



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

Suitability of High-Temperature Martensitic Steels for Next
Generation Diesel Engine Pistons

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- **Industry Partners:**

- Tenneco (formerly Federal-Mogul) Powertrain



MOTIVATION



- Performance requirements: Military ground vehicles must operate in all climates – arctic to desert – with the propulsion system under armor (engine, transmission, intake, exhaust, cooling, lubrication, etc)
- IC engine development: trends toward higher in-cylinder gas pressures and temperatures, which are ultimately limited by maximum piston temperatures and piston durability
- Traditional steel piston alloys: Current piston alloys (quenched and tempered 4140 and microalloyed steel (MAS), or equivalent) are constrained primarily by a temperature limit (~500-550 °C max)



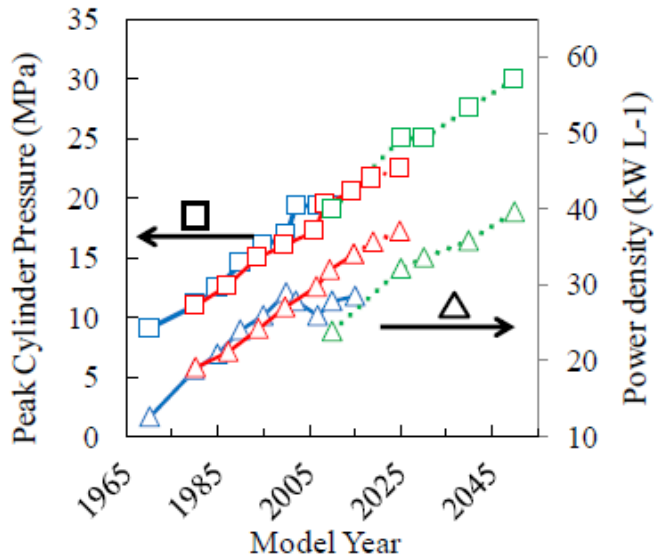
High power density, low heat rejection



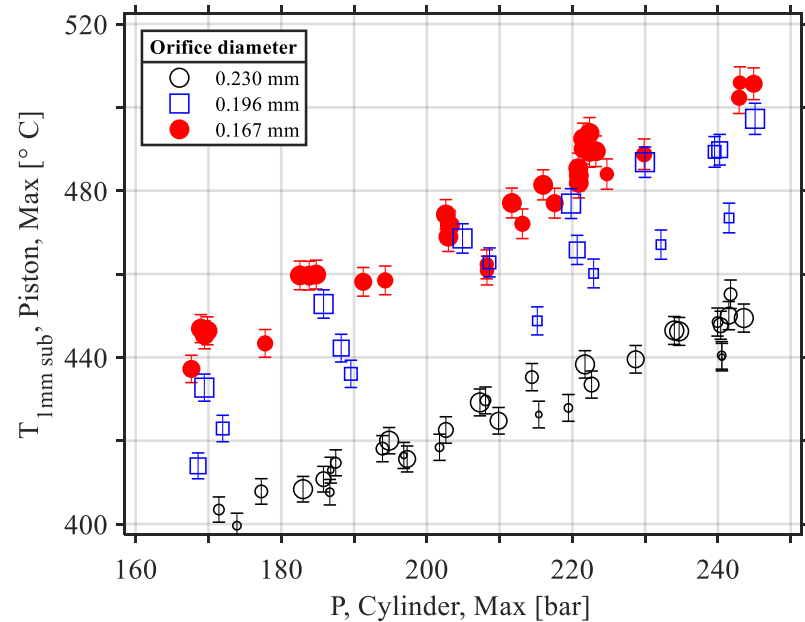
Pathways to higher efficiency force a materials solution



Requires strength & oxidation resistance at high temperature



Pierce et al., Prog. Mater. Sci, 2019



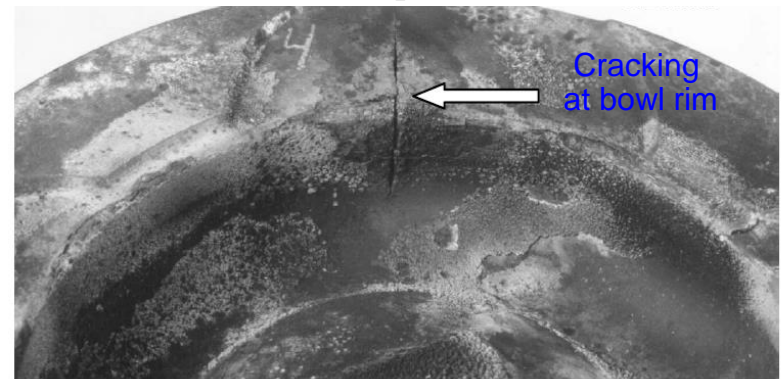
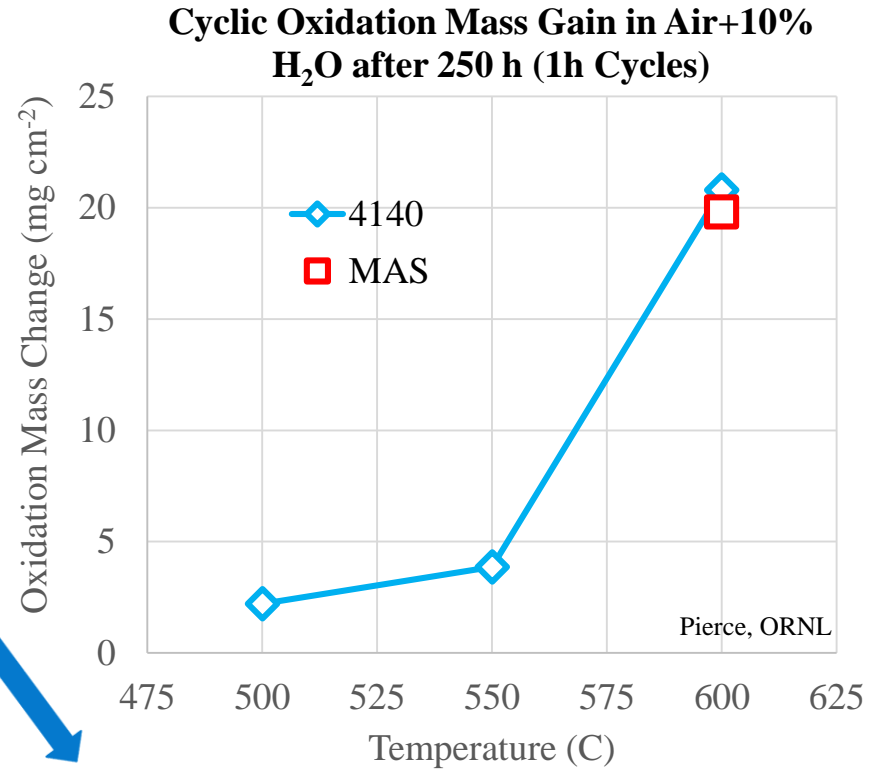
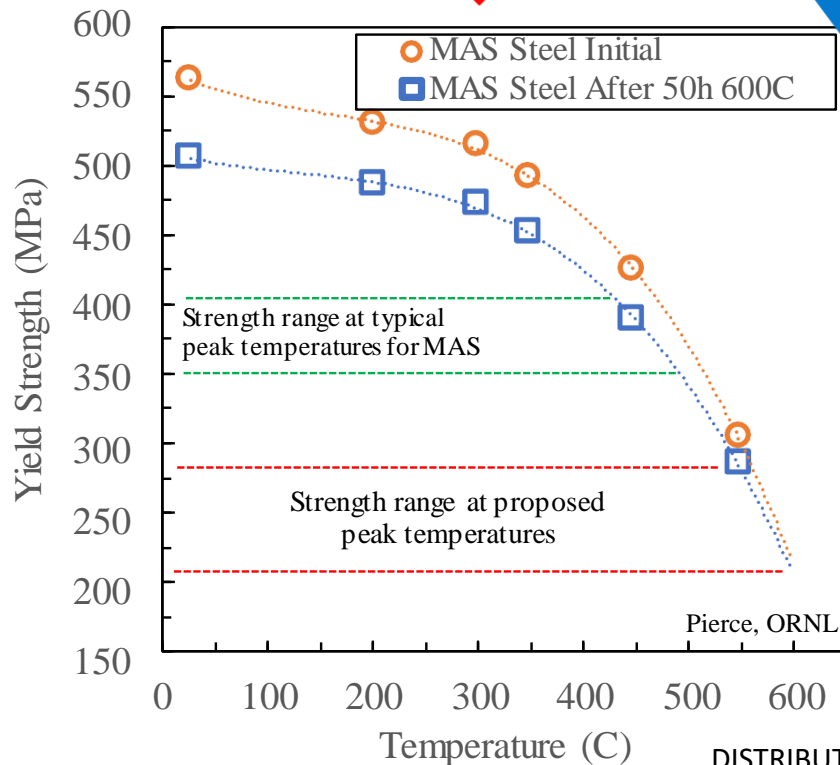
Tess et al., unpublished



