Biographical Sketch

Dr. Laura Bartlett Ph.D.
Department of Engineering Technology - Texas State University
Phone: 512-245-3064, Email: lnb29@txstate.edu

(i) Professional Preparation
Missouri University of Science and Technology, Rolla MO
Metallurgical Engineering B.S. 2008
Missouri University of Science and Technology, Rolla MO
Metallurgical Engineering Ph.D. 2013

(ii) Appointments
Adjunct Assistant Professor, January, 2015 – Present
Missouri University of Science and Technology, Department of Materials Science and Engineering, Rolla, Missouri

Assistant Professor, January, 2013 – Present
Texas State University, Department of Engineering Technology, San Marcos, Texas

Instructor, August, 2011 – December, 2011
Missouri University of Science and Technology, Materials Science and Engineering, Rolla, MO

Graduate Research/Teaching Assistant, January, 2009 – December, 2012
Missouri University of Science and Technology, Materials Science and Engineering, Rolla, MO

Metallurgical Engineering Intern, May, 2008 – August, 2008
TyssenKrupp Waupaca, Metallurgy Department, Tell City, Indiana

(iii) Products
L.N. Bartlett and S. Serino, "Nitriding of High Manganese and Aluminum Steels" Accepted to AFS Transactions (2015)

S. Serino and L.N. Bartlett, "Nitriding of Lightweitht High Manganese and Aluminum Steels" International Journal of Metalcasting, Winter Edition (2015).

L.N. Bartlett, D.C. Van Aken, J. Medvedeva, D. Isheim, N. Medvedeva, and K. Song, "An Atom Probe Tomographic Study of Kappa Carbide Precipitation in Lightweight Steel: Effect of Phosphorus," Metallurgical and Materials Transactions A. *Under Revision (2015)*.

L.N. Bartlett and D.C. Van Aken, "High Manganese and Aluminum Steels for the Military and Transportation Industry," Journal of Materials, *published online August 2, (2014)*. DOI 10.1007/s11837-014-1068-y.

L.N. Bartlett, D.C. Van Aken, J. Medvedeva, D. Isheim, N. Medvedeva, and K. Song, “An Atom Probe Study of Kappa Carbide Precipitation and the Effect of Silicon Addition,” Metallurgical and Materials Transactions A Vol. 45, pp. 2421-2435 (2014**).* Editor’s Choice for Excellence**

L.N. Bartlett, A. Dash, D.C. Van Aken, V.L. Richards, and K.D. Peaslee, “Dynamic Fracture Toughness of High Strength Cast Steels,” International Journal of Metalcasting Vol. 7, Issue 4, (2013) *** Cover Article**

L.N. Bartlett and D.C. Van Aken, “On the Effect of Aluminum and Carbon on the Dynamic Fracture Toughness of Fe-Mn-Al-C Steels,” AFS Transactions, Vol. 121, No. 13-1344 (2013).

L.N. Bartlett, A. Dash, D.C. Van Aken, V.L. Richards, and K.D. Peaslee, “Dynamic Fracture Toughness of High Strength Steels,” AFS Transactions, Vol. 120, No. 12-054 (2012).

L.N. Bartlett, D.C. Van Aken, S. Lekakh, and K.D. Peaslee, “Mechanical Properties of Cerium Treated Fe-Mn-Al-C Steel Castings,” AFS Transactions, Vol. 119, pp. 545-560 (2011).

L.N. Bartlett, A. Schulte, D. Van Aken, K. Peaslee, and R. Howell, “A Review of the Physical and Mechanical Properties of a Cast and Lightweight Fe-Mn-Al-C Steel,” MS&T Conference Proceedings, Houston, Texas Oct. 17-21 (2010).

(iv) Synergistic Activities
FEF Key Professor of Metalcasting Technology

Two Best Paper Awards in Steel Division, American Foundry Society (2011, 2012)

American Foundry Society Steel Division 9 Technical Committee, Secretary (2014)

Faculty Mentor for the Texas State University SPARK Program

Texas Chapter of the American Foundry Society, Director (2014 – 2017)

TMS 2015: Materials Processing & Manufacturing Division Symposium Organizer

Member of Association of Iron and Steel Technology – AIST

Member of the Minerals, Metals, and Materials Society –TMS

(v) Collaborators & Other Affiliations
Dr. Clois Powell, Dr. D.C. Van Aken, Dr. V.L. Richards, Dr. D. Ishiem, Dr. Sam Matson, Dr. Qingkai Yu, Dr. Bahram Asiabanbour

(vi) Thesis Advised
Supervisor for Master of Science in Technology Thesis, Michael Grams, Texas State University (2013 – present)

Texas State Advanced Metallic Materials Research

Dr. Laura Bartlett
Assistant Professor
FEF Key Professor of Metalcasting Technology
Department of Engineering Technology
Email: lnb29@txstate.edu

February 27, 2015

TEXAS STATE UNIVERSITY®

College of Science and Engineering
Department of Engineering Technology

Department of Engineering Technology
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Outline

- ❖ Background
- ❖ Metal Casting Program
- ❖ Student Professional Societies
- ❖ Research Interests
- ❖ Recent Publications

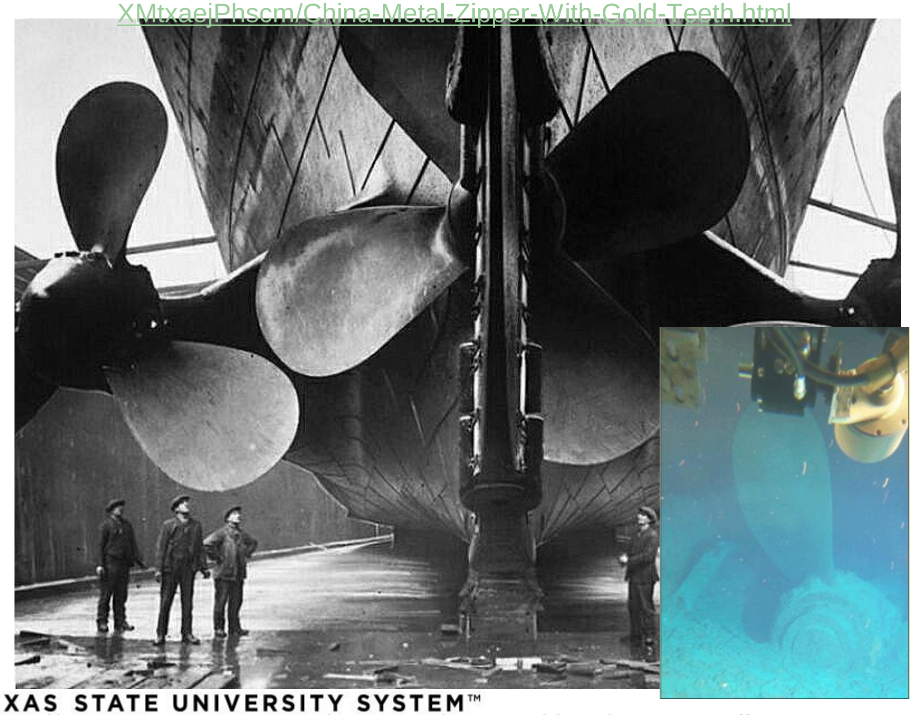
Introductions:

- My background is in Metallurgical Engineering
- ***Metallurgy*** - study of the physical, mechanical, and chemical behavior of metals, their alloys, and intermetallic compounds
- Labs:
  - Advanced Metallic Materials Characterization Lab
  - Foundry and Thermal Processing Lab
- Research:
  - Lightweight high performance alloys and metal matrix composites
  - Advanced coatings for extreme environments
  - Computational modeling of fluid flow, heat transfer, and phase transformations

Introduction to metal casting

- **Merriam-Webster definition:** Process by which a metal is melted, heated to proper temp., poured into a mold, and allowed to solidify
- *Much more science behind the definition!*
- Complex shapes in a single step process
- Sizes range from a fraction of an inch to over 30 ft
- More than 90% of all manufactured goods contain castings

http://helena203.en.made-in-china.com/product/XMtxaejPhscm/China-Metal-Zipper-With-Gold-Teeth.html

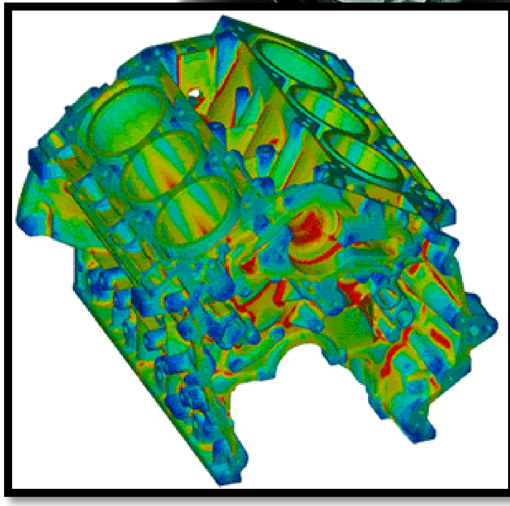


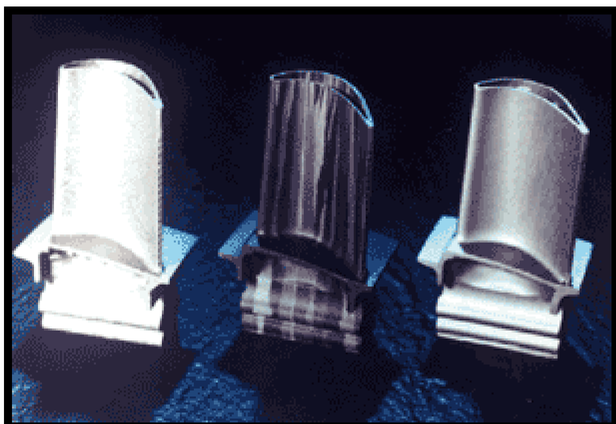
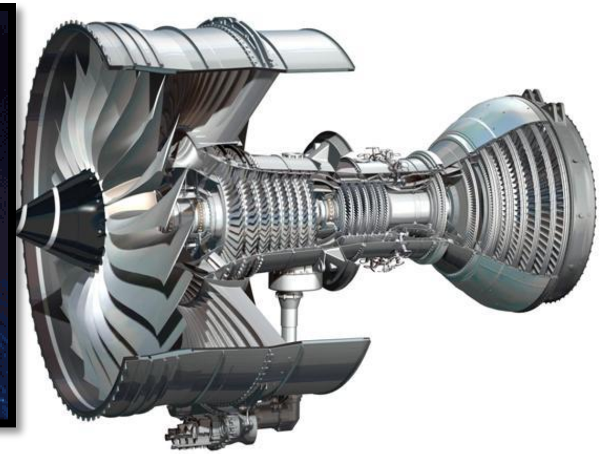
XAS STATE UNIVERSITY SYSTEM™

http://www.awesomestories.com/assets/titanics-propellers

Why is Metal casting important?

- Many things we take for granted would be impossible without metal casting
- 90% of all manufactured goods contain castings
- Metal casting science is constantly evolving
- New materials and processes drive technology

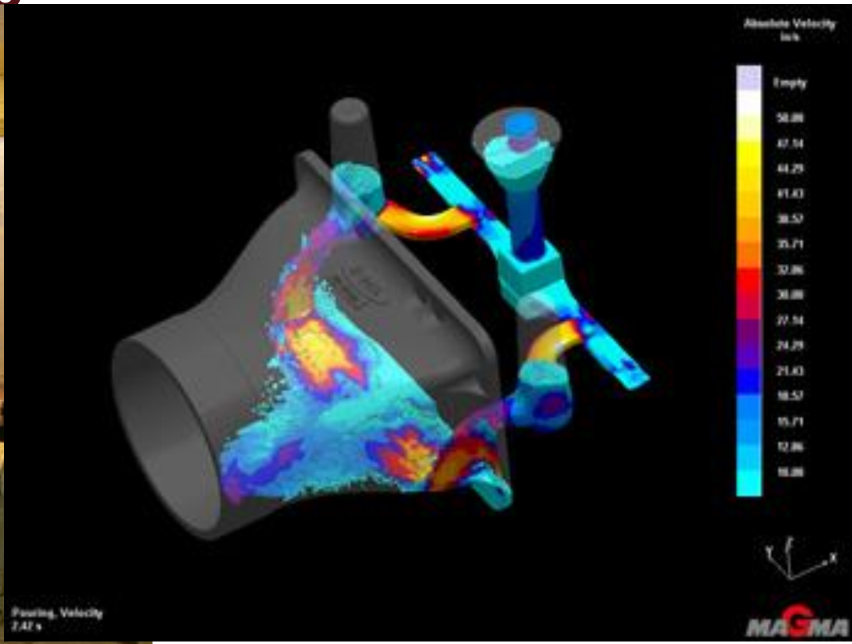



Castings in the automotive industry

- The average vehicle has more than 600 lbs. of castings!

