Project ID: mat193

Higher Temperature Heavy-Duty Piston Alloys*

*Subtask 2A2 under the Powertrain Materials Core Program (PMCP)

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Oak Ridge National Laboratory

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Program Overview: VTO Powertrain Materials Core Program

Timeline/Budget

- Lab Call Award: July 2018
- Budget: $30M/5 years
- Program Start: Oct 2018
- Program End: Sept 2023
- 30% Complete

Barriers

- Increasing engine power densities & higher efficiency engines; resulting in increasingly extreme materials demands (increased pressure and/or temperature)
- Affordability of advanced engine materials & components
- Accelerating development time of advanced materials
- Scaling new materials technologies to commercialization

FY20 Program Research Thrusts	FY20 Budget	Participating Labs
1. Cost Effective LW High Temp Engine Alloys	$1.05M	ORNL
2. Cost Effective Higher Temp Engine Alloys	**$1.525M**	**ORNL, PNNL**
3. Additive Manufacturing of Powertrain Alloys	$1.075M	ORNL
4A. Advanced Characterization	$1.025M	ORNL, PNNL, ANL
4B. Advanced Computation	$0.60M	ORNL
5. Exploratory Research: Emerging Technologies	$0.75M	ORNL, PNNL, ANL

Partners

- Program Lead Lab
  - –Oak Ridge National Lab (ORNL)
- Program Partner Labs
  - –Pacific Northwest National Lab (PNNL)
  - –Argonne National Lab (ANL)

Program structure includes three alloy development thrusts (1-3), a foundational support thrust (4), and a thrust for one-year exploratory projects (5).

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Project Overview: Subtask 2A-2 Higher Temperature Heavy Duty Piston Alloys

Timeline/Budget

- Subtask 2A2 funding
  - FY19: $250k
  - FY20: $200k
  - Pct. Complete: 30%

Barriers

- Accelerating alloy development time.
- Improving elevated temperature strength
- Maintaining oxidation resistance
- Affordability
- Manufacturability.

Thrust 2: Tasks/Subtasks	TRL	PI(s)	FY19	FY20
Task 2A. Advanced Affordable Wrought Engine Alloys				
• 2A1. Oxidation Resistant Valve Alloys (900-950°C)	Low/ Mid	Muralidharan Pint	$400k	$400k
• 2A2. High Temperature HD Piston Alloys	**Low**	**Dean Pierce Muralidharan**	**$250k**	**$200k**
• 2A3. High Temperature Coatings	Low	Armstrong Dryepondt	$175k	$175k
• 2A4. High Temperature Oxidation	Low	Pillai Haynes	$150k	$175k
Task 2B. Affordable, High Performance Cast Engine Alloys				
-•2B1. *Cast Higher Temp Austenitic Alloys*	Low	Brady Yamamoto	$250k	$275k
		Subtotals	**$1,225k**	**$1,225k**

Partners

- Subtask 2A2 Lead
  - ORNL
- Subtask 2A2 Partners
  - Thrust 4

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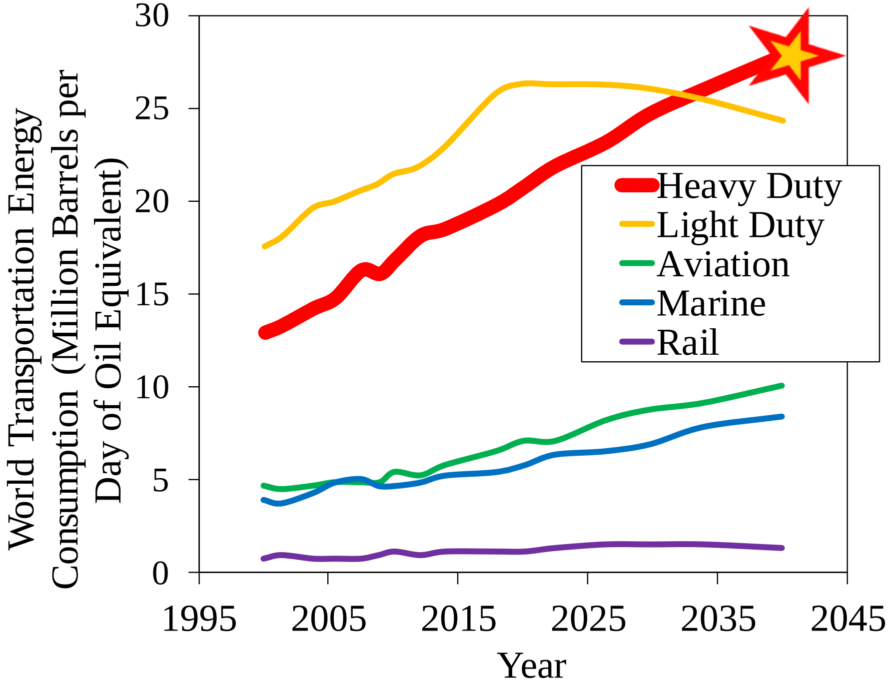
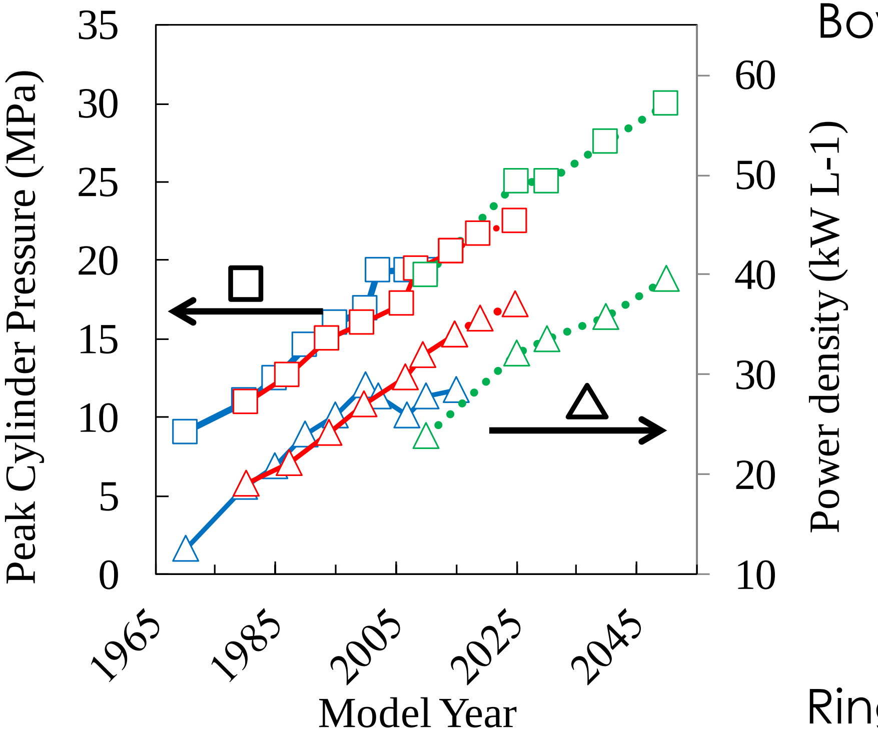
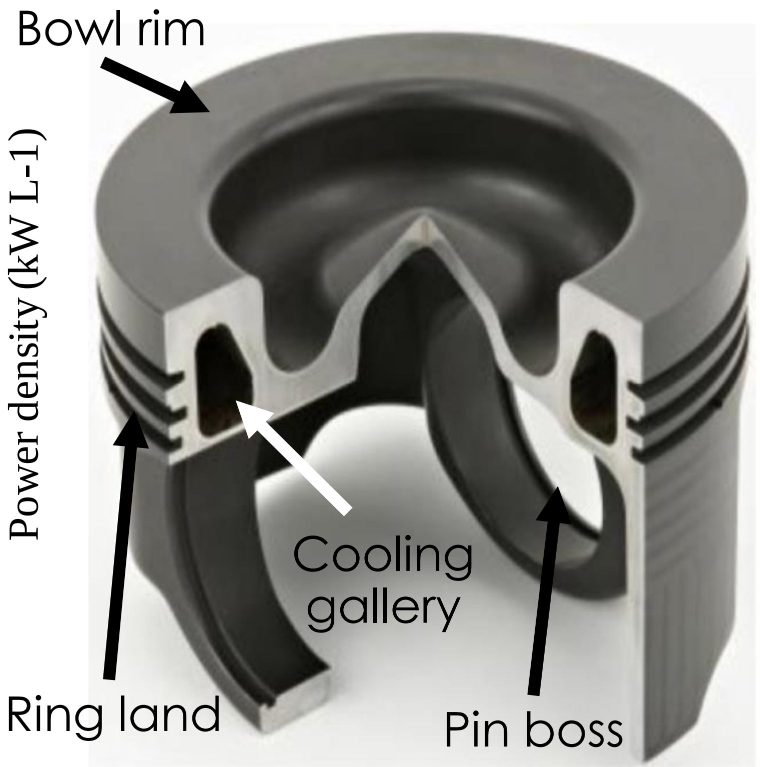
Relevance

