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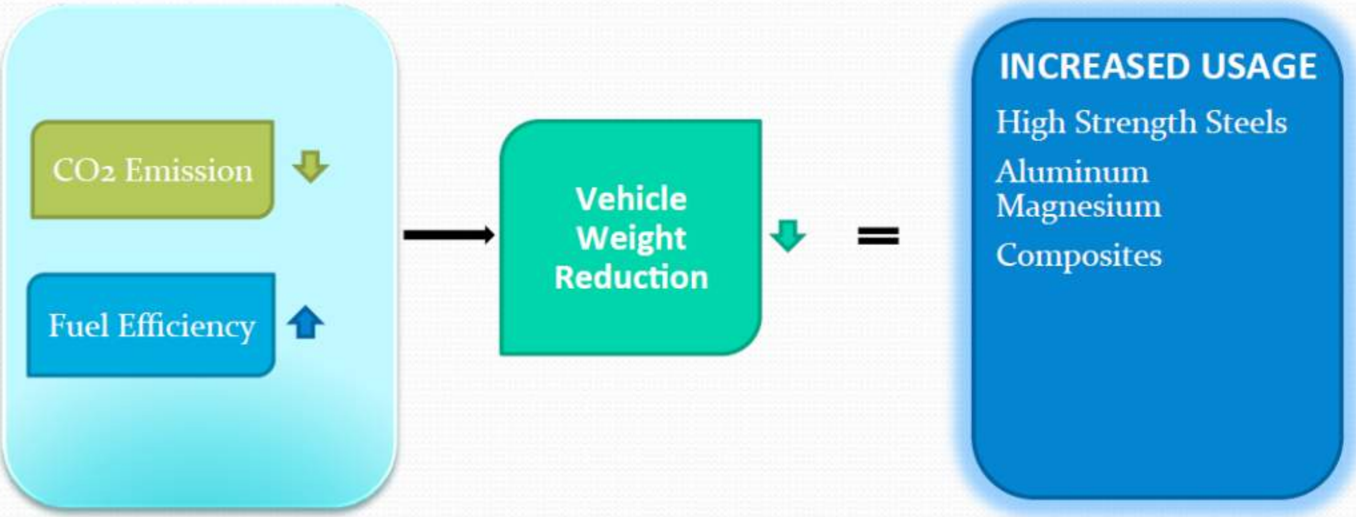
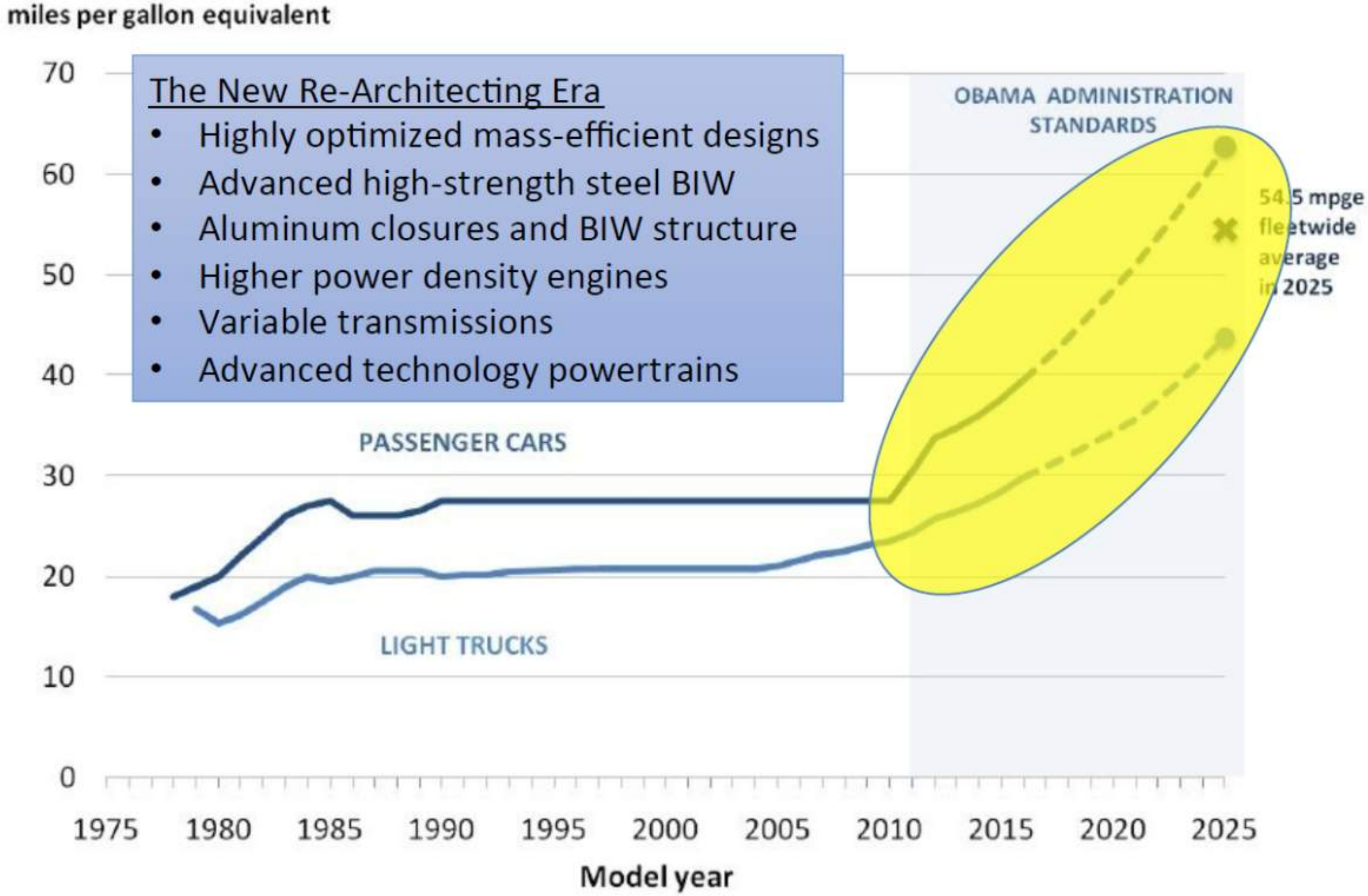
Lightweight and Smart Materials to Reduce Fuel Consumption in Cars, Trucks, Railways, and Two-Wheelers

Pradeep Rohatgi
State of Wisconsin and UWM Distinguished Professor
Director of the UWM Center for Composite Materials

Global Market Trend



RB&W



MY1978-2011 figures are NHTSA Corporate Average Fuel Economy (CAFE) standards in miles per gallon. Standards for MY2012-2025 are EPA greenhouse gas emission standards in miles per gallon equivalent, incorporating air conditioning improvements. Dashed lines denote that standards for MY2017-2025 reflect percentage increases in Notice of Intent.

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LIGHTWEIGHT HEXAGON

„R-M-C“ factors

- Regulations
- Materials
- Costs

„P-J-D“ factors

- Performance
- Joining
- Design

BUILDING TRUST Sika

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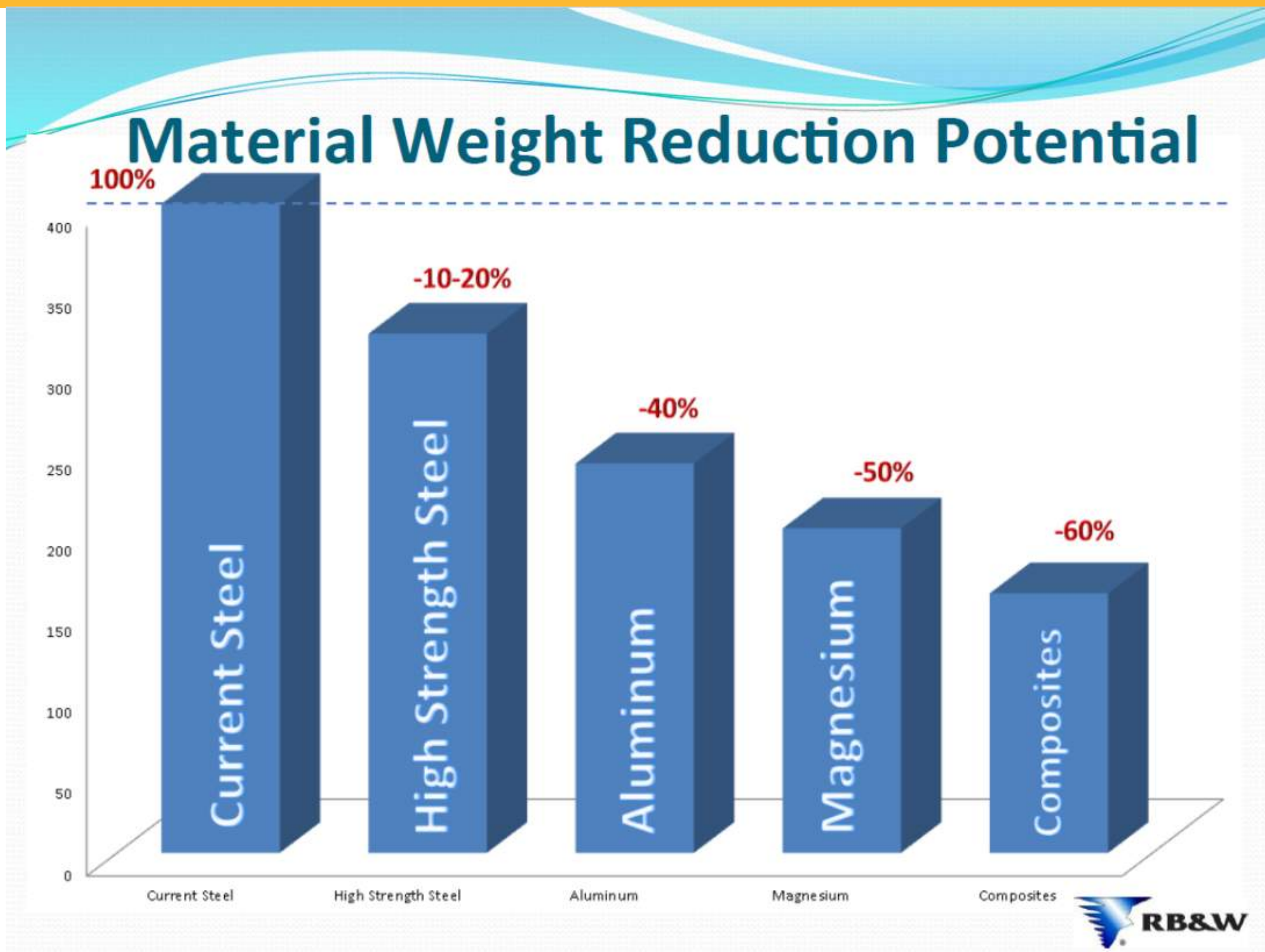
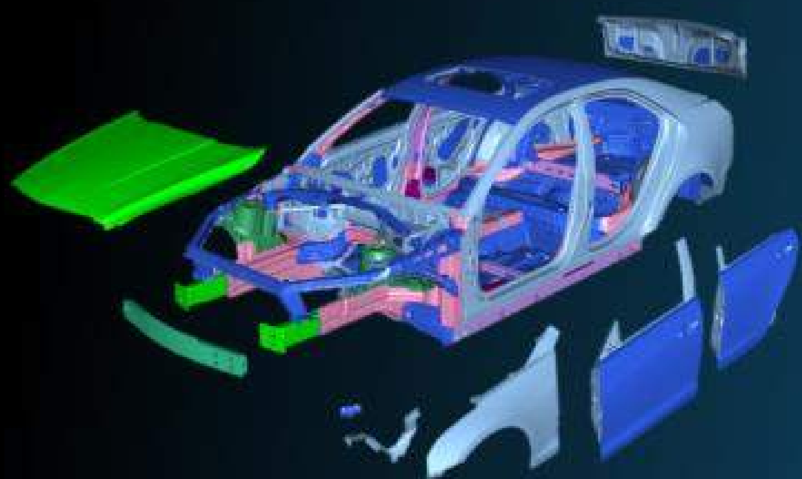


MATERIAL STRATEGY

Cadillac steel strength trends



Yield strength (average mPa)

Tensile strength (average mPa)

YS_{avg} = 23% increase

TS_{avg} = 16% increase

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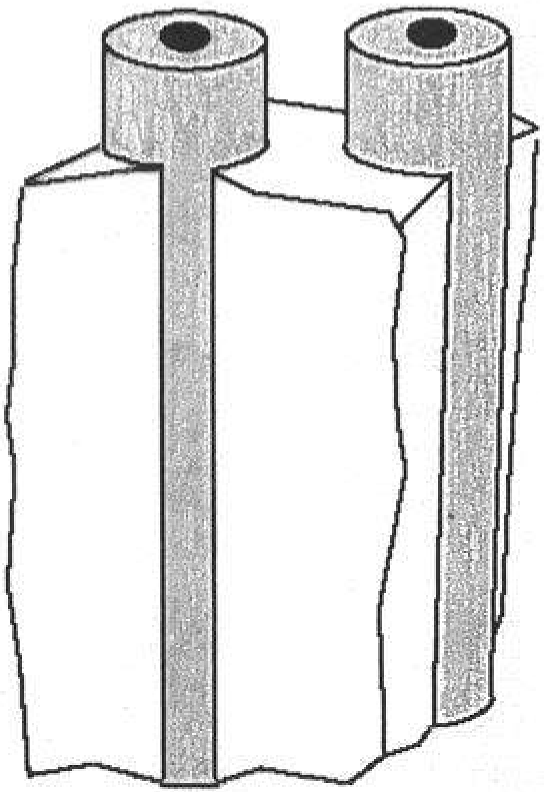
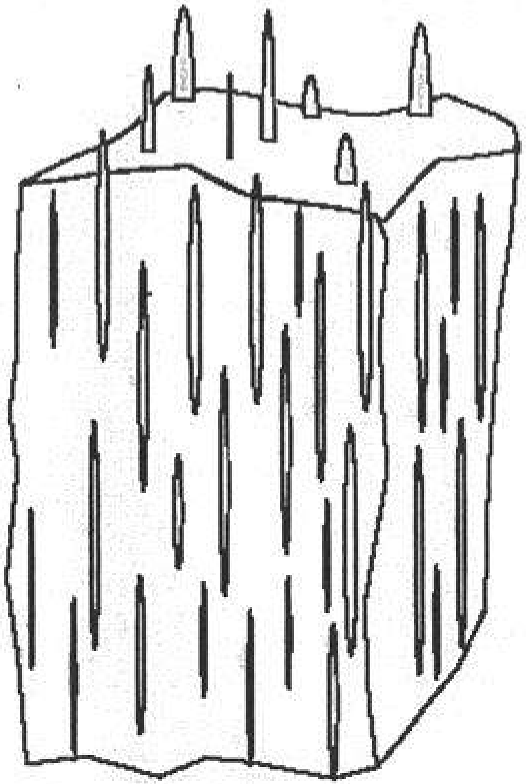
Presentation Guide

- Introduction to Metal Matrix Composites
- Metal Matrix Composite Applications
- Syntactic Foams
- Nanocomposites
- Self Lubricating, Self Healing, and Self Cleaning Composites
- Composites and Capabilities at UWM
- Concluding Remarks

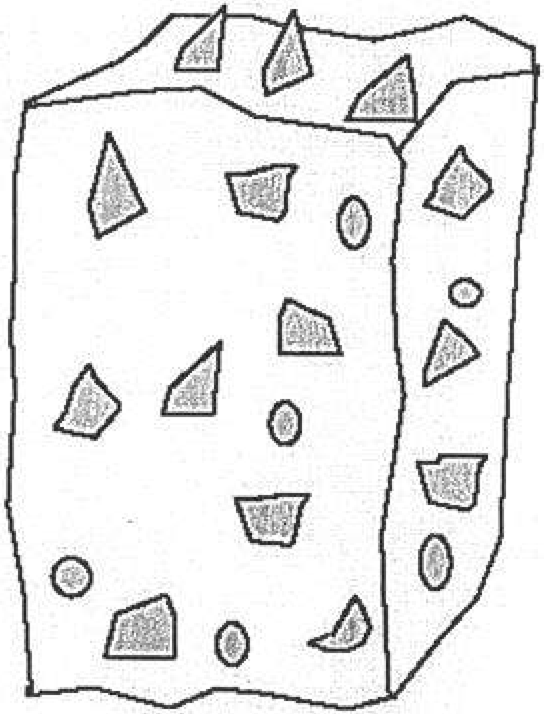
A Survey of MMC Types and Developments



Monofilaments



Whiskers/Staple Fibres

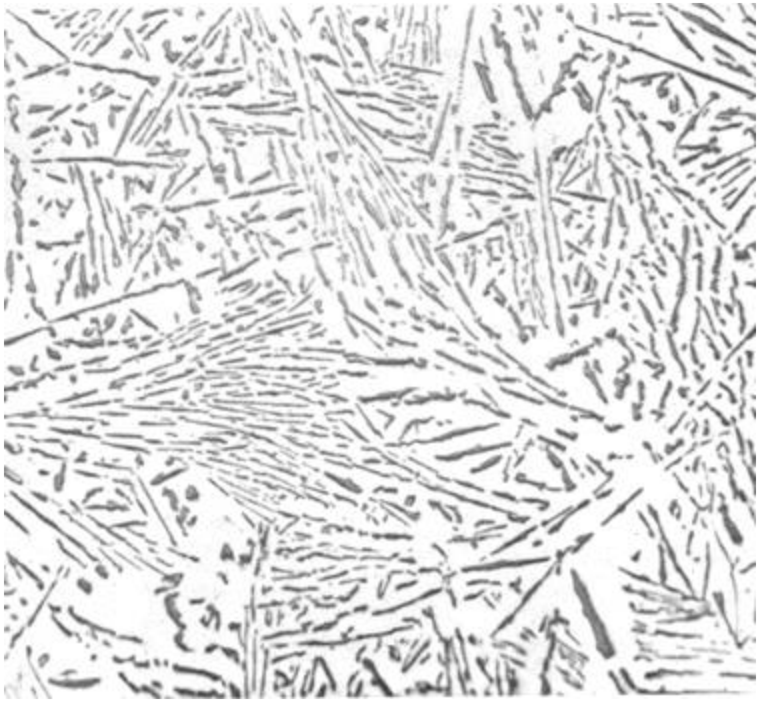


Particulate

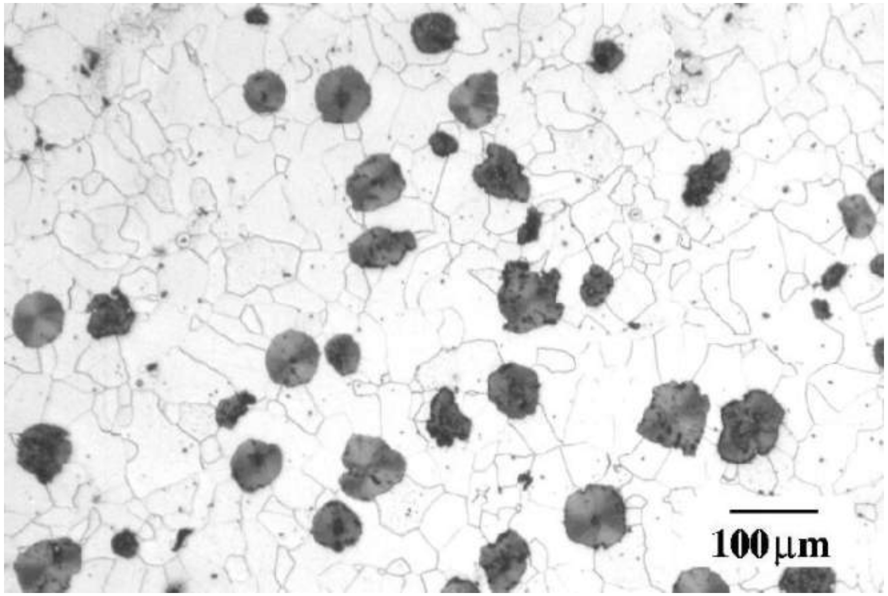
Reinforcement, Processing and Cost of MMCs

COST	Reinforcement	Processing
HIGH	FIBERS	DIFFUSION BONDING
	CONTINUOUS FIBER WHISKERS	POWDER METALLURGY $22-37/kg
LOW	PARTICULATE	LIQUID METAL $4-11/kg

