Development of Aluminium Alloys for High Temperature Applications in Diesel Engines

- Overview of selected research activities -

CANMET Materials Technology Laboratory, Ottawa, Canada

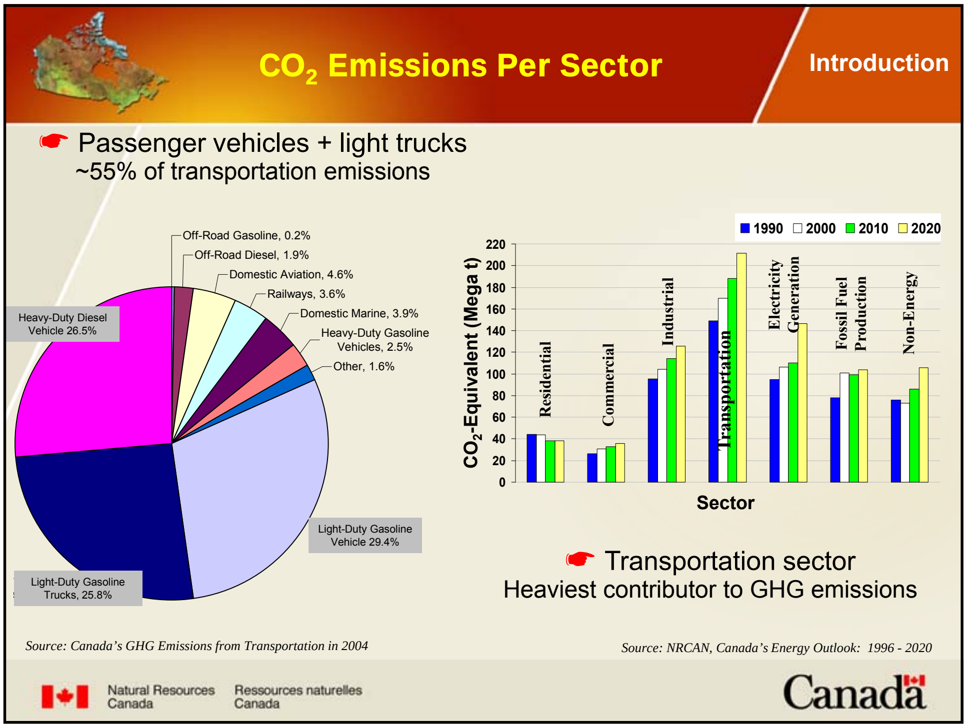
(Program: Advanced Structural Materials for Next Generation Vehicles)

W. Kasprzak, M. Sahoo, D. Emadi

MDEC Conference 2009, Sheraton Parkway, Toronto North, Richmond Hill, October 4 - 9, 2009

Presentation Overview

- Introduction
  - Emissions in automotive sector
  - Strategies for emission reduction
    - Vehicle weight reduction
    - Innovations in manufacturing processes
- Existing Al alloys for diesel engine components and requirements
  - Alloy survey
  - Performance challenges
- Al Alloy development activities at CANMET-MTL
- Energy efficient heat treatment strategies
- New trends for engine casting's performance improvement