- Higher cylinder pressures and temperatures = higher efficiency.
- Current heavy duty diesel (HDD) piston steels (4140 & micro alloyed steel (MAS)) not suitable for temperatures ≥~500ºC (low oxidation & fatigue resistance).
- Objective: develop affordable, innovative, higher temperature piston alloys



Exxon Mobil. 2018 outlook for energy: a view to 2040; 2017



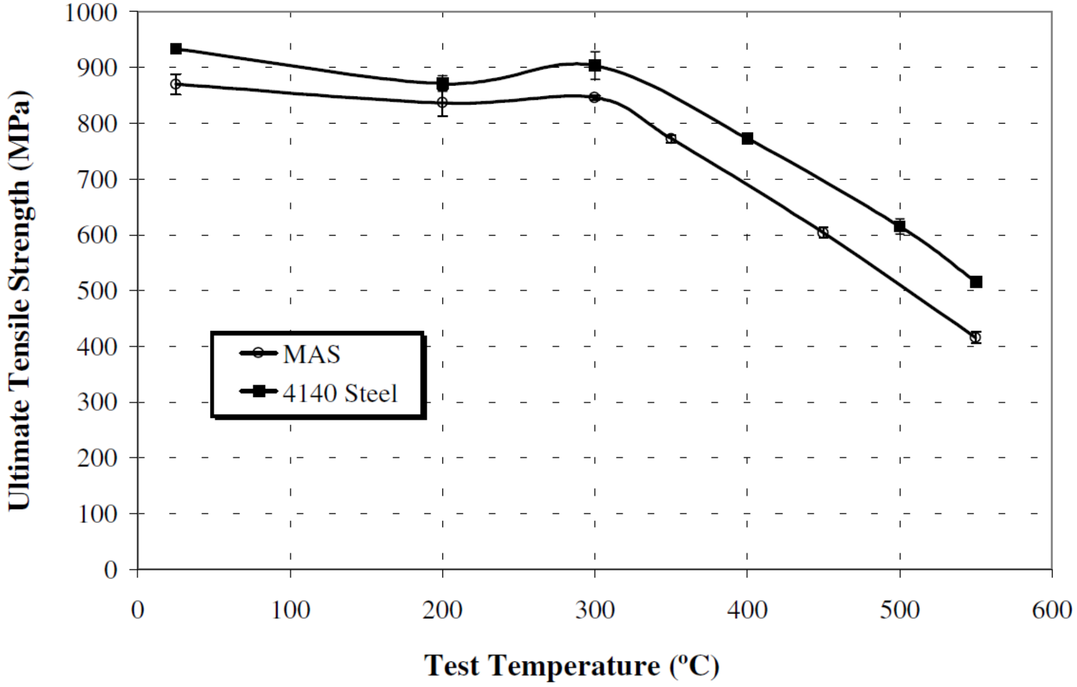


Pierce et al., Prog. Mat. Sci. 103 (2019) p. 109).

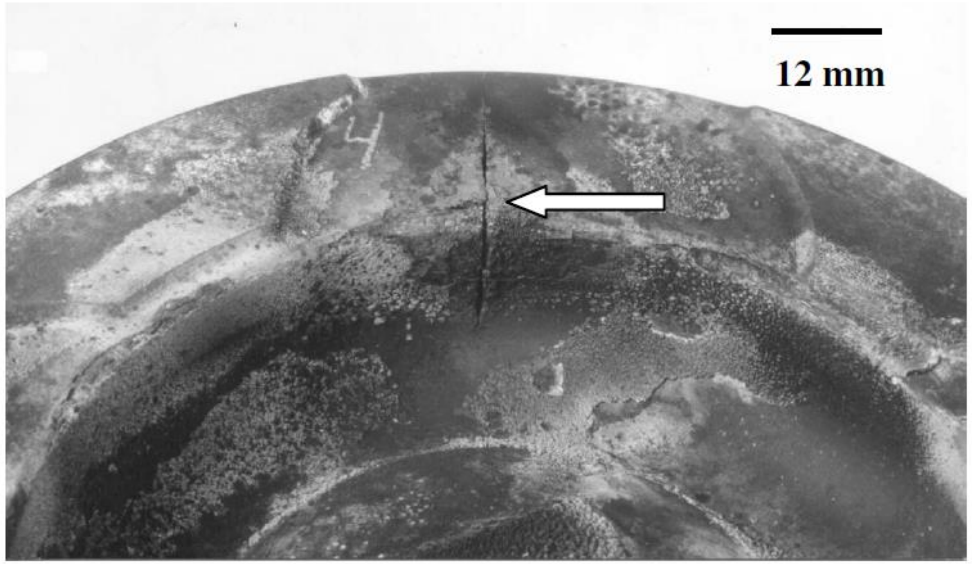
Subtask Targets:

- 4140 and MAS limited to ~500 °C.
  - Current industry baseline alloys
  - Strength loss above 500°C
  - Poor oxidation resistance above 500°C
- New developmental steel **targets:**
  - Operation between 600 & 800°C
  - Yield strength: 400 MPa @ ≥600 °C
  - Ultimate Tensile Strength: 525 MPa @ ≥600°C
  - Cyclic oxidation resistance @ peak temperatures, in air + water vapor
  - Long term microstructural stability
  - Affordable & manufacturable

