Discontinuously Reinforced Light Metals for Automotive Applications

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OPEN TECHNOLOGY FORUM

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Outline:

- Introduction
- Overview: Composite materials
- Properties and theoretical limits of Metal Matrix Composites
- MMC for automotive applications
- New manufacturing techniques for discontinuously reinforced MMC
- Summary and conclusions

Types of MMC

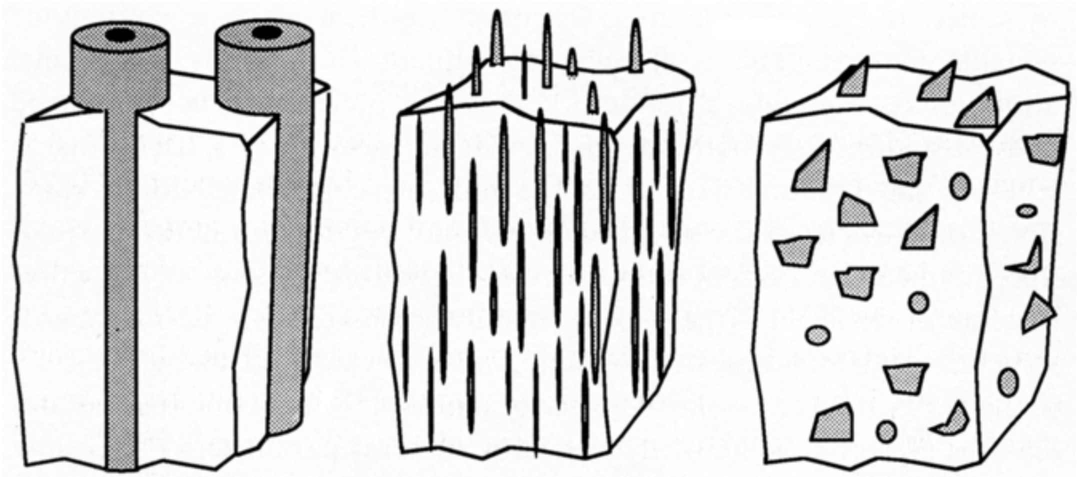
Distinction by the shape, character and orientation of the reinforcement phase:

Continuous and *discontinuous* reinforcement.

- endless fibers / long fibers
  - UD (uni-directional)
  - 2D (woven structures)
  - 3D (complex preforms)
- monofilaments

- short fibers
- staple fibers
- whiskers
- particles
- platelets
- in-situ reinforcement

(short fibers, staple fibers, whiskers:)
- aligned discontinuous fibers
- off-axis aligned ...
- randomly oriented ...



acc: *T. W. Clyne, P. J. Withers: An Introduction to Metal Matrix Composites. Cambridge : University Press, 1993*

Properties of Aluminum Matrix Composites (AMC)

Comparison of properties for particle (PRM), short fiber (SFRM) and continuous fiber (CFRM/UD) reinforcement

Material		Al alloy (reference)	PRM	SFRM	CFRM/UD[1]
density	(g/cm^3)	2.7-2.8	2.6-3.2	2.4-3.1	2.2-3.2
Young's modulus	(GPa)	69-75	90-250	80-120	150-450
strength	(MPa)	20-600	300-1000	200-600	500-1800
"ductility"		++	- /o	- -	- -
hot strength		- /o	- /o	+	++
fatigue resistance		-	+	o/+	++
wear resistance		- -	+/++	+	o/+
thermal conductivity	(W/m K)	100-240	200-700[2]	100-180	100-800[3]
thermal expansion coeff.	(10^{-6}/K)	18-23	5-18	14-18	0-10
Cost		++	- /+	- /o	- -
Formability		++	o/+	o	-

!

[1] continuous, unidirectional reinforcement; properties in longitudinal direction (direction of fiber orientation)
[2] SiC or rather diamond particles
[3] alumina (Al_2O_3) or rather graphite fibers

acc: E. Moeller: Handbuch Konstruktionswerkstoffe. München : Hanser, 2008

Cost of Commercial MMC Materials and Reinforcements

Stir-casting MMC (PRM):	**5 – 25 €/kg (e.g., Duralcan)**
Sprayed MMC (PRM):	**10 – 50 €/kg (e.g., Peak)**
PM (PRM):	**15 – 150 €/kg (e.g., AMC, DWA); Dartal: 28 €/kg**
Particles:	**1 – 10 €/kg (except B_4C: 40 €/kg)**
Short ceramic fibre preform:	**200 €/kg (Saffil)**
Carbon multifilaments:	**15 (HT) – 2000 (HM) €/kg**
Ceramic multifilaments:	**> 350 €/kg**
Ceramic monofilaments:	**> 5000 €/kg**

Consequence:

Fibres only for small components or as selective reinforcement

source: Achim Schoberth (EADS), "MMC for Aerospace Applications", DFG, AK CMC, Bremen, 11. März 2005

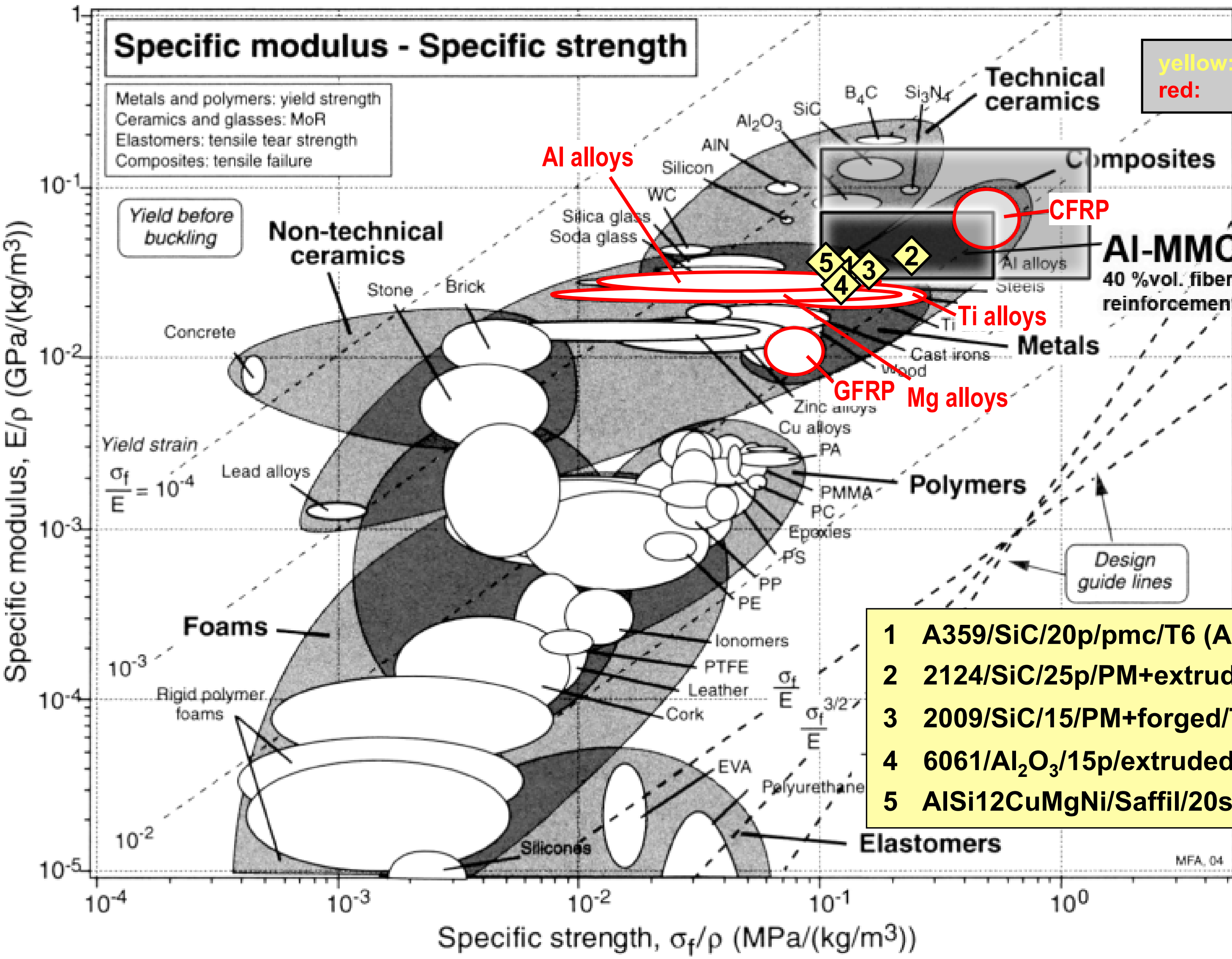
Properties of Discontinuously Reinforced MMC – Examples