CHALLENGES WITH EXISTING MATERIALS



- Higher temperatures and pressures in next generation HD diesel engines
- Higher temperatures lead to:
 - Much higher oxidation rates
 - Significant loss of strength



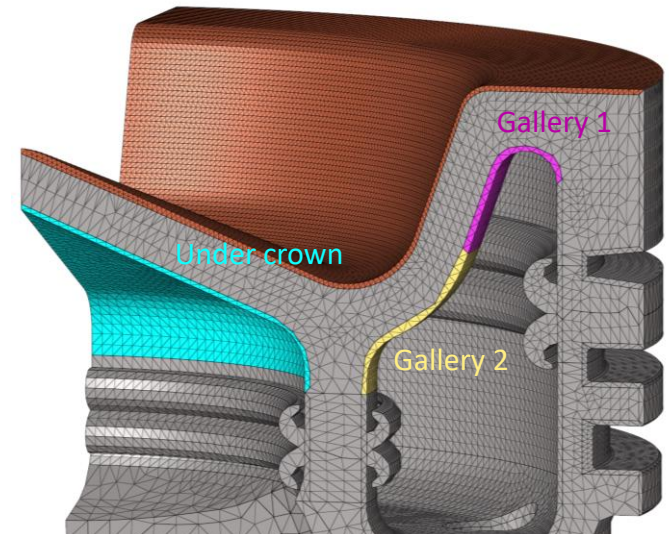
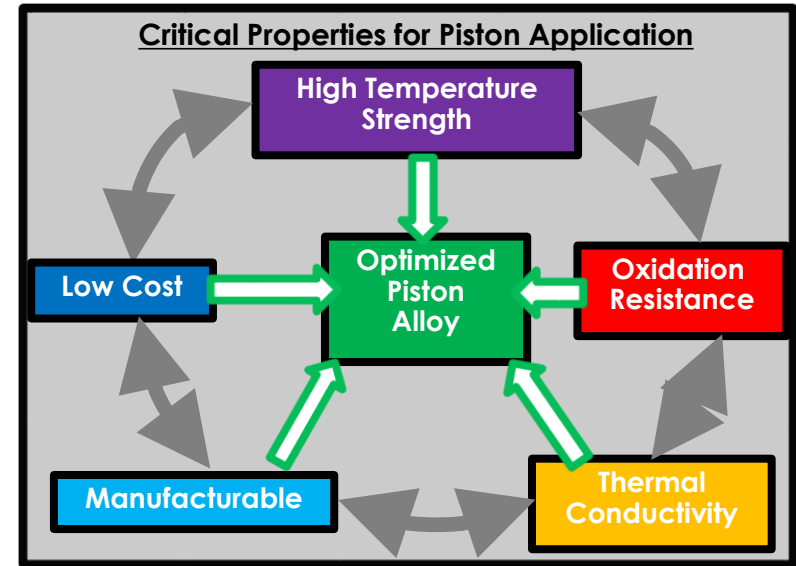
Chen and Worden, SAE 2000-01-1232



SELECTION CRITERIA FOR CANDIDATE COMMERCIAL ALLOYS



- Significant increase in oxidation resistance (relative to MAS and 4140)
 - Acceptable oxidation kinetics
 - Resistance to spallation
 - Resistance to oxide intrusion
- Mechanical properties
 - Hardness, strength and elastic properties
 - Must also pass fatigue life assessment
- Thermal properties
 - Conductivity, $k = \alpha\rho c_p$
 - Thermal expansion
- Manufacturability
 - Rotary-friction weldable to 4140 bottom forging (constraint for prototyping)
 - Machinability (≤ 35 HRC)
- Non-developmental and affordable ~ \$4/lb
- Service life
 - Military qualification purposes
 - 250-500 hrs at peak piston temperature (rated power condition)





COMMERCIAL STEELS OF INTEREST



- Seek candidate alloys to replace baseline piston crown materials (4140 and MAS) while using same manufacturing methods and bowl geometry
- Green: candidates with some potential to meet future performance requirements
- Yellow: under investigation to evaluate potential for meeting performance requirements
- Red: Existing commercial steels used in HD pistons, which may not be suitable for next generation wrought/forged pistons

Table: Weight percent elemental composition of candidate alloys

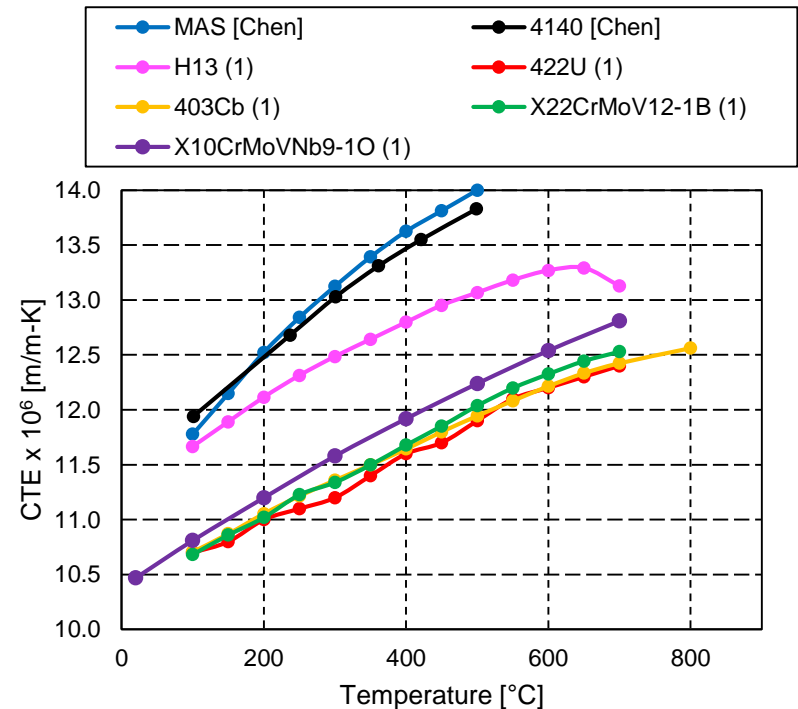
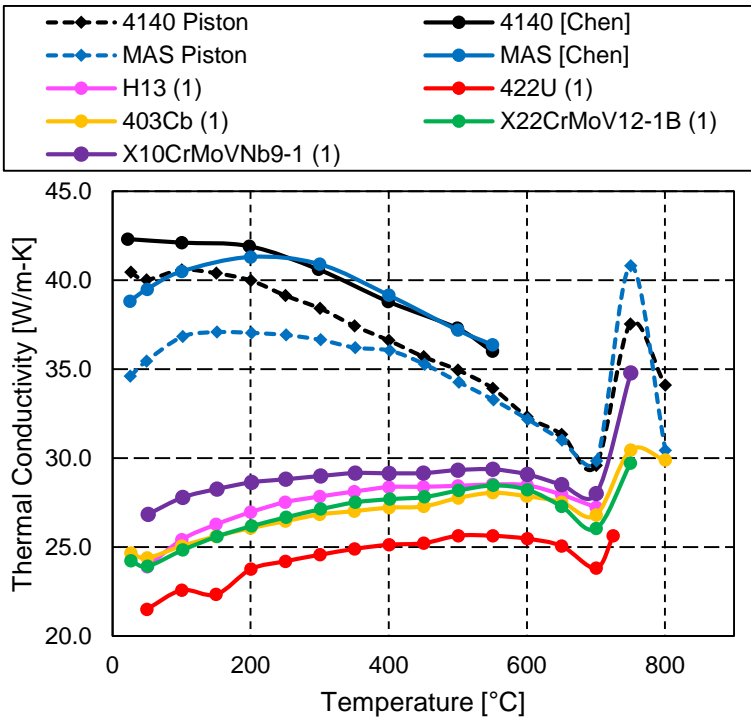
Element	Ni	Mn	C	Cr	Si	V	Mo	Cu	W	Al	N	S	P	O	Ti	Co	Nb	B	Fe
MAS 38MnVS6 Piston	0.4	1.4	0.41	0.15	0.52	0.09	0.04	0.08	-	-	0.02	0.045	0.013	0.002	<0.0005		<0.002		97
4140CS	0.42	0.88	0.42	0.92	0.29	0	0.21	0.17	-	0.026	0.01	0.024	0.01	-	0.002		0.002	2E-04	
4140T	-	1	0.4	1	0.3	-	0.2	-	-	-	0.01	0.03	0.01	-	-	-	-	-	
4140 Piston	0.21	0.88	0.41	0.99	0.26	0.001	0.21	0.17	-	0.026	-	0.012	0.009	-	-	-	-	3E-04	97
H13	0.16	0.39	0.4	5.18	1.07	0.96	1.49	0.08	0.046		0.02	0.003	0.01		0.0024	0.015	<0.002		90
X10CrMoVNb9-1B	0.33	0.455	0.1	8.63	0.35	0.21	0.9	0.1	<0.001	0.007	0.05	0.0006	0.011	0.003	0.0005	0.015	0.06		89
X10CrMoVNb9-1O [22]	0.09	0.37	0.08	8.61	0.11	0.21	0.89	0.04	-	0.007	0.06	0.003	0.01	-	0.004	0.01	0.072	<0.09	
403Cb+	0.52	0.71	0.17	10.5	0.39	0.21	0.83	0.05	<0.05	0.015	0.06	0.0005	0.009		<0.005	<0.05	0.36		86
X22CrMoV12-1T	0.43	0.553	0.2	11	0.37	0.26	0.83	0.06	<0.04	<0.001	TBD	<0.003	<0.005	-	0.0045	0.017	<0.002	-	86
X22CrMoV12-1B	0.65	0.59	0.21	11.5	0.36	0.26	0.9	-	-	-	-	<0.0010	0.008	-	-	0.014	-	-	
422U	0.8	0.66	0.21	11.2	0.3	0.24	0.98	0.09	1		0.06	<0.0005	0.016	0.004					84
422C	0.79	0.78	0.23	12.1	0.36	0.22	1.08	0.08	0.96		0.05	0.006	0.019	-					83