Current commercial heavy duty piston alloys



Heavily oxidized MAS piston with crack



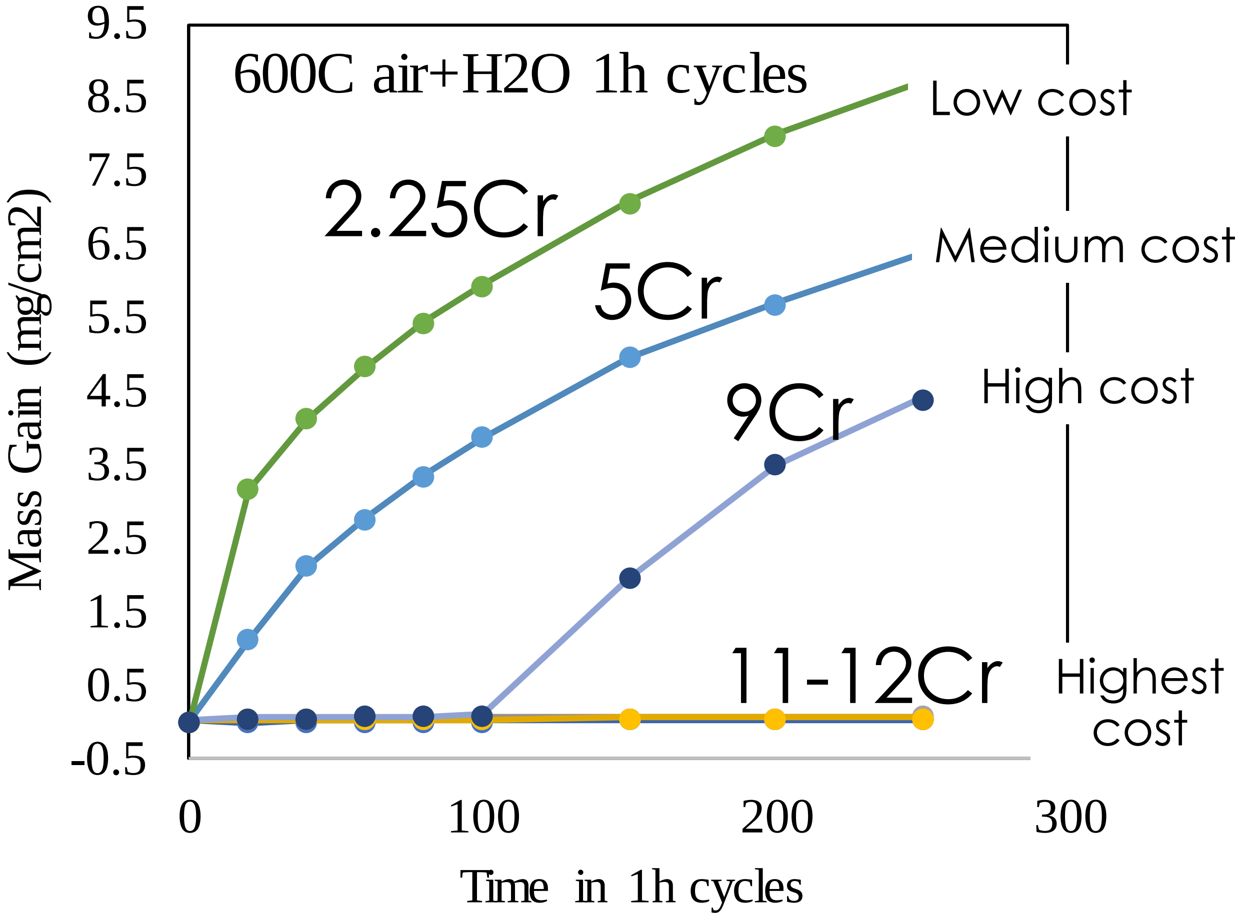
Chen et al., SAE Technical Paper Series, 2000-01-1232.

Milestones

2020	Task 2A2: Higher Temperature Heavy-Duty Piston Alloys
Q1	Milestone: Perform testing of mechanical and oxidation properties of different developmental alloys and down select promising alloy concepts. Status: **COMPLETE**, mechanical testing and oxidation testing completed. Down selected three concept groups.
Q2	Milestone: Fabricate and process optimized alloys for further evaluation Status: **COMPLETE**, New optimized alloys have been arc melted and processed.
Q3	Milestone: Evaluate mechanical properties and correlate with microstructure of optimized alloys. Status: **ON TRACK**
Q4	Milestone: Evaluate oxidation and thermal properties of optimized alloys Status: **ON TRACK**

Approach:

- Evaluate existing, higher-temperature commercial steels
  - Two 12Cr martensitic steels (12Cr-A and 12Cr-B)
    - High alloy content = Good performance but high cost
  - 4140 (1Cr-1Mn wt.%)
- Evaluate novel, developmental martensitic steels
- Three developmental concepts:
  - **Low chromium (Cr) alloys (0-3 wt.%):** Lowest cost, high strength, 550-600°C.
  - **Medium Cr alloys (3-8wt.% Cr):** Moderate cost, high strength, good oxidation resistance, 600-650°C
  - **High Cr (8-15 wt.% Cr):** Highest cost and oxidation resistance,650-700°C.



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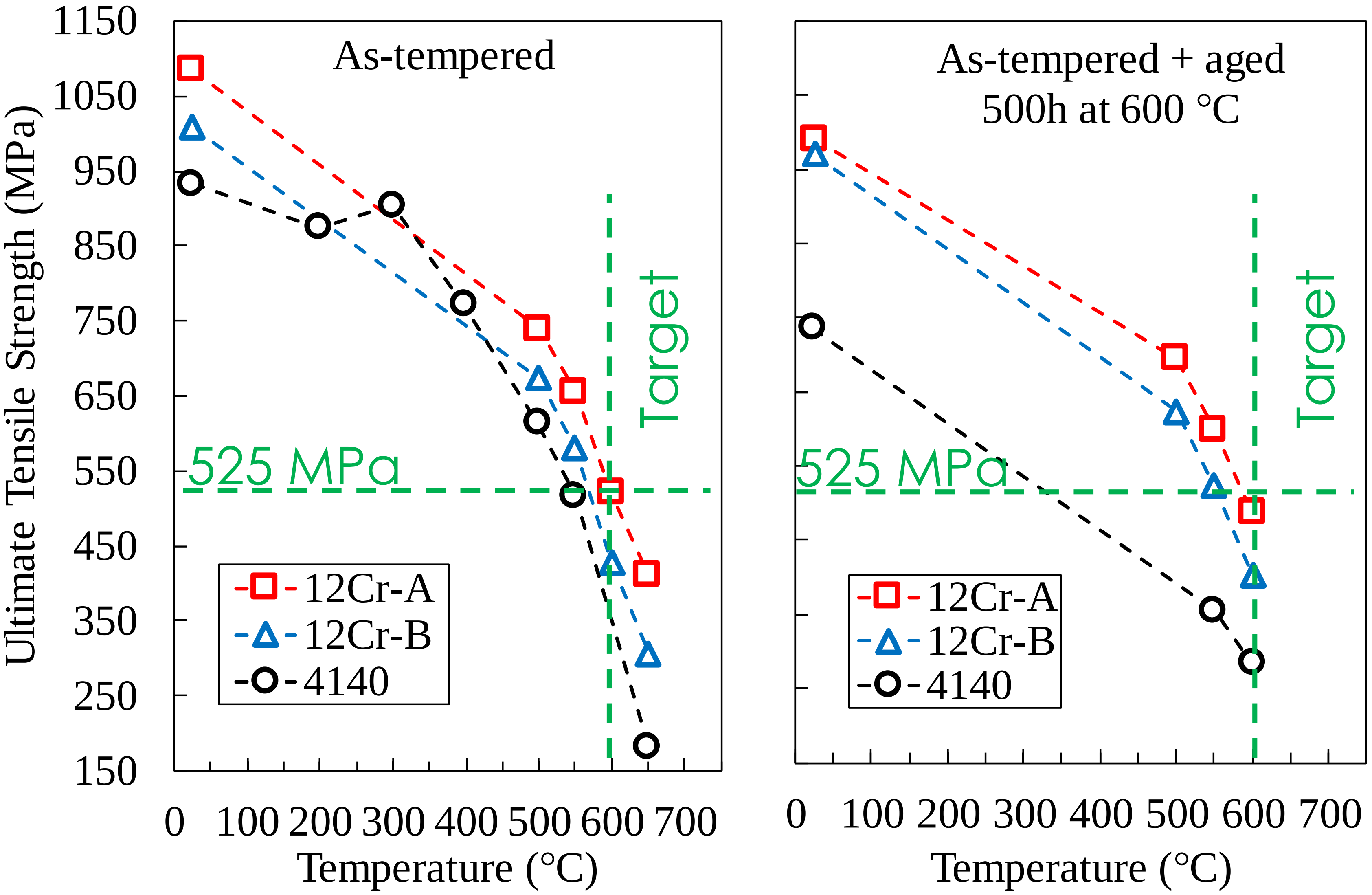
Commercial Alloy Mechanical Property Evaluation