CO2 Emissions Per Sector
Introduction
Passenger vehicles + light trucks
~55% of transportation emissions
Off-Road Gasoline, 0.2%
Off-Road Diesel, 1.9%
Domestic Aviation, 4.6%
Railways, 3.6%
Domestic Marine, 3.9%
Heavy-Duty Gasoline Vehicles, 2.5%
Other, 1.6%
Heavy-Duty Diesel Vehicle 26.5%
Light-Duty Gasoline Vehicle 29.4%
Light-Duty Gasoline Trucks, 25.8%
1990
2000
2010
2020
CO2-Equivalent (Mega t)
0
20
40
60
80
100
120
140
160
180
200
220
Residential
Commercial
Industrial
Transportation
Electricity Generation
Fossil Fuel Production
Non-Energy
Sector
Transportation sector
Heaviest contributor to GHG emissions
Source: Canada's GHG Emissions from Transportation in 2004
Source: NRCAN, Canada's Energy Outlook: 1996 - 2020
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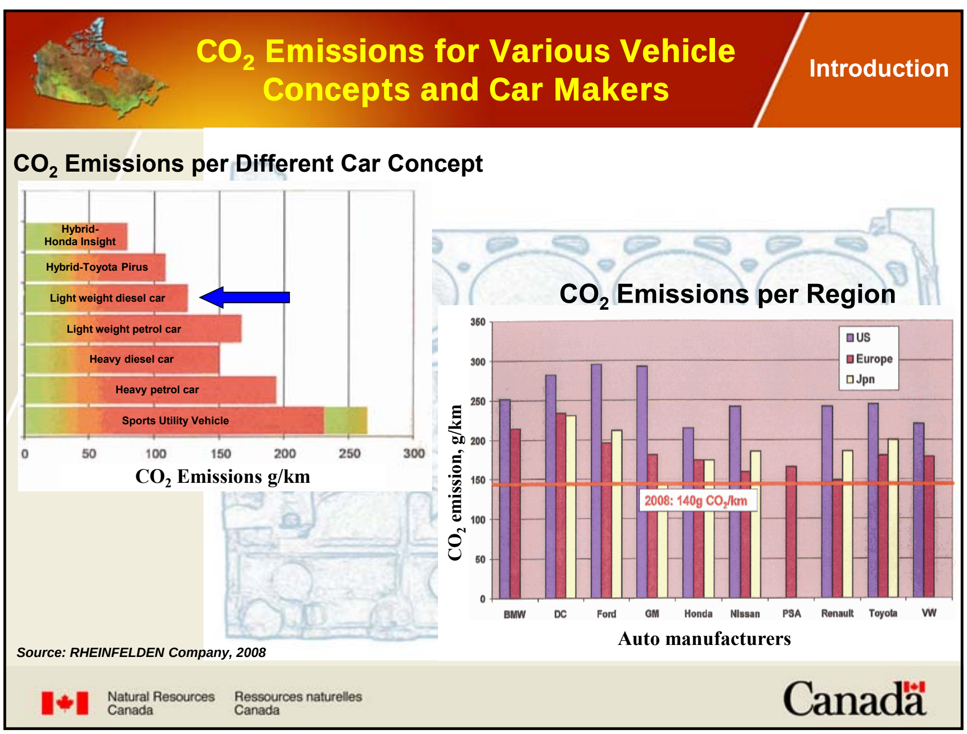
CO2 Emissions for Various Vehicle Concepts and Car Makers
Introduction
CO2 Emissions per Different Car Concept
Hybrid-Honda Insight
Hybrid-Toyota Pirus
Light weight diesel car
Light weight petrol car
Heavy diesel car
Heavy petrol car
Sports Utility Vehicle
0
50
100
150
200
250
300
CO2 Emissions g/km
CO2 Emissions per Region
US
Europe
Jpn
CO2 emission, g/km
2008: 140g CO2/km
BMW
DC
Ford
GM
Honda
Nissan
PSA
Renault
Toyota
VW
Auto manufacturers
Source: RHEINFELDEN Company, 2008
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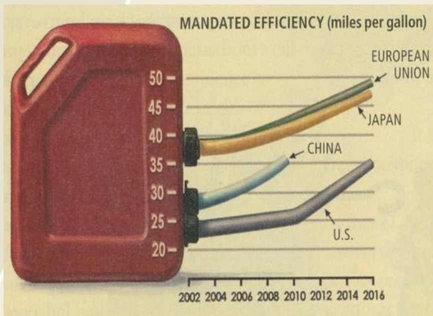
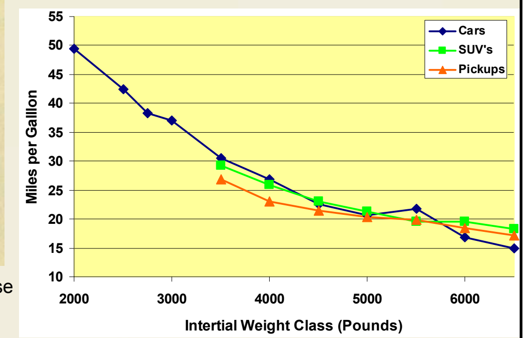
Vehicle Weight Reduction for Improved Fuel Efficiency and CO_2 Reduction

Introduction





- Mileage of cars and light trucks sold in US must rise from current 25 to 35.5 mpg by 2016.
- Will be not enough to bring US in line with vehicles sold now in Japan and Europe.

☛ Approx. 10% drop in weight

☛ 6-8% better fuel economy

Source: U.S Environmental Protection Agency (http://epa.gov)

Activities with Major Impact on Weight Reduction and CO_2 Emissions

Introduction

Major Activities:

- Application of light weight alloys,
- Innovations in manufacturing process,
- Component design.

