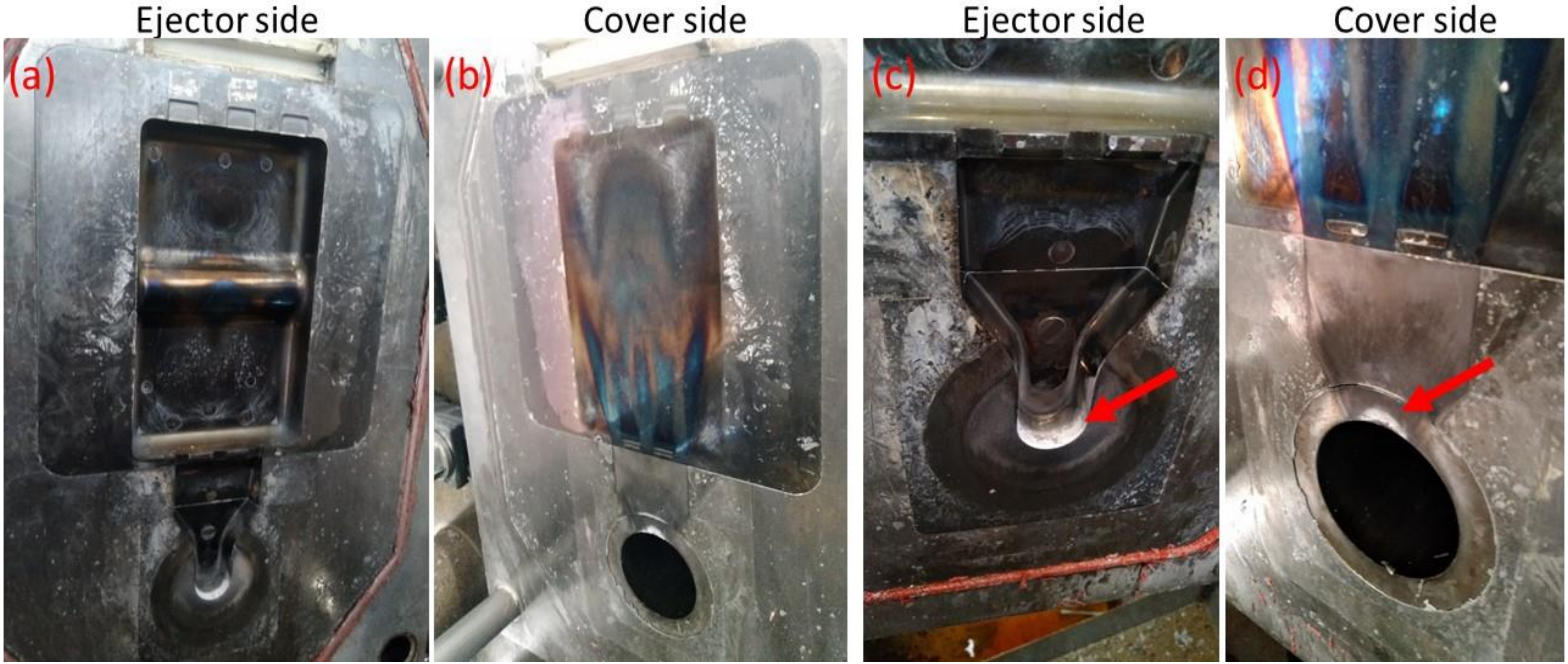
Castings		Temperature (°C)		Condition
#	Quantity	A380	Oil	Lube
1 to 5	5	680	200	BN, spray
6 to 25	20	680	200	Lube-Free
26 to 45	20	720	200	
46 to 61	16	720	230	
-	-	720	260	-
-	-	720	290	

Results Die #2



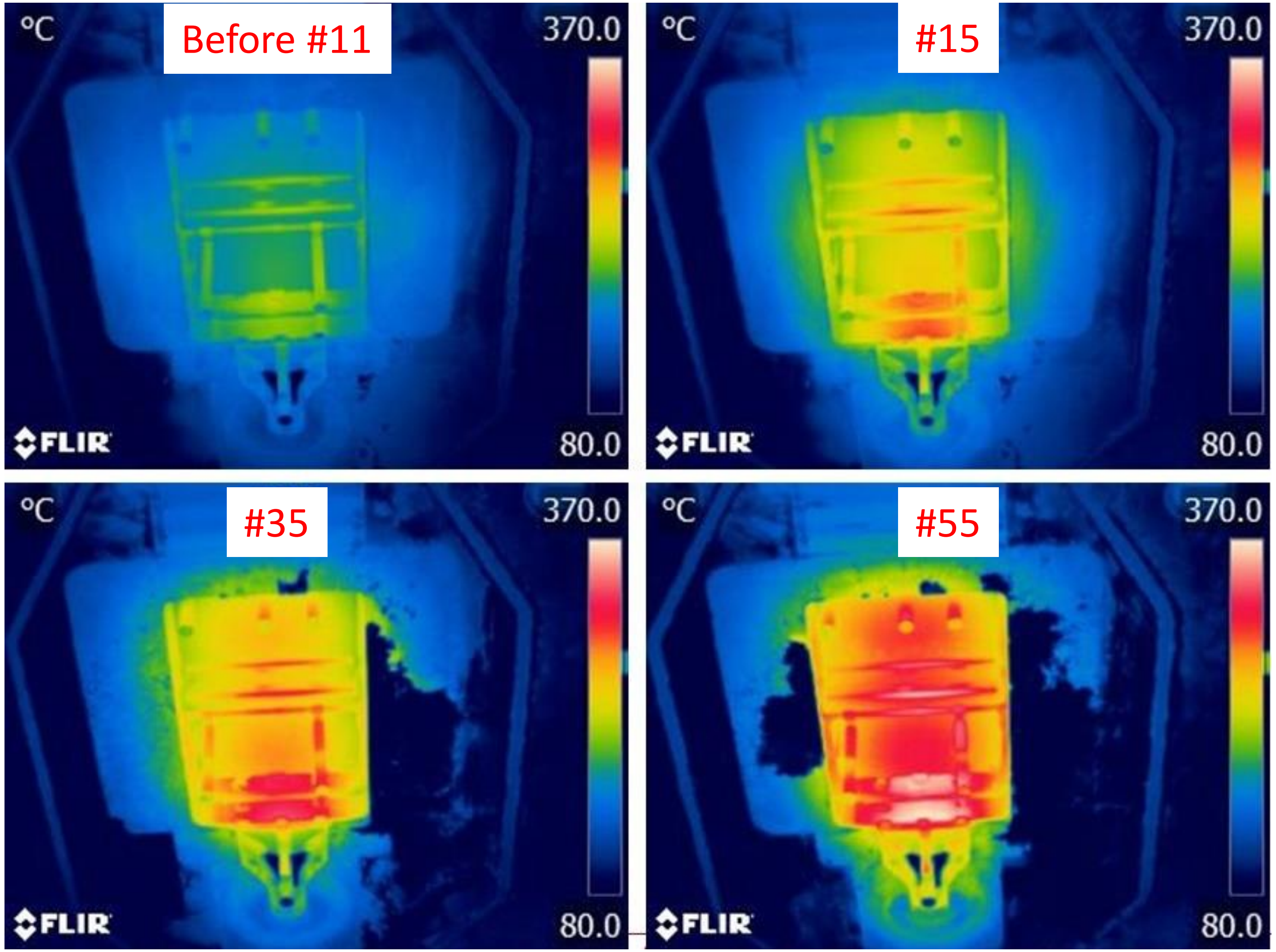
- Casting sometimes stuck to tips of ejector pins, but almost no force needed to separate
- Flashing occurred due to spike in machine pressure during injection

