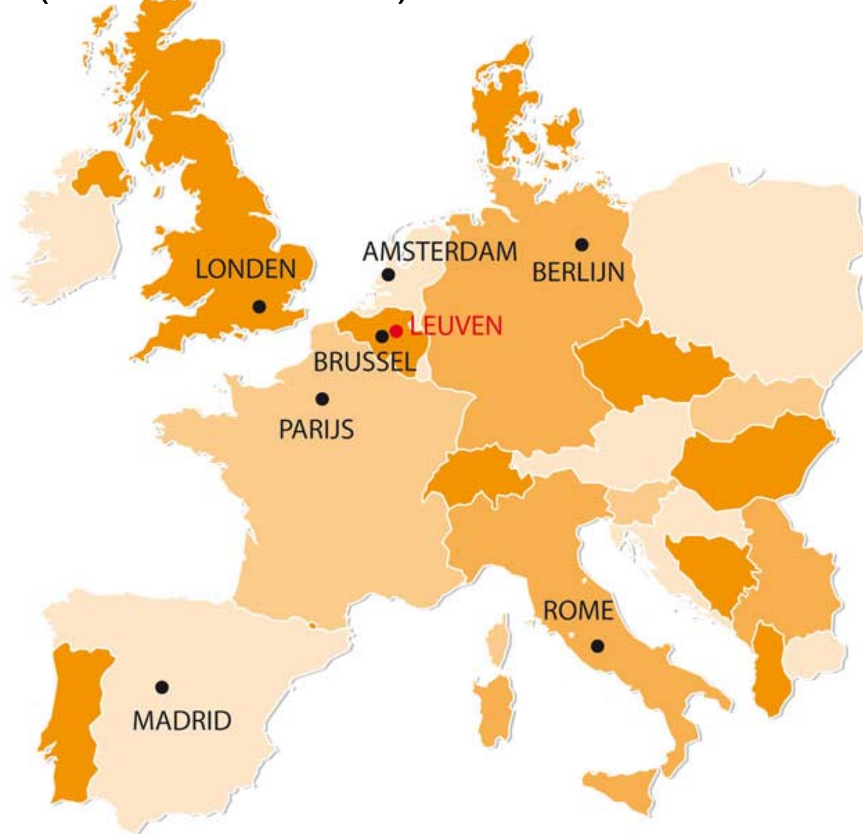
Powder Bed Fusion Additive Manufacturing

Prof. Dr. Ir. Jean-Pierre Kruth
KU Leuven university, Belgium

Introducing KU Leuven university

- Located 20 km East of Brussels, Belgium
- Founded anno 1425 as oldest catholic university
- 1970: split between KU Leuven and UCLouvain
- KU Leuven = largest university in Belgium (>30.000 student)
- Long tradition in manufacturing
  - CIRP Intern. Academy for Production Eng.
  - SME Univ. LEAD award (1998)

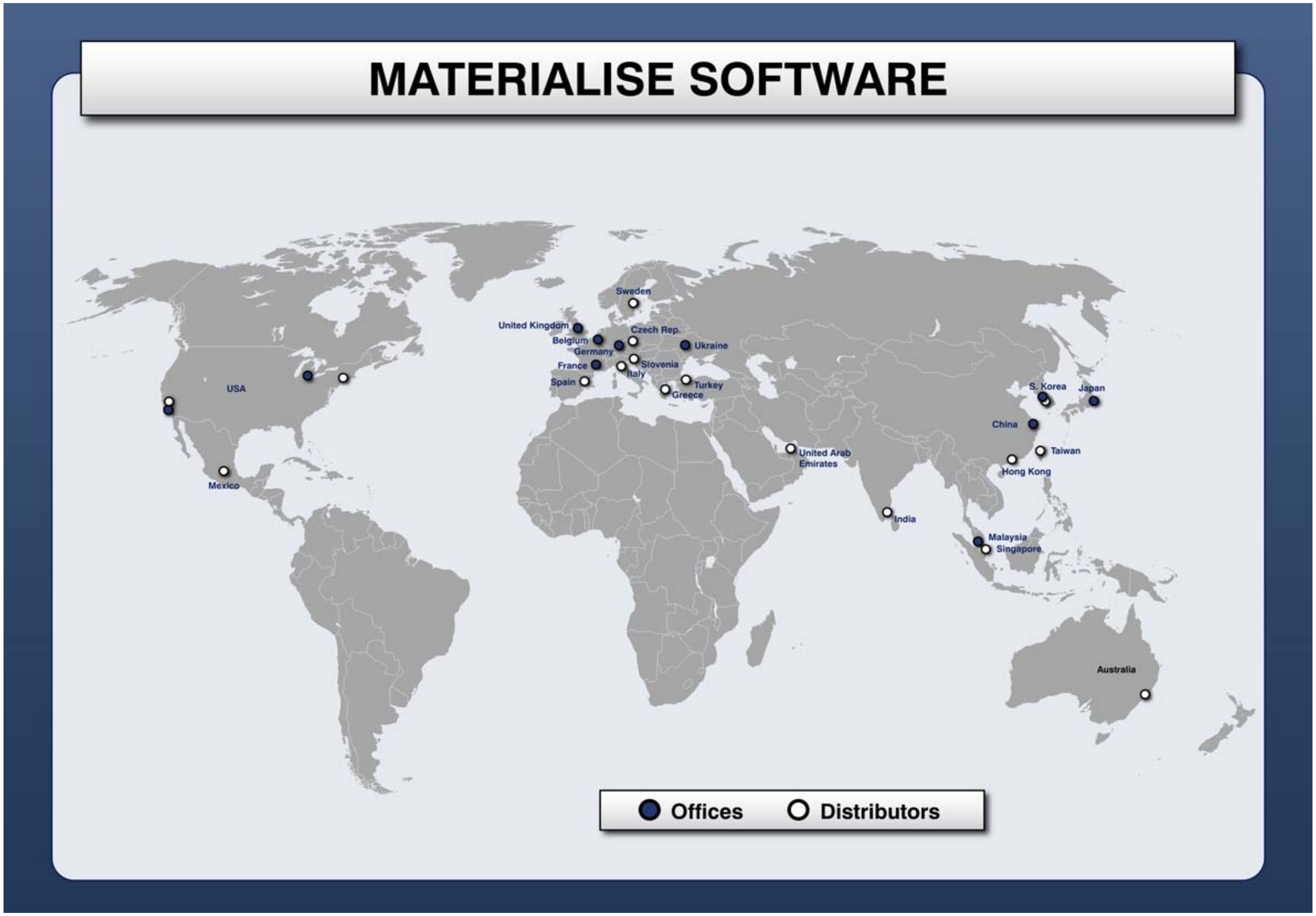


Introducing AM activities of KU Leuven university

- **Company: Materialise N.V., Leuven**
- Initial activity: producing prototypes in plastics by layerwise Rapid Prototyping techniques
- Spin-off of KU Leuven (Division PMA)
- Start: 1990 (Founder: W. Vancraen)
- Today:
  - Largest RP or AM service bureau (>85 RP/AM machines in one location; >300.000 parts/year in 2011)
  - Largest RP/AM software developer a world
- From 2 to 1000 persons (2011: Materialise Dental splits off)

1995: Mammoth Stereolithography machine (build capacity 2200 x 840 x 800mm)

Introducing AM activities of KU Leuven university



Softwares

Magics
(RP, RM, supports, ERP, e-software,...)

3-matic
(facetted CAD)

Mimics
(medical)

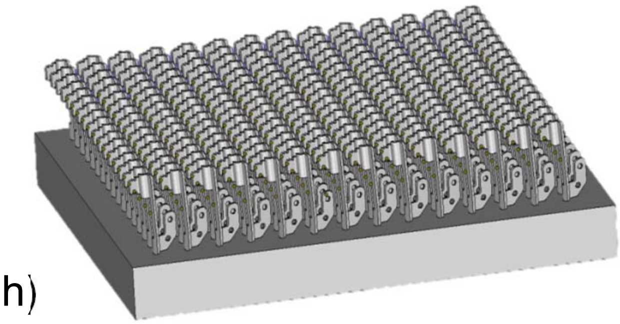
SurgiCase
(surgery planning)

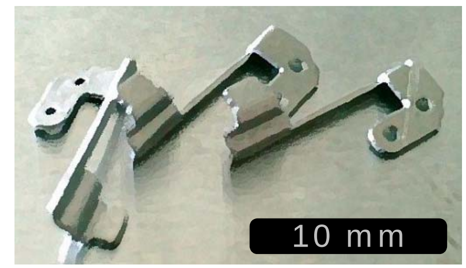
RSM
(hearing aids)

Etc.