Metallurgy and Metalcasting Science is Constantly Evolving



- ❖ Greater understanding of structure property relationships
- ❖ Increased automation and efficiency
- ❖ Process modeling and design
- ❖ More environmentally friendly

Our Metal Casting Program at Texas State

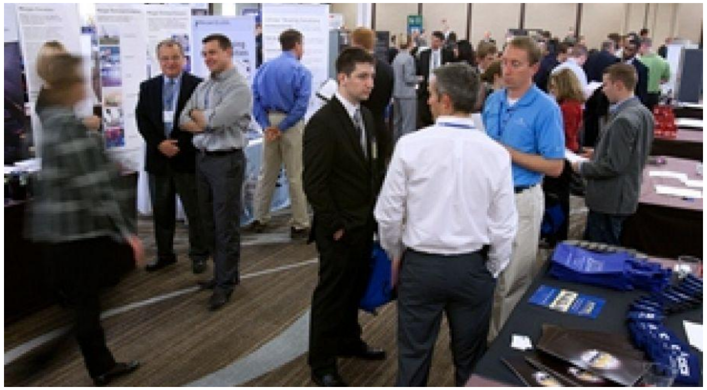
- ❖ Texas State is one of the few universities that has a working foundry
- ❖ Our students melt and cast most types of engineering alloys into useful items
- ❖ Texas State is one of only 20 Foundry Education Foundation accredited schools

Texas State is an FEF accredited school

- ***Foundry Education Foundation***
- Mission Statement: strengthen the metal casting industry by supporting partnerships among students, educators and industry: *helping today's students become tomorrow's leaders.*
- Why you should register with FEF.

1. Links to careers in the metal casting industry
2. Scholarships and student design competitions
3. CIC – College Industry Conference – Largest recruiting event of the year
4. Link to website

http://www.fefinc.org/students/student-home.php



More than $44,550 in scholarships Presented to 20 students at 2014 CIC

Texas State students at 2014 CIC

What is AFS and why join?

- **AFS -American foundry Society** - leading U.S. based metalcasting society
- Supports areas **of technology, management and education** in the metalcasting industry
- Networking and job searches!
- Tours of several foundries and trips to regional and national conferences!
- Career development – Full time and internship job opportunities (all kinds of engineering and technology majors)
- ***Scholarships and Internship assistance***
- AFS meetings and events –

1. Guest lectures from industry + free pizza!
2. Metalcasting Congress (April) – Columbus, OH
3. Open Foundry Days!

Texas AFS Chapter
of the American Foundry Society

Texas State AFS Students host Open Foundry Day

- Texas State Student Chapter of the American Foundry Society hosts Mountain Valley Middle School in Canyon Lake for Open Foundry Day.

TEXAS STATE UNIVERSITY

The rising STAR of Texas

October 2014 Open Foundry Day

- ❖ First Open Foundry Day of the fall semester was a great success
- ❖ Attracted lots of new students interested in metalcasting

October 2014 Open Foundry Day

- Brass bobcat heads are a hit with the students!
- Perhaps we can invite the football team next time and get some good press!

Texas State Foundry Casts Brass Medallions for the Winners of the City of San Marcos Storm Drain Design Competition

- City of San Marcos and Texas State University sponsored an art competition to design storm drain manhole covers that have been installed on all new City-owned storm drains
- This past summer the Texas State Foundry cast brass medallion replicas for the winners, Mabel Lopez and Andrea Weissenbuehler
- Brass medallions were a 1/6 scale model of the artists' original design and were presented to the artists this July in a ceremony that took place in the Texas State Foundry
- Actual storm drains are made of cast iron and were cast by East Jordan Ironworks in Ardmore OK

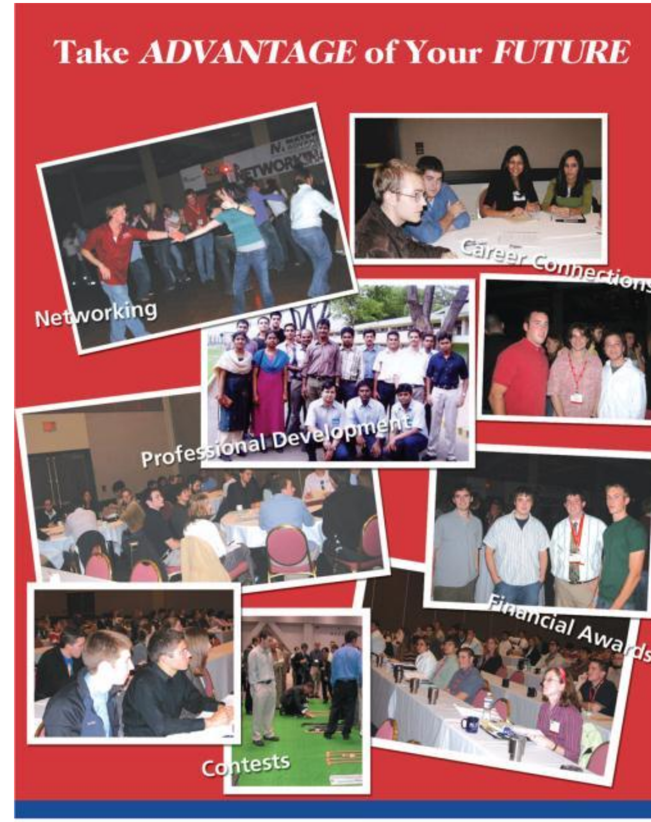
- AFS and FEF Students attend Industry Tours and National Conferences
- Last academic year more than $15,000 was awarded in scholarships to AFS and FEF students from Texas State
- This academic year we plan to award almost $20,000 in scholarships

Material Advantage and AIST

- Material Advantage – Student professional society for Materials Science and Engineering
- AIST – Association for Iron and Steel Technology

Material Advantage

- **WHO ARE THE PARTNERS OF MATERIAL ADVANTAGE?**
  - The American Ceramic Society (ACerS)
  - The Association for Iron & Steel Technology (AIST)
  - ASM International® (ASM)- The materials information society
  - The Minerals, Metals, & Materials Society (TMS)

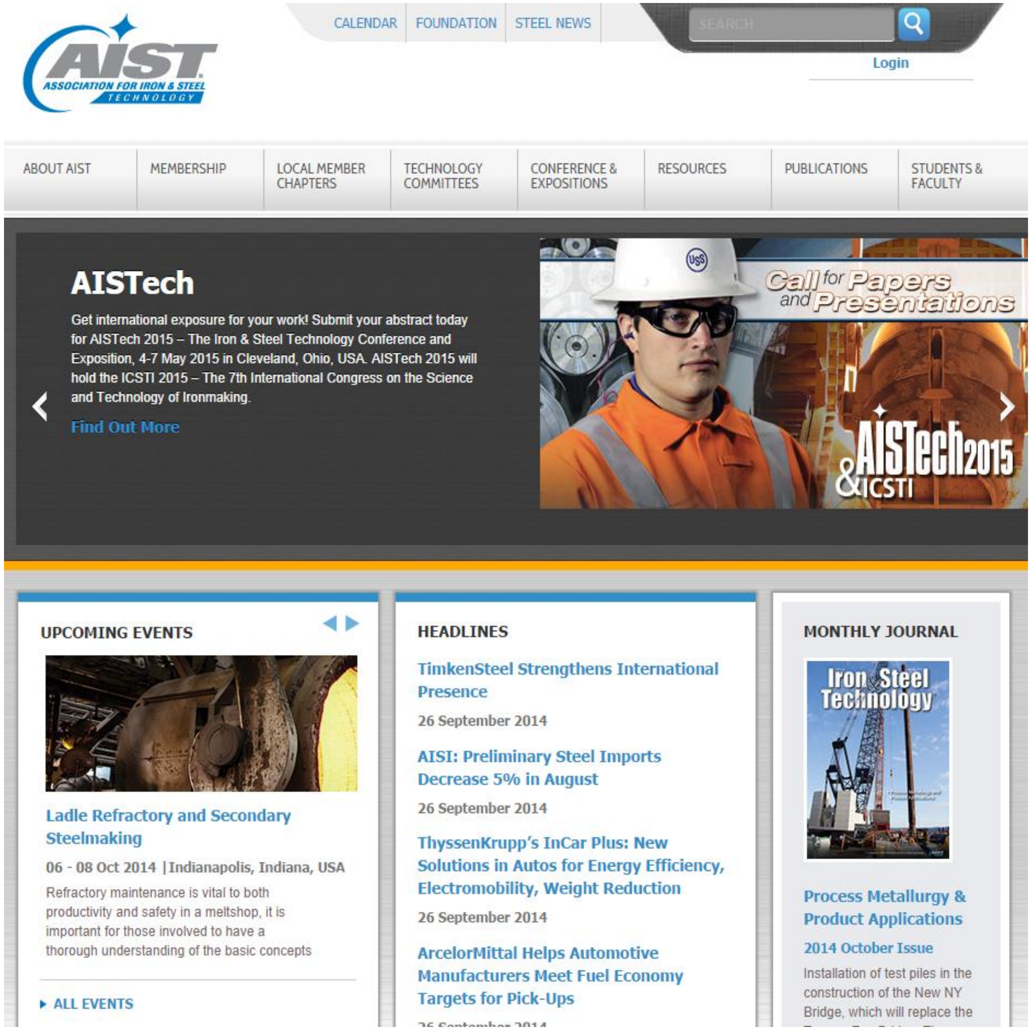


MATERIAL™ ADVANTAGE
The Student Program for Materials Science and Engineering

TEXAS STATE UNIVERSITY
The rising STAR of Texas

Association for Iron and Steel Technology

- AIST
- Association for iron and steel technology
- Professional society to advance the technical development of steel
- More than $600,000 worth of scholarships annually
- Internships and full time careers!



Society of Manufacturing Engineers

AFS TEXAS Chapter

ASME SETTING THE STANDARD

MATERIAL ADVANTAGE™

"3-D Printing: Revolutionizing Manufacturing"

Speaker: Mike Browning
Sales Manager
ExOne Digital Part Materialization

WHEN:
Wednesday, March 4, 2015
9:00 - 9:50 a.m.

WHERE:
RFM 4231

- **Learn more about 3-D printed materials!**
- **Find out about internship and full time job opportunities!**

Join us for breakfast!

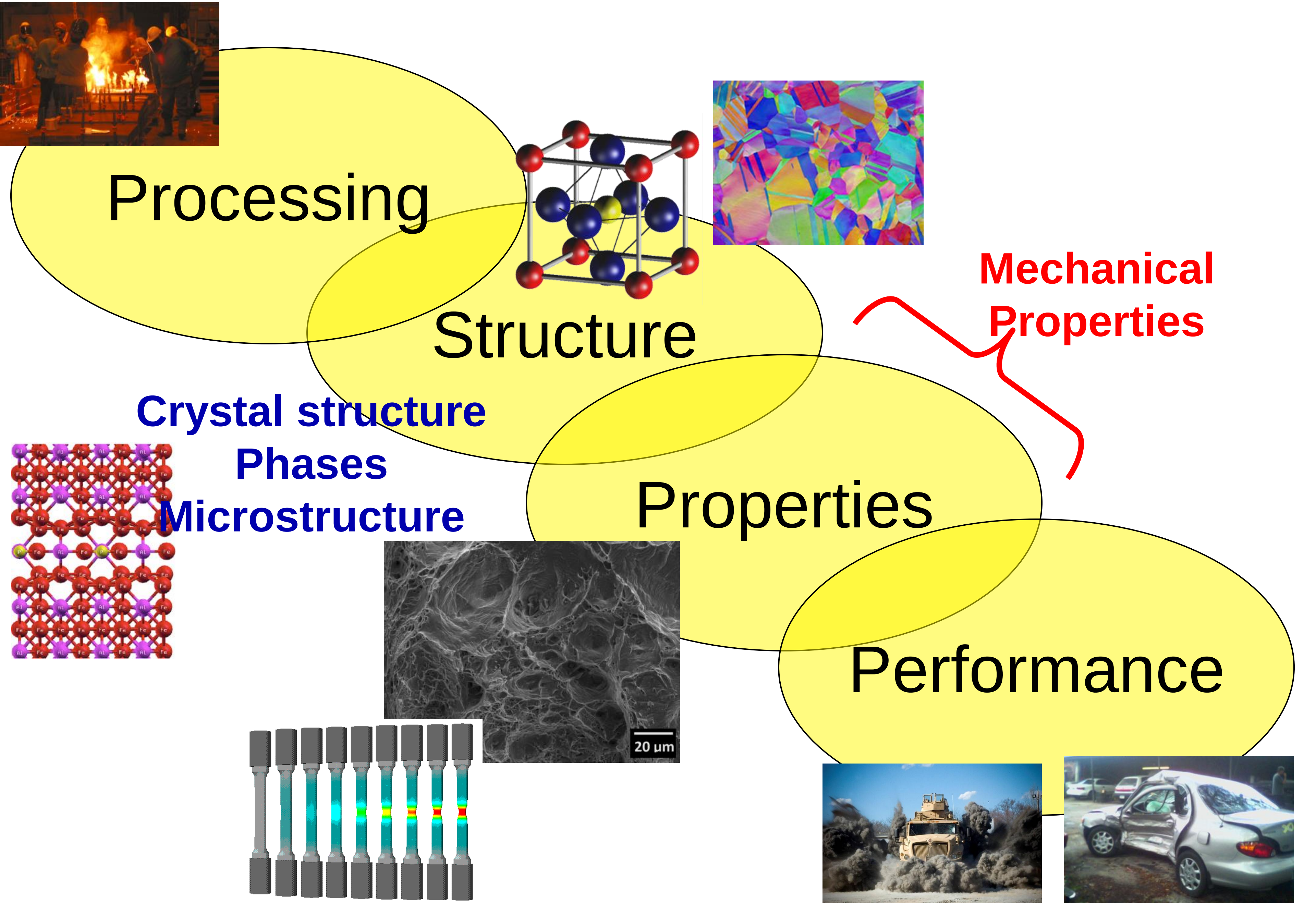
Free Donuts and Drinks!

