U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – GROUND VEHICLE SYSTEMS CENTER

2020 DoD Steels Research Summit:

Engine Testing and Evaluation of Steels for Next Generation Diesel Engine Pistons

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COLLABORATORS

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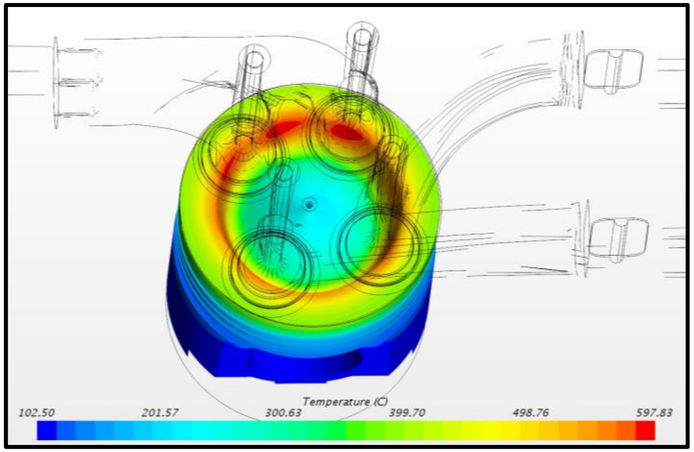
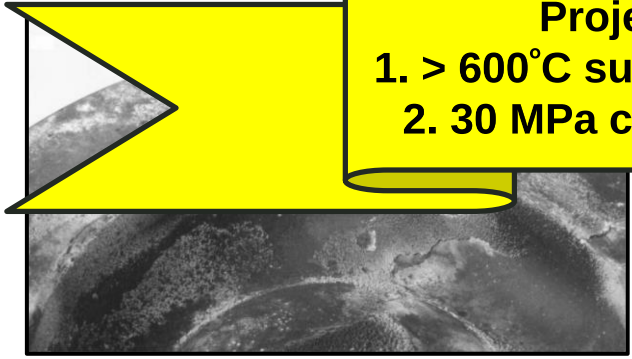
- **Industry Partners:**
  - Tenneco (formerly Federal-Mogul) Powertrain
  - Cummins

BACKGROUND AND MOTIVATION

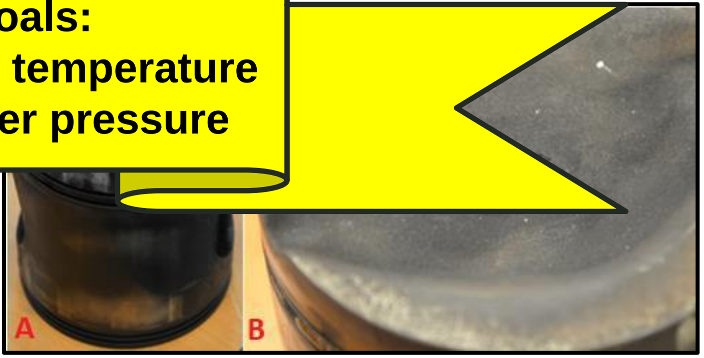
- <u>IC engine development</u>: Advances in both military and commercial diesel engines have resulted in trends toward higher in-cylinder gas temperatures and pressures, which are ultimately limited by maximum piston temperatures and piston durability failures
- <u>Engine cooling burden</u>: requirements for military ground vehicles generally include automotive (speed / range) and mobility performance targets in all climates – arctic to desert – with the propulsion system under armor
- <u>Traditional steel piston alloys</u>: not suitable at service temperatures above ~520 °C



Project Goals:
1. > 600°C surface temperature
2. 30 MPa cylinder pressure



Four-stroke piston, Ref: Chen and Worden, SAE 2000-01-1232

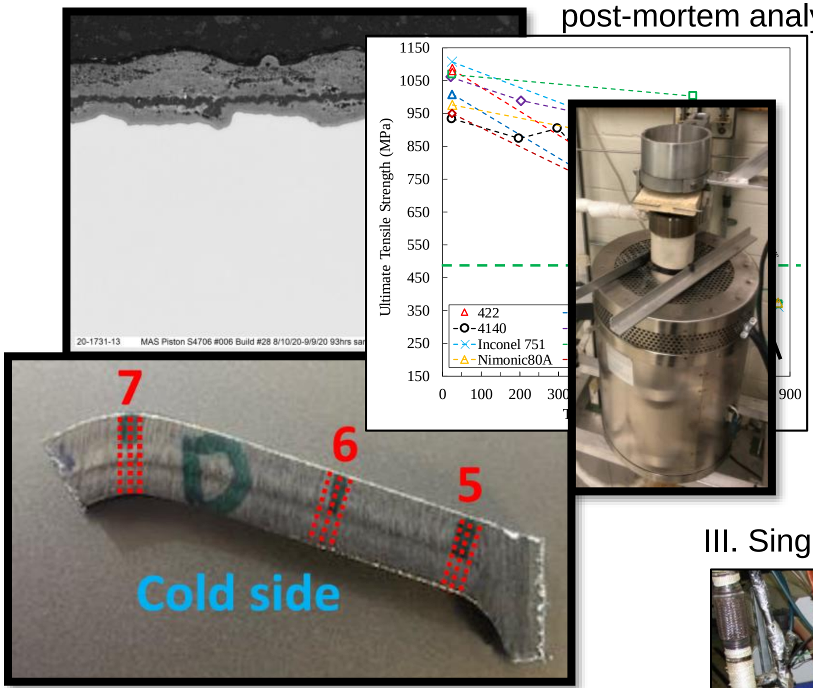


Opposed-piston two-stroke architecture piston

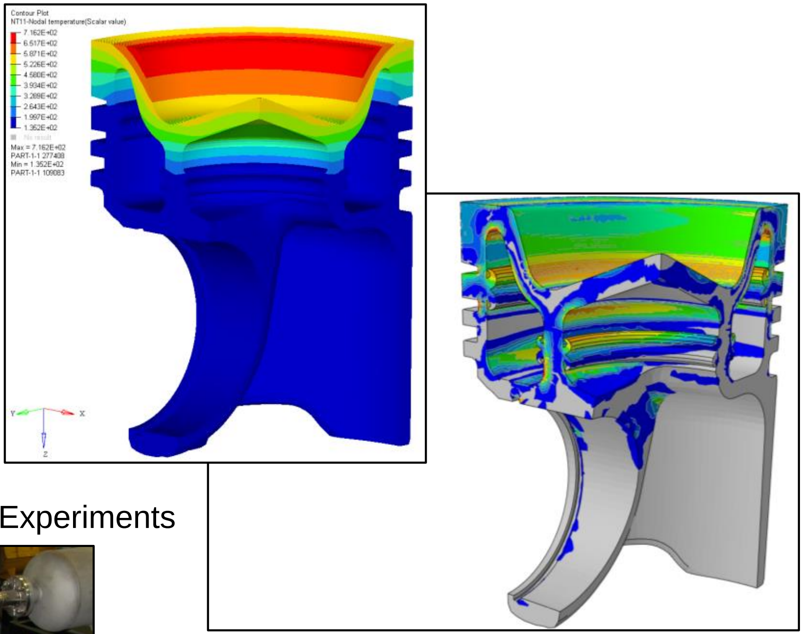
- How do we solve the diesel piston thermal management problem?
  - High-temperature alloy
  - Piston crown coatings (thermal and/or environmental barrier coatings)
  - Novel piston cooling architectures

