Lightweight metal matrix composites with tailored textile engineering for automotive applications

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Outline

- Introduction: Potentials and application of MMC materials
- Basics of semi-solid processing
- Conventional routes to semi-solid processing
- Thermal spraying of matrix material on fiber reinforcements
- Pilot plant for industrial scale prepreg manufacturing
- Densification of MMC by thixoforging
- Mechanical properties of thixoforged MMC samples
- Summary and conclusions

IFKB Universität Stuttgart

Technologie Transfer Initiative

New Materials Technologies

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OPEN TECHNOLOGY FORUM

POWERTRAIN DEVELOPMENT

Light Weight Engineering in Automotive Industries

application of new composite materials and surface technologies

fiber composites

- bumper shields, chassis and body components, axle drive, cardan shaft, connecting rods (GFRP or CFRP components)
- ➢ exhaust and hot gas conducting elements, **brake disks (CMC)**
- ➢ **wheels**, bearings, pistons, connecting rods **(MMC)**

particulate composites

- brake disks and drums (SiC particulate reinforced aluminum)
- Al - infiltrated oxide ceramics (Lanxide^{TM} , DIMOX^{TM} - type)

layer composites and coatings

- overhead cam shaft, valve cups and tappets
- ➢ cylinder liners in light metal crankcase (oxide ceramics or cermets on aluminum)
- ceramic lacquers for die casted magnesium components, combined coatings
- calipers and brake lining carriers
- piston and valve coatings

Light Weight Composites for Tribological Applications

- **functional coatings on light metal alloy–components** **(Coatings)**
  oxide ceramic, metallurgical and cermet layers on aluminum and magnesium alloys
  ceramic and cermet layers on titanium
  combined coating systems with dry lubrication ability

➢ **metal matrix composites** **(MMC)**
  carbon–, boron– or alumina–fiber reinforced light metal alloys
  ceramic powder particles as dispersion in metal matrix (SiC reinforced aluminum)
  RB–oxide ceramic with residual metal matrix (Lanxide^{TM}, DIMOX^{TM}-process)

- **carbon fiber reinforced carbon and graphite** **(CFC)**
  pitch and thermosetting resin infiltrated UD, 2D, 3D or short fiber composites
  matrix deposition by CVI technique

➢ **fiber reinforced ceramic composites** (UD, 2D, 3D, short fiber reinforcement) **(CMC)**
  reaction bonded carbon fiber reinforced silicon based ceramics
  e.g. CMC with silicon metal infiltration (SiC) or
  heterogeneous gas reaction (SiC and Si_3N_4)
  CMC with oxide and non oxide matrices from ceramic precursors polymers

Motivation for continuous fiber reinforcement of light metals

- **Advanced mechanical properties:**
  - high modulus
  - high tensile strength
  - improved wear resistance
  - improved fatigue behavior
  - creep resistance at elevated temperatures
  - adjustable thermophysical properties

- **Carbon and ceramic fibers show low density, high thermal and electrical conductivity and low thermal expansion**

  ⇨ **High modulus/density ratio (E/ρ)**

- **Potential for tailored, non-isotropic material**

Reinforced bearing seat

Courtesy EMPA, Thun, Switzerland

Reinforced pistons and push rods

Courtesy Mahle AG, Stuttgart, Germany

Conventional methods for manufacturing of fiber reinforced light metals

- **Liquid phase impregnation in a preformed fiber structure:**
  - Squeeze casting
  - Gas pressure infiltration

Advantages:
- easy to manufacture
- fast process

Disadvantages:
- no complex geometries available
- manufacturing of a rugged preform
- fiber damage due to chemical reaction

- **Hot pressing and solid phase impregnation:**
  - Hot pressing of powder metallurgical fiber compounds
  - Diffusion bonding

Advantages:
- precise orientation of the fibers

Disadvantages:
- no complex geometries available
- fiber damage due to chemical reaction and shear stress
- long process times
- complex process

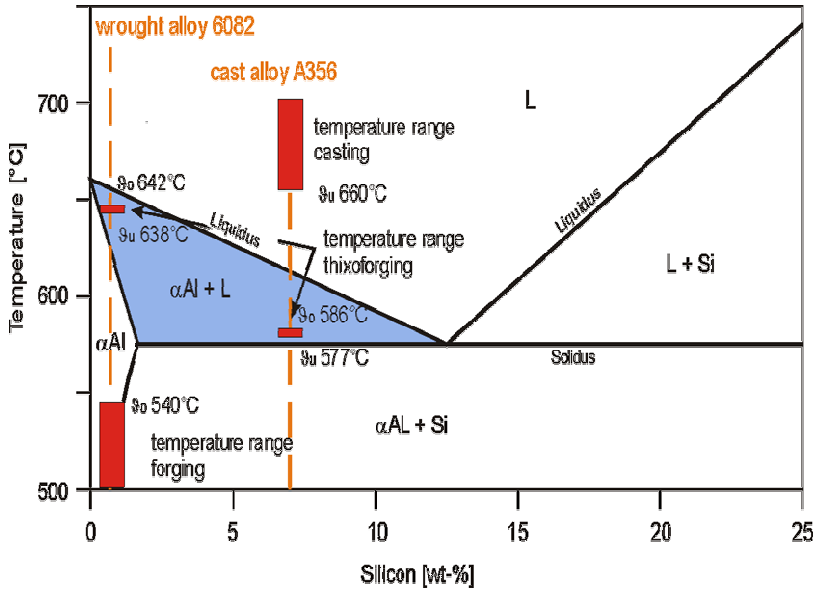
⇨ ***New method:***

Semi-solid forming and shaping of thermally sprayed prepregs to dense, solid metal matrix composites (MMC)

Semi-solid forging (thixoforging)

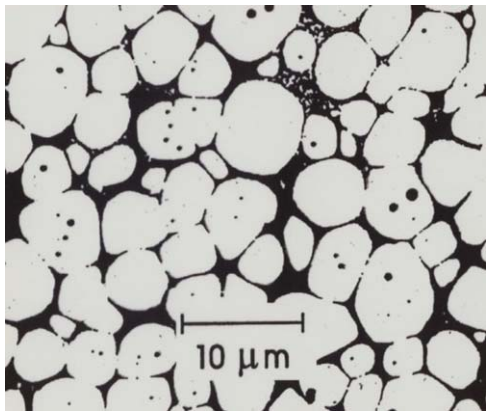
Characteristics of thixoforging:

- Distinct solidification interval where solid and liquid phases coexist during processing
- globular microstructure without any dendritic grains
- temperature range set to obtain a liquid fraction of f_l = 20 - 50 vol.%
- solid grains which build a rigid scaffold in a liquid matrix
- fine grain size (2 - 10 µm)

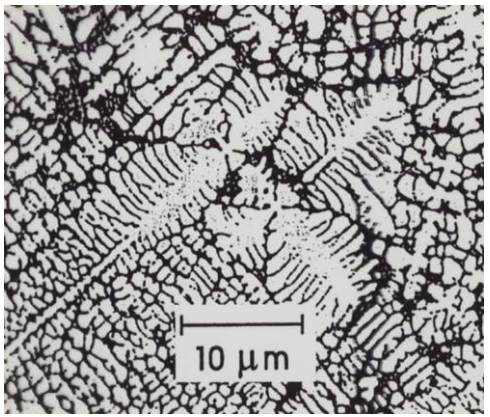


Combination of features from

molding	and	forging
- near-net-shape - low wall thickness - complex geometries		- high strength - high elongation - pressure and gas tight structure



ideal globular structure



dendritic structure

Properties and characteristics of the thixoforging process

Thixoforging compared with forging:

+ Low forging forces	- Reheating of billet rods
+ Low tool wear	- Expensive starting material
+ Complex geometries	- Longer process cycles
+ Near-net- shape	- Complex process technology

Thixoforging compared with molding:

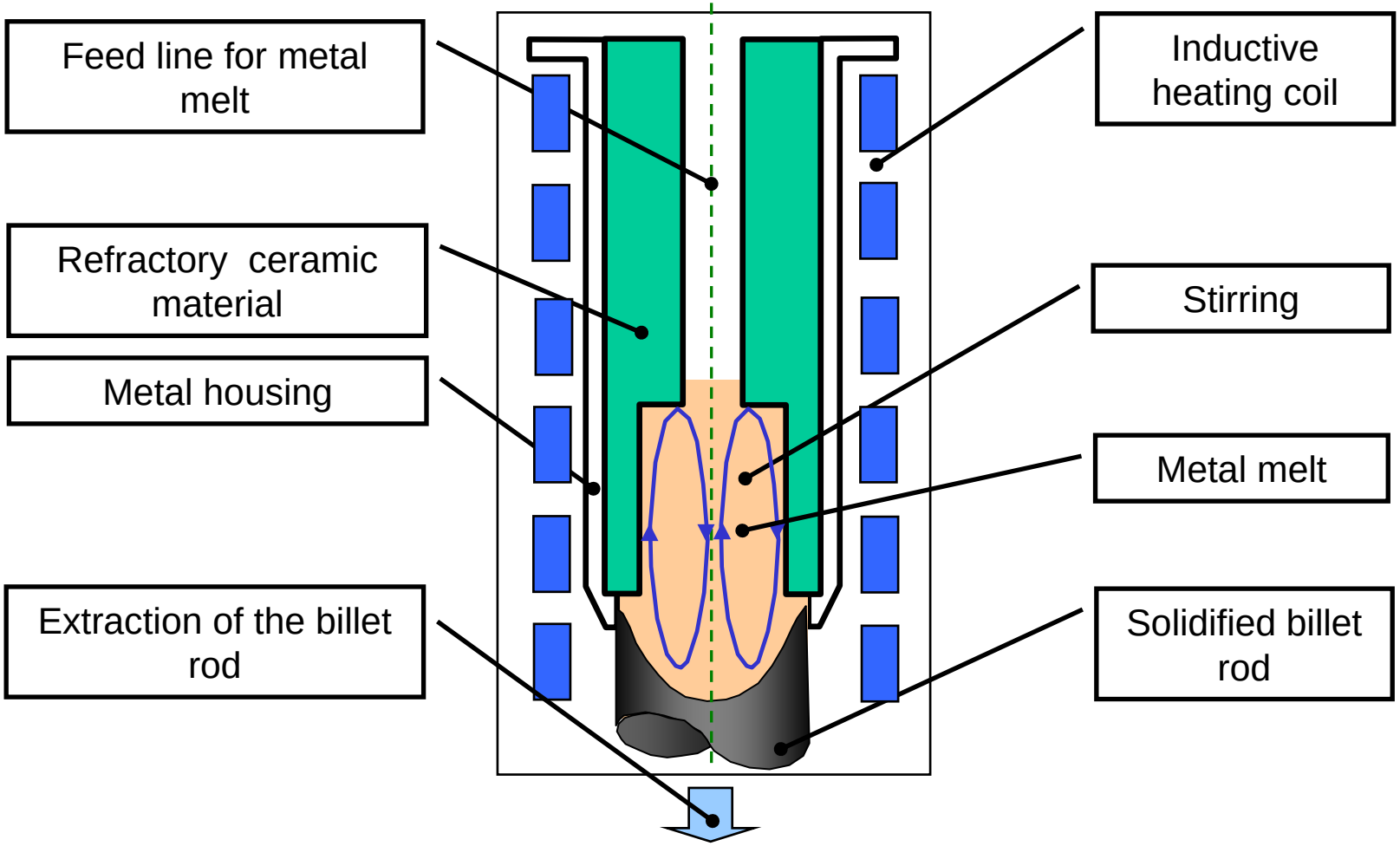
+ Less pores and blow holes	- Reheating of billet rods
+ Shorter process cycles	- Expensive starting material
+ Better surfaces	
+ Larger variety of alloys	
+ Fine grained and homogeneous microstructure	

Using the advantages of thixoforging for the production of MMC components

- **short cycle times, low forces and short flow paths**
- **reduced fiber damage due to short cycle times, low temperatures and chemical activity of a liquid fraction of only f_l = 20 - 50 vol.%**

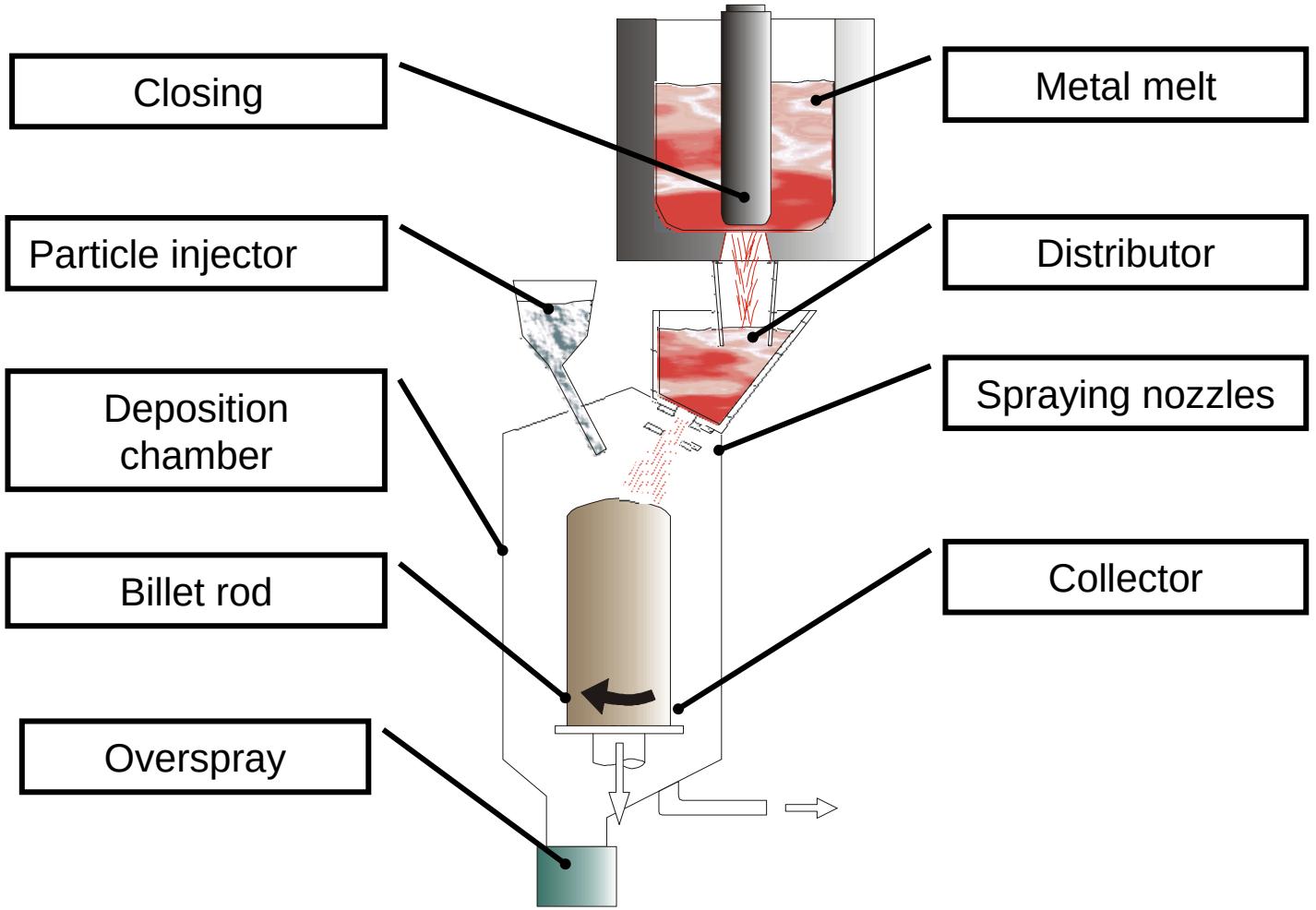
Conventional production of thixo-formable material

Rheocasting: Continuous casting with electromagnetic stirring



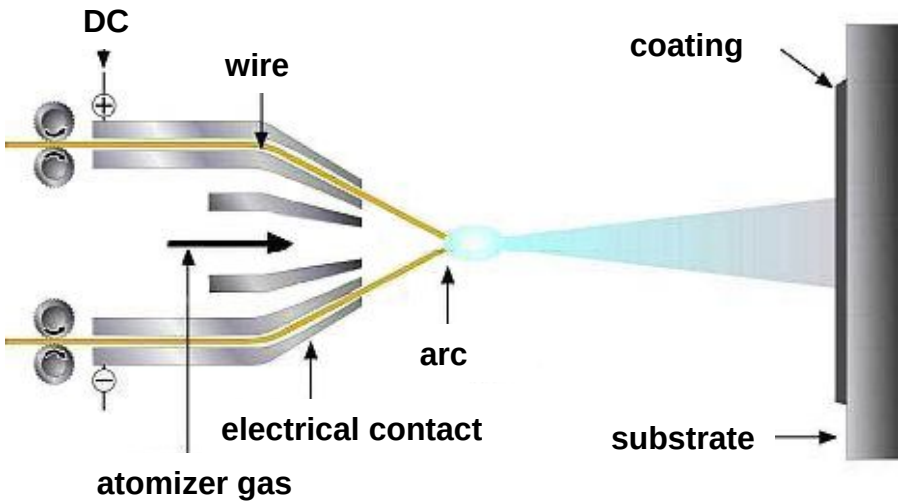
Conventional production of thixo-formable material