Reducing the weight of vehicle by 100kg results in:

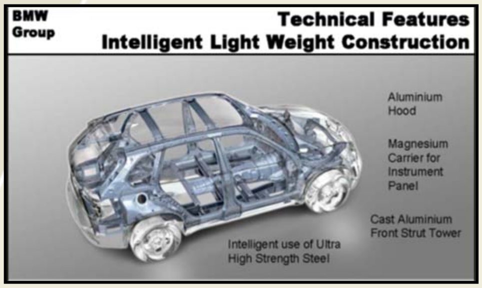
- Reduces fuel consumption by 0.3 to 0.5l/100km,
- Extends the cruising range by 7.5%,
- Allows to reach 100km/h six (6) meters sooner,
- 8 to 11 less grams of hydrocarbon emission every kilometre,
- Active and passive safety improvement:
  - Quicker reaction to driver's inputs,
  - Brings less energy to a crash.

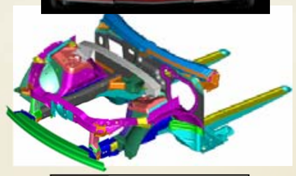
Activities with Major Impact on Weight Reduction and CO_2 Emissions - cont.

Introduction

1. Application of light weight alloys

Chassis and body





Steel baseline design
79 Parts & 84.3 kg

Magnesium design
35 Parts & 46.1 kg

38.2 kg mass reduction (45%)
44 part reduction (55%)

- ☛ 100kg weight reduction
- ☛ 2-3% better fuel economy
- ☛ 3.5g/km CO_2 reduction

Source: US-Canada-China Collaborative R&D Project (MFERD), CANMET-MTL, 2009

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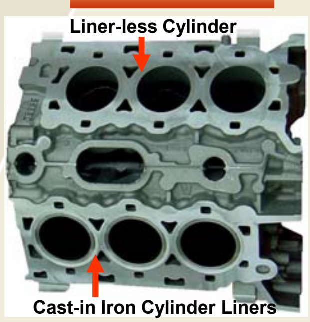
Activities with Major Impact on Weight Reduction and CO_2 Emissions - cont.

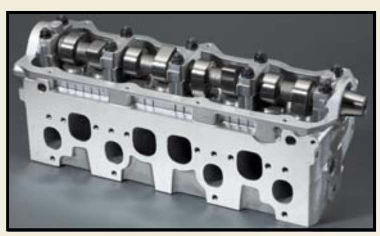
Introduction

1. Application of light weight alloys

Powertrain



3.0l V6 Engine Block (Al-Si-Cu alloy)



Heat resistant Al Cylinder Head (Al-6%Si-3%Cu alloy)

Forged Al Piston (Al-11%Si-3%Cu-0.5%Mg alloy)

- ☛ 30% Engine downsizing
- ☛ 10-15% less engine weight
- ☛ 10-20 % less CO_2 emissions

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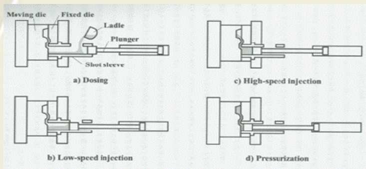
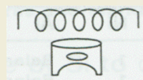
Activities with Major Impact on Weight Reduction and CO_2 Emissions - cont.

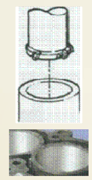
Introduction

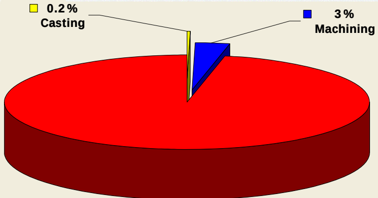
2. Innovations in Manufacturing Process – **Energy Efficient Heat Treatments**

HPDC Casting process → Heat treatment → Machining → Honing









Process	Duration, min		Improvement, %
	Existing	Revised	
Vacuum HPDC	1	1	N/A
Heat treatment (T6)	480	175	63
Machining Engine block Cylinder bore (honing)	15.5 13.5 2	15.5 13.5 2	N/A

W. Kasprzak, et. al., "Development of Energy Efficient Heat Treatment Processes for Light Weight Automotive Castings", 25th ASM Heat Treating Society Conference, IN, USA, p. 1-10, 2009

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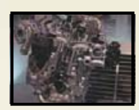
Upcoming Diesel Cars in 2009/2010