PROJECT APPROACH AND SCOPE

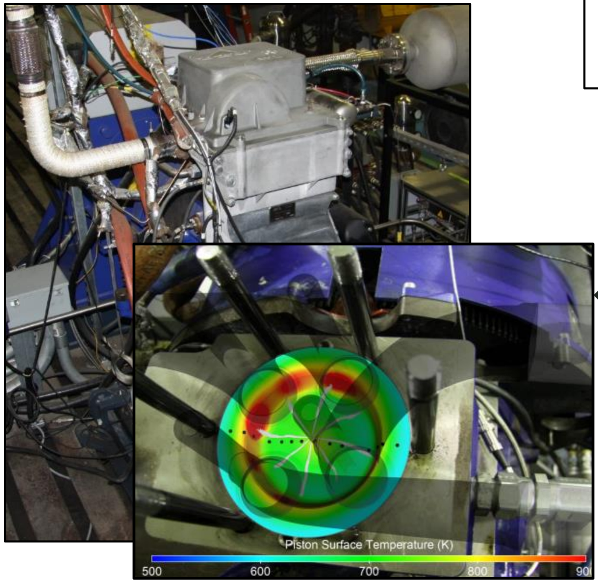
I. Commercial alloy selection, material property data, and post-mortem analysis



II. Piston Thermal and Structural Analysis (FEA and CFD)



III. Single-Cylinder Engine Experiments



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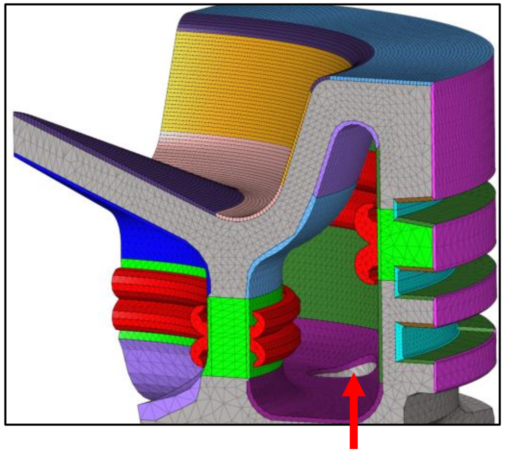
SINGLE-CYLINDER RESEARCH ENGINE (SCRE)

Piston alloy *screening* tests

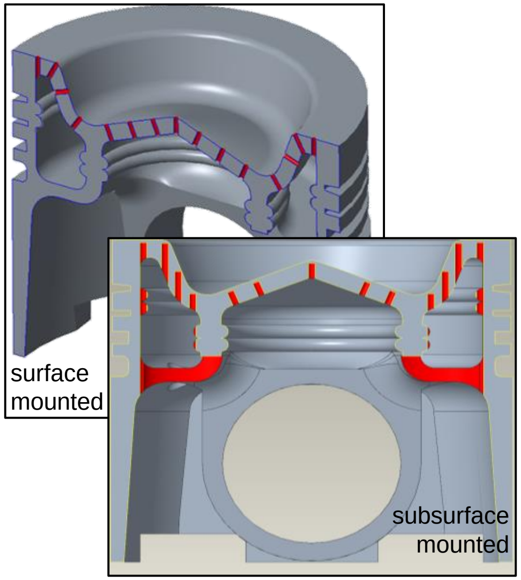
- 40 hrs baseline performance testing (range of piston surface temperatures, 420˚C to 520˚C)
- 50 hrs @ high-temperature abuse condition (target surface temperatures 530˚C, 600˚C, and > 600˚C for future testing)

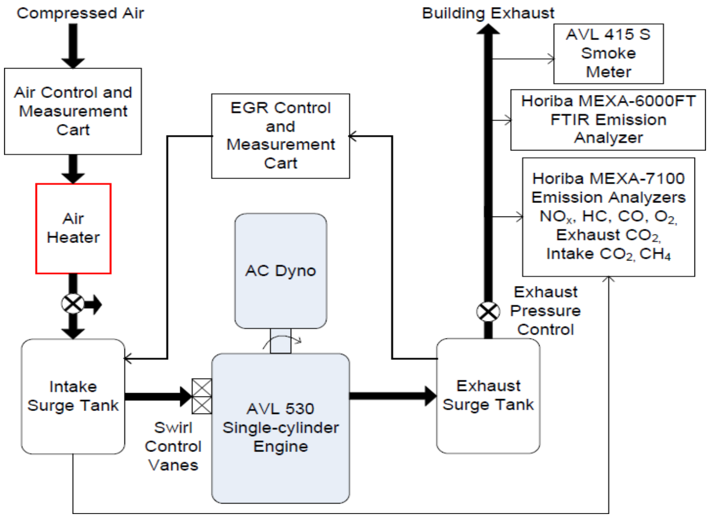
Displacement (L)	1.49
Bore (mm)	122
Stroke (mm)	128
Number of Valves (-)	4
Compression Ratio (-)	14.5
Swirl Ratio	0-3.5 (variable)
Peak Firing Pressure (bar)	250
Max. Injection Pressure (bar)	2000
Injector Nozzle Geometry (mm)	8 hole x 0.167