Spray forming: Atomization and deposition of droplets in controlled atmosphere

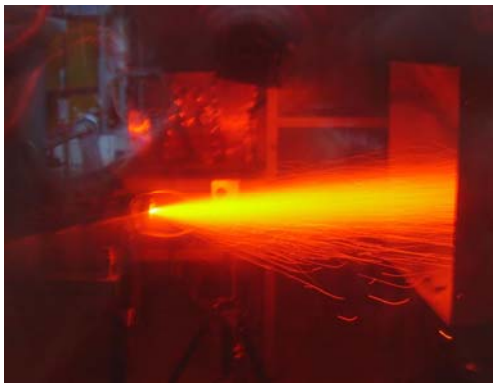


Material deposition by arc wire spraying

Arc wire spray torch (schematic):

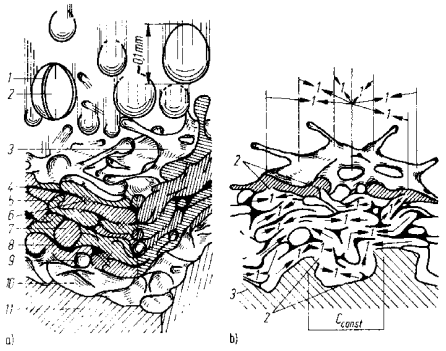


from: www.Schooperen.nl

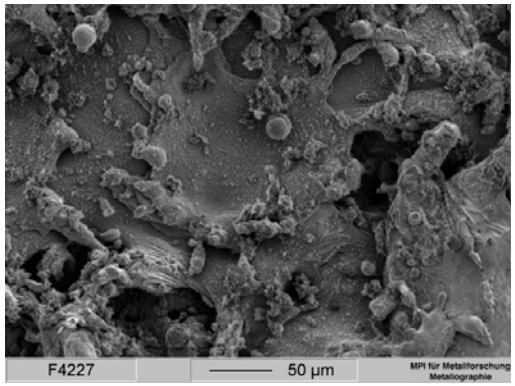


Arc wire spraying with a GTV sparc 400

Energy source:	electric arc
Max. process temp.:	4000 °C
Materials:	metals, alloys, cored wires with ceramic particles
Particle velocity:	150 m/s
Deposition rate:	20 - 300 kg/h



from: Pursche, Oberflächenschutz vor Verschleiß, 1990

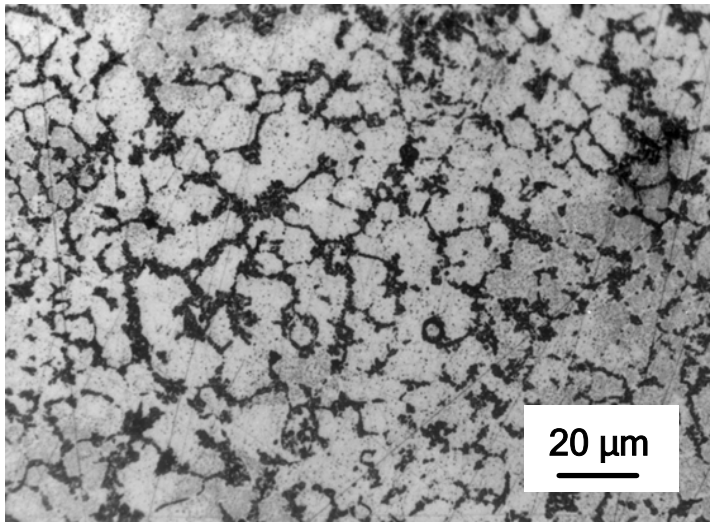


SEM of a AlSi6 coating surface by arc wire spraying

Thixoforging of thermally sprayed solid billet rods

“Cut” test

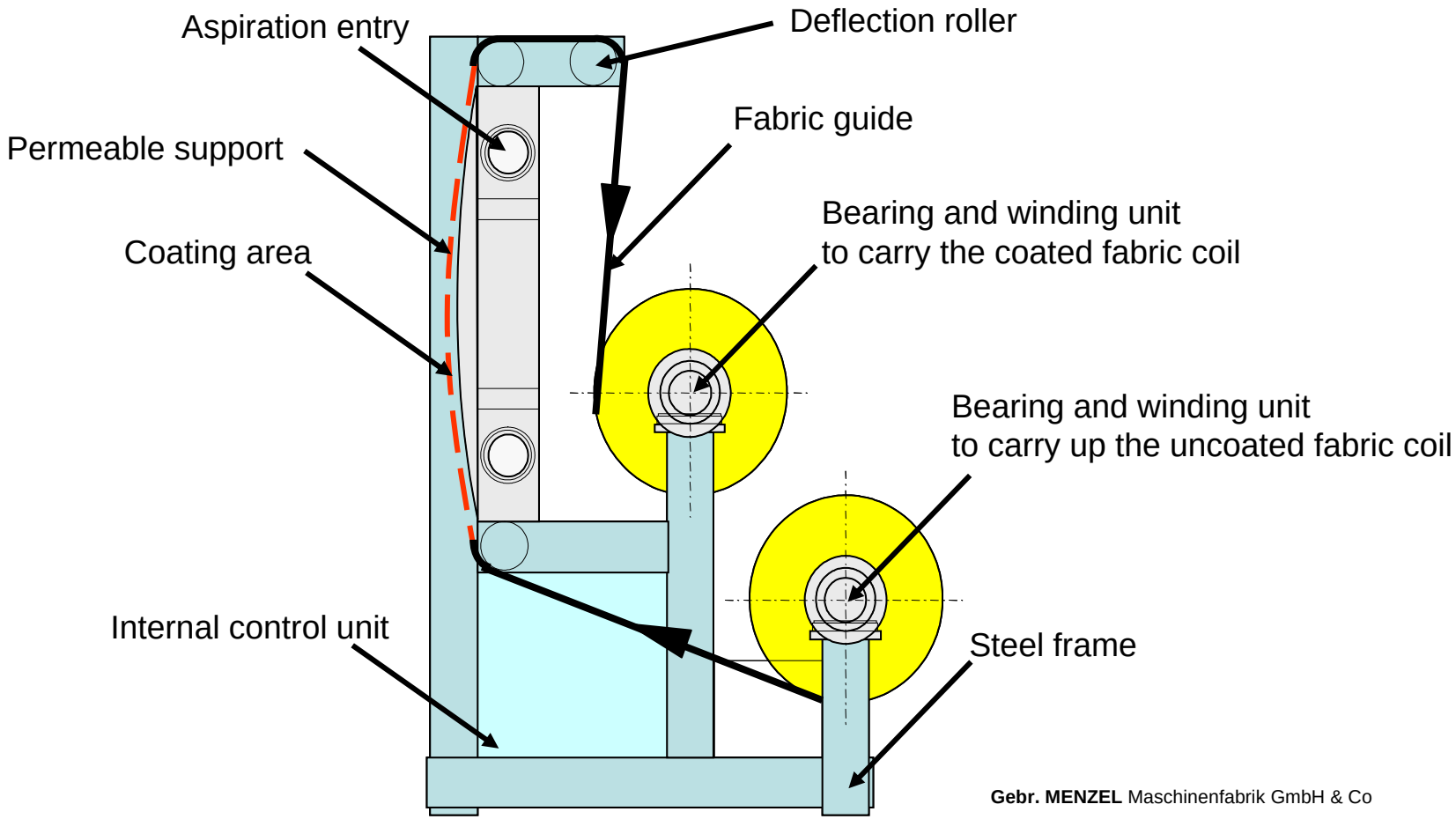
Arc wire sprayed AlSi6 billet rod heated into the semi-solid state and cut easily by a kitchen knife