THERMAL PROPERTIES



- Alloying elements tend to reduce thermal conductivity, particularly when in solid solution
- Cr additions substantially reduce thermal conductivity when relatively large amounts are in solid solution, such as for H13, X10CrMoVNb9-1, 403Cb+, X22, and 422
- Si strongly reduces thermal conductivity (1.07 wt.% in H13 steel)
- Coefficient of thermal expansion (CTE) trends lower with Cr additions

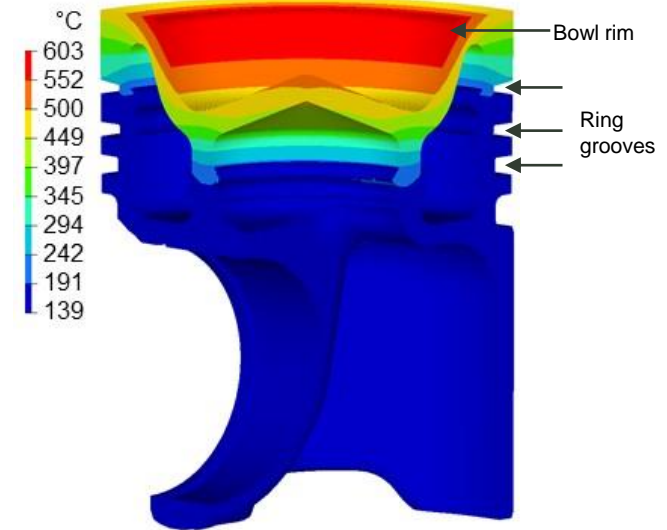




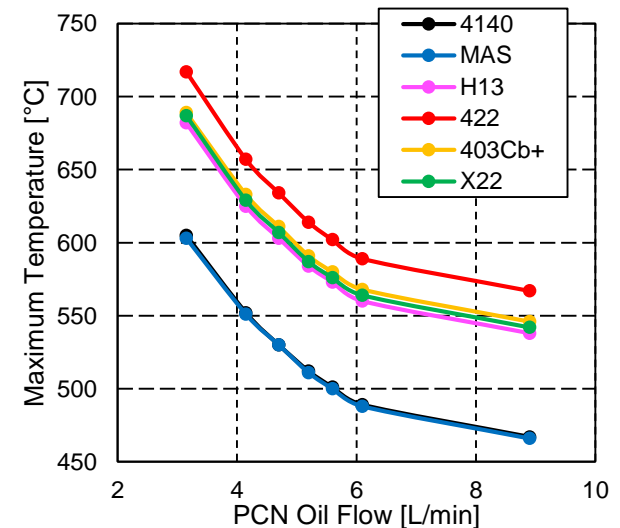
PISTON THERMAL MODELING



- Steady-state thermal analysis using finite element software Abaqus at a severe engine operating condition
 - ❑ Experimentally derived heat flux on combustion chamber side
 - ❑ Heat transfer coefficients on undercrown surfaces were calibrated to measured subsurface temperatures
- Two key regions of interest:
 - ❑ Bowl rim: max surface temperature and susceptible to stress and oxidation induced cracking
 - ❑ Ring grooves: relatively high stress but lower temperature, stress in part influenced by higher temperature crown regions (thermal arching)
- Key results:
 - ❑ Lower thermal conductivity of candidate alloys results in a substantial increase (50 to +100°C) in maximum piston temperature relative to baseline materials with same geometry and engine conditions
 - ❑ In selecting a candidate alloy, must balance impacts of alloy content on thermal conductivity, as well as strength and oxidation resistance at operating temperatures



Predicted steady-state temperature for MAS under severe operating condition



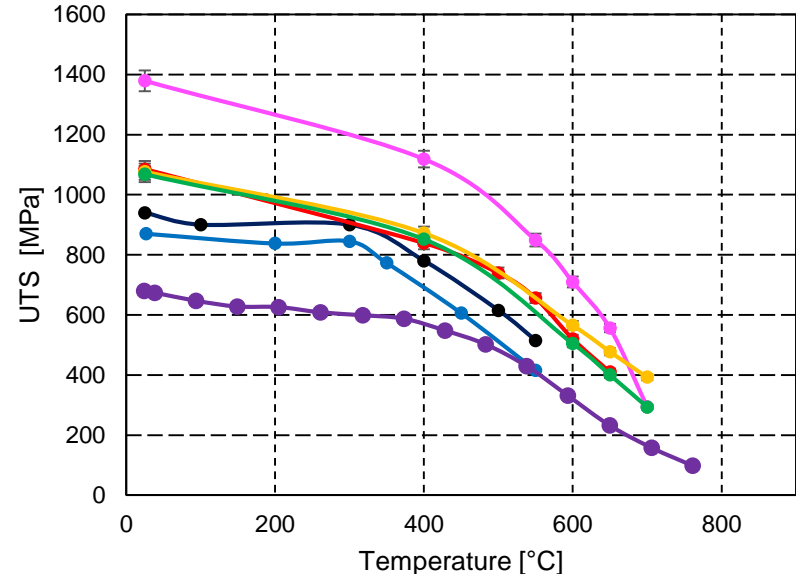
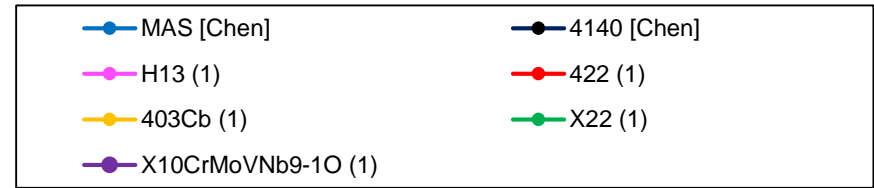
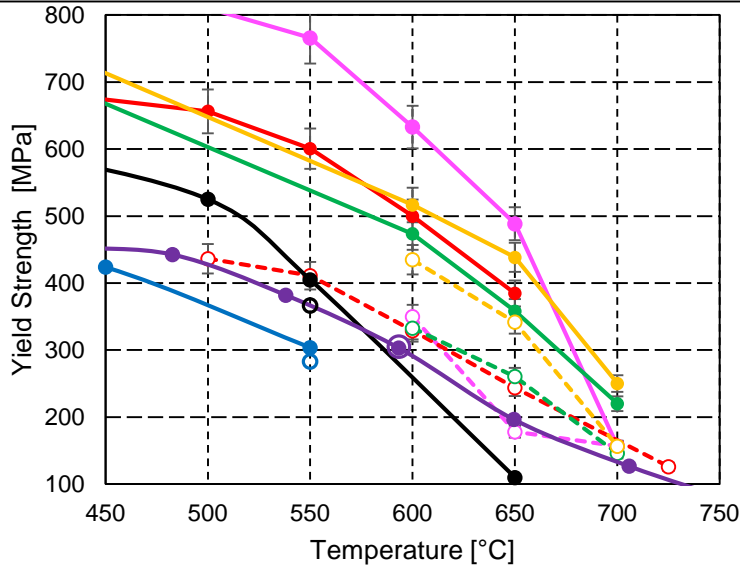
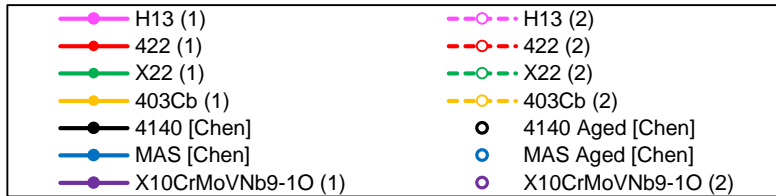
Predicted maximum temperature using constant heat flux assumption. Actual temperatures of candidate alloys may be lower.