Cooling gallery inlet/outlet

Telemetry pistons





Compressed Air

Air Control and Measurement Cart

Air Heater

Intake Surge Tank

Swirl Control Vanes

EGR Control and Measurement Cart

AC Dyno

AVL 530 Single-cylinder Engine

Exhaust Surge Tank

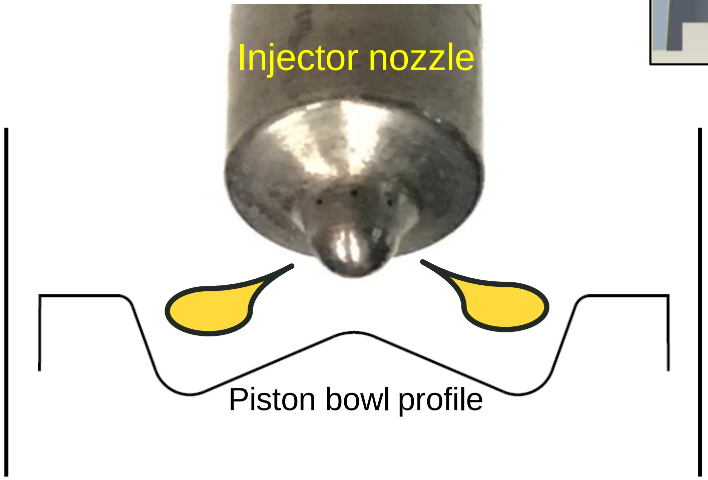
Exhaust Pressure Control

Building Exhaust

AVL 415 S Smoke Meter

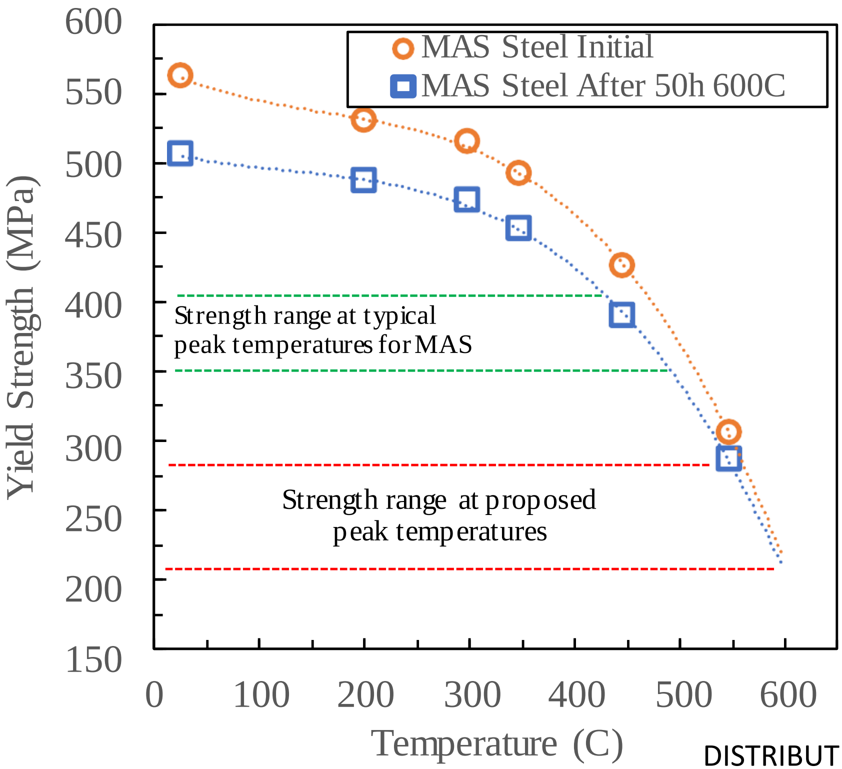
Horiba MEXA-6000FT FTIR Emission Analyzer

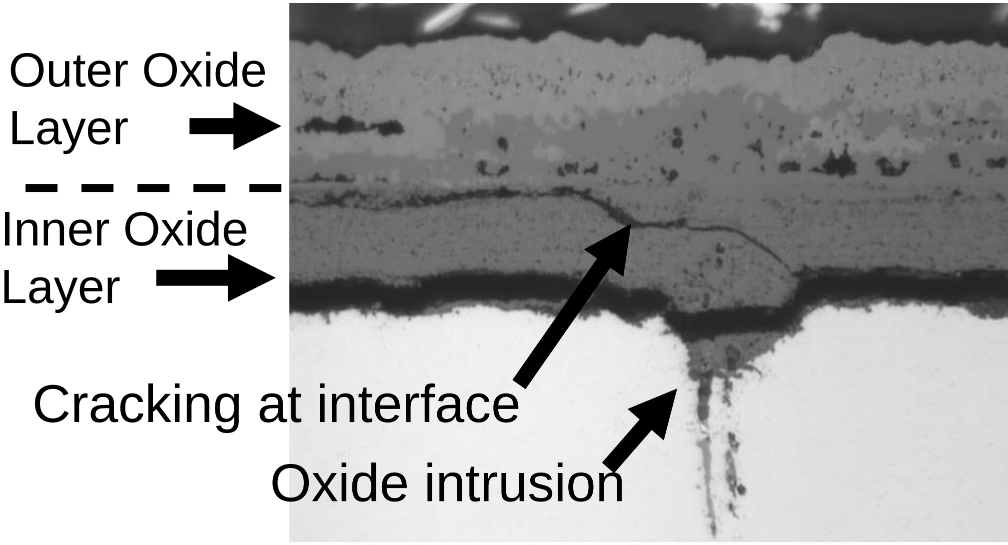
Horiba MEXA-7100 Emission Analyzers NO_x, HC, CO, O_2, Exhaust CO_2, Intake CO_2, CH_4



DEFICIENCIES OF TRADITIONAL STEEL PISTON ALLOYS

- Current heavy-duty (HD) diesel steel piston alloys: micro-alloyed steel (MAS), 38MnSiVS5 or equivalent, 4140
- MAS strength levels expected to drop ~40% when increasing operating temperature from 500 °C to 600 °C
- Expect ~4x increase in oxidation mass gain at 600 °C compared to 500 °C
- Oxide intrusions into base metal can serve as crack nucleation sites



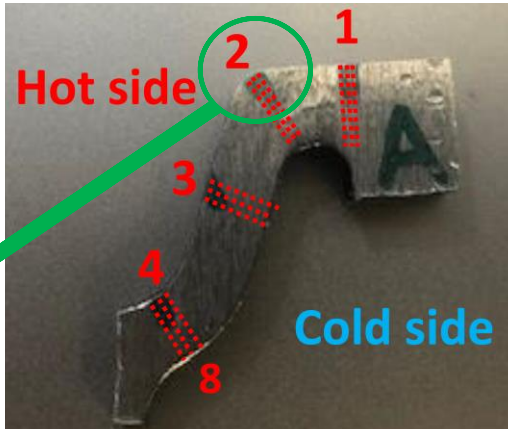


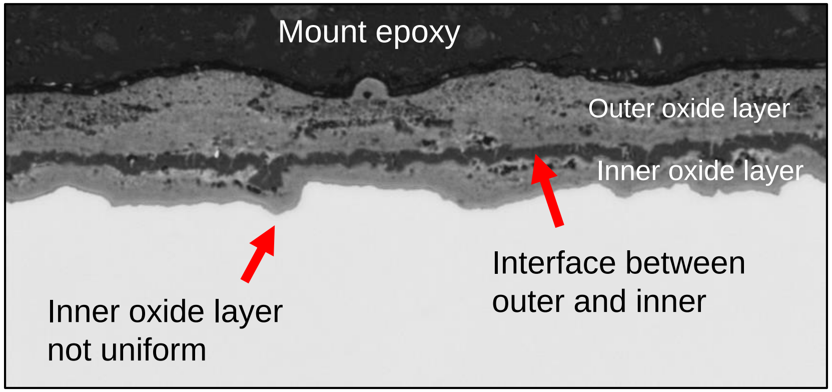
4140: 550°C, 250h, 1h Cycles, Air + 10% H_2O