Mechanical and thermophysical properties of some automotive aluminum alloys, Al Si5A (which was used in this work) and AMC materials; var. sources

Material (alloy or composite)	Stiffness (GPa)	UTS (MPa)	YS (MPa)	Breaking strain (%)	CTE (10^{-6} K^{-1})
EN AW-2024 [Al Cu4Mg1]	73	180–460	140–400	2–15	24.7
EN AW-4043A [Al Si5A]	70	100–140	90	10–15	23.7
EN AW-6061 [Al Mg1SiCu]	70	120–300	85–240	3–18	23.0
A356.0-T6 (EN AC-42100 [Al Si7Mg0,3])	72.4	234	190	2–3.5	23.2
A226 bzw. 226 D (VAR) EN AC-46000 [Al Si9Cu3(Fe)]	73	160–240	140	1–3	22.3
Al Si17Cu4Mg (B390.0)	81.4	317–370	248–360	up to 1	22.5
A359/SiC/20p/pmc/T6	98.6	359	338	0.4	17.5–21.4
2124/SiC/25p/extruded/T4	115	690	487	5	15.5
6061/Al_2O_3/15p/extruded/T6	88.9	365	324	6	19.6–20.3
Al Si12CuMgNi/Saffil/20sf/SC[1]	105	310	-	0.2–0.5	≈ 16

[1] sf: short fiber; SC: squeeze casting

Specific Properties – Material Comparison for Design Engineers



yellow: aluminum MMC (AMC)
red: light-metals and PMC

1 A359/SiC/20p/pmc/T6 (Alcan F3S.20S)
2 2124/SiC/25p/PM+extruded/T4 (AMC225xe)
3 2009/SiC/15/PM+forged/T4 (Dartal 15A)
4 6061/Al_2O_3/15p/extruded/T6 (Alcan W6A.15A)
5 AlSi12CuMgNi/Saffil/20sf/squeeze casting

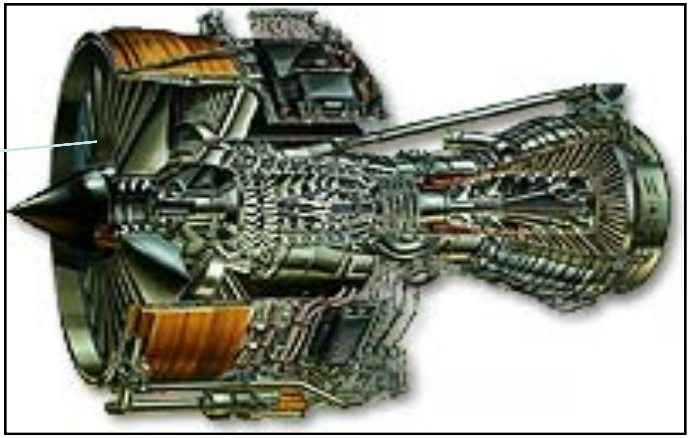
var. sources

according to. M.F. Ashby: Materials Selection in Mechanical Design. 3rd ed. Burlington: Butterworth-Heinemann, 2005

Application Example: Aerospace Industry

- Application for Powder Metallurgy PRM with isotropic material's properties -

Turbine blades for aero engines (gas turbines):



Weight savings: 500 g / vane
Cost savings: 15 %
} vs. SPF DB Ti6-4

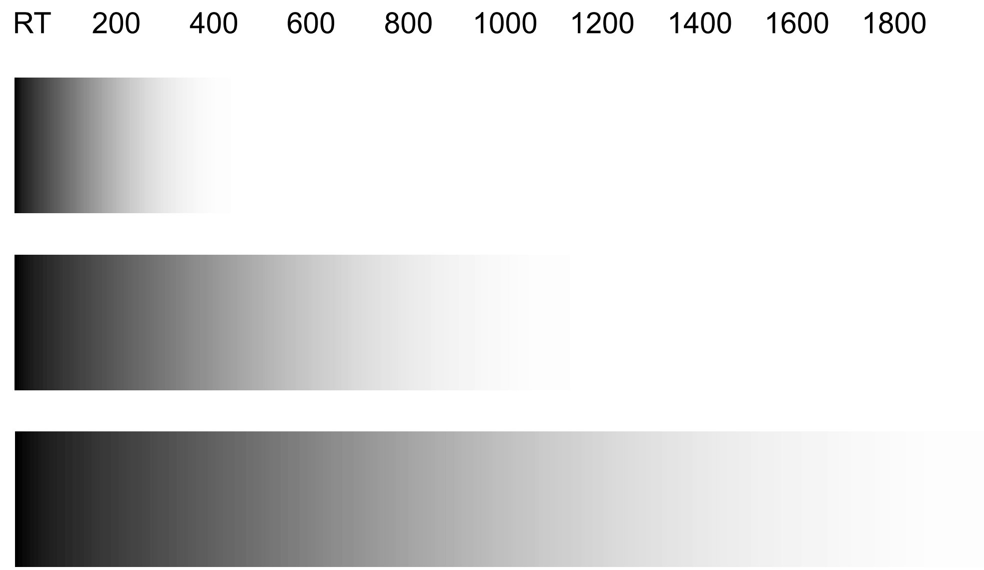
FORGES DE BOLOGNE
Groupe Manoir Industries

Rolls-Royce

Service Temperatures for Composites with different Matrix Materials

composites	matrix	reinforcements
PMC	Epoxy	Glass fibers
	Phenolic	Carbon fibers
	Polyimide	Aramide fibers
MMC	Aluminum	Carbon fibers
	Titanium	SiC–particles
	Magnesium	Al_2O_3–fibers
CMC	(Si)SiC	Carbon fibers
	Al_2O_3	Al_2O_3–fibers
	Si_3N_4	SiC–fibers

service temperature (°C)



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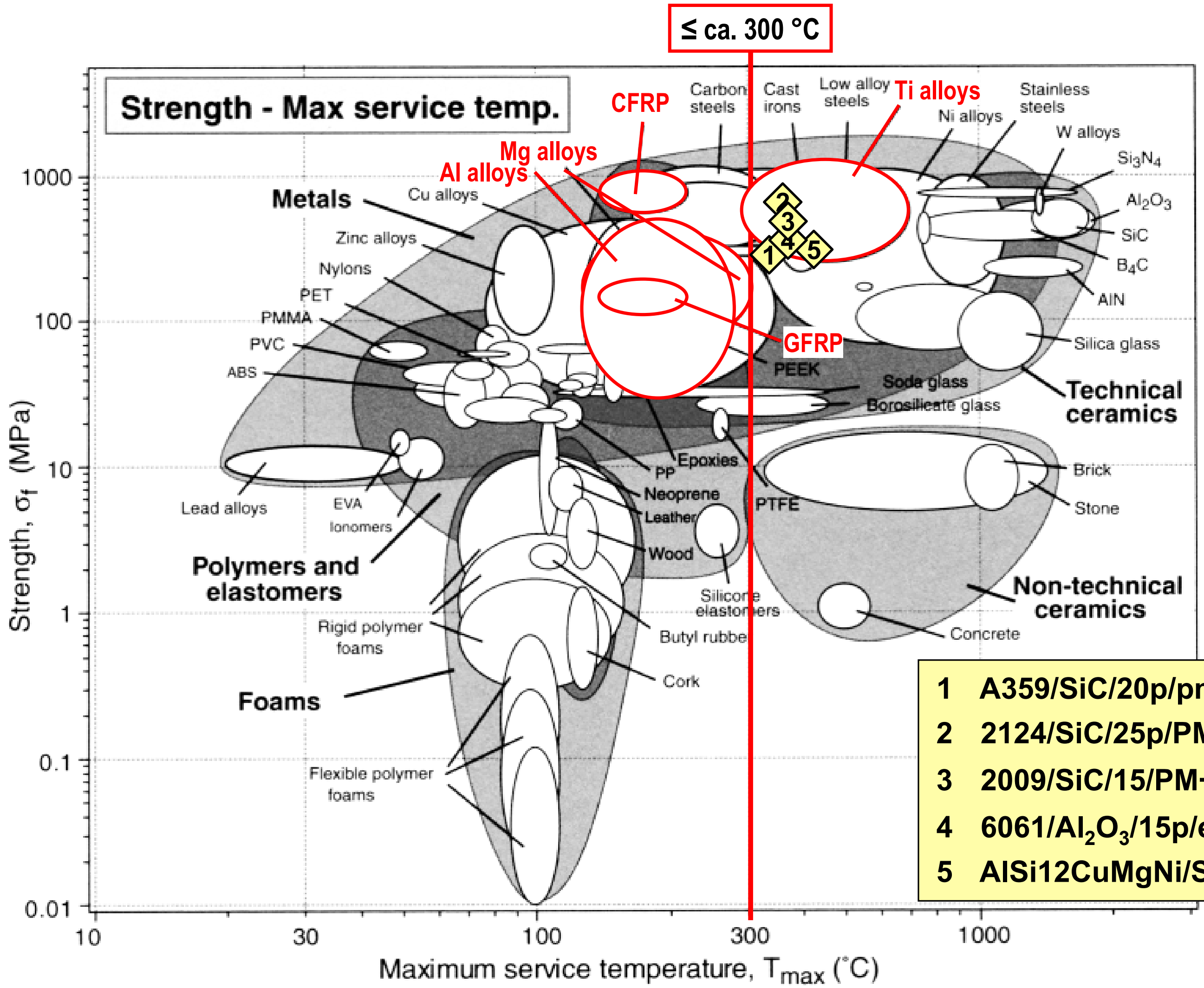
R. Gadow , M. Wenzelburger
IFKB P-571c