Technical Accomplishment

- Commercial 12Cr strength superior to alloy 4140
- 12Cr commercial alloys near targets in as-tempered condition.
- But - strength drops after long term thermal aging



4140 data from: Chen et al., SAE Technical Paper Series, 2000-01-1232 and SAE J775 2004-11

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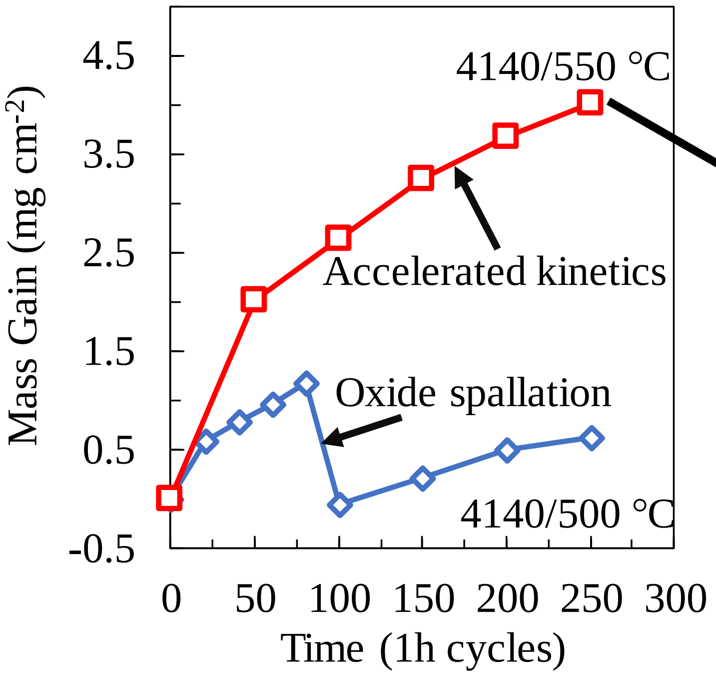
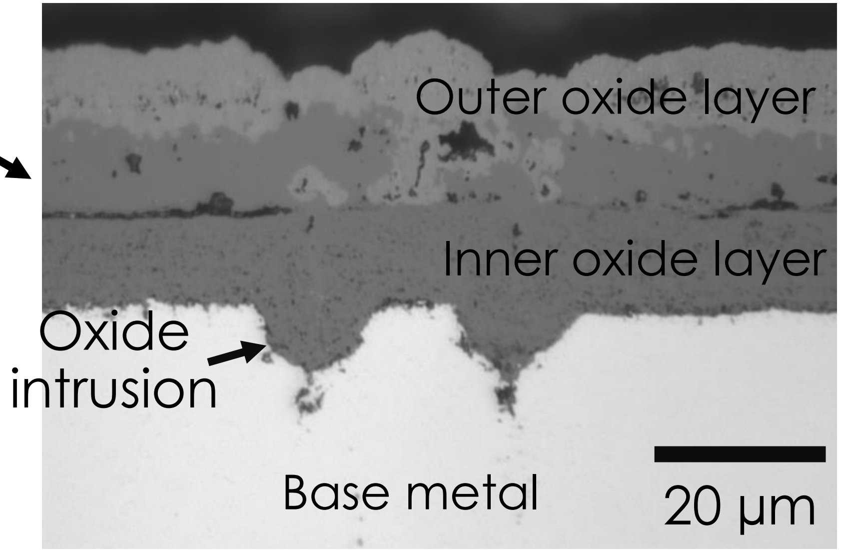
Commercial Alloy Oxidation Evaluation

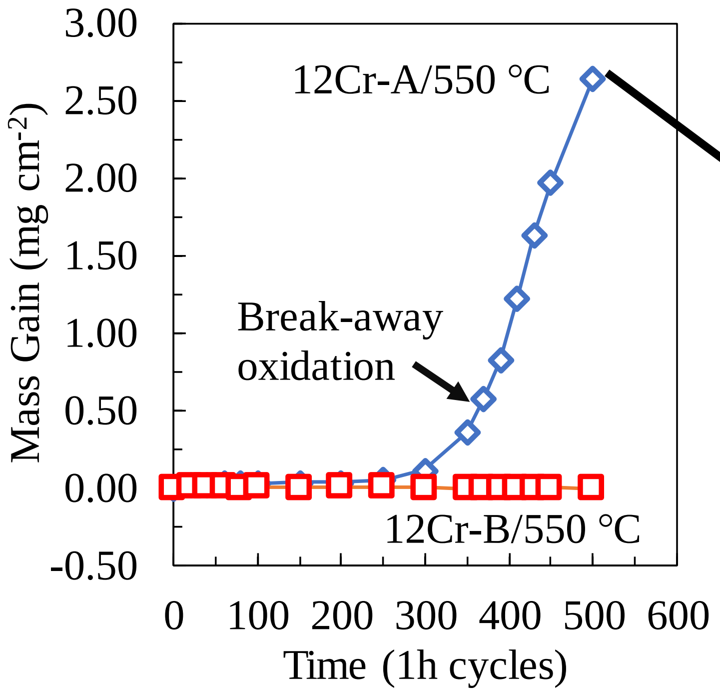
- Alloy 4140:
  - Accelerated oxidation kinetics @500 & 550°C
  - Oxide intrusion
  - Spallation

