Discontinuously Reinforced Light Metals for Engine Applications

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OPEN TECHNOLOGY FORUM

Alternative materials and grades to improve powertrain characteristics

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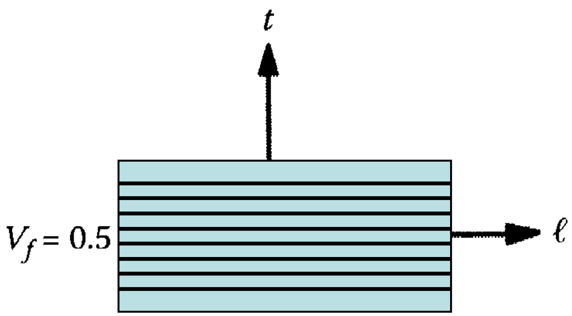
Outline:

- Introduction
- Overview about and properties of MMC materials
- MMC in automotive applications: review
- Reinforcement materials
- Theoretical limits of MMC properties
- New manufacturing techniques for particle and short fiber MMC
- Summary and conclusions

PMC vs. MMC Mechanical Properties - Continuous Fibers



	Boron/Epoxy	Boron/Aluminum
Specific mass (kg/m^3)	1950	2650
Longitudinal tensile strength (MPa)	1400	1400
Longitudinal compressive strength (MPa)	2600	3000
Transverse tensile strength (MPa)	80	120
Longitudinal elastic modulus E_ℓ (MPa)	210,000	220,000
Transverse elastic modulus E_t (MPa)	12,000	140,000
Shear modulus $G_{\ell t}$ (MPa)		7500
Longitudinal coefficient of thermal expansion at 20°C, α_ℓ (°C^{-1})	0.5×10^{-5}	0.65×10^{-5}

fiber volume fraction: f = 50 %

acc: D. Gay and S. V. Hoa: Composite Materials. CRC Press, 2nd ed.

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

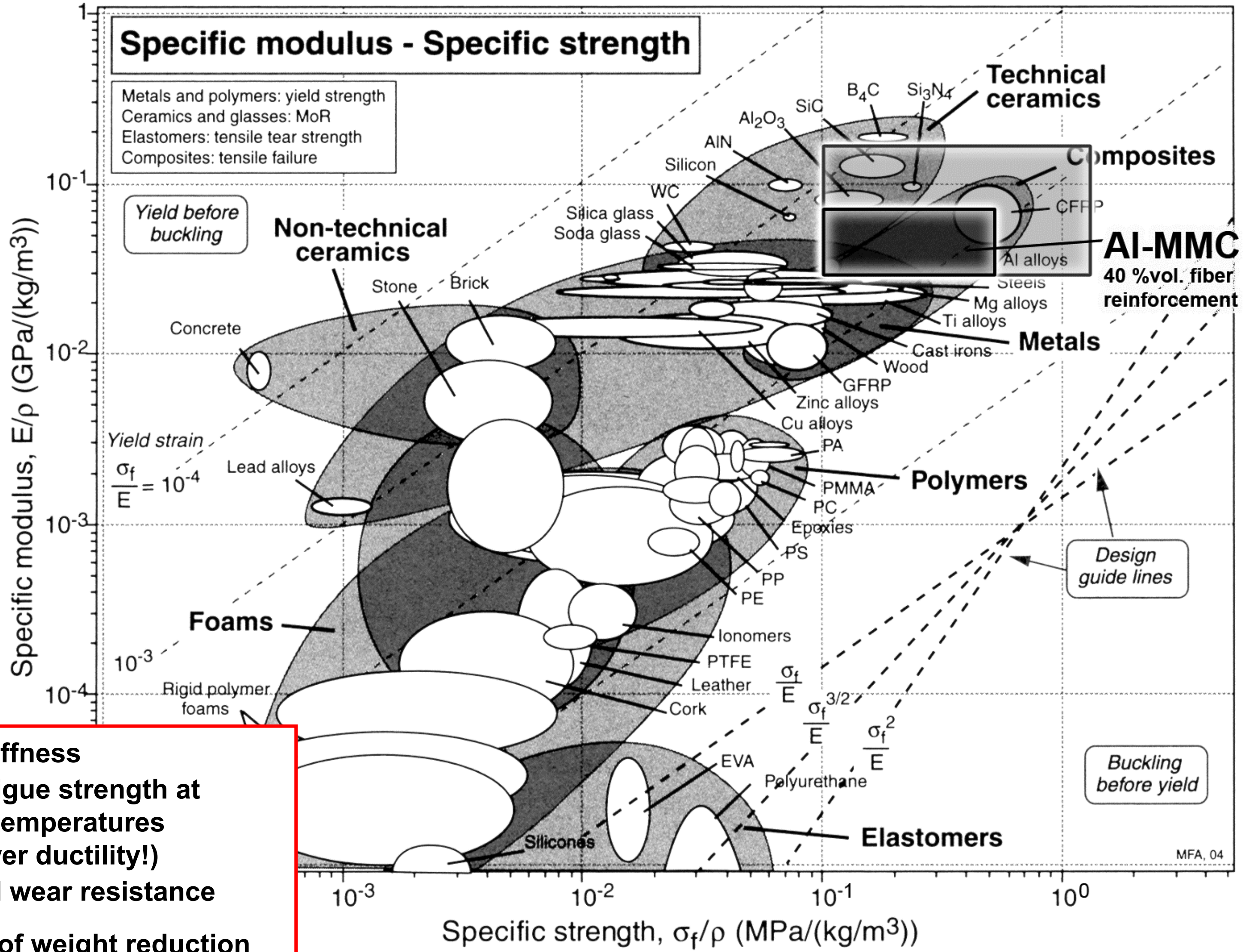
With respect to PMC:

- 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.)

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

Materials' Specific (!) Properties according to Ashby

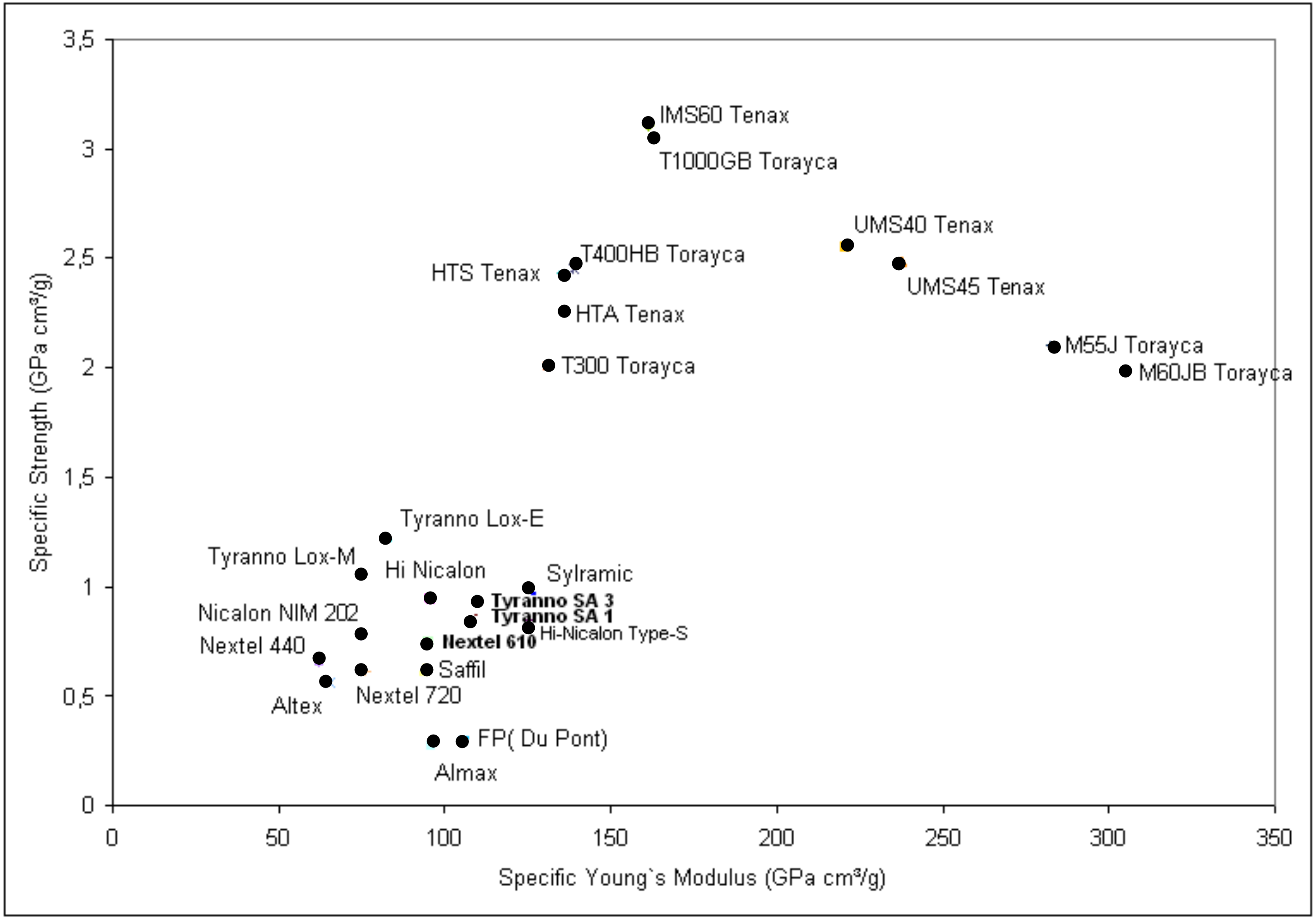
according to. M.F. Ashby: Materials Selection in Mechanical Design. 3rd ed. Burlington: Butterworth-Heinemann, 2005



- Higher stiffness
- Better fatigue strength at elevated temperatures (BUT: lower ductility!)
- Increased wear resistance

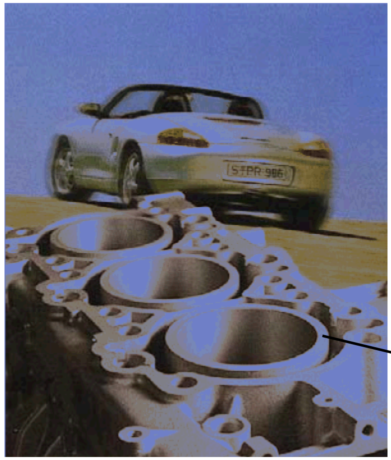
⇨ Potential of weight reduction

Specific Mechanical Properties of Reinforcement Fibers



Review of MMC Applications in Automotive Industry

Light metal crankcase; particle reinforcement of cylinders and bedplates

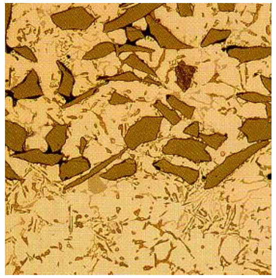


acc: P. Stingl, CeramTec AG: Keramik im Automobil - Vision oder Wirklichkeit. In: „Technische Keramik i. d. Praxis“, Seminarreihe 2005. Selb : Verb. d. keram. Industrie, 2005.