Introduction

Honda Accord Tourner Concept

- 2.2 liter i-DTEC diesel
- The i-DTEC technology is aimed at meeting Europe's tougher Euro 6NOx regulations in 2014

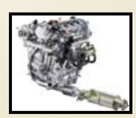



BMW 335d

- Twin-turbo 3.0 liter in-line engine
- 23 mpg in the city and 33 mpg on the highway

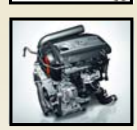

Acura TSX Diesel

- New 2.2 liter i-DTEC four-cylinder clean diesel engine

Volkswagen Jetta TDI

- 2.0 liter four-cylinder turbo-diesel engine

☞ **Good evidence for alloy development activities**

http://www.autotropolis.com/wiki/index.php?title=Upcoming_Diesel_Cars

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Al Castings for Engine Applications in Passenger Vehicles

Performance Challenges

Components	Engine Block	Cylinder Head	Piston
Alloy System	Al-Si-Mg-(?) Al-Si-Cu-(?)	Al-Si-Mg-(?) Al-Si-Cu-(?)	Al-Si-Cu-Ni-(?)
Operating Temperature (°C)	135	250	400
Operating Pressure (bar)	-	>180	-
HCF (MPa)	180	140	>200
Creep $_{\sigma\ 0.1/100}$	-	44	-
SDAS (μm)	20	20	-
Process	LPSP, HPDC	SPM	SPM, Forging

LPSP - Low Pressure Sand Package
SPM - Semi-Permanent Mold
HPDC - High Pressure Die Casting

Limitations:

Elevated operating temperature and internal pressure disqualify existing Al alloys for small, turbocharged, energy efficient automotive engines

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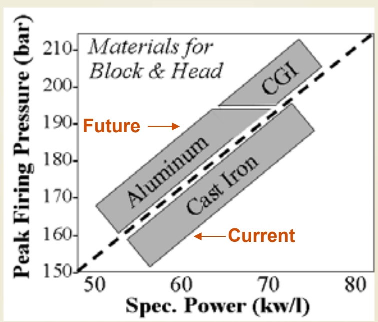
Alloy Chemistries used for High Temperature Powertrain Applications (Passenger Vehicles)

Existing Alloys

The aluminum alloys claimed to be used for gasoline and diesel engine cylinder heads:



Category 1:

- Al-Si-Mg alloys (ex: A356, A357)
  - (good ductility, lack of strength >250°C)

Category 2:

- Al-Si-Mg-Cu alloys (ex: A356 + 0.5% Cu)
  - (good ductility, retaining strength between 200-250°C)

Category 3:

- Al-Si-Mg-Cu alloys with Mn, Zr, V, Ti and Cr
  (ex: A356+1%Cu+0.15%Zr+0.15%Cr and A319+0.15%Mn+0.25%V+0.15%Zr)
  - (lower ductility, higher YS and creep at 250°C)

R.Fuoco, M.F.Moreira, Fatigue Cracks in Aluminum Cylinder Heads for Diesel Engines, AFS 2009, 09-117

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Alloy Chemistry Survey for Diesel Cylinder Heads (Passenger Vehicles)

Existing Alloys

(Europe 1998 Model)

A

(Europe 2003 Model)

B

(Asia 2005 Model)

C

Product	Alloying Elements, %													
	Si	Cu	Mg	Zn	Fe	Ti	Mn	Ni	Cr	Sn	Pb	Sr	V	Zr
A	6.4	3.2	0.22	0.52	0.52	0.15	0.40	0.032	0.028	0.007	0.074	0.01	-	-
B	5.5	3.2	0.19	0.035	0.29	0.12	0.34	0.017	0.010	0.005	0.01	0.01	-	-
C	5.3	3.4	0.14	0.27	0.56	-	0.56	0.023	0.03	0.02	0.02	-	-	-

☞Strong popularity of conventional alloys (Al-Si-Cu-Mg)

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Development of the Al Alloy Chemical Compositions

R&D Activities

Al Alloy chemistries under evaluation based on 356, 319, 390 grades with various addition levels

Si	Cu	Mg	Fe	Sr	Ni	Zr	Ti	V	Sc
7→20	0.1 →4	0.1 →1	0.1 → 0.4	0 → 0.2	0 → 0.5	0 → 0.4	0 → 0.2	0 → 0.4	0 → 0.4