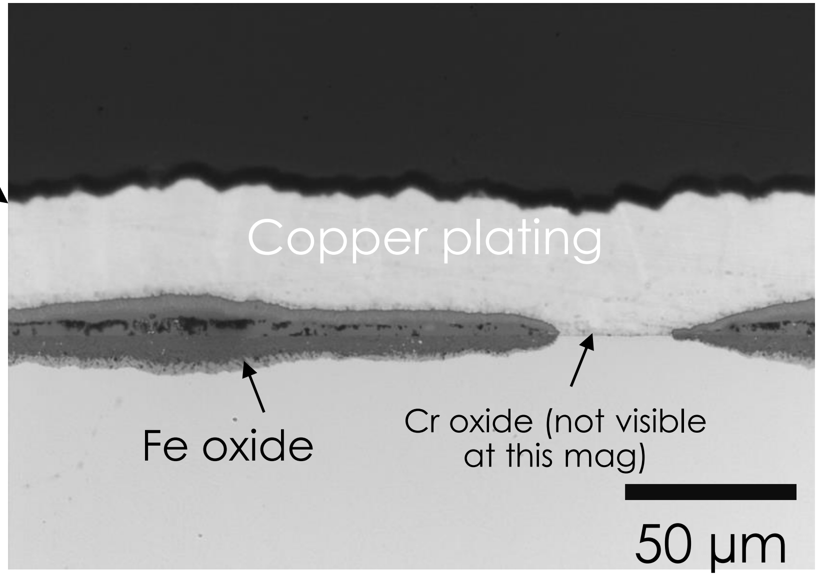




4140: 550°C 250h

- 12Cr commercial
  - **600°C:** 12CrA/B optimal slow growing chromia scale
  - **550°C:** 12Cr-A break-away oxidation
  - **550°C:** 12Cr-B stable oxidation behavior to 500h





Break-away iron oxidation at 550C in 12Cr-A After 500h

Technical Accomplishment

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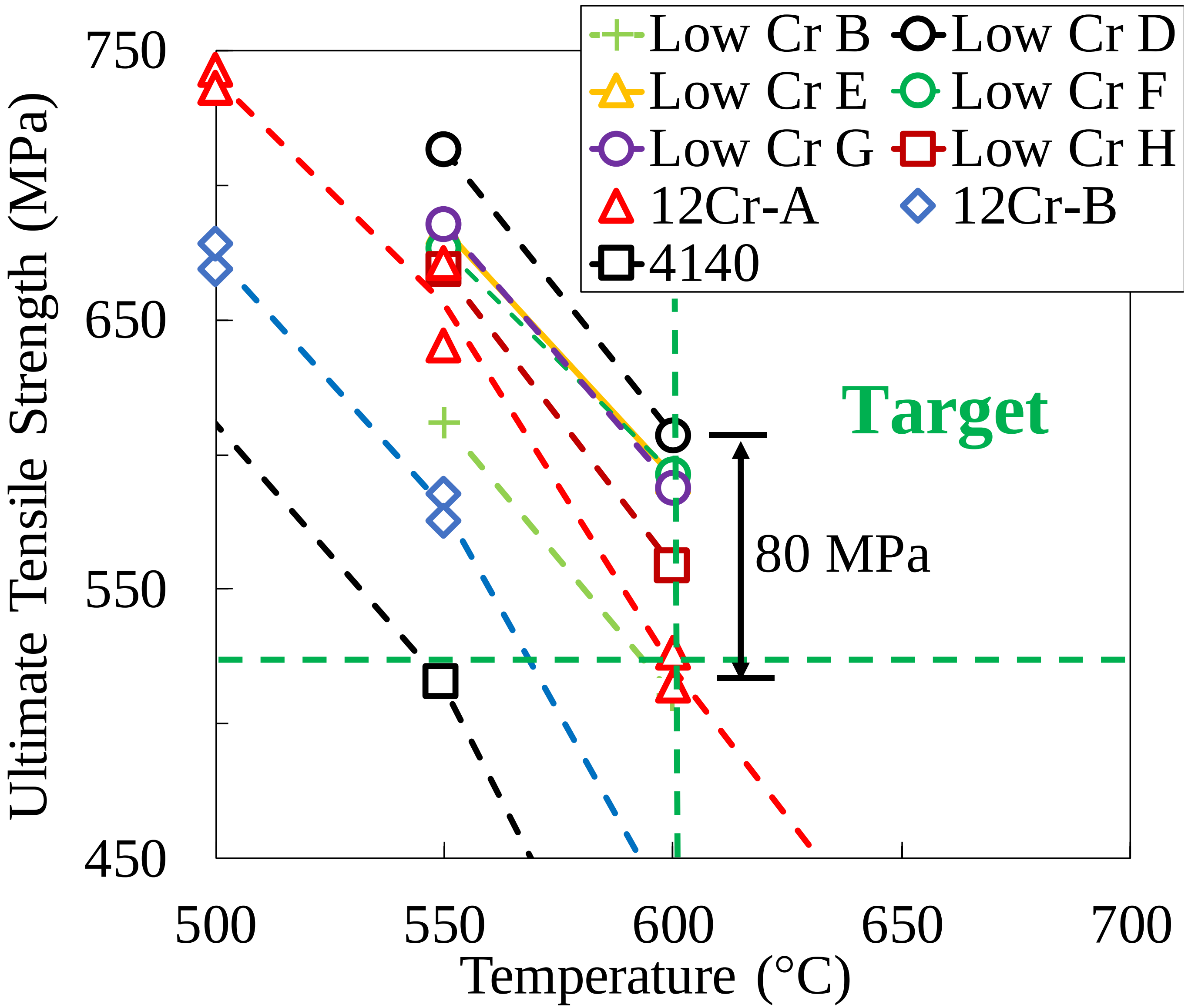
Low Cost Low Cr alloys Retain Strength at High Temperature

- Achieved target strength levels

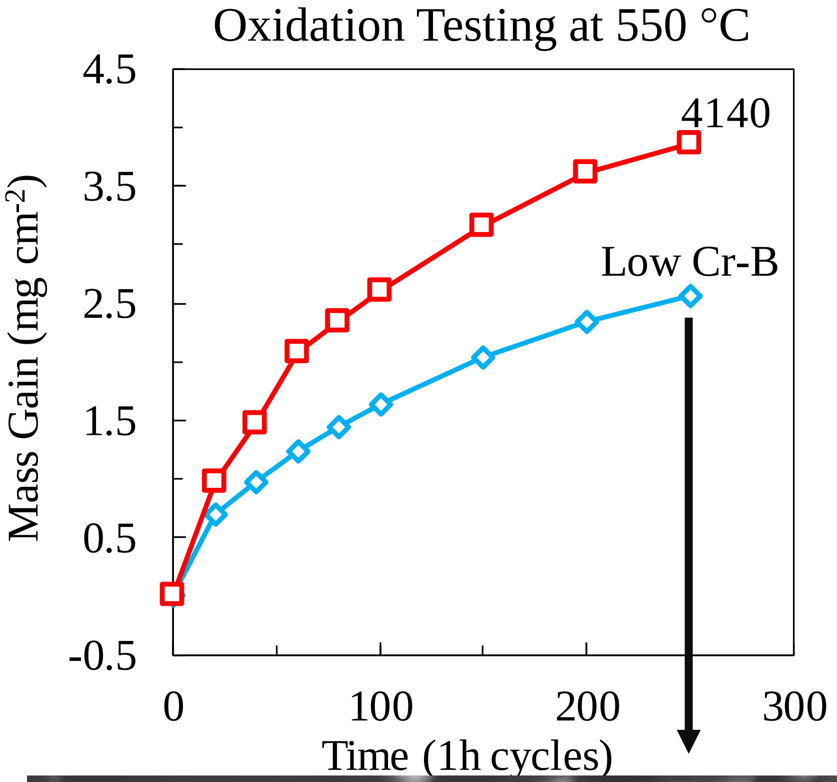
Commercial and low Cr developmental alloys: as-tempered condition



4140 data from: Chen et al., SAE Technical Paper Series, 2000-01-1232.