Comparison of Material's Properties



1	A359/SiC/20p/pmc/T6
2	2124/SiC/25p/PM+extruded/T4
3	2009/SiC/15/PM+forged/T4
4	6061/Al_2O_3/15p/extruded/T6
5	AlSi12CuMgNi/Saffil/20sf/squeeze casting

var. sources

according to. M.F. Ashby: Materials Selection in Mechanical Design. 3rd ed. Burlington: Butterworth-Heinemann, 2005

Residual tensile strength at 350 °C: – *Aluminum Matrix Composites:* *ca. 150 MPa*
– *non-reinforced Al:* *ca. 80 MPa*

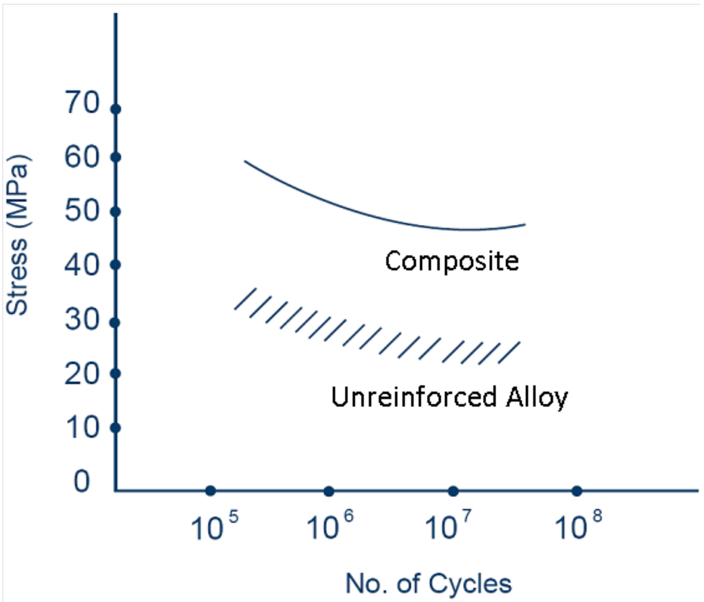
Properties at Elevated Temperatures – Short Fiber Reinforcement

Ultimate tensile strength and fatigue strength under reversed bending at different temperatures for Al Si12CuMgNi/Saffil/20sf/SC and its pure matrix alloy

Material	UTS (MPa)		High cycle bending fatigue strength (MPa) / *N* = 25*10⁶ cycles	
	20 °C	350 °C	20 °C	350 °C
Al Si12CuMgNi alloy	270	≤ 100	100	30
Al Si12CuMgNi/Saffil/20sf/SC	310	≈ 130	160	57

acc.: Henning, W.; Neite, G.: Herstellung, Eigenschaften und Anwendung von kurzfaserverstärkten Aluminiumlegierungen. In: Kainer, Karl U. (ed.): Metallische Verbundwerkstoffe. Oberursel: DGM Informationsges., 1994, p. 169–191

Fatigue test data at 350 °C for Al Si12CuMgNi/Saffil/20sf/SC



acc.: Saffil Automotive Ltd., Flintshire, UK: Properties of Metal Matrix Composites. – Online data sheet

Advantages of MMC vs. Unreinforced Metals and PMC

With respect to metals:

- Major weight savings due to higher strength-to-weight ratio
- Exceptional dimensional stability (compare for example SiC_p/Al to Al)
- High temperature stability (creep resistance)
- Significantly improved cyclic fatigue characteristics
- Improved wear resistance

With respect to PMC:

- Higher compressive strength and stiffness, plasticity and toughness
- Higher operation temperatures
- Higher electrical and/or thermal conductivity
- Better transversal properties
- Ability for welding and soldering
- Easier integration in metal structures
- Radiation resistance (UV, IR, laser, nuclear, etc.)

→ *Applies for fibrous and particle reinforced MMC!*

acc.: N. Chawla and K. K. Chawla, Metal Matrix Composites, New York: Springer, 2006.

Review of MMC Applications in Automotive Industry

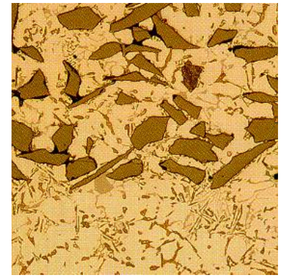
acc: P. Stingl, CeramTec AG: Keramik im Automobil - Vision oder Wirklichkeit. In: „Technische Keramik i. d. Praxis“, Seminarreihe 2005. Selb : Verb. d. keram. Industrie, 2005.

Light metal crankcase; particle reinforcement of cylinders and bedplates

Heterogeneous solutions
cast iron & AlSi bushings (Silitec®)

Monolithic solutions
AlSi17Cu4Mg (Alusil®)
hypereutectic alloy

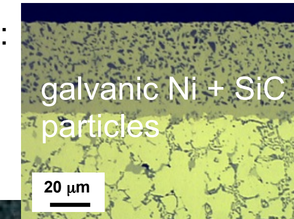
Quasi-monolithic solutions
preform infiltration (Lokasil®)
& various coatings



Lokasil II®: squeeze casting of Si cylinder liner preform

acc: Kolbenschmidt Pierburg AG, Neckarsulm, 2010

Nikasil®:



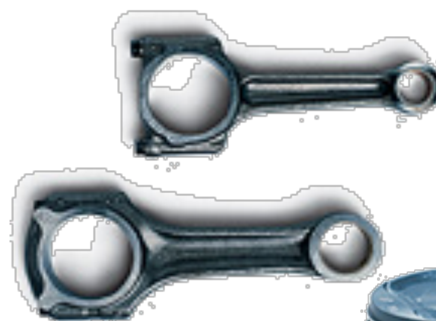
Lokasil® bedplate (particle or fiber/particle preform)

Reinforced piston rods and piston; short fiber or particle reinforcements

Piston rod, ZC71/ SiC/12p; microstructure after forging

Process: stir casting of billets, hot extrusion and die-forging.

acc: V. M. Kevorkijan: Mg MMC Closed Die Forgings for Automotive Applications. Am. Ceram. Soc. Bull., Feb. 2004



acc: Mahle AG, Stuttgart

acc: Kolbenschmidt AG, 1992

Piston, 20 %vol. Saffil (δ-Al_2O_3) short fiber reinforced aluminium

(Al Si12CuMgNi (KS1275) / Saffil / 20sf / squeeze casting)

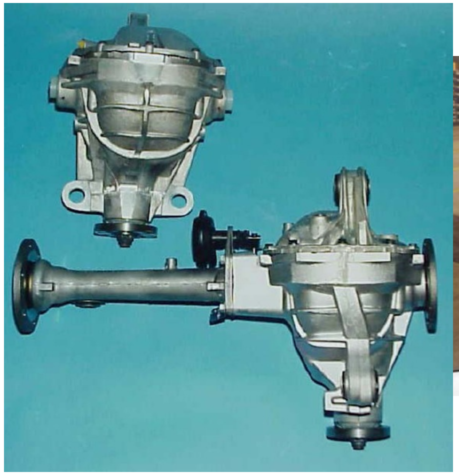
Review of MMC Applications in Automotive Industry

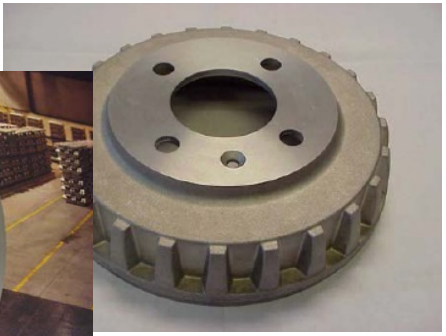
4“ AccuBond™ Duralcan™ MMC driveshaft

($6061/Al_2O_3/20p$/extruded/T6)

acc: Mark Williams Enterprises, Louisville (CO), USA, 2010

Duralcan™ driveline housing, brake rotor and brake drum (A359/SiC/20p/pmc/T6, and A360/SiC/20p/hpdc/T5)