MMCs are Old Hat for Foundrymen

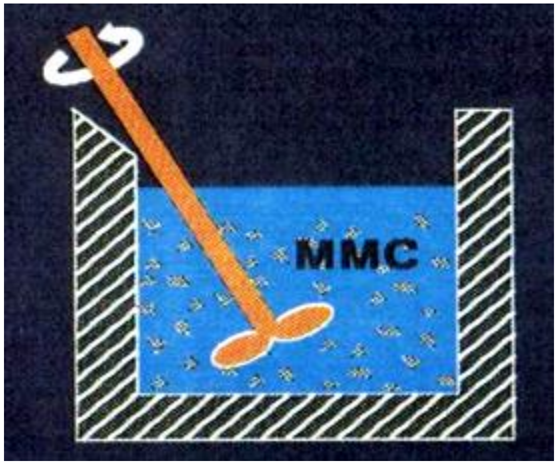


Al-Si alloy

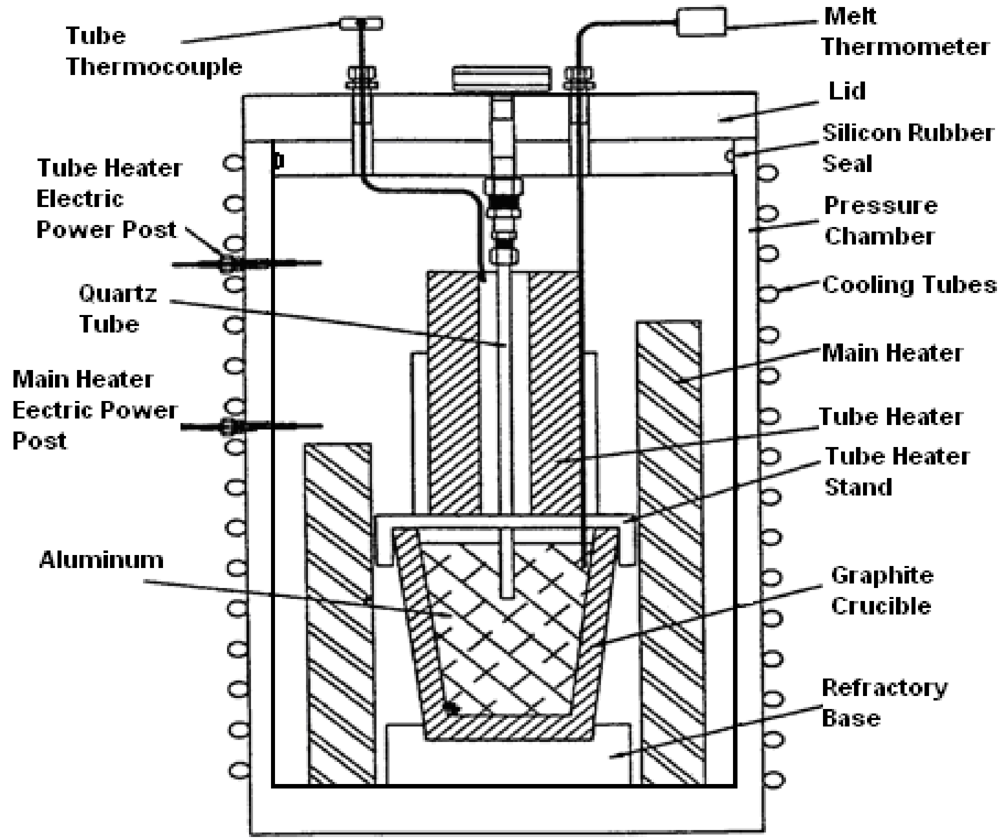


Ductile Cast Iron

MMC Forming Processes

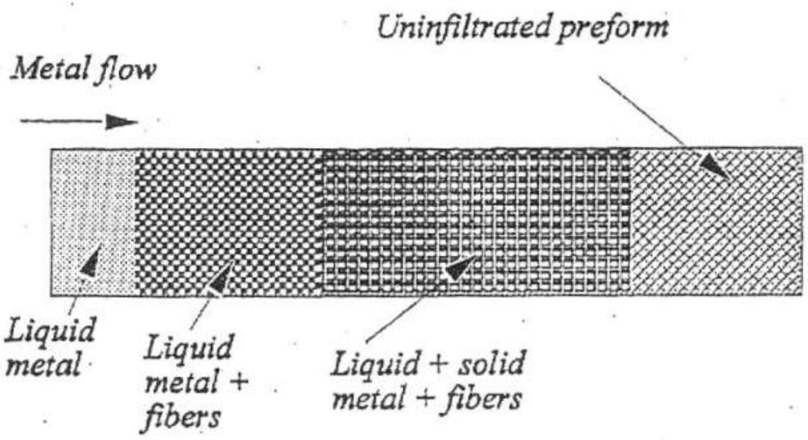


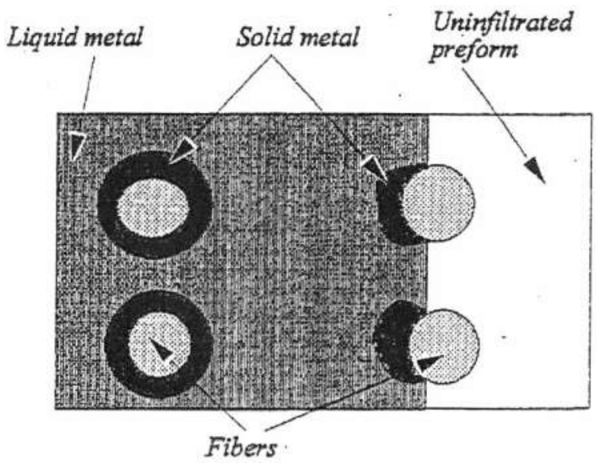
Stir Mixing

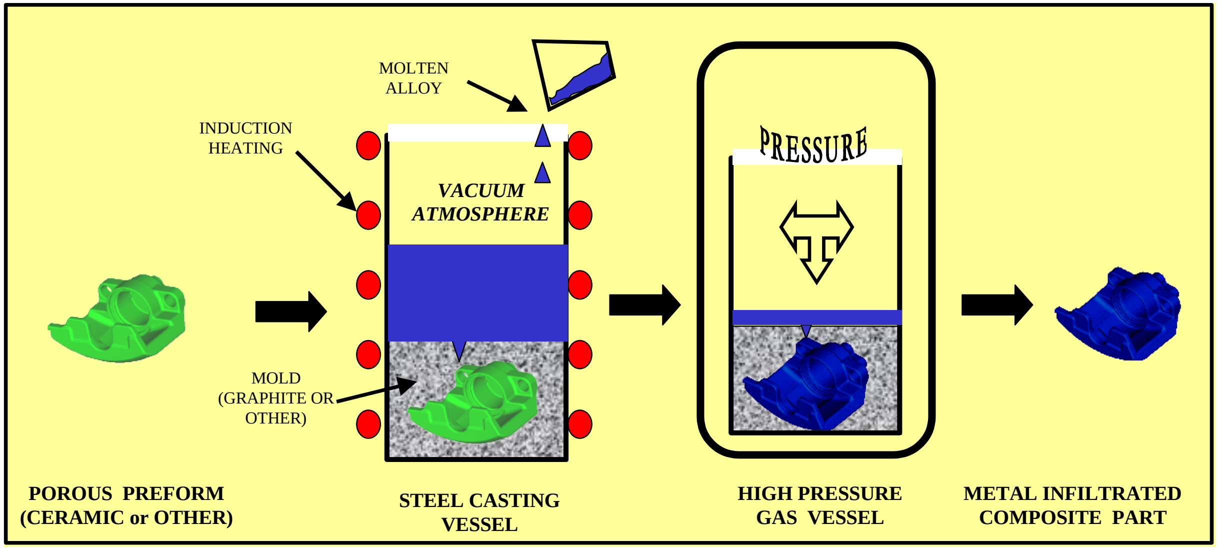


Infiltration

MMC Forming Processes







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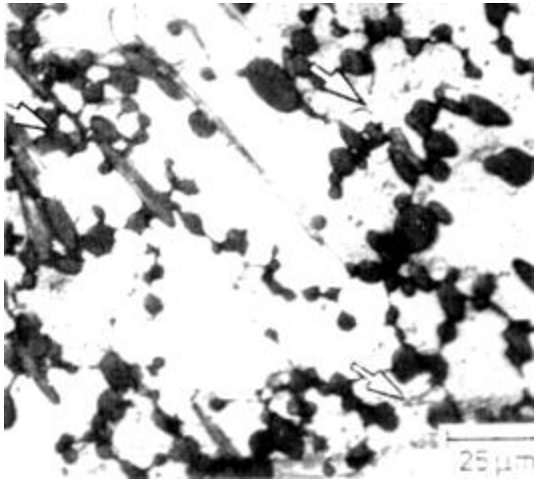
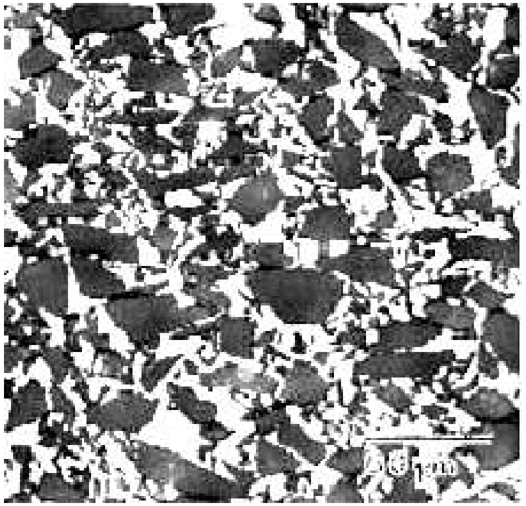
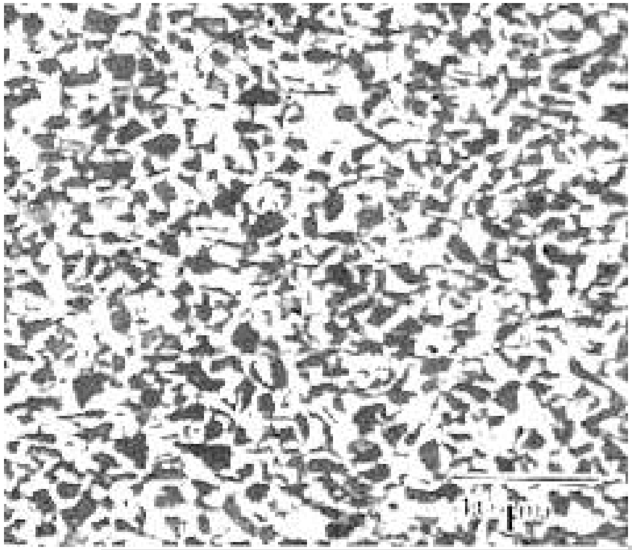
Train Rotor with Interrupted Pour Gating

Liquid Metal Infiltration

a) 

b) 

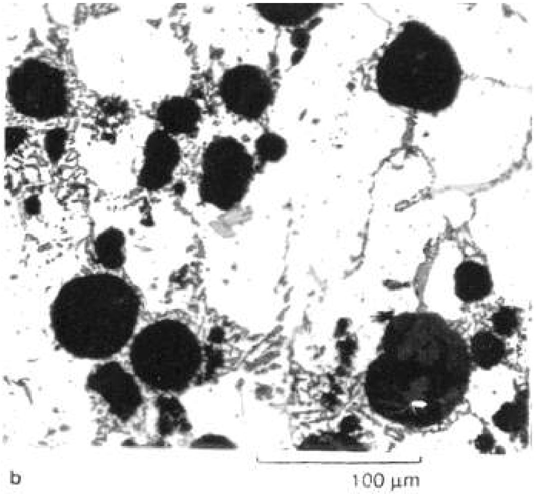
c) 

- **a) Al-Si/Saffil Fiber produced by Toyota**
- **b) A356/SiC/70p**
- **c) A356/SiC/60p**

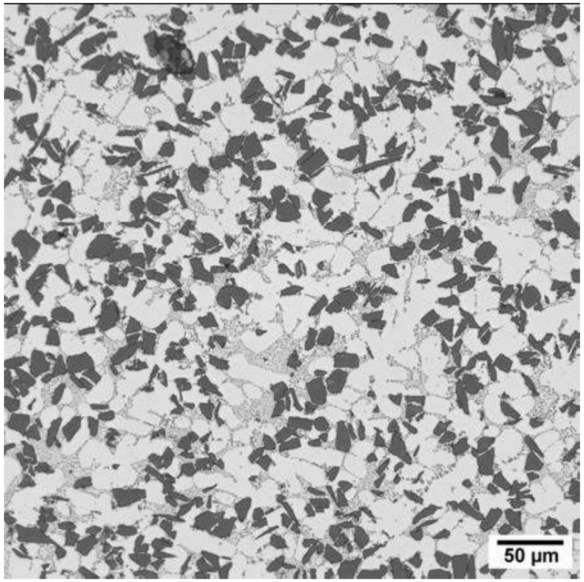
Microstructures of typical MMCs

(a)

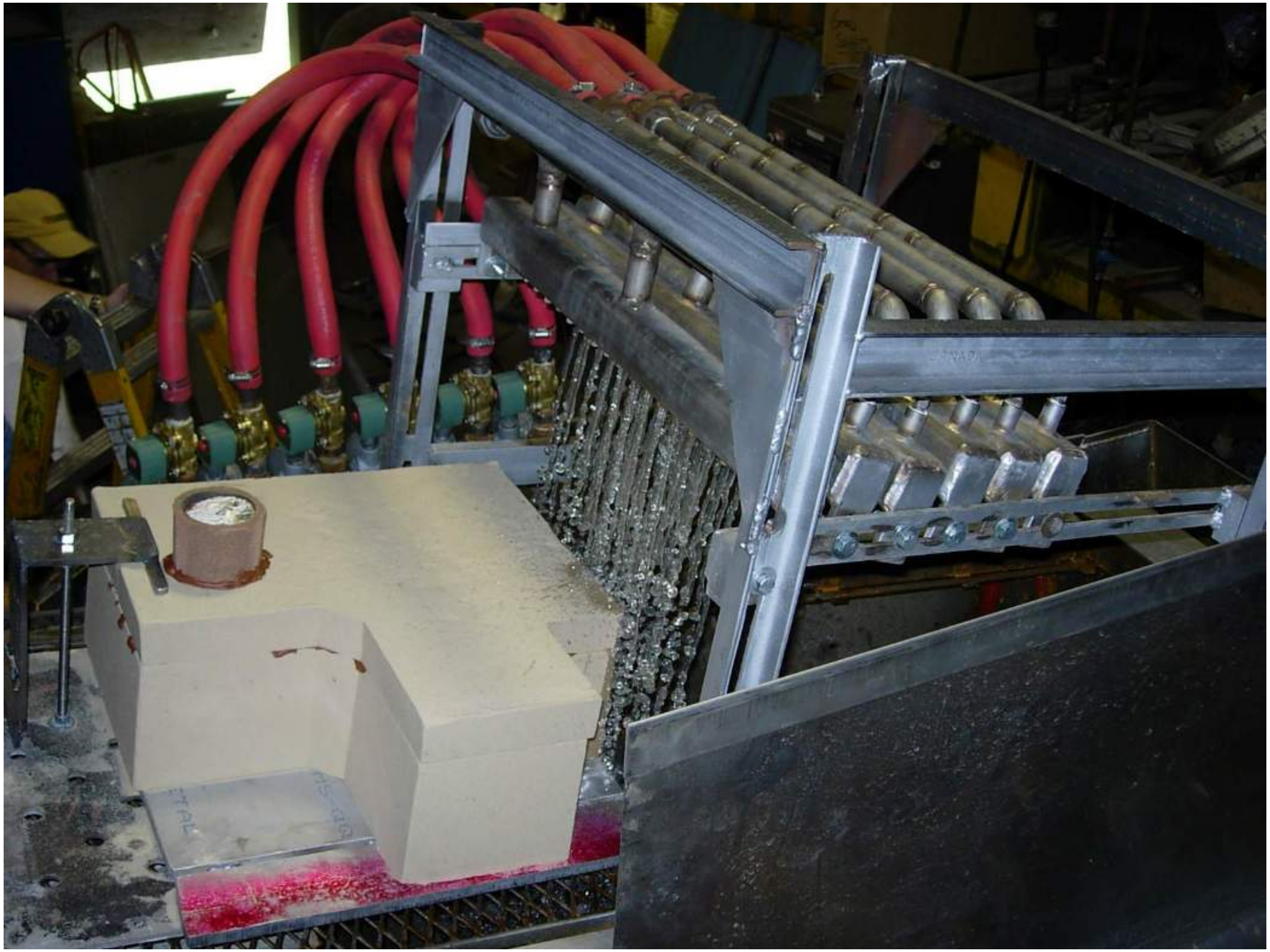
(b)



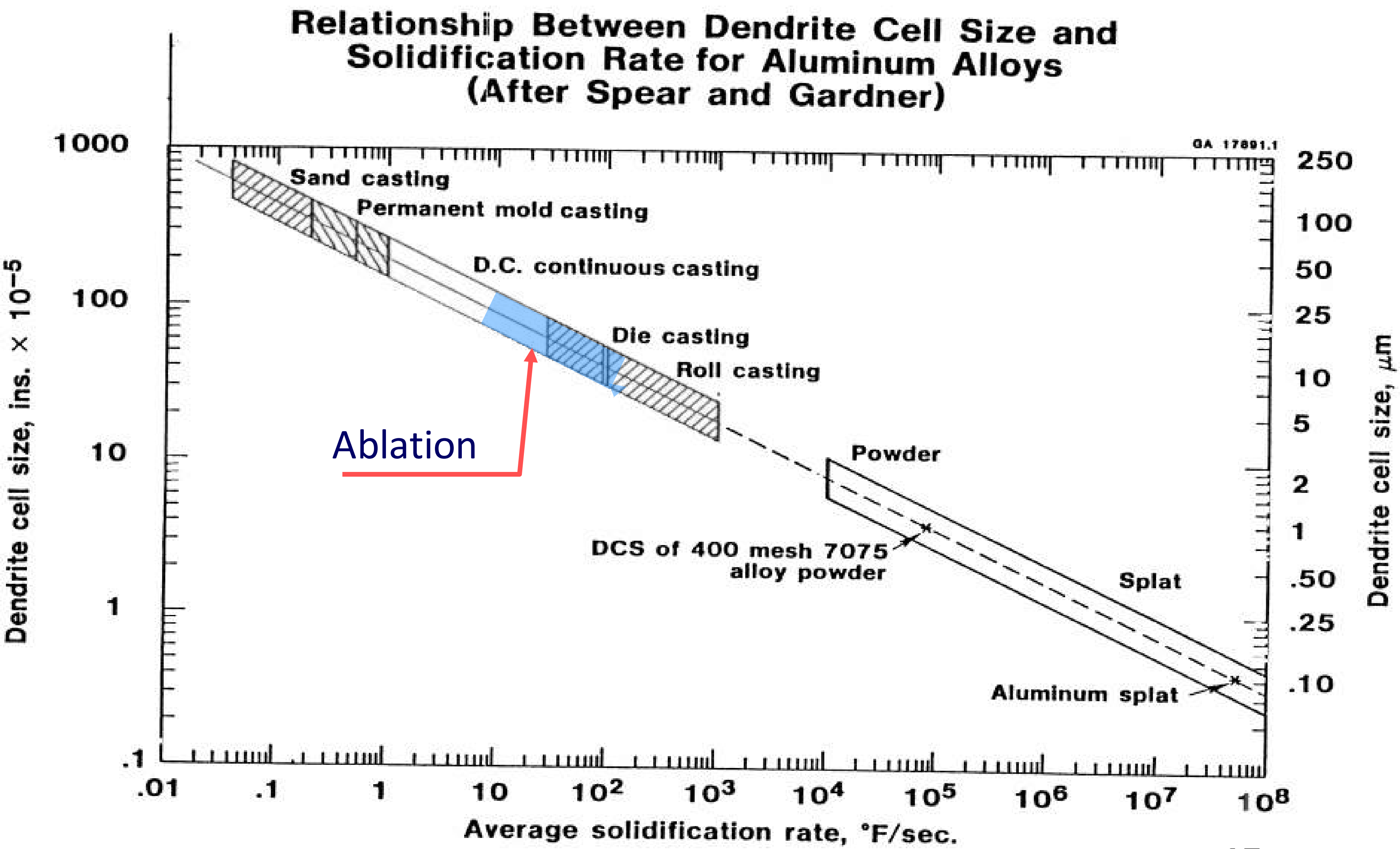
(c)



- (a) Al-Si/20 vol% Gr_p at the University of Wisconsin-Milwaukee;
- (b) Al-Si/20 vol% spherical Al_2O_{3p} made by Comalco
- (c) Al-SiC_p made by Duralcan.