Low Cost Low Cr alloys With Improved Oxidation Resistance over 4140

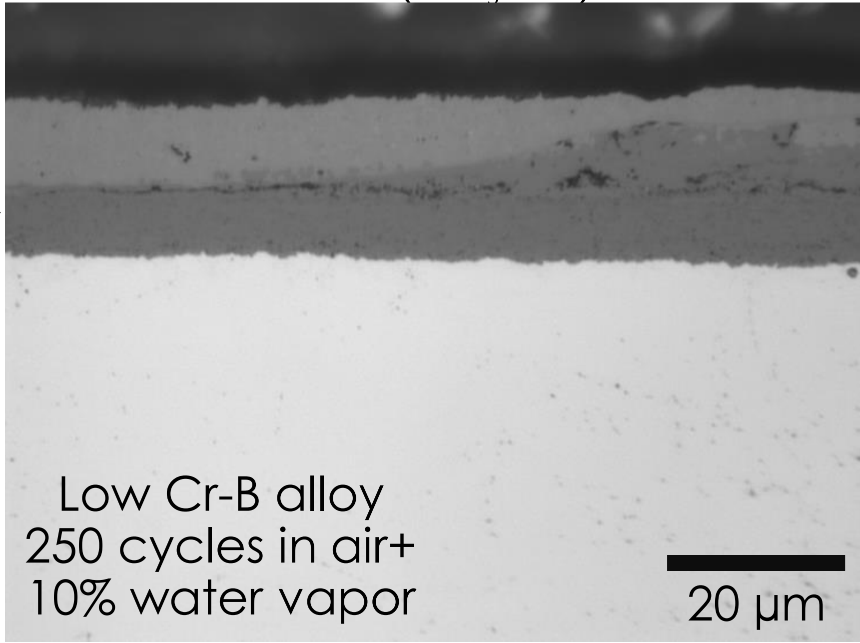
- Novel alloying strategies employed
- Lower operating temperatures
- Potential for improved oxidation resistance and strength over 4140 at limited extra cost



Outer hematite (Fe_2O_3)oxide layer

Inner magnetite (Fe_3O_4) oxide layer

Base alloy

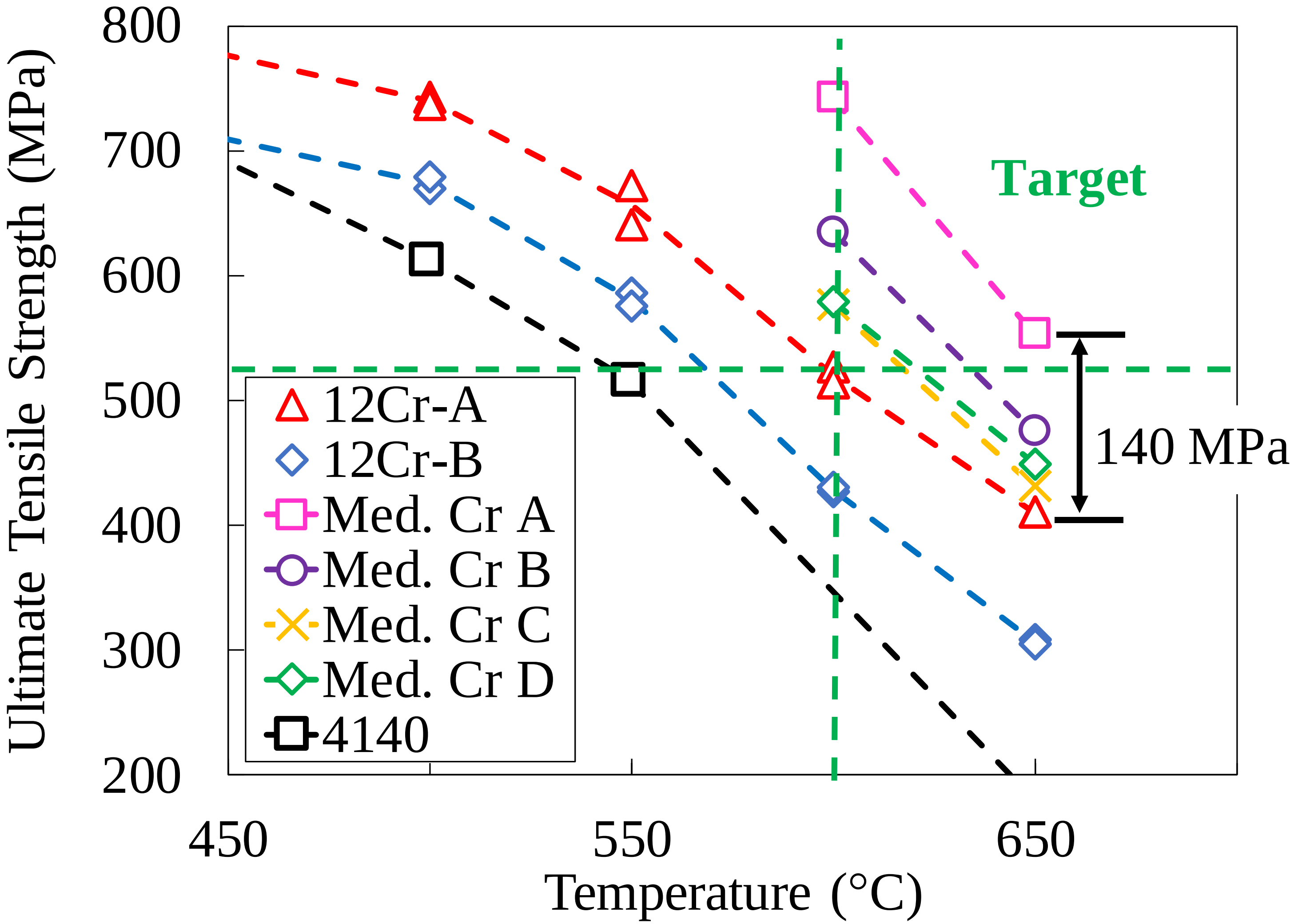


Medium Cr Developmental Alloys Show Exceptional Strength

Technical Accomplishment

- Strength targets met in as-tempered condition
- Long term aging to be-conducted