Soldering Die #2



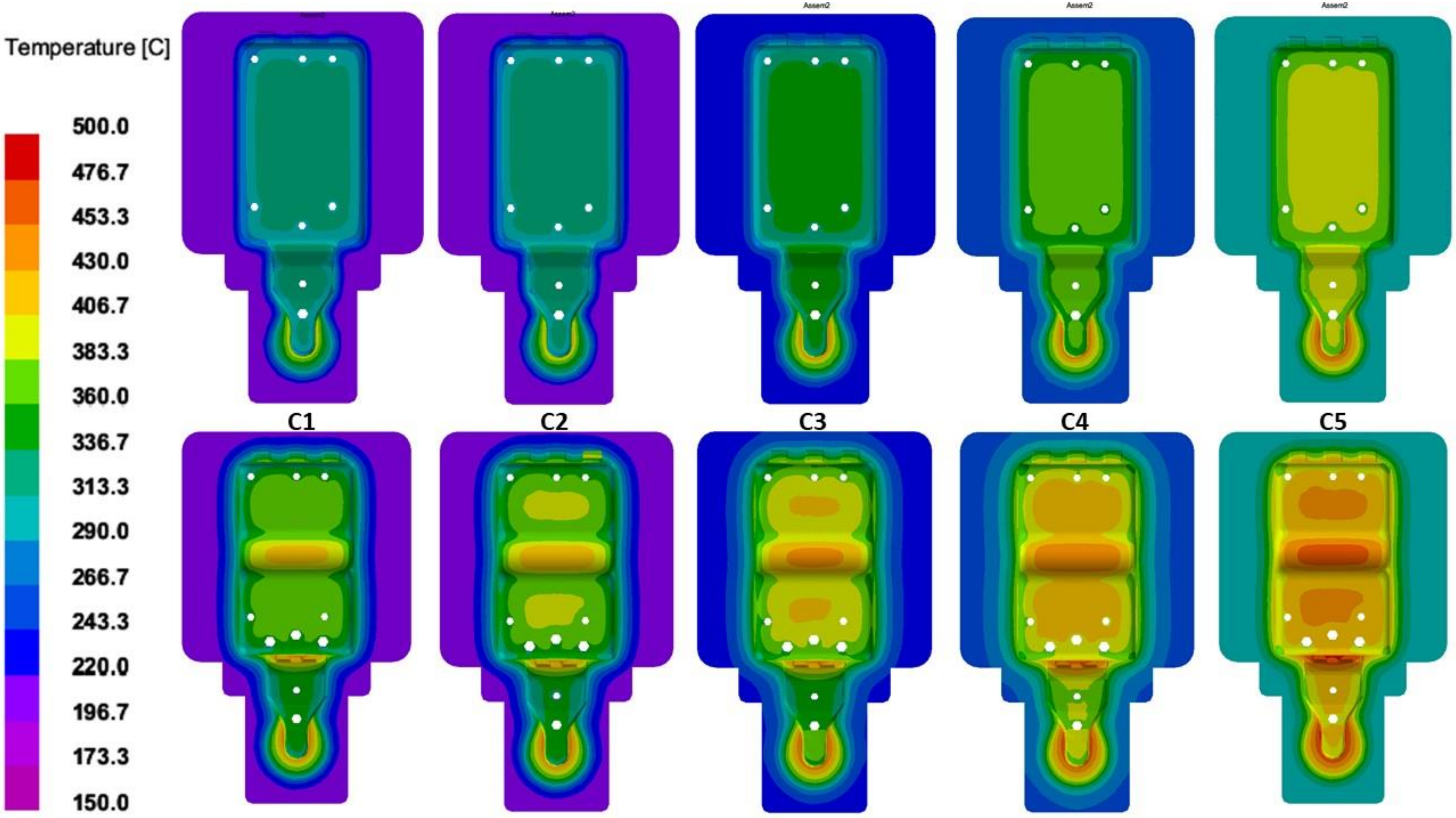
- Significant soldering developed on the uncoated shot block and shot block cover
- Did not prevent lube-free operation

Die #2 – Temperature Track



- Thermal camera used to track die surface temperature between castings
- Die temperature increased and temperature was better distributed during trial
- Temperature on die #2 increased significantly more than on die #1
  - May have encouraged the observed soldering