ABLATION Cast Process



Wish List (Light, low cost, blast resistant, fire resistant, self healing)

↓

Design of microstructure to meet properties of monolithic alloys, composites, foams

↓

Design of process to make small samples with requisite microstructure

↓

Make and test samples

↓

Modify test samples

↓

Modify process

↓

Make prototype with help of Wisconsin industry

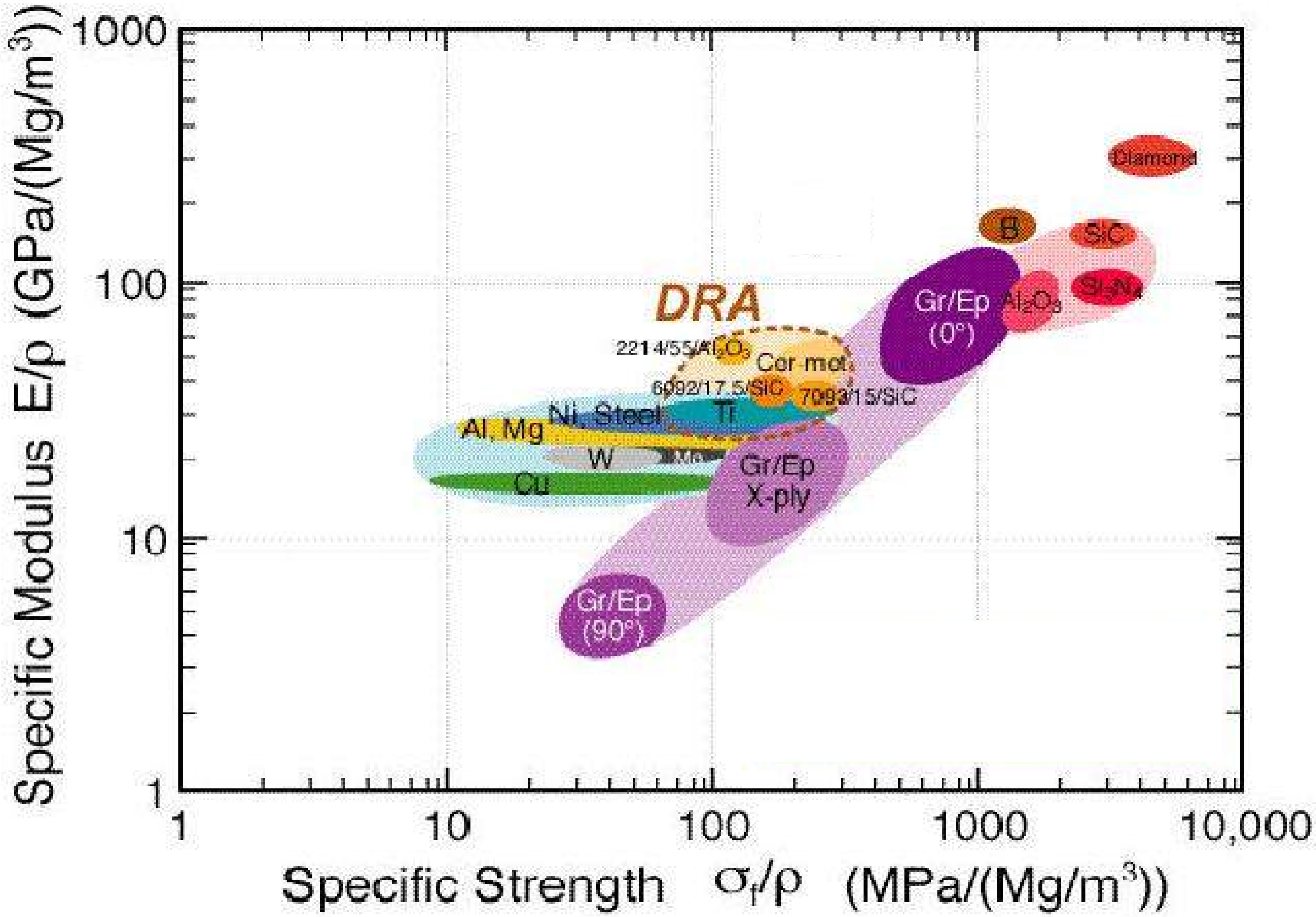
↓

Help test prototype

↓

Help in production in US industry

Specific Stiffness vs. Specific Strength for Structural Materials



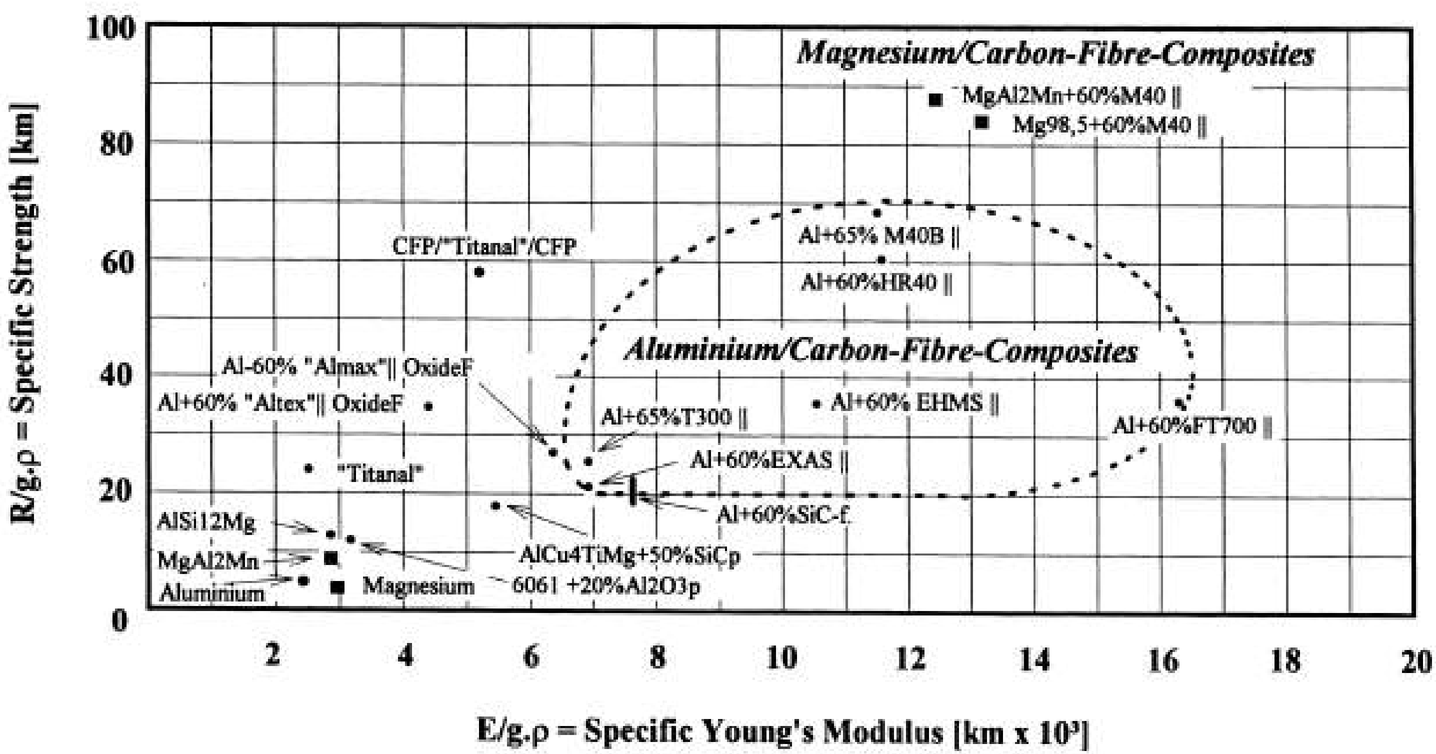


Figure 4 Comparison of specific properties of aluminium and magnesium matrix composites[11] indicating the increase of stiffness and strength with respect to the matrix (longitudinal CFRM properties)

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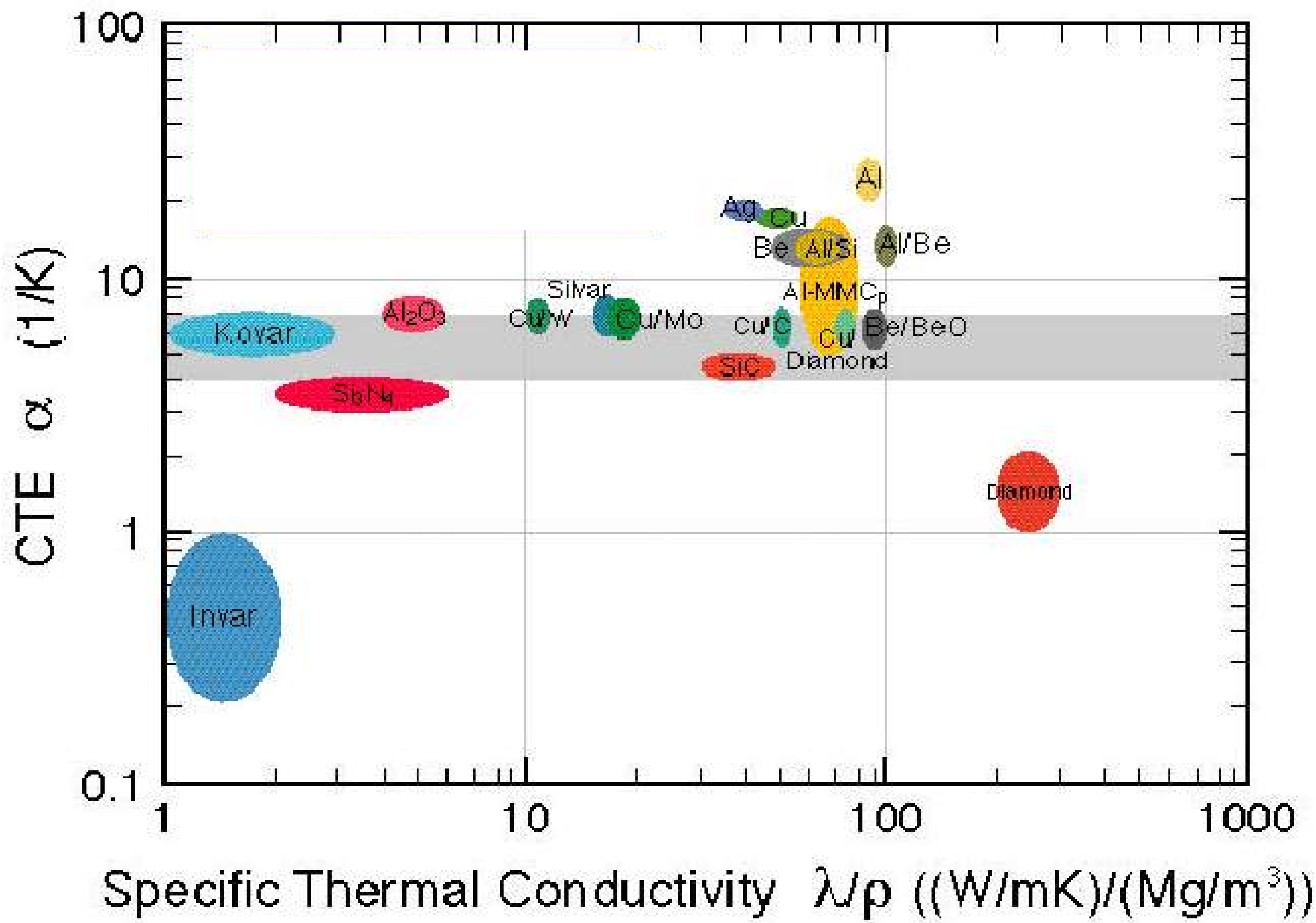
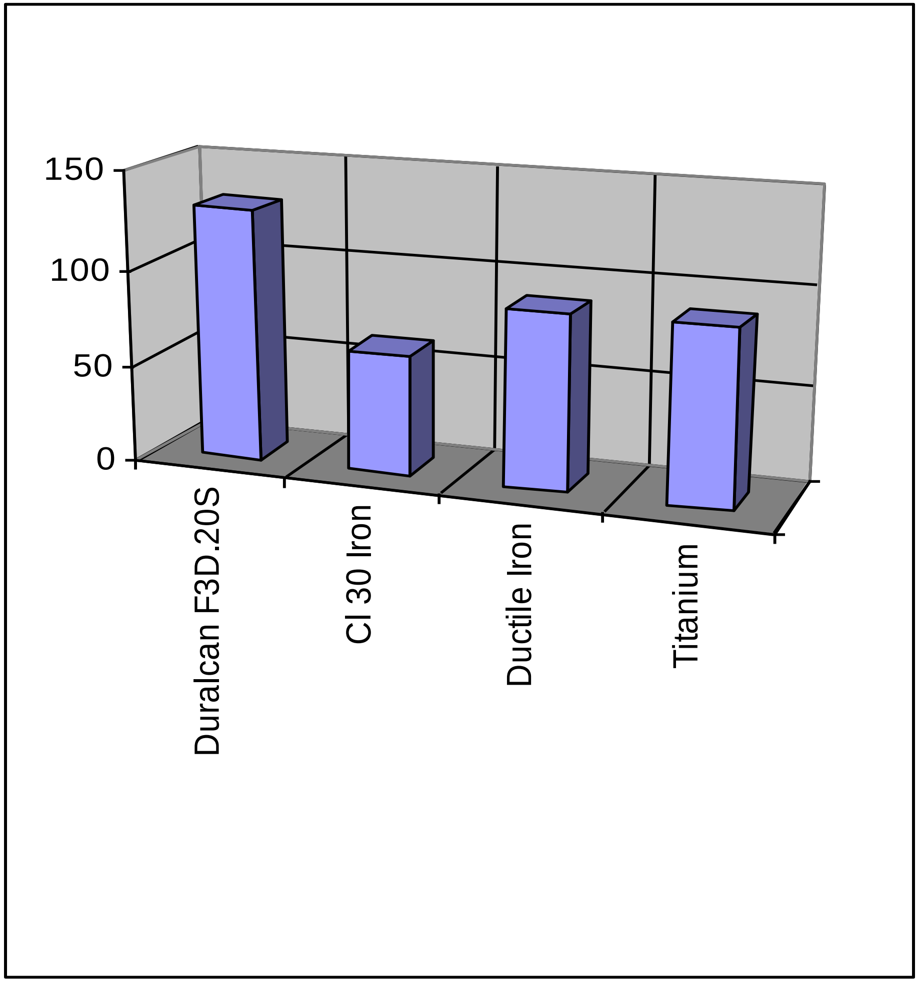
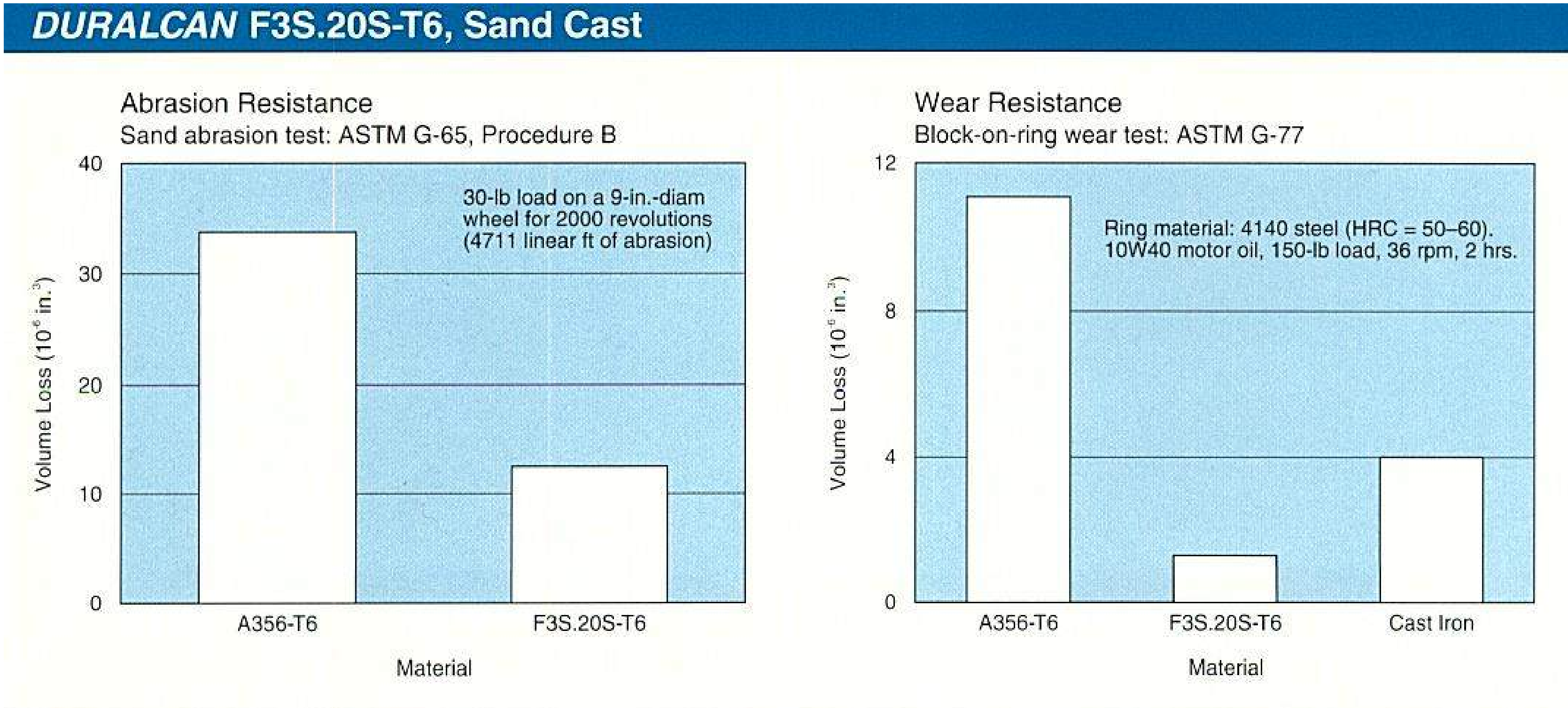
Materials Selection Chart for Thermal Management Applications



Specific Modulus of Structural Alloys



Wear resistance ASTM G-65



DURALCAN

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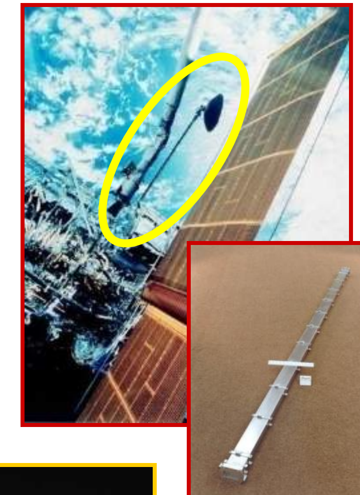
Aerospace Applications

Discontinuous and continuous MMCs on F-16

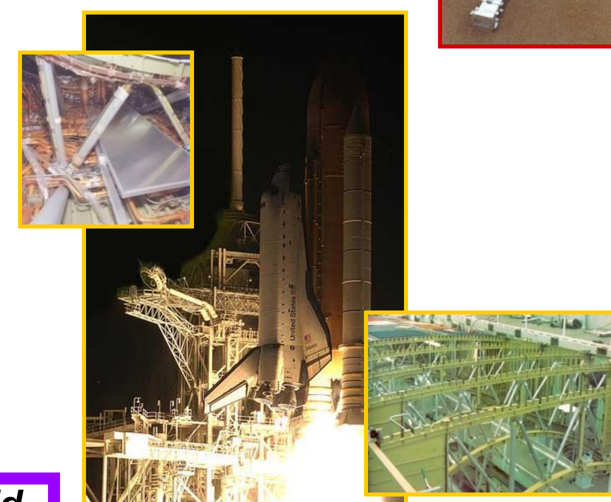
DRA replaced gr/epoxy FEGV in PW 4XXX engines

Al/gr antenna waveguide on Hubble Telescope



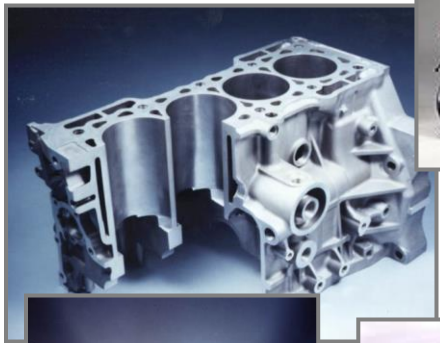
DRA replaced Ti in flight-critical parts on Eurocopter Helicopters

DRA Hydraulic Fluid Manifold End Gland in F/A 18E/F



Al/B continuous MMC for Shuttle Orbiter

Automotive Applications



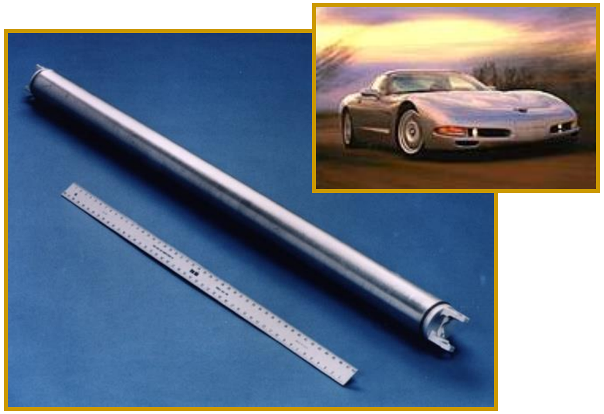

DRA Cylinder Liners for Autos and Motorcycles



DRA Automotive Brake Rotors


Ti/TiB for Intake and Exhaust Valves in Toyota Altezza


DRA Brake Components for Rail Applications



DRA Driveshafts for Corvette, S/T trucks, Crown Victoria

MMC Brake Applications

The 1st Generation Lotus Elise used Al-SiC_p MMC rotors for all four brakes. 2000 units were produced with the MMC rotors

VW Lupo 3L utilized Cast Al-SiC_p rear brake drums to achieve 78 mpg (or 3L/100km)

The German High Speed Train used Duralcan AlSi7Mg+SiC brake rotors, with a weight savings of 44kg/rotor