Commercial and medium Cr developmental alloys: as-tempered condition



4140 data from: Chen et al., SAE Technical Paper Series, 2000-01-1232 and SAE J775 2004-11

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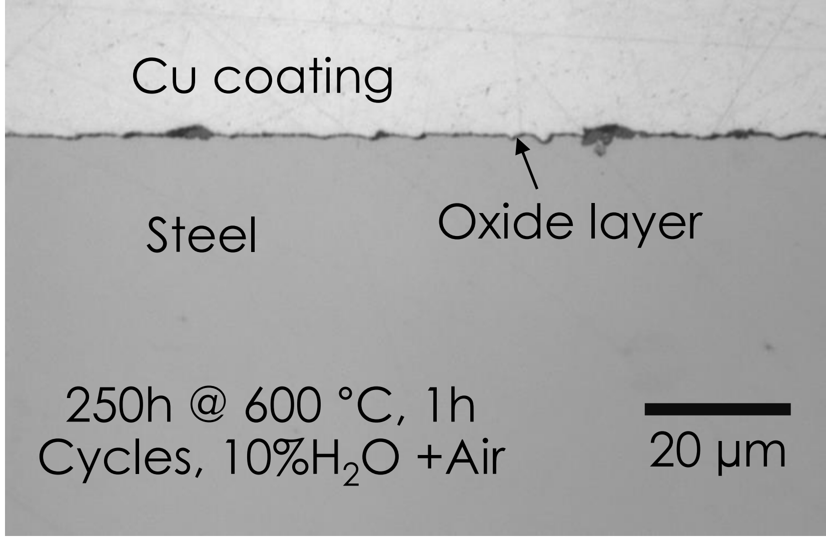
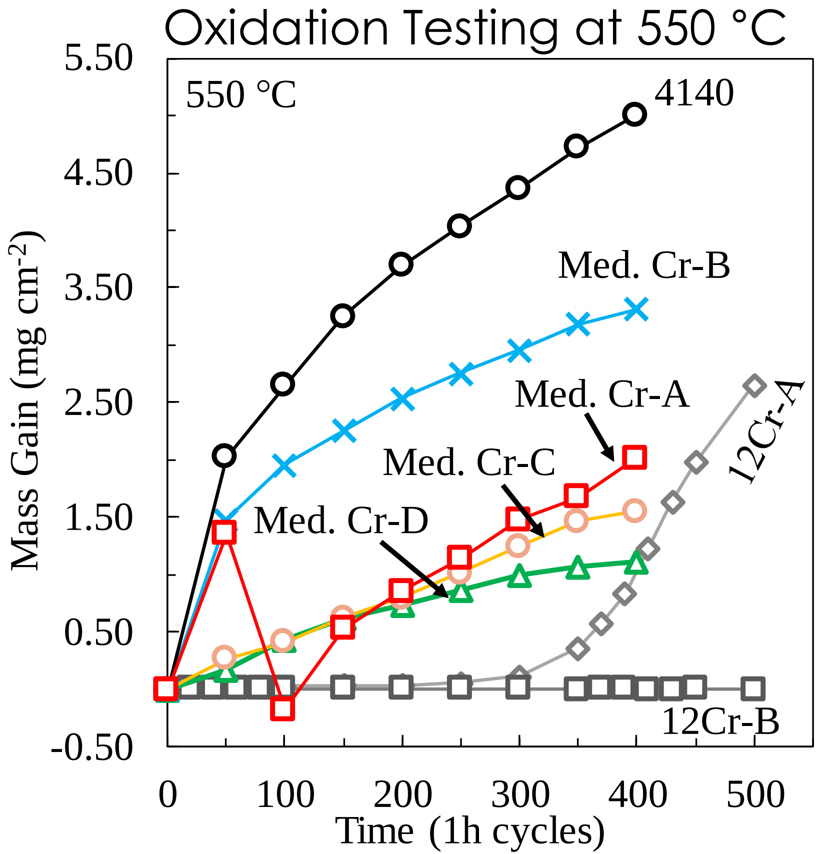
Medium Cr Developmental Alloys Show Good Oxidation Resistance

- 1^{st} iteration:
  - exceptional oxidation resistance, low strength
- 2^{nd} iteration:
  - Novel alloying to improve strength, maintain oxidation resistance.
  - Med. Cr-A and B: fast kinetics (spallation in A)
  - Med. Cr-C and D: slow kinetics (no spall)
  - 600 °C testing ongoing
- 3^{rd} iteration underway