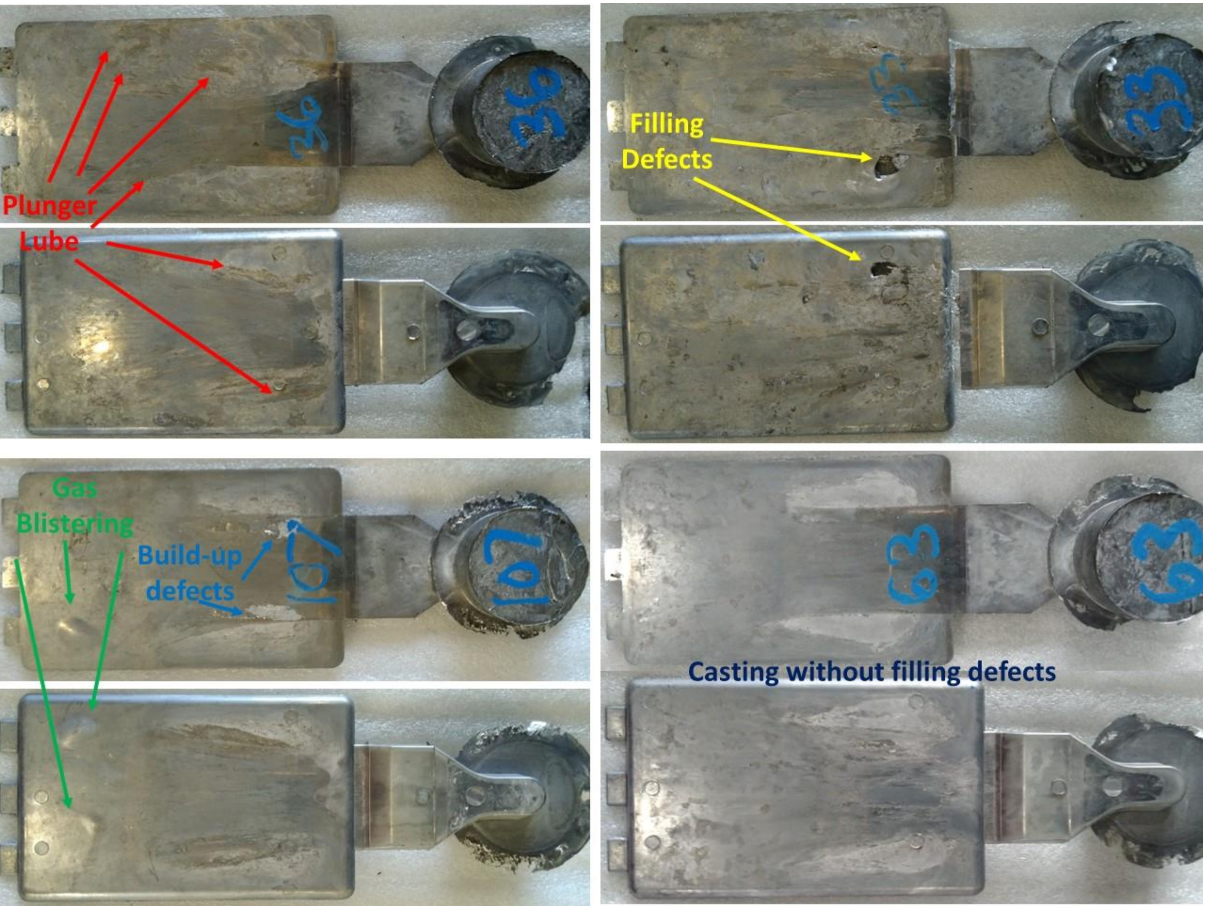
ProCast Simulation – Die Temperature

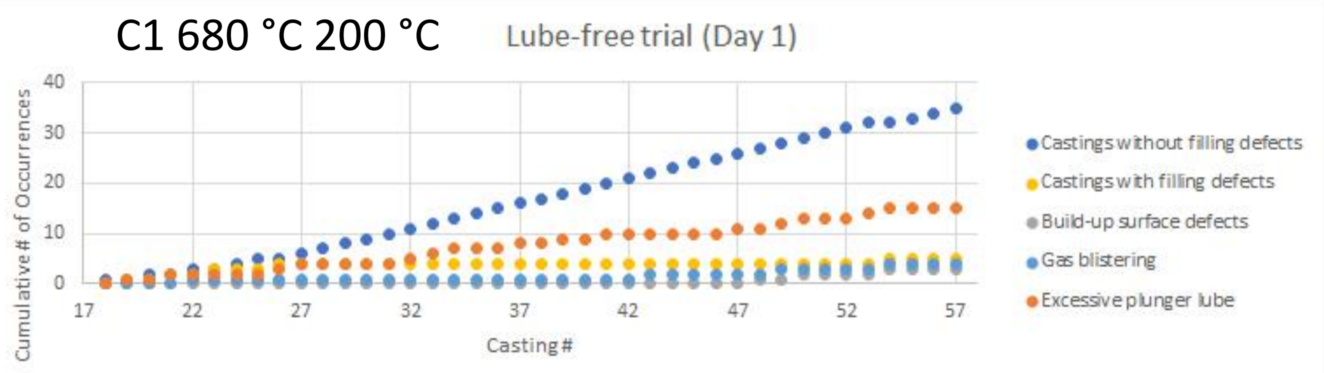


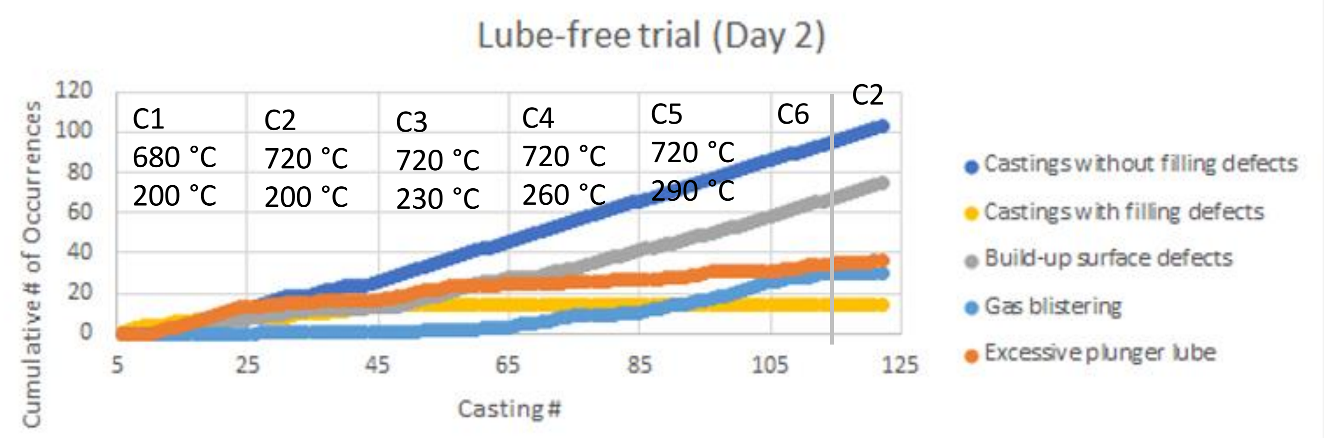
#	Temperature (°C)	
	A380	Oil
C1	680	200
C2	720	200
C3	720	230
C4	720	260
C5	720	290

- Agrees with observations
- Soldering location occurred at highest temperature locations