Plymouth used Al-SiC rear brake rotors for the Prowler

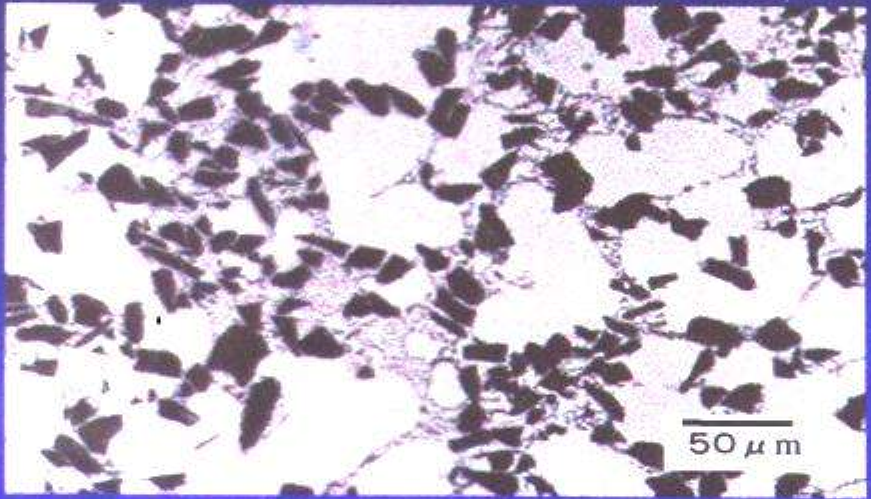
Flyash reinforced brake drums were developed and tested for Peugeot-Citroen

http://blog.autoworld.com.my/wp-content/uploads/2008/09/peugeot_308_gt_thp_175_5_large.jpg
http://www.seriouswheels.com/pics-2000-2003/2001-Plymouth-Prowler-1600x1200.jpg
http://upload.wikimedia.org/wikipedia/commons/e/e3/ICE2_007_K%C3%B6ln_Bonn_Airport_Steuerwagen.jpg
http://lotus-elise.oodam.com/lotus-elise-photos/lotus-elise-front-side.jpg

Other Applications at TOYOTA

■ MMC Disk Brake Rotor

Front Disk Brake Rotor



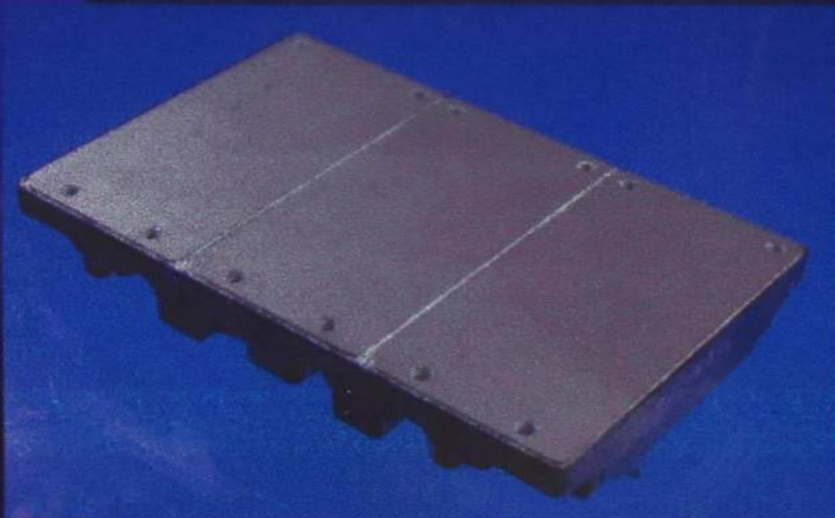
MMC Microstructure

SiC_p(Vf20%)／A359

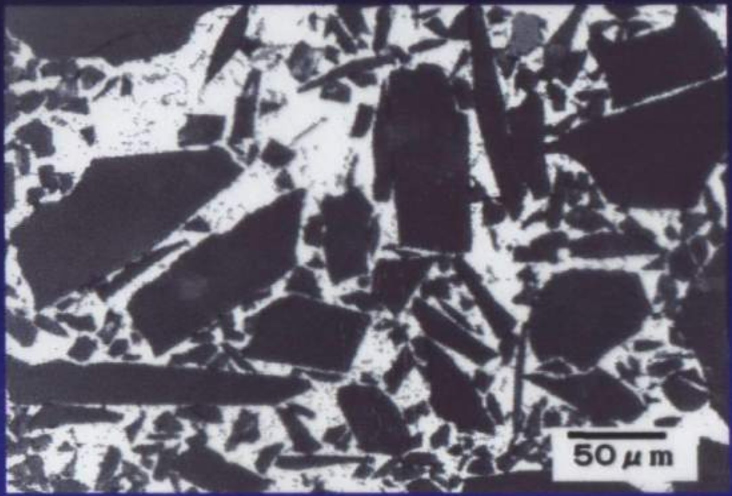
RAV4-EV

Other Applications at TOYOTA

■ MMC Electronics Cooling Plate

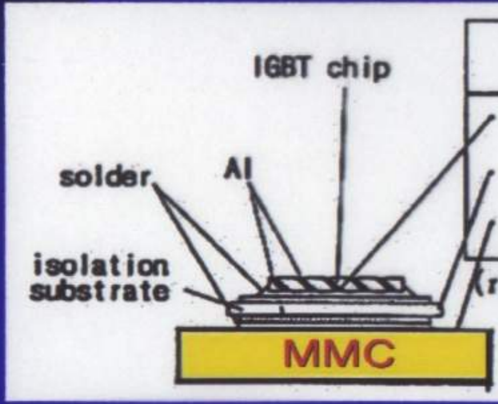


IGBT Power Device



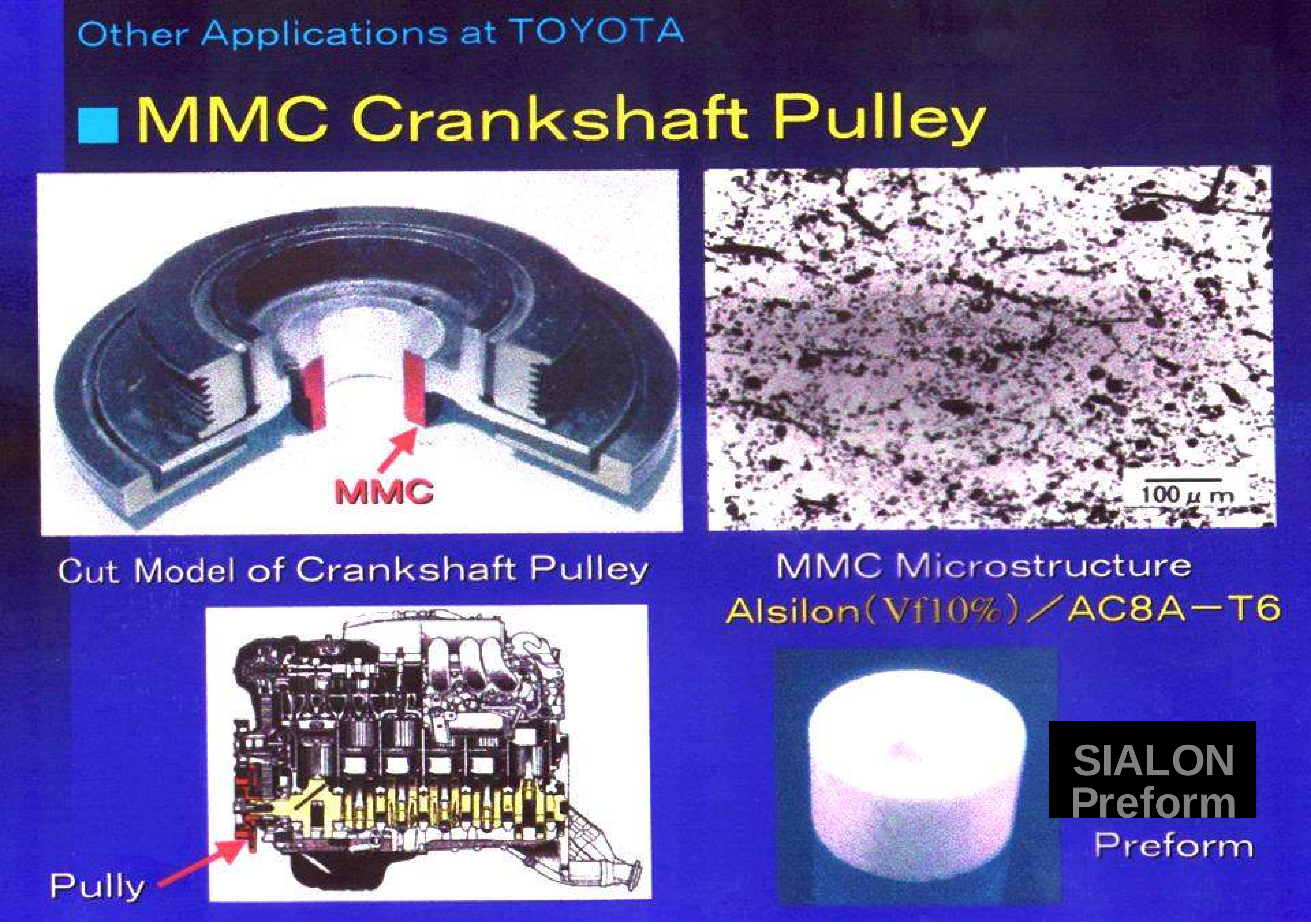
MMC Microstructure

SiC_p(Vf60%)/Al-7Si-0.3Mg

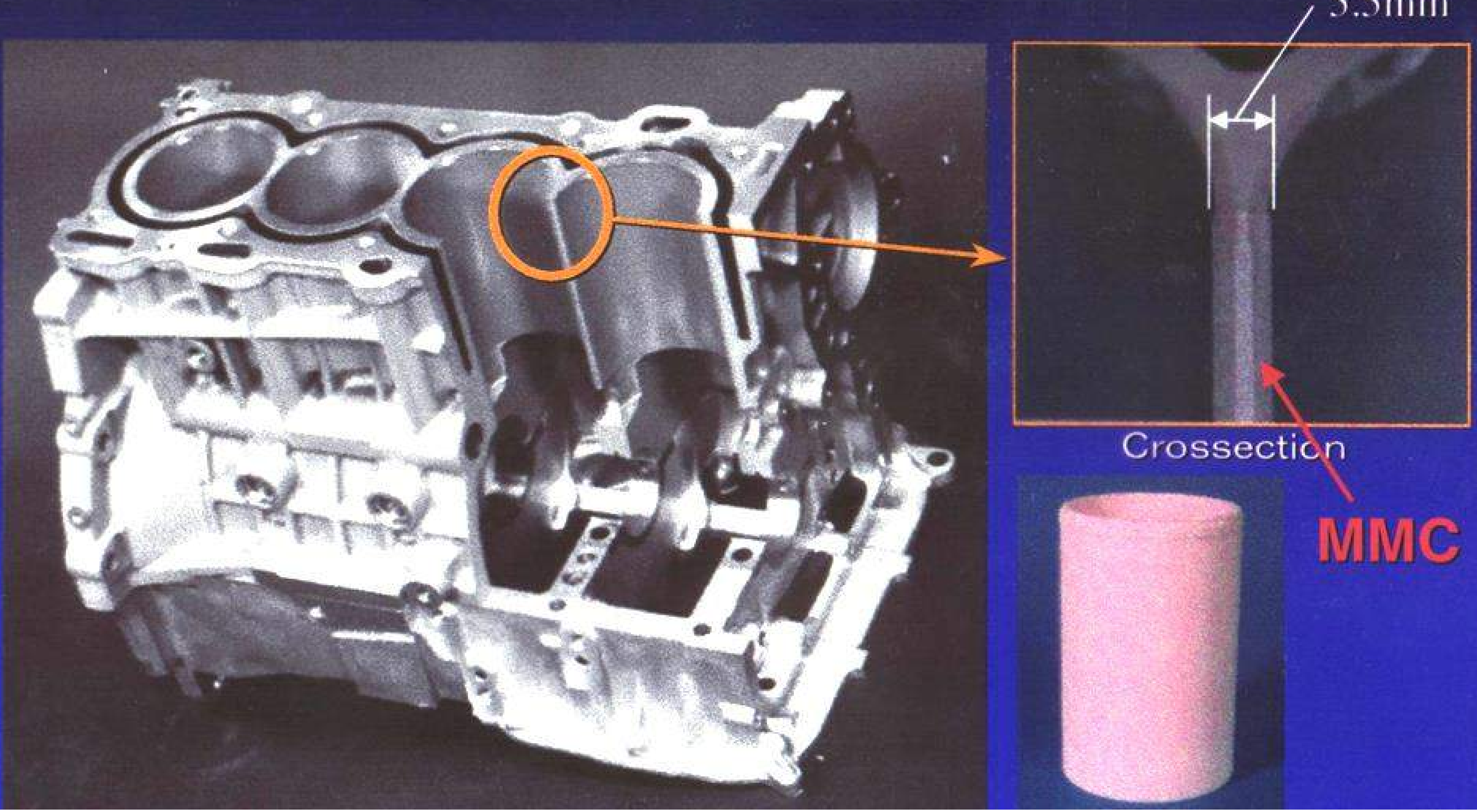


Material	CTE [ppm/K]
Si	4.2
AlN	4.5
Al+SiC	7.2
(reference)Cu	16.5

Hyblid vehicle PRIUS


Other Applications at TOYOTA
MMC Crankshaft Pulley
MMC
100 μm
Cut Model of Crankshaft Pulley
MMC Microstructure
Alsilon(Vf10%)/AC8A−T6
SIALON
Preform
Preform
Pully

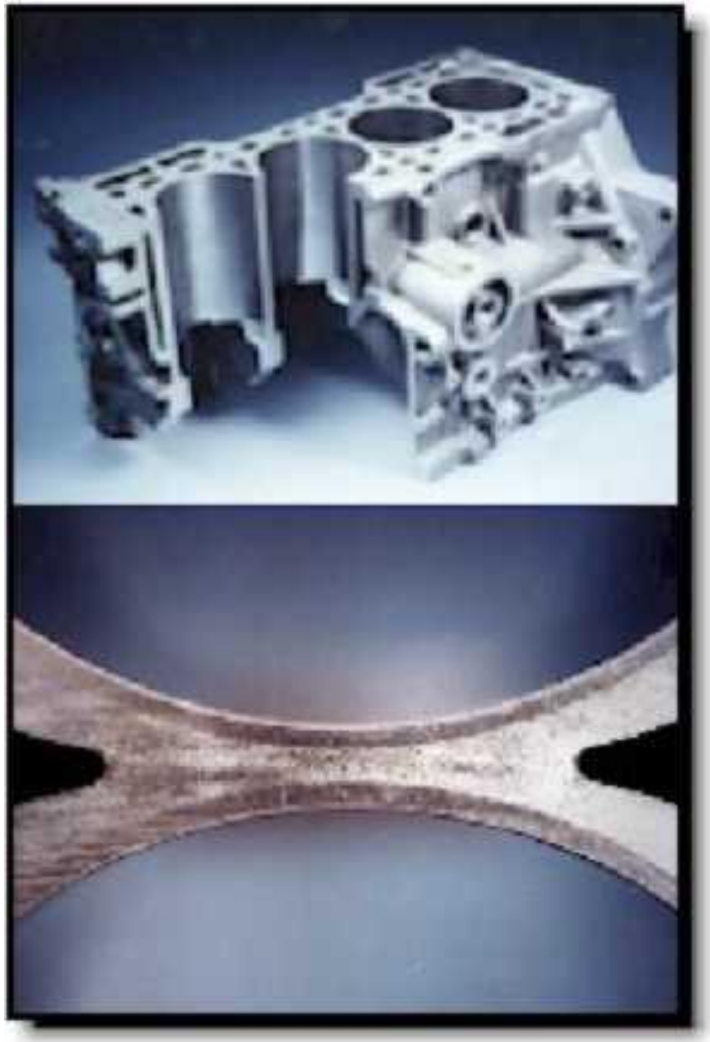
MMC Cylinder Bore

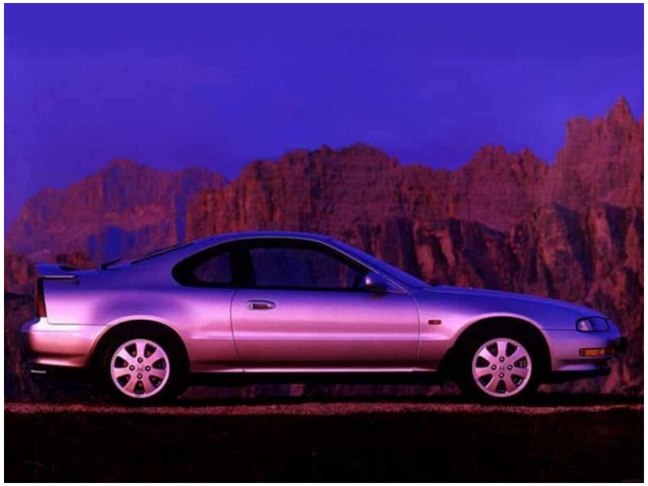


Cut Model of the Toyota 2ZZ-GE Engine

Alumina-silica short fiber and mullite particles Preform

- Al/Al_2O_3-Graphite DRA 12% Al_2O_3 for Wear 9% Graphite for Lubricity
- Integrally Cast With Al-Engine Block
- Improved Wear
- 50% the Weight of Cast Iron
- Improved Cooling Efficiency





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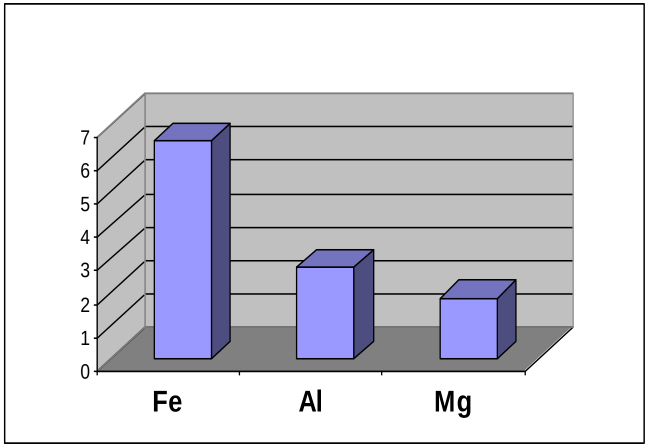
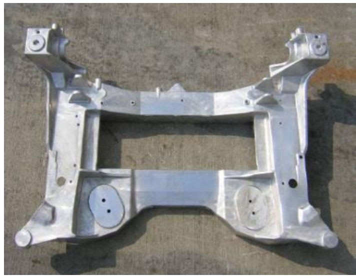
Magnesium

- The lightest structural automotive
  - Potential to reduce mass;
    increase fuel economy and performance
  - 33% lighter than Al and 80% lighter than Fe
  - Mg has competitive specific modulus (stiffness, *E/density*) and very good specific yield strength (σ_Y*/density*).
- Manufacturing advantages
  - Parts consolidation and thinner walls
  - Shorter part to part production
- Automotive successes
  - instrument panels, suspensions
  - transfer cases, valve covers

Densities of Automotive Metals



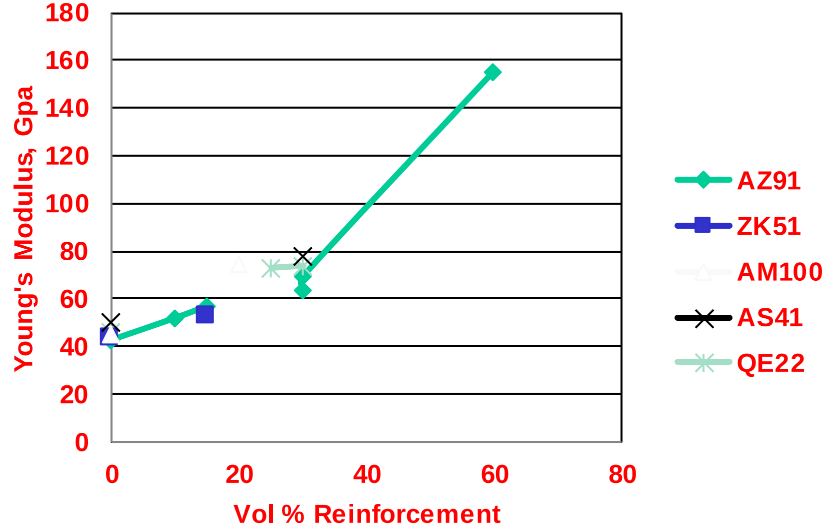


Reinforcement Properties in Magnesium

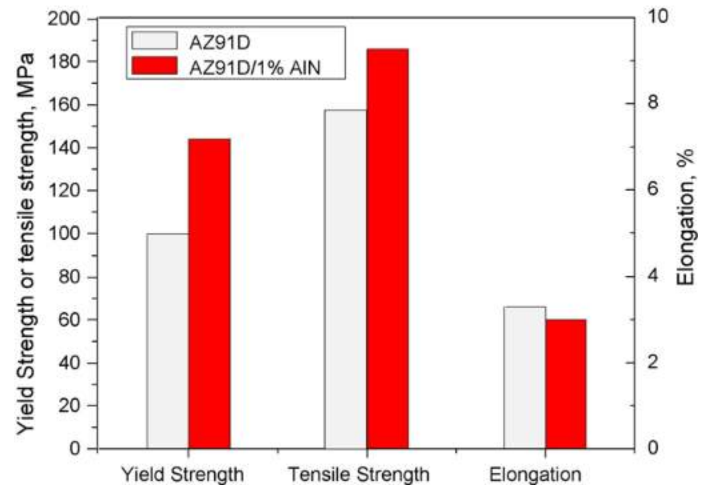
Reinforcement	Density, g/cc	Strength, MPa	Modulus, GPa	Size, µm	CTE, 10^{-6} K^{-1}
Al_2O_3 particles	3.0		410	Variable	8.3
SiC particles	3.2		480	Variable	5.0
TiC particles	4.9		320		7.4
Kaowool	2.6	1,200	100	2.5	
Saffil fibers	3.3	1,800	210	3 (dia)	
Carbon fibers		>5,500 (low E)	>500 (low σ)	5-11	
CNT (MW) (theoretical)	2.0	500,000*	1,000		<1.0
AZ91D Mg	1.8	250	45		26