ExOne™
DIGITAL PART MATERIALIZATION

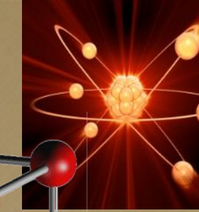
Why else should you join AFS and Material Advantage?

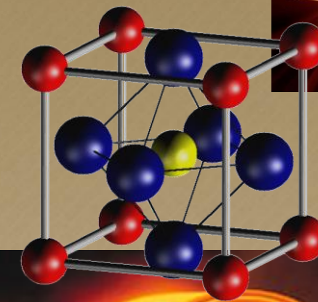
- ❖ Because it's a lot of fun!!!
- ❖ And you get to play with Hot Metal!

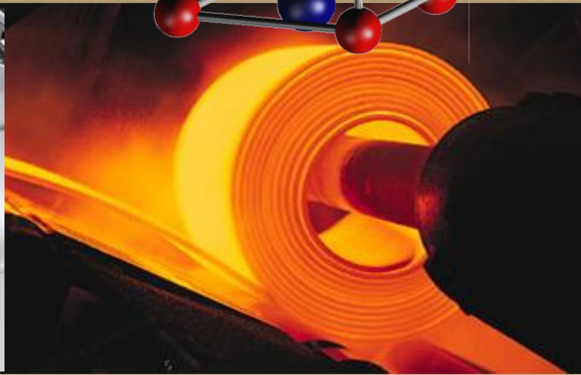
Design of novel high strength and lightweight alloys



ADVANCED HIGH STRENGTH AND LIGHTWEIGHT STEELS FOR MILITARY, TRANSPORTATION, AND ENERGY







TAR of Texas

Mine Resistant Ambush Protected
MRAP

"V" shaped hull for blast protection

Insufficient side protection from EFPs

Lightweight steel for Military P900 Armor Plate

- ❖ Need a lightweight alternative to cast 4130 steel
- ❖ New material needs to:

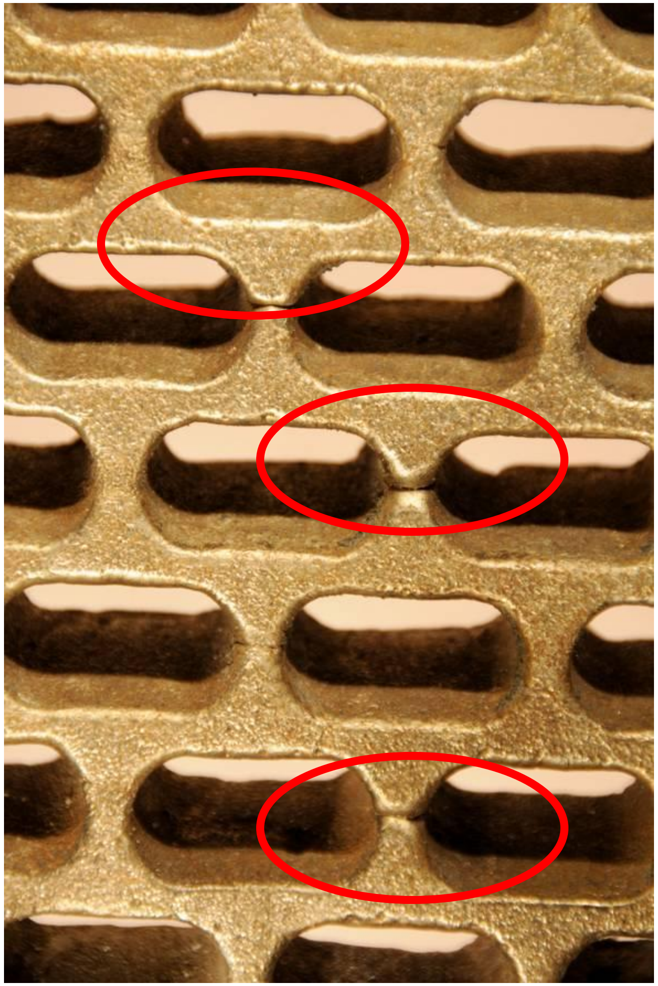
1. Meet military specifications
2. Have good castability
3. Have equivalent mechanical properties as 4130

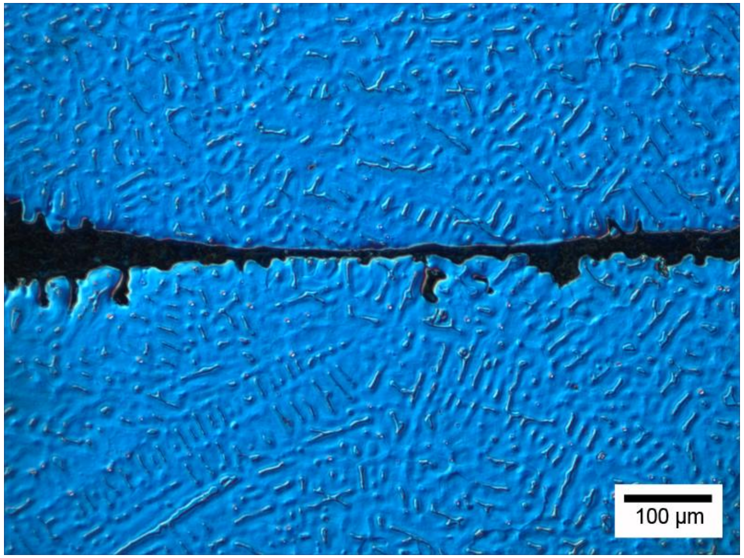
- ❖ What makes good armor plate?
- ❖ Main factors to consider:

1. Composition
2. Processing history

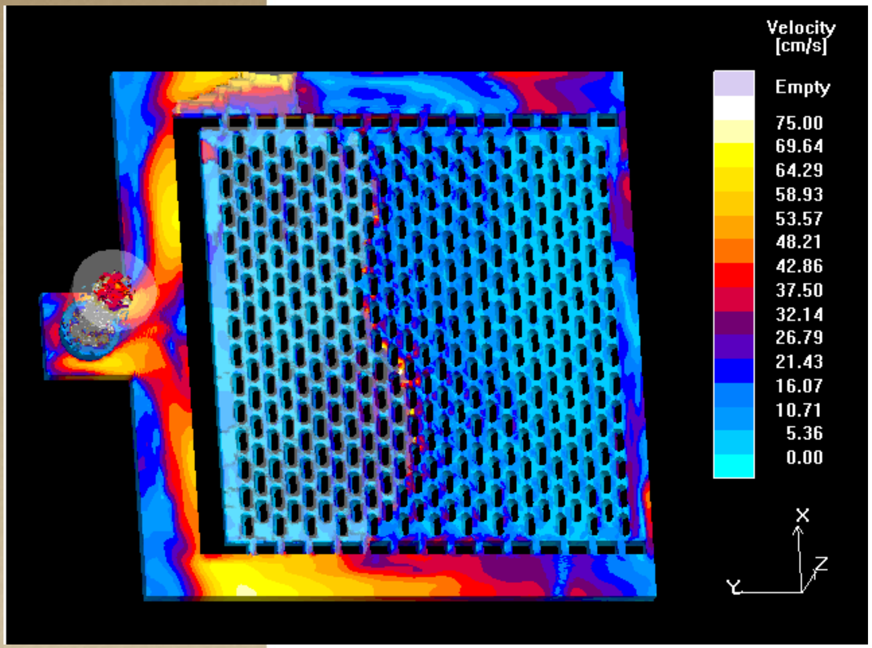
Use of computer modeling to prevent cold shuts in armor plate

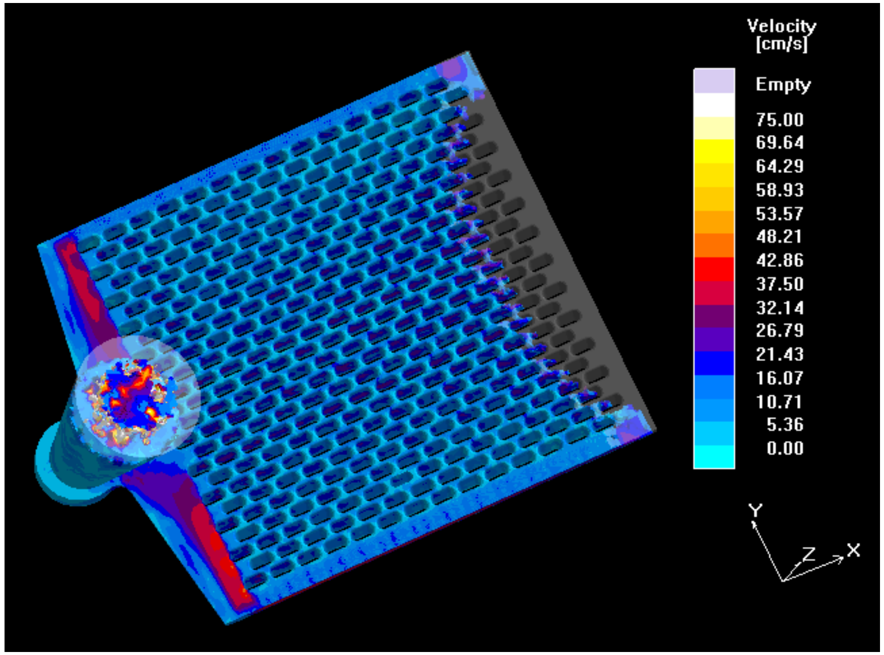
- Common defect in P900
  - Low superheat
  - Poor venting
  - Oxide films