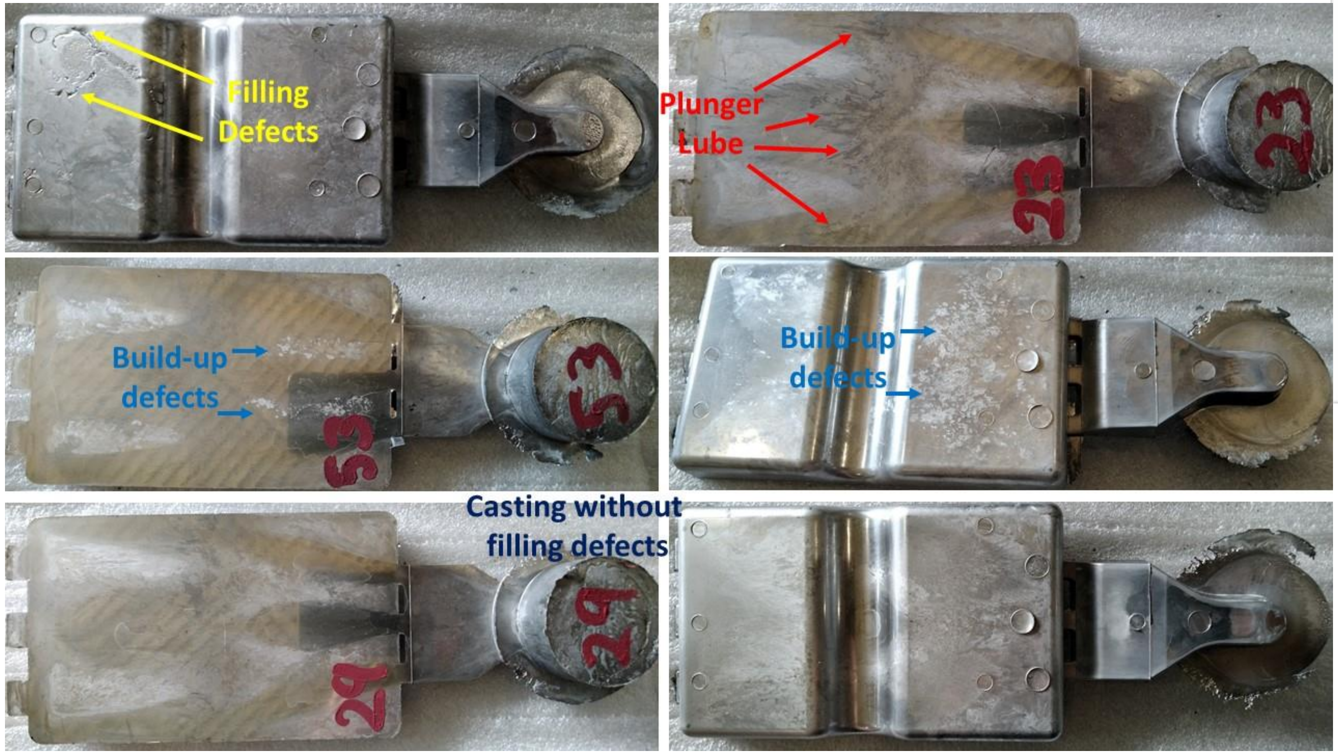
Casting Quality Criteria - Die #1

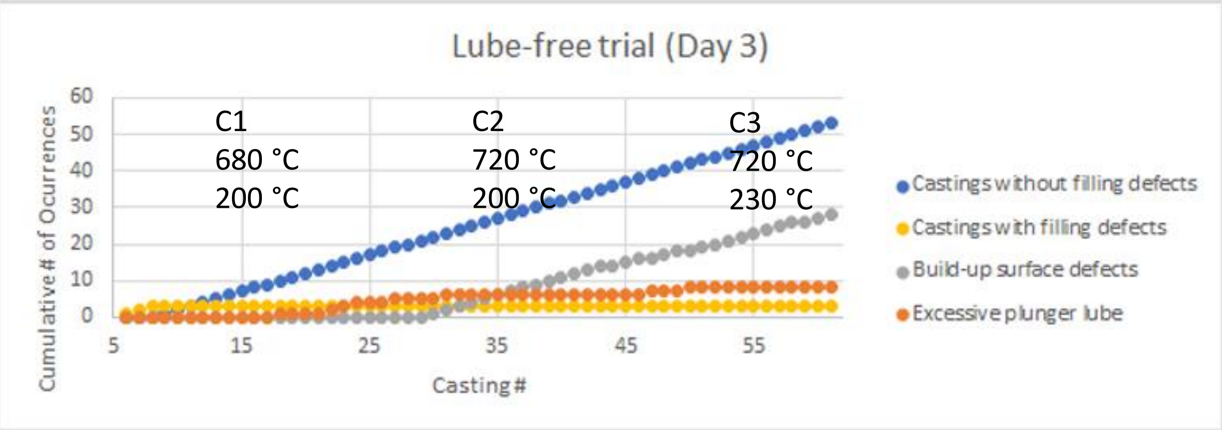






Casting Quality Criteria - Die #2



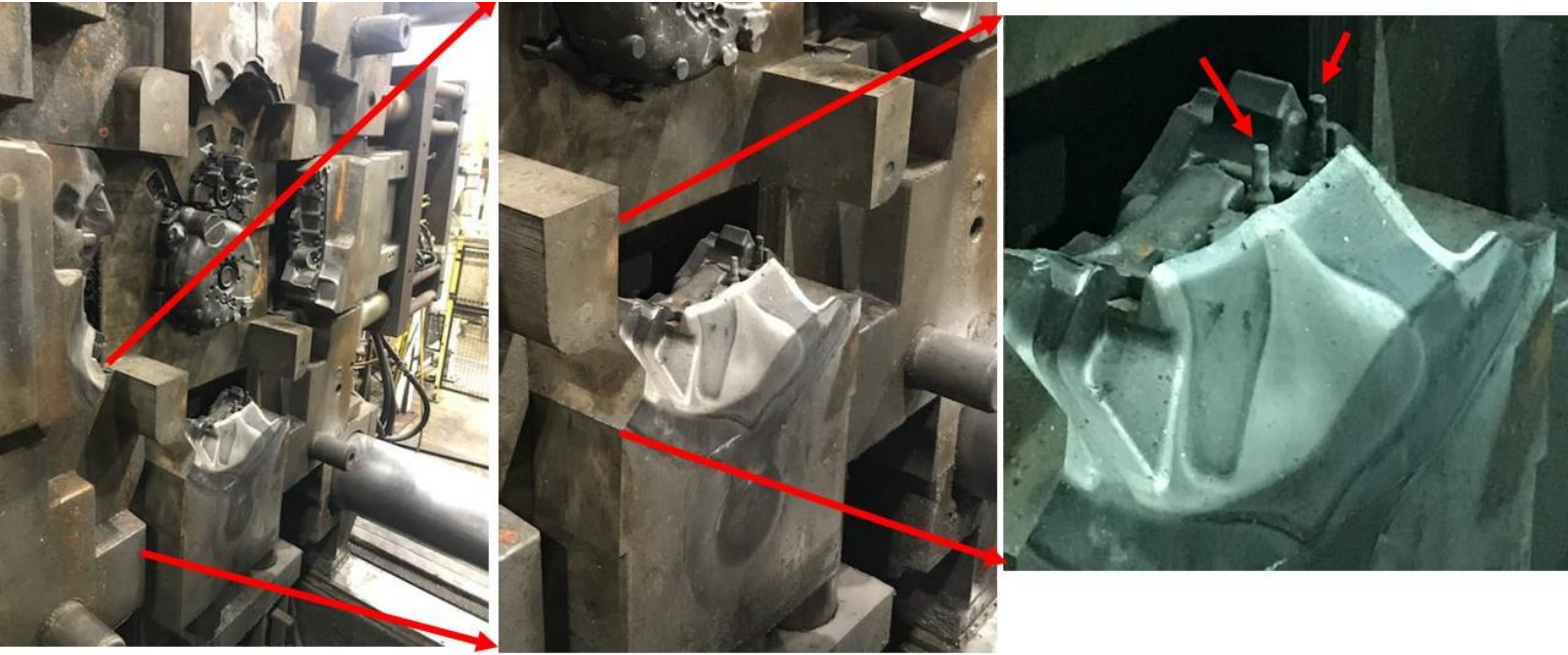


- As the die temperature increased
  - Higher percentage of castings without filling defects
  - Greater percentage of castings with build-up surface defect marks and with gas blistering

Testing at Stellantis

(Kokomo Die Casting Plant)

Core Pin Soldering at Stellantis



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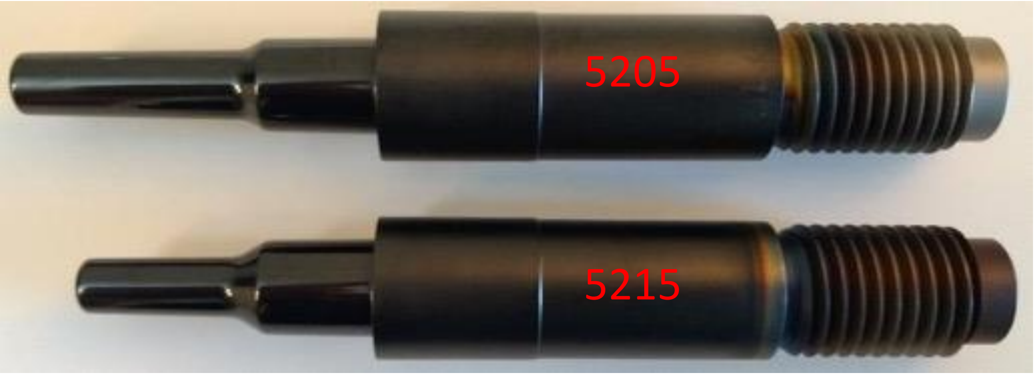
Core Pins Chosen for Trial at Stellantis

- Die chosen for trial is a 9-speed torque converter (bell) housing
- Runs single cavity on a 3,000-ton die casting machine
- The two very similar core pins are shown on the right
  - Utilize internal water cooling
- Core pins with two surface finishes were PVD coated
  - Rougher draw-polish finish