Heterogeneous solutions
cast iron & AlSi bushings (Silitec®)

Monolithic solutions
AlSi17Cu4Mg
(Alusil®)
hypereutectic alloy

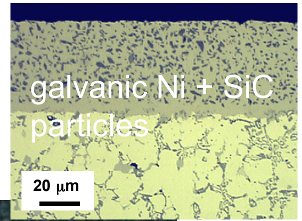
Quasi-monolithic solutions
preform infiltration (Lokasil®)
& various coatings



Lokasil II®: squeeze casting of Si cylinder liner preform

acc: Kolbenschmidt Pierburg AG, Neckarsulm, 2010

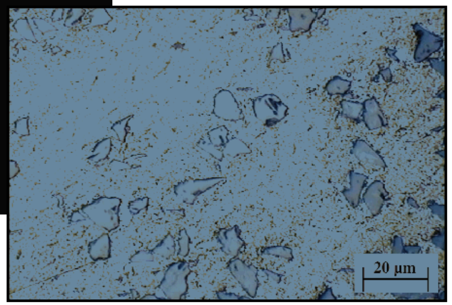
Nikasil®:



Lokasil® bedplate (particle or fiber/particle preform)

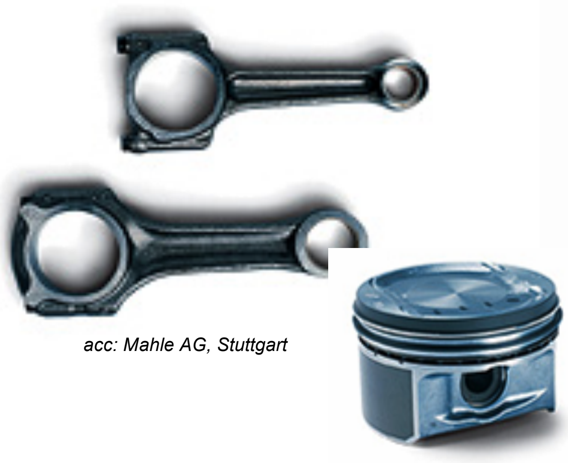
Reinforced piston rods and piston; short fiber or particle reinforcements

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

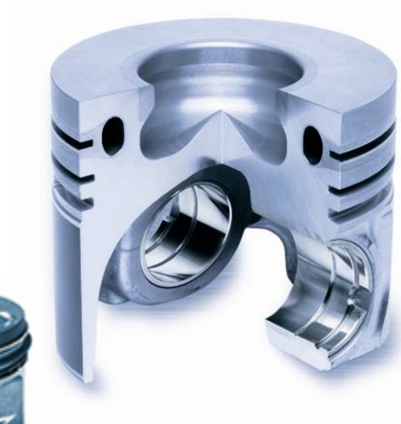


Process: stir casting of billets, hot extrusion and die-forging.

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

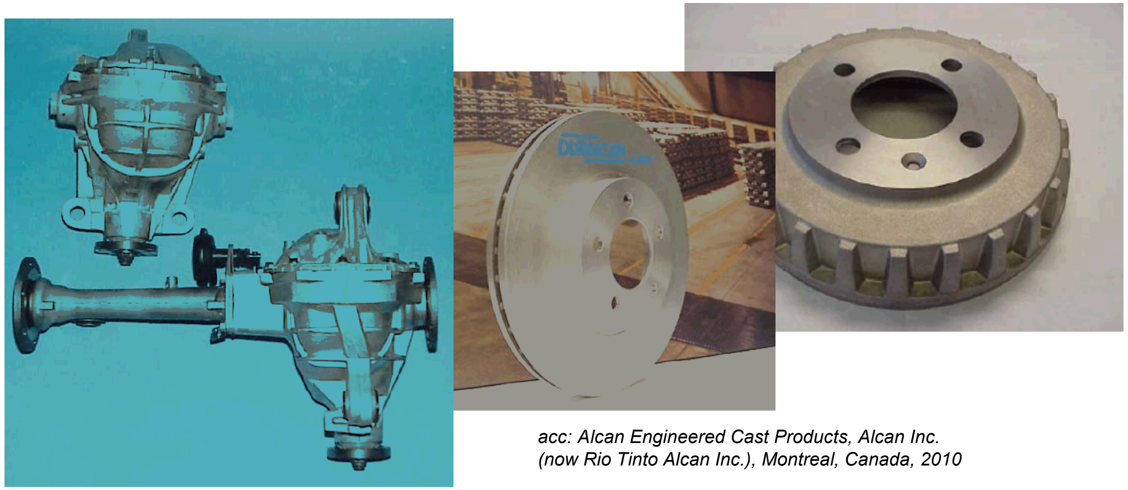
Review of MMC Applications in Automotive Industry

4“ AccuBond™ Duralcan™ MMC driveshaft

Duralcan (here):
AA6061/Al2O3/20p

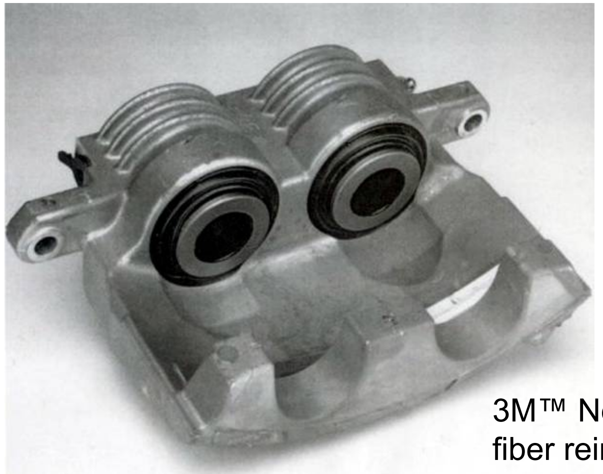
acc: Mark Williams Enterprises, Louisville (CO), USA, 2010

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



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

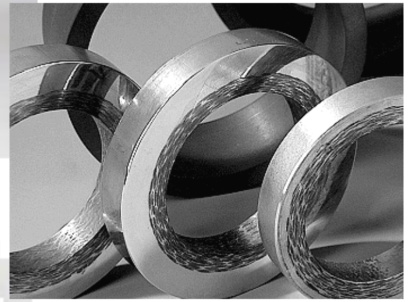
Disc brake caliper with fiber reinforcement



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

Types of MMC

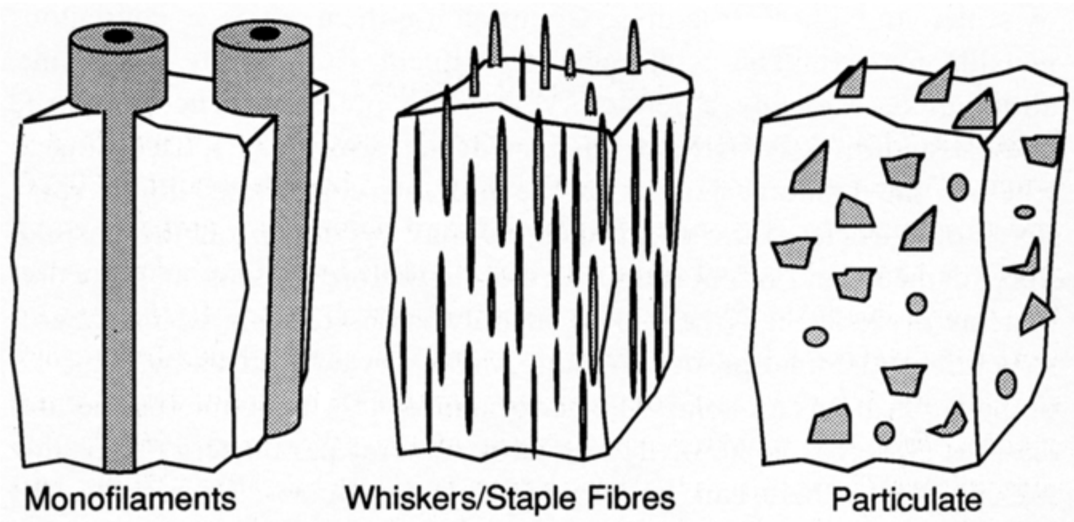
Distinction by the shape, character and orientation of the reinforcement phase:

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

Fibers for Light Metal Reinforcement

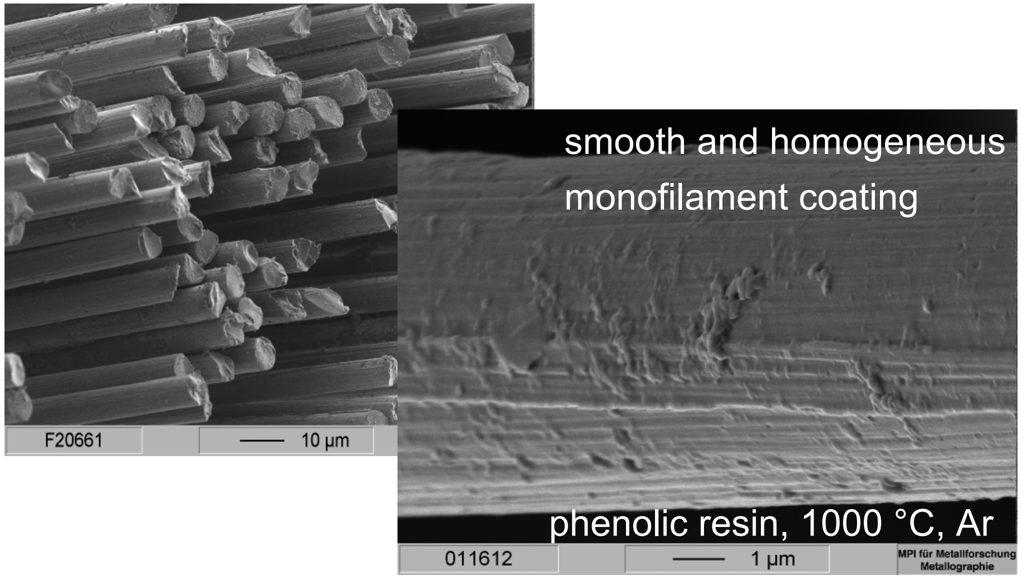
Fiber materials for MMC:

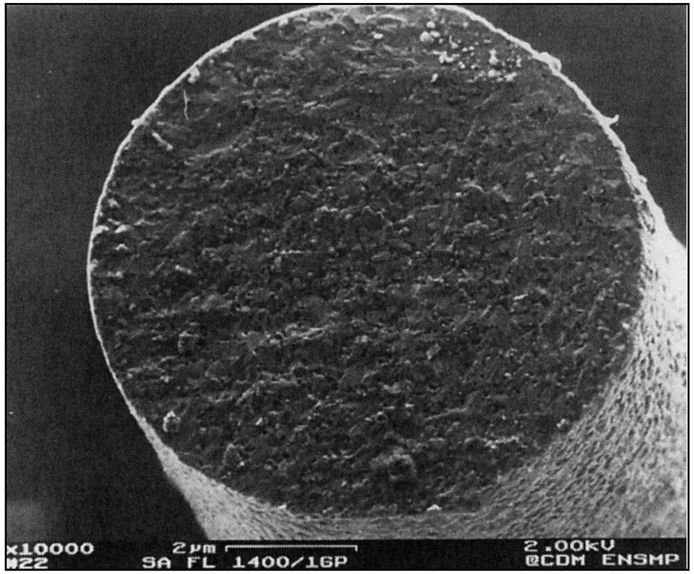
- ⇨ carbon (HT, IMS, HMS, UMS)): ρ = 1.7-1.8 g/cm^3 !
- ⇨ SiC (Nicalon, Tyranno etc.)
- ⇨ alumina, Al_2O_3 (e.g., Nextel 610)
- ⇨ mixed oxides
  (e. g., alumina-silica (Nextel 720), basalt etc.)
- ⇨ B, W, Mo, Ta, Nb, Be
- ⇨ stainless steel, Ti, Ni superalloys

Required properties of fibers for MMC:

- high strength and stiffness
- long-term thermo-chemical stability
- microstructural and mechanical stability
- good bonding to matrix material (interface wetting and adhesion)
- high creep resistance

<u>HT carbon fibers, coated with precursor based ceramics:</u>





Fracture surface of Tyranno SA fiber, failed in creep at 1400°C at an applied stress of 1000 MPa

acc: A. R. Bunsell, M.-H. Berger: Fine Ceramic Fibers. New York : Marcel Dekker, 1999