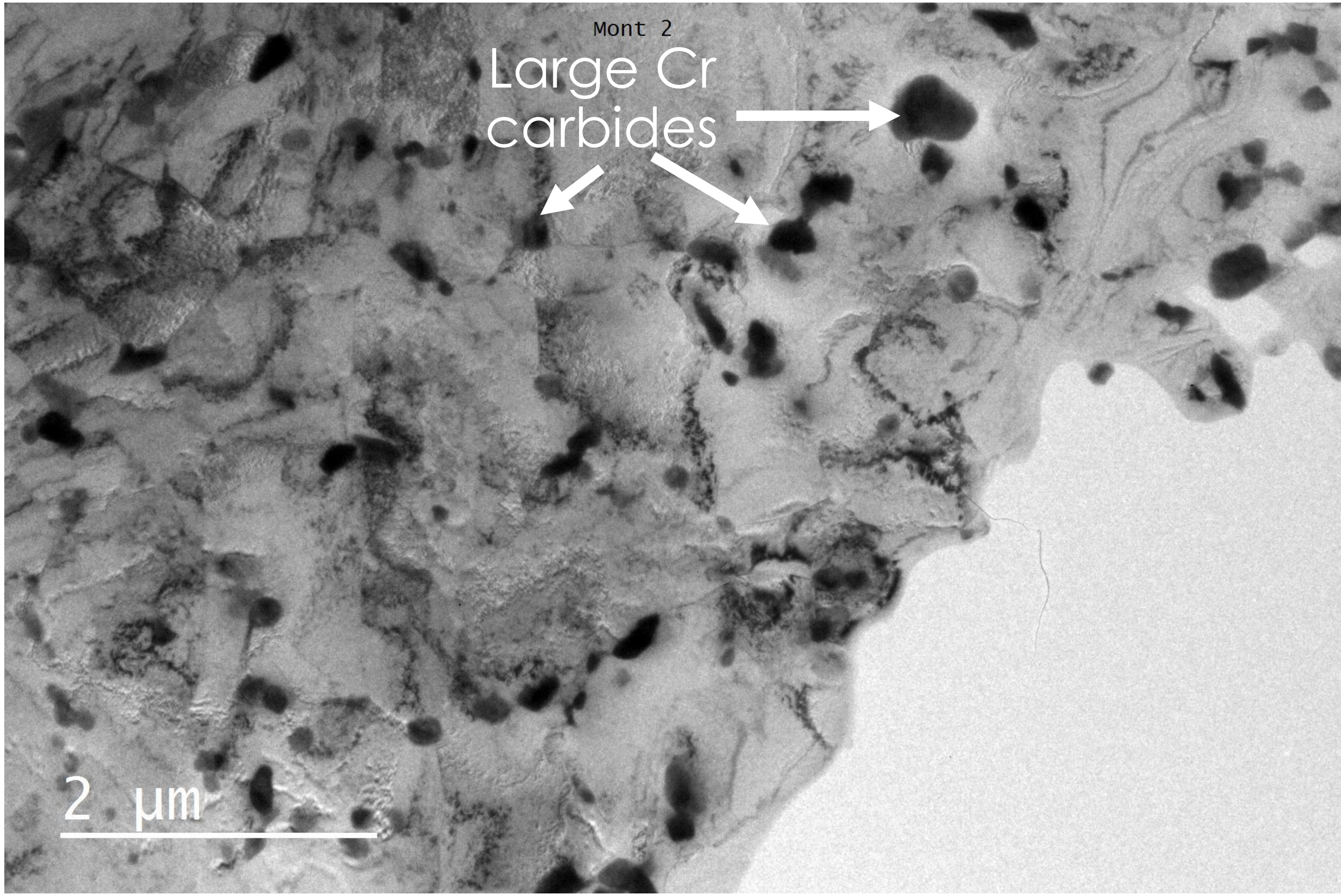




Technical Accomplishment

Collaborations

- Thrust 4A: Advanced Characterization-ORNL
  - Transmission Electron Microscopy & Atom Probe Tomography
  - **Resulting design knowledge:** Large Cr carbides in 12Cr steel provide minimal strengthening



Commercial 12Cr-B Tempered 650 °C then aged 500h at 650 °C

Responses to Previous Year Reviewer's comments

- Project was not reviewed last year

Remaining Challenges and Barriers

- Increase oxidation performance of low and medium Cr alloys while maintaining low cost.
- Further understand mechanisms resulting in improved strength and oxidation resistance in lower cost alloys
- Manufacturability of developmental alloys (melting practice and forgeability)

Proposed Future Research

- FY21:
  - Scale up material to larger sizes to permit full size test specimens and different types of testing.
  - Perform more relevant tests (long term oxidation and elevated temperature fatigue testing) to better simulate engine operation
  - Establish collaborations with industry partners to begin addressing barriers to commercialization of new alloys

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

Project Summary

Commercial Alloy Evaluation

- Evaluated elevated temperature mechanical and oxidation behavior of commercial martensitic 12Cr steels relative to current piston steels.
- 12Cr commercial steels may offer acceptable strength and oxidation resistance but at high cost.

Medium Cr Developmental Alloy Evaluation

- Novel alloys with improved strength, similar oxidation resistance, and 20-40% lower material cost relative to 12Cr commercial alloys have been developed

Low Cr Developmental Alloy Evaluation

- Low cost low Cr alloys developed with higher strength than commercial 12Cr alloys and good oxidation resistance from 500 to 575°C.

Back up slides

Technical Backup Slide: Chemical Composition of Current Industry Steels

Composition in wt.% of Steels Currently used in Heavy Duty Diesel Engines										
Alloy	C	Si	Mn	P	S	Cr	V	Ti	Mo	Fe
MAS	0.34	0.65	1.58	0.01	0.035	0.11	0.09	0.01	-	97.18
4140H	0.47	0.18	1.03	0.027	0.027	0.99	-	-	0.2	97.08

Compositions from: Chen et al., SAE Technical Paper Series, 2000-01-1232

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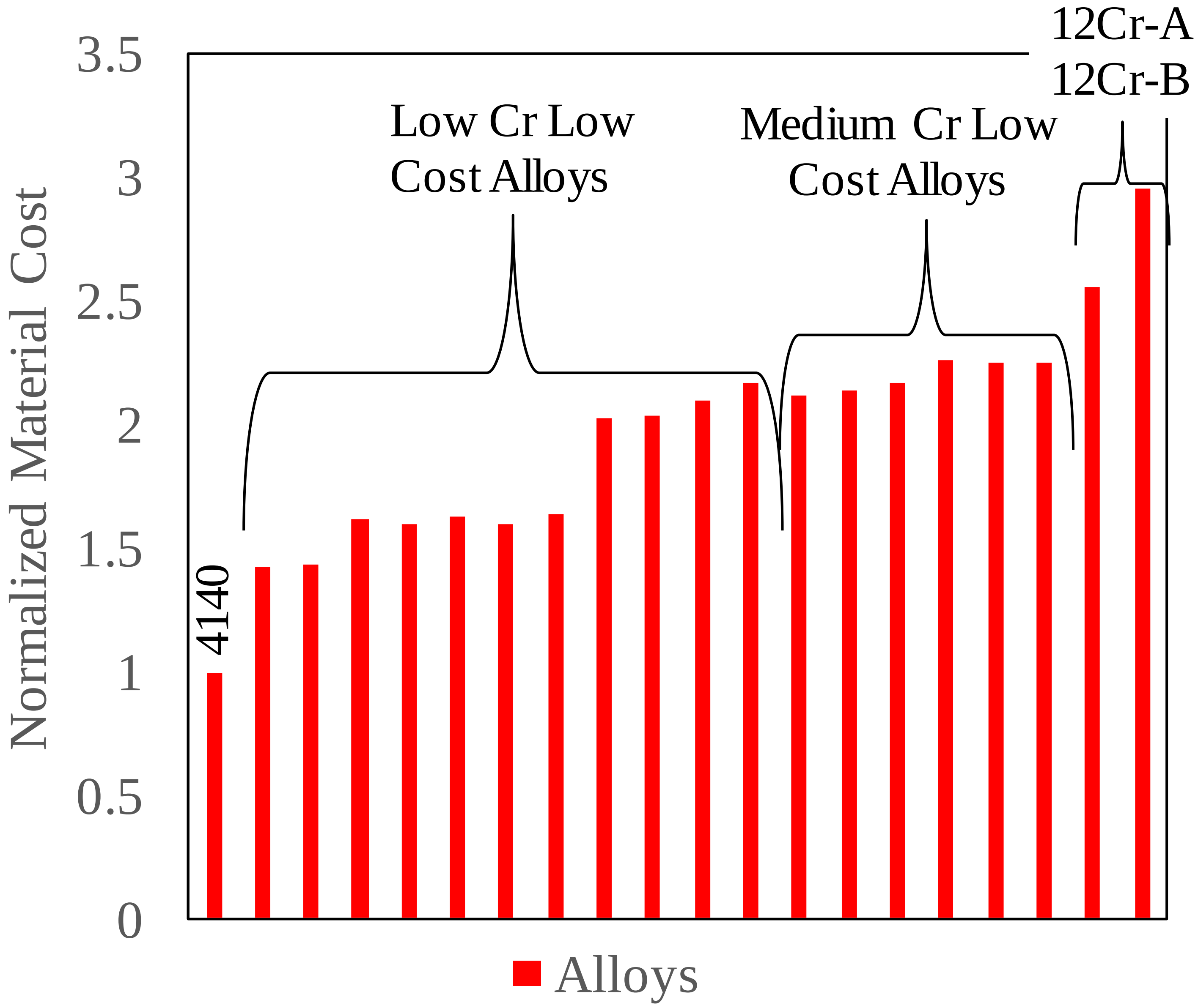
Technical Backup Slide: Developmental Alloy Cost Summary

- Estimated and normalized raw material cost of developmental alloys relative to 4140



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