MECHANICAL PROPERTIES



- 403Cb+ shows the best overall combination of elevated temperature yield strength (YS) and ultimate tensile strength (UTS) considering the as-tempered (650°C/2h + 650°C/2h) and as aged conditions (650°C 500h), denoted by (1) and (2), respectively, in legend
- H13 exhibits highest strength level up to 650°C, but also the largest strength reduction after aging, despite a lower aging temperature (600°C 500h)
- Elevated temperature YS and UTS of X10CrMoVNb9-1 lower than other alloys, but tempering temperature more severe (760°C/1h)

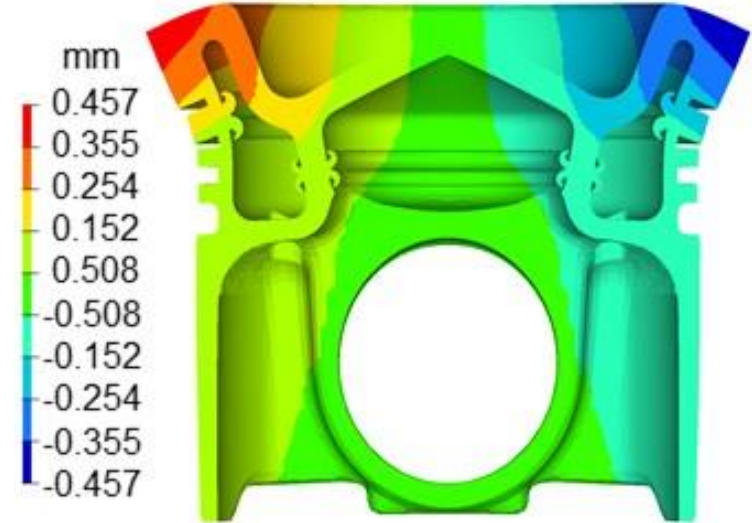




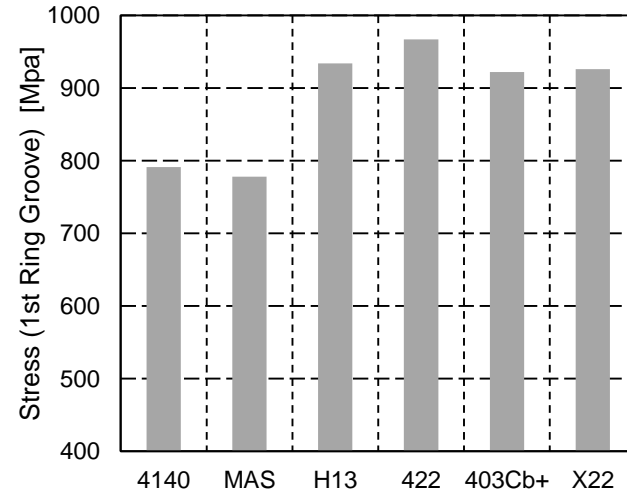
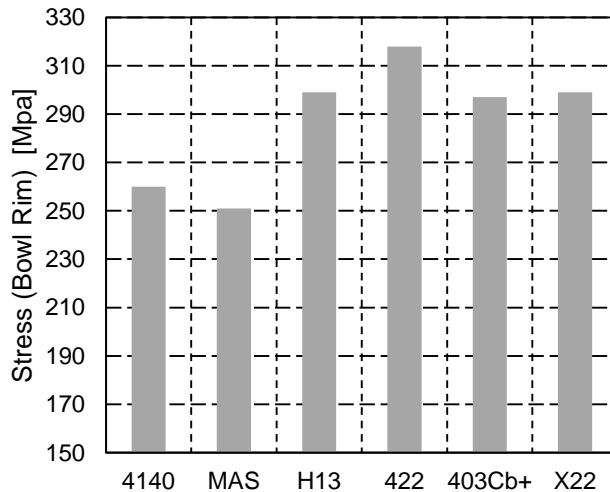
PISTON STRUCTURAL MODELING



- FEA structural analysis uses linear-elastic model, whereas loading on piston is highly complex with potential for creep at high temperature locations in some alloys
- Asymmetrical deformation pattern results from a bending moment about ring groove areas and weld zone, which is primarily driven by thermal arching phenomenon
- Stresses increase for candidate alloys at two key regions:
 - ❑ Bowl rim - highest temperature, subject to aging
 - ❑ Top ring groove - highest stress, material strength controlled by tempering, no significant aging occurs
- Actual performance of candidate alloys in a piston is subject to further investigation



Displacement (exaggerated 40x) for MAS piston under severe operating condition with combined thermal and pressure loads