  - Smoother diamond polish

Polished: Ra = 52 ± 17 nm and Rz = 0.304 ± 0.096 μm



Draw finish: Ra = 326 ± 27 nm and Rz = 2.904 ± 0.240 μm

Metrics for the Stellantis Core Pin Tests

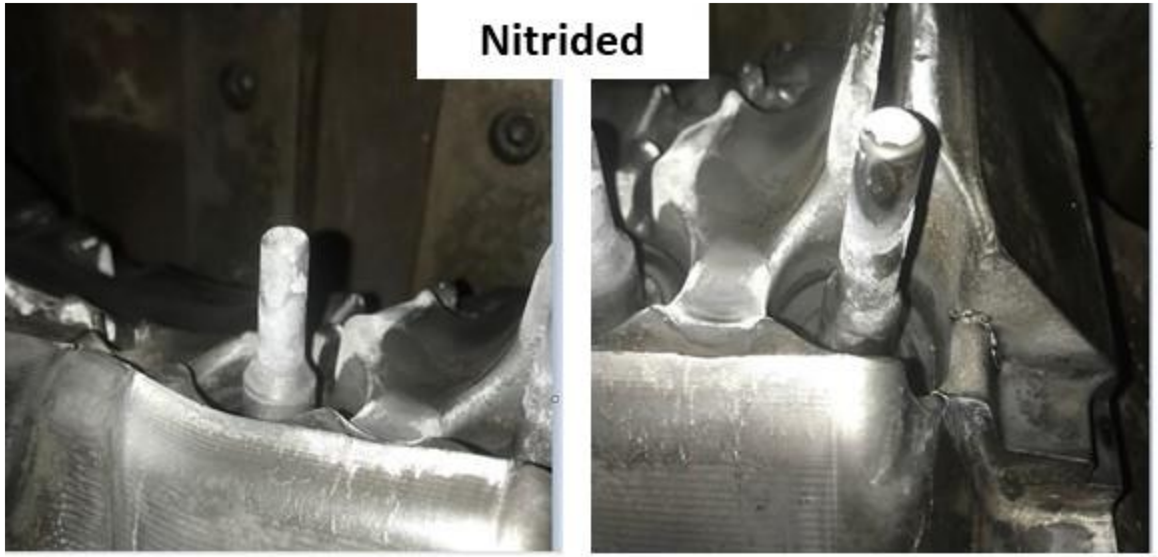
- Core pins placed in front of the gate
  - Critical position for soldering
- A week of aluminum die castings will be made to track steady-state soldering
  - Around 2,500 castings
- Core pins have two surface finishes
  - Draw-polish finish (rougher) and diamond polished (smoother)
- Steady-state soldering resistance of the various PVD coatings in two surface finishes will be evaluated using same techniques
  - Weight increase of the pins (due to soldered aluminum)
  - Percentage of the pins' surface covered with aluminum solder
  - Location of the solder on the pins
  - Metallography of the interface between the aluminum and the PVD coating
    - Characterized using the SEM or TEM