Introducing AM activities of KU Leuven university

- **Company: LayerWise N.V., Leuven**
- Field: RP & AM of metalic products
- Spin-off of KU Leuven (Division PMA)
- Start: 2008 (Founders: P. Mercelis, J. Van Vaerenbergh)
- Today: 45 persons
- Production: > 20,000 metallic parts/year (2011)
- Activities:
  - Industrial, medical & dental applications (also artwork)
  - Several patents (dental and others)

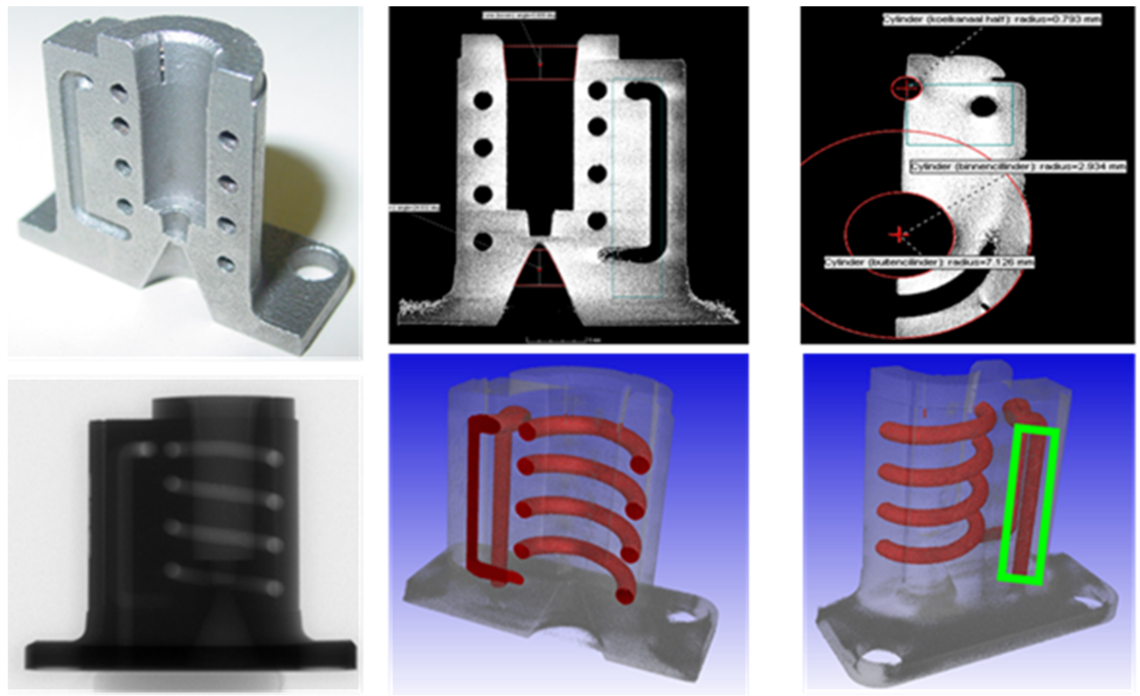




Introducing AM activities of KU Leuven university

- **Company: Metris N.V., Leuven** (since 2009 Nikon Metrology Europe N.V.)
- Spin-off of KU Leuven (Division PMA)
- Start: 1995 (Founders: B. Van Coppenolle, L. De Jonge)
- Today: 1000 persons
- **Activities:** (Reverse engineering), **3D coordinate metrology & quality control**
  - 3D CMM, laser scanning probes
  - **X-ray CT** for measuring **internal & external geometry** (tolerances) and **material quality** (e.g. porosity)

Industrial CT scanner (450 kV)



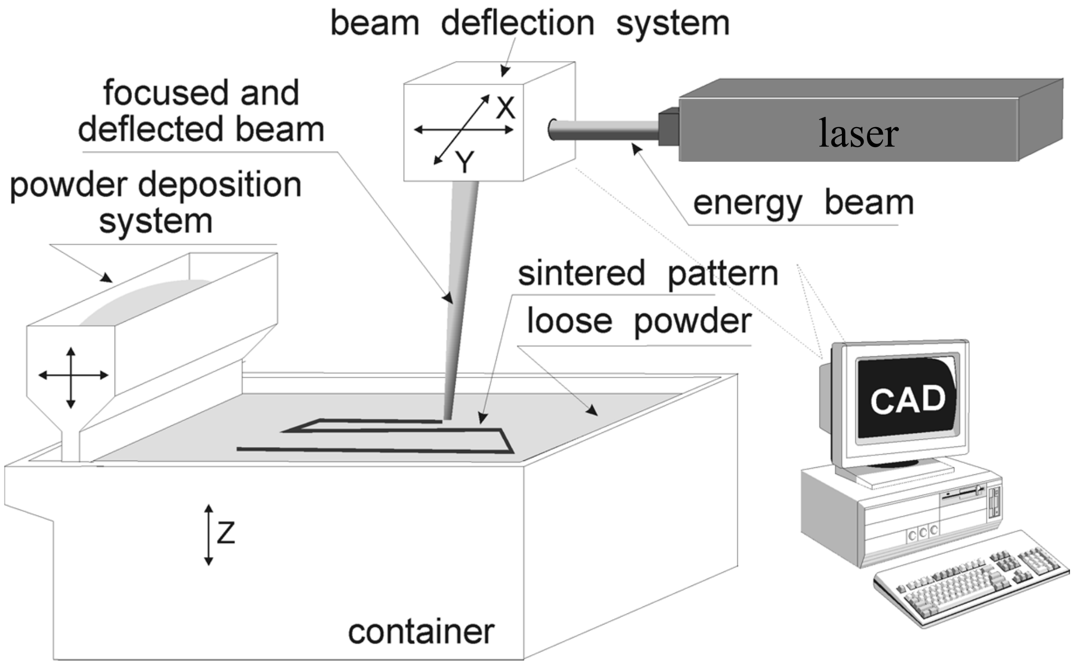
Materials and Processing Issues in Powder Bed Fusion Additive Manufacturing

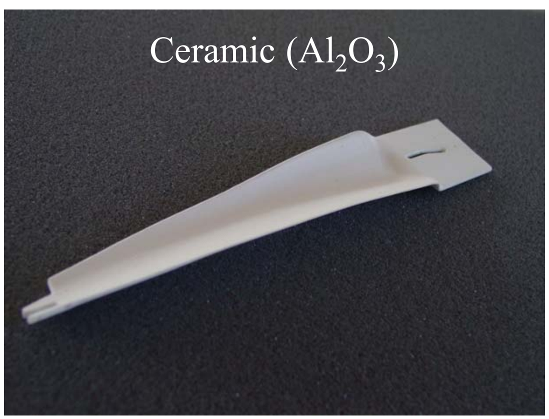
Prof. Dr. Ir. Jean-Pierre Kruth
KU Leuven university, Belgium

KATHOLIEKE UNIVERSITEIT
LEUVEN

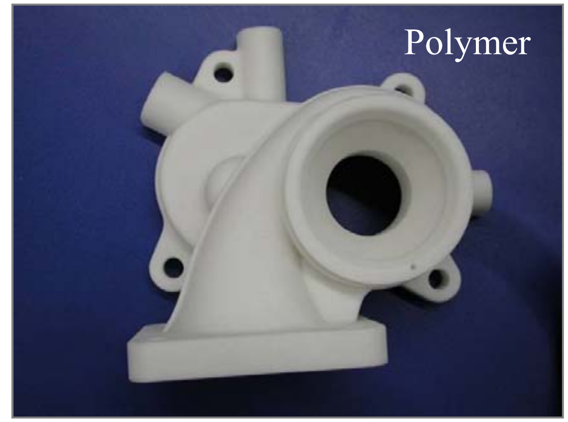
CIRP

Laser powder-bed fusion AM: SLS, SLM, …




Ceramic (Al_2O_3)


Composite (Cermet-HM)
(WC-Co infiltrated with Cu)


Polymer


Ferro Metal (Steel)

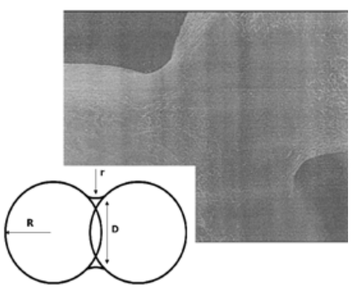
Non-ferro Metal (Ti)

Classification of binding mechanisms

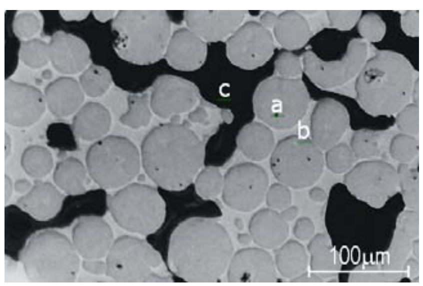
Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
  - 2.1 different binder and structural materials
    - 2.1.1 separate structural and binder particles
    - 2.1.2 composite particles
    - 2.1.3 coated grains particles
  - 2.2 no distinct binder and structural materials
    - 2.2.1 single phase material partially molten
    - 2.2.2 fusing powder mixture
- **3. Full Melting**
  - 3.1 single component single material
  - 3.2 single component alloyed material
  - 3.3 fusing powder mixture
- **4. Chemically Induced Binding**

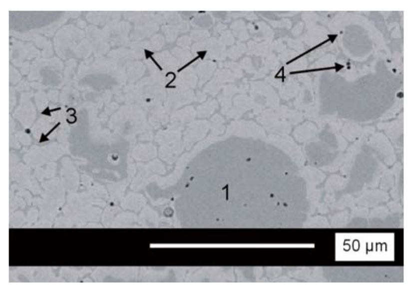
Solid State Sintering



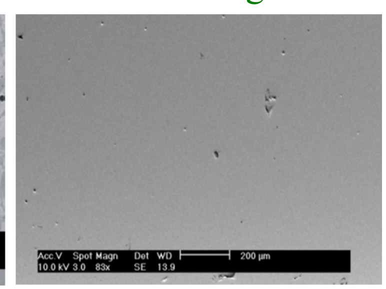
Liquid Phase Sintering



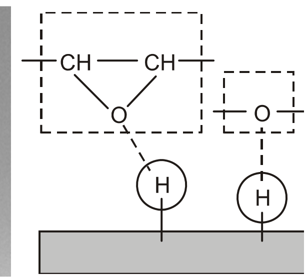
Partial Melting



Full Melting



Chemical binding



Main binding mechanisms for polymers

Polymers

Binding mechanism classification

- **1. Solid State Sintering**
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- **4. Chemically Induced Binding**