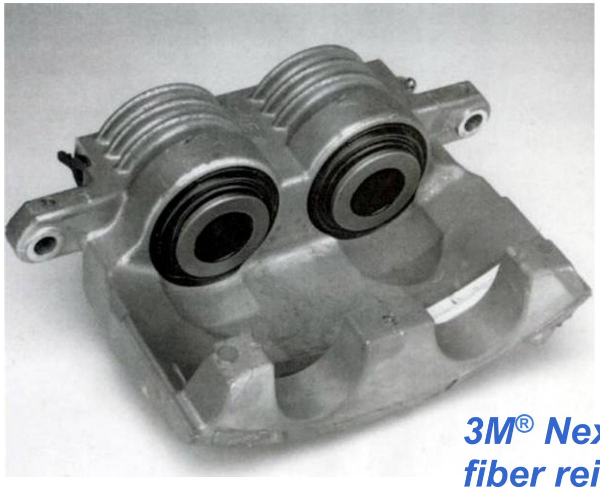




acc: Alcan Engineered Cast Products, Alcan Inc. (now Rio Tinto Alcan Inc.), Montreal, Canada, 2010

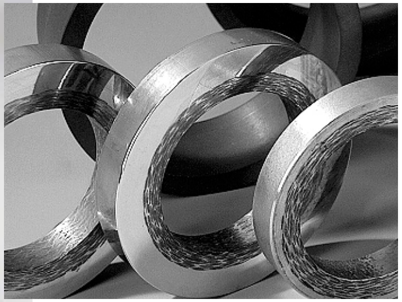
Disc brake caliper with fiber reinforcement

acc: K. U. Kainer: Metallishe Verbundwerkstoffe. Weinheim : Wiley-VCH, 2003



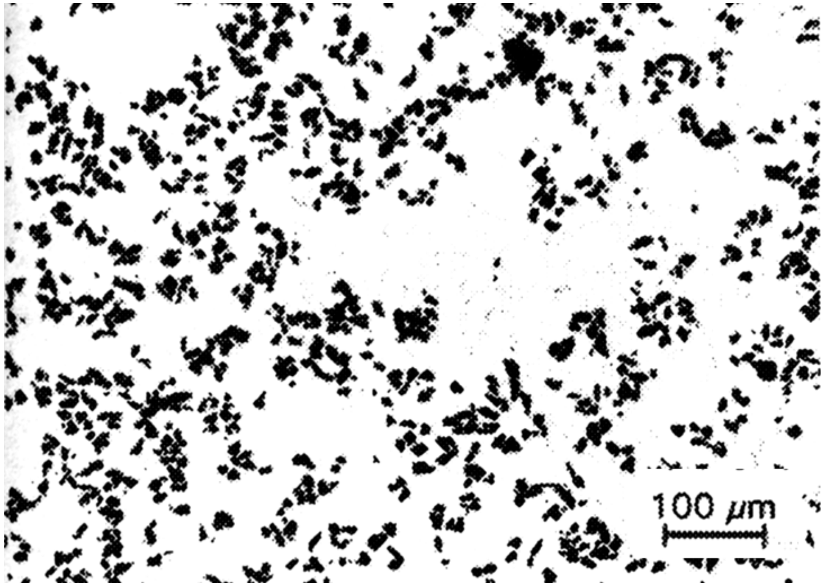
3M® Nextel 610 long fiber reinforced AMC

Fiber reinforced wheel hub / bearing seat; continuous fiber reinforcement (Mg/C_F or Al/C_F inserts)!

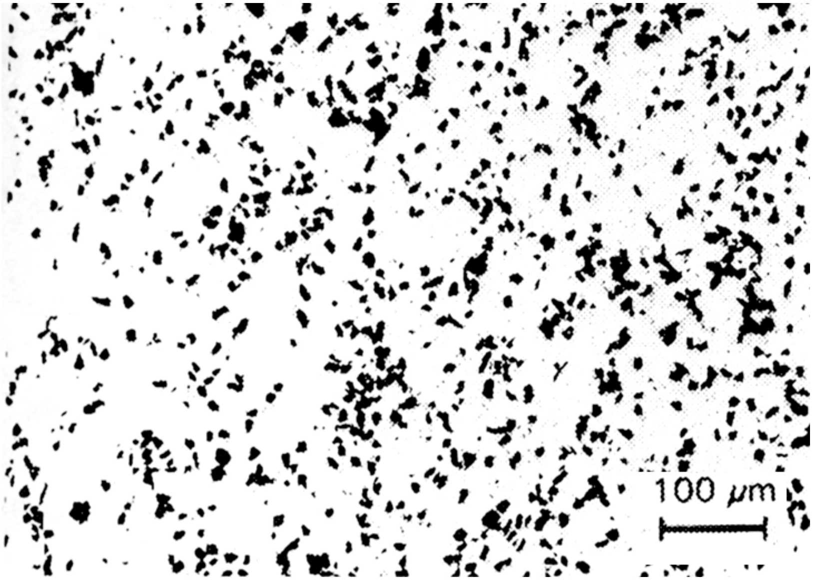


acc: EMPA, Thun, Schweiz

Microstructures for Different PRM Processes



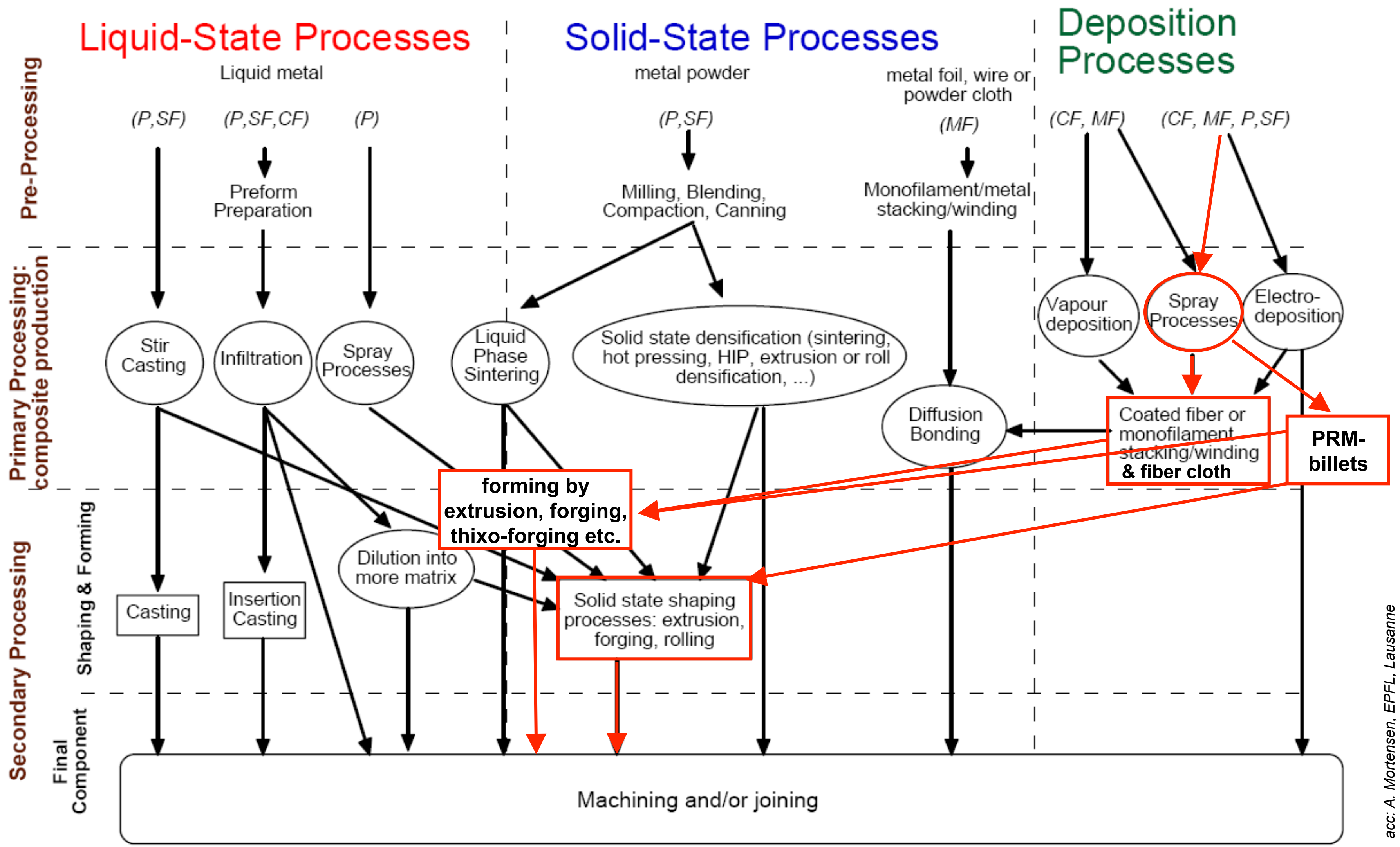
Structure as-cast
(Duralcan™ 6061/Al_2O_3/15p)