Mechanical Testing

Tensile | *Creep* | *Fatigue*

Thermo/Physical Testing

Thermal Analysis | *Dilatometry* | *Electrical Resistivity*

→ Casting High Temperature Performance

☞Only compromise will lead to optimum alloy chemistry

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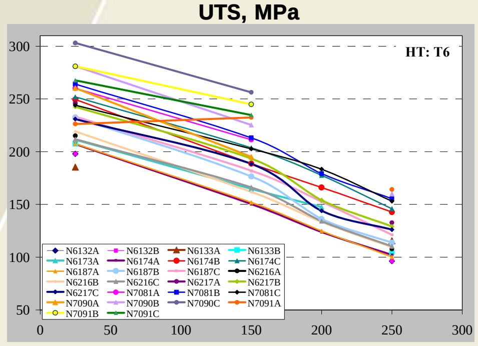
Mechanical Testing (Tensile at 25-250°C)

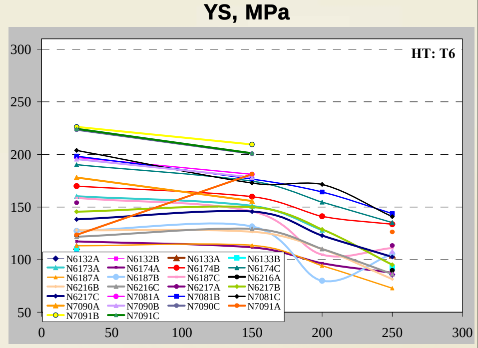
Mechanical Properties

UTS, MPa



Testing temperature, °C

YS, MPa



Testing temperature, °C

- Proper development of alloy chemical composition has an significant effect on mechanical properties at room and elevated temperatures

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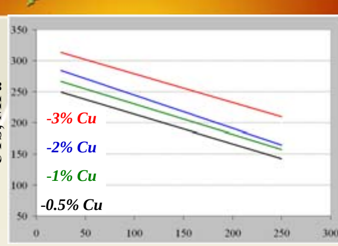
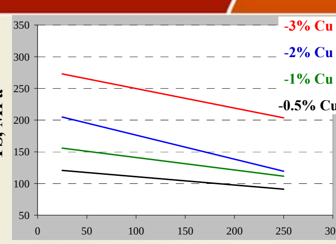
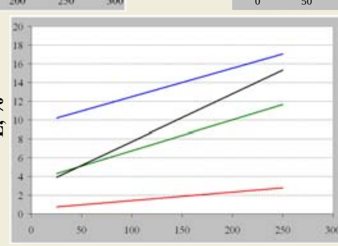
Mechanical Testing - cont. (Tensile at 25-250°C)

Mechanical Properties

T6: ST@505°C/9hrs+AA@250°C/100mins







Testing temperature, °C

- Increased Cu has a predominant effect on elevated mechanical properties up to 250°C.
- Effect of Zr, V, Ti overlaps with Cu, Mg additions

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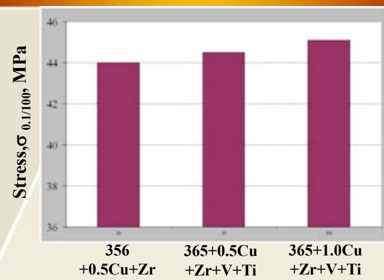
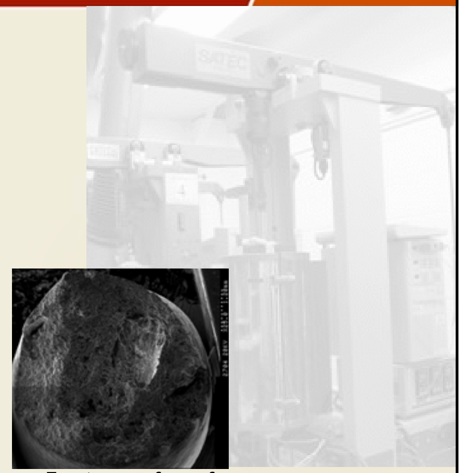
High Temperature Performance Assessment (Creep)

Mechanical Properties



Stress levels for 0.1% elongation after 100hrs exposure for 356 based alloys tested in T7 condition

Alloy	Hardness (HR15T)	
	Before Creep	After Creep
A	58	61
B	56	57
C	80	71



Fracture surface of 356+1.0Cu+Zr+V+Ti alloy

☞ *Additions of Zr, V, Ti improves creep performance due to formation of dispersoid phase*