SLS elastomer

Polyamide (nylon)

Main binding mechanisms for metals

Metals

Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
  - 2.1 different binder and structural materials
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- **4. Chemically Induced Binding**

Steel

Titanium

Main binding mechanisms for ceramics

Ceramics

Binding mechanism classification

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- **4. Chemically Induced Binding**

Alumina

Main binding mechanisms for composites

Composites (cermets and others)

Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
  - 2.1 different binder and structural materials
    - 2.1.1 separate structural and binder particles
    - 2.1.2 composite particles
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  - 3.2 single component alloyed material
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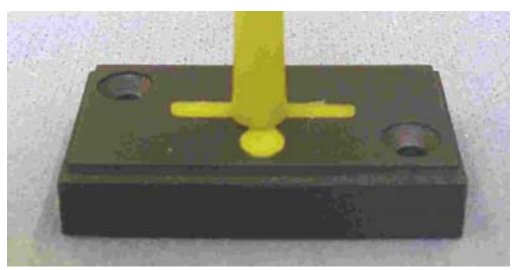
- **4. Chemically Induced Binding**

WC-Co (+ Cu) Cermet/HM



Cu-PA mold

Main binding mechanisms for polymers

Polymers

Binding mechanism classification

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- **4. Chemically Induced Binding**

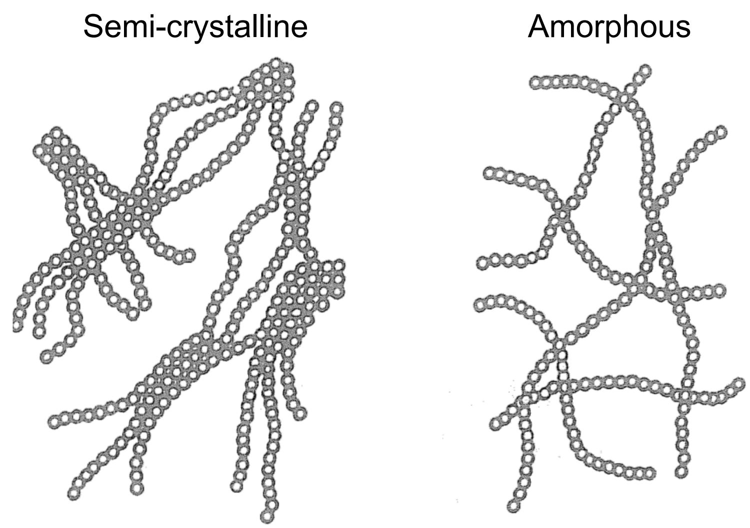
SLS elastomer

Polyamide (nylon)

Main distinction in SLS of polymers

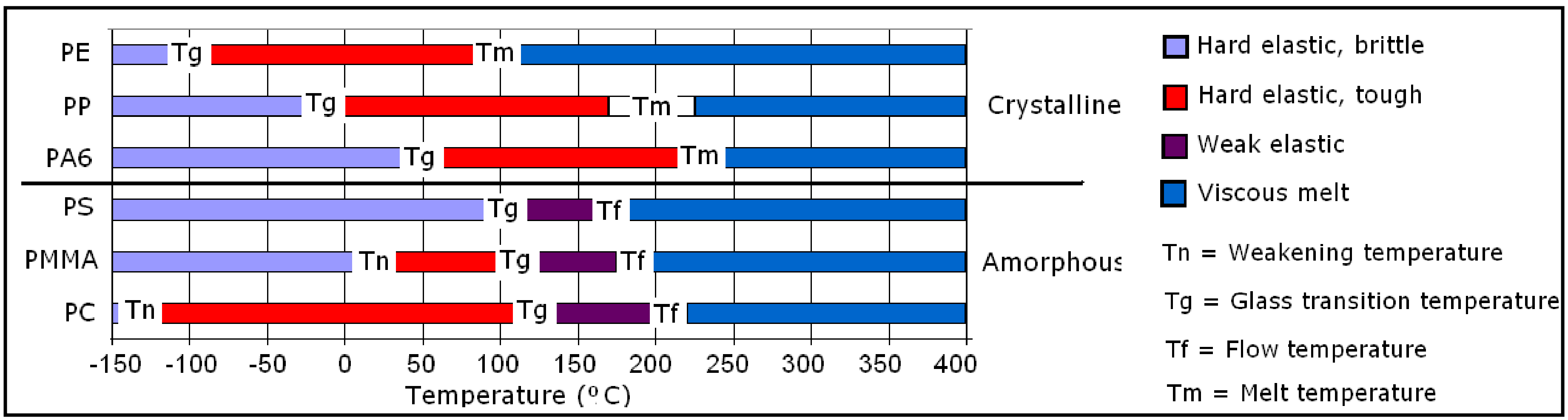
Mainly thermoplastics:

- (Semi-)crystalline
- Amorphous



Main SLS consolidation:

Partial or full <u>melting</u>



Main distinction in SLS of polymers

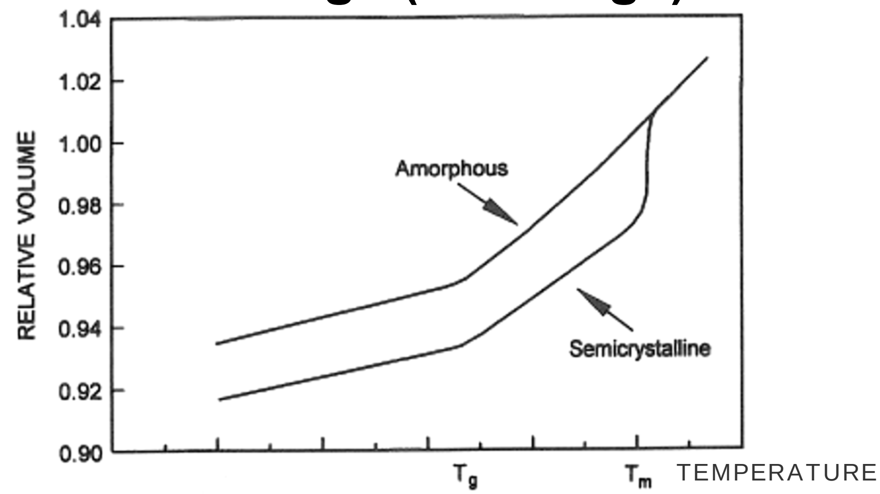
Mainly thermoplastics:

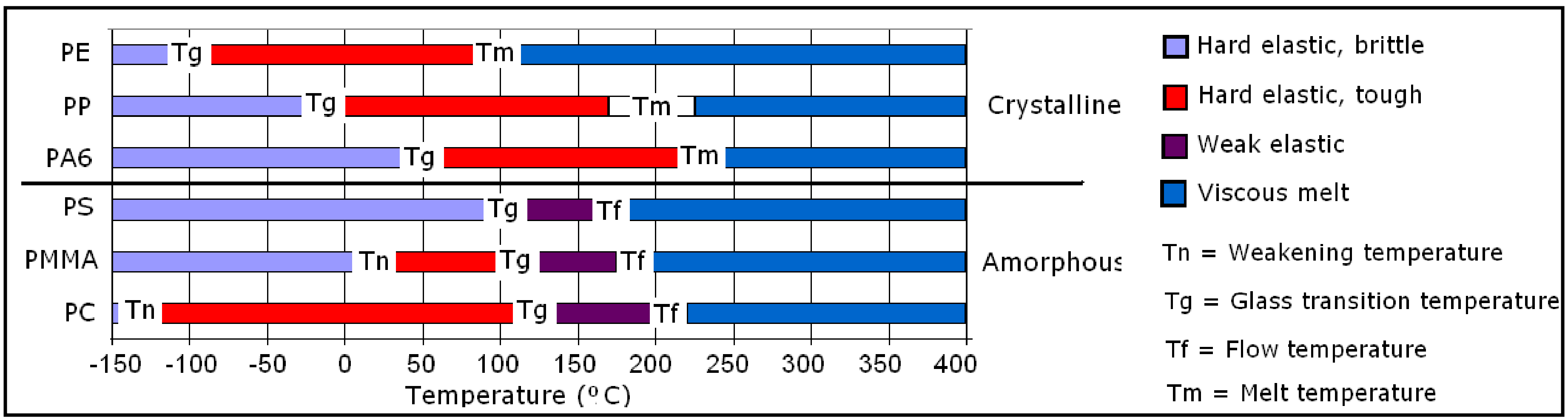
- (Semi-)crystalline
- Amorphous

Main SLS consolidation:

Partial or full <u>melting</u>

Volume change (shrinkage):