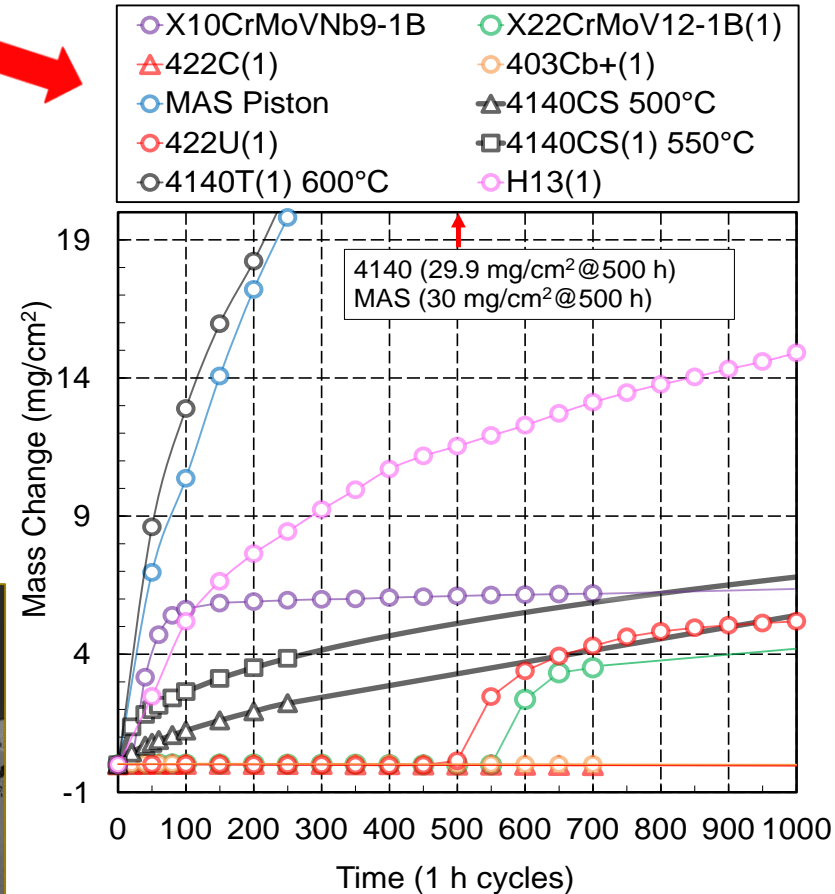




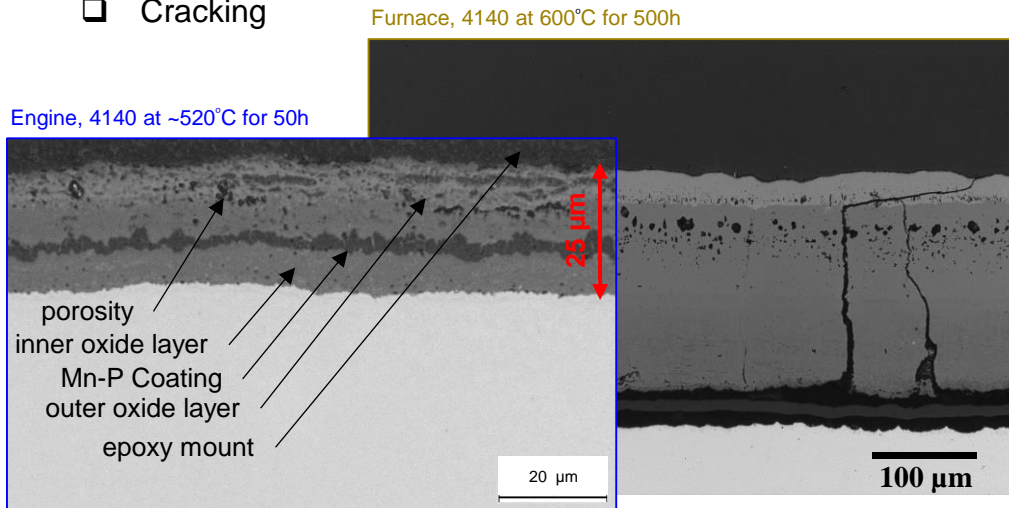
LONG-TERM CYCLIC OXIDATION TESTING (1 OF 2)



- Two methods of evaluating piston oxidation
 - ❑ Cyclic furnace tests of coupon samples in air + 10% H₂O at various test durations (250-1000h) and temperatures (500-700°C)
 - ❑ 50h engine tests of baseline materials at 500-520°C surface temperatures
- Evaluate mass increase or decrease due to formation of oxide scale
 - ❑ Fast growing Fe-oxide for MAS, 4140 at 600°C
 - ❑ Slow growing, adherent chromium oxide scale, as chromium content increases to a critical level
- Micrographs to characterize oxidation layers
 - ❑ Thickness
 - ❑ Intrusions
 - ❑ Cracking



Furnace coupon oxidation mass change as a function of time at 600°C. 4140 data at 500°C and 550°C extrapolated out to 1000h. X10, X22, 403Cb+, and 422C are also extrapolated out to 1000h.

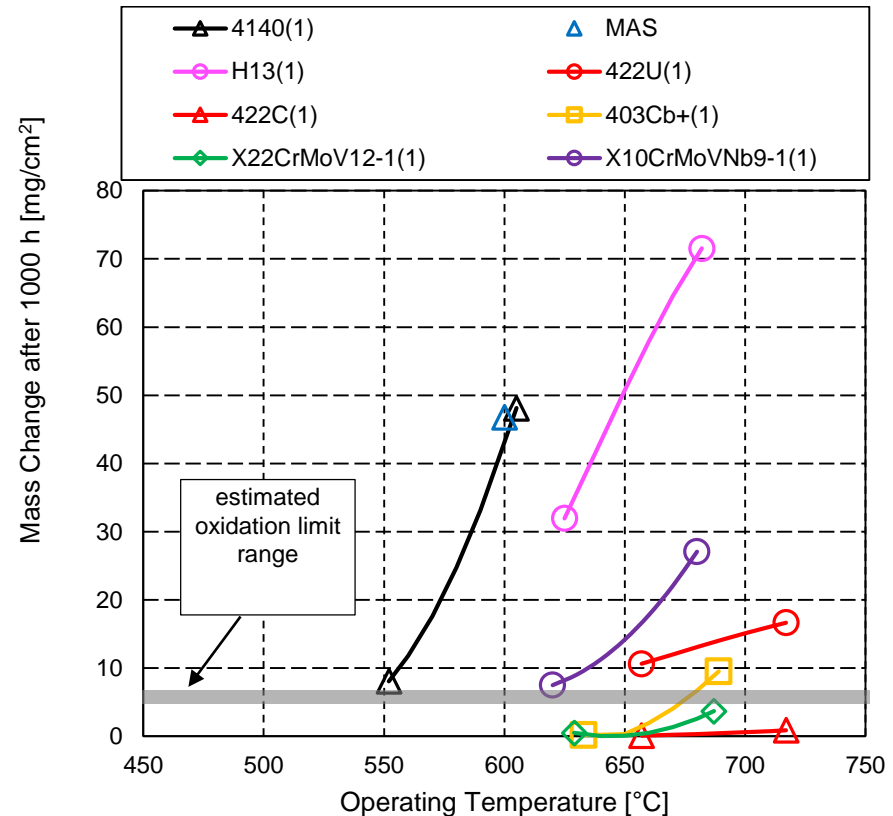




LONG-TERM CYCLIC OXIDATION TESTING (2 OF 2)



- Oxidation limit range (5-7 mg/cm²) estimated from mass change of 4140 at 500°C and 550°C after 1000 cycles
- Assess oxidation performance of each candidate alloy relative to:
 - Equivalent limit of 4140 at nominal engine condition (lower bound)
 - Max temperature under more severe engine condition (upper bound)
- Key results:
 - ❑ H13, Cr of 5 wt.% insufficient to form protective Cr-oxide, yet greatly increases piston temperature – results in predicted oxidation gain greater than baseline alloys
 - ❑ Cr of 8.6 wt.% or greater gives slower oxidation mass gain at operating temperatures relative to baseline alloys, and additional Cr can result in chromia oxide scale formation, further reducing oxidation rates
 - ❑ Other factors including processing (austenitization, tempering temperatures), microstructure characteristics (grain size, carbide size and distribution, etc.) and elements other than Cr are also influencing oxidation behavior





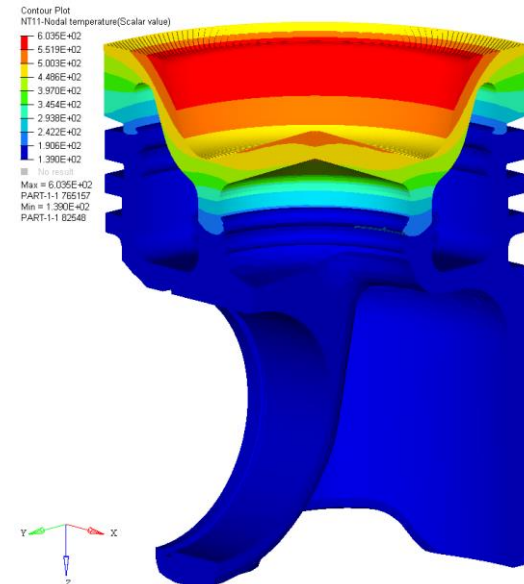
SUMMARY / FUTURE WORK



- The additional alloying content of high-temperature martensitic steels tends to reduce conductivity, greatly increasing the piston operating temperatures
- Stresses at the bowl rim and top ring groove increase for the candidate alloys, likely due to thermal arching, may be partially mitigated by higher strength
- 403Cb+, X22, and 422 displayed potential increases in the oxidation temperature limit
- Significant metallurgical challenge to balance strength, oxidation resistance, thermal conductivity, manufacturability, and cost

Future Work

- Down-selection of four commercial alloys
- Prototype piston manufacturing
 - Alloy 422 currently in progress
- Single-cylinder engine testing
- Post-mortem analysis
- Longer-term multi-cylinder engine testing
- Development alloys





Thank You!

Questions?