Microstructure of an AlSi6 billet rod after heating *and* forging

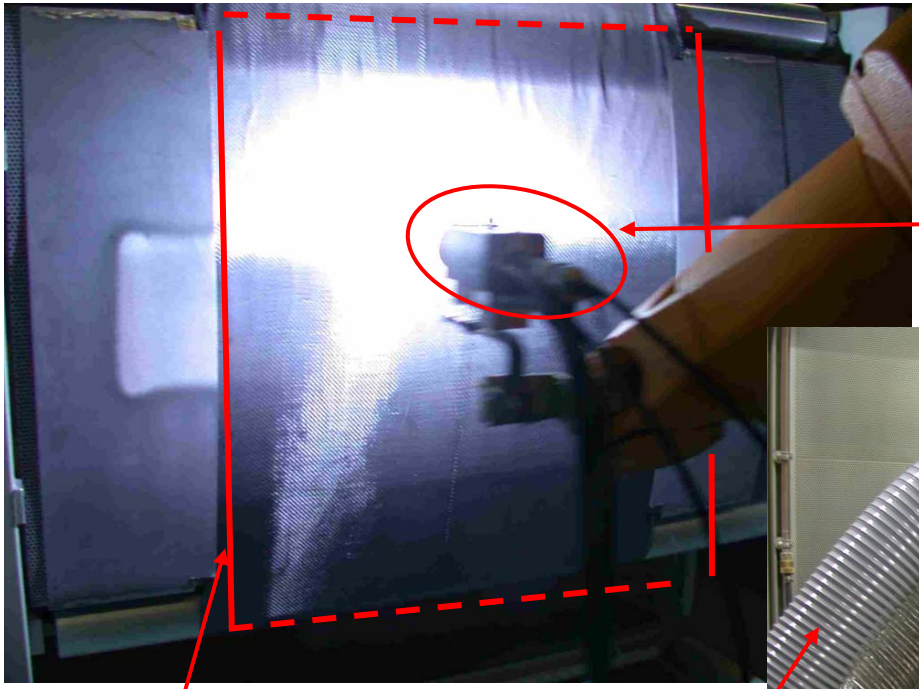
Manufacturing of semi-finished parts (prepregs) for thixoforging

Winding equipment to fix and stretch the textile fabrics during coating operation continuously from “coil to coil” up to a web- width of 1500 mm



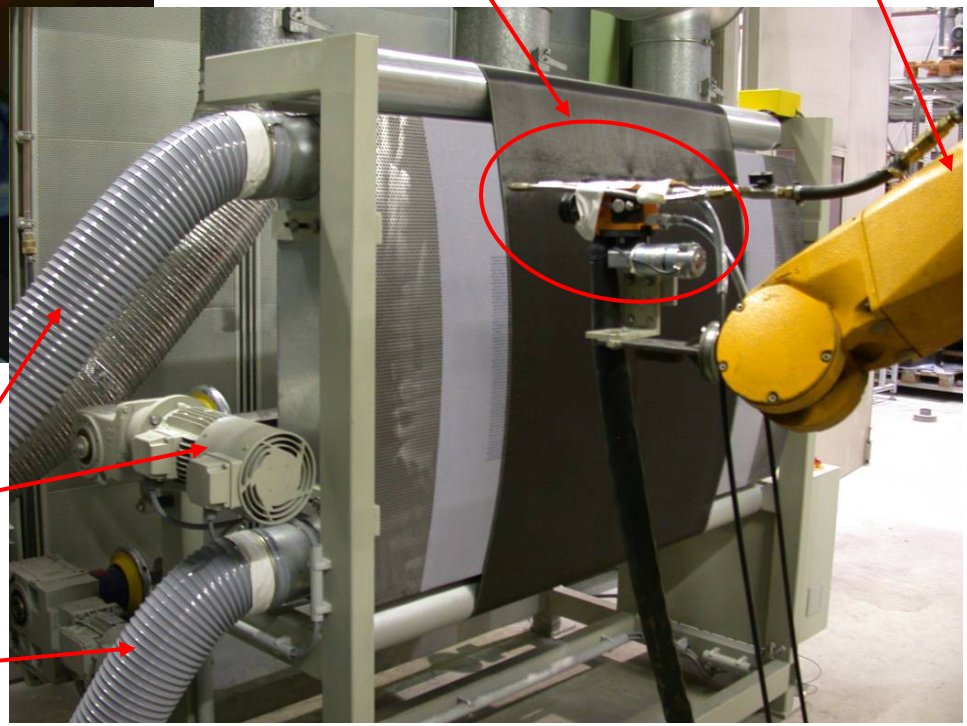
Gebr. MENZEL Maschinenfabrik GmbH & Co

Manufacturing of semi-finished parts (prepregs) for thixoforging



6-axis robot system

arc-wire torch

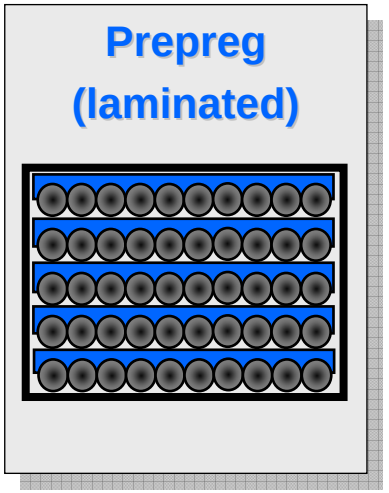


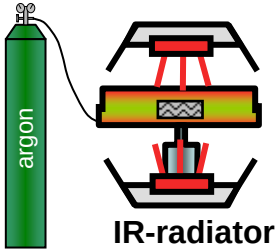
carbon-fiber fabric

winding equipment

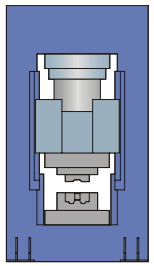
aspiration vents

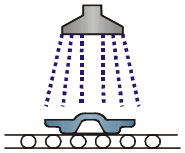
Manufacturing technology for fabric reinforced MMC components