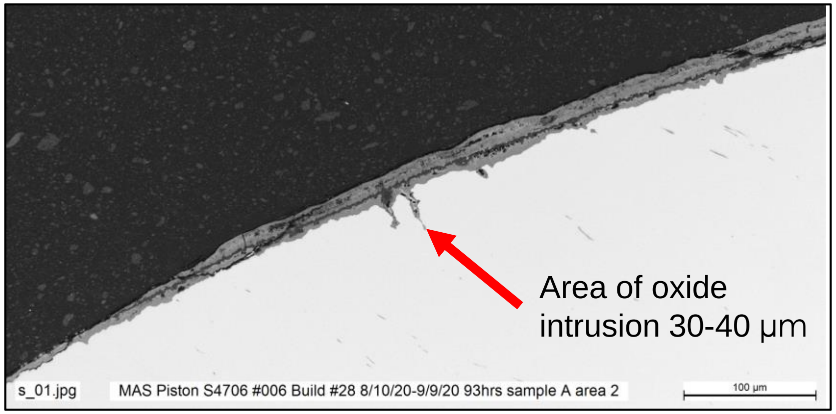
DISTRIBUTION A. See first page.

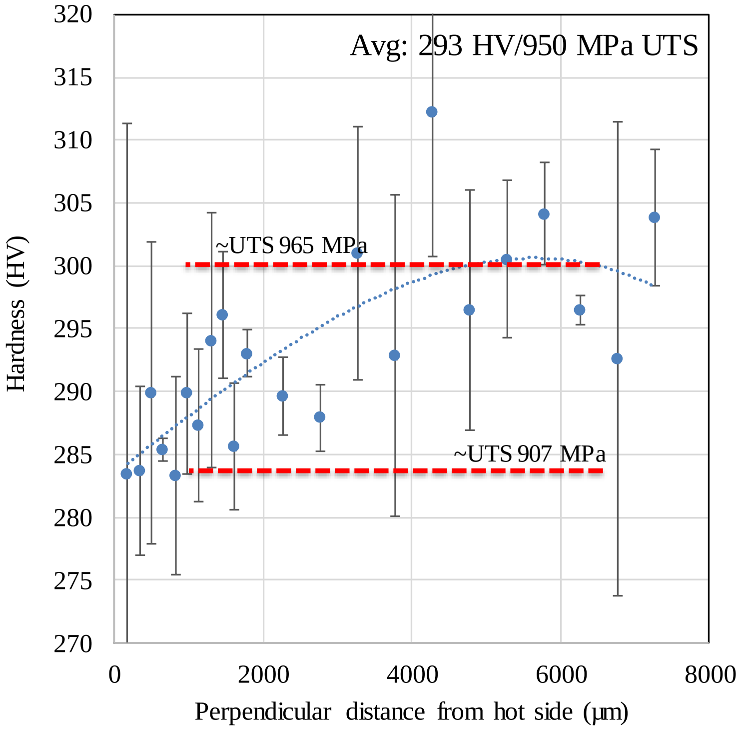
MAS PISTON OXIDATION BEHAVIOR AND HARDNESS DATA AT 530 °C

- Oxide thickness at piston bowl rim region ~20 µm
- Multi-layer iron oxide
- Localized areas of oxide intrusion noted (crack nucleation sites)
- Adherent oxide (no major spallation observed)
- Hardness traverses suggest moderate softening (6-7%) at surface due to thermal exposure



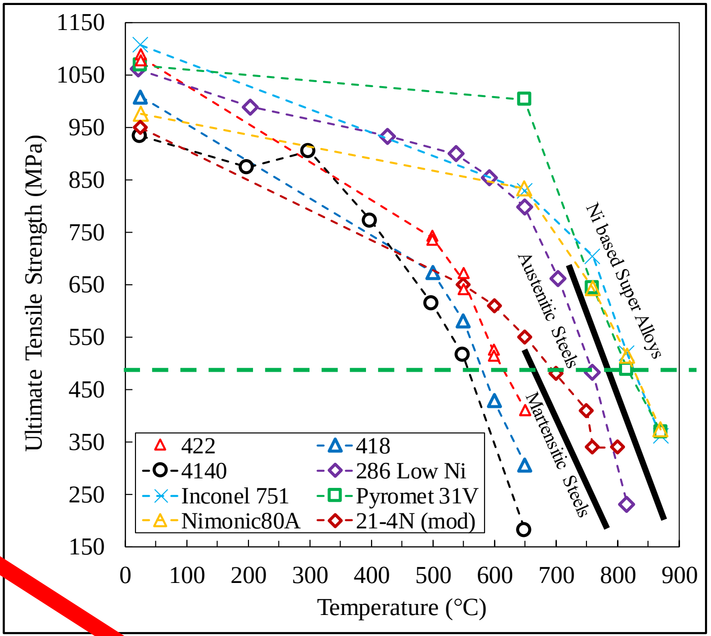






SELECTION CRITERIA FOR CANDIDATE COMMERCIAL ALLOYS

- Operating surface temperature target:
  - 600 °C (threshold)
  - 650 °C (objective)
- Significant increase in oxidation resistance relative to MAS or 4140:
  - Acceptable oxidation kinetics at 600-650 °C
  - Resistance to spallation during cyclic oxidation
  - Resistance to oxide intrusion
- Mechanical strength target:
  - Must also pass fatigue life assessment
  - Structural analysis in progress
- Manufacturability
  - Rotary friction weldable to 4140 skirt
  - Machinability
  - Availability in 5-6 inch round bar
- Cost limit: $4/lb (soft target)
- Expected service life for military qualification purposes: 250-500 h at peak piston temperature (rated power condition)



Oxide spallation on MAS crown surface after 50h at 600 °C in engine test

CURRENT COMMERCIAL STEELS OF INTEREST

- Green: Strong candidates to meet current performance requirements
- Orange: Improved properties over 4140 and MAS, but unlikely to meet requirements
- Red: Existing commercial steels used in HD pistons (not suitable for next generation)

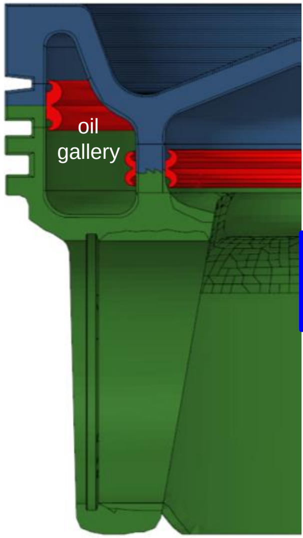
Table: Weight percent elemental composition of candidate alloys