Backup Slides



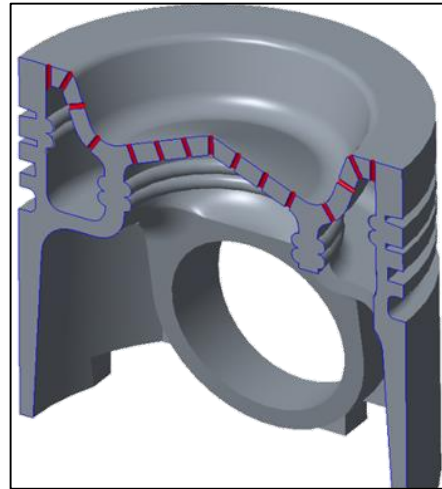
SINGLE-CYLINDER RESEARCH ENGINE (SCRE)



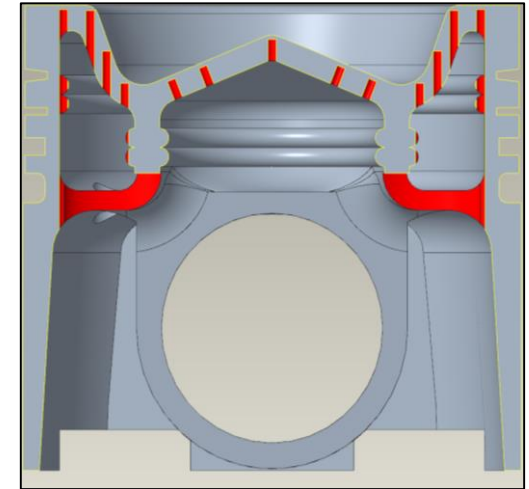
Full engine instrumentation and piston telemetry system supports thermal survey of piston → boundary conditions for piston FEA

- Subsurface piston temperatures
- Surface heat flux

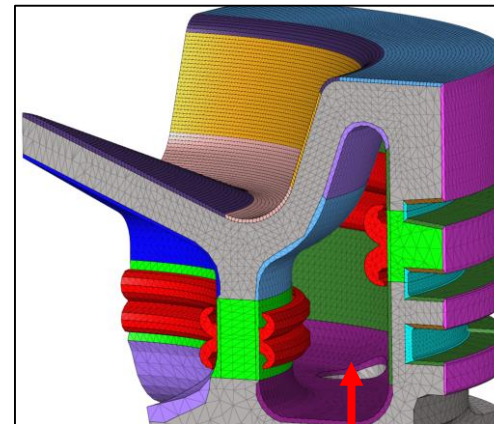
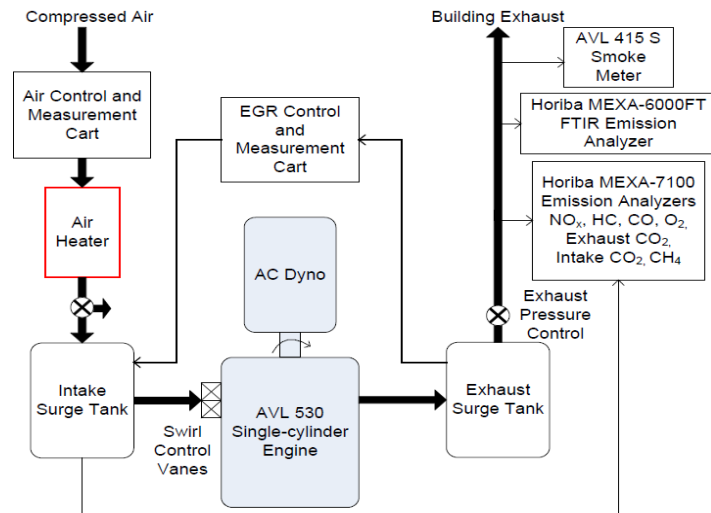
Displacement (L)	1.49
Bore (mm)	122
Stroke (mm)	128
Number of Valves (-)	4
Compression Ratio (-)	14.5
Swirl Ratio	0-3.5 (variable)
Peak Firing Pressure (bar)	250
Max. Injection Pressure (bar)	2000
Injector Nozzle Geometry (mm)	8 hole x 0.167



surface mounted TCs



subsurface mounted TCs



Cooling gallery inlet/outlet

Piston Construction:

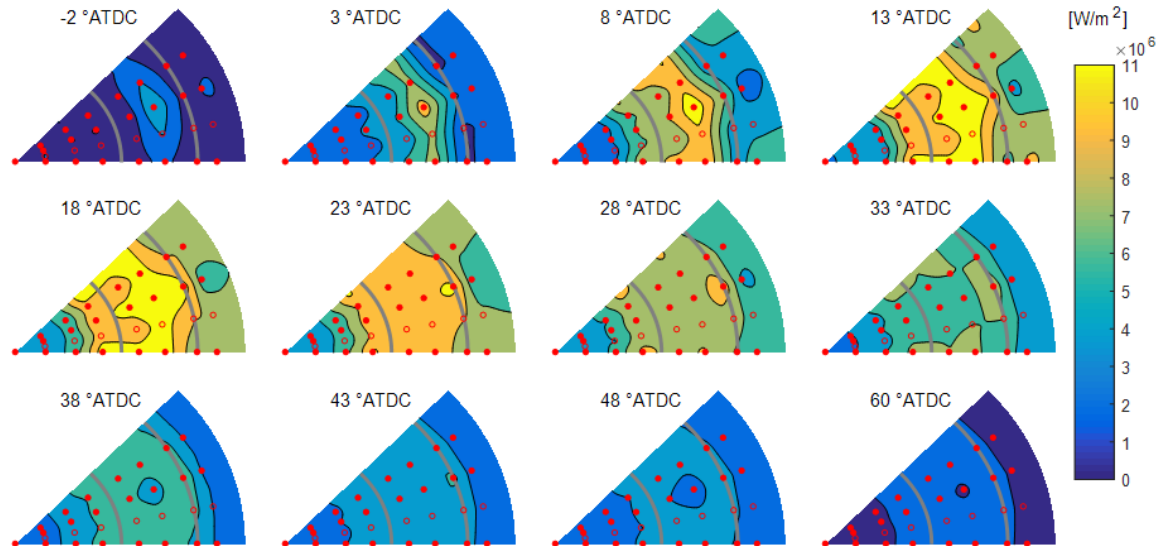
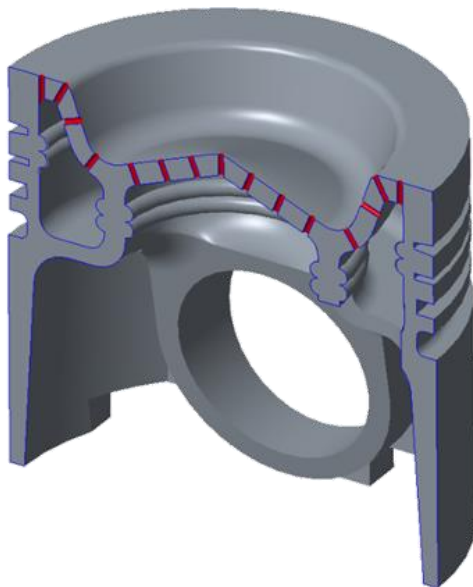
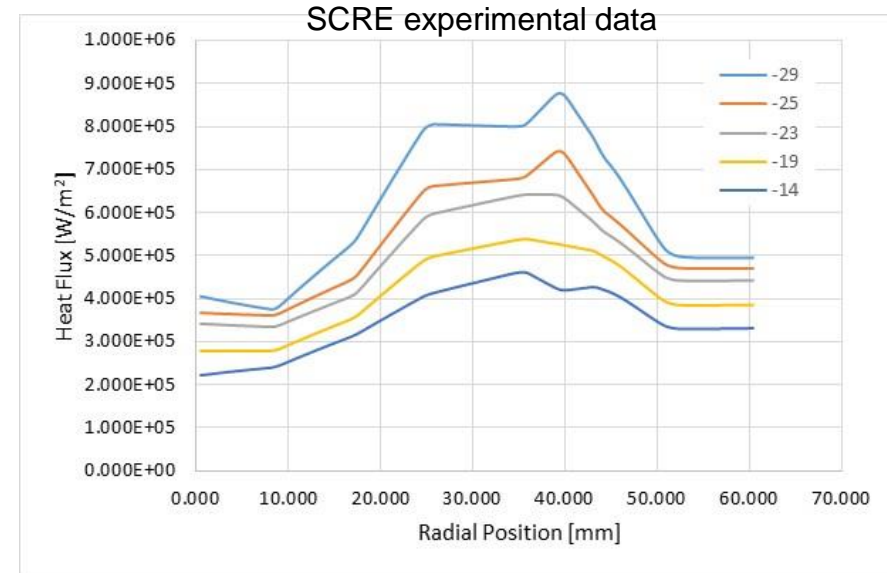
- Machined crown
- Forged skirt/bottom
- Rotary friction weld
- Bushingless design
- Manganese phosphate coating



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.