Sprayforming structure
(6082/SiC/15p)

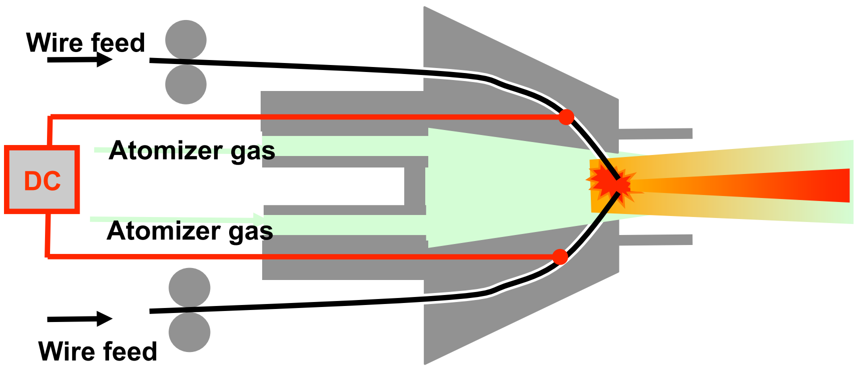
acc.: Degischer, H.P.: Schmelzmetallurgische Herstellung von Metallmatrix-Verbundwerkstoffen. In: Kainer, Karl U. (ed.): Metallische Verbundwerkstoffe. Oberursel: DGM Informationsges., 1994, p. 139–168

New Process Development



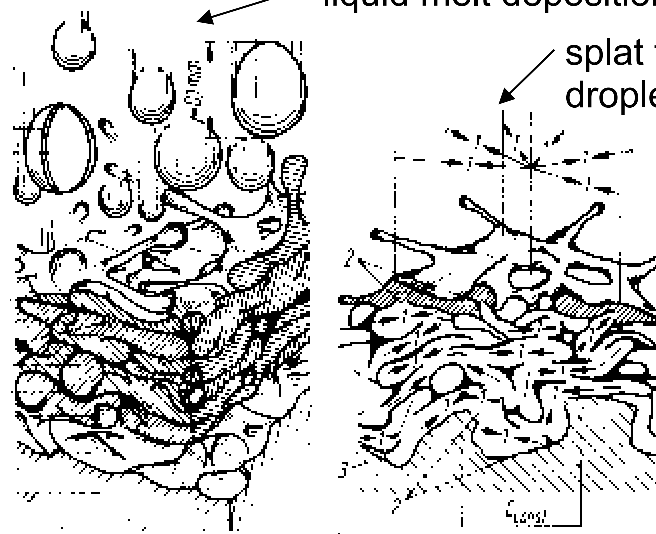
Reinforcements: P = particles, *SF* = short-fibers, *CF* = continuous fibers, *MF* = monofilaments

Material Deposition by Twin-Wire Electric Arc Spraying

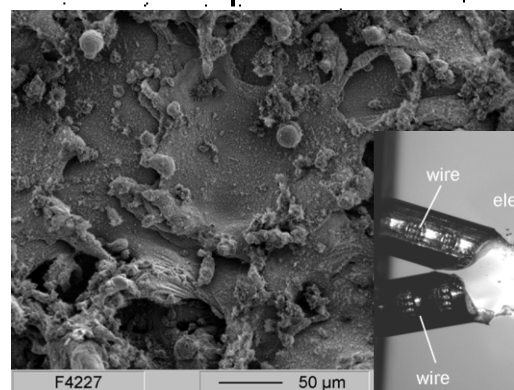


liquid melt deposition

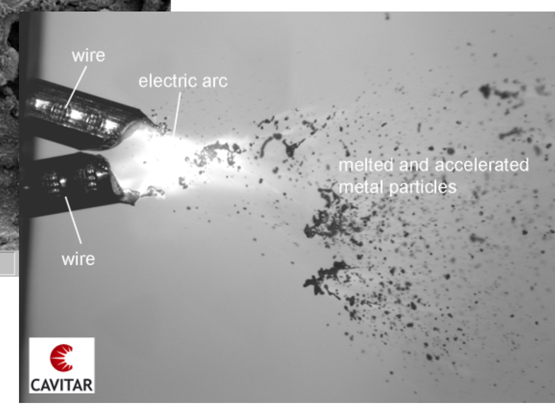
splat formation /
droplet fragmentation



acc. Pursche, Oberflächenschutz vor Verschleiß, 1990



Thermal spray Al Si5
surface (SEM)



High-speed image of twin-wire
electric arc spraying

Energy source:	electric arc
Max. process temp.:	4000 °C
Materials:	metals, alloys, cored wires with ceramic particles
Particle velocities:	< 150 m/s
Deposition rate:	20 – 300 kg/h
Wire diameter applied:	1.6 mm

Materials Chosen for Thermal Spray and Thixoforging Experiments

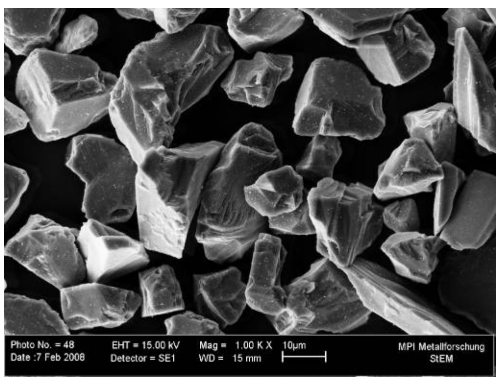
Table: Properties of different reinforcement particles

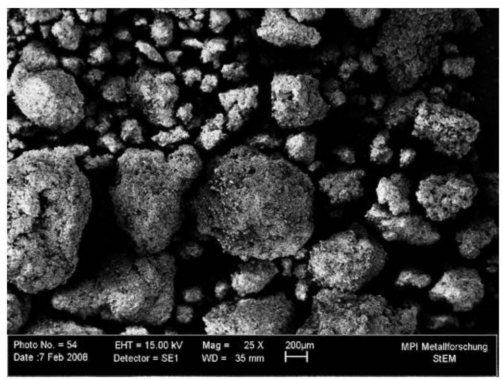
various sources

	density ρ (g/cm³)	melting point / th. decomp. T_S, T_m (°C)	thermal expansion coeff. $\alpha_{20\text{-}1000}$ (10^{-6} K^{-1})	Young's modulus E (GPa)	Vickers hardness HV (kp/mm²)
Al_2O_3	3.7 - 3.97	2050	7.0 - 8.8	300 - 380	1700 - 2370
SiC	3.08 - 3.20	2760	4 - 4.8	370 - 450	2500 - 3300
B_4C	2.52	2445	4.5 - 5.6	450 - 470	4980
silicon	2.33	1420	2.3 - 7.6	112.8	1120

Table: Properties of EN AW-5754 [Al Mg3]

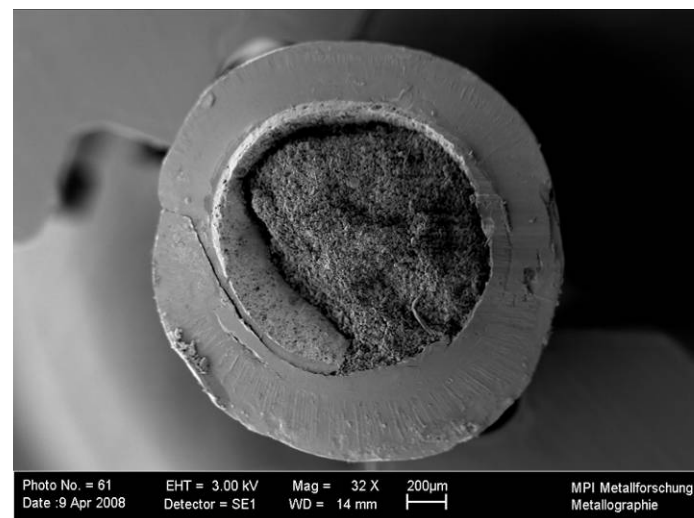
		AlMg3
ρ	(g/cm³)	2.67
T_m	(°C)	600 - 645
α	(10^{-6} K^{-1})	23.8
E	(GPa)	70
HV	(kp/mm²)	~ 47 - 93