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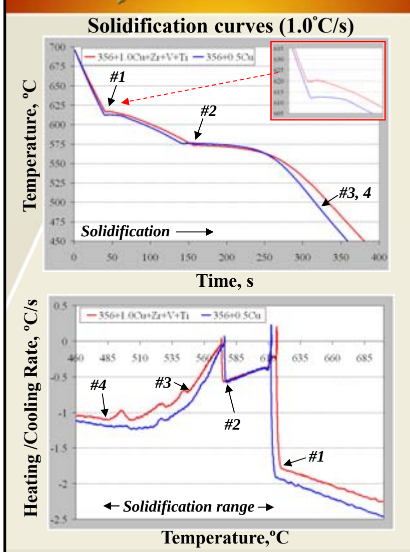
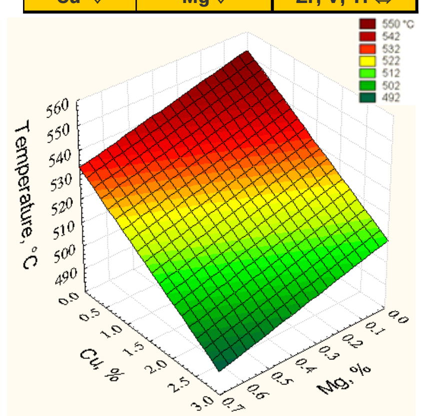
Microstructure Evaluation in the As-Cast Condition

Microstructure Analysis



Cu ⇓	Mg ⇓	Zr, V, Ti ⇔



The effect of Cu, Mg additions on incipient melting temperature

☞ *0% Mg - higher solution & better homogenization*

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Alloy Phase Identification - Neutron Diffraction during Solidification Process

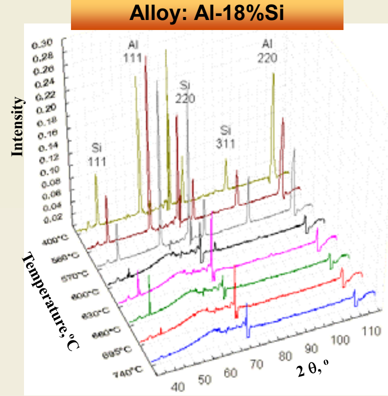
Microstructure Analysis

NRU Atomic Reactor

Thermal-neutron spectrometers

NRU Reactor (Chalk River, Canada): Thermal neutron source (120MWth), Medium flux (~3 x 1014/cm²/s)

Alloy: Al-18%Si



Neutron diffraction spectrum for Al-18%Si alloy obtained during solidification with ~1°C/s

Solidification Cell

☞ Improved signal resolution for more detailed solidification analysis

W. Kasprzak, D. Sediako et al., Characterization of Hypereutectic Al-Si Alloys using In-Situ Neutron Diffraction and Thermal Analysis Techniques, TMS 2010

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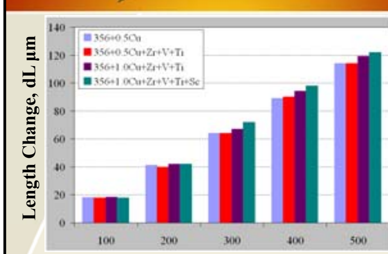
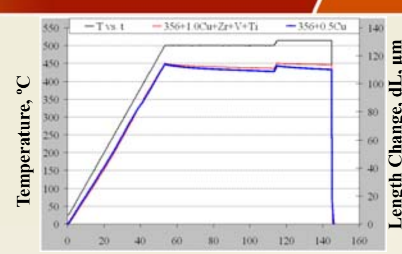
Effect of Alloy Chemistry on Casting Dimensional Stability

Thermo-physical Properties



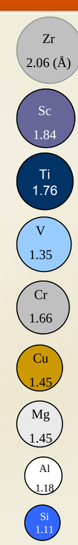
Length change between 100-500°C for various alloy chemistries