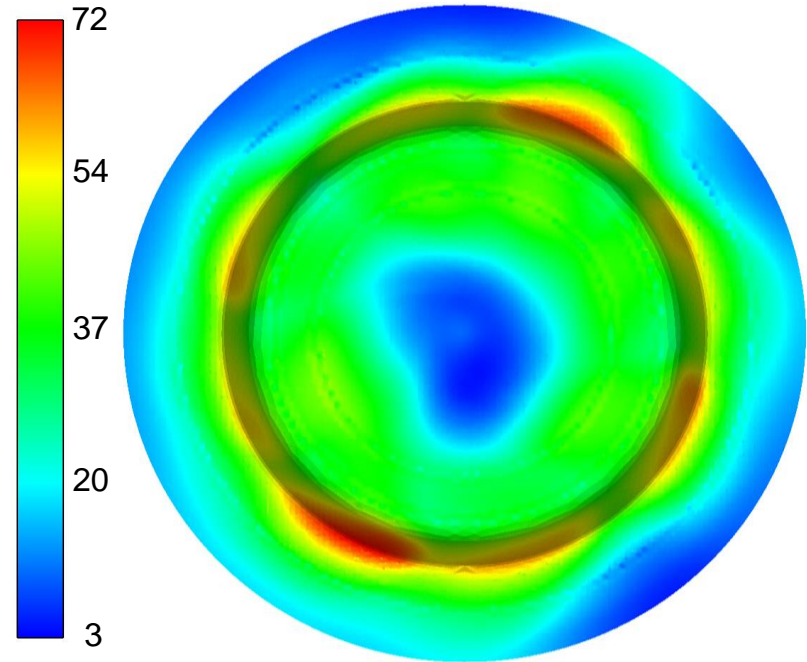
DISTRIBUTION A. See first page.



CONSTANT HEAT FLUX ASSUMPTION



- Experimental heat flux measurements acquired with MAS piston material
- FEA thermal analyses of baseline and candidate alloys assumed a constant heat flux, whereas the elevated piston temperatures for the candidate alloys are expected to decrease the surface heat flux in the engine (lower temperature difference between the gas and solid)
- Comparison of predicted maximum piston surface temperature difference between 422 and MAS materials:
 - Computational fluid dynamics (CFD) simulations with conjugate heat transfer gives 72 °C (CFD predicted heat fluxes)
 - FEA simulations gives 114 °C (constant heat flux assumption)
- FEA simulations are expected to over predict the steady-state piston operating temperatures of the candidate alloys



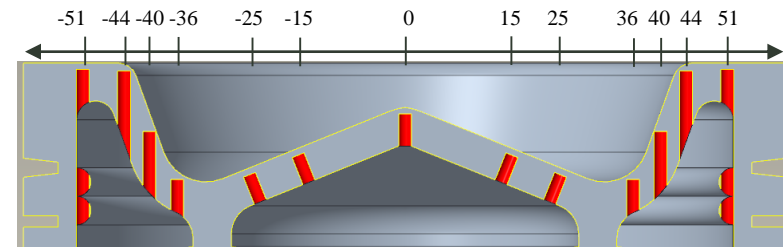
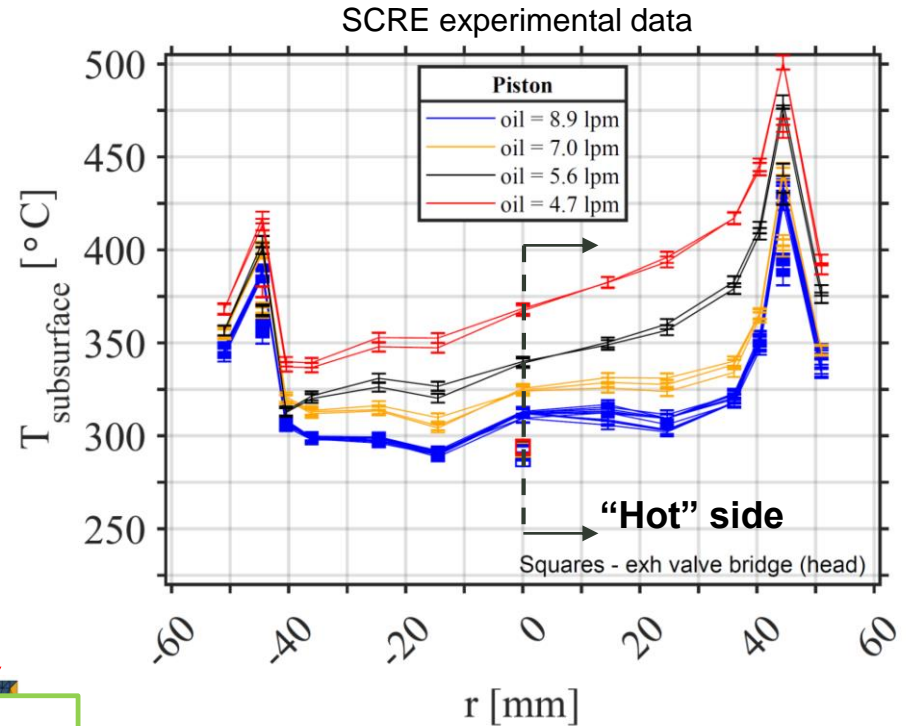
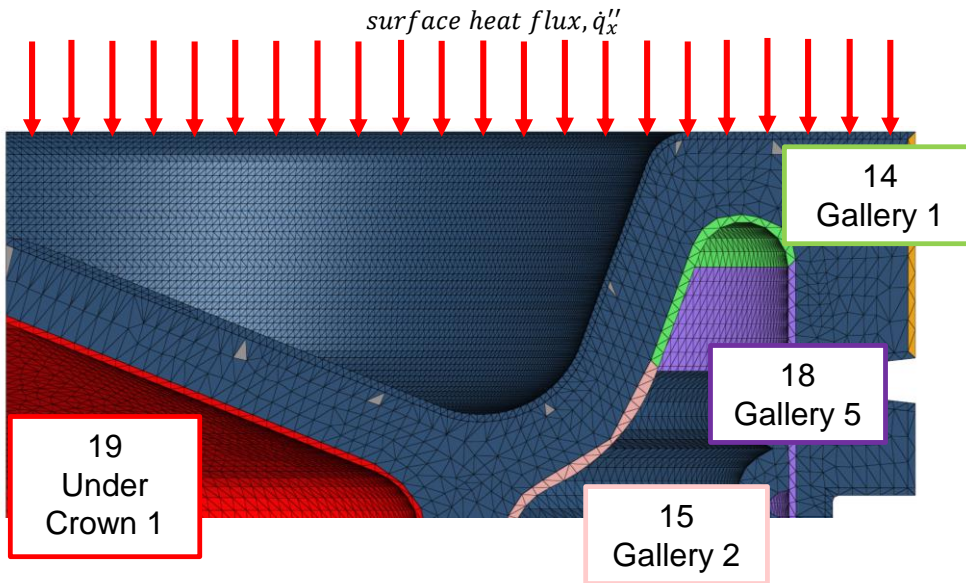
Predicted temperature difference (°C) between 422 and MAS using conjugate heat transfer simultaneously predicting heat transfer in both solid and fluid



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

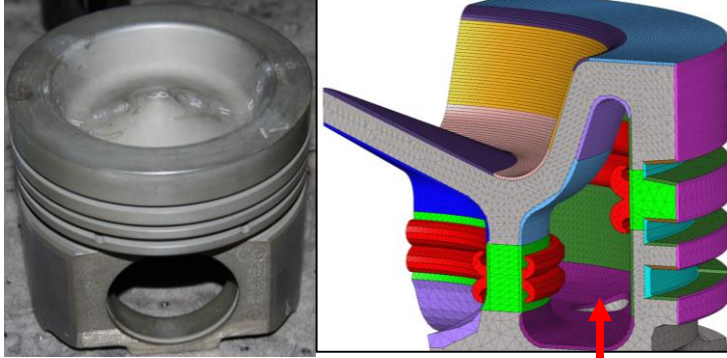




BASELINE: 4140 PISTON @ ~520 °C BOWL RIM TEMPERATURE (1 OF 2)