Commercial Reinforcement Fibers and Properties

Fiber	Typical Diameter (μm)[a]	Density (g/cm³)	Tensile Modulus GPa (Msi)	Tensile Strength GPa (ksi)	Strain-to-Failure (%)	Coefficient of Thermal Expansion (10^{-6}/°C)[b]	Poisson's Ratio
Glass							
E-glass	10 (round)	2.54	72.4 (10.5)	3.45 (500)	4.8	5	0.2
S-glass	10 (round)	2.49	86.9 (12.6)	4.30 (625)	5.0	2.9	0.22
PAN carbon							
T-300[c]	7 (round)	1.76	231 (33.5)	3.65 (530)	1.4	−0.6 (longitudinal) 7–12 (radial)	0.2
AS-1[d]	8 (round)	1.80	228 (33)	3.10 (450)	1.32		
AS-4[d]	7 (round)	1.80	248 (36)	4.07 (590)	1.65		
T-40[c]	5.1 (round)	1.81	290 (42)	5.65 (820)	1.8	−0.75 (longitudinal)	
IM-7[d]	5 (round)	1.78	301 (43.6)	5.31 (770)	1.81		
HMS-4[d]	8 (round)	1.80	345 (50)	2.48 (360)	0.7		
GY-70[e]	8.4 (bilobal)	1.96	483 (70)	1.52 (220)	0.38		
Pitch carbon							
P-55[c]	10	2.0	380 (55)	1.90 (275)	0.5	−1.3 (longitudinal)	
P-100[c]	10	2.15	758 (110)	2.41 (350)	0.32	−1.45 (longitudinal)	
Aramid							
Kevlar 49[f]	11.9 (round)	1.45	131 (19)	3.62 (525)	2.8	−2 (longitudinal) 59 (radial)	0.35
Kevlar 149[f]		1.47	179 (26)	3.45 (500)	1.9		
Technora[g]		1.39	70 (10.1)	3.0 (435)	4.6	−6 (longitudinal)	
Extended chain polyethylene							
Spectra 900[h]	38	0.97	117 (17)	2.59 (375)	3.5		
Spectra 1000[h]	27	0.97	172 (25)	3.0 (435)	2.7		
Boron	140 (round)	2.7	393 (57)	3.1 (450)	0.79	5	0.2
SiC							
Monofilament	140 (round)	3.08	400 (58)	3.44 (499)	0.86	1.5	
Nicalon[i] (multifilament)	14.5 (round)	2.55	196 (28.4)	2.75 (399)	1.4		
Al_2O_3							
Nextel 610[j]	10–12 (round)	3.9	380 (55)	3.1 (450)		8	
Nextel 720[j]	10–12	3.4	260 (38)	2.1 (300)		6	
Al_2O_3–SiO_2							
Fiberfrax (discontinuous)	2–12	2.73	103 (15)	1.03–1.72 (150–250)			

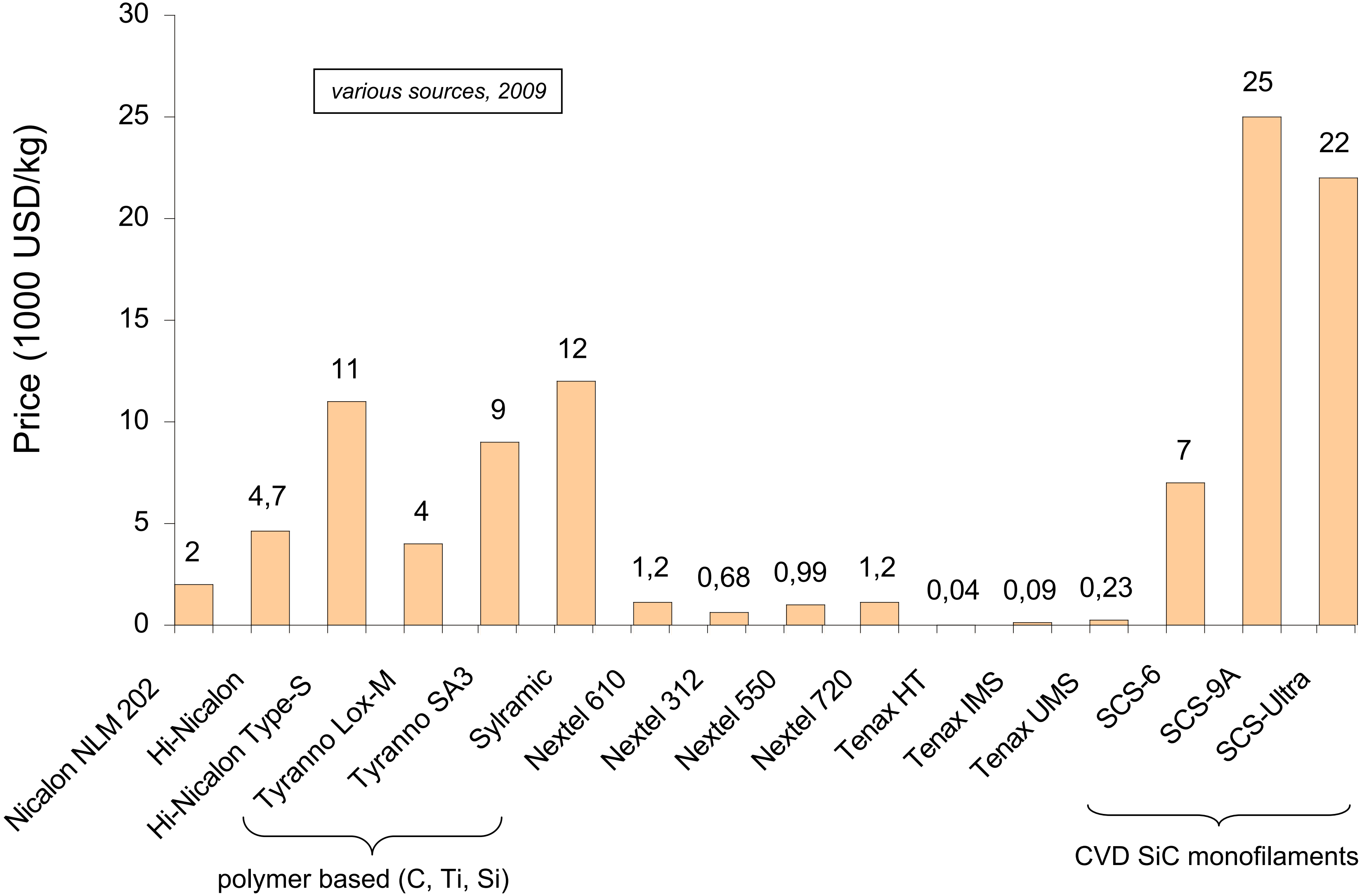
MMC

MMC

[a] 1 μm = 0.0000393 in.
[b] m/m per °C = 0.556 in./in. per °F.
[c] Amoco.
[d] Hercules.
[e] BASF.
[f] DuPont.
[g] Teijin.
[h] Honeywell.
[i] Nippon carbon.
[j] 3-M.

acc: P.K. Mallick: Fiber-reinforced composites. Boca Raton (FL) : CRC Press, 3rd ed., 2008

Cost of Fiber Reinforcements



Particles for Light Metal Reinforcement

Powder materials for MMC:

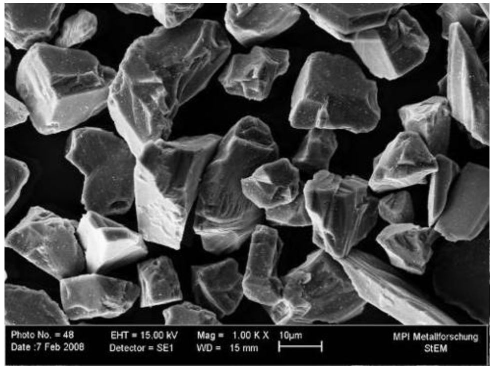
- ⇨ silicon carbide, SiC
- ⇨ boron carbide, boron nitride, B_4C
- ⇨ aluminum oxide (corundum), Al_2O_3
- ⇨ pure silicon, Si
- ⇨ steel or cast iron granulates
- ➲ Choice depends on required properties!

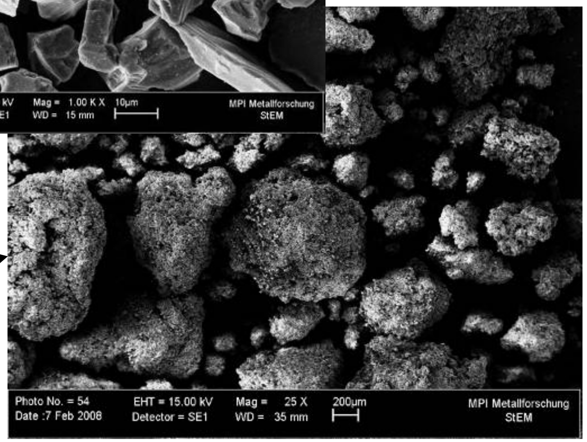
Table: Properties of reinforcement particles

	density ρ (g/cm³)	melting point / th. decomp. 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
Si	2.33	1420	2.3 - 7.6	112.8	1120

various sources

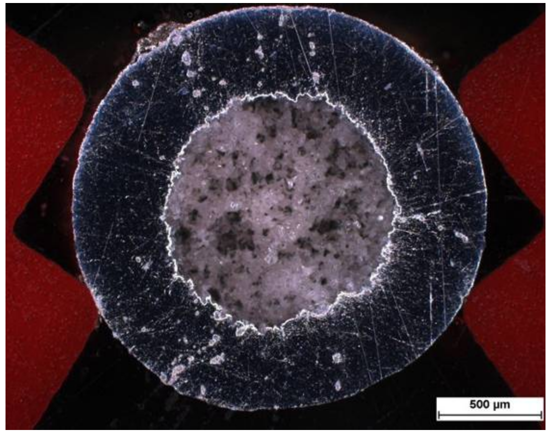
Alumina powder, fused and crushed (SEM)
D50 = xx µm





SiC powder, agglomerated (SEM)
D50 (primary) = 20 µm
D50 (agglomerates) = 173 µm (D90 = 536 µm)

Cored wire (d = 2 mm):
AA2017 (AlCu4MgSi) mantle,
Al_2O_3 particle filling



Theoretical Limits of MMC Properties - Stiffness

Theoretical calculation of maximum achievable Young's moduli:

→ Assumption: endless fiber length!

- Equal strain assumption for axial loading of continuous, aligned fibers

  ⇨ **Voigt Model;**
  also: *Rule of Mixture*!

  $$E_{Voigt,axial} = (1-f)E_M + fE_F$$

  ⇨ Theoretical maximum value for UD continuous reinforcement

- Equal stress assumption for transversal loading perpendicular to the fiber direction

  ⇨ **Reuss Model**

  $$E_{Reuss,transversal} = \left[\frac{f}{E_F} + \frac{(1-f)}{E_M}\right]^{-1}$$

  ⇨ other possibility: Halpin-Tsai model

→ Voigt is the maximum and Reuss the minimum value of real fiber composites!

Problem: aligned or stochastically oriented short fibers or particles do not fit to idealized models above!