Alloy	Crystal Structure	Ni	Mn	C	Cr	Si	V	Mo	Cu	W	Al	N	S	P	O	Fe	Ti	Co	Nb
H10 modified	BCC	0	0.55	0.4	3.25	1	0.4	2.5								89.9		2	
H13	BCC	0	0.3	0.4	5	0.9	1	1.25								91.15			
422	BCC	0.8	0.66	0.21	11.22	0.3	0.24	0.98	0.09	1		0.06	<0.0005	0.016	0.004	84.42			
418	BCC	2	0.37	0.17	12.3	0.23	0.04	0.08	0.15	2.78		0.029	<0.0005	0.016	0.006	81.829			
A286	FCC	25.5	2	0.08	14.8	1	0.3	1.25								52.97	2.1		
DHA-HS1	BCC																		
DH31-EX	BCC	0.14	0.92	0.33	5.43	0.34	0.53	2.36	0.06				<0.002	0.011		89.879			
EXELL Tuf-Die	BCC		0.35	0.39	5.07	0.25	0.65	1.8								91.49			
EXELL Hot Die	BCC		0.35	0.36	5.07	0.25	0.65	2.8								90.52			
Toolox44	BCC	0.7	0.9	0.31	1.35	0.6	0.145	0.8								95.195			
17-22AV	BCC	0	0.75	0.275	1.25	0.65	0.85	0.5								95.725			
17-22 A	BCC	0	0.55	0.45	1.25	0.65	0.25	0.5								96.35			
17-22AS	BCC	0	0.55	0.305	1.25	0.65	0.25	0.5								96.495			
30 CrMoV 9	BCC	0	0.55	0.3	2.5	0.4	0.2	0.2								95.85			
EXELL FORGEDIE	BCC	0.55	0.95	0.45	1.6	0.25	0.1	0.3								95.8			
2714	BCC	1.6	0.8	0.55	1.15	0.25	0.1	0.5								95.05			
S7 Tool Steel	BCC	0	0.75	0.5	3.25	0.25		1.4								93.85			
P20	BCC	0	0.8	0.34	1.75	0.34		0.4								96.37			
MAS (Chen)	BCC	-	1.58	0.34	0.11	0.65	0.09	-	-	-	-	-	0.035	0.01		97.175	0.01		
MAS (Tess)	BCC	0.4	1.4	0.41	0.15	0.52	0.09	0.036	0.082	-	-	0.016	0.045	0.013	0.002	96.836	<0.0005		<0.002
4140	BCC	0	0.9	0.4	1	0.3	0	0.2	0	0		0.007	0.024	0.01		97.559			

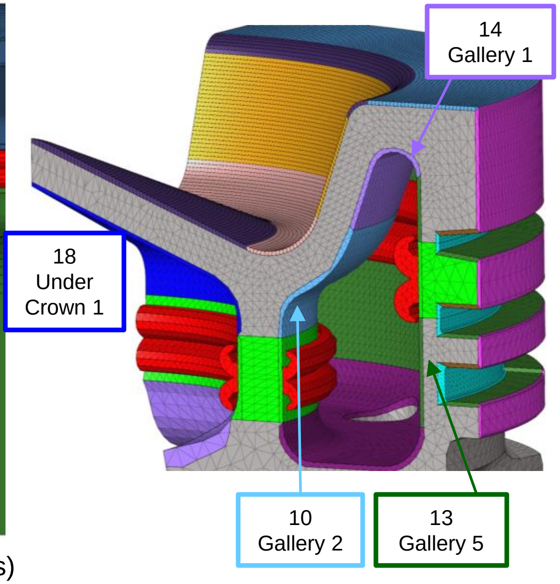
THERMAL AND STRUCTURAL ANALYSIS

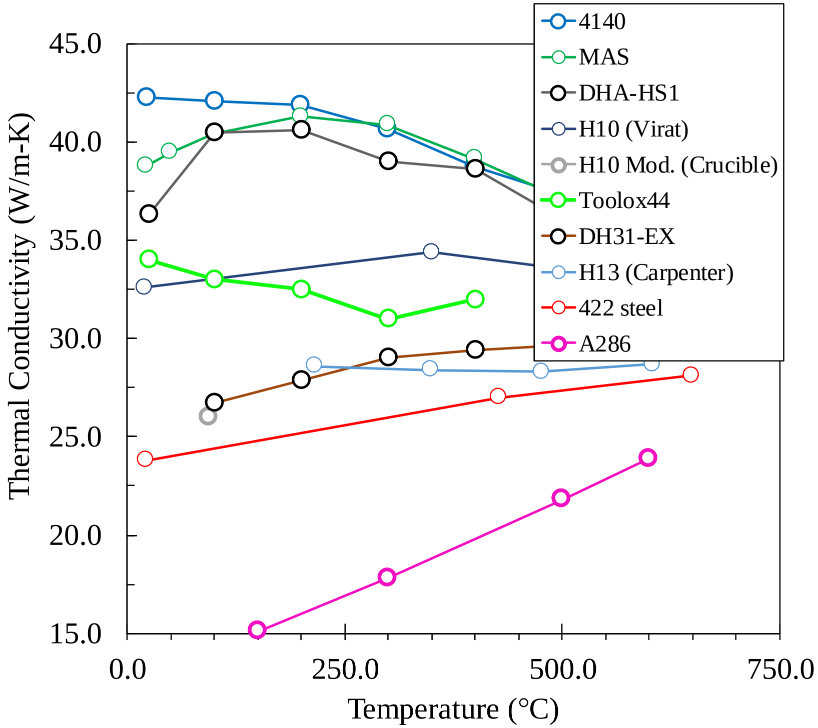
- Perform a steady-state thermal-stress analysis:
  - Given experimental measurements of a) piston surface heat flux and b) subsurface temperature for MAS piston, calibrated the under-crown heat transfer coefficients in the model
  - Given a) experimental surface heat flux and b) calibrated heat transfer coefficients from previous step, model the piston temperature profiles when changing to conductivity of high-temperature commercial alloys:
    - ☐ A286 (UNS S66282)
    - ☐ **422 (UNS S42200)**
    - ☐ DHA-HS1 (Daido Steel)
    - ☐ H10 (UNS T20810)
- Perform a structural analysis of multi-material piston (4140 bottom forging joined to high-temperature alloy crown)

MAS / A286 / 422 / DHA-HS1 / H10
(Above Friction Welds)



4140 (Below Friction Welds)