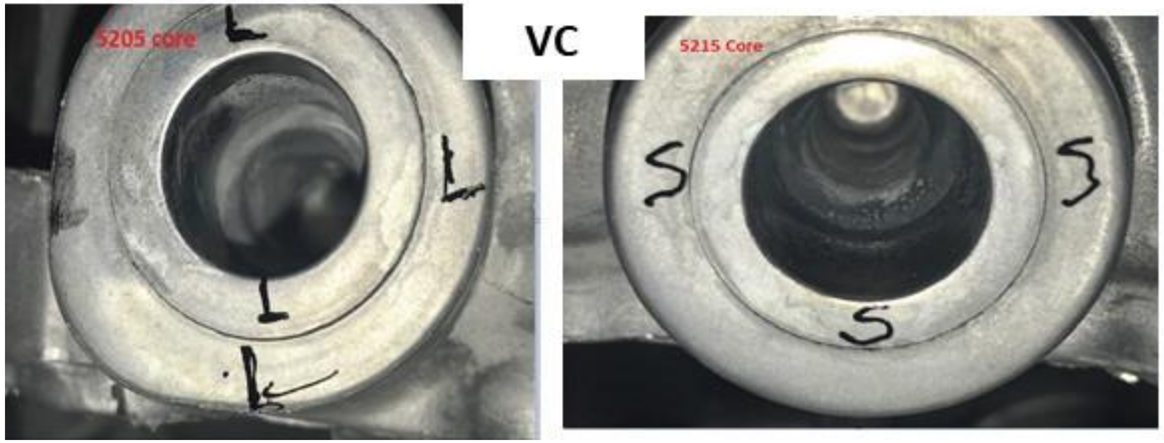
List of PVD Coatings for Stellantis Test

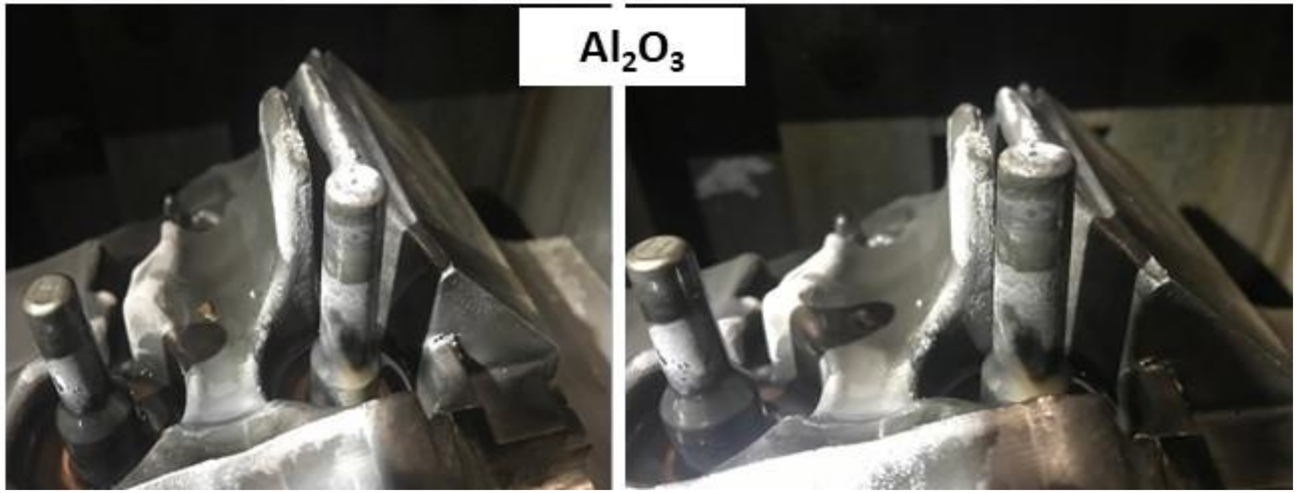
Type	Composition	Supplier
Lubricious high temperature oxides (coatings contain V and W)	TiAlVN	#1
	AlCrVN	#1
	VC	#1
	CrWN	#3
Lubricious compounds	AlTiN/BN	#2
	CrN/BN	#2
	Si-DLC	#1
Stable oxides	Al_2O_3	#1
	ZrOC	#4
	$ZrOC/ZrO_2$	#4
Nitrides	AlCrCN	#5
	AlCrN	#5
	AlCrN+	#6
Carbides	CrC	#1
Uncoated	Nitriding	Stellantis