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

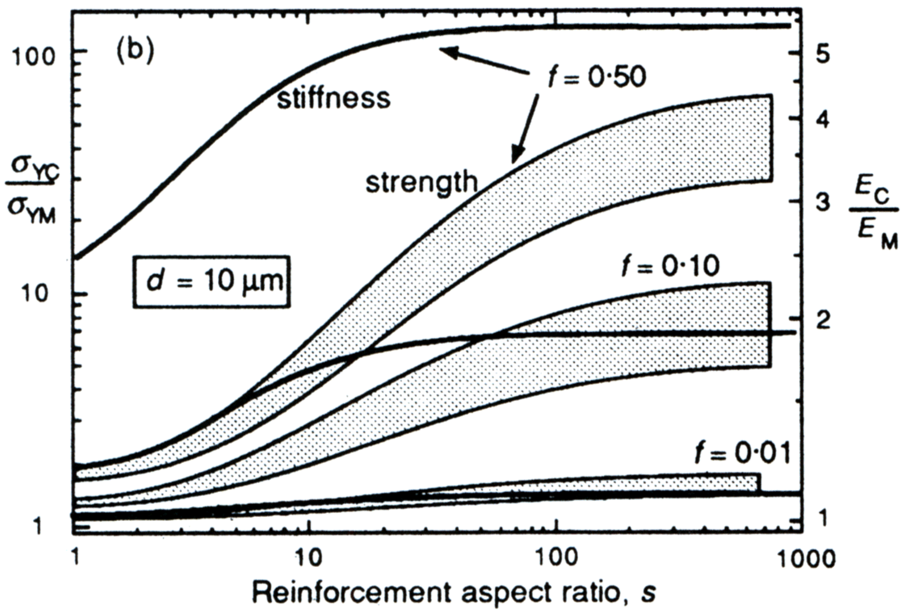
Properties of Discontinuous MMC

For short fibers, whiskers and particles, the average stress in the reinforcement is limited, because

1. *load is transferred from matrix to fibers by shear stresses*
2. *normal stresses in the fiber/particle decrease at fiber/particle ends*

→ fibers/particles need a critical length to have a strengthening effect, which depends on the diameter!

→ The factor to estimate this effect is the aspect ratio: s = l/d (length/diameter)



Dependency of strengthening and stiffening factor on reinforcement volume fraction and shape:

- Methods to estimate reinforcement effect and composite properties for non-idealized inclusions:
  - ⇨ experimental data
  - ⇨ modelling (e. g., Eshelby approach)
  - ⇨ modified rule of mixture

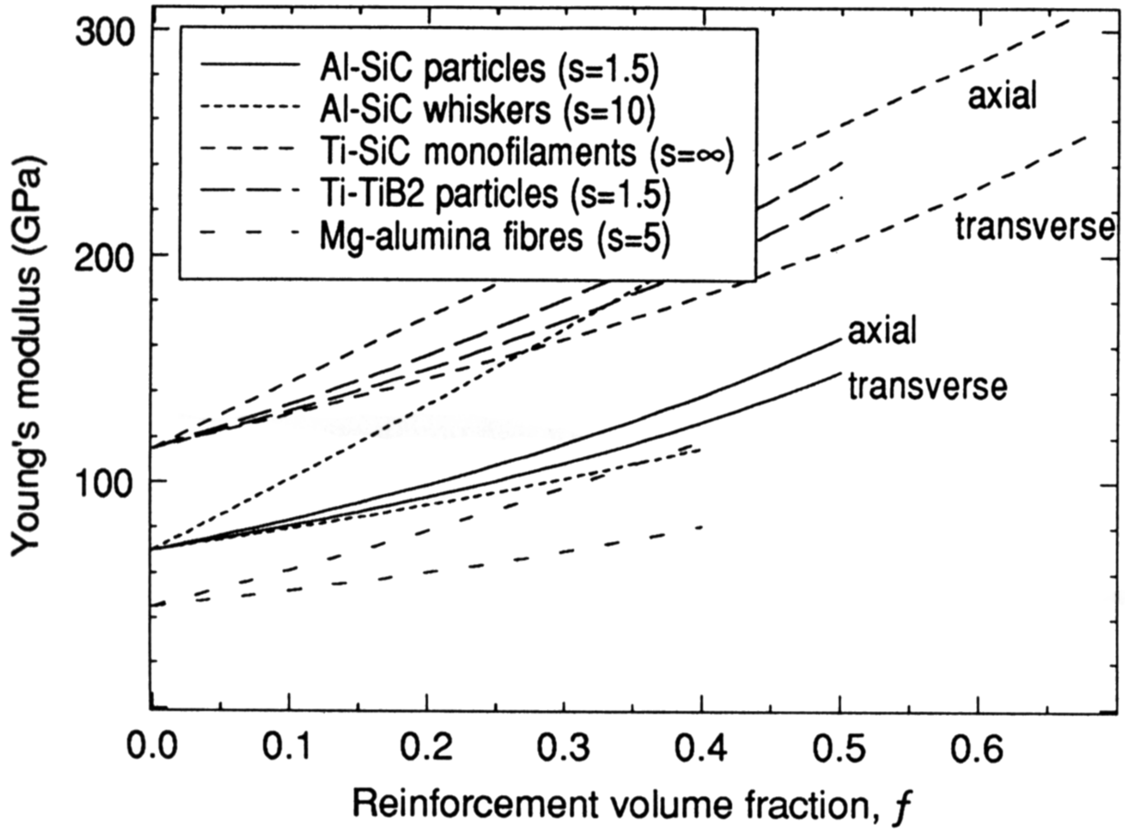
acc: T. W. Clyne, P. J. Withers: An Introduction to Metal Matrix Composites. Cambridge : University Press, 1993

acc: J. Schlichting et al.: Verbundwerkstoffe. Grafenau (Württ.) : Lexika-Verlag, 1978

Properties of MMC - Stiffness

Stiffness depending on:

- matrix alloy
- reinforcement phase
- reinforcement volume fraction, f
- reinforcement aspect ratio, s



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

Potential of Discontinuously Reinforced MMC for Engine Environment

- Lightweight potential for reduction of weight AND increase of specific properties!
- Carbon fibers have the highest potential, but are sensitive.
- Ceramic particles are suitable for increased stiffness, creep strength and, additionally, tribological behavior.
- Mainly increase of hot strength, fatigue strength and wear resistance
  → increase of important properties in engine environments !
- Thermophysical properties (e. g., thermal expansion) can be influenced in a wider range than for continuous fiber MMC

Drawbacks

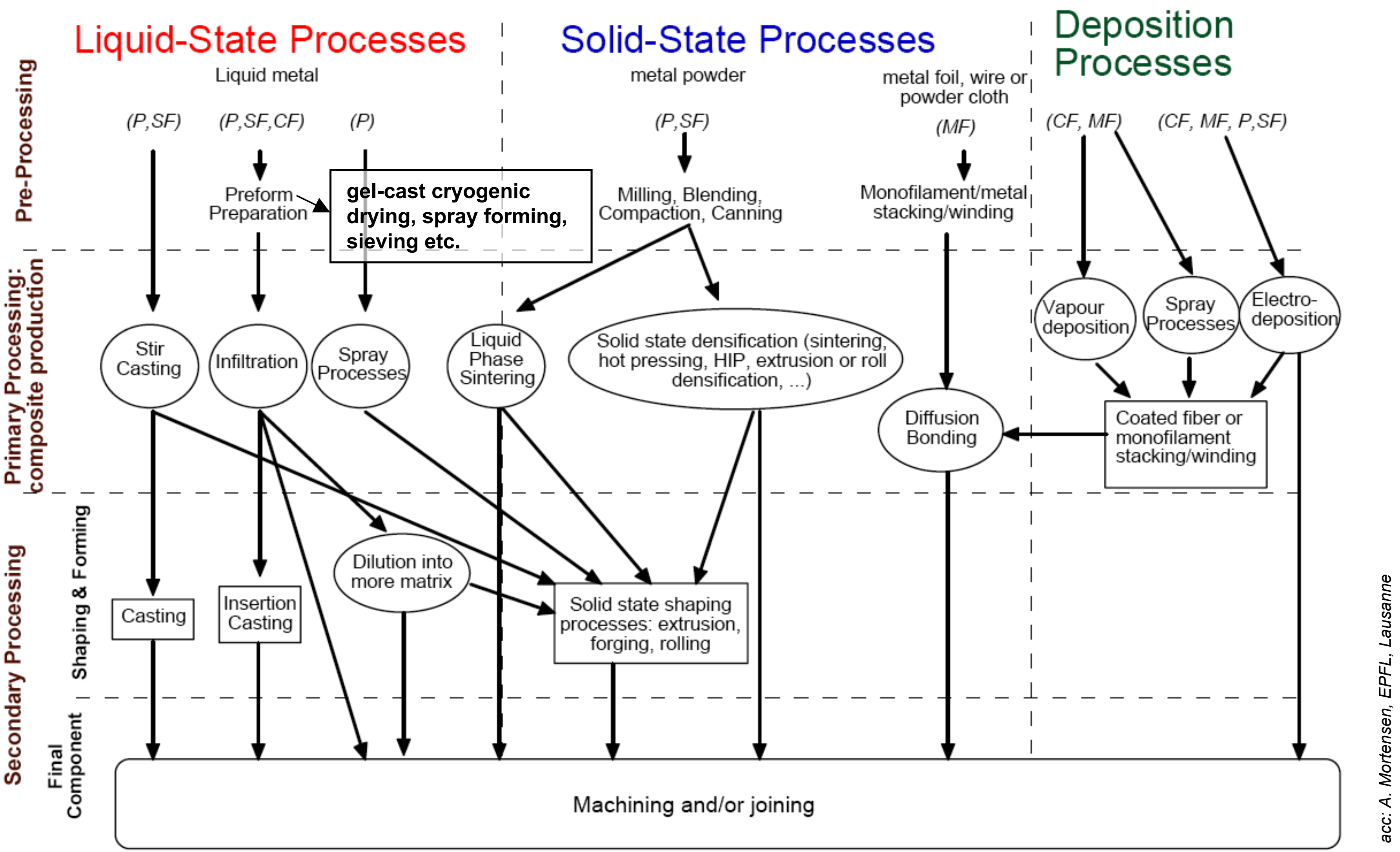
- Reinforced materials with metal matrix show interesting specific properties, and thus, are suitable for weight reduction and performance increase of automotive vehicles.
- NO important strengthening at room temperature for discontinuous reinforcement (rather increase of creep resistance and strength at elevated temperature!)
- Low plastic deformation capability, low ultimate strain (however, more deformation than for PMC, e. g. CFRP, and continuously reinforced metals)
- High cost of materials AND of production for available standard processes

Challenges for AMC Process Development

- Suitable embedding of the reinforcement phase (good reinforcement/matrix interface!)
- Improvement of carbon fiber useability through fiber surface engineering by fiber coating
- Limitation of cost by new, simple processing methods

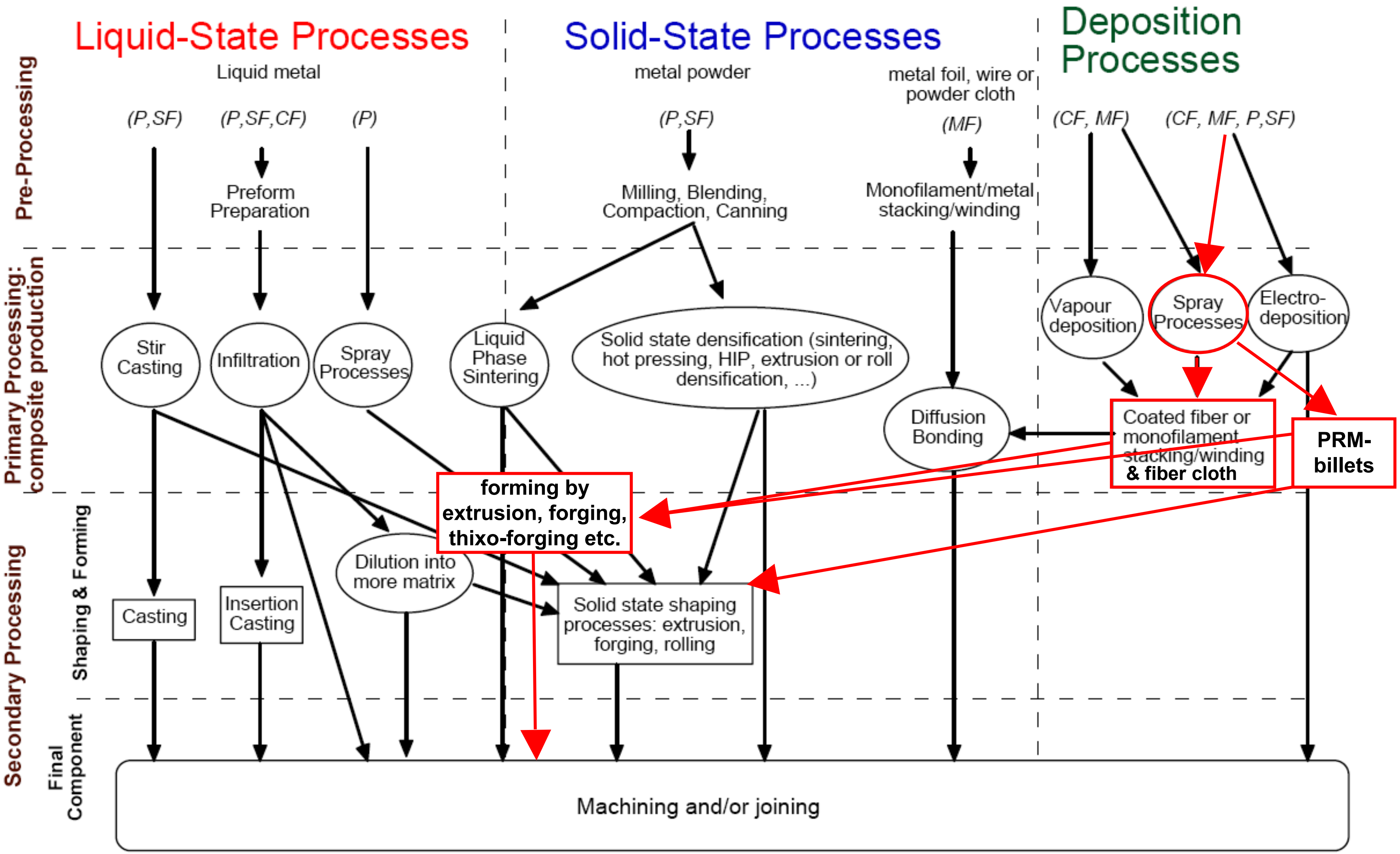
→ Process engineering is the key to success !