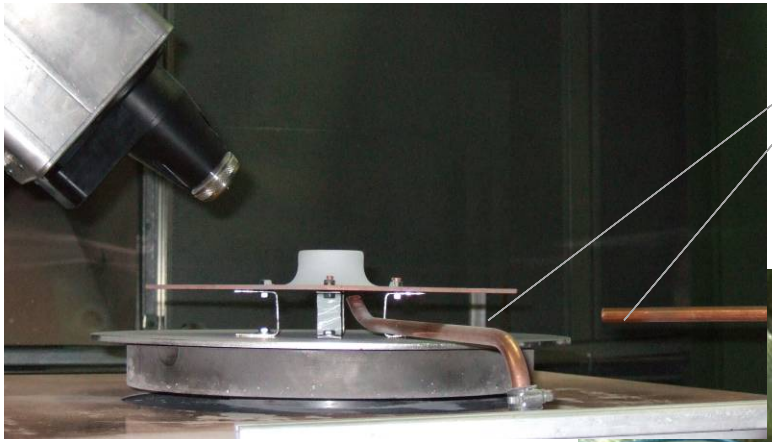


<u>particle material used in this work:</u>
SiC, agglomerated (SEM on the right)
D50 (primary) = 20 µm
D50 (agglomerates) = 173 µm (D90 = 536 µm)

<u>cored wire:</u> AA-5754-SiC
26.2 vol.% particle content
diameter: 2.15 mm

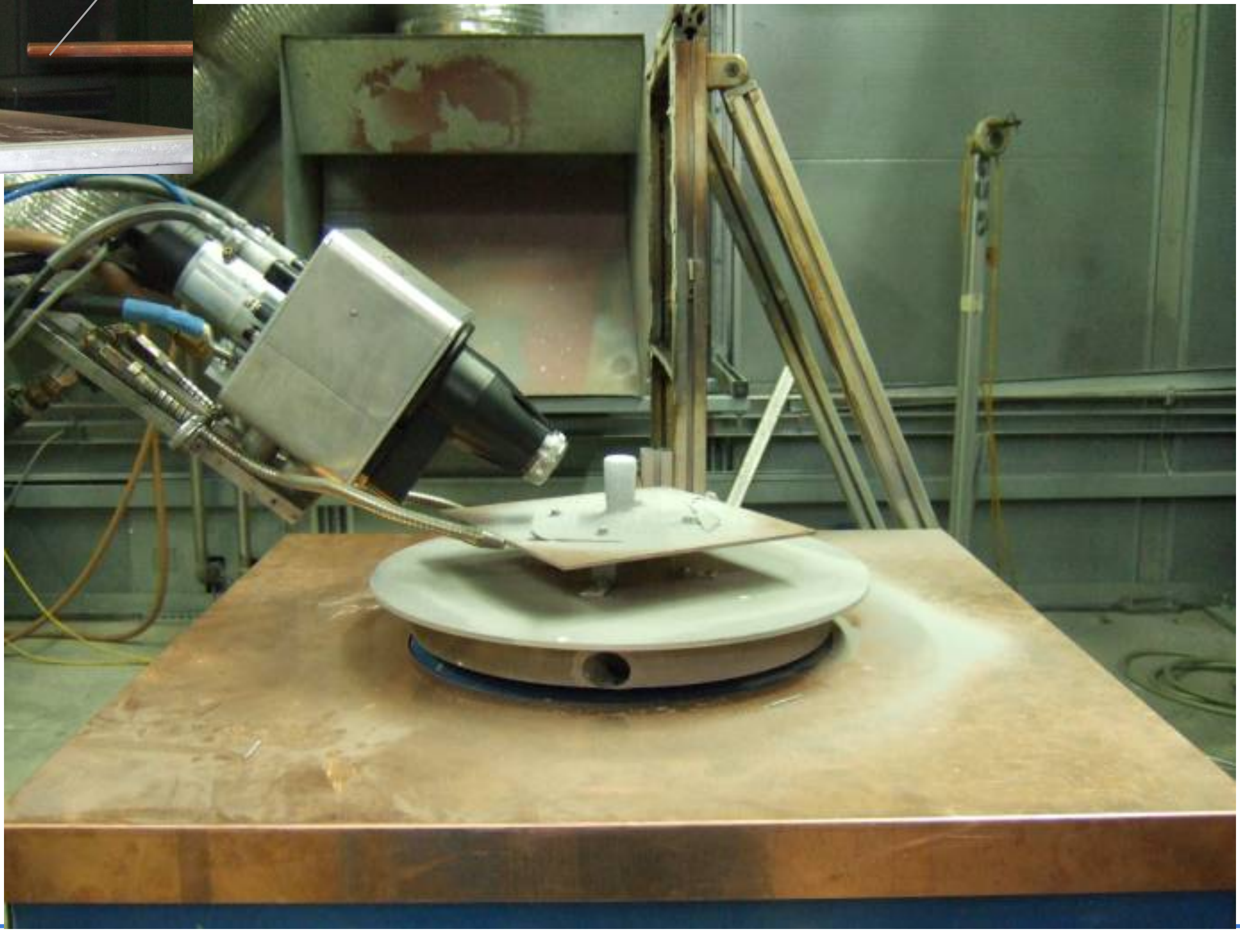


Semi-Finished PRM Material by Thermal Spray Deposition



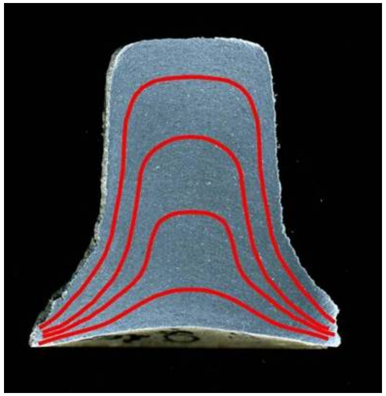
Cooling of the material during deposition

Rotating table, wire arc spray gun and billet



Billet size:

Ø = 26 mm
H = 42 mm

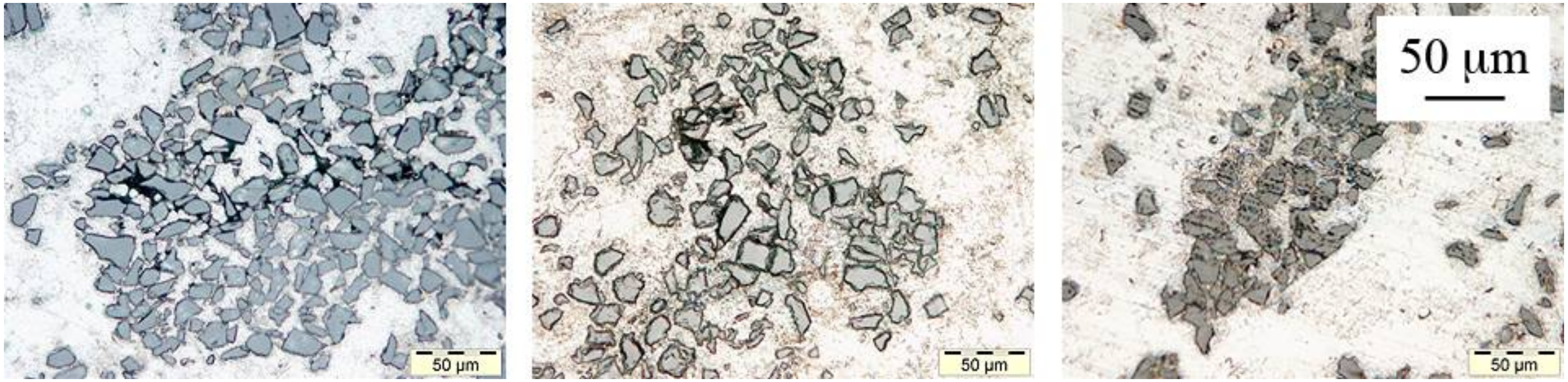


5754/SiC/10p Billets for Semi-Solid Forming

Microstructure of Semi-Solid Forged 5754/SiC/10p

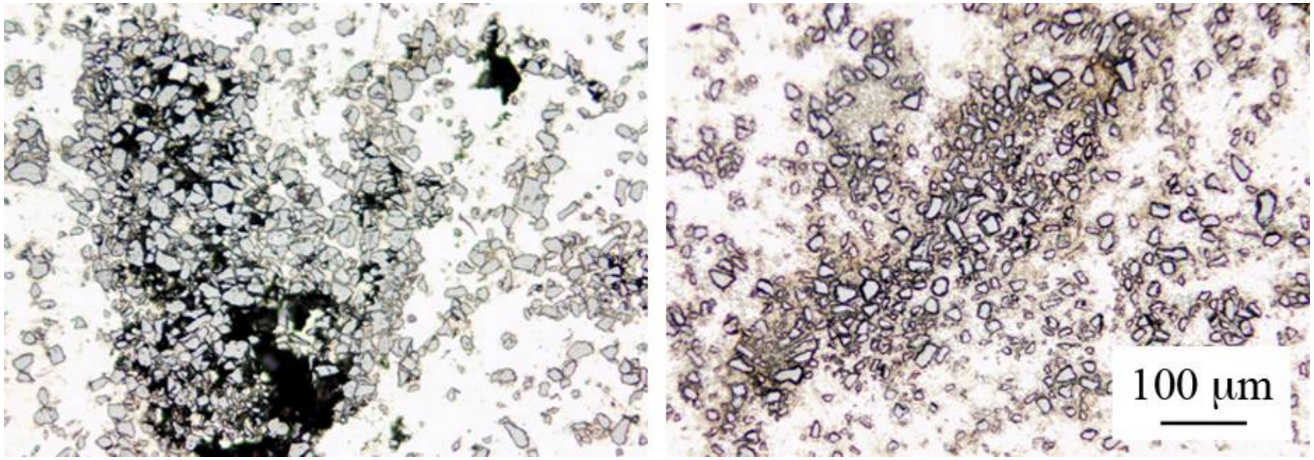
Dependency on Thermal Spray Parameters:

- press force: 20 kN;
- left to right billets: TS-2 (27.5 V / 4 bar), TS-1 (22.0 V / 4 bar) and TS-4 (27.5 V / 6 bar)

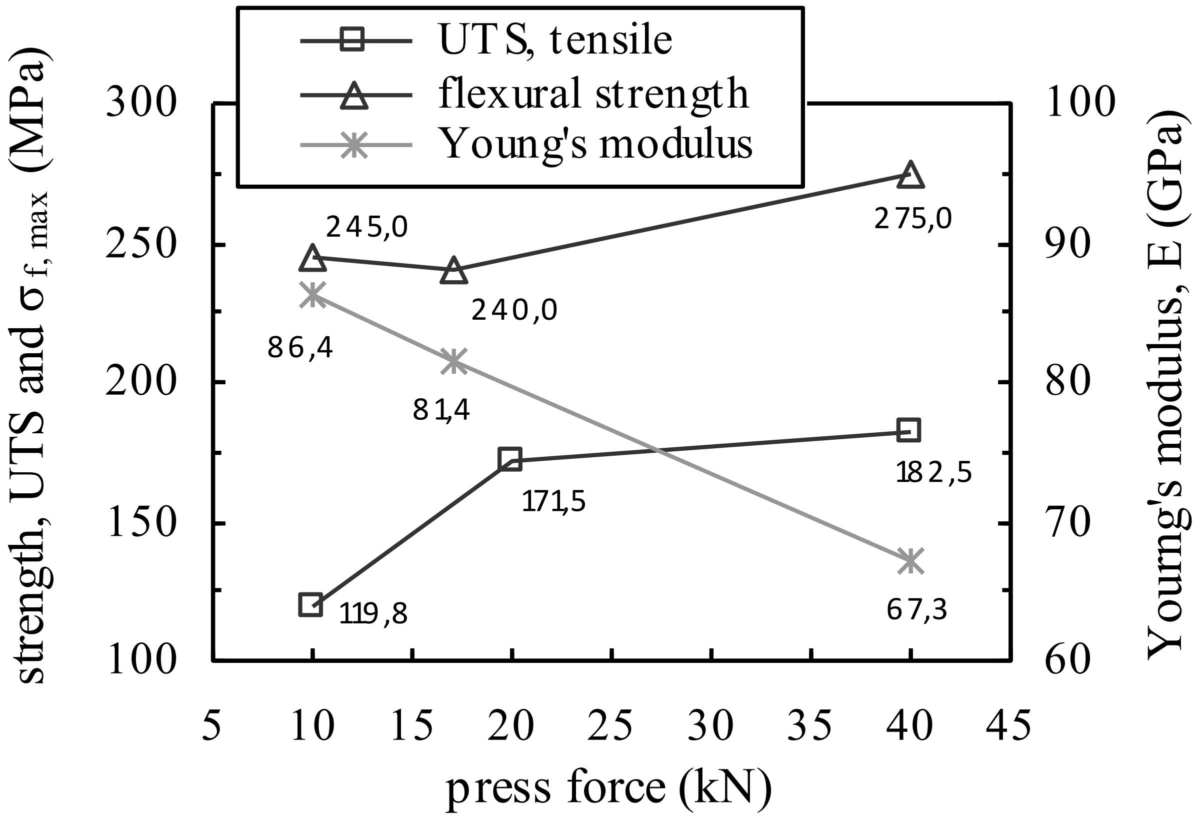


Dependency on Press Force during Thixoforging:

- Thermal spray parameters: standard TS-2 (27.5 V / 4 bar)
- press force 10 kN (left), 40 kN (right)



Characterisation – Mechanical Properties (Strength and Stiffness)



- Mechanical results show dependency on press force during thixoforging. Possible reason: residual porosity (sources of defects)
- Tensile properties much lower than bending properties (presumably due to notch effects in combination with reduced plasticity for MMC)
- Stiffness decreases with increasing press force during thixoforging (measured during bending experiments) - Reason not clear.

Powder Metallurgical, Particle Reinforced MMC

Commercial material (mainly Aerospace applications):
DARTAL 15A® (Aluminum (AA-2009) / SiC / 15p / PM / T4) from Manoir Industries, France

Process route:

<u>Compounding</u>
powder mixture (pure metals)

↓

<u>Compaction</u>
CIP (cold isostatic pressing)

↓

<u>Densification</u>
forging for homogenization

↓

<u>Forming</u>
die forging

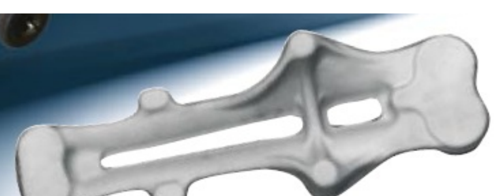
↓

<u>Final Heat Treatment</u>

Piston
Program : Formula 1
Sector : Auto racing engine

Outer Guide Vane

Program : Jet engine
Sector : Commercial aerospace



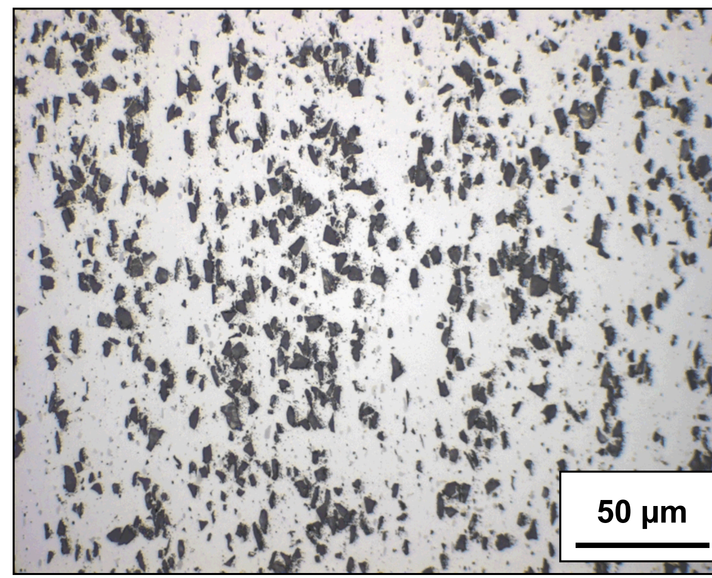
Main rotor blade sleeve
Program : Dolphin N4
Sector : Commercial helicopter

Properties:

density: ρ = 2,83 g/cm^3
fracture toughness: K_{Ic} > 24 MPa·√m

orientation		L	T
yield strength, σ_y	(N/mm^2)	>350	>340
UTS, $\sigma_{t,m}$	(N/mm^2)	>480	>480
fracture strain	(%); L_0 = 5d	>5	>3
stiffness, E	(GPa)	93 +/-3	91 +/-3

values by manufacturer; room temperature



Dartal 15A®: final microstructure

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Powder Metallurgy Techniques – Resulting Microstructure

Particles and Milled Fibres:

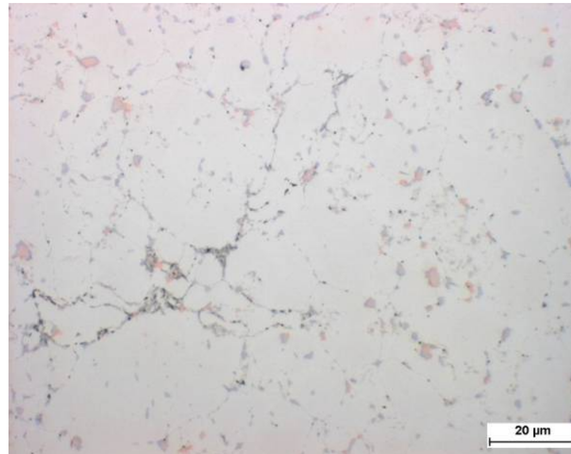
<u>Compounding</u>
mixing of powder and fibers / particles

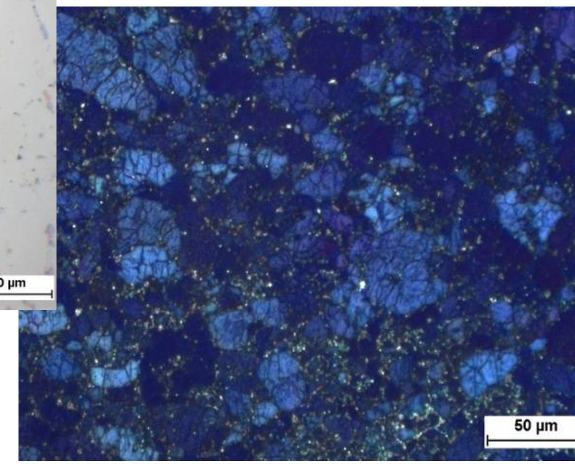
↓

<u>Compaction</u>
CIP (cold isostatic pressing)

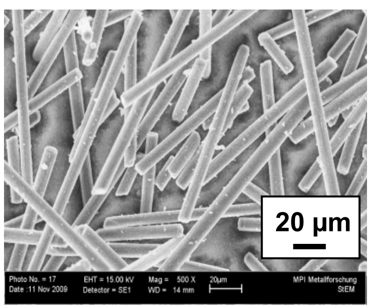
↓

<u>Densification</u>
open die forging

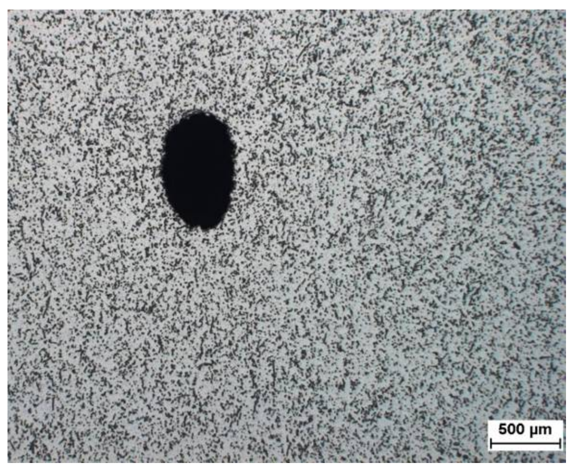


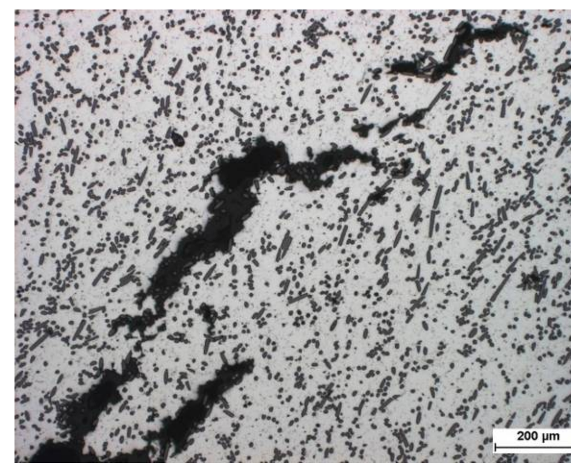


Aluminium AA-2009 after CIP, annealing and forging
(right: Barker etching and polarised light microscopy)



C fibers, HT Type-A
M100 (milled),
Toho Tenax



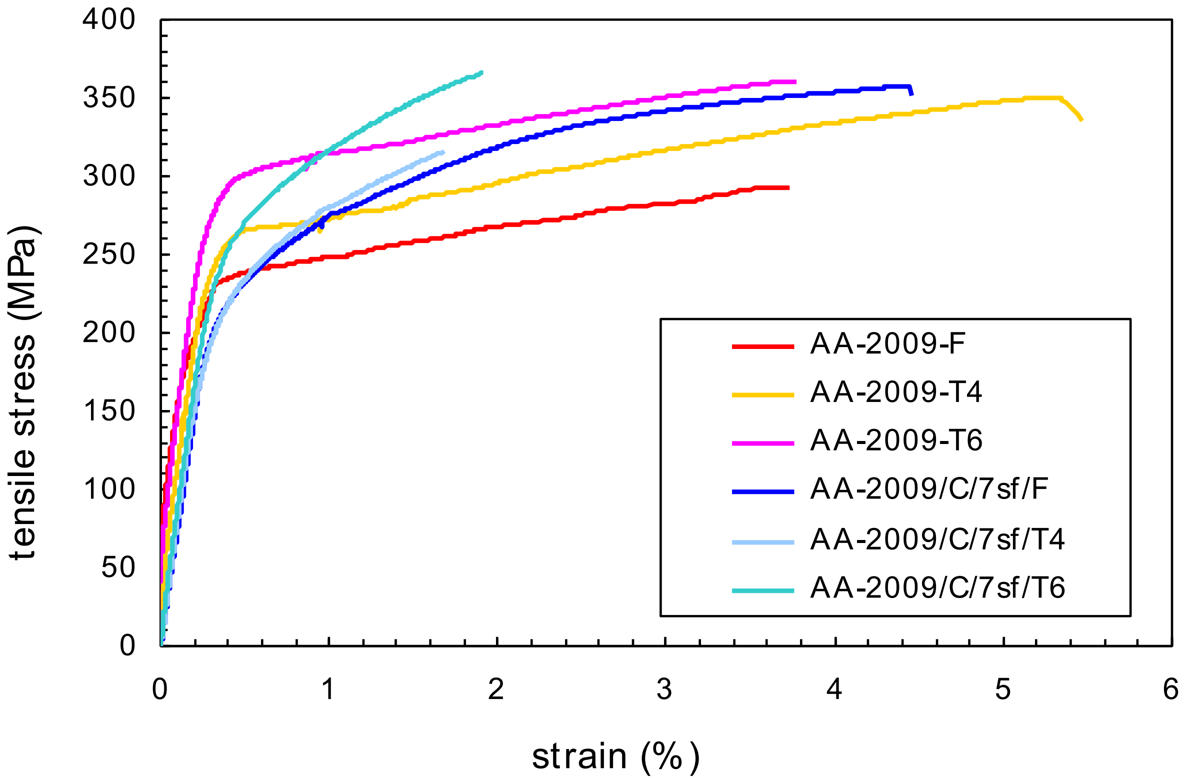


AA-2009/C-fiber milled/15sf, CIP (70-100 MPa), annealed, forged (open die forging)

Mechanical Characterisation (Tensile Properties, Room Temp.)

Tensile properties of aluminium EN AW-2009 [Al Cu4Mg1,3]

- non-reinforced alloy vs. reinforced MMC with milled C-fibres (7 %vol.)
- different heat treatment conditions



AA-2009 / C / 7sf / T6:	
UTS:	365 MPa
Youngs Modulus:	88 GPa

→ ***TO DO:***
3-point-bending for elimination of the influence of structural defects!

⇨ Solution heat treatment and densification processes not optimized (see micrographs)
⇨ Obtained mechanical properties suffer limitation due to pores, defects, agglomerates etc.
⇨ Even better mechanical results expected for optimised manufacturing conditions!

Summary and Conclusions

- Reinforced materials with metal matrix show interesting specific properties, and thus, are suitable for weight reduction of automotive vehicles.
- Physically determined drawbacks (especially low elongation) have to be considered.
- High materials' cost is a limitation to automotive applications to date.
- New manufacturing processes should enable perfect use of fiber/particle properties and production at low cost.
- TO DO:
  - Further work on processing of semi-finished material for forging (TS and CIP)
  - Work on process stability for pressing / solution heat treatment / forging.
  - Further analysis of composite materials' properties (static mechanical properties at different temperature, creep and fatigue resistance, wear resistance etc.)

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