Magnesium Composites

- Stiffness (Shapiro, 2005)
  - Reinforcement increases E
    - Independent of alloy
    - Independent of reinforcement
      - Particles – SiC, TiC
      - Fibers – C, Saffil, SiC



- Strength (Cao, 2008)
  - AlN-reinforced AZ91D
    - Ultrasonic dispersion in melt
    - Higher strength
      - Maintained ductility



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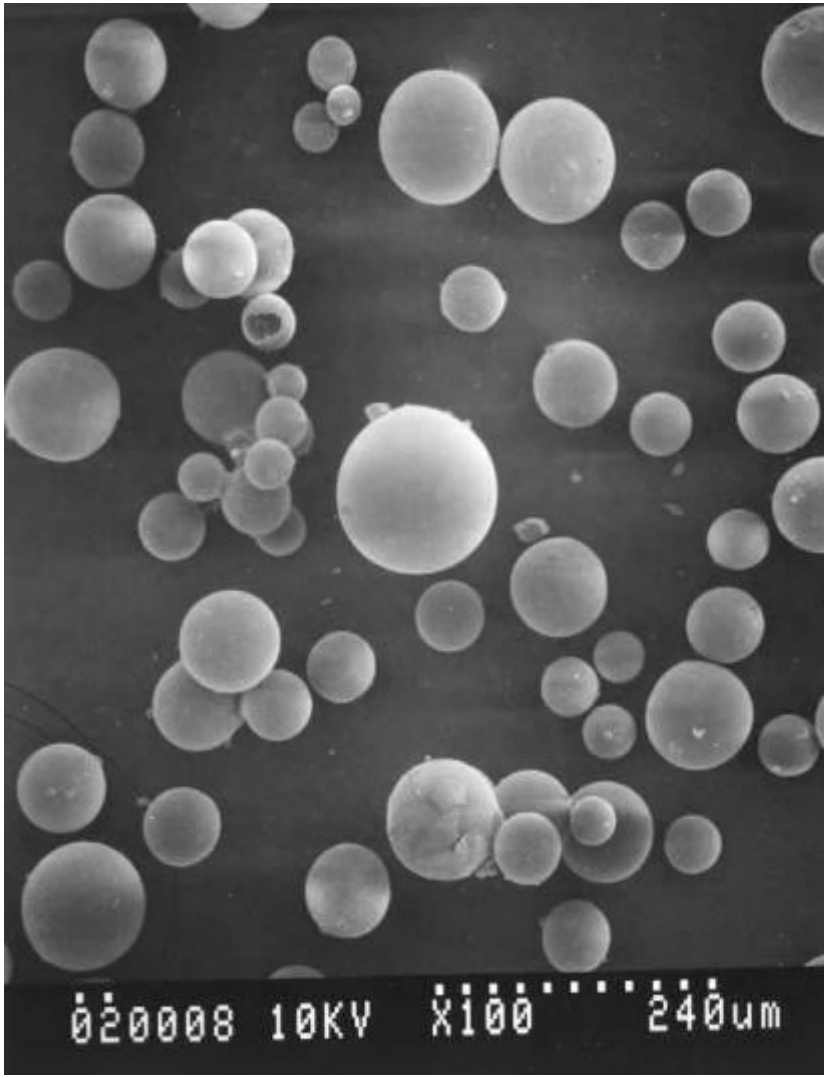
UWM Blast Resistant MMC's

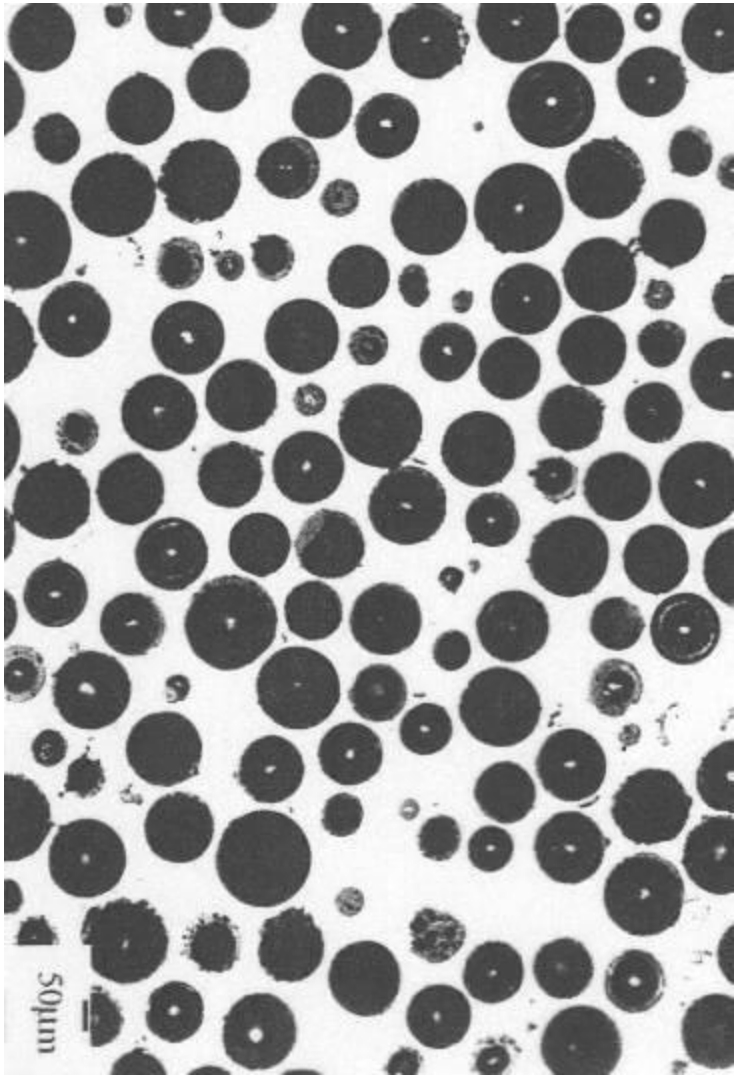
Monolithic and Syntactic Foams

- Hollow Sphere Metal Matrix Composites have low densities, and because the material acts like a sponge it can absorb and dampen significant amounts of impact energy.
- Metal Foams can also be produced with gas-filled pores. These have low densities, lower thermal conductivity, and, like the Hollow Sphere MMC's, they have high impact energy absorption capabilities.

Flyash Cenospheres

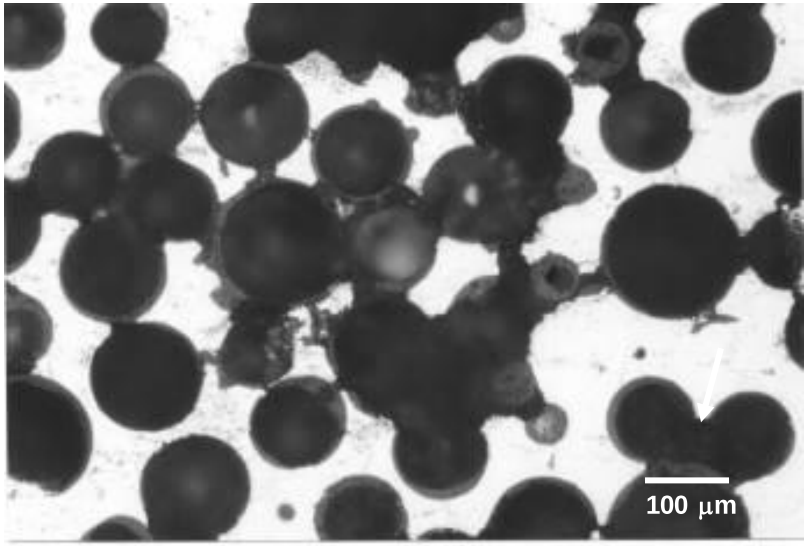


Syntactic Foam



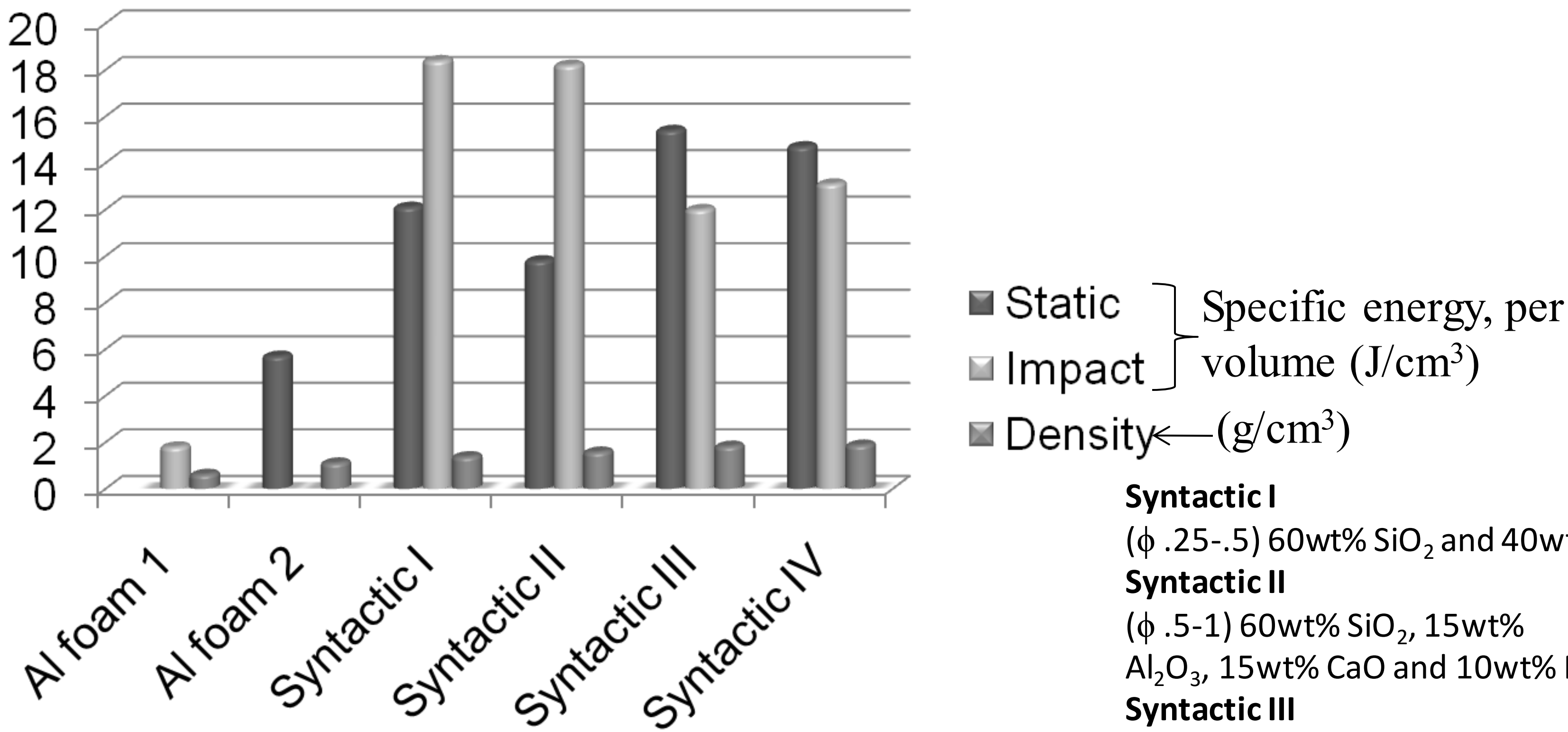
Syntactic Foam - Advantages

- **Syntactic foam**
  - High specific compressive strength.
  - High dimensional stability - Low moisture absorption and thermal expansion.
  - High damage tolerance.
  - Damping characteristics.



- **Sandwich Composites**
  - Tailoring of properties according to requirements.
  - Low density.
  - Higher damage tolerance.

Al-foam vs. syntactic foams

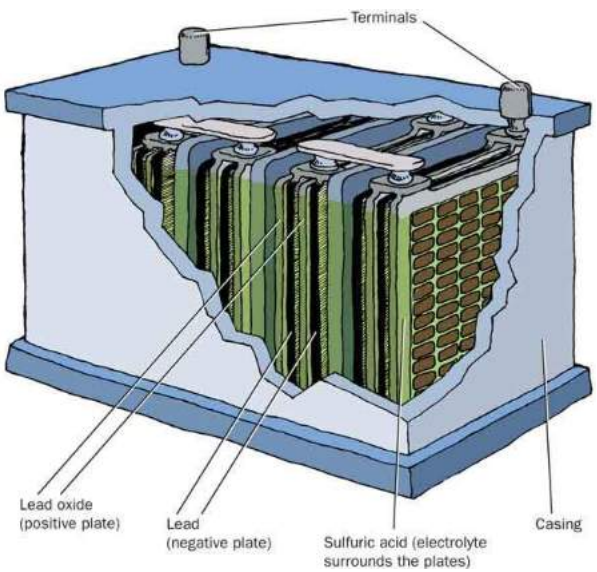


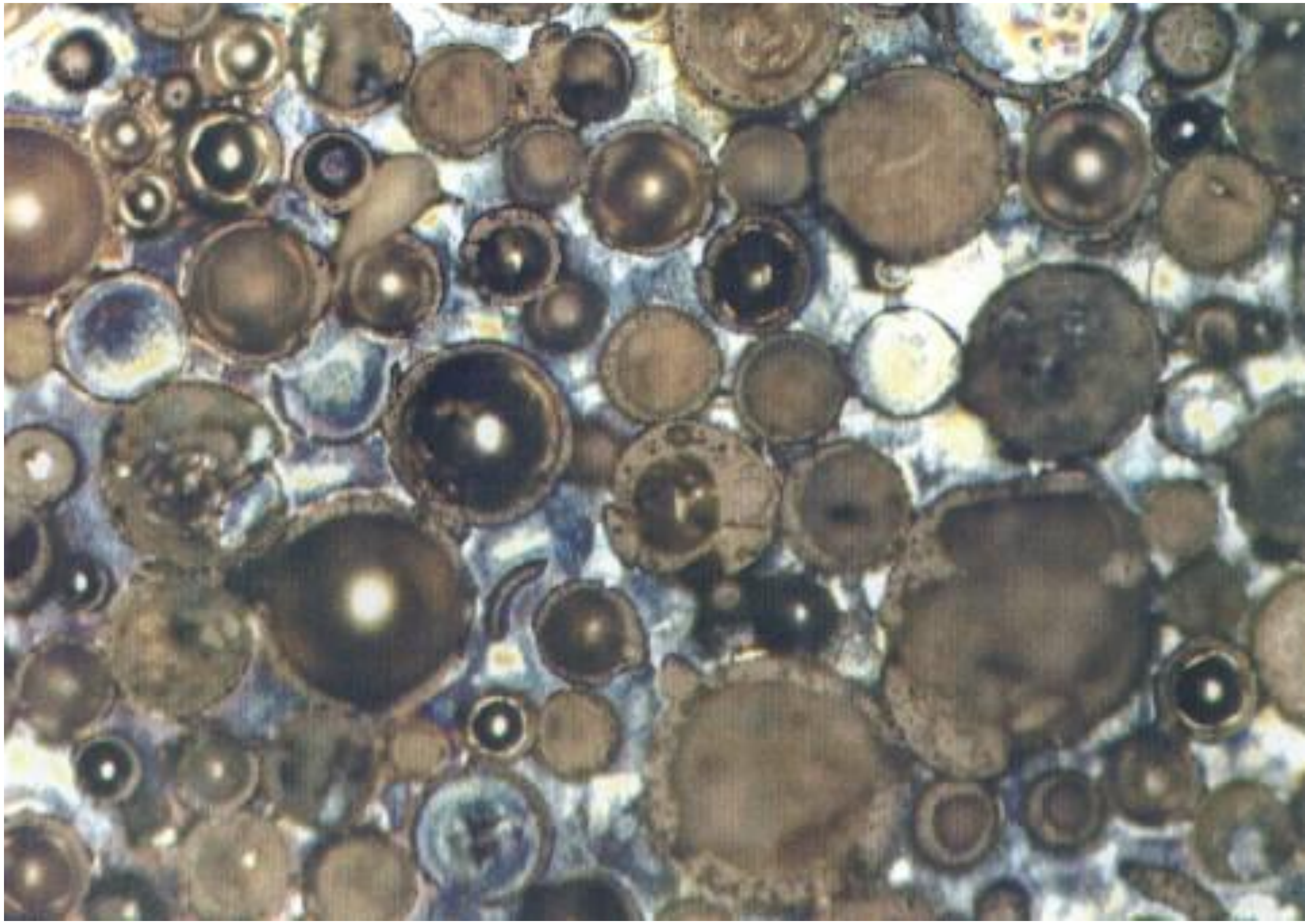
Syntactic I
(ϕ .25-.5) 60wt% SiO_2 and 40wt% Al_2O_3
Syntactic II
(ϕ .5-1) 60wt% SiO_2, 15wt% Al_2O_3, 15wt% CaO and 10wt% Na_2O
Syntactic III
(ϕ 1-2) 60wt% SiO_2, 15wt% Al_2O_3, 15wt% CaO and 10wt% Na_2O
Syntactic IV
(ϕ 2-4) 60wt% SiO_2, 15wt% Al_2O_3, 15wt% CaO and 10wt% Na_2O

Syntactic Foams Absorb much greater energy than open celled foams!

Zhang et al J Comp Materials 2007

Lead-Fly Ash Composite





Hollow Fly Ash cenospheres dispersed in the matrix of lead to reduce density

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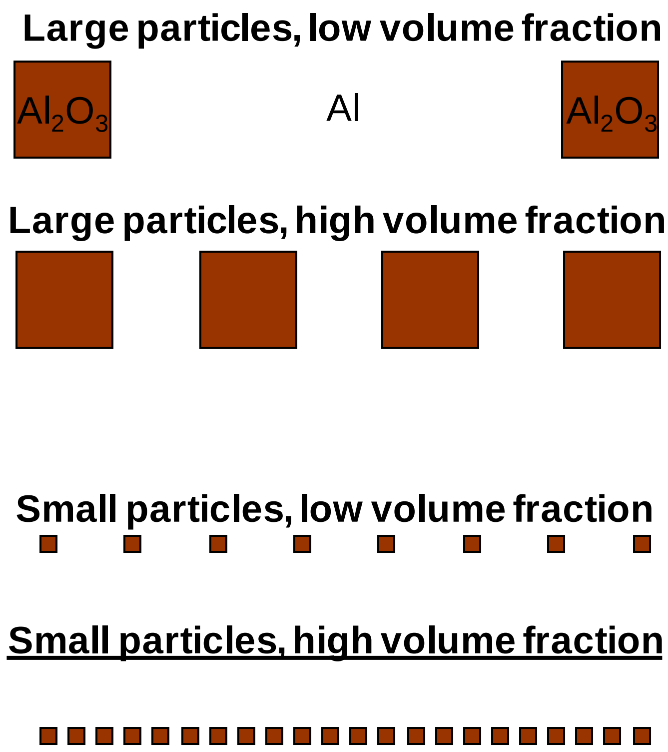
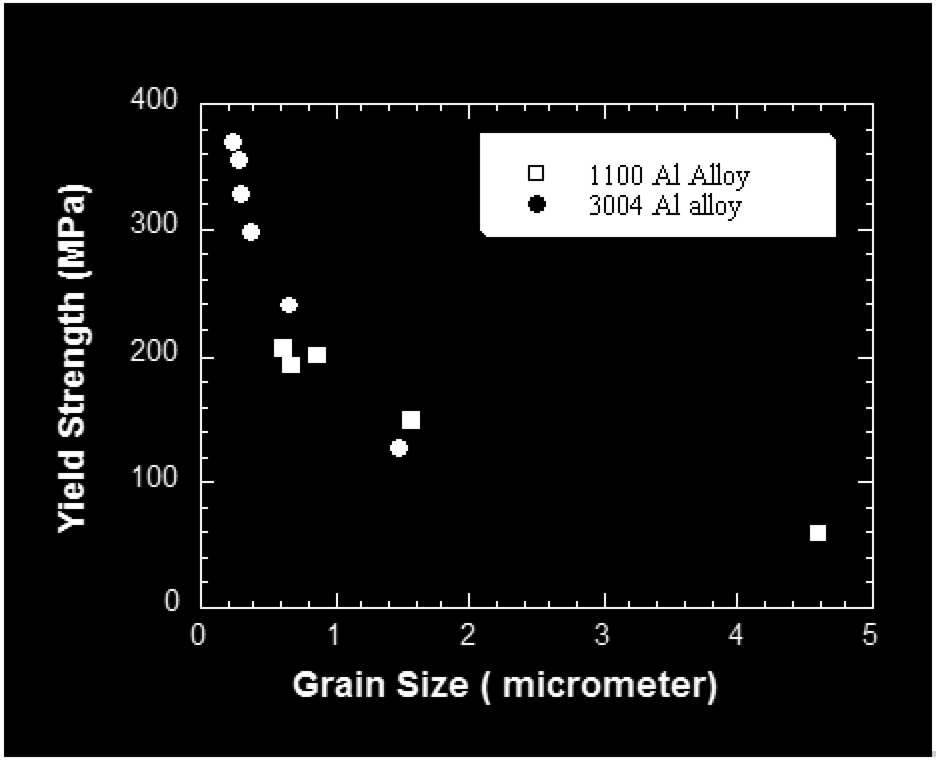
Why Nanocomposites?