Velocity profile – minimize turbulence

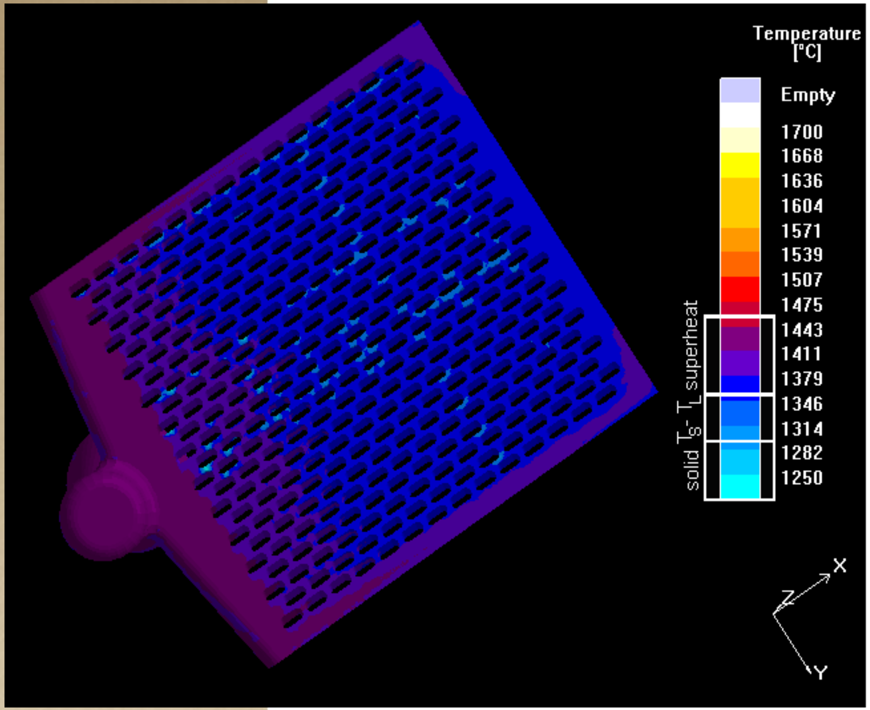


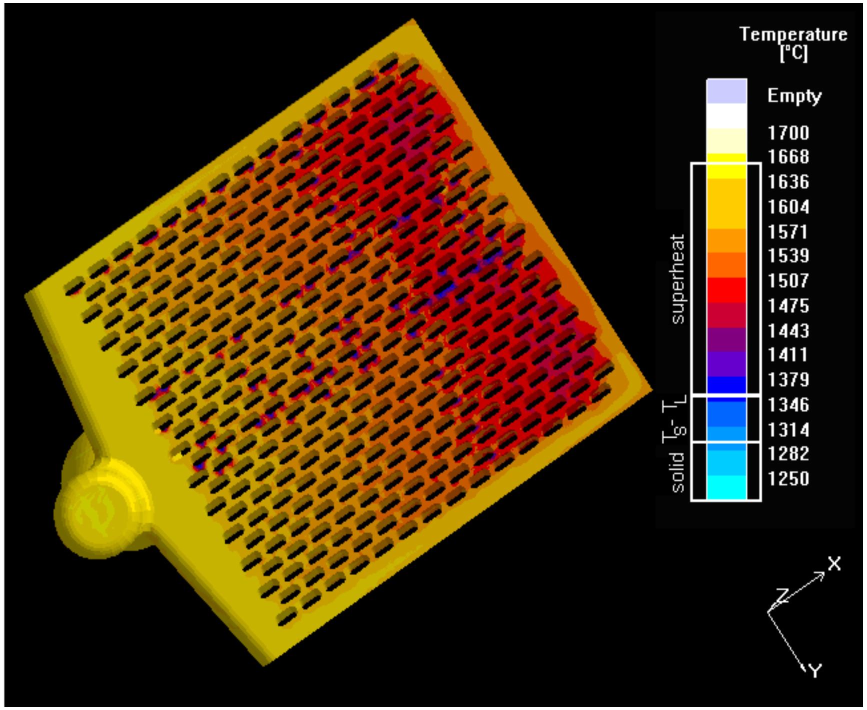


300º superheat
0º tilt

300º superheat
15º tilt

Use of solidification modeling to predict defects





100º superheat

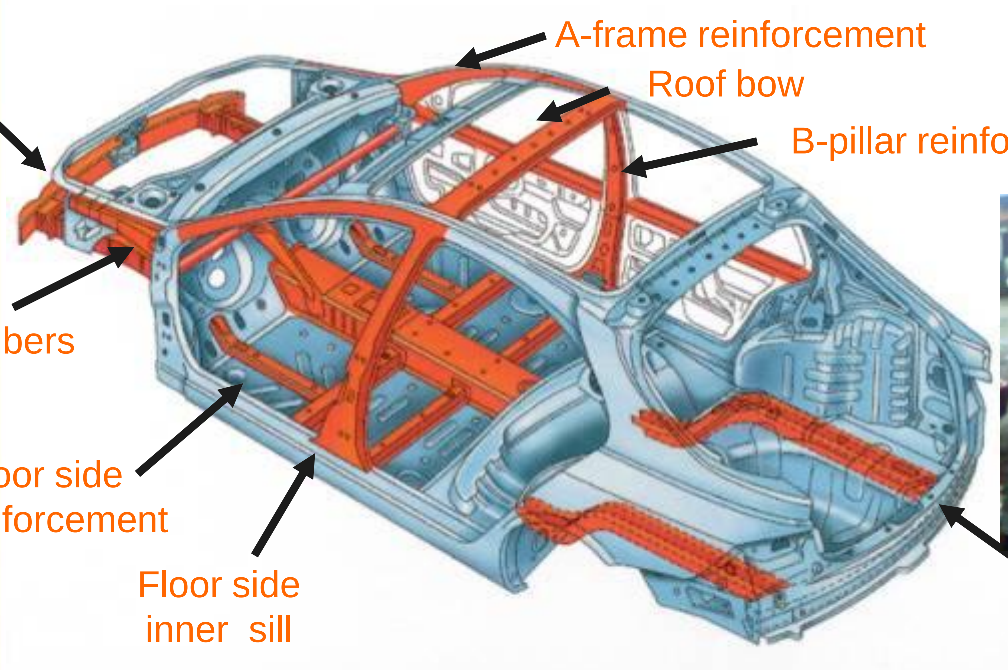
300º superheat

Mechanical Properties of lightweight steel

Alloy	Brinell Hardness	0.2% YS, MPa	UTS, MPa	Total Elongation	CVN Energy (J), -40° C	DFT, kJ/m² (room temp.)
Cast 4130	341	867	1,011	13%	15	94
Lightweight steel						
1.07% Si	303	728	795	28%	53	376
	350	873	953	20%	18	153
1.56% Si	309	800	834	30%	23	265
	360	937	1,016	13%	11	144
0.59% Si	304	-	-	-	-	242
	366	-	-	-	-	95

- Mechanical properties meet or *exceed* that of Q&T 4130 currently used for P900 at almost *15% reduction in density*!

Transitioning Lightweight Steel to Transportation Industry



Why is Lightweight Steel Important?

- Reduce CO_2 emissions
- Reduce fuel consumption
- Safety requirements

Car structure mass reduction

- Down-gauging
- Higher crash performance
- Cost effective

Reduced Injuries

moreLIKETHIS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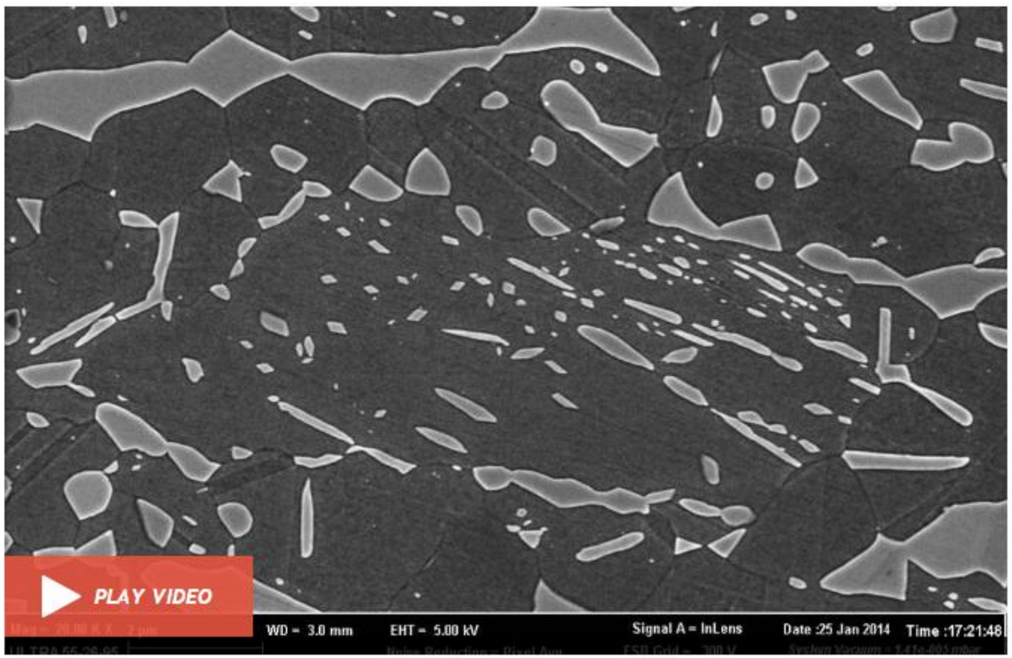
From Trekking To Survival To Sports, Check Out Adventure!


The World In 2025: 10 Scientific Breakthroughs

TECH

New Steel Alloy Stronger Than Titanium

FEB 4, 2015 01:04 PM ET // BY GLENN MCDONALD



Annealed microstructure of high-specific-strength steel (HSSS). Fine FeAl-type B2 precipitates form during annealing in between the B2 stringer bands in steel matrix. The specimen was annealed for 15 min at 900 C.

HANSOO KIM

Big news from the metallurgy desk this week: It looks like steel is about to get a lot steelier.

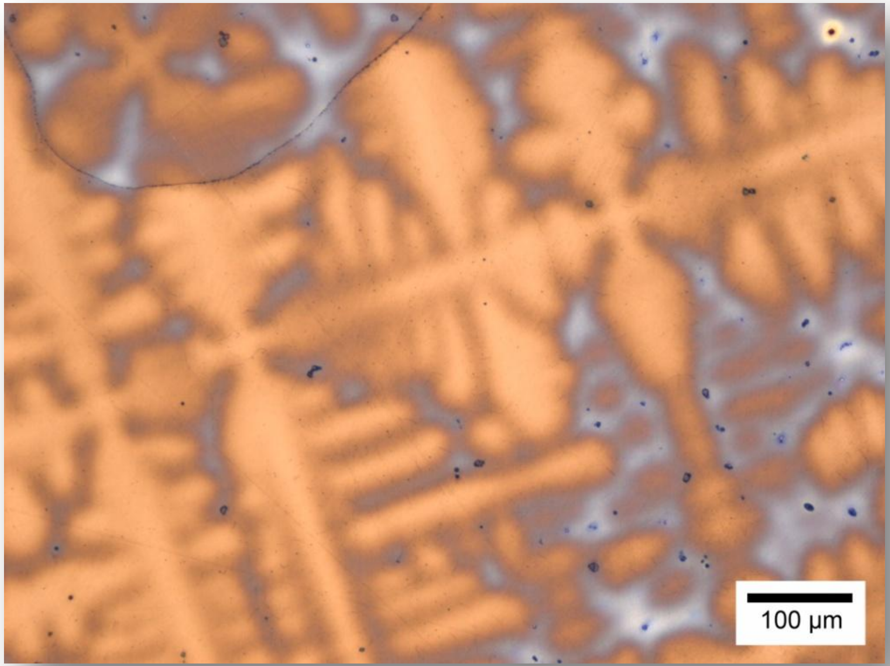
DNEWSvideo

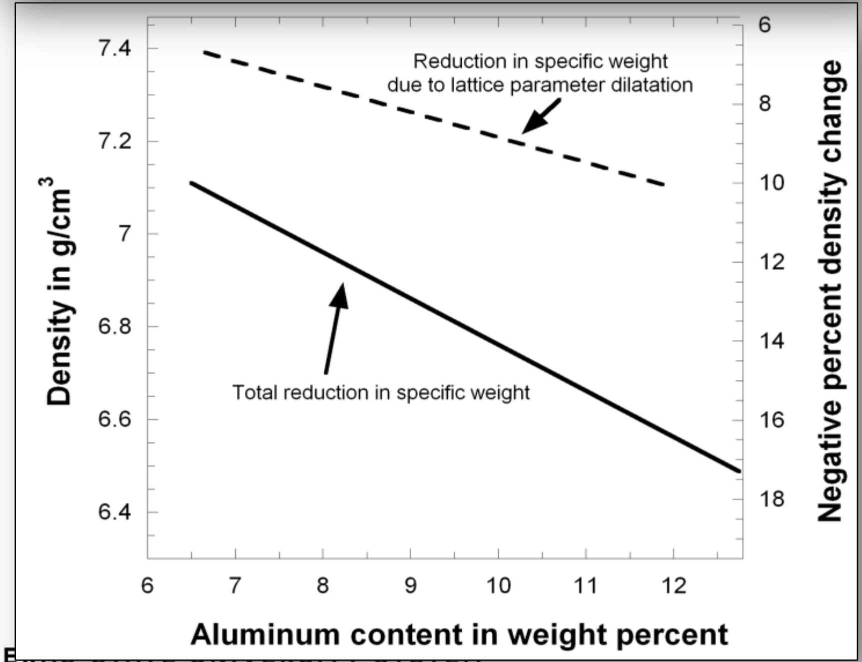
DNews: A New Reason Why Soda Could Mess With Your Health

TEXAS STATE UNIVERSITY
The rising STAR of Texas

What are *lightweight* steels?

- *Fe-Mn-Al-C* steels
- Originally developed as alternatives to Ni and Cr SS
- Mn (15 to 30%) and aluminum (up to 12%)
- Cast microstructure → austenite dendrites <u>or</u> duplex structure
- Age hardenable grades: > 5% Al and 0.3% C
- *Up to 18% reduction in weight*!
- Up to 2GPa in strength and 70% elongation





STATE UNIVERSITY
The rising STAR of Texas

MEMBER THE TEXAS STATE UNIVERSITY SYSTEM

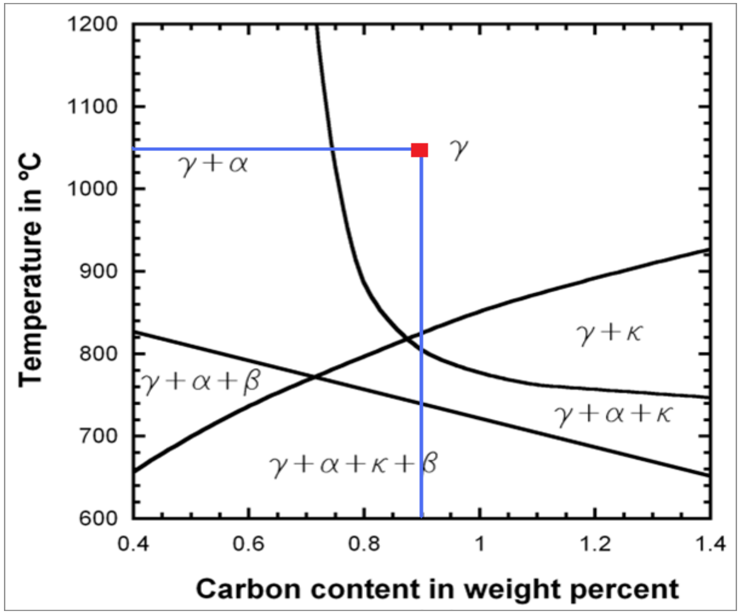
Typical Heat Treatment

- Base composition →
  Fe-30Mn-9Al-XSi-0.9C-0.5Mo
- "as-cast" alloy is soft with low toughness
- Heat treatment to improve mechanical properties