*Received

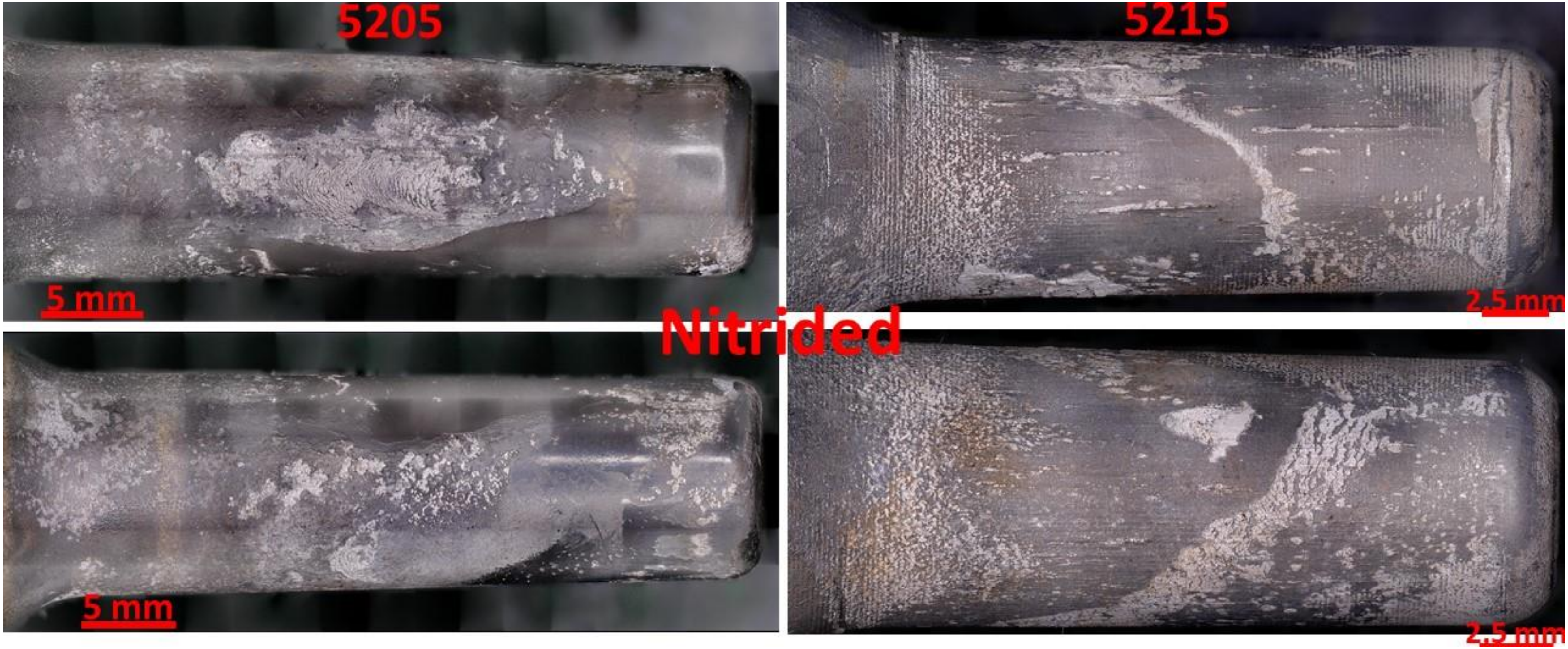
Pictures of the Tested Core Pins







Nitrided @ 2,500 shots

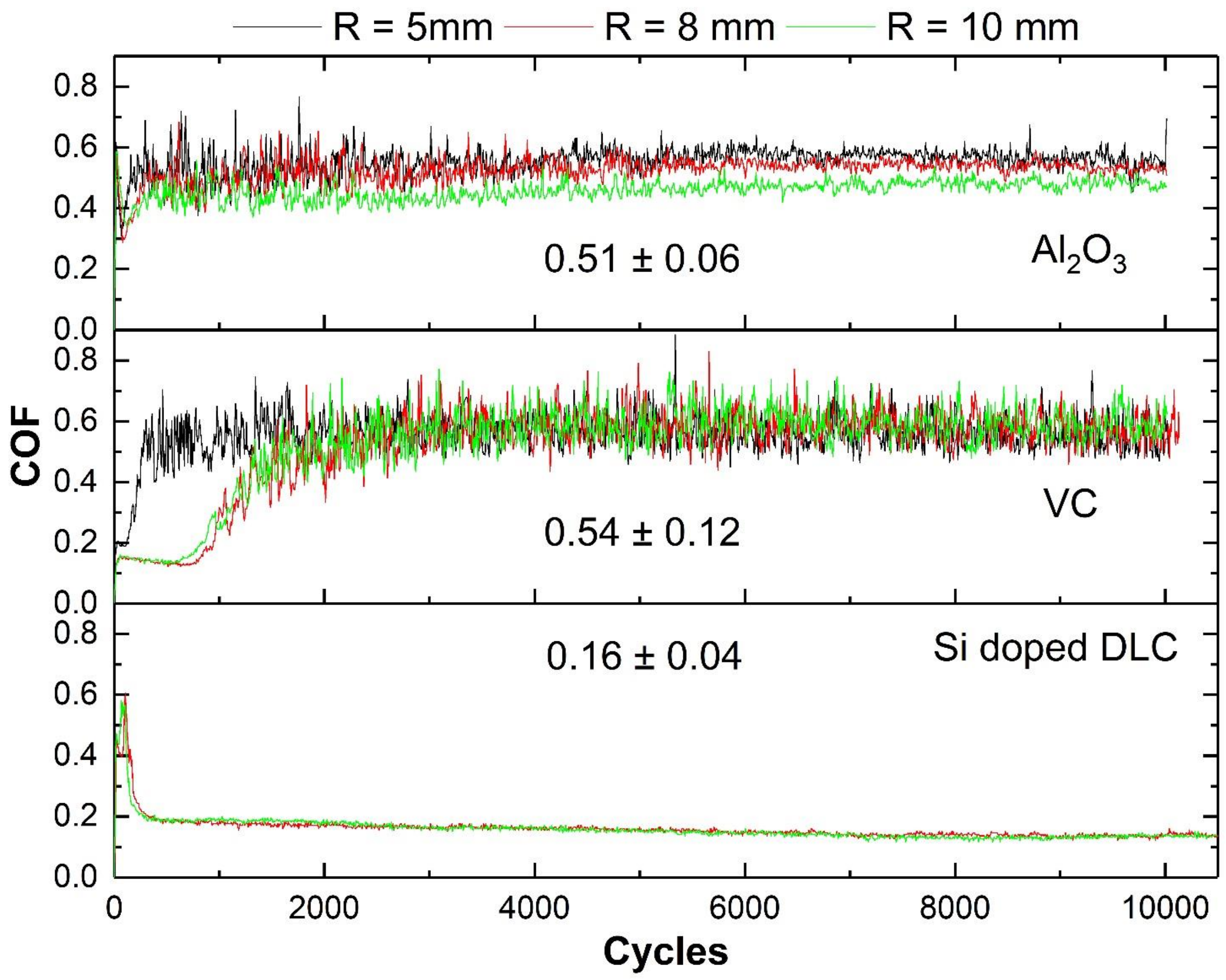


Si-DLC Coating @ 2,430 shots

Qualitative Grade and Quantitative Results

Coating	Coating Supplier	# of Shots	Stellantis Observations	Stellantis Grade	Mass change (5205)	Mass change (5215)	Surface Soldered (5205)	Surface Soldered (5215)
Nitrided	-	2500	Both cores soldered	D	N/A	N/A	46 ± 5 %	58 ± 5 %
Si doped DLC	#1	2430	Cores basically clean - no solder. Coating looks like it is intermittent.	A-	+ 0.20 g	+ 0.28 g	31 ± 9 %	38 ± 17 %
VC	#1	4469	Some light solder (cores destroyed)	B-	N/A	N/A	N/A	N/A
Al_2O_3	#1	2572	Some solder (cores destroyed)	C+	N/A	N/A	N/A	N/A

Coatings Tribology (Al pin-on-disk)