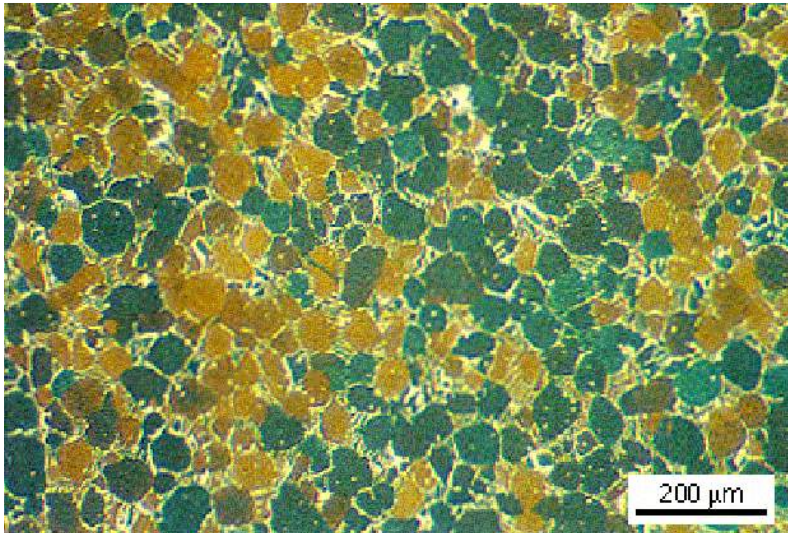
- Increasing the concentration of hard phase in a conventional composite usually only mildly increase the strength, but
  - Sacrifices the ductility,
  - Reduces thermal conductivity,
  - Increasing the difficulties for processing and machining, and
  - Makes the surface more abrasive.
- Therefore, nanocomposites are desired, but
  - Only very low concentration of hard phase reported in literature.



Reducing grain size to the nanoscale increases strength in most metals and alloys

Conventional metals and alloys have grain sizes in the range of a few to many microns.





In low alloyed metals strength depends significantly on grain size.

Metallicum, LLC
The Nanostructured Metals Company

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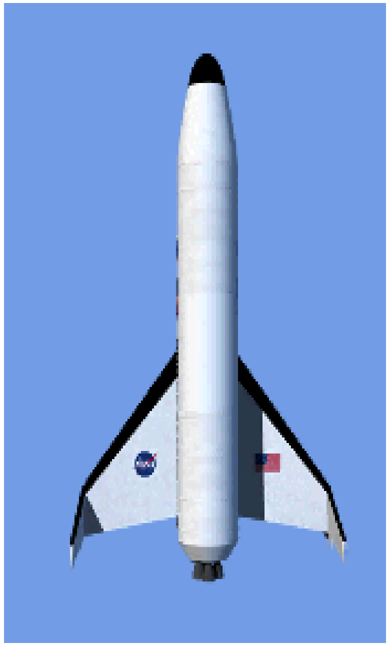
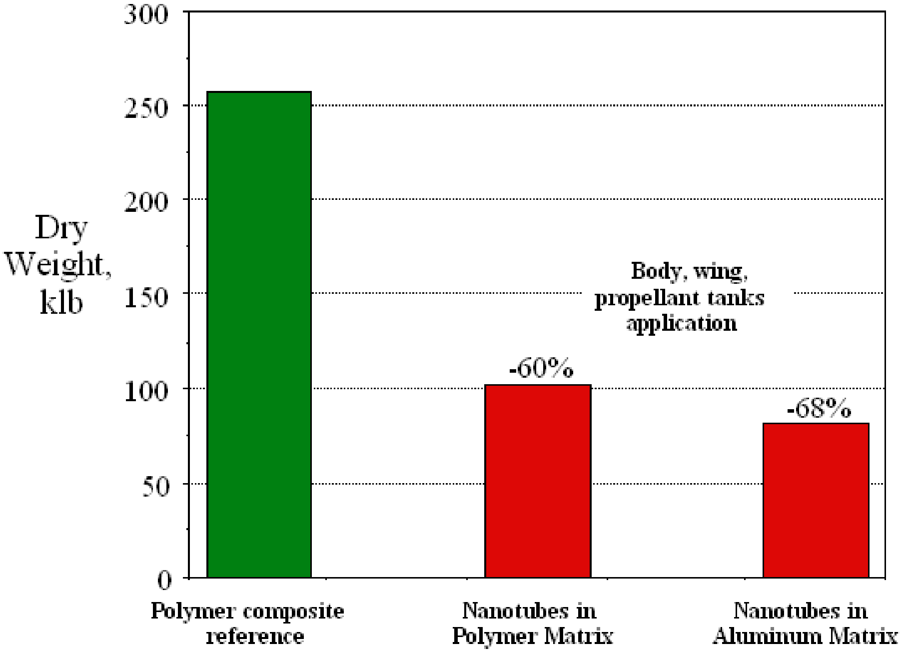
Nanotechnology: SSTO Systems Analysis Results

Results for Nanotube-Reinforced Polymer (CNTFRP) and Nanotube-Reinforced Aluminum (CNT/Al) Composites compared to an advanced carbon fiber reinforced polymer (IM7 CFRP) composite



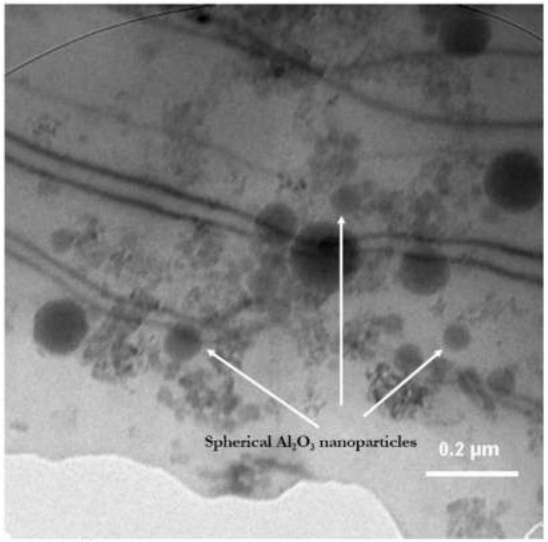


Results: Total gross weight is reduced by over 50% relative to the best available composite material under development.

Hirschbein, NASA

- 1-4 wt% Nanosize Al_2O_3 (47 nm) incorporated in aluminum alloy A206 by implementing stir mixing, ultrasonic mixing, reactive wetting agents, and squeeze casting

TEM photomicrograph of an A206-2v%Al2O3 (47 nm) –2 wt%Mg composite synthesized in this study. Composite slurry was mixed for 20 minutes and then squeeze cast.



Al-Al_2O_3 Nanocomposite Wear

Figure 1 Shows a Transmission Electron Microscope (TEM) Micrograph of the Microstructure Obtained by Ball Milling Pure Metals and Nanopowders, Followed by Hot Pressing/Sintering to Form a Nanocomposite [[1]].

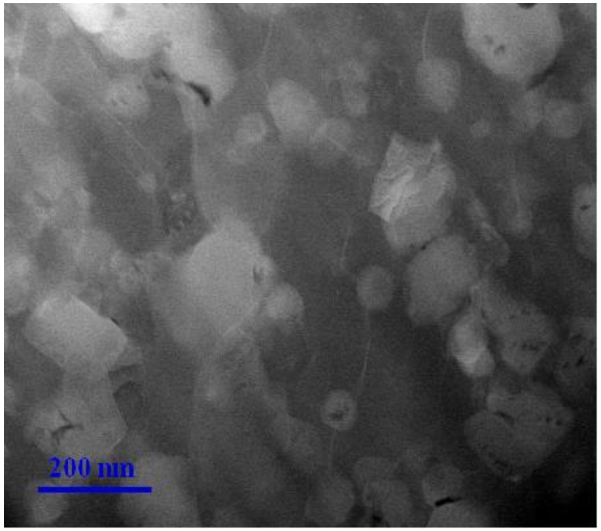
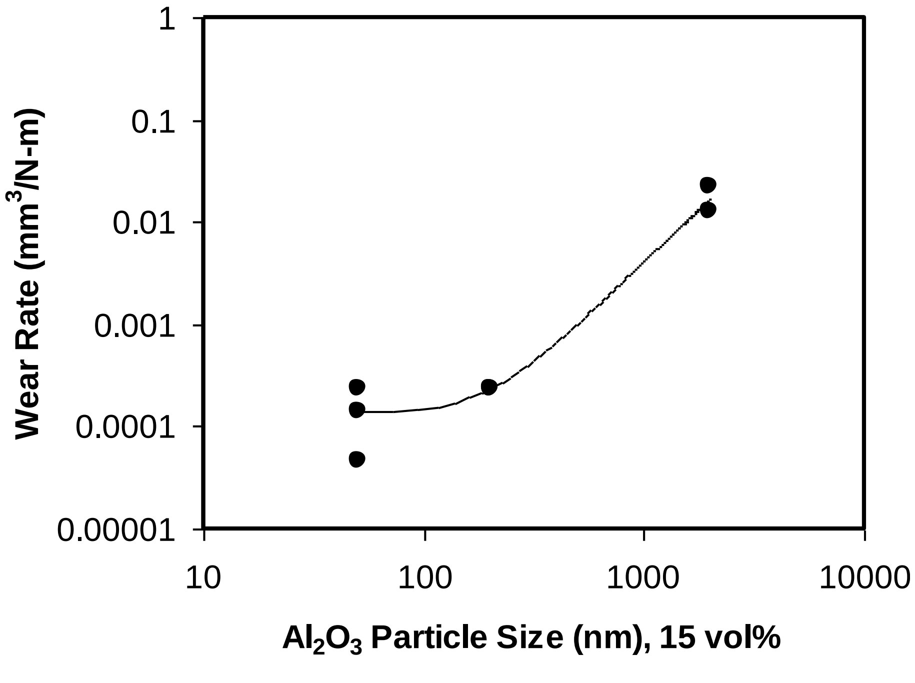


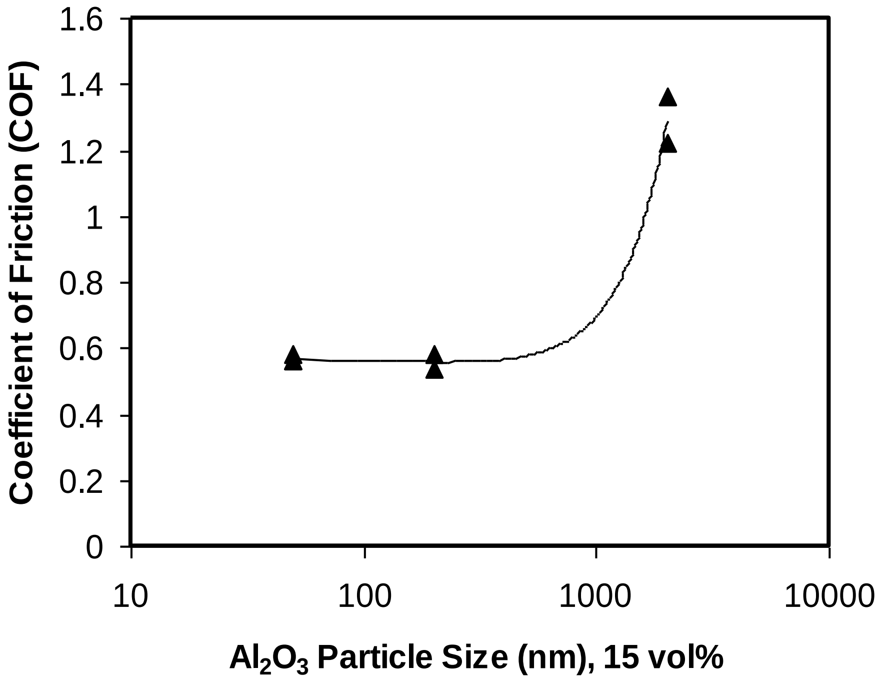
Figure 1. Powder metallurgy based Aluminum alloy-15 vol% Al_2O_3 [1]

[1] Jun, Q., Linan, A. & Blau, P. J. *Sliding friction and wear characteristics of Al2O3-Al nanocomposites* (STLE/ASME International Joint Tribology Conference, IJTC 2006 Ser. 2006, American Society of Mechanical Engineers, New York, NY 10016-5990, United States, 2006).

Al-15vol% Al_2O_3 Metal Matrix Composites

Effect of Particle Size on Coefficient of Friction and Wear Rate of Al-15vol% Al_2O_3 Metal Matrix Composites. Both the Wear Rate and Coefficient of Friction are Dramatically Reduced When the Particle Size is Reduced Below 1 mm [1]





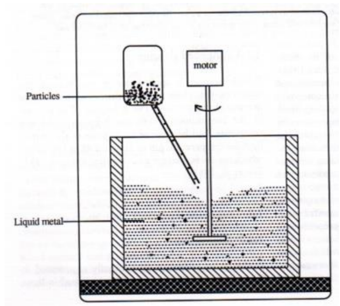
[1] Jun, Q., Linan, A. & Blau, P. J. *Sliding friction and wear characteristics of Al2O3-Al nanocomposites* (STLE/ASME International Joint Tribology Conference, IJTC 2006 Ser. 2006, American Society of Mechanical Engineers, New York, NY 10016-5990, United States, 2006).

Significantly Improved Mechanical Properties

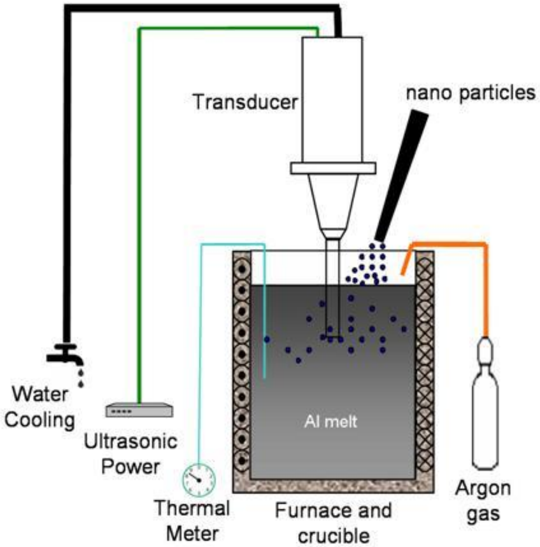
Material	Particle Size	Concentration (vol%)	Strength at $\sigma_{0.2\%}$ (MPa)	Microindentation Hardness HV (GPa)
Al 1100	*n/a*		33*	0.35
Al_2O_3-Al composites	29 µm	46	86*	-
	4.5 µm	39	148*	-
	50 nm	5	491	1.04
	50 nm	10	515	1.22
Cast Al 319	6 wt% Silicon		Yield: 138*	0.85
AISI 304 Stainless	*n/a*		310* **Literature data*	3.16

Melt Casting of Magnesium Matrix Composites

- Dispersing the Reinforcement into the Melt
  - Stirring (and Rheostirring)
  - Sonication
    - Stirring
    - Sonication
- Maintaining Stable Dispersion
  - In melt
  - During Solidification
- Casting Issues
  - Maintaining fluidity
  - Limited range of reinforcement types
    - Buoyancy, reactivity

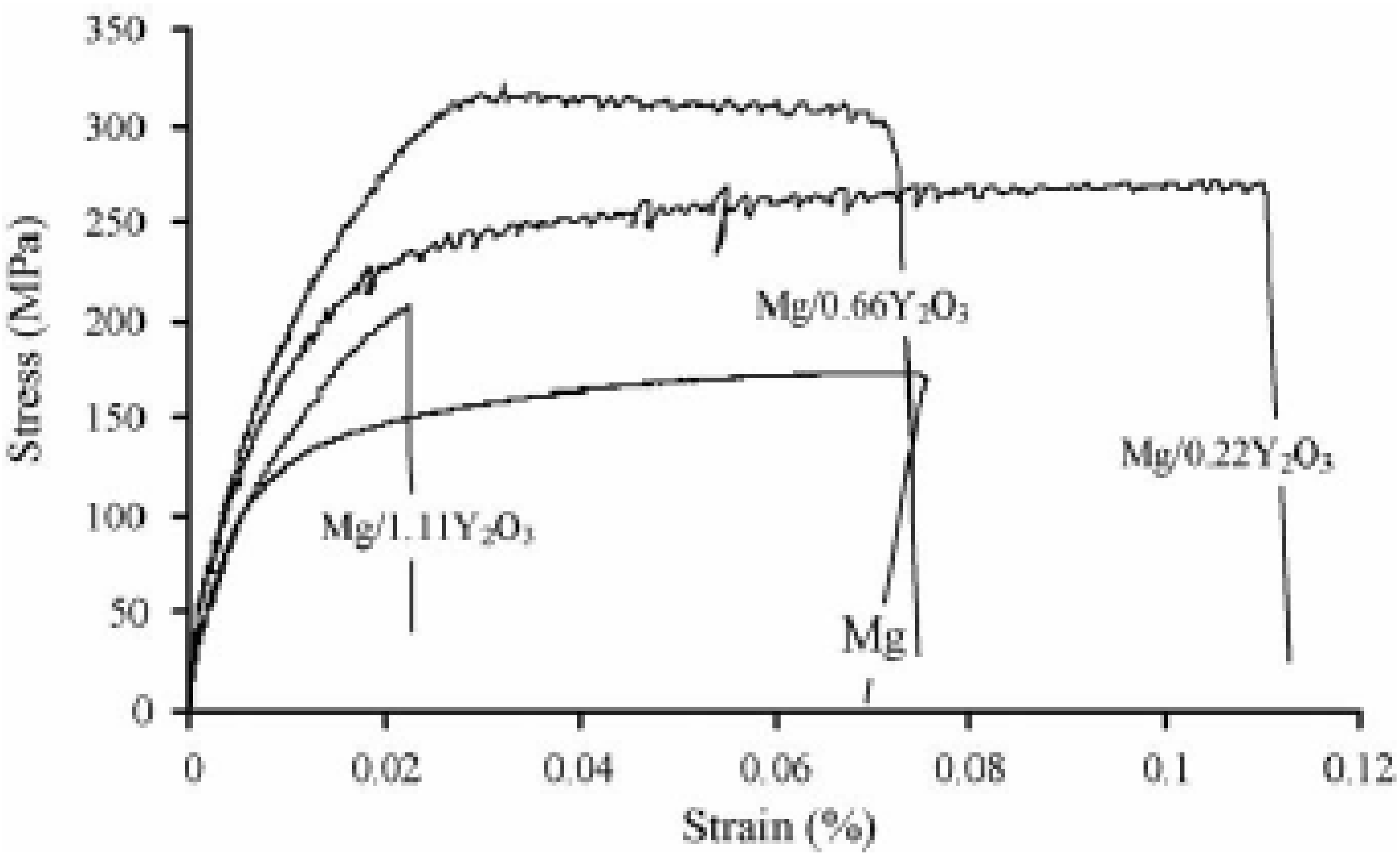


Courtesy C. Lavender, PNNL



Courtesy X, Li,
University of Wisconsin

Representative tensile stress–strain curves of magnesium and its nanocomposites.



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Composites at UWM

- Introduction to Metal Matrix Composites
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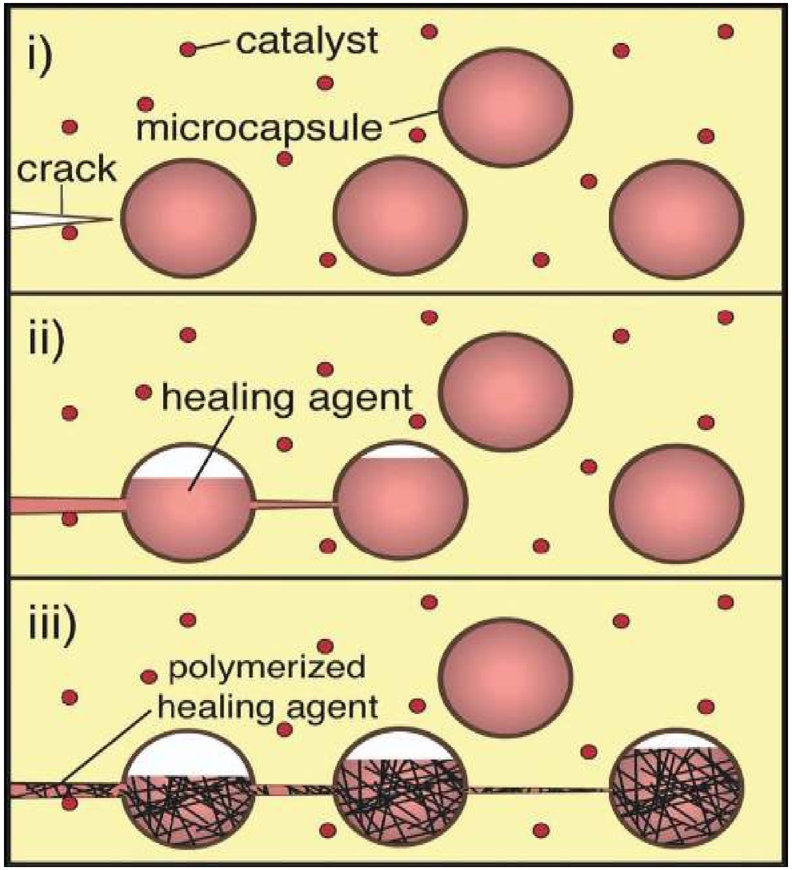
- Syntactic Foams
- Nanocomposites
- Self Healing, Self Lubricating and Self Cleaning Composites
- Composites and Capabilities at UWM
- Concluding Remarks

Self Healing Materials

- One of the biggest problems in engineering is the eventual wear and degradation of the materials used.
- If materials could be designed to heal themselves when stressed, cracked or punctured, the entire engineering world would be revolutionized
- A material must sense and repair the problem without human interaction. The material should regain a fraction of its original strength in order to be considered a self healing material.