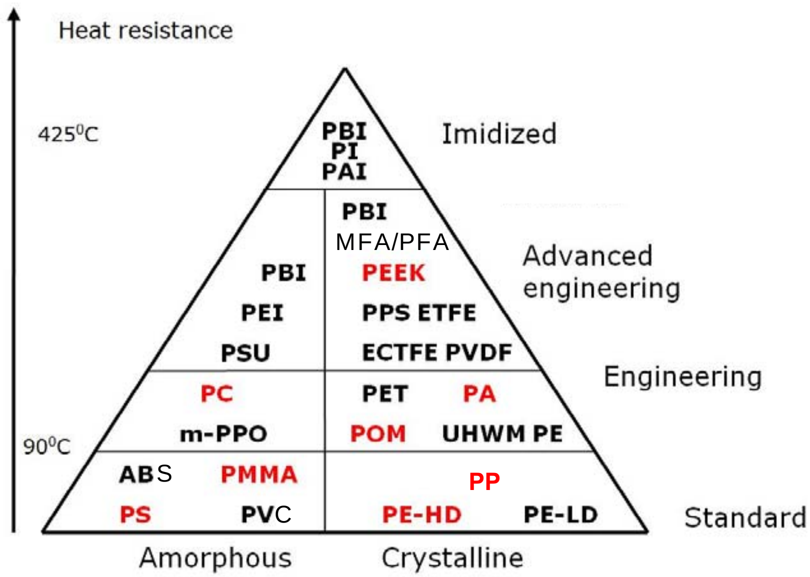
Polymers

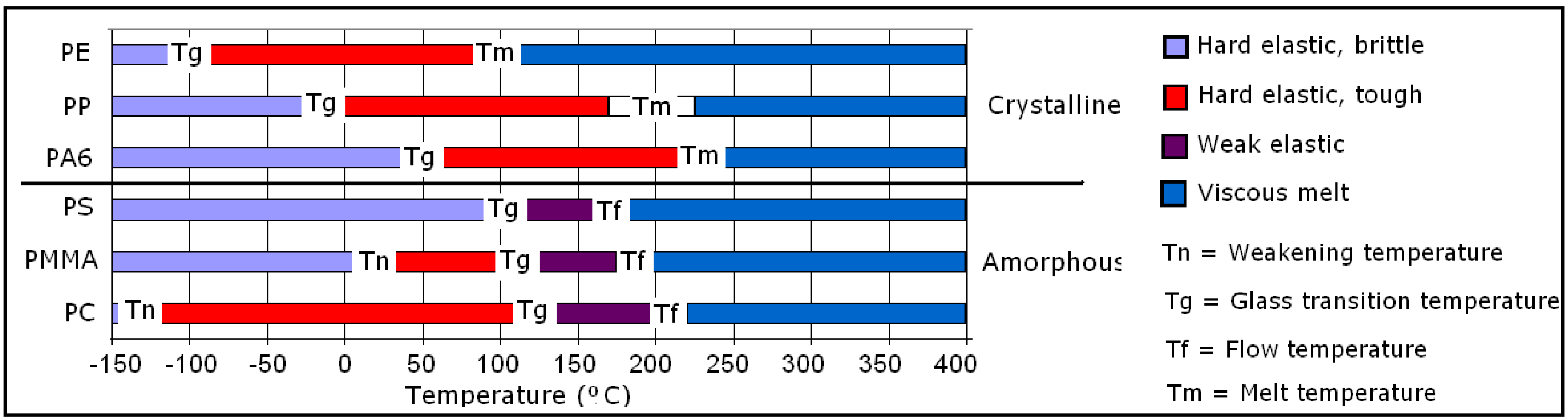
Main consolidation:

Partial or full melting

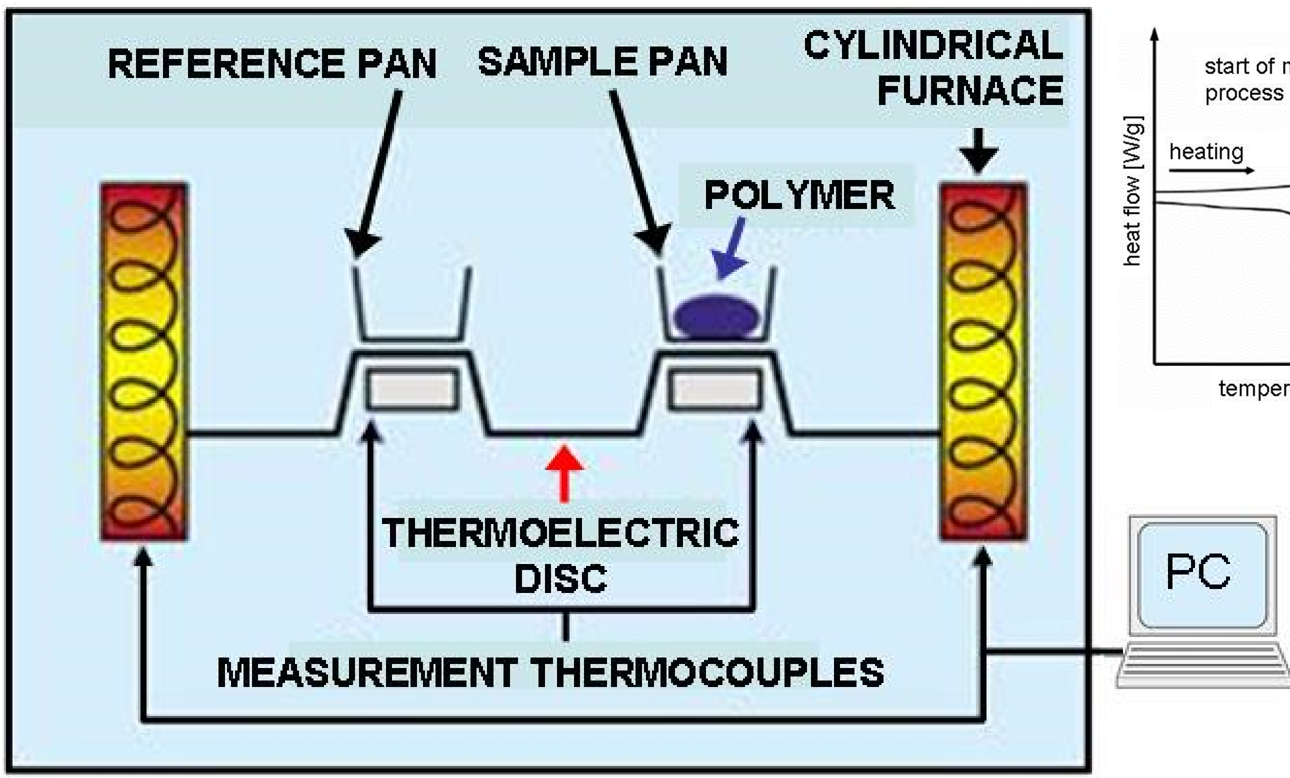
Major distinction:

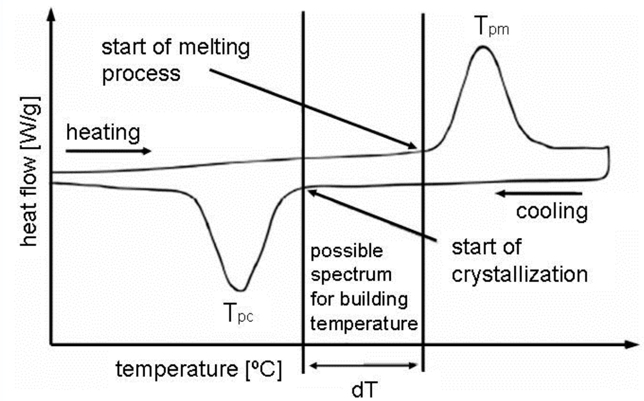
- (Semi-)crystalline
- Amorphous





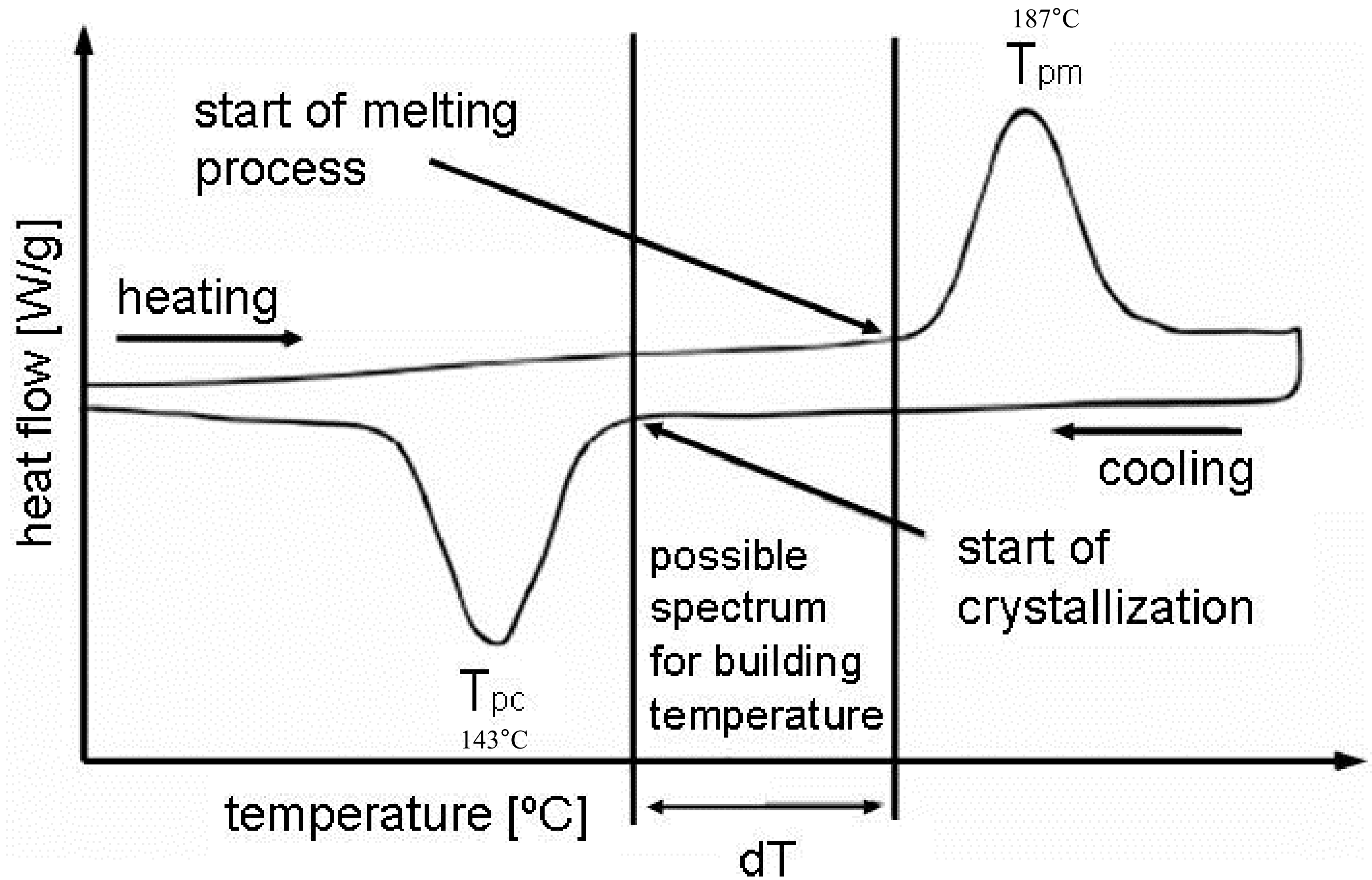
Differential Scanning Calorimetry (DSC)





DSC curve: melting & recristalisation peaks

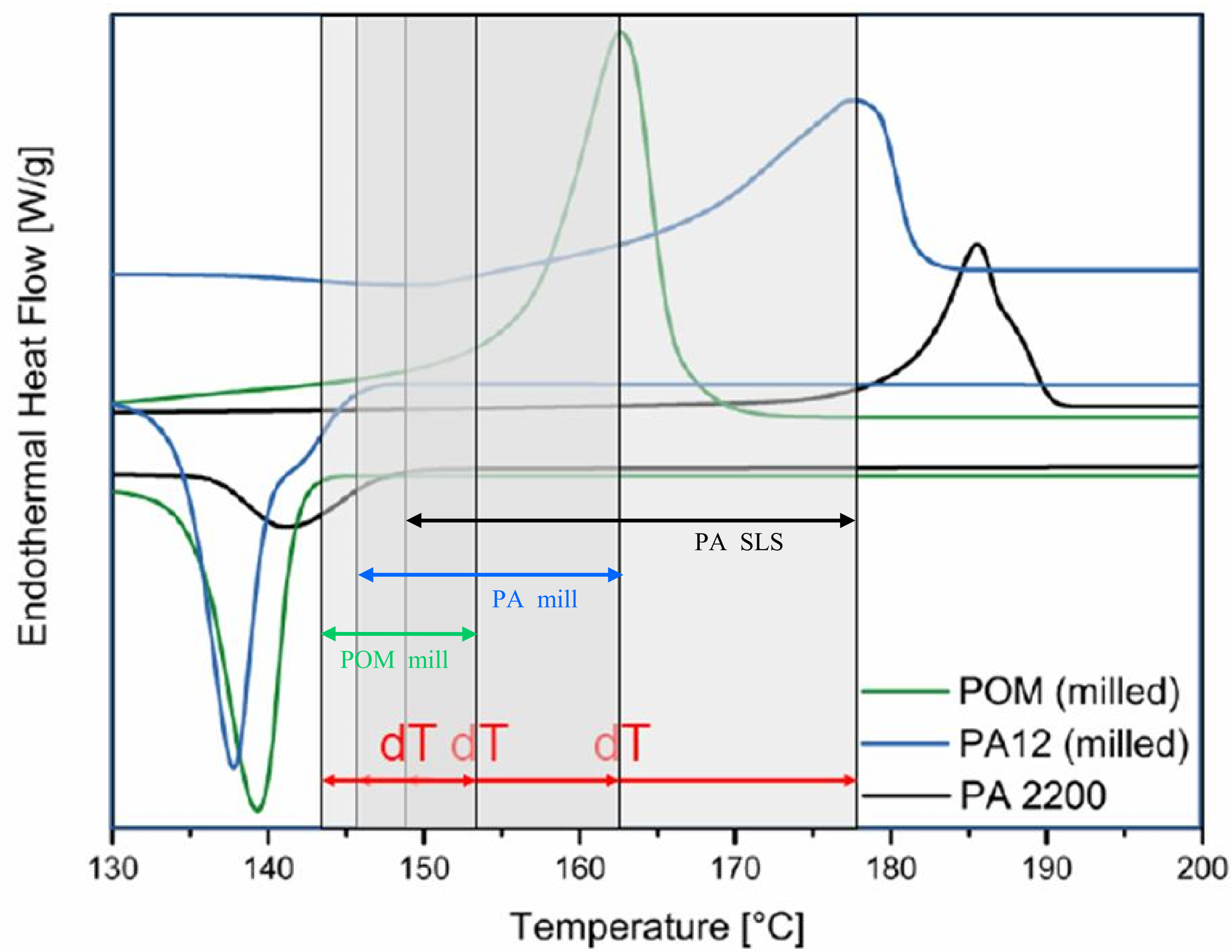
- DSC curve for PA12 (Differential Scanning Calorimetry)



Semi-crystalline polymers – DSC curves

Comparison of DSC curves:

- PA12 for SLS (PA 2200)
- PA12 milled
- POM milled

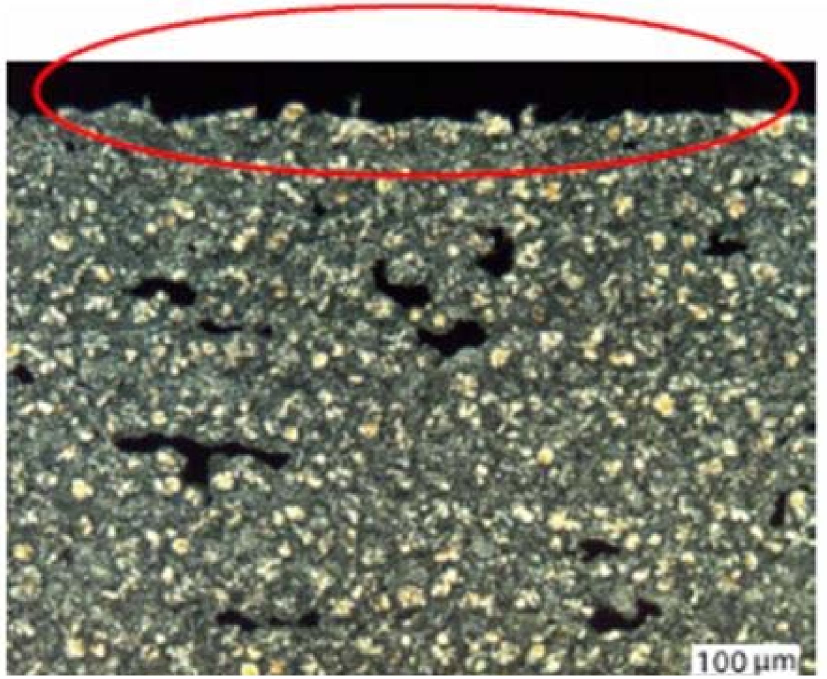


Source: University Erlangen

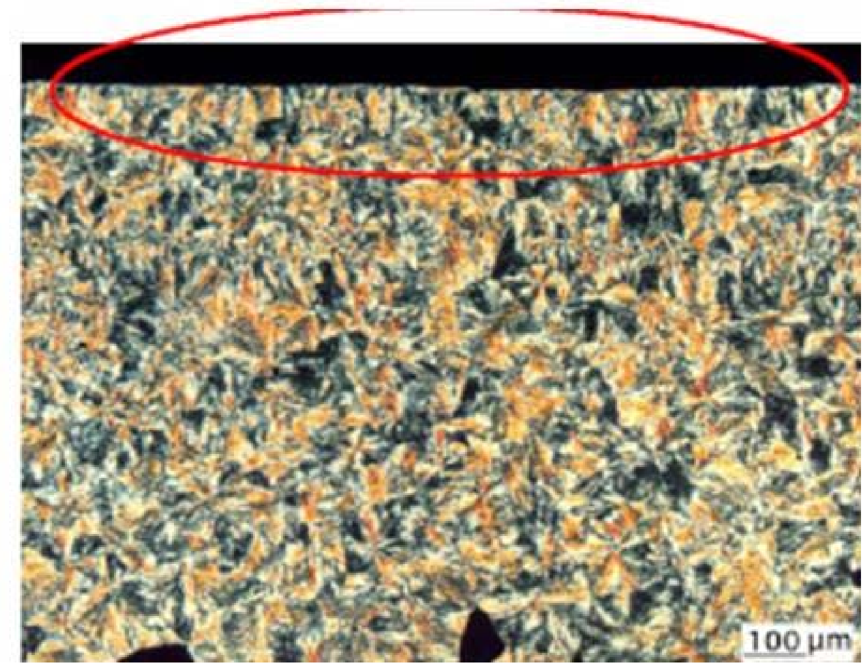
SLS of Semi-crystalline plastics (e.g. POM)