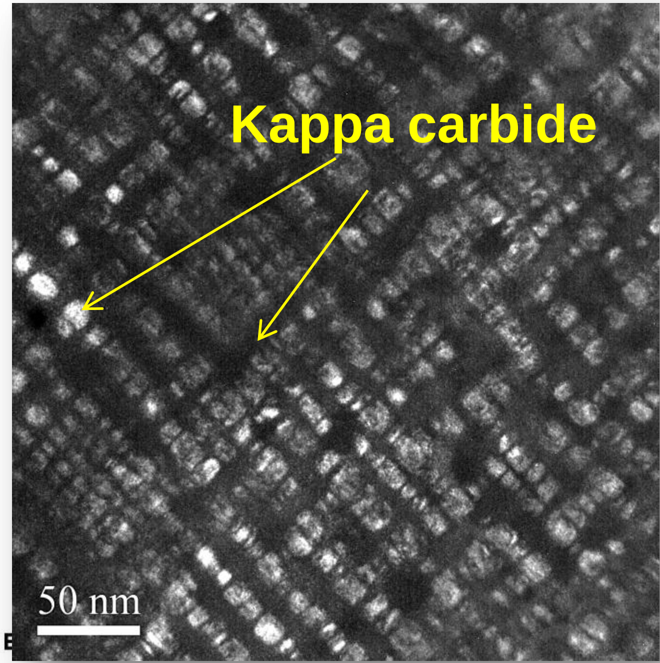
1. Solution treatment
2. Quench
3. Age harden - 530° C

   precipitation of κ-carbide, $(Fe,Mn)_3AlC$

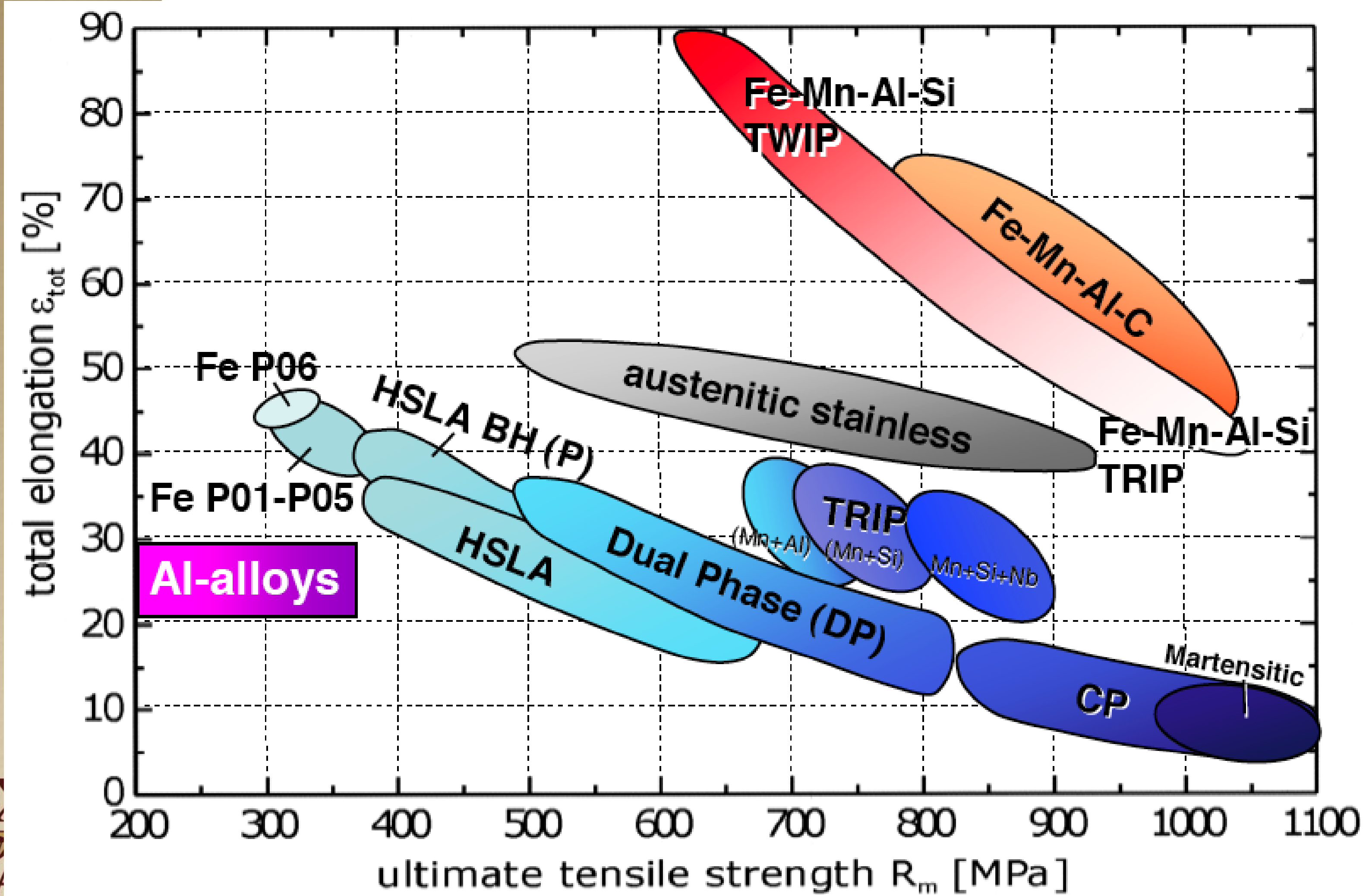
Alloy is a nano-strengthened material



Fe-30Mn-10Al-XC

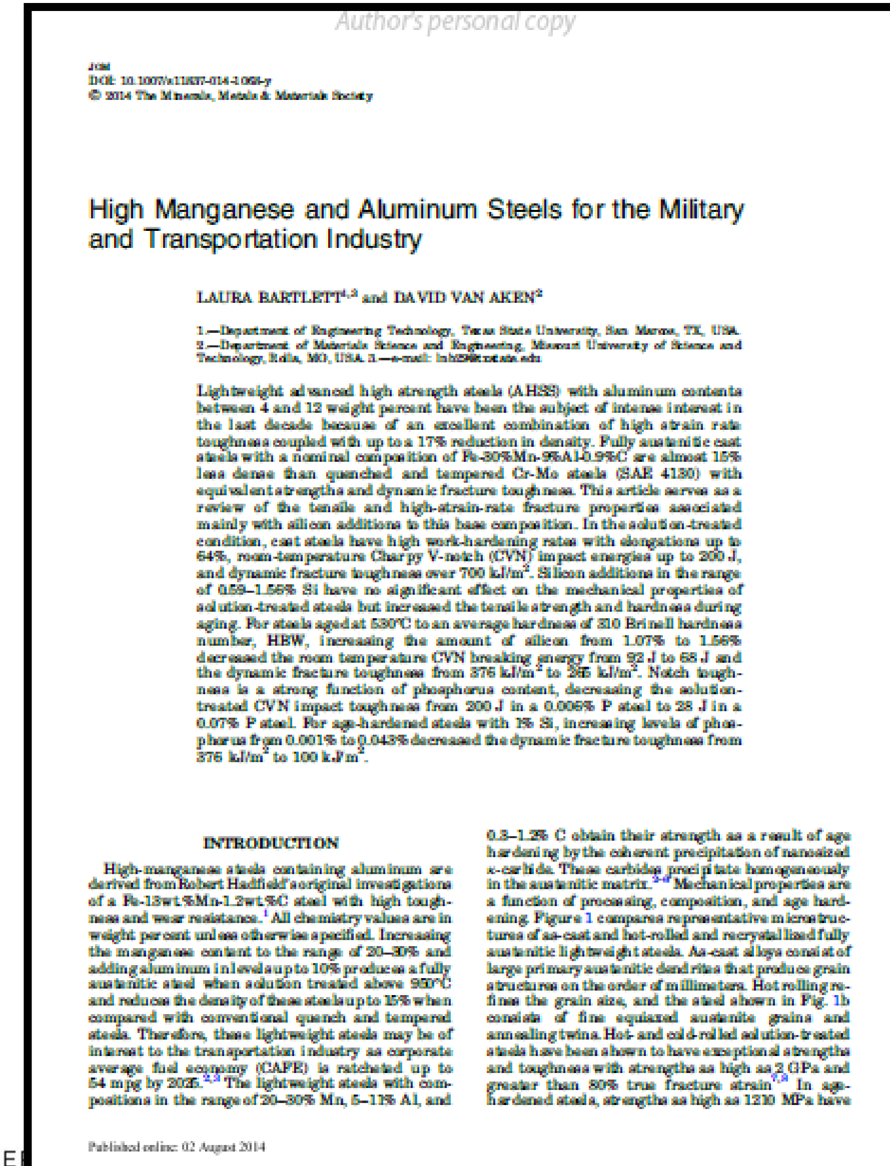


Lightweight steels in comparison to traditional wrought steels



Most Recent Research Featured in JOM

- Special issue on high strength lightweight steels
- Paper focuses on fracture and mechanical properties of high Mn and Al steels



JOM
DOI: 10.1007/s11837-014-1068-y

High Manganese and Aluminum Steels for the Military and Transportation Industry

LAURA BARTLETT[1,3] and DAVID VAN AKEN[2]

1.—Department of Engineering Technology, Texas State University, San Marcos, TX, USA. 2.—Department of Materials Science and Engineering, Missouri University of Science and Technology, Rolla, MO, USA. 3.—e-mail: lnb29@txstate.edu

Lightweight advanced high strength steels (AHSS) with aluminum contents between 4 and 12 weight percent have been the subject of intense interest in the last decade because of an excellent combination of high strain rate toughness coupled with up to a 17% reduction in density. Fully austenitic cast steels with a nominal composition of Fe-30%Mn-9%Al-0.9%C are almost 15% less dense than quenched and tempered Cr-Mo steels (SAE 4130) with equivalent strengths and dynamic fracture toughness. This article serves as a review of the tensile and high-strain-rate fracture properties associated mainly with silicon additions to this base composition. In the solution-treated condition, cast steels have high work-hardening rates with elongations up to 64%, room-temperature Charpy V-notch (CVN) impact energies up to 200 J, and dynamic fracture toughness over 700 kJ/m^2. Silicon additions in the range of 0.59–1.56% Si have no significant effect on the mechanical properties of solution-treated steels but increased the tensile strength and hardness during aging. For steels aged at 530°C to an average hardness of 310 Brinell hardness number, HBW, increasing the amount of silicon from 1.07% to 1.56% decreased the room temperature CVN breaking energy from 92 J to 68 J and the dynamic fracture toughness from 376 kJ/m^2 to 265 kJ/m^2. Notch toughness is a strong function of phosphorus content, decreasing the solution-treated CVN impact toughness from 200 J in a 0.006% P steel to 28 J in a 0.07% P steel. For age-hardened steels with 1% Si, increasing levels of phosphorus from 0.001% to 0.043% decreased the dynamic fracture toughness from 376 kJ/m^2 to 100 kJ/m^2.

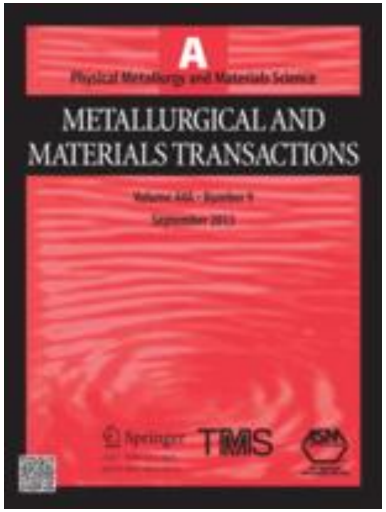
INTRODUCTION

High-manganese steels containing aluminum are derived from Robert Hadfield's original investigations of a Fe-13wt.%Mn-1.2wt.%C steel with high toughness and wear resistance.[1] All chemistry values are in weight percent unless otherwise specified. Increasing the manganese content to the range of 20–30% and adding aluminum in levels up to 10% produces a fully austenitic steel when solution treated above 950°C and reduces the density of these steels up to 15% when compared with conventional quench and tempered steels. Therefore, these lightweight steels may be of interest to the transportation industry as corporate average fuel economy (CAFE) is ratcheted up to 54 mpg by 2025.[2,3] The lightweight steels with compositions in the range of 20–30% Mn, 5–11% Al, and 0.3–1.2% C obtain their strength as a result of age hardening by the coherent precipitation of nanosized κ-carbide. These carbides precipitate homogeneously in the austenitic matrix.[3-6] Mechanical properties are a function of processing, composition, and age hardening. Figure 1 compares representative microstructures of as-cast and hot-rolled and recrystallized fully austenitic lightweight steels. As-cast alloys consist of large primary austenitic dendrites that produce grain structures on the order of millimeters. Hot rolling refines the grain size, and the steel shown in Fig. 1b consists of fine equiaxed austenite grains and annealing twins. Hot- and cold-rolled solution-treated steels have been shown to have exceptional strengths and toughness with strengths as high as 2 GPa and greater than 80% true fracture strain.[7,8] In age-hardened steels, strengths as high as 1210 MPa have

Published online: 02 August 2014

“An Atom Probe Study of Kappa Carbide Precipitation and the Effect of Silicon Addition”

- Results of this study published in Metallurgical and Materials Transactions A
- Open access article through Springer



An Atom Probe Study of Kappa Carbide Precipitation and the Effect of Silicon Addition

LAURA N. BARTLETT, DAVID C. VAN AKEN, JULIA MEDVEDEVA, DIETER ISHEIM, NADEZHDA I. MEDVEDEVA, and KAI SONG

The influence of silicon on κ-carbide precipitation in lightweight austenitic Fe-30Mn-9Al-(0.59-1.56)Si-0.9C-0.5Mo cast steels was investigated utilizing transmission electron microscopy, 3D atom-probe tomography, X-ray diffraction, *ab initio* calculations, and thermodynamic modeling. Increasing the amount of silicon from 0.59 to 1.56 pct Si accelerated formation of the κ-carbide precipitates but did not increase the volume fraction. Silicon was shown to increase the activity of carbon in austenite and stabilize the κ-carbide at higher temperatures. Increasing the silicon from 0.59 to 1.56 pct increased the partitioning coefficient of carbon from 2.1 to 2.9 for steels aged 60 hours at 803 K (530 °C). The increase in strength during aging of Fe-Mn-Al-C steels was found to be a direct function of the increase in the concentration amplitude of carbon during spinodal decomposition. The predicted increase in the yield strength, as determined using a spinodal hardening mechanism, was calculated to be 120 MPa/wt pct Si for specimens aged at 803 K (530 °C) for 60 hours and this is in agreement with experimental results. Silicon was shown to partition to the austenite during aging and to slightly reduce the austenite lattice parameter. First-principles calculations show that the Si-C interaction is repulsive and this is the reason for enhanced carbon activity in austenite. The lattice parameter and thermodynamic stability of κ-carbide depend on the carbon stoichiometry and on which sublattice the silicon substitutes. Silicon was shown to favor vacancy ordering in κ-carbide due to a strong attractive Si-vacancy interaction. It was predicted that Si occupies the Fe sites in nonstoichiometric κ-carbide and the formation of Si-vacancy complexes increases the stability as well as the lattice parameter of κ-carbide. A comparison of how Si affects the enthalpy of formation for austenite and κ-carbide shows that the most energetically favorable position for silicon is in austenite, in agreement with the experimentally measured partitioning ratios.