Self Healing in Polymers

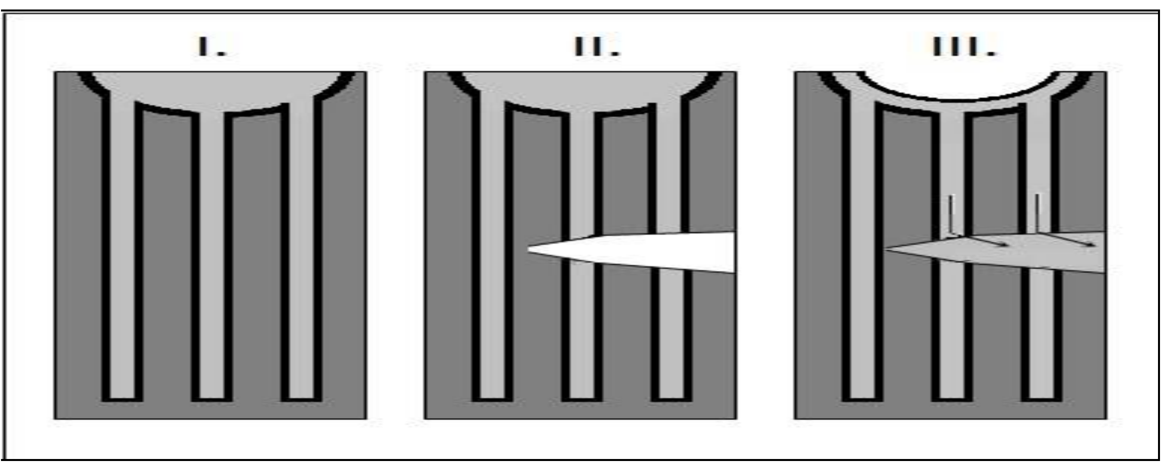
- When a crack ruptures the wall of a microsphere, the liquid healing agent flows into the crack via capillary action.
- Then the healing agent comes in contact with a catalyst it polymerizes, healing the damage by filling and sealing the crack

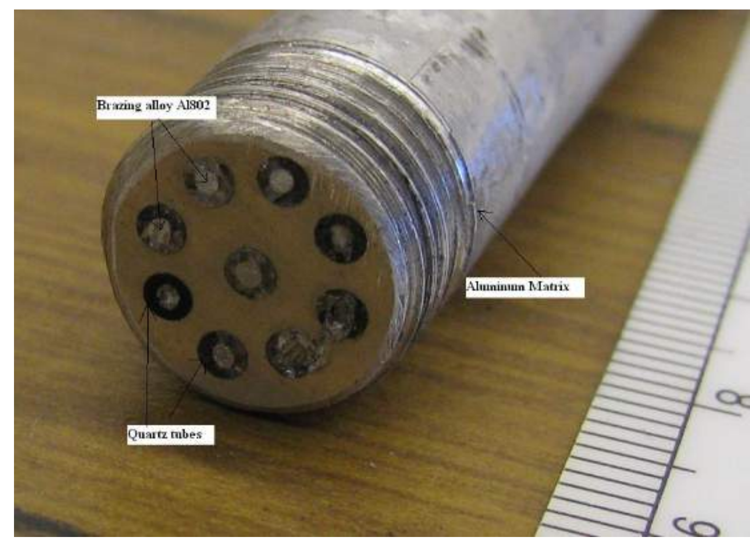


Self-Healing Metals

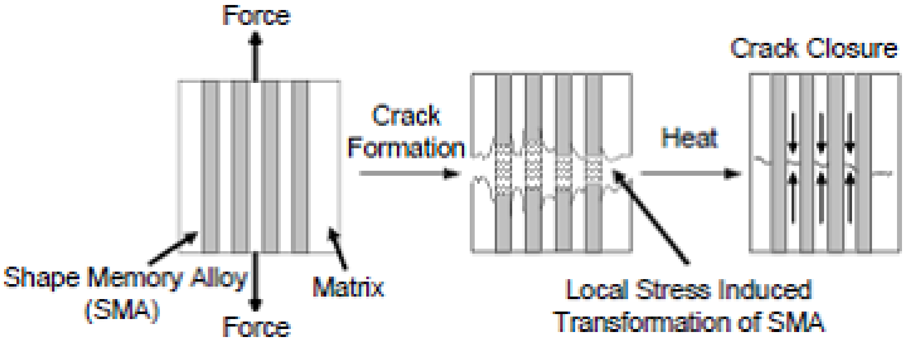
Interconnecting Networks of Low T_m Alloys

- A continuous network of low melting temperature metal is either cast or infiltrated into a matrix with a higher melting point.
- Any damage that occurs in the material can be healed by heating the material above the temperature of the low T_m alloy and applying pressure to the reserve pool.
- Liquid is then forced into the damage area and when cooled the damage has been repaired.

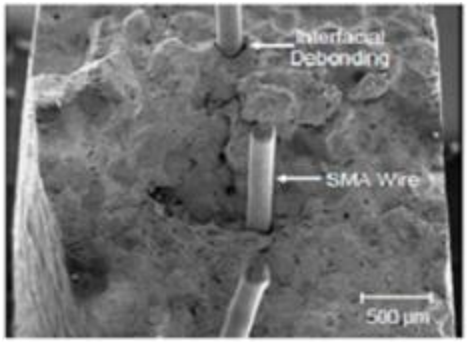




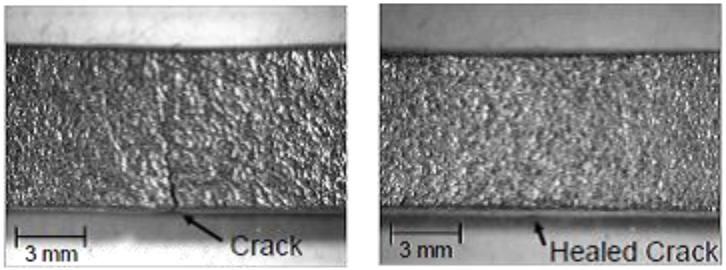
Self-Healing in Metals



This figure shows the process of healing. The local stress induced by the crack transforms SMA to a Martensite phase.



Shape Memory Alloy (SMA) wires in micro size TiNi as the reinforcements, the figure shows the microstructure of the alloy matrix reinforced with Nitinol fibers in micro-scale.



G. Olson, Northwestern University
Biomimetic Self-Healing Metals
Proc. 1st Intl. Conference on Self-Healing Materials, 2007

To heal the matrix heat is applied on the surface. Then the SMA nano-fibers recover their original shape sealing the crack. The figure shows how the crack was healed after the heat treatment.

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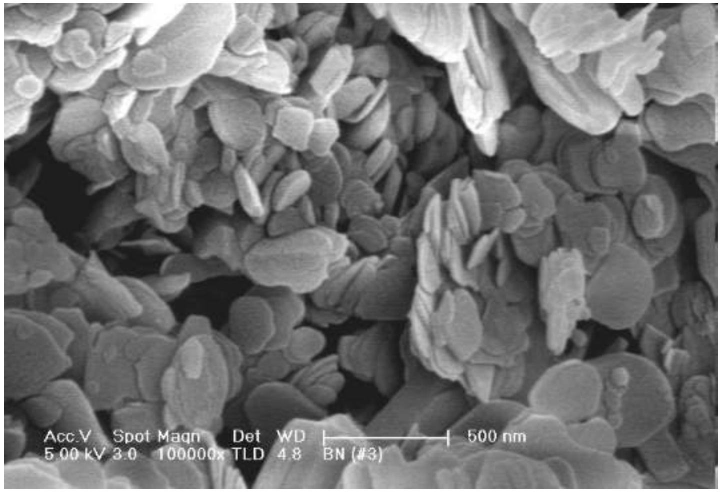
Self Lubricating MMC’s

Lubricants used in Self-Lubricating Composites

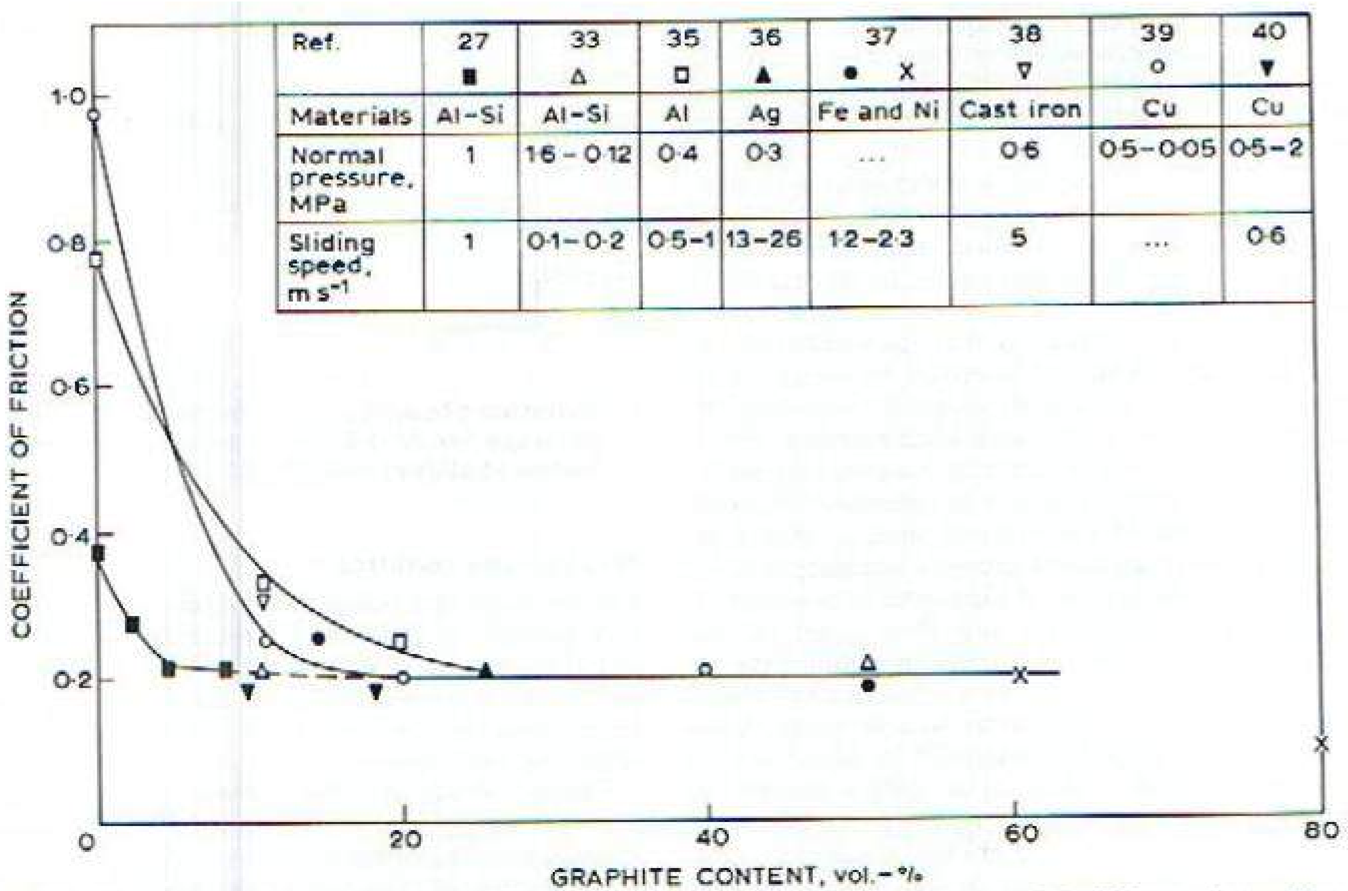
- Graphite
- Molybdenum disulfide
- Hexagonal Boron Nitride
- Talc
- Mica



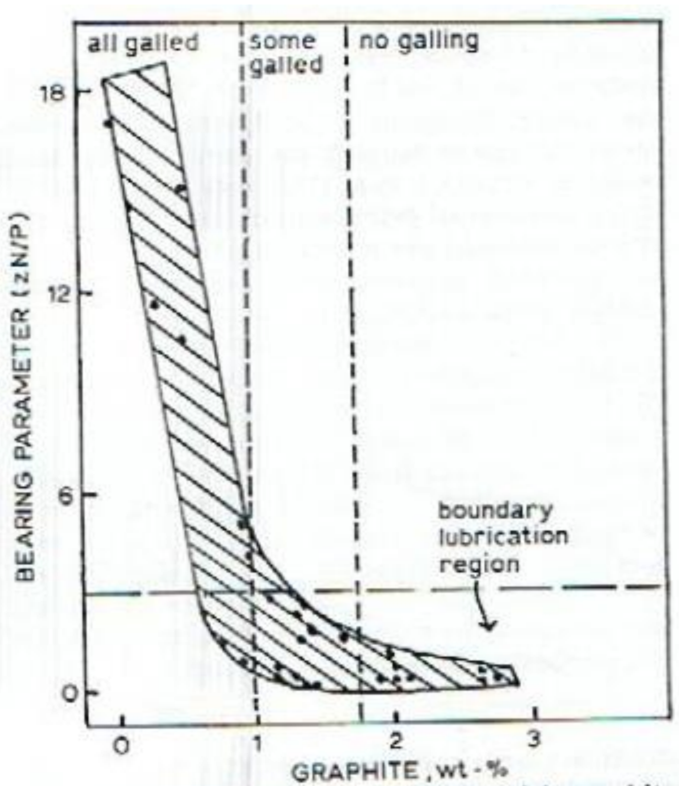
- Properties depend on the original materials, concentrations in the composite, dispersion and interactions with the matrix and the lubricant.

Applications for Self-Lubricating Composites

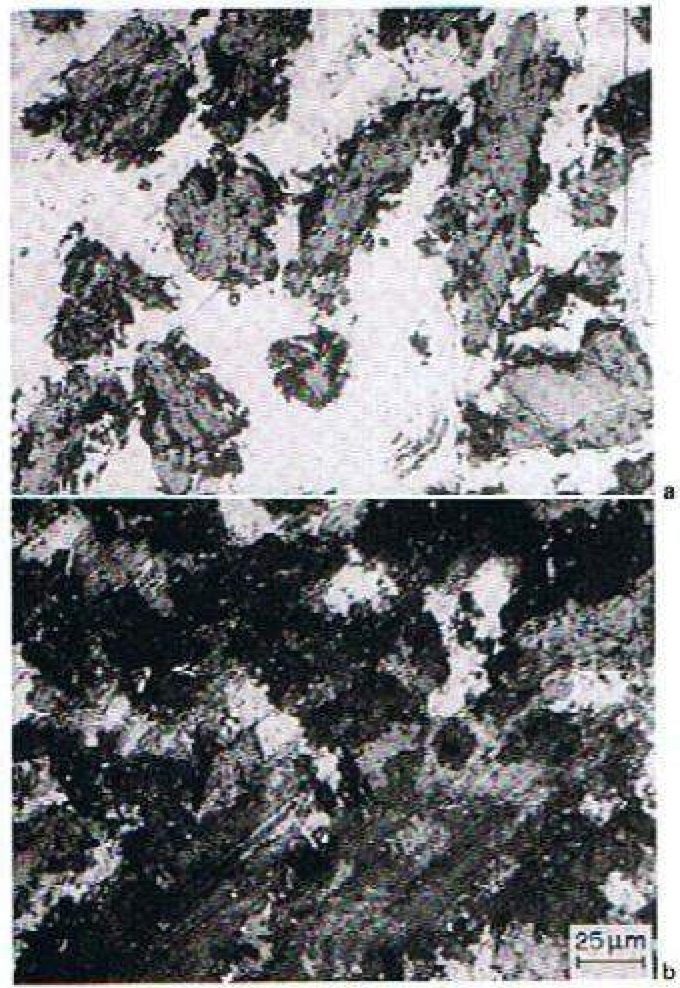
- Engine Pistons, turbines
- Cylinder Liners
- Bearings/Bushings
- Compressor vanes
- Wear plates



3 Variation of coefficient of friction with graphite content for composites with different base alloys



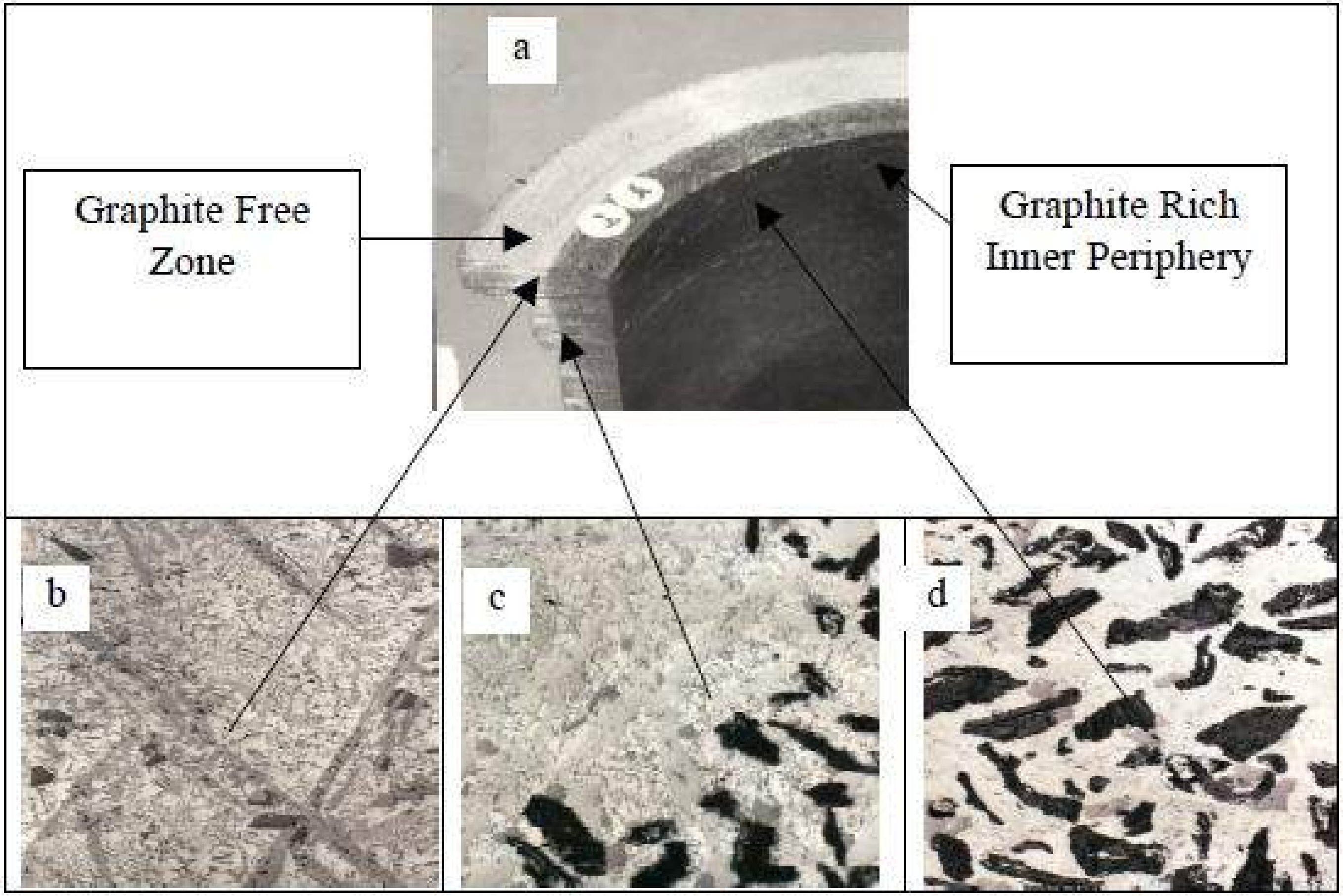
15 **Variation of bearing parameter with graphite content for Al–Si alloy base composites**



a before; *b* after

23 **Effect of sliding on microstructure of aluminium–graphite composite**

Centrifugal Casting




INTELLIGENT COMPOSITES
ZERO PLATING REQUIRED
HIGH-PERFORMANCE CYLINDER SLEEVES
EVEN PARTICLE DISTIBUTION
Aluminum (Al)
Silicon Carbide (SiC)
Graphite (G)
Graphite Reduces Friction Between the Piston and Cylinder Sleeves
Aluminum Matrix Matches the Thermal Expansion of the Piston and Block
Silicon Carbide Delivers Better Wear Resistance Than Cast Iron
Tighter Tolerances Reduce Oil Consumption and Emissions
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INTELLIGENT COMPOSITES

HIGH-PERFORMANCE CYLINDER SLEEVES

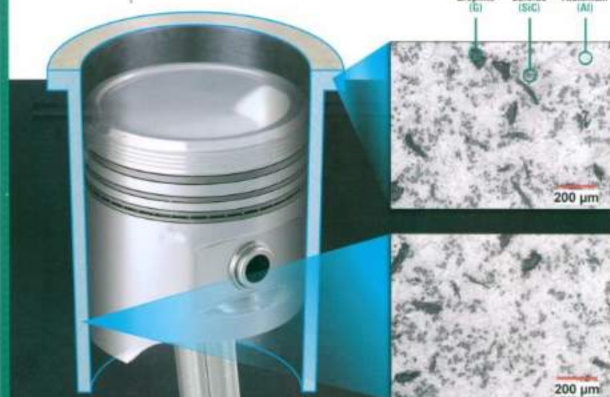
ALUMINUM (Al) - SILICON CARBIDE (SiC) - GRAPHITE (G)

lowers friction and wear inside internal combustion engines

— No plating or surface coating required —

Intelligent Composites' manufacturing process uniformly distributes graphite and silicon carbide particles throughout the entire casting. When friction occurs, microscopic graphite particles shear and create a tribo-film that adds lubricity to any environment.