Transmission light microscopy images of microtome sections

PA (rough surface)



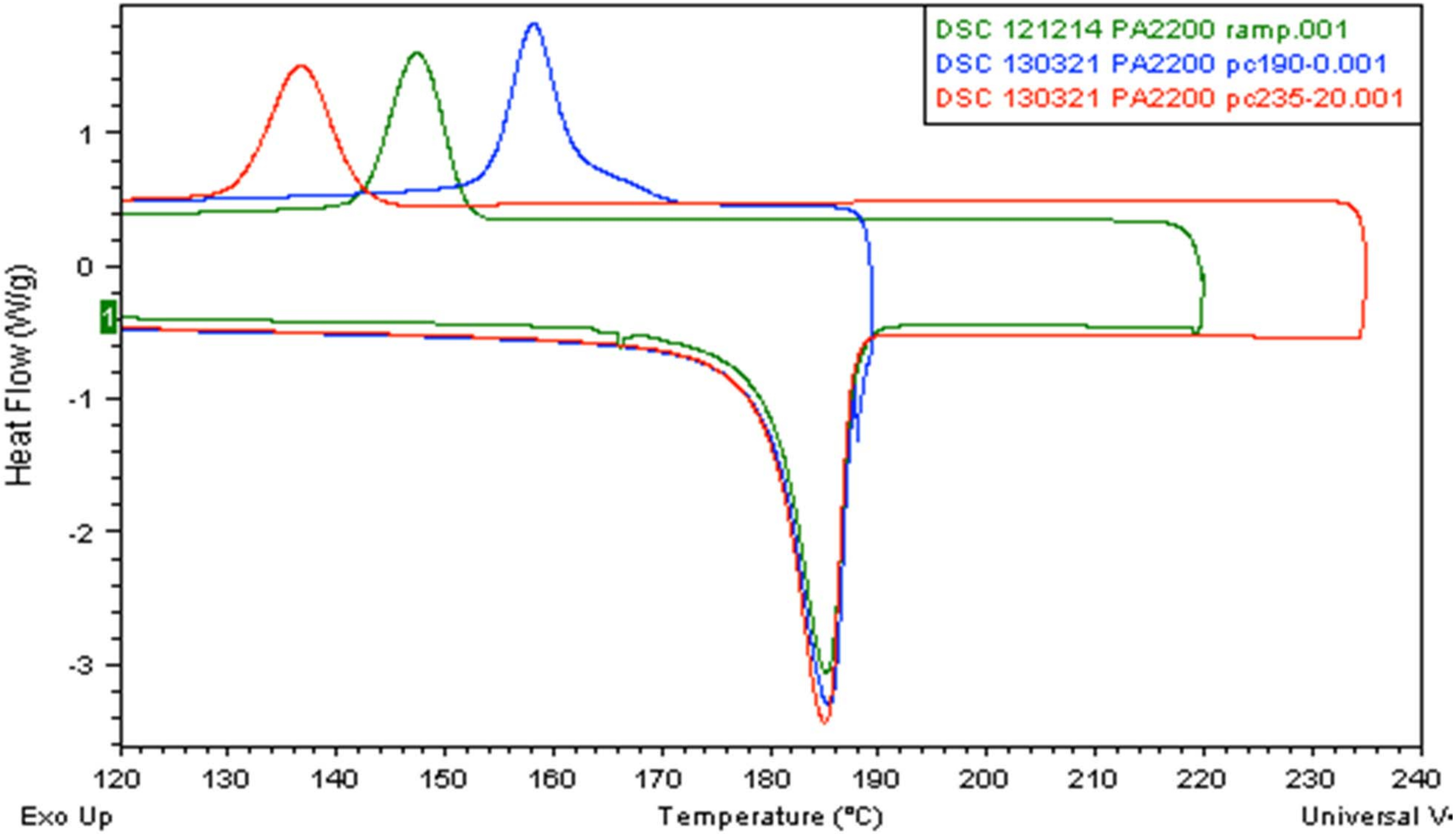
POM (smooth surface)



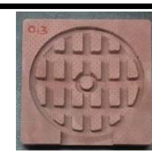
Source: University Erlangen

DSC curve: melting & recristalisation peaks

- DSC curve for PA12 (Differential Scanning Calorimetry)

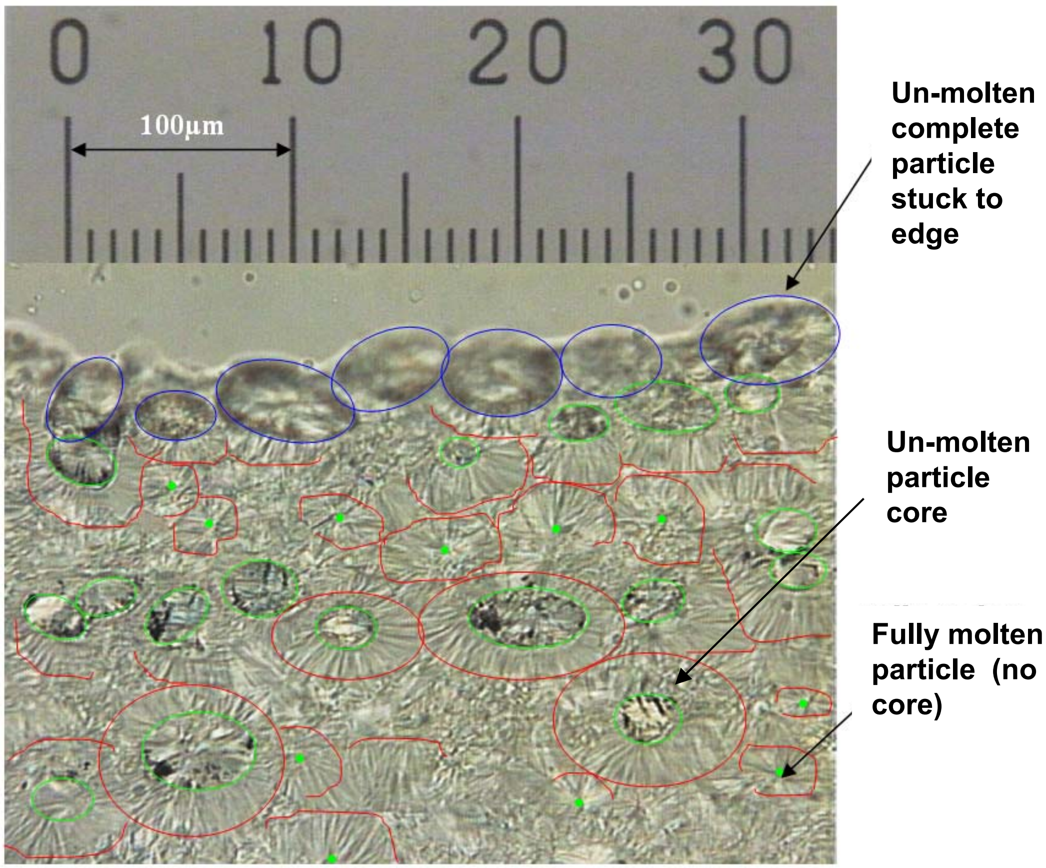


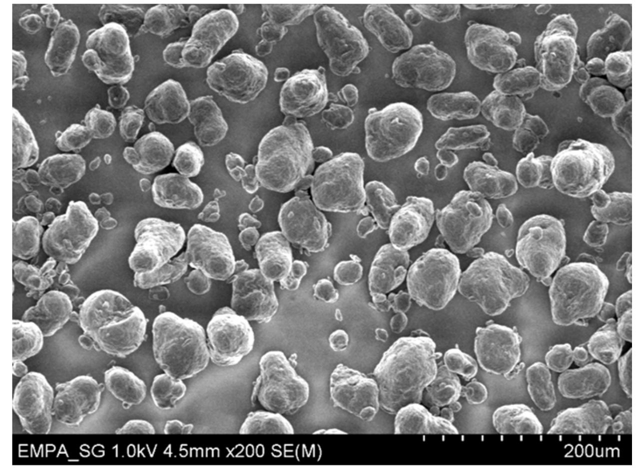
Polymers: types and applications

Polymer powder material	Application field	Example	Main properties
Semi Crystalline Polymers e.g. PA-12	(Semi-)Rigid **polymer parts**		Long term useable
Amorphous Polymer e.g. PS	Investment Casting Lost **patterns**		Accurate Partially porous
Sacrificial Polymers used as binder e.g. PMMA	**Metal or Ceramic Parts**		Thermally degradable amorphous polymers
Filled Semi Crystalline Polymers e.g. PA-GF, PA-Al, PA-Cu	Parts with **special properties**		Long term useable Can withstand high loads
Elastomeric Polymers e.g. Polyester	**Elastic parts**		Long term useable
Polymer-Polymer Blends	Emerging Extreme Applications		
Thermo-setting Polymers e.g. epoxy resin			