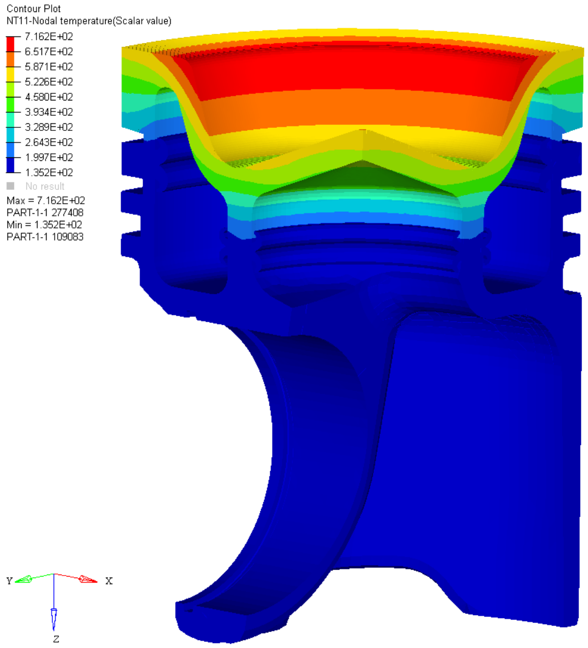


422 / 4140 PISTON
OPERATING CONDITION 3 (2500RPM, 20.3BAR IMEP$_g$)
3.15 LPM PISTON COOLING NOZZLE FLOW (ACCELERATED ABUSE CONDITION)

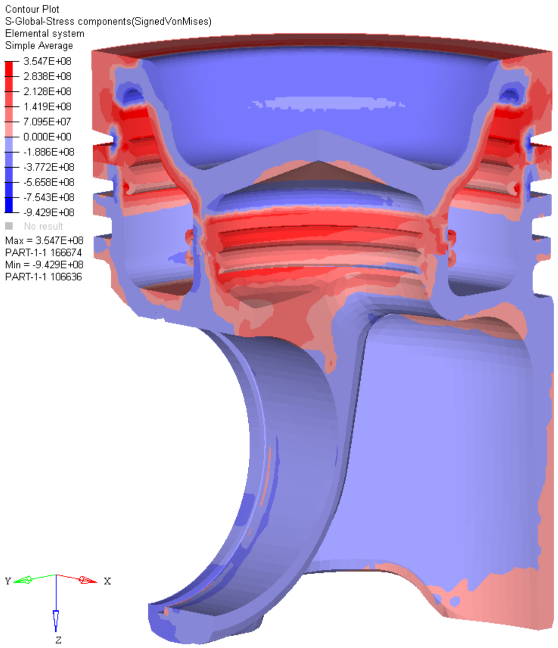
- Total thermal load = 8557 W
- Peak cylinder pressure = 20 MPa

Group	Group Name	Surface Temperatures C
1	Bowl Apex	589
2	Bowl Bot	583
3	Bowl Wall	711
4	**Bowl Rim**	**716**
5	Bowl Top	698
6	Grv 1st RT	244
7	Grv 2nd RT	149
8	Grv 3rd RT	146
9	Gallery 1	546
10	Gallery 2	475
11	Gallery 3	247
12	Gallery 4	154
13	Gallery 5	372
14	Pin Bore	151
15	Saddle Rib	158
17	Skirt A Rid	142
18	Under Crown 1	501

Steady-State Temperature (C)



Signed VonMises Stress (Pa)
+ Tensile Stresses
- Compressive Stresses



Quarter symmetry view, but full piston model was analyzed.

OXIDATION TEMPERATURE LIMITS

- **Challenge:** Steels with higher oxidation resistance exhibit lower thermal conductivity, causing higher operating temperature, partially negating improved oxidation resistance
- “Usable temperature” increases” are obtained based on material oxidation limits

- 12Cr 422 forms slow growing, adherent, chromia scale, with high oxidation resistance to ~760˚C
- 3-5 wt.%Cr DH31-EX and H11 form fast growing Fe oxide scale, result in lower “usable temp” increase
- HTCS-130 high thermal conductivity steel exhibits excellent usable temperature increase, despite Fe oxide formation, but potential oil coking

Oil Flow Rate, lpm	A286	422	DH31-EX	H10	MAS	HTCS-130 (estimated)
8.9	619	550	528	494	466	391
6.1	638	571	550	516	488	413
5.6	649	584	562	528	500	425
5.2	659	595	573	539	511	436
4.7	676	614	592	557	530	455
4.15	695	636	614	579	551	476
3.15	746	690	669	632	604	529
Oxidation Limit	704	760	600	585		550
Usable Temp increase over MAS (oxidation limited)	28	146	8	28		95

Only minor oxidation expected at these temperatures for 250-500h

Modearte Oxidation, likely acceptable for 250-500h

Rapid Oxidation, not reccomended for 250-500h

Above manufacturers reccomendation of 704C. Testing at ORNL reccomended

SUMMARY / FUTURE WORK

- **Multi-disciplinary project to evaluate the use of commercially available, high-temperature alloys for use in a piston application in advanced diesel engines**
  - Materials science
  - Structural and thermal engineering
  - Engine and combustion research
- **Several commercially available alloys were identified with potential increases in the oxidation temperature limit**
- **Significant metallurgical challenge to balance strength, oxidation resistance, thermal conductivity, manufacturability, and cost**

Future Work

- **Selected high-temperature alloys will be manufactured into pistons and screened in a single-cylinder engine**

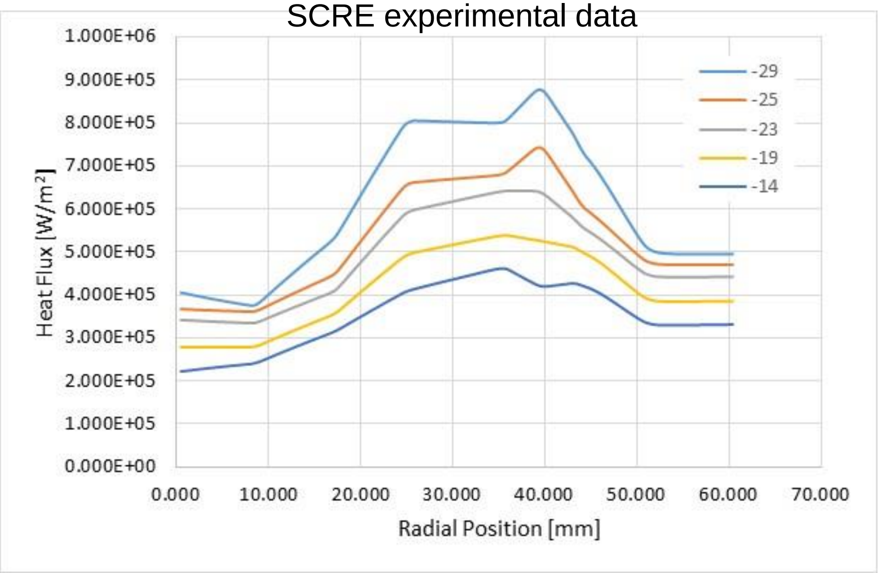
Thank You!