IR-radiator furnace



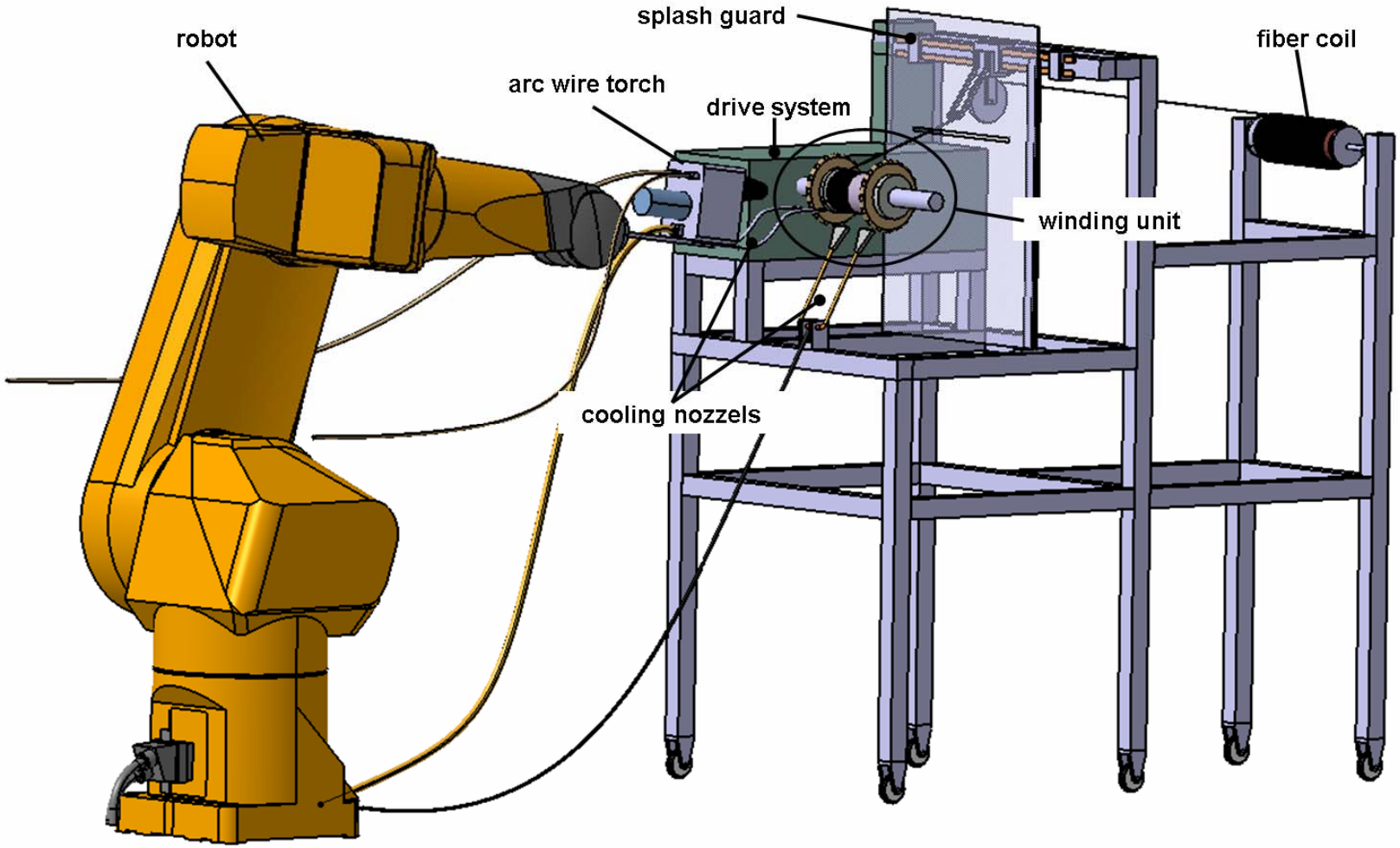


Prepreg-Heating

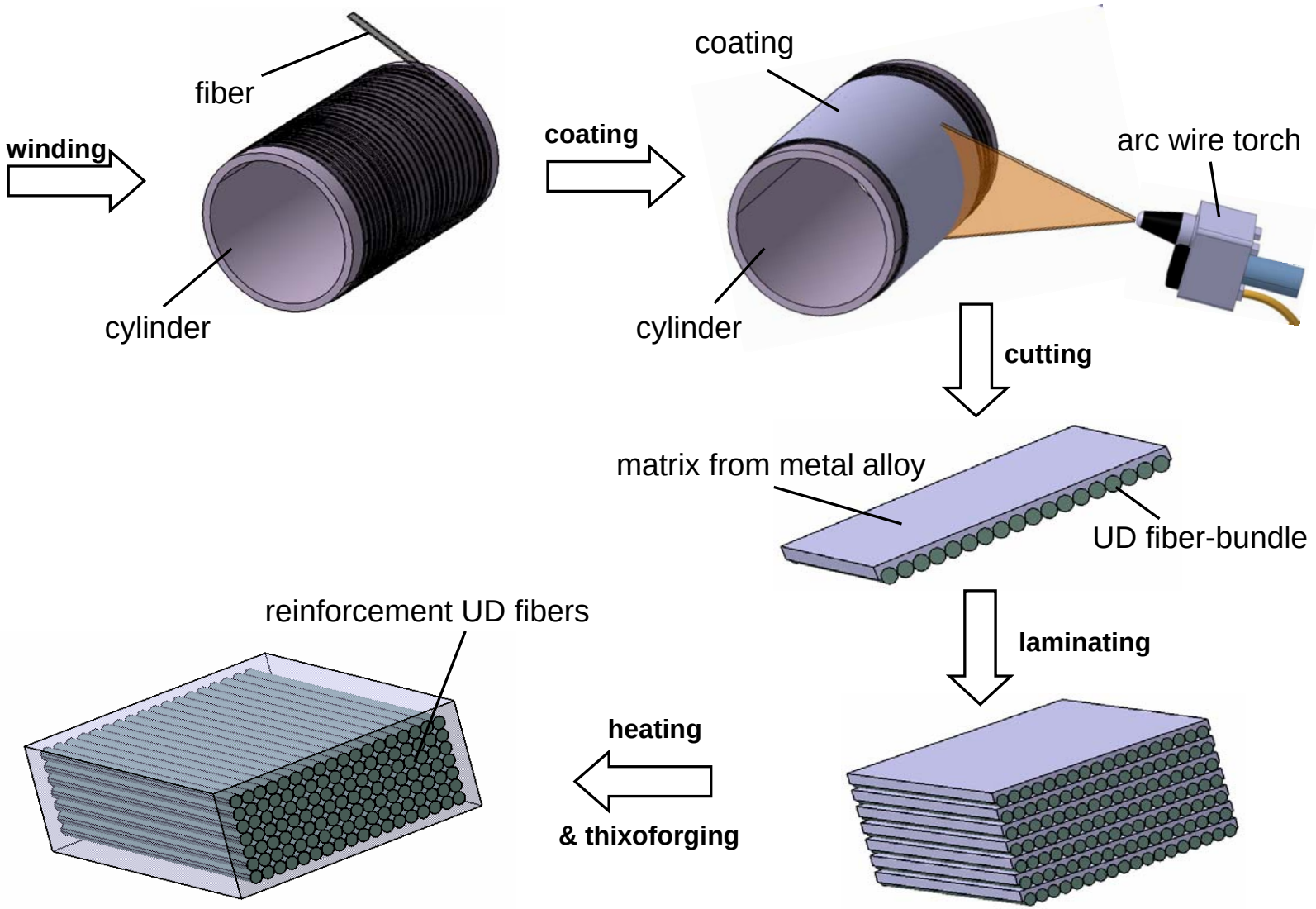
Forging:
MMC- & component production

Cooling/
Thermal treatment

Manufacturing process of UD-fiber-reinforced prepregs

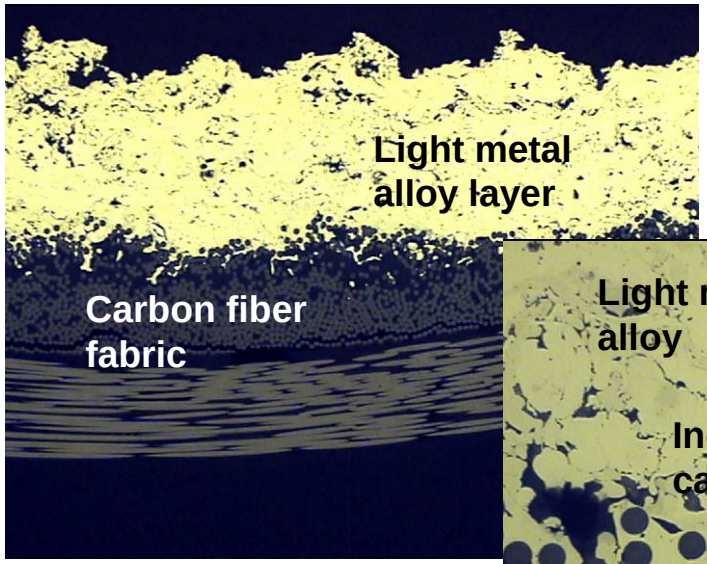


Process chain for the manufacturing of UD fiber reinforced MMC

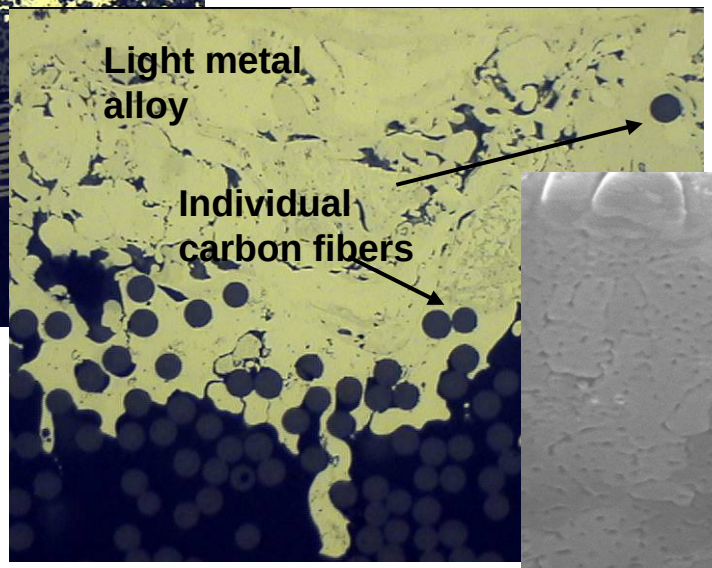


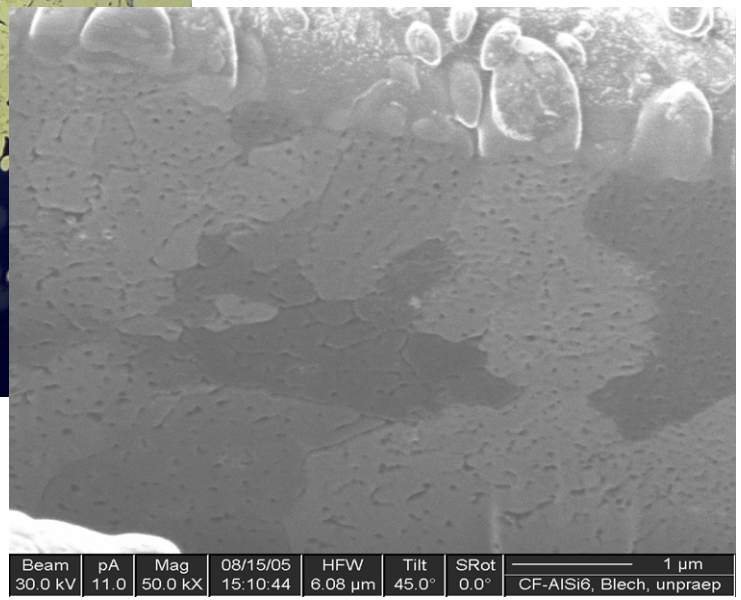
Microstructure of thermally sprayed prepregs