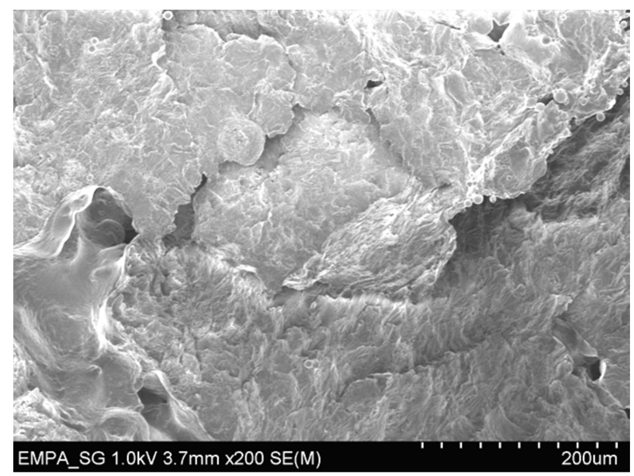
Polymers 1: Semi-crystalline (e.g. PA12)

Partial or full melting





Loose un-sintered PA-12 powder



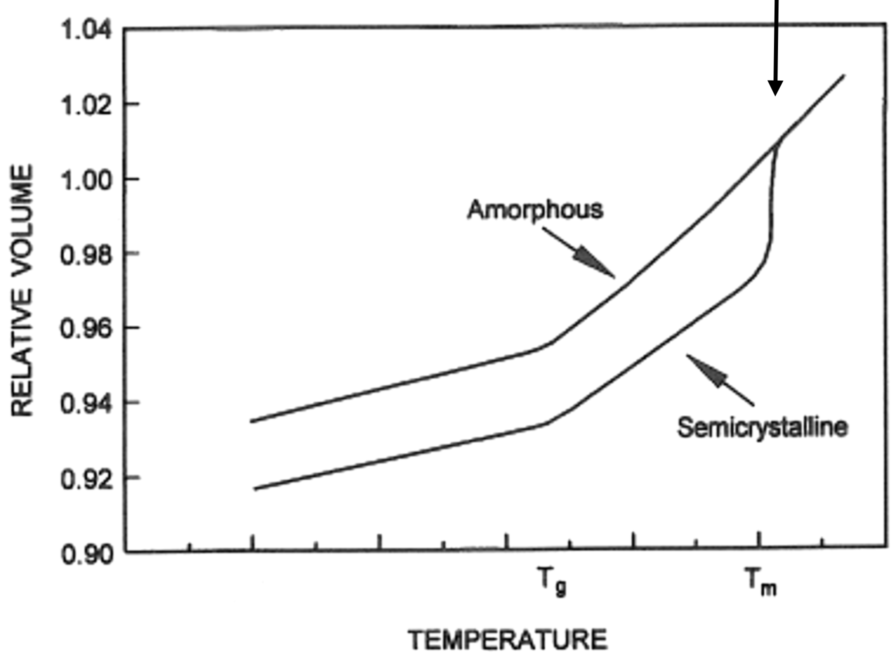
Tensile break surface showing some air voids

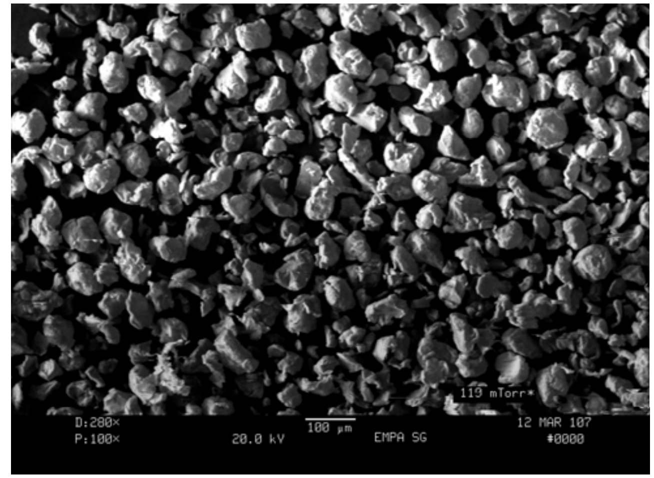
Polymers 2: Amorphous (e.g. PS)

Partial melting

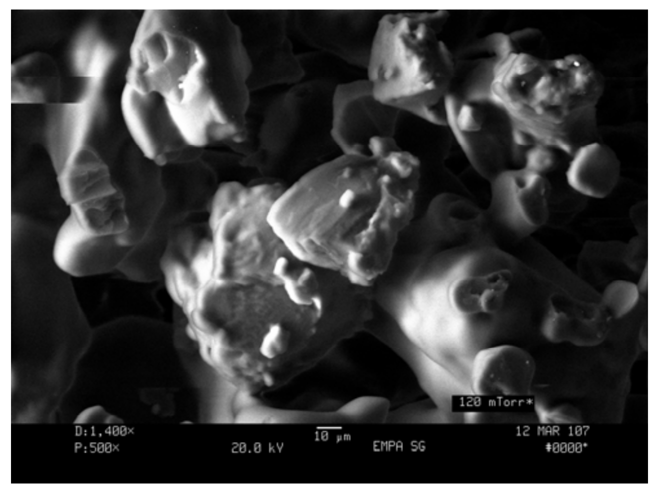
Low strength: only partial consolidation

Better accuracy: no sudden shrink (jump) when solidifying (crystalline shrink at T_m)





Loose un-sintered PS powder

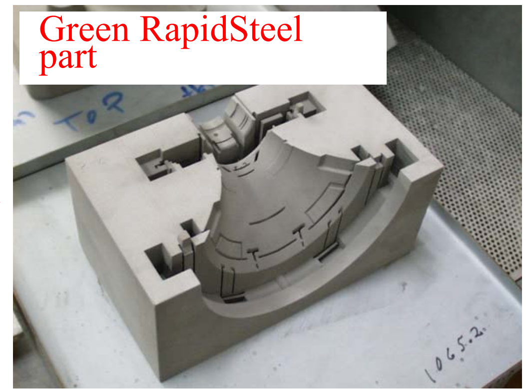


Tensile break surface showing some air voids

Polymers 3: Debindable polymers (e.g. amorph. PMMA)

Partial melting / LPS

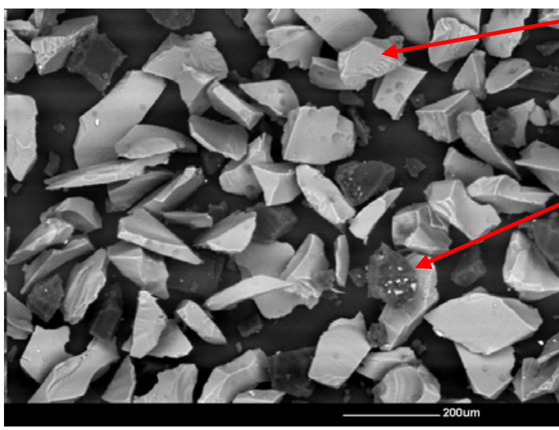
- Thermal debinding (depolymerisation) should occur in furnace at 350°-450°C, while not occurring during SLS
- Suited polymers: PMMA or MMA-BMA co-polymers, PA, PP
- May involve some cross-linkers (thermosetters)



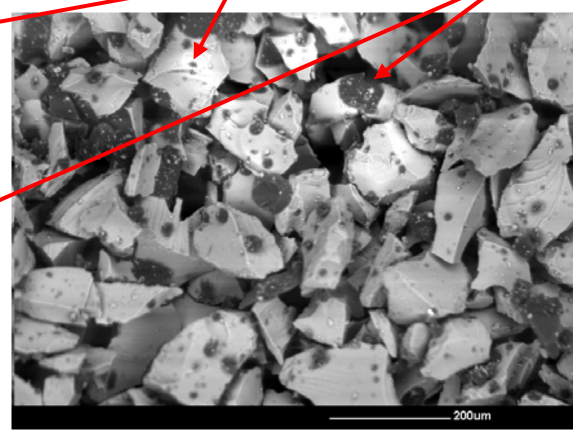
Examples:

- Steel (RapidSteel, Laserform)
- AW glass ceramics (Dalgarno)