Possibilities in MMC Manufacturing



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

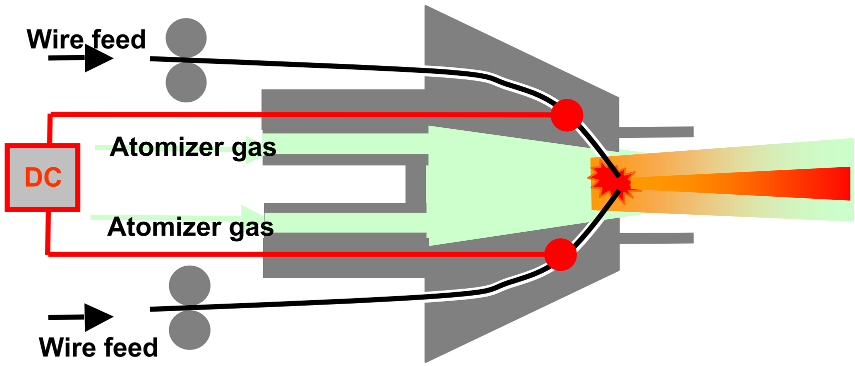
New Process Developments – Reducing Cost for Automotive Usability



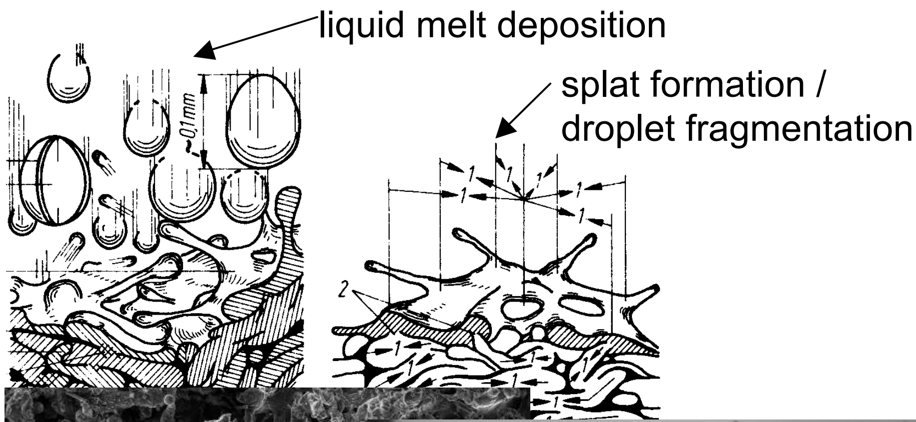
Reinforcements: P = particles, *SF* = short-fibers, *CF* = continuous fibers, *MF* = monofilaments

M. Wenzelburger, M. Silber, R. Gadow

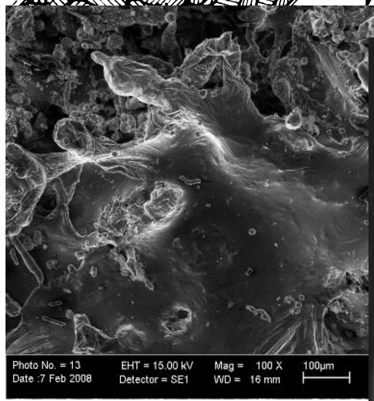
Material Deposition by Twin-Wire Electric Arc Spraying

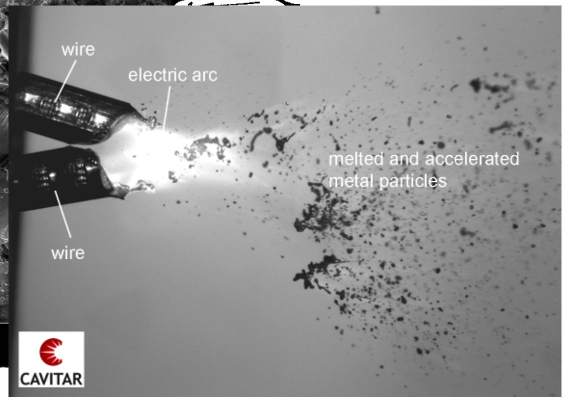


Energy source:	electric arc
Max. process temp.:	4000 °C
Materials:	metals, alloys, cored wires with ceramic particles
Particle velocities:	< 150 m/s
Deposition rate:	20 – 300 kg/h
Wire diameter applied:	1.6 mm



acc. Pursche, Oberflächenschutz vor Verschleiß, 1990



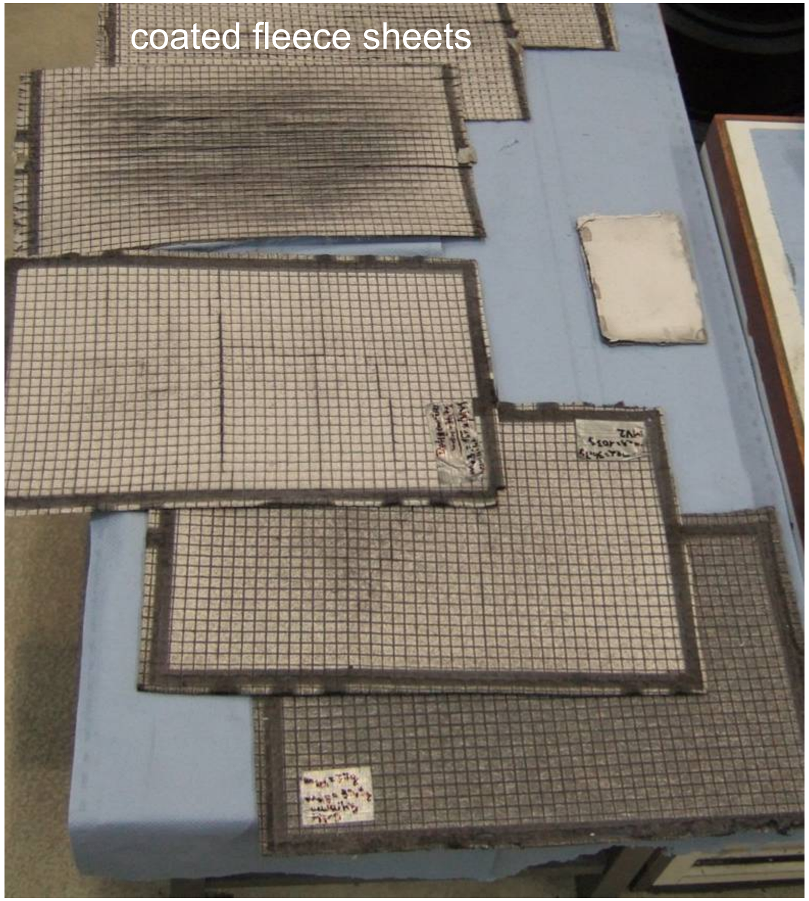


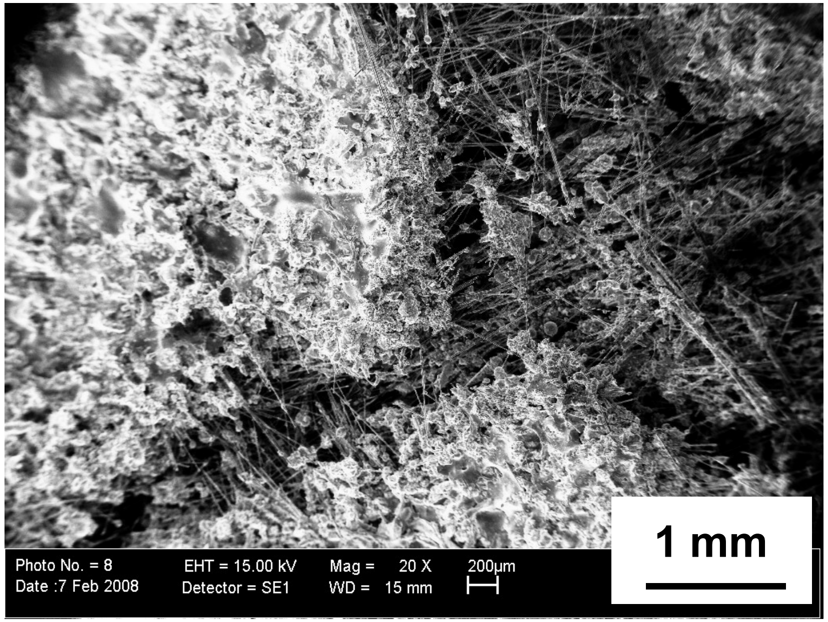
Process parameters of the twin wire electric arc process applied in this work:

	Voltage, U (V)	Feed Rate, f (m/min)	Air Pressure, p (bar)	Particle Velocity, v_p (m/s)	Particle Temp., ϑ_p (°C)
Machine parameters	22.0	3.3	3.0	-	-
Direct spray parameters	-	-	-	1000 – 110	2,400 – 2,500

Manufacturing of Short Fiber Prepregs by Thermal Spraying (TS)