Alloying Element	Thermal Expansion
Cu, Mg, Sc, Cr	⇑
Zr, V, Ti	TBD



Heat treatment needs to be optimized to control stress development

Heat treatment crack between cylinder bores



☞ Minimized residual stress for improved fatigue performance

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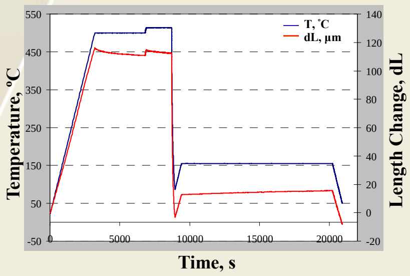
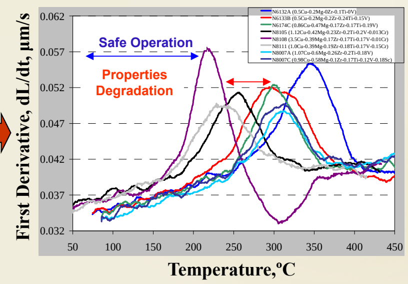
Effect of Alloy Chemistry on High Temperature Performance

In-Service Assessment

Alloy: 356 base + Cu, Zr, V, Ti, Sc





Alloying Elements
Cu
Mg
Ni
Zr
V
Ti
Sc

Heat Treatment simulation using Quench Dilatometer

Over-aging temperature varies between 210-360°C depending from alloy chemistry

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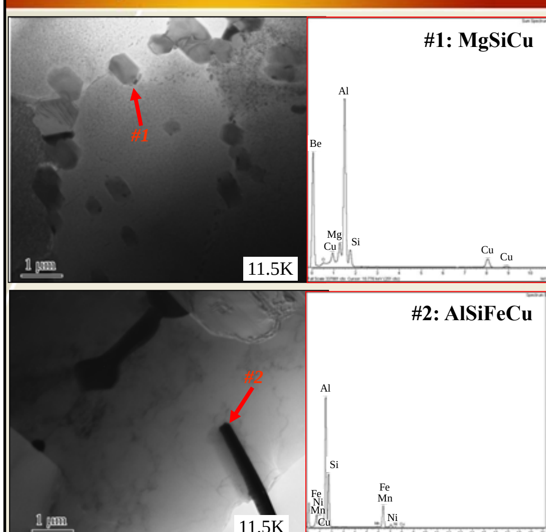
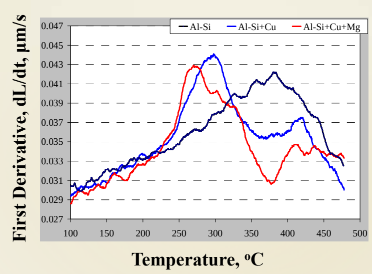
Effect of Alloy Chemistry on High Temperature Performance – cont.

In-Service Assessment



Alloys: Al-Si, Al-Si-Cu, Al-Si-Cu-Mg

Si ⇑	Cu ⇓	Mg ⇓	Zr / V / Ti ?



☞ *Effect of individual alloying elements on over-aging temperature - TBD*

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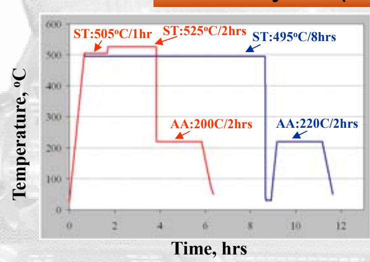
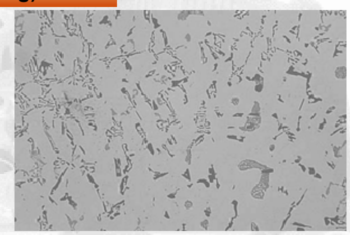
Energy Efficient Heat Treatment for Diesel Cylinder Head

Heat Treatment Development

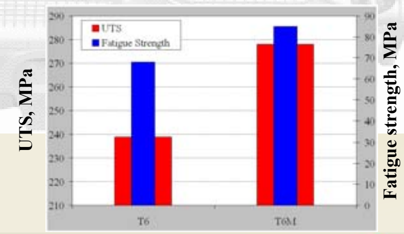
Alloy: 319 (Al-7Si-3Cu-0.5Mg)





LOM micrographs (100x) of the 319 alloy heat treated test sample (T6M)

☞ Potential for improved fatigue performance:
- *Two-step solution treatment*
- *Interrupted quenching*
- *Mild quench rate (5˚C/s $_{525-200}$)*



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Government
- NRC-CNRC, Chalk River, Canada
- NRC-CNRC, Ottawa, Canada

Academic
- University of Windsor, Windsor, Canada
- Ryerson University, Canada

Industrial
- NEMAK of Canada Corporation, Canada
- Yamaha Motor, Japan
- Nissan Motor, Japan

Thank you!

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