Arc wire sprayed AlSi 6 coated carbon fabric *before* heating



Cross section of a coated carbon fiber fabric

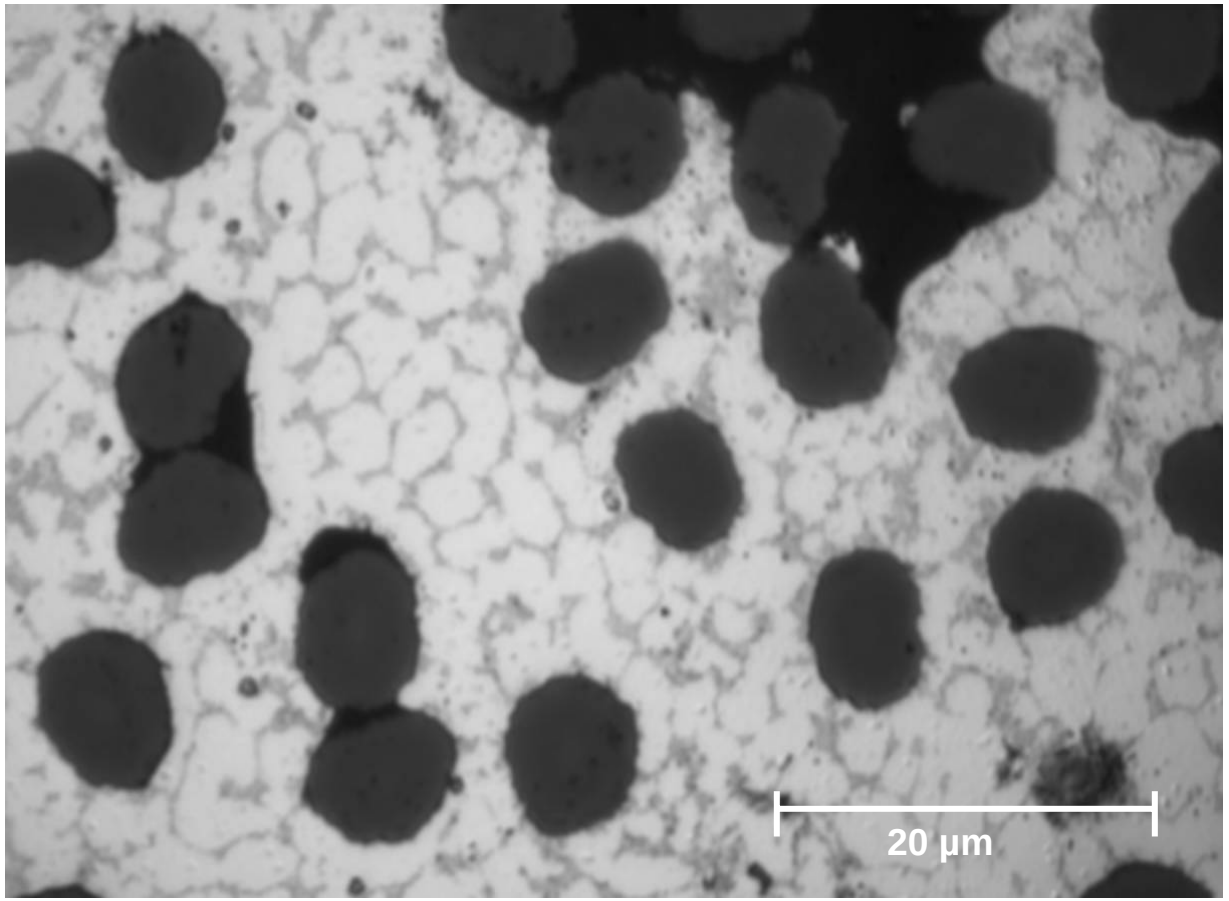




FIB (focussed ion beam) microscopy of the fine grained structure

Microstructure of thermally sprayed prepregs

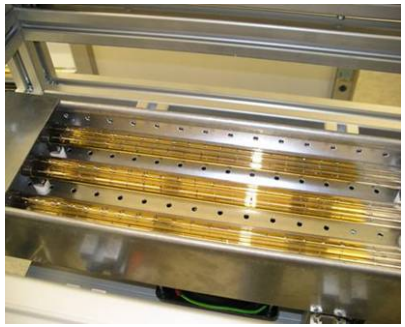
Arc wire sprayed AlSi 6 coated carbon fabric *after* heating



SEM micrograph of a cross section of coated carbon fiber fabric after heating

Manufacturing of MMC by thixoforging

Heating by infra-red radiator



Technical specifications of the infrared module

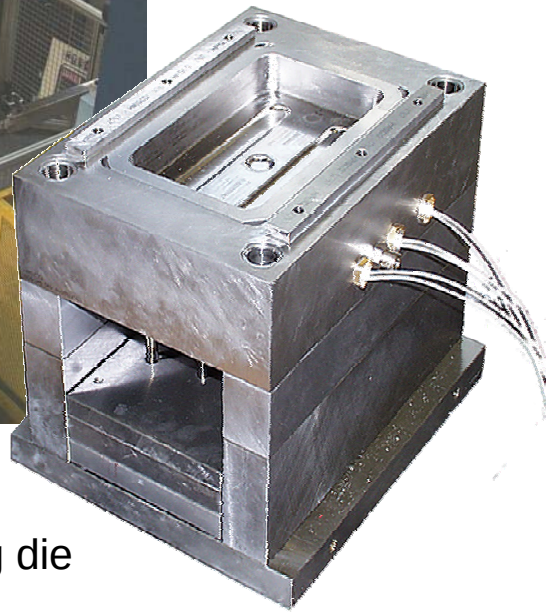
- nominal output: 7,5 kW
- emission maximum: 1200 -1400 nm
- heated area: 130 x 280 mm^2

Heating time from room temperature to 650 °C in 120 s !

Manufacturing of MMC by thixoforging

hydraulic press

Thixoforged by Institute for Metal Forming Technology, Universität Stuttgart, Germany



forging die

Hydraulic single-action 5.000 kN-press for the thixoforging process of AlSi / AlMg fiber prepregs

- max. press force: 5.000 kN
- ram stroke: 300 mm
- max. ram velocity: up to 800 mm/s
  ⇨ velocity profile adjustable
- pressure period: 8 - 30 s