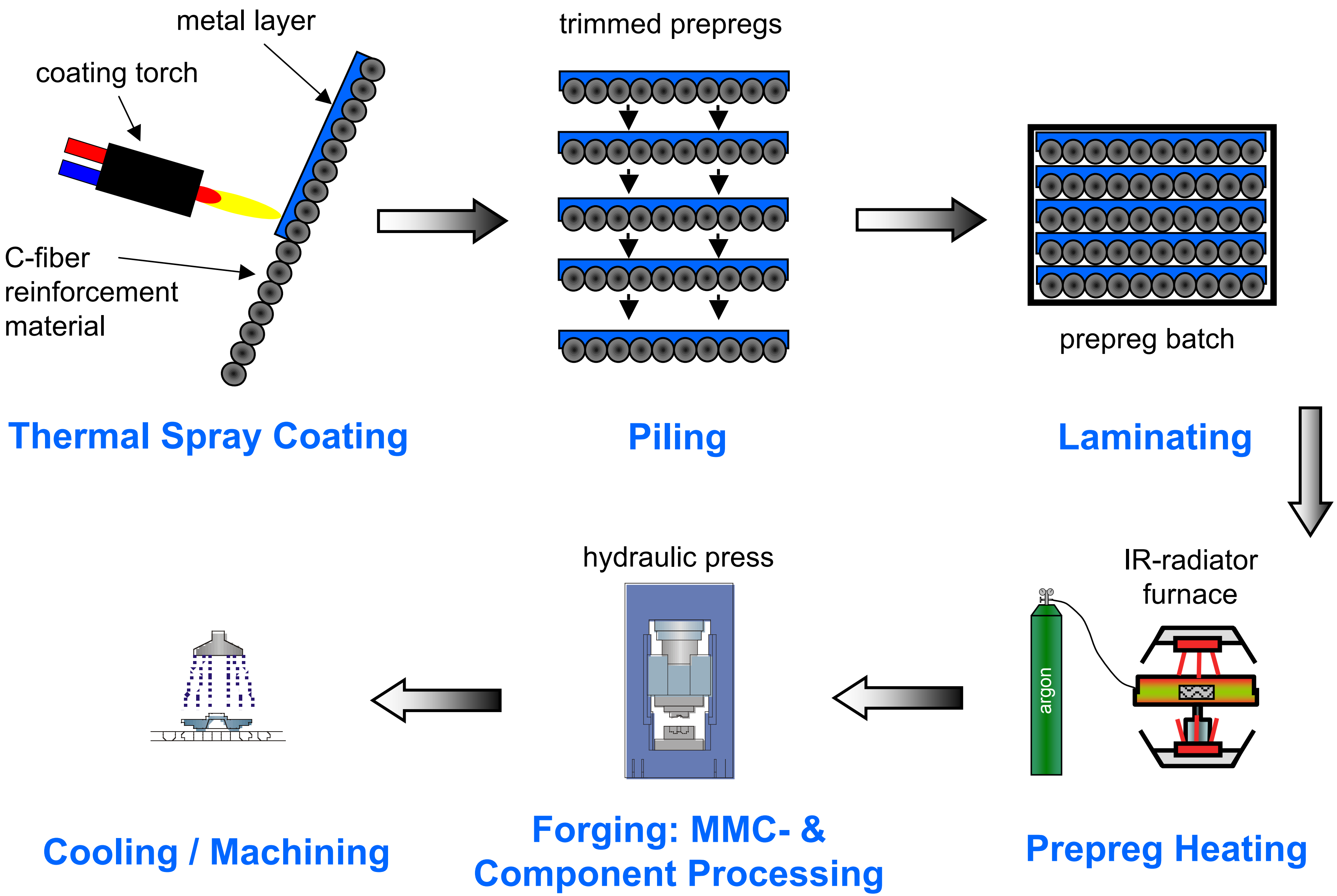
Coated fleece sheets with different coating thickness:
⇨ *Tailoring of the fiber volume content!*



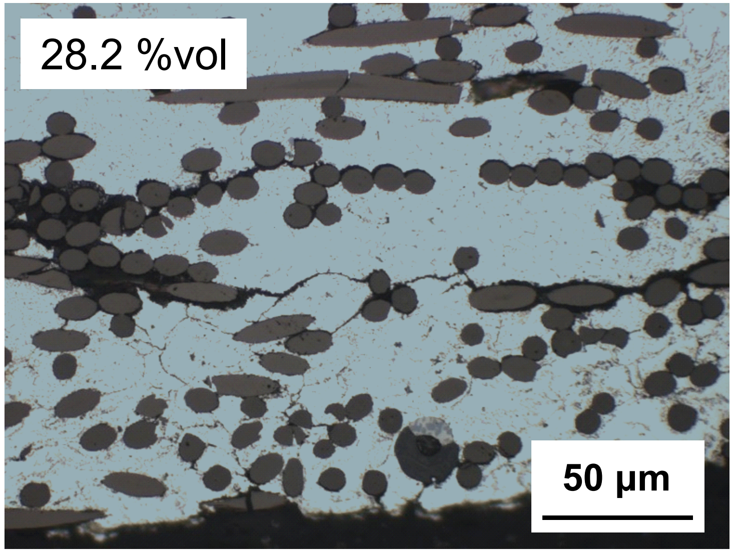


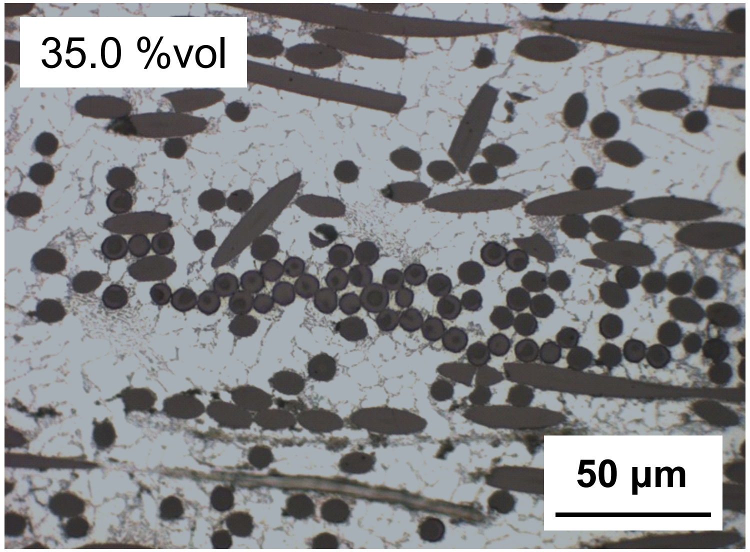
Thermally sprayed Al Si5 matrix and HT carbon fiber fleece substrate (SEM).

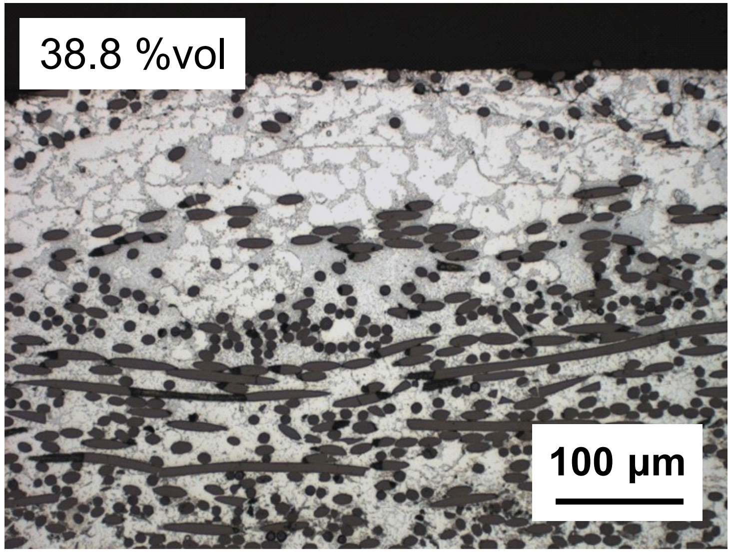
Complete Process Chain for MMC Manufacturing



Microstructure of C-Fiber/Al Si5-MMC (Thixoforged)



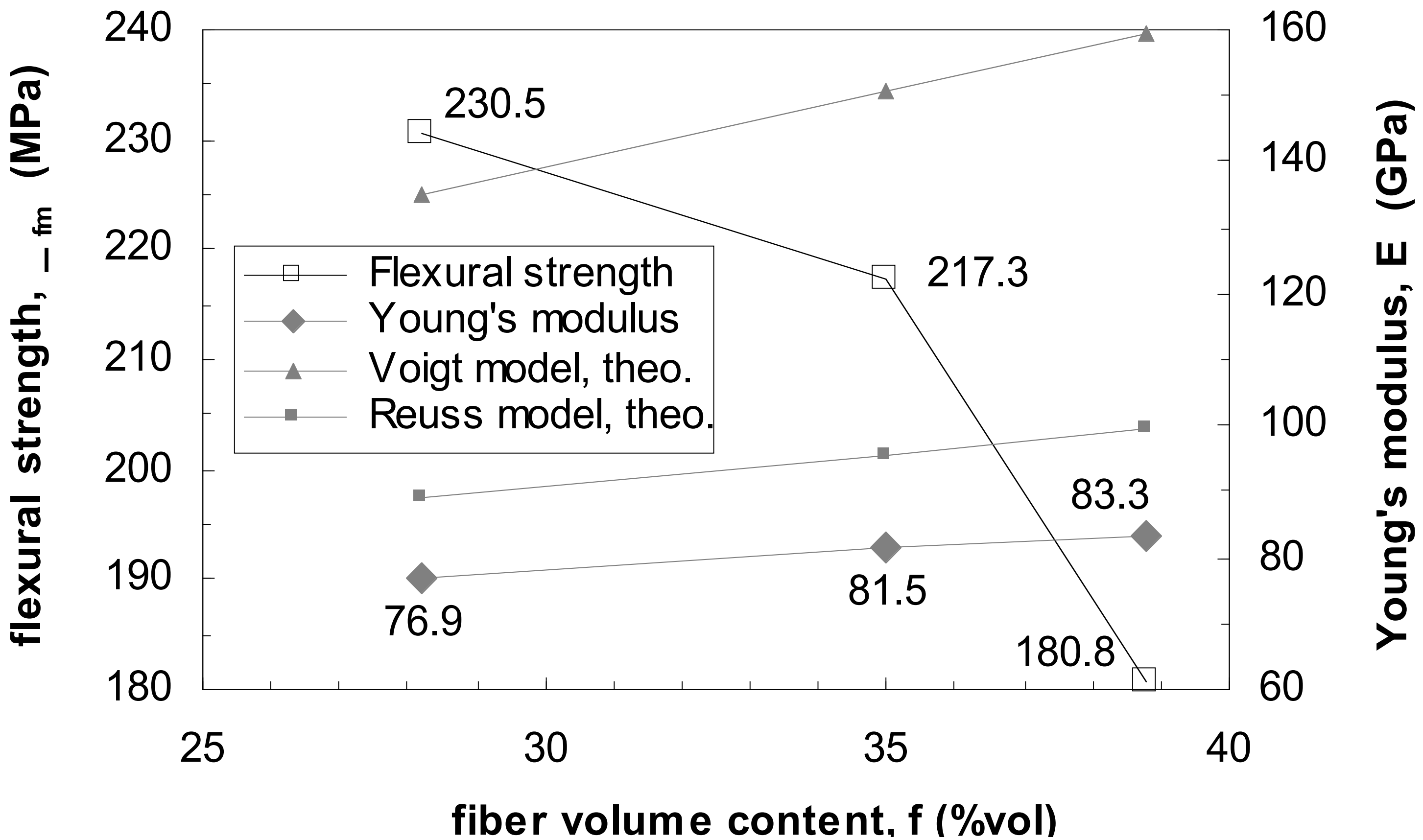




Micrographs of thixoforged C-short-fiber/Al Si5-MMC after bending experiments, different fiber volume contents.

- Residual porosity of ≤ 0.5 %vol.
- Homogeneous, stochastic fiber distribution.
- Matrix accumulation at component surface.
  - ⇨ Thereby, change of fiber volume content!
- Grain growth due to slow cooling in the die.
- Clustering of eutectic (liquid) phase in prepreg porosity.

Experimental MMC Properties Depending on Fiber Volume Content



Flexural strength, σ_{fm} (4-point bending), and Young's modulus, E, for C-short-fiber/Al Si5-MMC with f = 28.2, 35.0, and 38.8 %vol.