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I. INTRODUCTION

CAST lightweight austenitic Fe-Mn-Al-C steels have both low melting points, less than (1623 K) 1350 °C, and good filling characteristics which are similar to cast irons.[1] Addition of 9 to 10 wt pct aluminum reduces

quenched and tempered steels when age hardened. However, the high manganese (20 to 30 wt pct) required to stabilize an austenitic matrix[1,2] may relegate this class of steel to castings, since electrolytic manganese is required to limit phosphorus and may be too costly for

New opportunities for lightweight steel: Bradley Fighting Vehicle

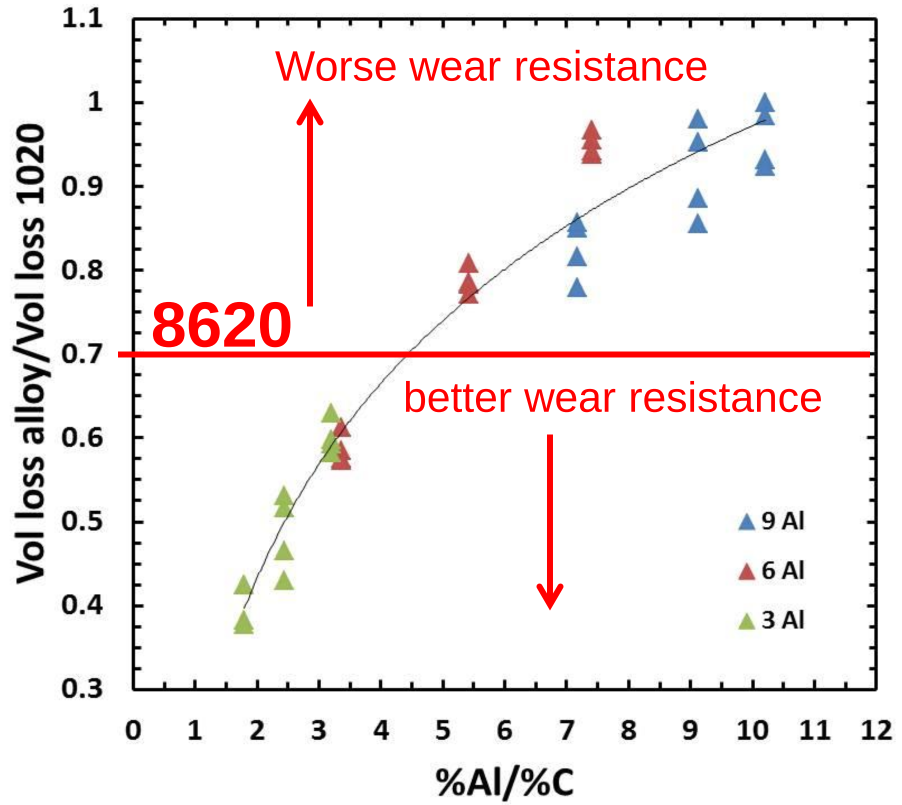
- Began service in 1981
- Crew of 3+
- Top speed: 41 mph
- Weight: 30 tons

Bradley Track Shoe

- Forged SAE 8620 steel
- 166 track shoes on Bradley fighting vehicle 5810 lbs total
- Replacement with *Fe-Mn-Al-C* reduces weight by 860 lbs
- Needs to have the same wear resistance as SAE 8620 steel

Abrasive wear results

- Lightweight steel: comparable wear resistance to forged 8620 at 10% reduction in density
- Current studies: surface treatment to increase wear resistance



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Metalcasting Congress 2015 Paper

- Nitriding of Mn and Al steels can be accomplished in an N_2 atmosphere
- Up to a 600 µm case depth of AlN can be produced in a few hours between 900 and 1100ºC
- AlN is very hard and wear resistant
- May also promote improved corrosion and fatigue properties

NITRIDING OF LIGHTWEIGHT HIGH MANGANESE AND ALUMINUM STEELS

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ABSTRACT

Austenitic high manganese and aluminum steels have exceptional combinations of high strength and toughness with excellent wear resistance. Adding aluminum in levels from 6 to 8.8wt.% reduces the density by 10 to 15% compared with quenched and tempered Cr and Mo steels but also decreases strain hardening and abrasive wear resistance. Wear resistance may be improved by a low cost heat treatment in a nitrogen atmosphere to produce a hard layer of surface AlN. In the current study, the effect of aluminum and silicon content on the kinetics of nitriding process was evaluated for a Fe-30%Mn-(6-9%)Al-(1-1.6%)Si-0.9%C steel in the temperature range of 900 to 1100°C. Results show that up to a 550 µm thick surface layer of AlN plates can be produced, depending on the time and temperature. Increasing the amount of silicon from 1.1% to 1.6%Si had no statistical effect on the diffusion of nitrogen in the temperature range of 900 to 1100°C. Increasing the amount of aluminum from 6% to 8.8% Al decreased the diffusivity of nitrogen and increased the calculated activation energy from 64 to 78 kJ/mol. The lower than expected values of the activation energy for the diffusion of nitrogen in austenite is suggested to be the result of the development of high diffusivity pathways at the interface between the AlN and the austenite matrix.

Fe-30Mn-9Al-1Si-0.9C-0.5Mo nominal composition. This composition was chosen to produce a completely austenitic microstructure when solution treated above 950° C.[3] Adding 9%Al produces an steel that is 15% less dense than traditional steels with up to three times the dynamic fracture toughness of quenched and tempered AISI 4130.[14] Silicon is added to increase the fluidity and to lower the melting point as well as to prevent the formation of brittle β-Mn during aging.[15]

Mechanical properties of cast *Fe-Mn-Al-C* alloys vary with composition, age-hardening, and alloy cleanliness. Age hardening greatly increases strength in cast alloys but sharply reduces work hardening, toughness, and abrasive wear resistance.[1,16,17] In addition to use in tough and wear resistant automotive components and ballistic armor plate, Fe-Mn-Al-C steels could be considered as a lightweight alternative for steel ground engaging components of track type vehicles as well as components in the mining industry. For example, if Fe-Mn-Al-C alloys with 15% lower density were substituted directly for the SAE 8620 steel track shoes of the Bradley Fighting Vehicle (BFV) the weight savings would be approximately 800 lbs.[17] However, the wear resistance of these alloys is dependent on composition and age hardening. Recently, Buckholz et al. studied the abrasive wear resistance and strain hardening ability of a Fe-30Mn-(3-9.5)Al-1Si-(0.9-1.8)C steel with respect to composition and age hardening with the goal of using a this steel as a lightweight alternative to

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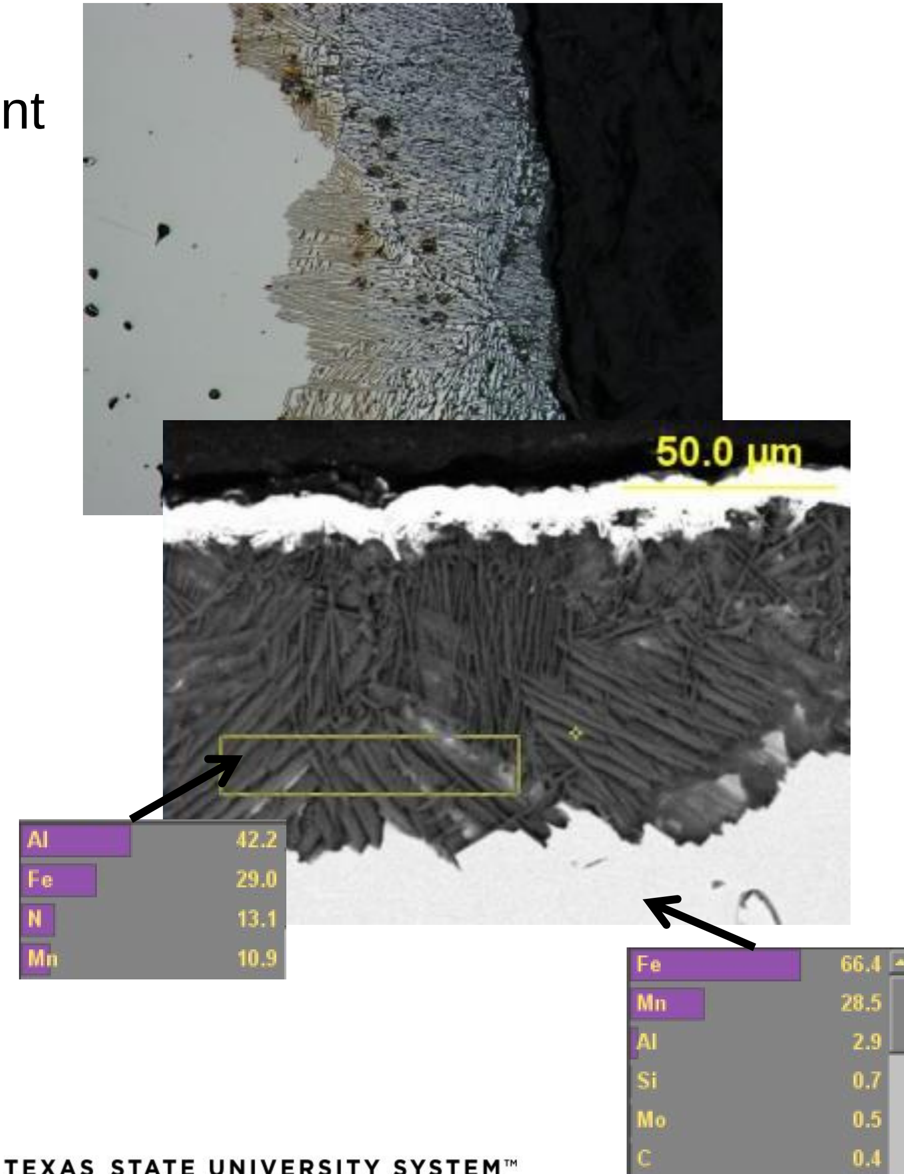
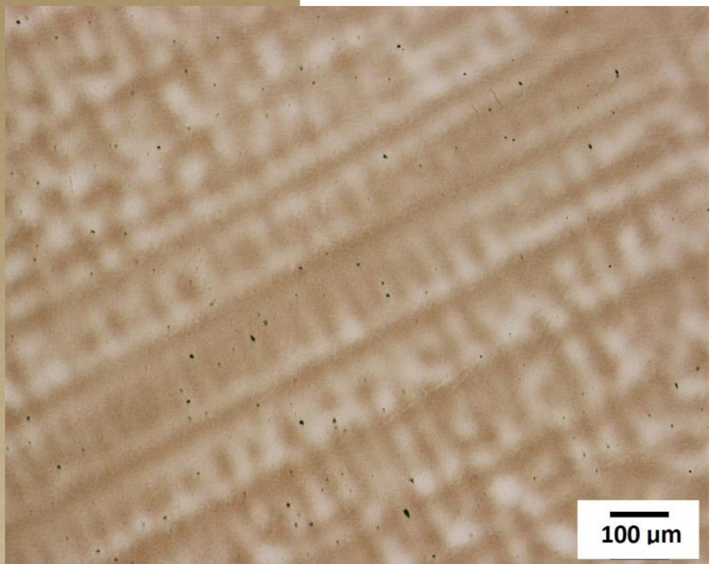
Nitriding of Fe-Mn-Al-C steels

- Nitriding was discovered by accident in specimens that were solution treated in air
- Initial study completed as part of undergraduate AFS/FEF student technology contest
- In a nitrogen atmosphere, kinetics are increased
- Case depth of 200 μm after 2hr solution treatment at 1100ºC
- Depletion of Al from surrounding matrix would also increase toughness and wear resistance