Heating parameters

- ϑ_{die} : 250 - 400 °C
- $\vartheta_{prepreg}$: 580 - 660 °C

Thixoforging of continuous fiber reinforced metals

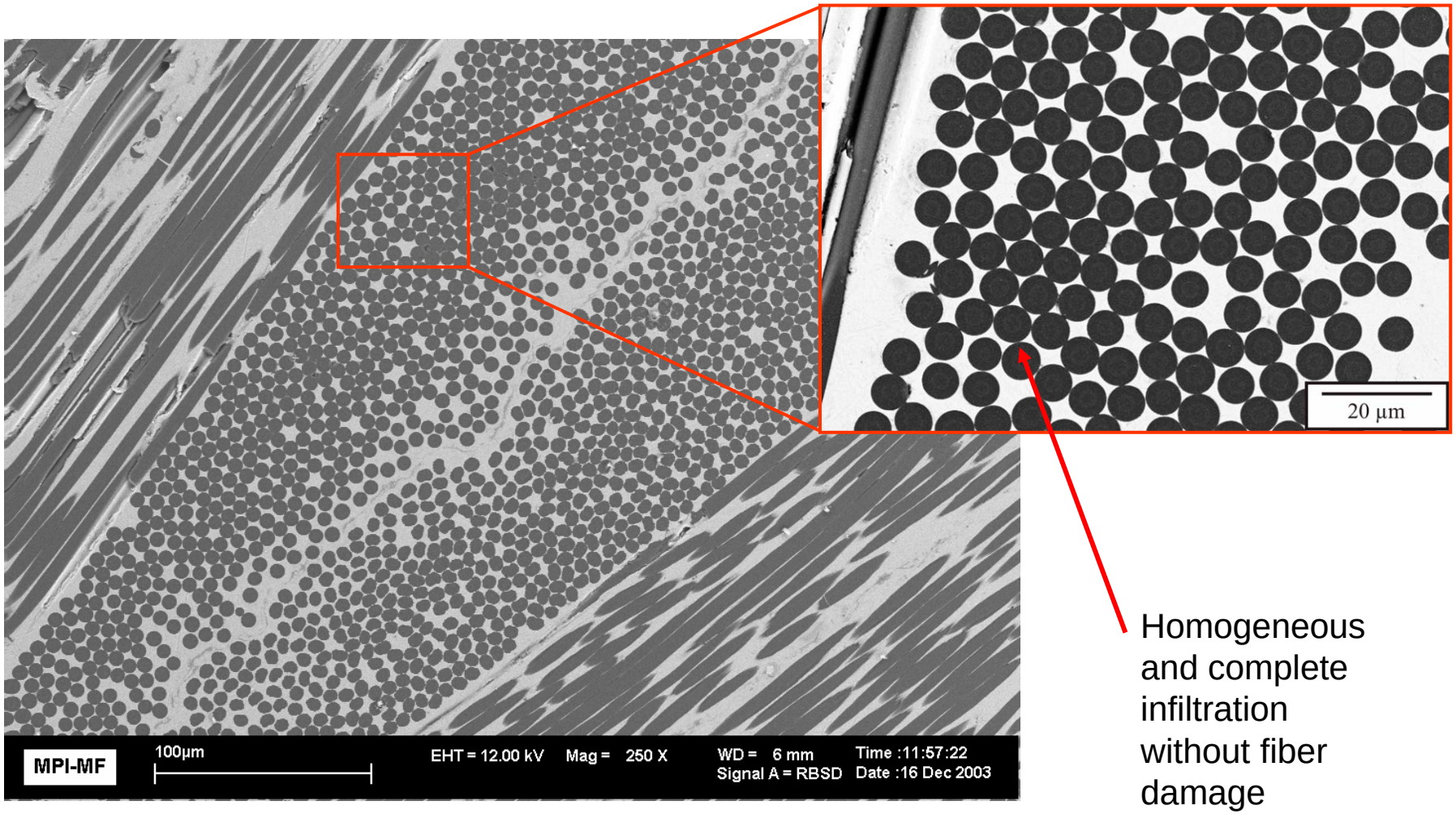
Features of the test reference part

Thixoforged carbon fiber reinforced CFRM with AlSi 6 matrix produced from TS-prepregs

Dimensions: 214 mm x 124 mm with 10 mm flanges

Infiltration behavior and microstructural results

Continuous HT carbon fiber reinforced component

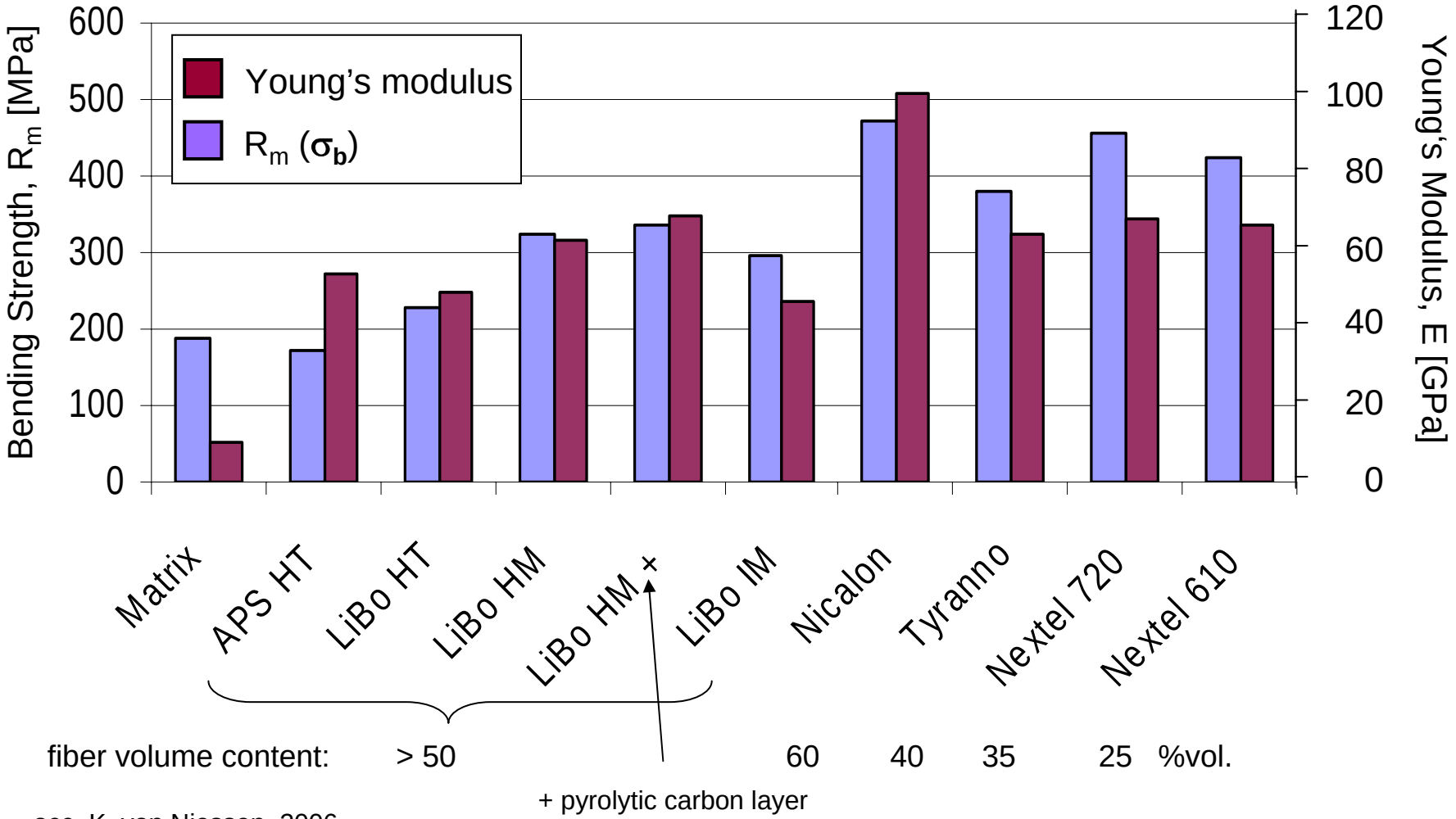


Homogeneous and complete infiltration without fiber damage

SEM micrograph of the cross section of the component

Mechanical properties of light metal MMC from TS-prepregs

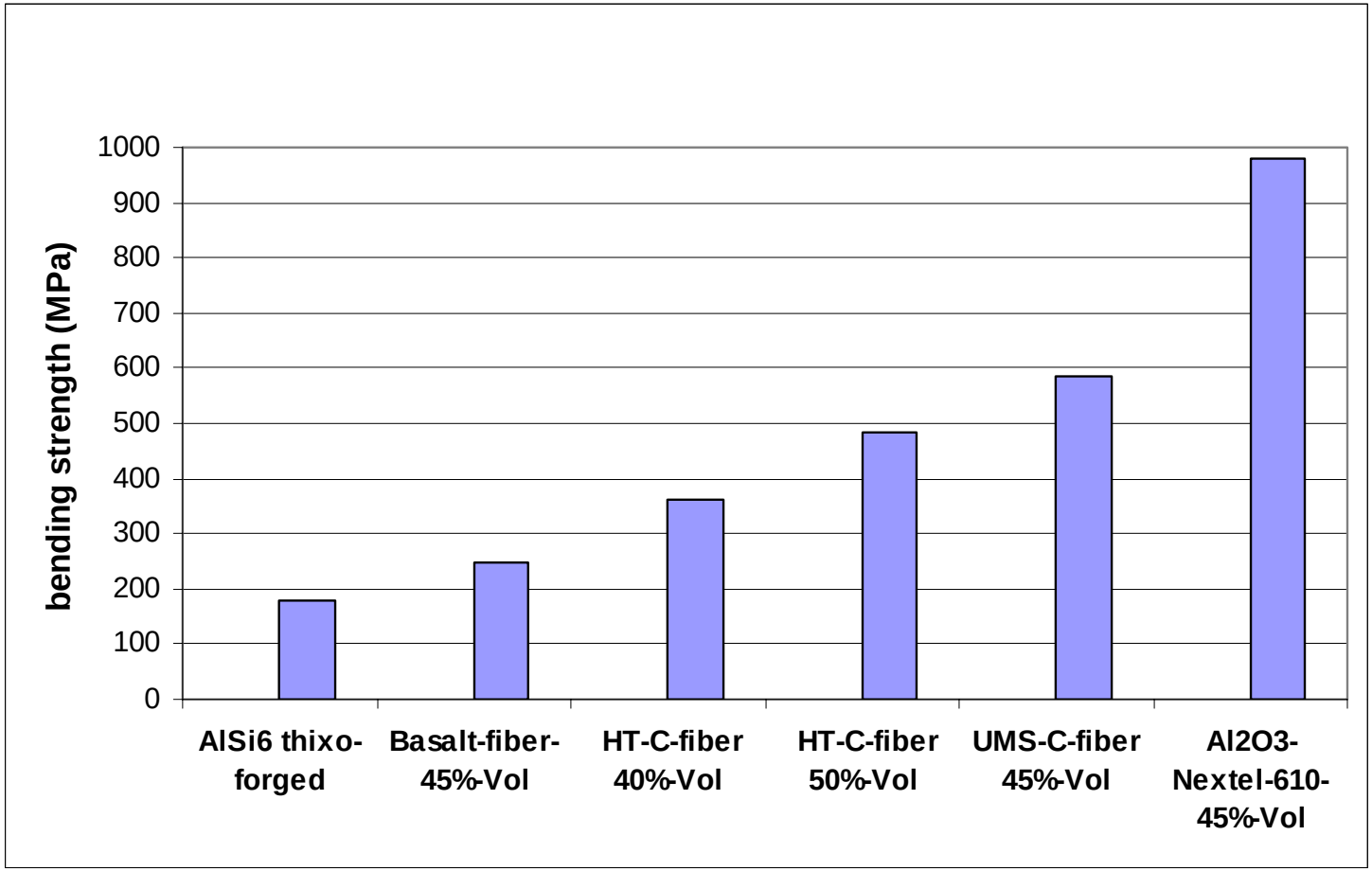
Results of 4-point-bending tests for different fibers:
(2D-woven reinforcements !)