Contact Intelligent Composites at (414) 758-0183 to learn how you can *GET MORE FROM YOUR ENGINE.*



COMPARATIVE ANALYSIS of CYLINDER SLEEVE MATERIALS

— JOHN LENNY JR., THESIS, RENSSELAER POLYTECHNIC INSTITUTE, 2011 —

MATERIAL	Al-SiC-G	Cast Iron	Al with Nikasil®	Al-Si	Al with Thermal Spray
PREVIOUS Applications	1	5	2	2	1
Wear Resistance	5	4	4	3	4
Scuffing Resistance	5	5	4	3	4
Thermal Conductivity	5	1	3	4	3
Low Friction	5	3	4	3	4
Fuel Economy	5	3	4	4	4
Emissions	5	3	4	4	4
Manufacturing Cost	3	5	2	3	3
Engine Performance	5	4	4	3	4
Mass Production Feasibility	3	5	3	4	5
TOTAL RATING	42	38	34	33	36

5 = Excellent 4 = Above Average 3 = Average 2 = Below Average 1 = Poor

CAST IN THE USA

WE MAKE ALUMINUM BETTER!

GET MORE FROM YOUR ENGINE

- ***MORE Horsepower***
- ***MORE Torque***
- ***MORE Fuel Efficient***
- ***LESS Emissions***

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Presentation Guide

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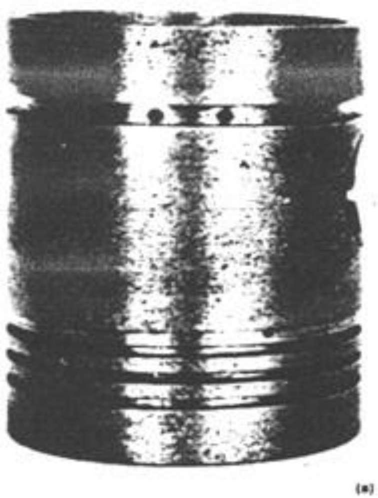
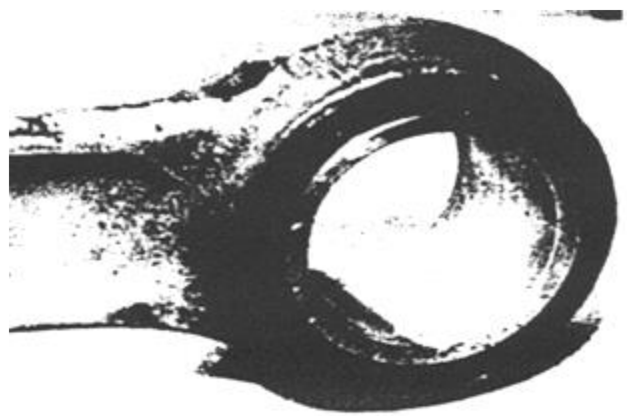
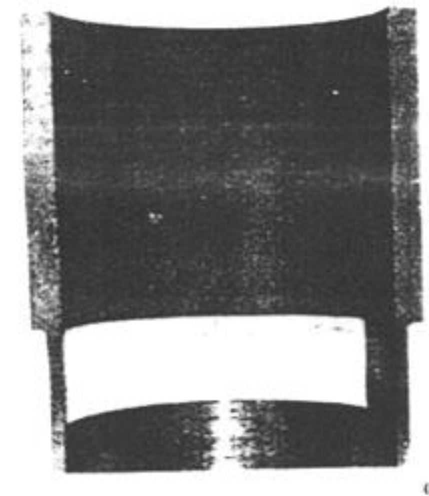
Composites at UW-Milwaukee



a)



b)



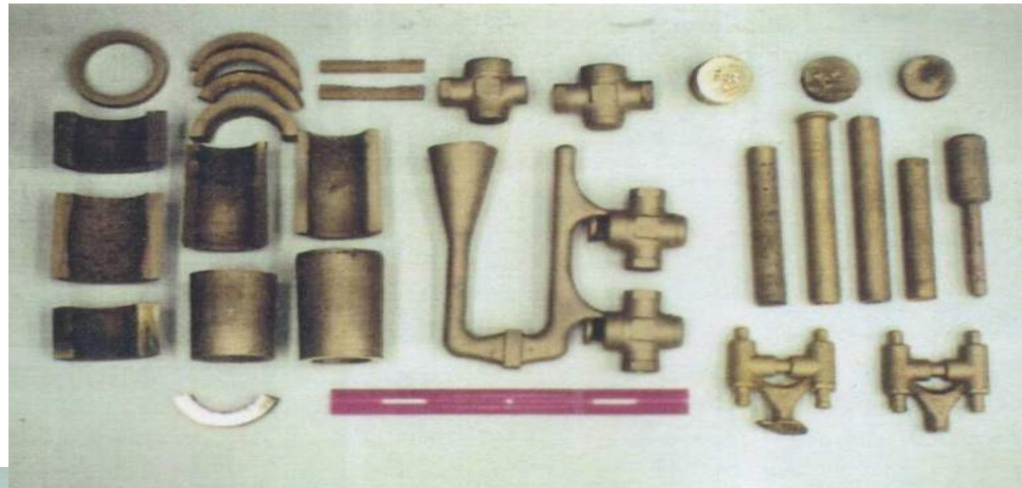
c)

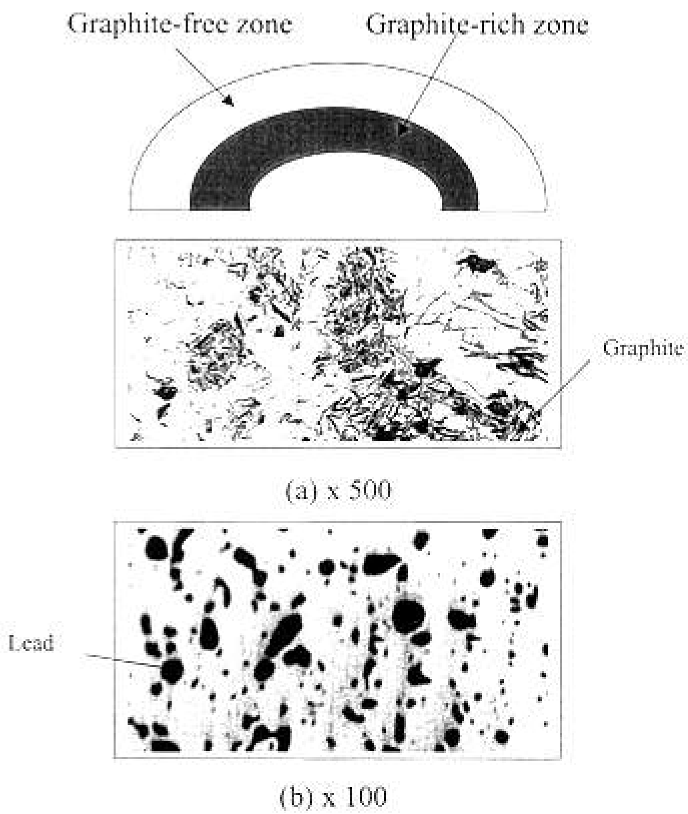
Automotive components made from cast Al/Gr_p composites.
(a) A composite piston successfully run in a 5 h.p. diesel engine ;
(b) A composite liner successfully run in an Alfa Romeo racing car engine ;
(c) A bearing successfully used as the small end of a connecting rod.

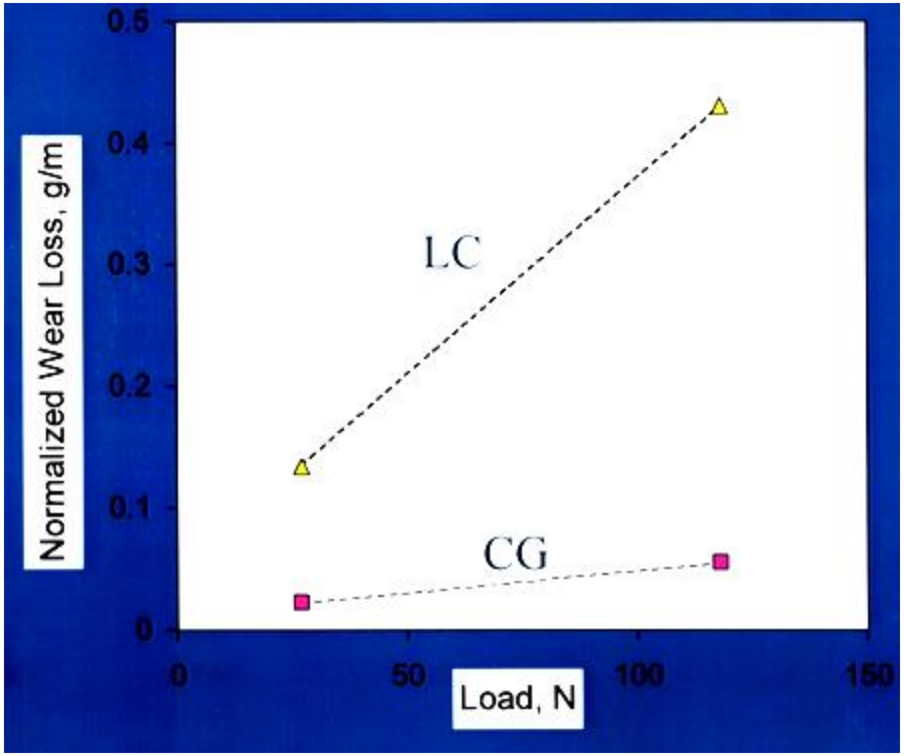
Composites at UW-Milwaukee

Aluminum Graphite Cast in Place Liner

Lead FREE Copper alloy-Graphite composite Castings





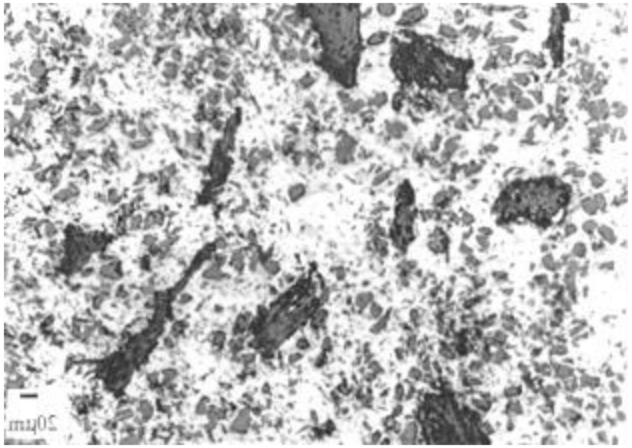


Microstructures of

(a) the graphite-rich zone of a centrifugally cast copper-graphite composite and

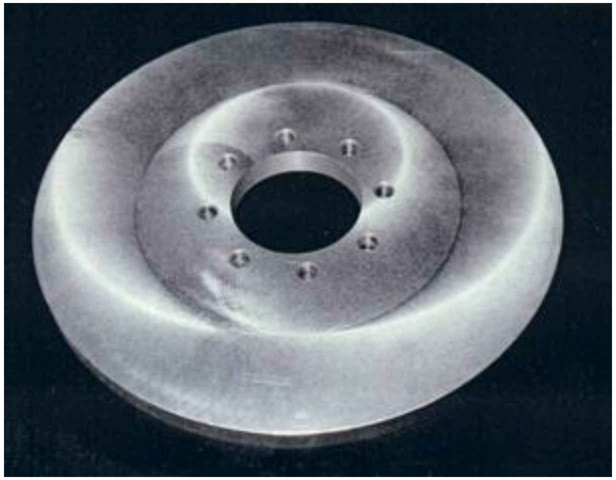
(b) the leaded-copper alloy (Cu-18~22Pb)

A356-10vol%SiC-4vol%Gr composites

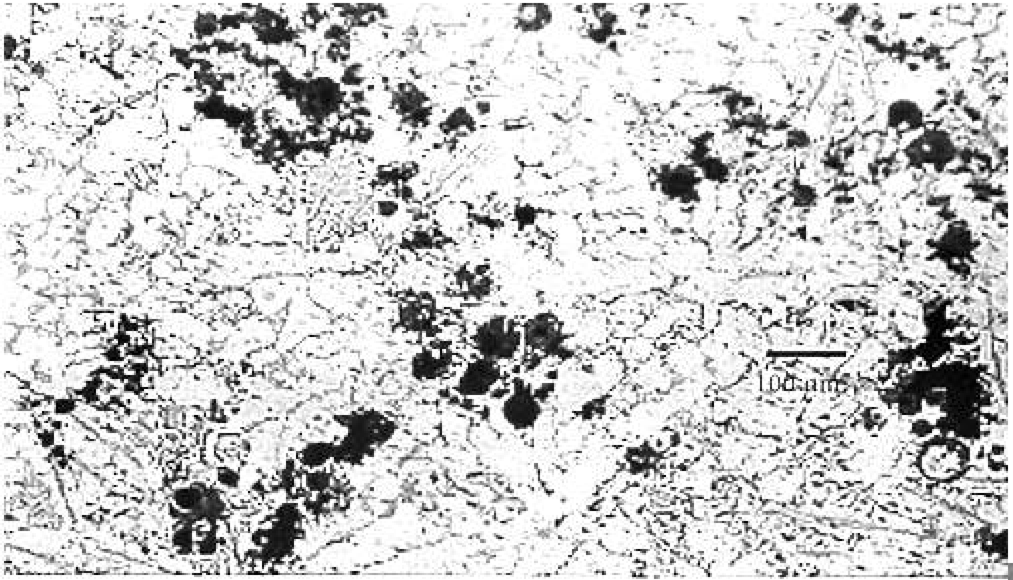
(a)


(b)

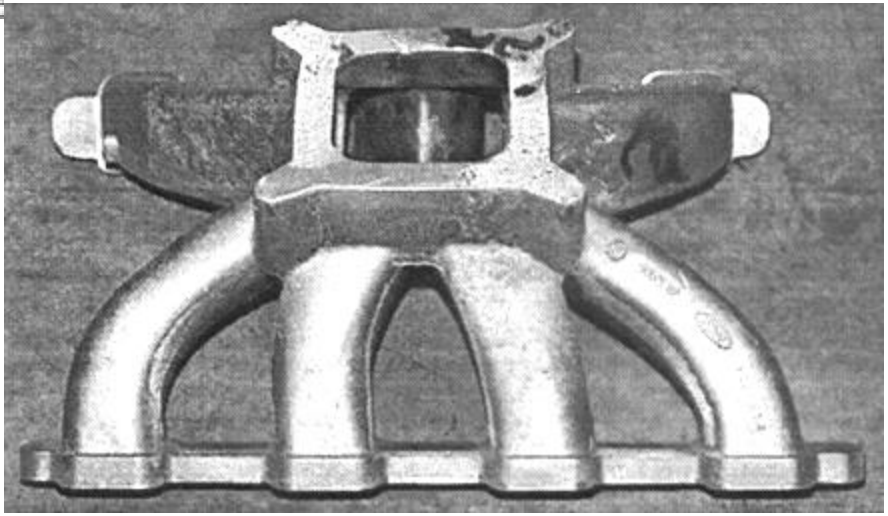

(c)


(d)


(a) microstructure, (b) cylinder liners, (c) drisc brake, (d) disc rotor.



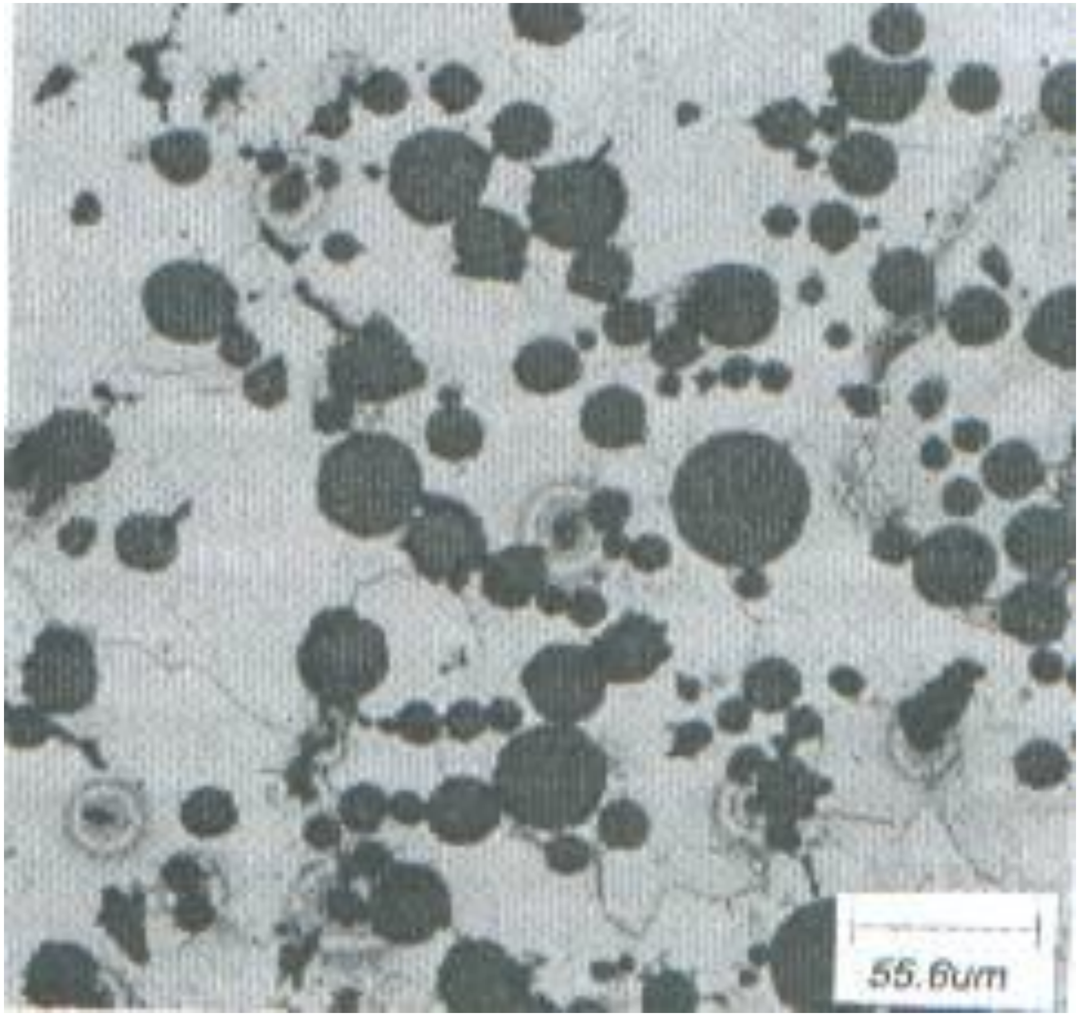
Microstructure of A356-10vol% fly ash composite



Intake Manifold cast from A356-10vol% fly ash composite

Aluminum, and Magnesium Compressor housing with Hybrid MMC cylinder liner insert

Fe-Alumina Composite



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Concluding Remarks

1. Metal Matrix Microcomposites can help reduce the weight while increasing the energy absorbing capability of transportation systems
2. While Polymer nanoclay nanocomposites have received considerable attention, the work on Metal Matrix Nanocomposites is in its infancy.
3. Powder metallurgy, cryomilling, solidification processing have been successfully used to incorporate nanosize particles including carbon nanotubes in metal matrices.

Concluding Remarks cont.

4. Exceptionally large increases in strength, hardness and wear resistance and reduction in friction coefficient have been obtained as a result of incorporation of very small volume percentages of nanoparticles in matrices of metals.

5. Self healing materials being developed at UWM can increase the survivability of Military Transportation Systems.

6. Self lubrication Metal Matrix Composites can decrease energy consumption and increase the reliability of Military Transportation Systems

7. Self cleaning composites can be synthesized which can increase the performance of military vehicles

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Thank You for your Attention!