Nitriding of Lightweight steel



- Studied different Al and Si compositions to determine the effect on kinetics of coating growth
- Different temperatures and times

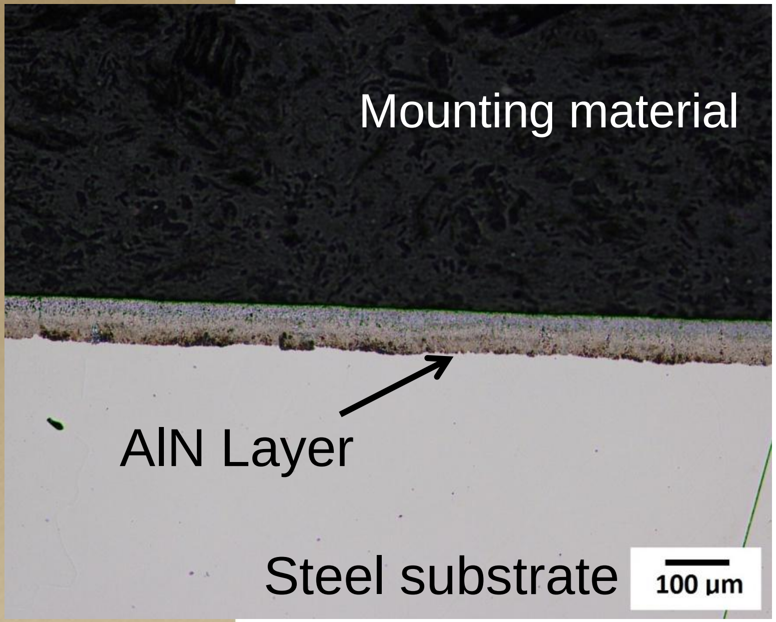
Table 1. Chemical composition of alloys in weight percent

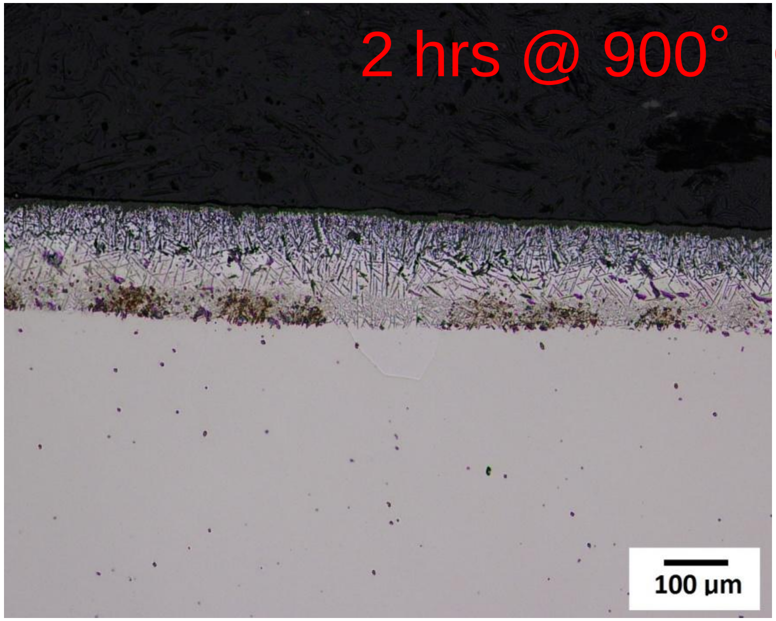
Alloy	Fe	C	Si	Mn	P	S	Mo	Ni	Al	Cu
Steel A	Bal.	0.90	1.07	30.42	0.001	0.006	0.54	-	8.83	0.006
Steel B	Bal.	0.89	1.56	29.97	0.002	0.007	0.53	-	8.81	0.006
Steel C	Bal.	0.94	1.57	30.22	0.001	0.012	0.61	0.011	5.98	0.010

Experimental Procedure

- Rectangular test specimens were milled from the center of plate and Y-block castings
- Solution treated at 1050° C for 2 hrs in protective stainless steel heat treating bags
- Quenched into ice water
- Surface polished to a 0.3 μm finish and ultrasonically cleaned in ethanol
- Heat treated 900 to 1100° C under 99.9% pure N_2 flowing at a rate of 30 SCFH

Optical Metallography of Nitrided Steels

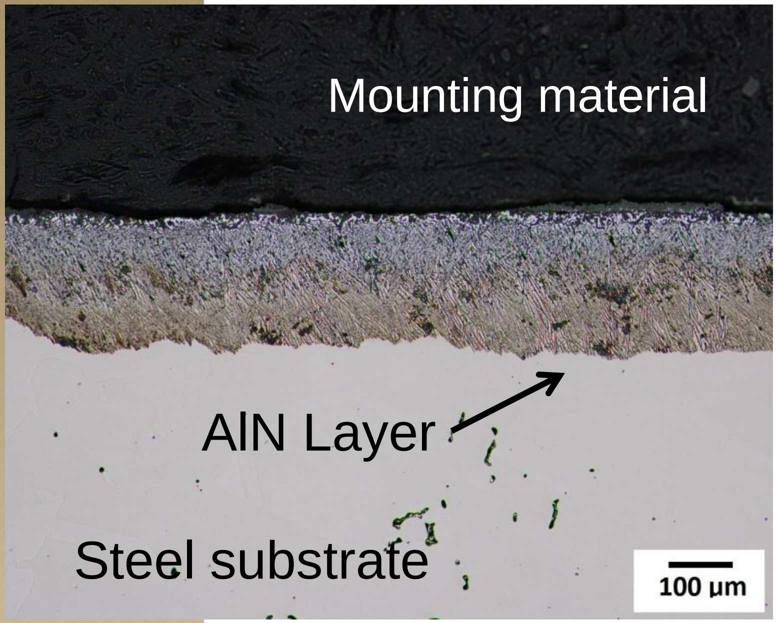




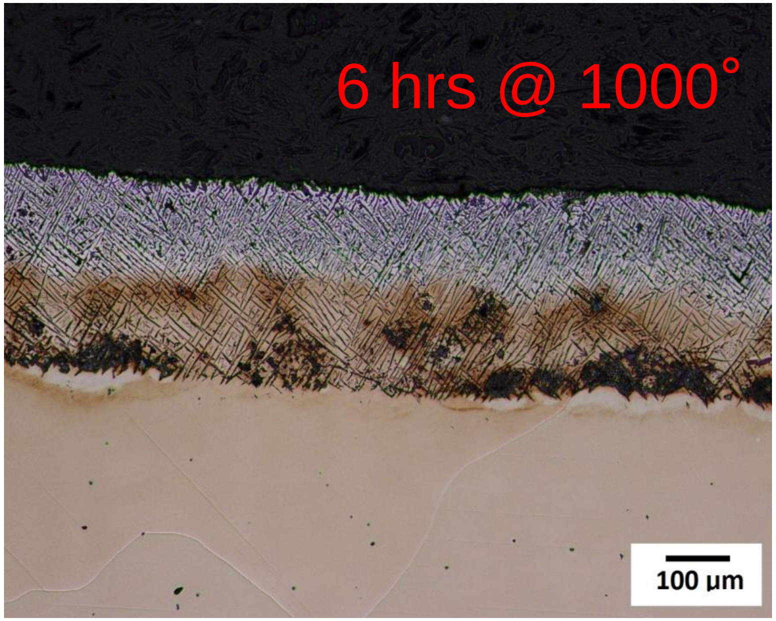
Steel B (8.8% Al, 1.6%Si) **Steel C (6% Al, 1.6%Si)**

- After 2 hrs at 900° C, the 6% Al specimen has an AlN case depth that is twice the depth of 8.8% Al specimen
- Depth of the AlN layer increased with time
- After 6 hrs at 900° C the AlN layer depth was 170 µm and 230 µm for Steels B and C, respectively

Optical Metallography of Nitrided Steels



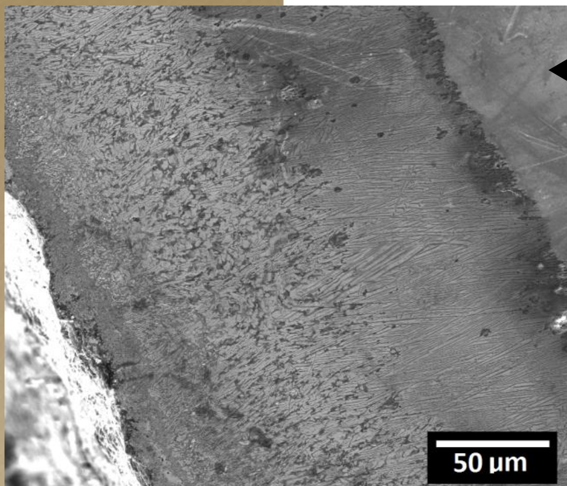
Steel B (8.8% Al, 1.6%Si)



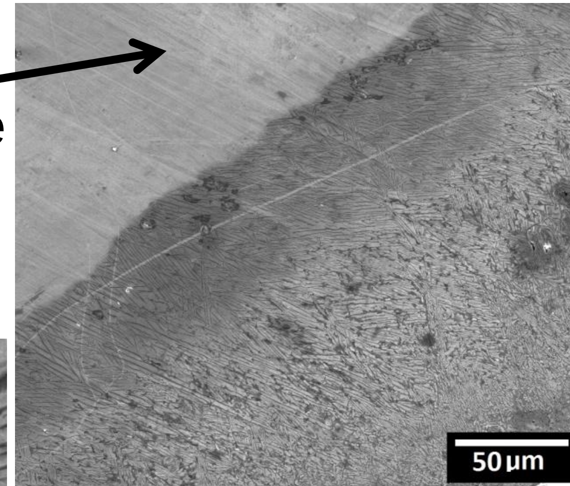
Steel C (6% Al, 1.6%Si)

- **Increasing time and temperature increases kinetics - AlN layer more than 300 µm.**
- **Decrease in kinetics with increasing aluminum content**
- **Silicon (1 to 1.6%) - no statistical effect**

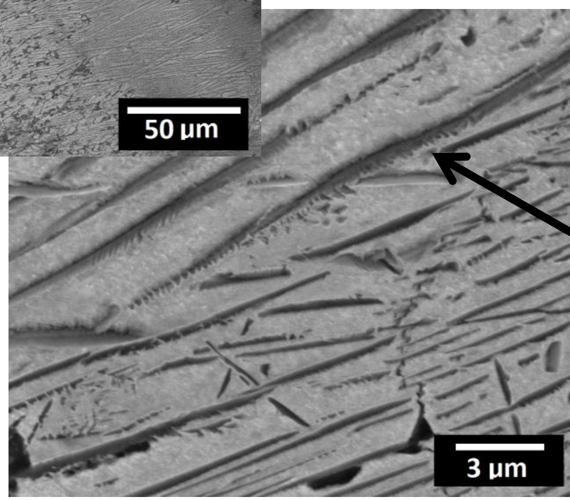
Electron Microscopy – Influence of Si



Steel substrate

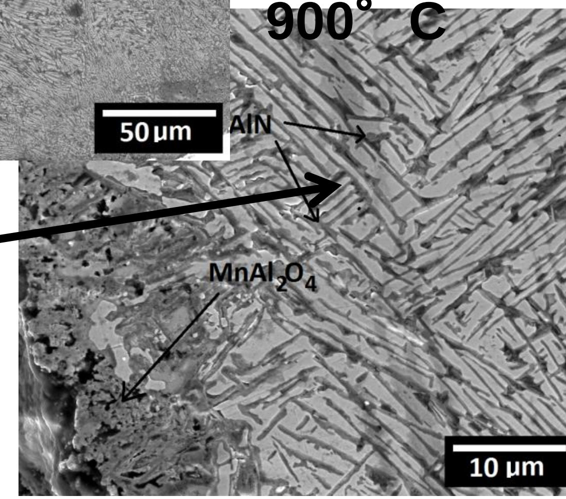


Steel B (8.8% Al, 1.6%Si)
8 hrs at 900° C



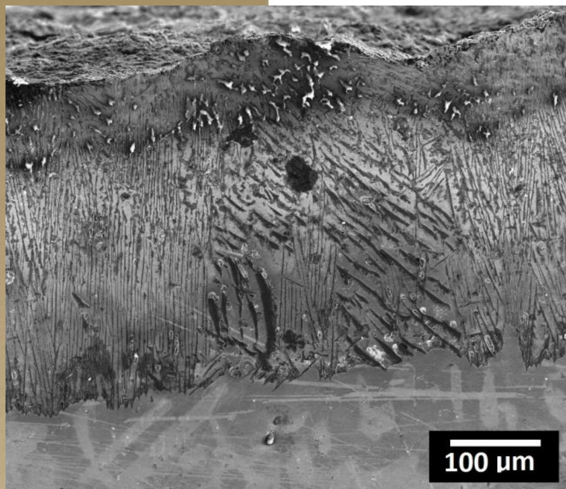
Steel A (8.8% Al, 1.1%Si)
8 hrs at 900° C