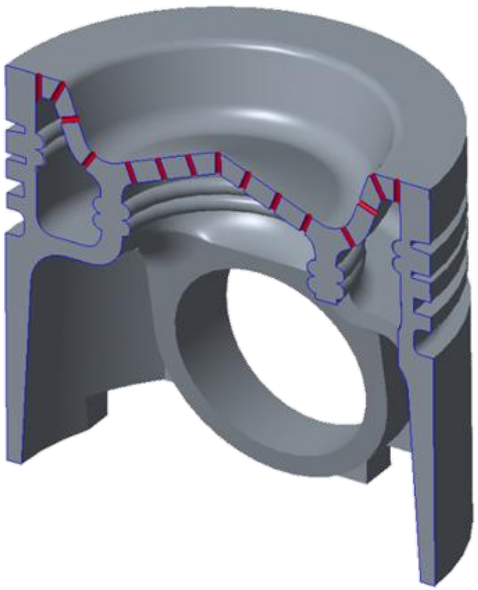
Questions?

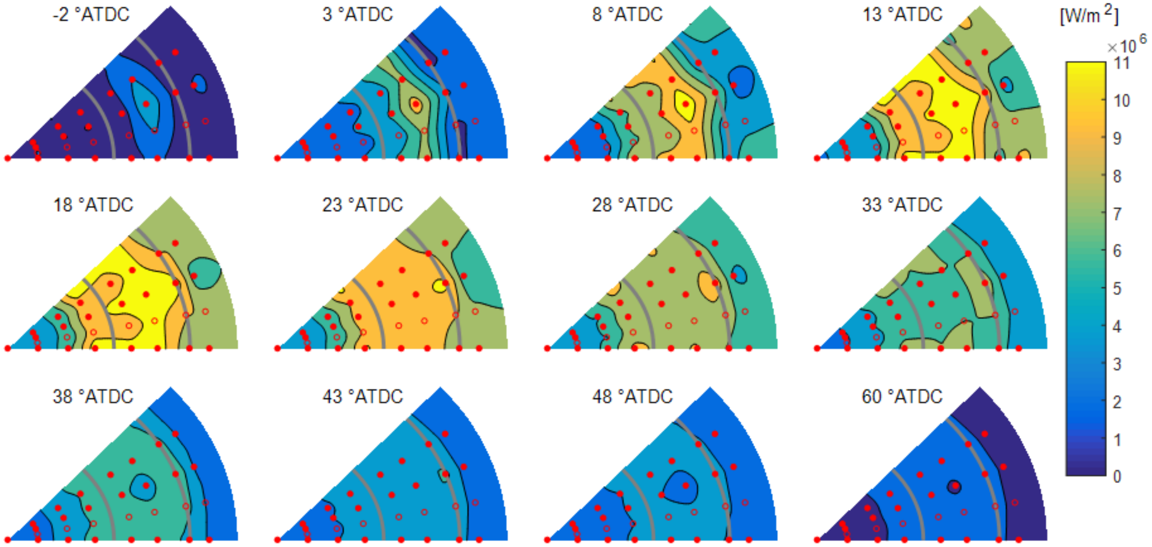
Backup Slides

PISTON CROWN HEAT FLUX BOUNDARY CONDITION

- Model rated power operating condition
  - 2500 rpm, IMEP$_g$= 20.3 bar
  - Start of injection command (SOIC) -25° aTDC
- Assume heat flux only a function of radius (constant in azimuthal direction)
- Heat flux generated from surface fast-response thermocouple measurements in a single-cylinder research engine (SCRE)
  - Gingrich, Eric, *High-output Diesel Engine Heat Transfer*. PhD dissertation, University of Wisconsin - Madison, 2020.