- Si doped DLC showed the lowest COF
  - 0.16 ± 0.04
- Higher wear resistance may be related to better performance on the die casting trial

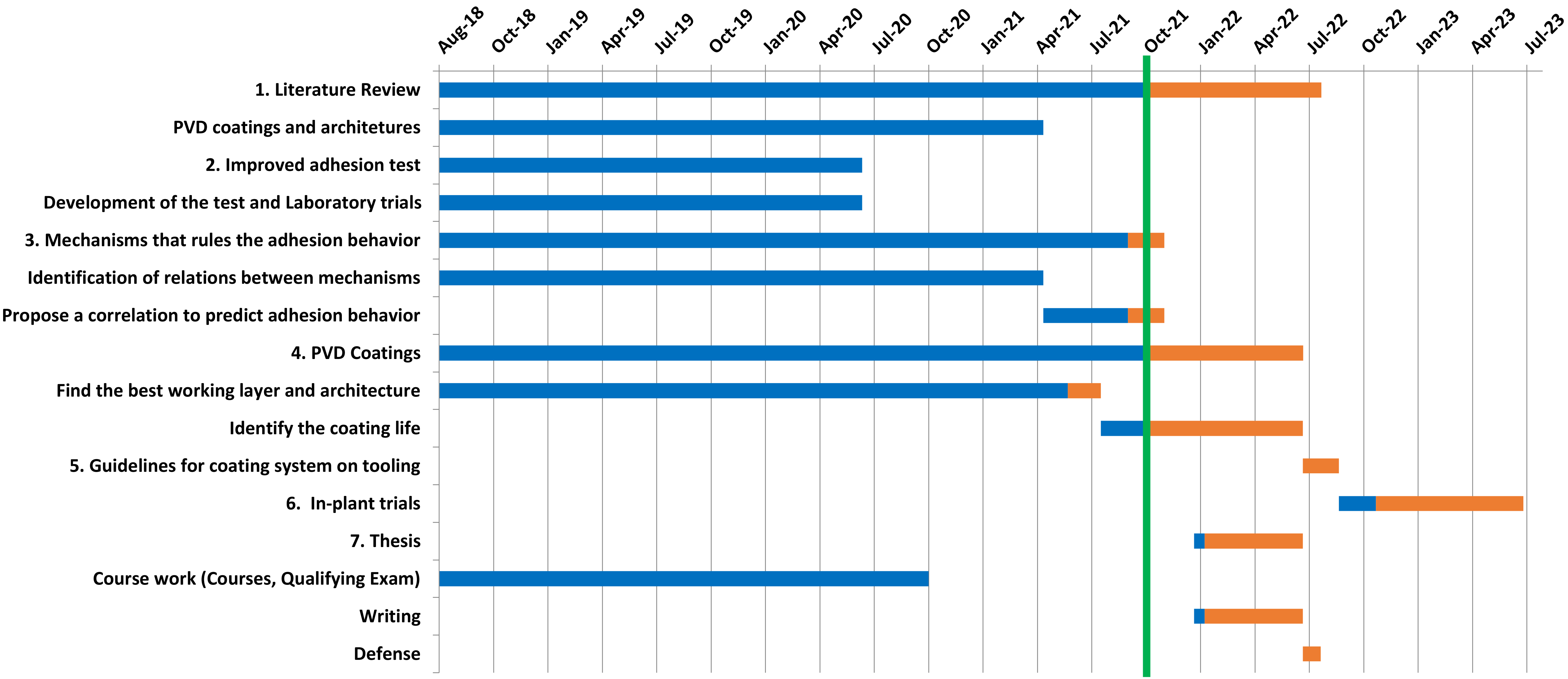
Summary & Conclusions

- Two dies coated with an AlCrN PVD coating and tested using a 250-ton die casting machine at OSU
  - Both dies ran in the lube-free condition (without the application of any die lubricant)
  - More than 200 lube free castings were produced.
- The temperature simulation on the dies matched the thermal camera measurements
  - Soldering developed at the hottest spots on the shot blocks and aluminum marks were observed inside the insert cavities.
- Aluminum build-up on the die surface occurred intermittently but did not result in soldering.
- Based on an analysis of the surface condition of the castings
  - Higher melt and die temperatures leaded to a greater percentage of castings experiencing build-up, surface defect marks, and with gas blistering.
- Casting trials at Stellantis conducted using coated core pins positioned directly in-front of the gate of a large commercial die casting
  - Core pin coated with Si-doped DLC coating exhibited the least amount of soldering.
- The results of both trials have shown that coatings can be used to minimize soldering and eliminate die lubricant in aluminum HPDC.

Future Work

- Continue coated core pins soldering trial at Stellantis
- Characterization of PVD coatings
  - Adhesion quality
  - Structure and microstructure
  - Roughness and surface defects
  - Wear and oxidation resistance
- Characterization of aluminum soldered samples
  - Examine the phases formed at the interface between the solidified aluminum and the tested coatings
- Characterization of the adhesion mechanisms related to soldering
- Transition the best coatings to die casters

Gantt Chart



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1. Literature Review
PVD coatings and architetures
2. Improved adhesion test
Development of the test and Laboratory trials
3. Mechanisms that rules the adhesion behavior
Identification of relations between mechanisms
Propose a correlation to predict adhesion behavior
4. PVD Coatings
Find the best working layer and architecture
Identify the coating life
5. Guidelines for coating system on tooling
6. In-plant trials
7. Thesis
Course work (Courses, Qualifying Exam)
Writing
Defense

Acknowledgements

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- Accu-Die & Mold in Stevensville, MI fabricated the die at no cost to the project
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- Century Sun Metal Treating in Traverse City, MI heat treated the steel for the die at no cost to the project
- Phygen Coatings in Minneapolis, MN for PVD coating the die cavities
- IBC Coatings in Lebanon, IN for polishing the core pins
- Stellantis in Kokomo, IN for helping the project
- Dr. Alan Luo and his group at OSU for receiving Nelson as a visiting researcher
- Dr. Ryan Brune at CDME (OSU) for helping in the die casting trials

Challenges & Opportunities

- Run controlled laboratory die casting experiments
  - At The Ohio State University
  - Laboratory size die casting machine (Buhler 250-ton)
  - Machine broke before finishing all proposed experiments
- Run industrial trials on selected coatings deposited on core pins in front of gate to understand steady-state soldering
  - Automotive die casting plant at Stellantis (Kokomo die casting plant)
  - High production volume
  - Difficult to control the trial in a production environment

Thank you!

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