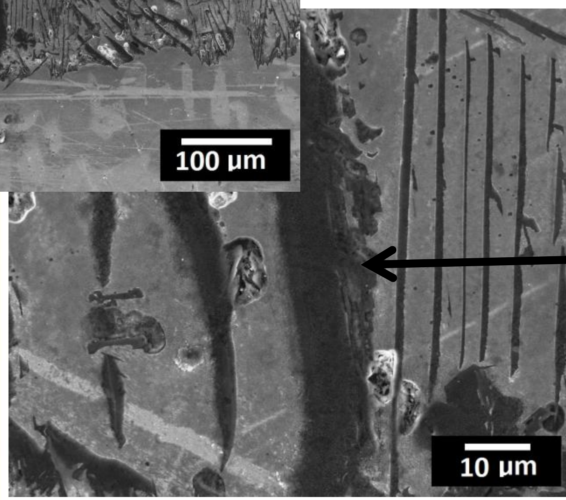
AlN needles



- ❖ **Case depth is similar regardless of Si**
- ❖ **Interfacial energy for the growth of AlN is lowest between (0001)AlN║(1-11)FCC - AlN plates grow along γ-(111)**
- ❖ **10-15 µm Oxide layers: $MnAl_2O_4$ and Al_2O_3 developed only after 8 hrs at 900° C**

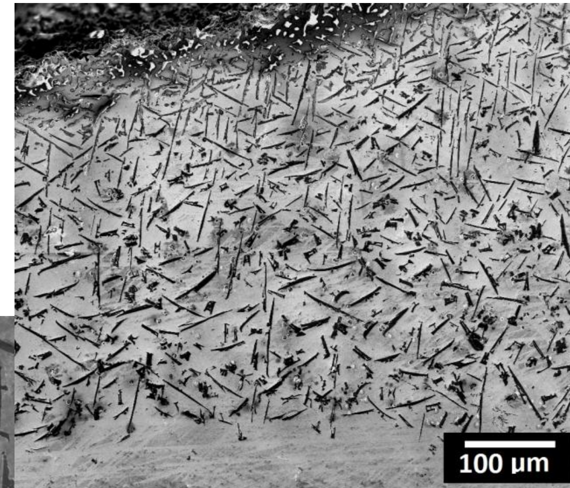
Electron Microscopy – Influence of Al



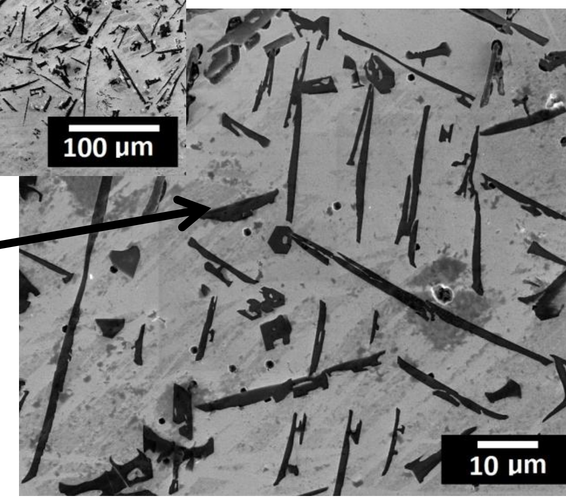


Steel B (8.8% Al, 1.6%Si) 8 hrs at 1100° C

AlN needles

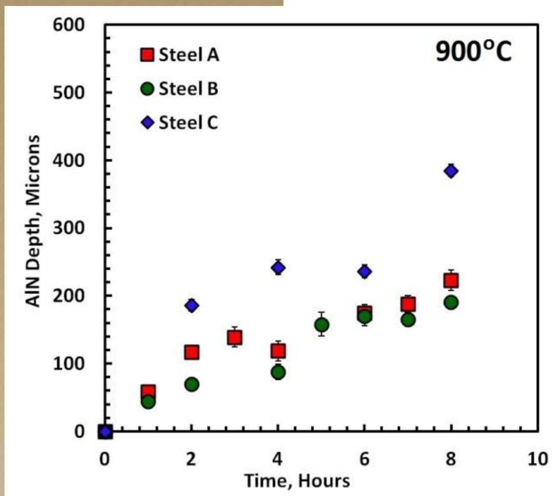


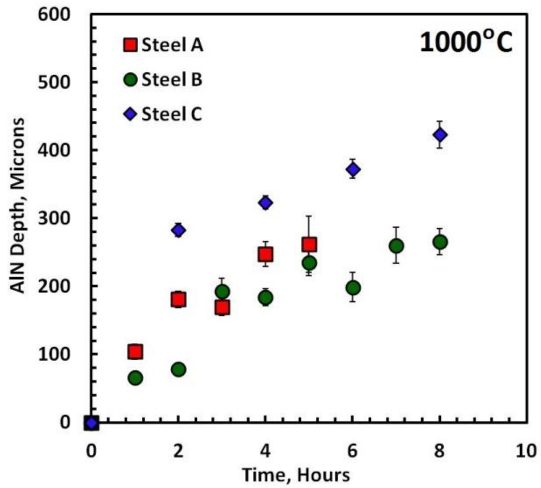
Steel C (6% Al, 1.6%Si) 8 hrs at 1100° C

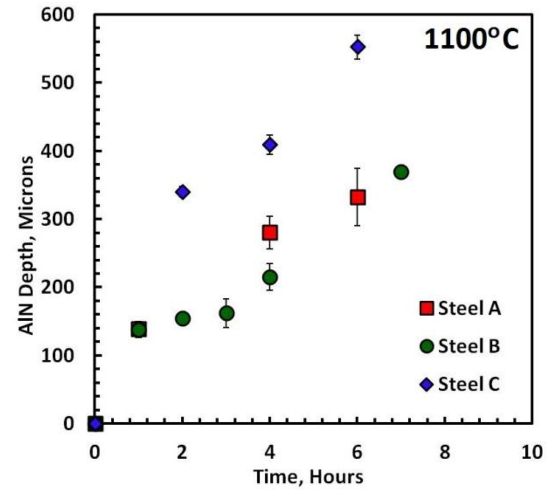


- Steel B, the AlN consists as a high density of longer and typically thinner plates that grow in (111) directions within the austenite
- As the Al content is reduced to 6%, density of AlN is much less - plate thickness is greater and case depth is almost 200 µm greater than in Steel B.

AlN Depth as a Function of Time and Temperature







- Growth of the AlN layer with time shows typical parabolic growth kinetics
- No statistical influence of Si on kinetics
- Decreasing Al increases growth of AlN layer over time

Summary of Kinetic Analysis

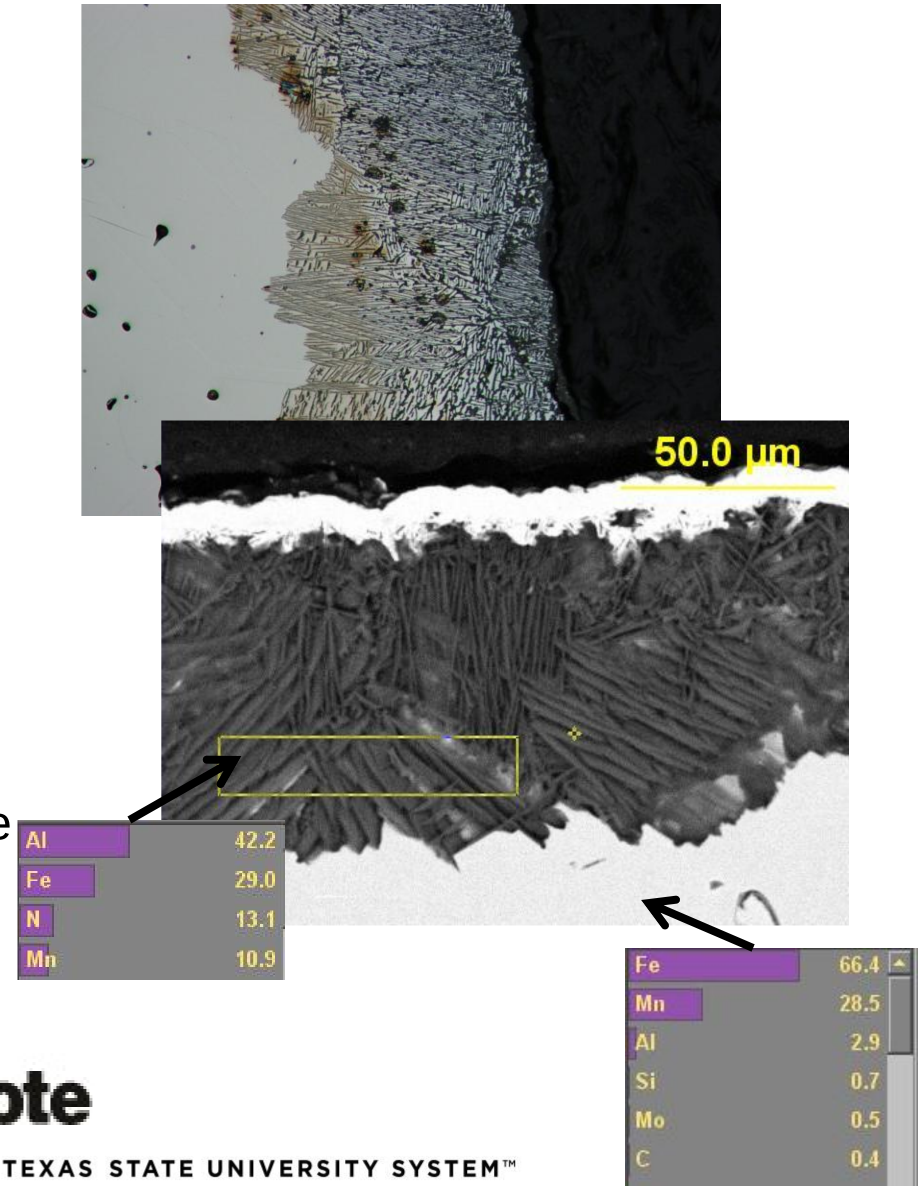
Experimentally determined kinetic parameters

Steel	T, °C	k, m/s	D_N, m²/s	Q, kJ/mol
Steel A	900	7.93E-13	1.49E-11	
	1000	2.00E-12	3.76E-11	
	1100	2.56E-12	4.79E-11	79
Steel B	900	6.75E-13	1.27E-11	
	1000	1.30E-12	2.43E-11	
	1100	2.16E-12	4.04E-11	78
Steel C	900	2.56E-12	3.32E-11	
	1000	3.29E-12	4.26E-11	
	1100	6.77E-12	8.77E-11	64

- Both Steel A and B show similar kinetic behavior with activation energies of 79 and 78 kJ/mol, respectively.
- Steel C was determined to have the fastest kinetics and the lowest activation energy of 64 kJ/mol

Nitriding of Fe-Mn-Al-C steels

- High aluminum content allows steel to be surface nitrided even in air!
- In a 100% nitrogen atmosphere, kinetics are increased
- Case depth of 200 µm after 2hr solution treatment at 1100ºC
- Depletion of Al from surrounding matrix would also increase toughness and wear resistance
- Plasma nitriding at Bodycote
- Future plans: Characterize wear resistance



Bodycote

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Publications

- L.N. Bartlett, D.C. Van Aken, J. Medvedeva, D. Isheim, N. Medvedeva, and K. Song, "An Atom Probe Tomographic Study of Kappa Carbide Precipitation in Lightweight Steel: Effect of Phosphorus," Metallurgical and Materials Transactions A. *Under Revision (2015)*.
- L.N. Bartlett and D.C. Van Aken, "High Manganese and Aluminum Steels for the Military and Transportation Industry," Journal of Materials, *published online August 2, (2014)*. DOI 10.1007/s11837-014-1068-y.
- L.N. Bartlett, D.C. Van Aken, J. Medvedeva, D. Isheim, N. Medvedeva, and K. Song, "An Atom Probe Study of Kappa Carbide Precipitation and the Effect of Silicon Addition,"
- Metallurgical and Materials Transactions A Vol. 45, pp. 2421-2435 (2014**).* Editor's Choice for Excellence** L.N. Bartlett, A. Dash, D.C. Van Aken, V.L. Richards, and K.D. Peaslee, "Dynamic
- Fracture Toughness of High Strength Cast Steels," International Journal of Metalcasting Vol. 7, Issue 4, (2013) *** Cover Article**

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Publications

- L.N. Bartlett and D.C. Van Aken, "On the Effect of Aluminum and Carbon on the Dynamic Fracture Toughness of Fe-Mn-Al-C Steels," AFS Transactions, Vol. 121, No. 13-1344 (2013).
- S.A. Buckholz, D.C. Van Aken, and L.N. Bartlett, "On the Influence of Aluminum and Carbon on Abrasion Resistance of High Manganese Steels," AFS Transactions, Vol. 121, No. 13-1343 (2013).
- D.C. Van Aken, S.A. Buckholz, and L.N. Bartlett, "Abrasion Resistance of High Manganese and Aluminum Steels," Paper 3.2, Steel Founders of America 66th Technical and Operating Conference, Chicago, IL, December 13, (2012).
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- L.N. Bartlett, A. Schulte, D. Van Aken, K. Peaslee, and R. Howell, "A Review of the Physical and Mechanical Properties of a Cast and Lightweight Fe-Mn-Al-C Steel," MS&T Conference Proceedings, Houston, Texas Oct. 17-21 (2010).