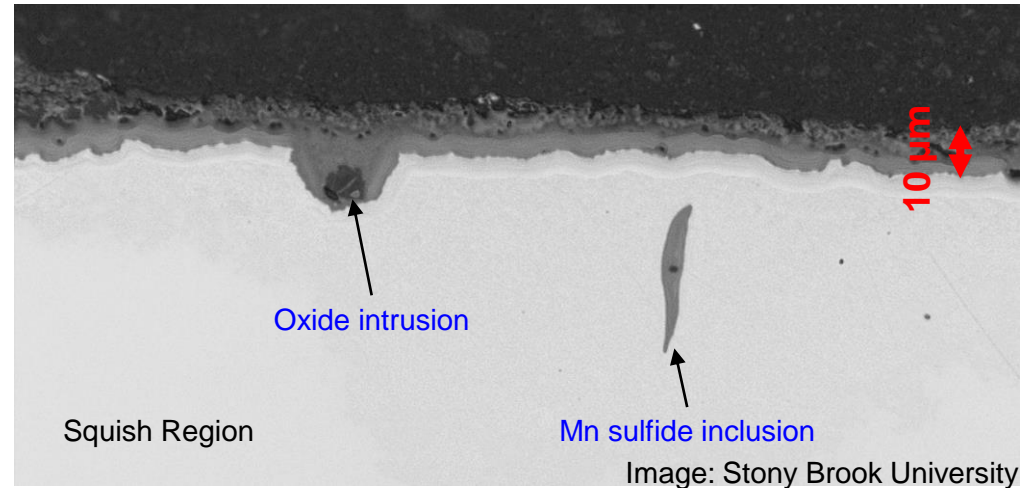
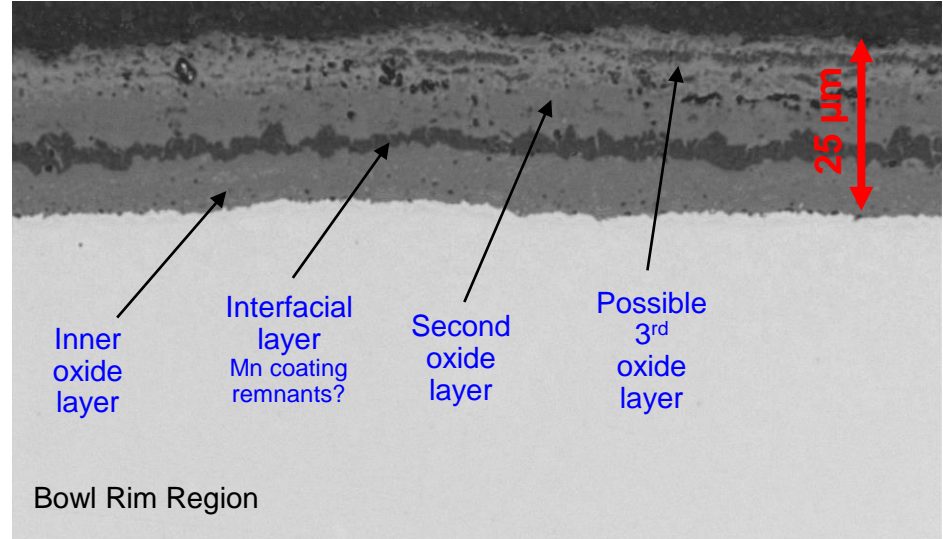


Example of new piston, pre-test (note Mn phosphate coating)



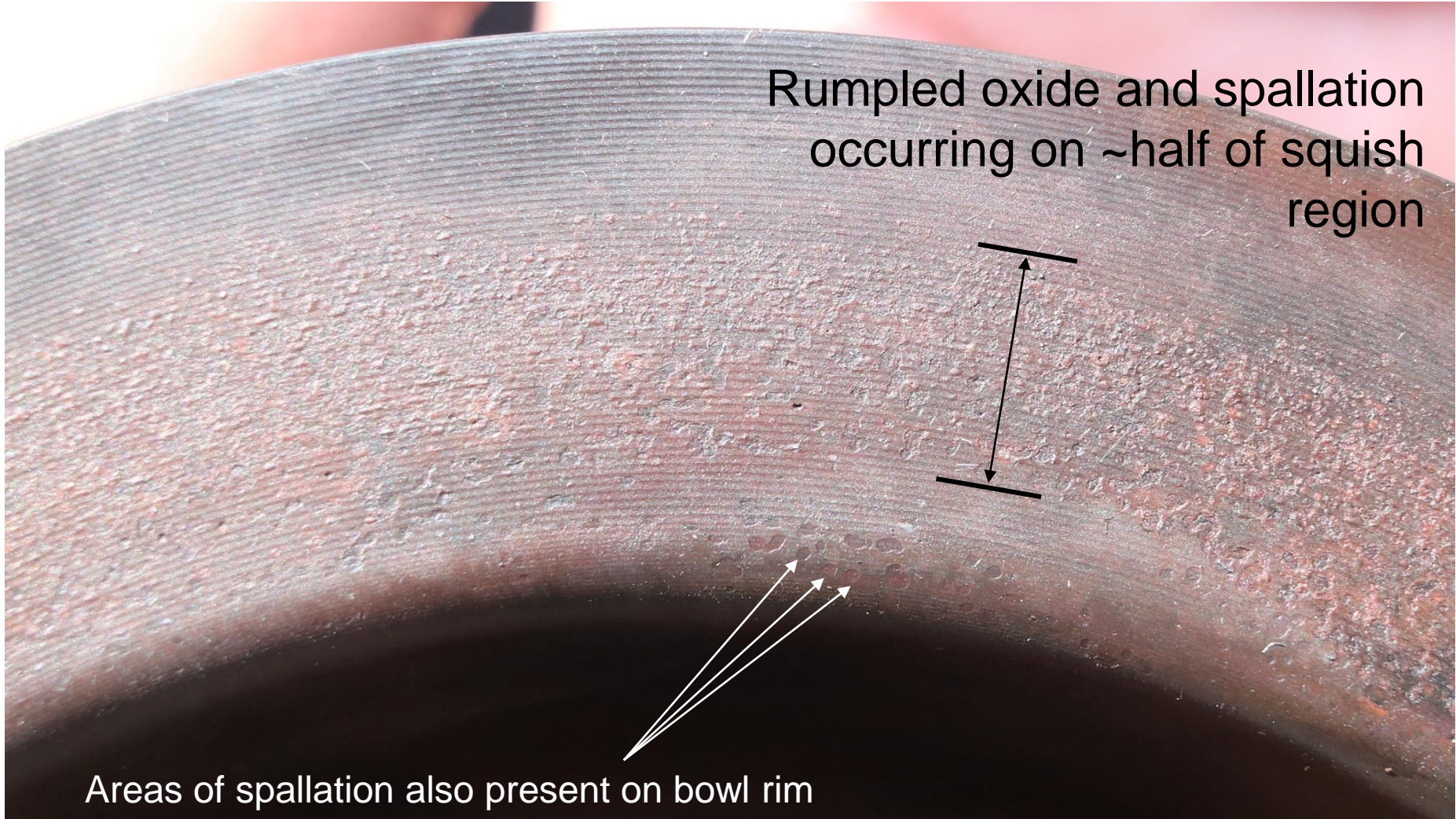
Cooling gallery inlet/outlet

Build 34 piston, post-test (100 hrs total operating time)

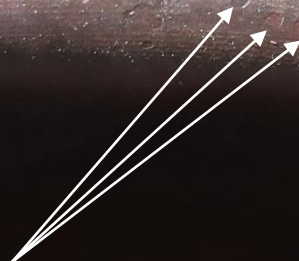




BASELINE: 4140 PISTON @ ~520 °C BOWL RIM TEMPERATURE (2 OF 2)



Rumpled oxide and spallation
occurring on ~half of squish
region



Areas of spallation also present on bowl rim