Comparison of Material Properties

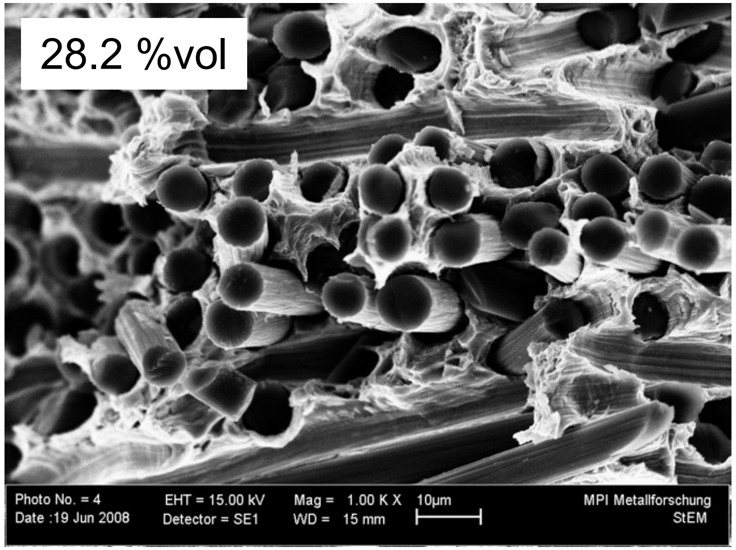
Mechanical properties of aluminum alloys and HT carbon fibers, tensile testing:

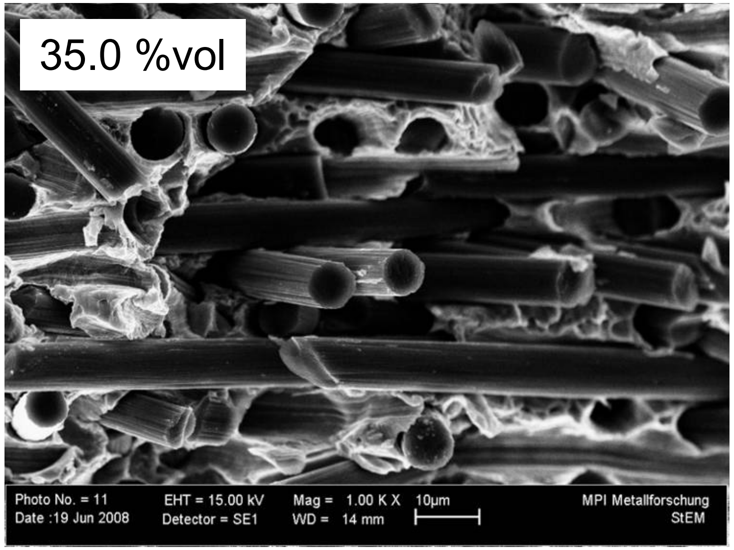
Alloy Material	Young's Modulus, E (GPa)	Tensile Strength, UTS, $\sigma_{t, m}$ (MPa)	Yield Strength, YS, σ_y (MPa)	Strain to Failure (%)
Al Si5 wire, T4	70	130	70	15
Al Si7Mg cast alloy	72.4	140 – 240	80 – 220	1 – 2.5
Al Si7Mg0.3 cast alloy	72.4	200 – 340	120 – 280	2 – 9
Carbon fiber, HT type	230 – 300	4,000 – 7,000	-	1.7 – 2.4

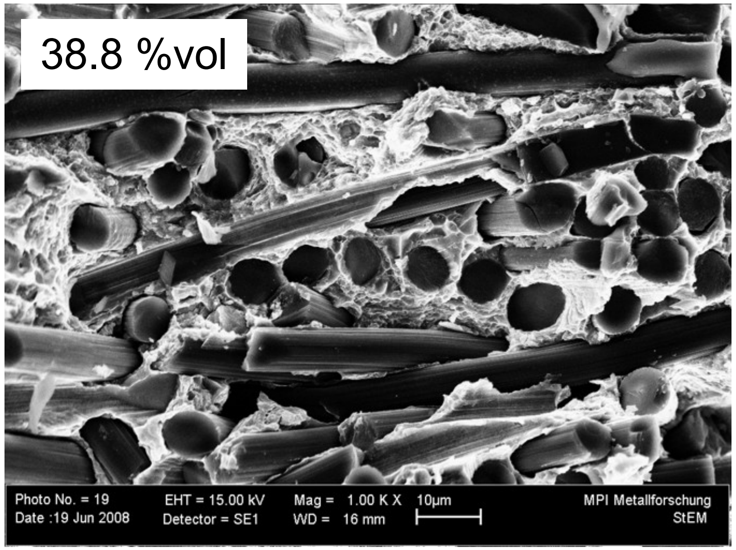
Mechanical properties of HT C-short-fiber/Al Si5-MMC, bending experiments:

C-fiber/Al Si5-MMC Fiber Volume Content, f (%vol)	Young's Modulus, E (GPa)	Flexural Strength, $\sigma_{f, m}$ (MPa)	Yield Strength, YS, σ_y (MPa)	Strain to Failure (%)
28.2	76.9	230.5	-	~ 0.8
35.0	81.5	217.3	-	~ 0.6
38.8	83.3	180.8	-	~ 0.4

Fracture Behavior (SEM Analysis)





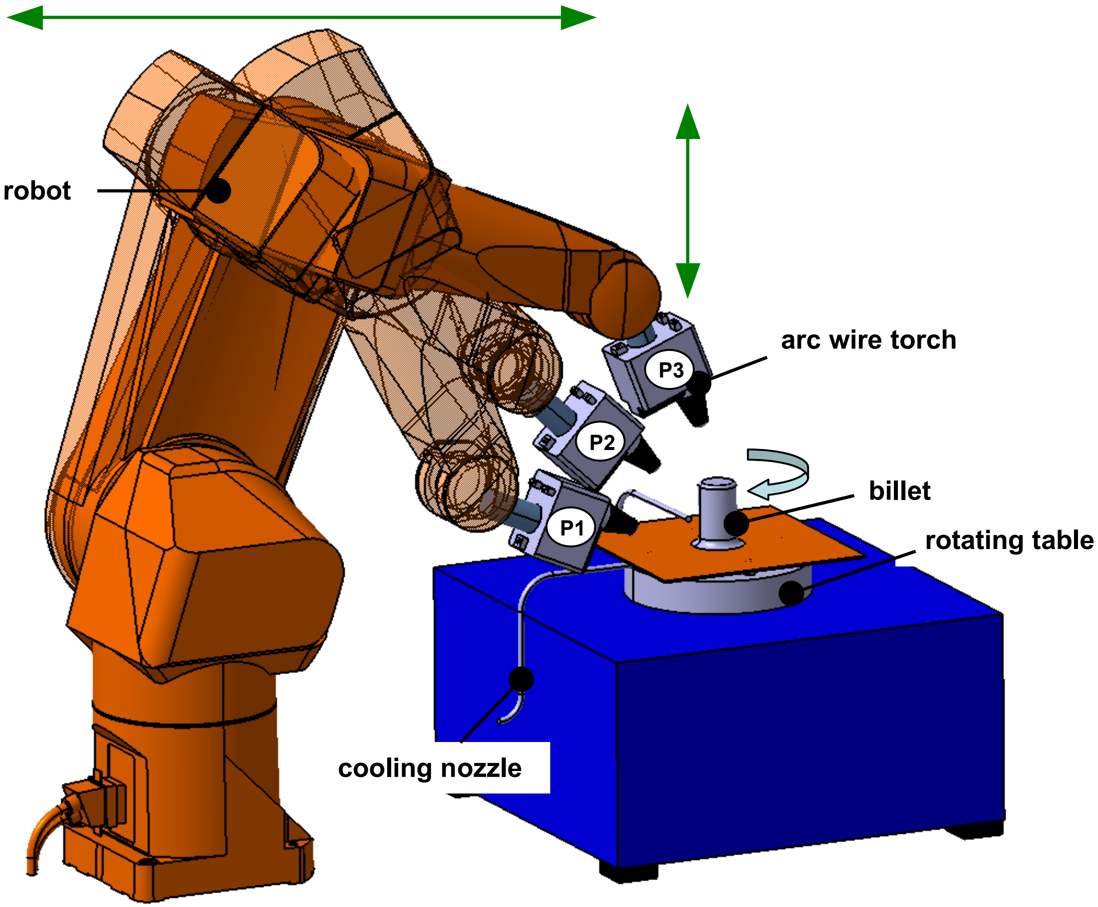


SEM of fracture surfaces from 4-point bending experiments, different fiber volume contents.

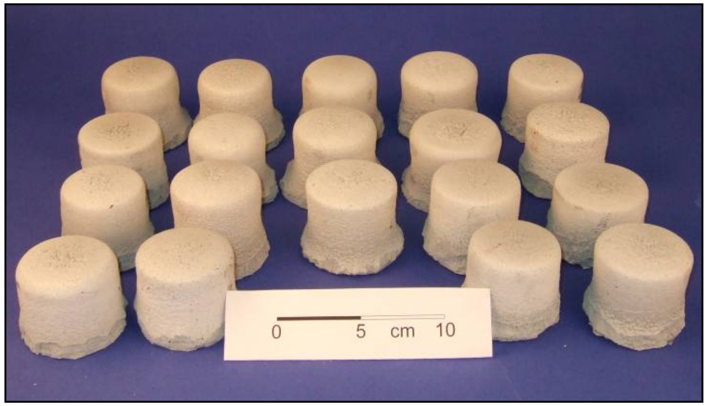
- Extensive debonding of transverse fibers.
- Low plastic deformation of the matrix material.
  - ⇨ Deformation in load direction, as would be expected for MMC, only in some areas!
- Interfacial debonding and (short) fiber pull-out.
  - ⇨ Structure of the thermally sprayed, reheated and thixoforged matrix more brittle than original Al Si5!
  - ⇨ Fiber/matrix bonding is relatively weak!

Deposition of PRM Billets by Arc Wire Spraying

Angle variation in order to avoid shadowing effects and influences on porosity and microstructure



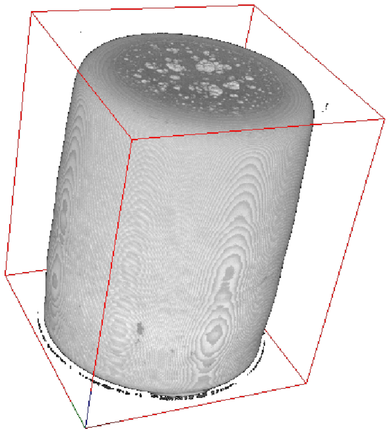
installation and processing for the deposition of massive spray billets on a rotating table by thermal spraying with the arc wire technique

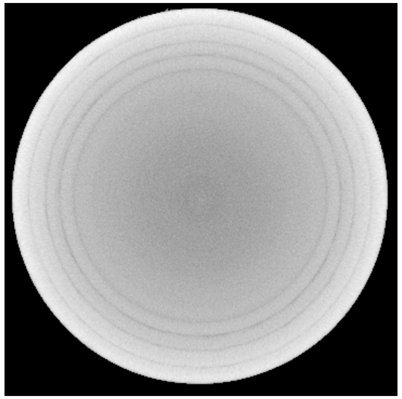


Different sizes of $Al_2O_{3,P}$ / AA2017(AlCu4MgSi), 31.0 %vol. particles billets

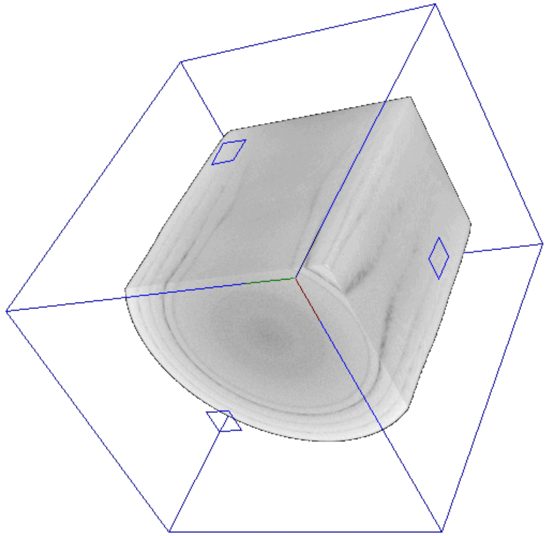
Analysis and Application

Micro computer tomography (1000*1000*1000 pixel)