acc. K. von Niessen, 2006

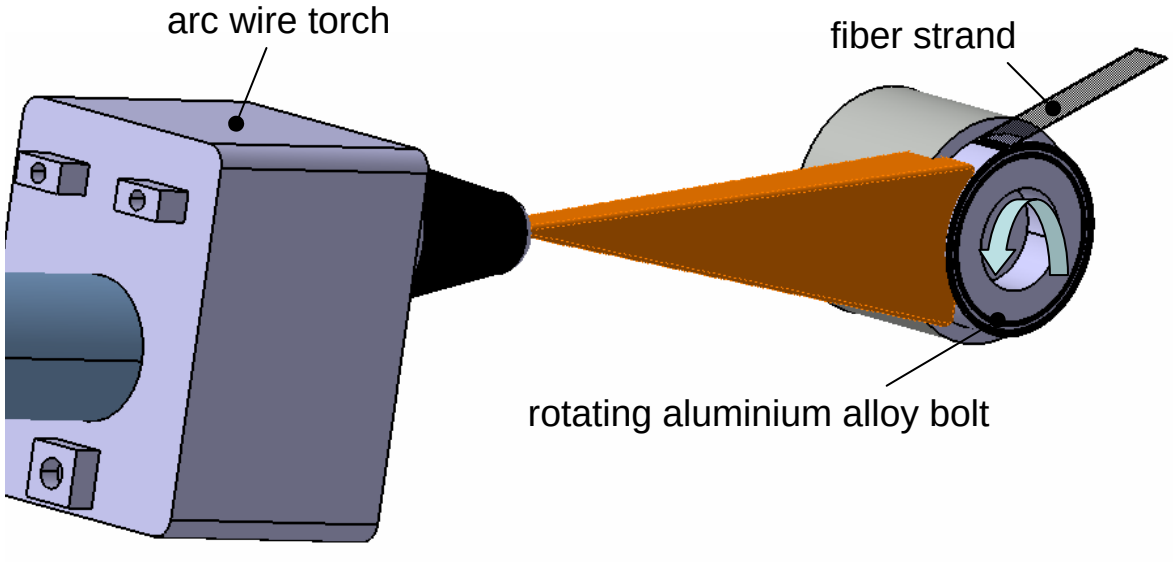
Mechanical properties of light metal MMC from TS-prepregs

Results of 4-point-bending tests for different fibers:
(unidirectional reinforcements !)

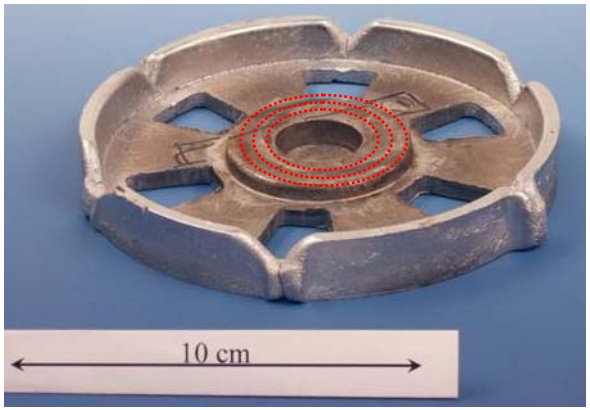


Tailored material in automotive applications: Local reinforcement

Lightweight MMC wheel rim, thixoforged C-fiber, AlSi6

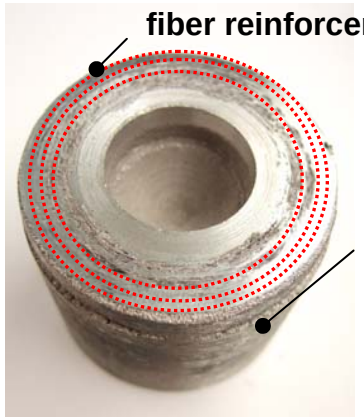


fiber reinforced rim, manufactured by thixoforging

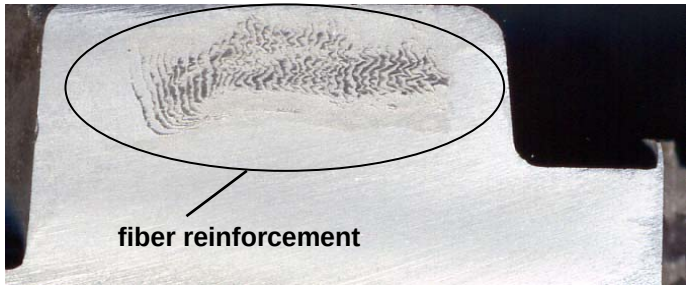


Thixoforged by Institute for Metal Forming Technology, Universität Stuttgart, Germany

bolt for thixoforging: main body A356 (AlSi7Mg); simultaneous winding and coating of the fiber by arc wire spraying (AlSi6)



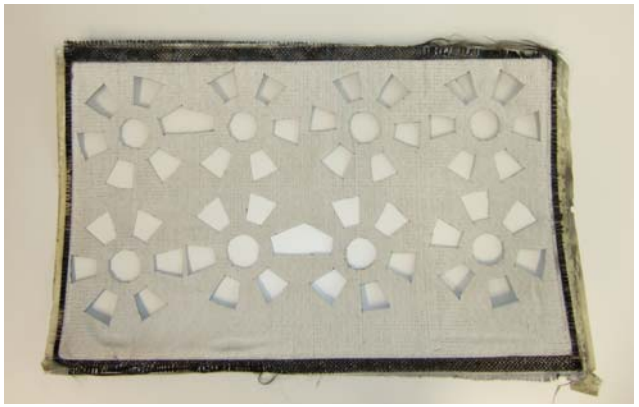
cross section of the rim center with applied fiber reinforcement



Fiber reinforced wheel rim by MMC fiber prepregs and semi solid forging

Extensive fiber reinforced lightweight wheel rim, thixoforged C-fiber fabric, AlSi6

coated and blanked carbon fabric



cutting

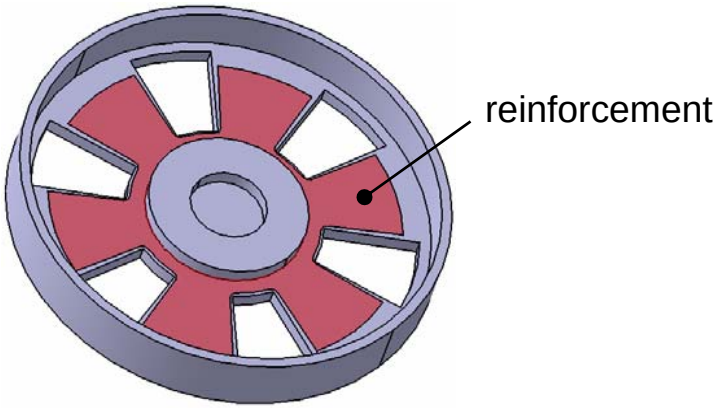
trimmed prepregs

laminating

heating

& forging

carbon fabric reinforced rim



Summary and Conclusions

- Thixoforging of fiber/matrix prepregs is a novel and promising method to manufacture net shape continuous fiber reinforced light metal components in short production cycle times
- Electric arc wire spraying is a most suitable method to produce well adherent metal layers with variable thickness, thereby tailoring the fiber volume content in the MMC
- Prepregs for thixoforging consist of dense partially impregnating coatings on fiber fabrics and UD tapes, depending on their textile structure and characteristics
- Arc spraying is a fast, cost effective and process stable deposition technique for light metals and offers the possibility to use simple or complex alloys and even non-equilibrium phases
- By thixoforging a very fast consolidation of micron and submicron metal splats, obtained during milliseconds in thermal spray deposition, to dense metal matrices with micro globular structure is feasible
- MMC with improved stiffness and strength were obtained depending on the fiber matrix combination and on the interface design

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