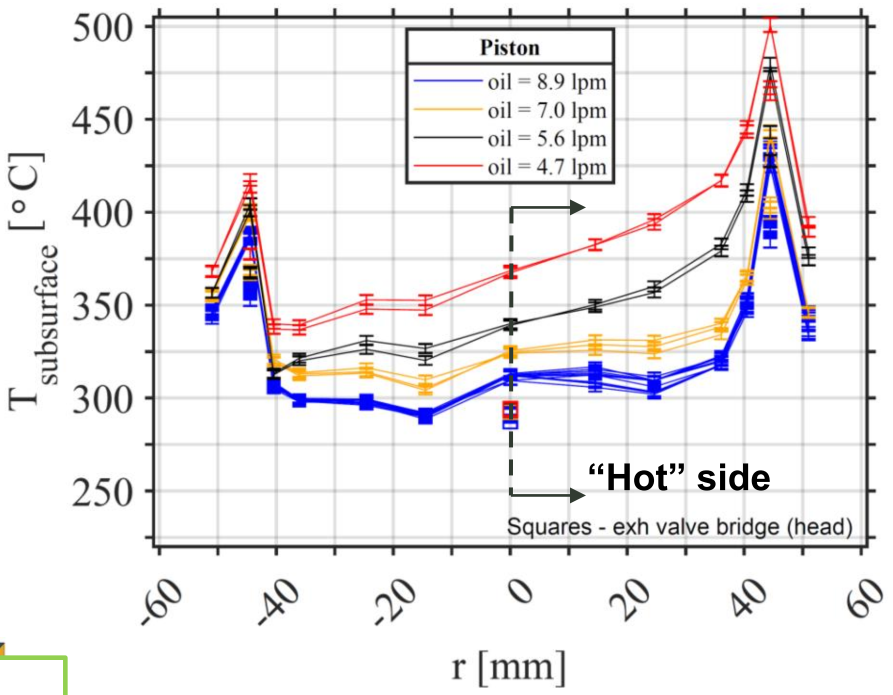


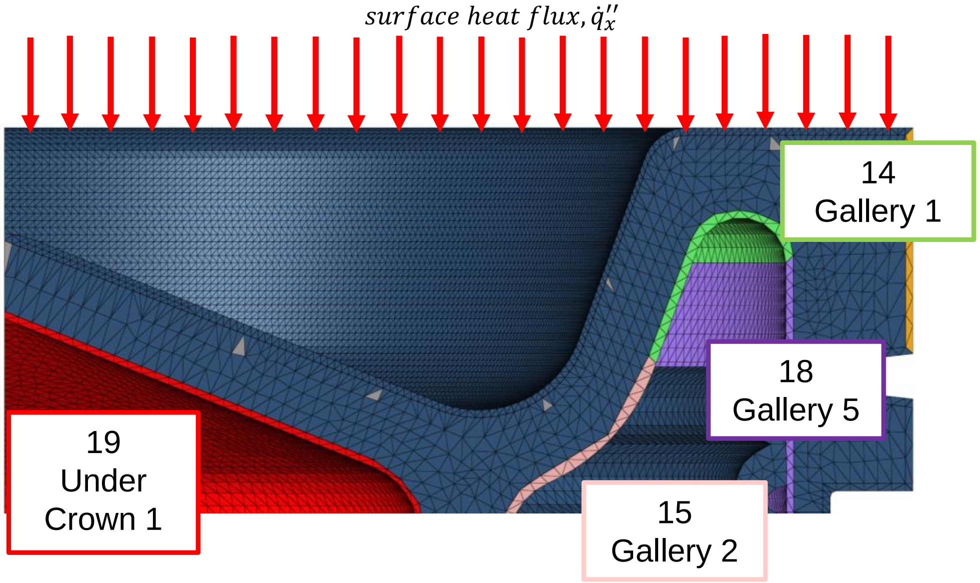


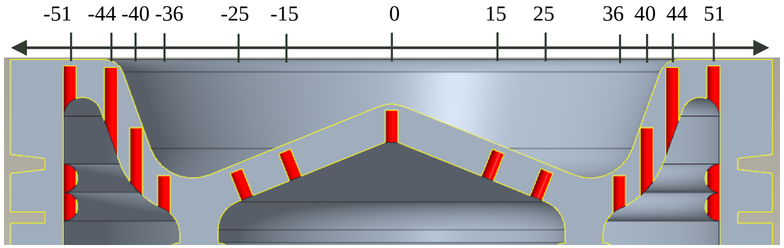
PISTON OIL GALLERY BOUNDARY CONDITION

- Operating condition:
  - 2500 rpm, 20.3 bar mean effective pressure
  - Peak cylinder pressure ~ 200 bar
- Surface heat flux on piston crown based on surface-mounted, fast-response piston thermocouple measurements in SCRE
- Calibrate the FE model heat transfer coefficients on the under-crown surfaces to match embedded (subsurface) thermocouple (TC) measurements of an MAS piston in SCRE

SCRE experimental data





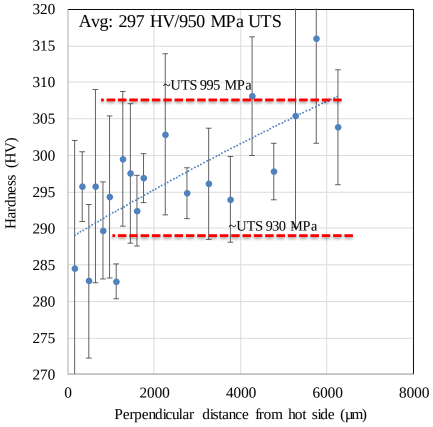


Embedded TC radial locations in SCRE
(all TCs nominally 1 mm below surface)

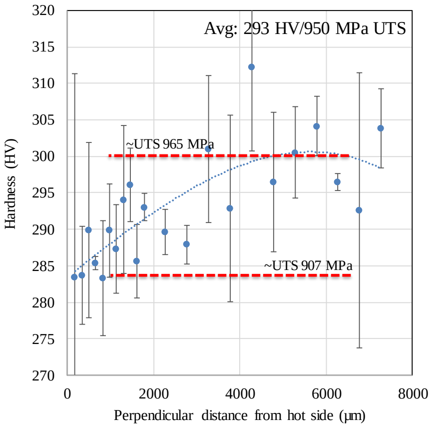
MAS PISTON HARDNESS DATA

- Each point is avg. of 3 indents
- Average hardness of each location consistent with exception of bowl apex (lower strength area and not sure why)
- The hardness traverses on areas 1 and 2 suggest some softening at surface is occurring due to high temperature
  - An ~6-7% reduction in strength at surface relative to bulk is observed.

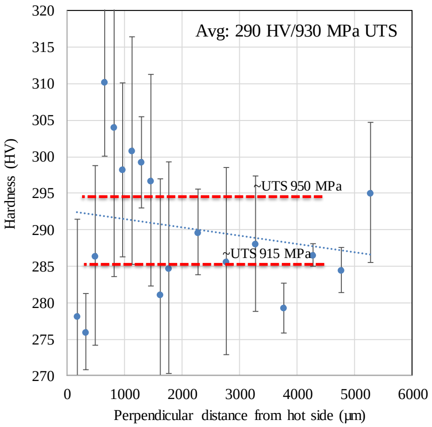
Area 1 - Bowl Top



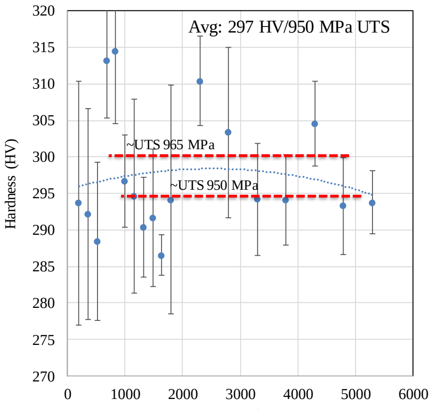
Area 2 - Bowl Rim



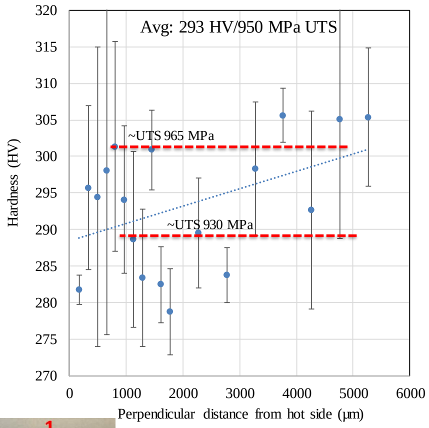
Area 3 - Bowl Wall



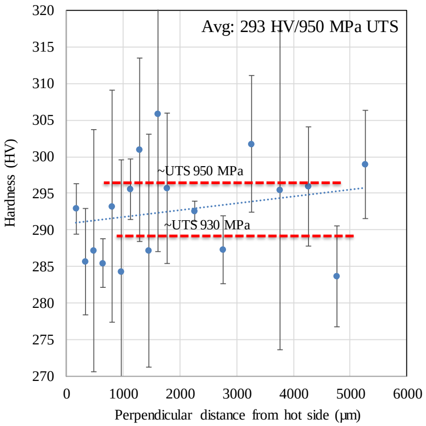
Area 4 - Bowl bottom



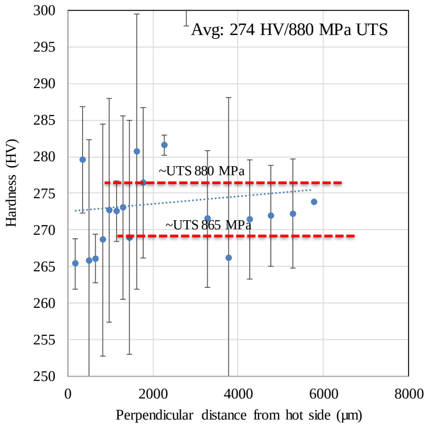
Area 5 - bottom/apex

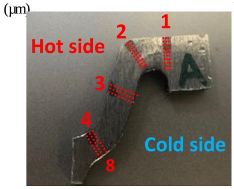


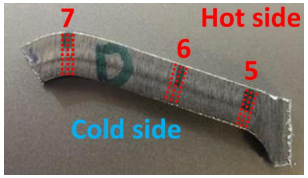
Area 6 - mid/apex



Area 7 - bowl apex







DISTRIBUTION A. See first page.