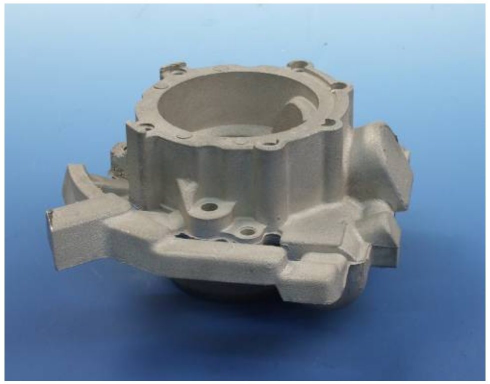


Cross section at billet top



courtesy: Prof. Dr.-Ing. L. Kallien, Dipl.-Ing. W. Leis
Steinbeis Transfer Centre "Gießerei Technologie Aalen (GTA)", Aalen Polytechnic, Germany

Pump body, manufactured by thixocasting; AA2017/SiC_P



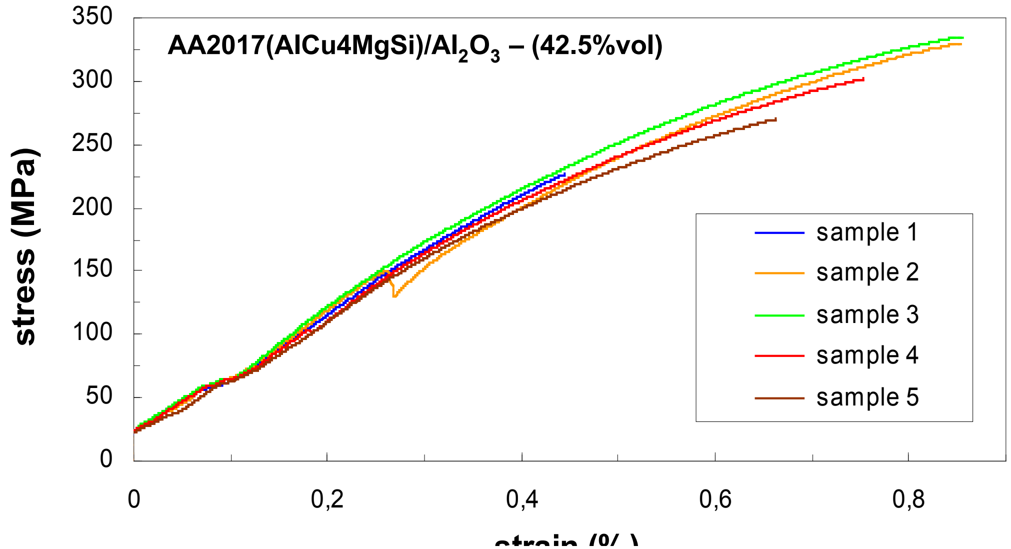
Thixocasting by W. Leis, Steinbeis Transfer Centre "Gießerei Technologie Aalen (GTA)", Aalen Polytechnic, Germany

Mechanical Properties of the Resulting, Forged PRM Material

4-point bending tests.
(material was NOT heat treated)

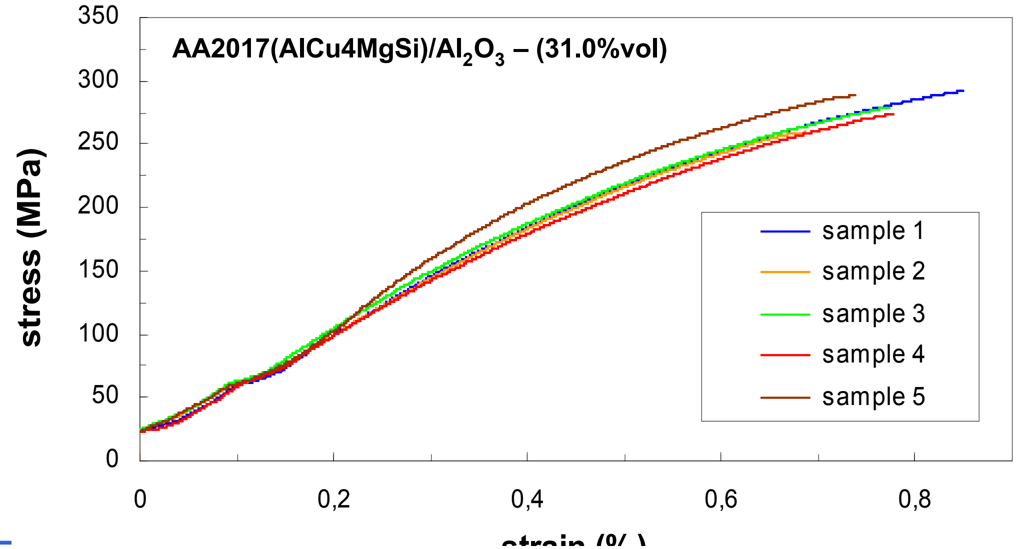
particle content 42.5 %vol.

⇨ Young's modulus, E 95-106 GPa
Bending strength, σ_b 291.6 MPa



particle content 31.0 %vol.

⇨ Young's modulus, E 90-93 GPa
⇨ Bending strength, σ_b 277.4 MPa



Powder Metallurgical, Particle Reinforced MMC

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

Prozess route:

Compounding
powder mixture (pure metals)

↓

Compaction
CIP (cold isostatic pressing)

↓

Forming
die-forging

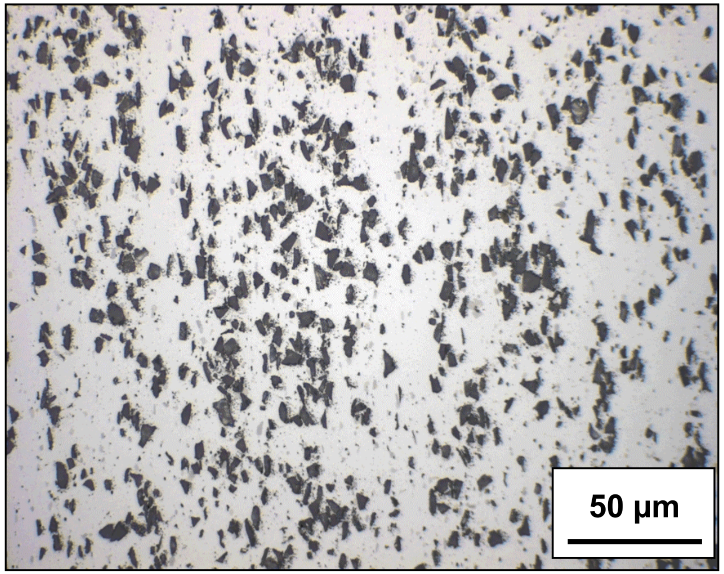
→

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

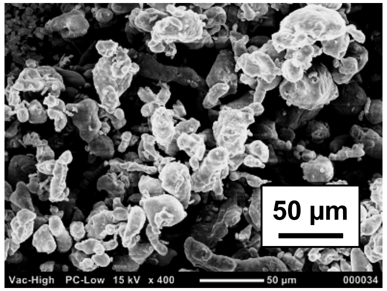


Dartal: forged microstructure

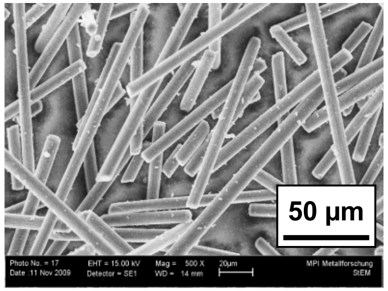
Short Fiber Reinforced Al via Metallurgical Technique

Process route for SFRM (15 %vol. fibers):

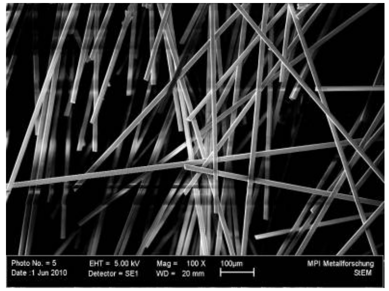
Compounding
mixing of powder and fibers



EN AW-2009 [Al Cu3,5Mg], powder mixture

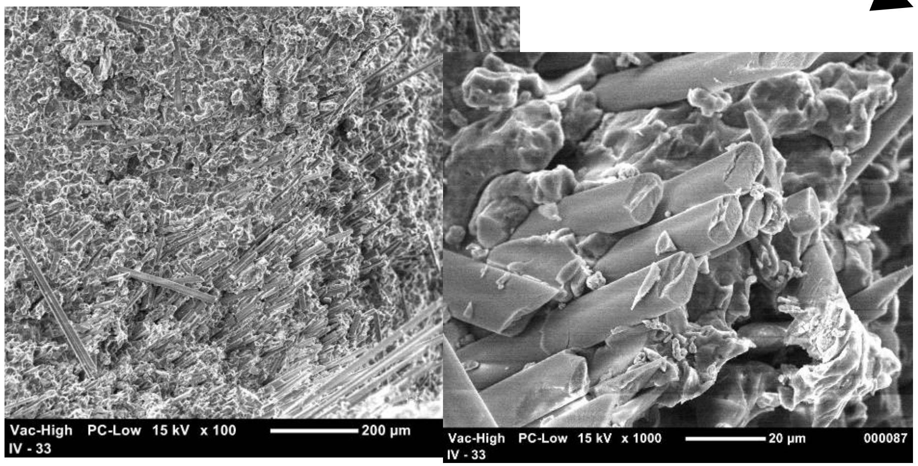


C fibers, HT Type-A M100 (milled), Toho Tenax

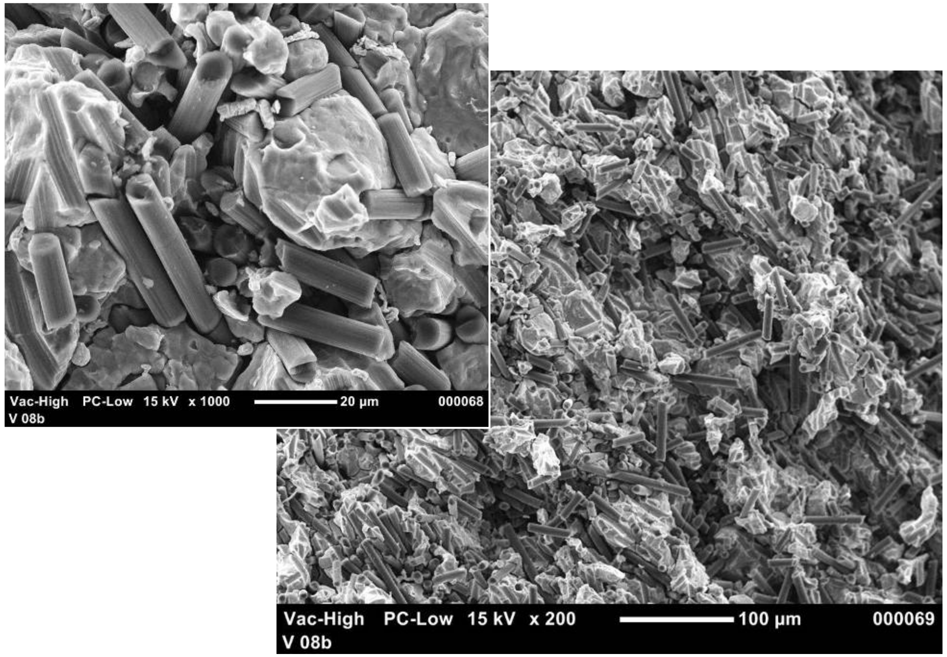


Alumina fibers Type 3M Nextel 610, chopped (3,2 mm), heat cleaned

Compaction
cold isostatic pressing (CIP)



AA2009/Al2O3-fiber(Nextel610 chopped)/15p, CIP (600 bar)



AA2009/C-fiber milled/30p, CIP (600 bar)

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