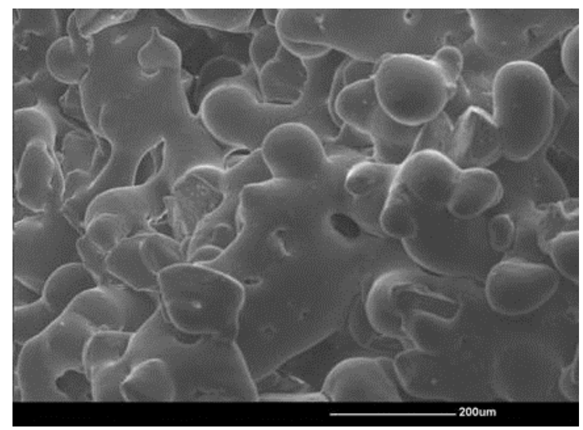
AW glass ceramic + MMA-BMA



Powder mixture



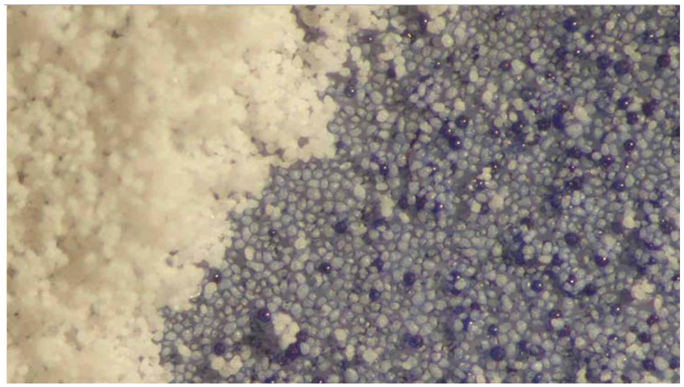
Green part (i.e. after SLS)



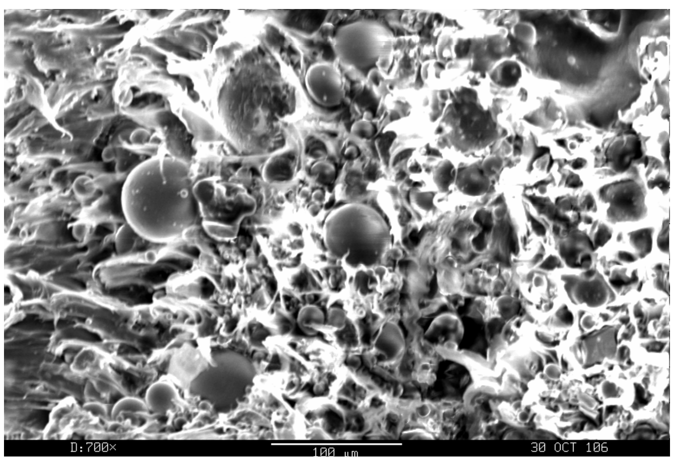
Brown part (i.e. after debinding & firing)

Polymers 4: Reinforced polymers (e.g. PA-GF)

Partial melting / LPS



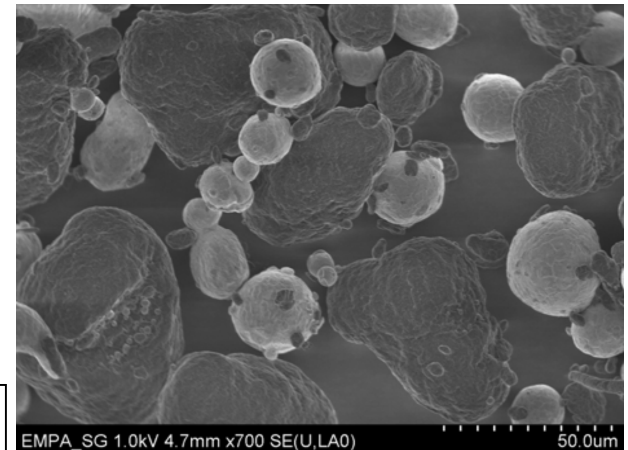
Loose un-sintered **PA-Glass** powder



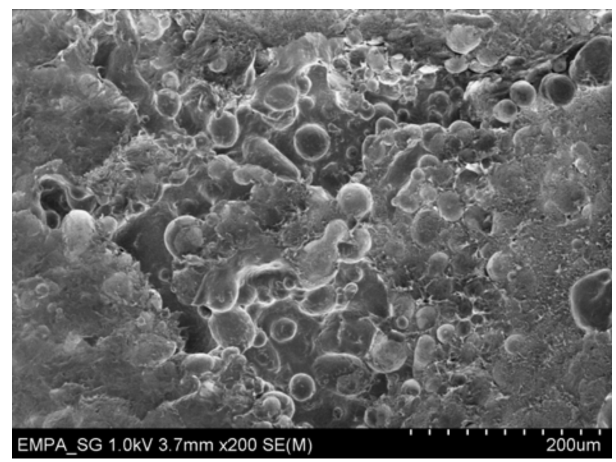
Tensile break surface showing some air voids

Polyamide + Glass beads

Polyamide + Alu beads



Loose un-sintered **PA-Al** powder (30% Al)



Tensile break surface showing some air voids

Polymers 4: Reinforced polymers (e.g. PA-Cu)

Partial melting / LPS

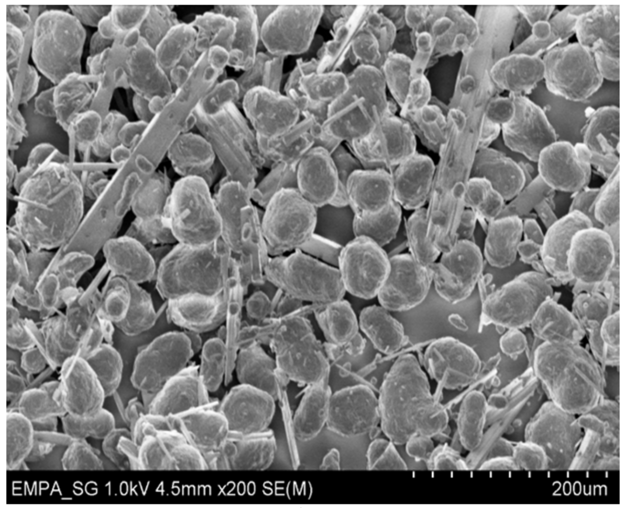
Injection mold made from
Cu-filled Polyamide and
Polypropylene molded parts
(injected at 2.76 MPa and 230°C)

Polymers 4: Reinforced polymers (long fillers)

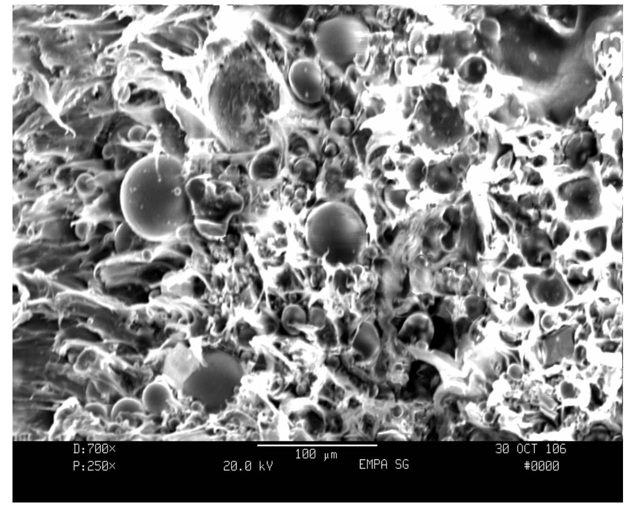
Polyamide (nylon) with elongated filler

Source: FHSG - Valspar

Elongated fibers (new)



Spherical glass particles (old)

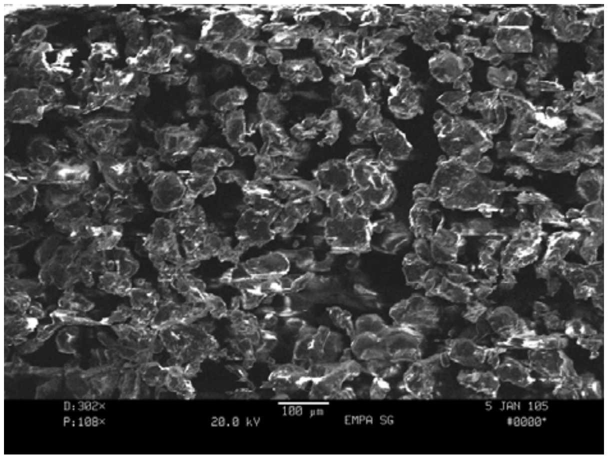


Property	DF-M*	3D PA	3D GF	3D AF
Tensile strength (MPa)	49.00	43.00	27.00	35.00
Tensigle elongation %	5.00%	14.00%	1.50%	1.50%
Tensigle Modulus (MPa)	5376	1586	4068	3960
HDT [1.82 Mpa]	165	95	134	137

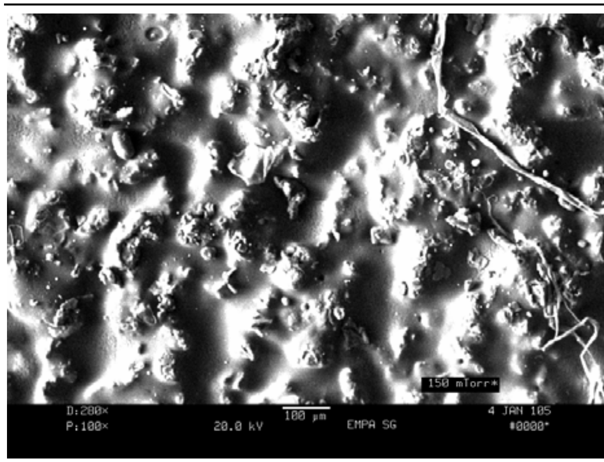
Polymers 5: Elastomeric polymer (e.g. polyester)

Partial melting

Polyester-based elastomer



Green part
(i.e. after SLS and
without infiltration)

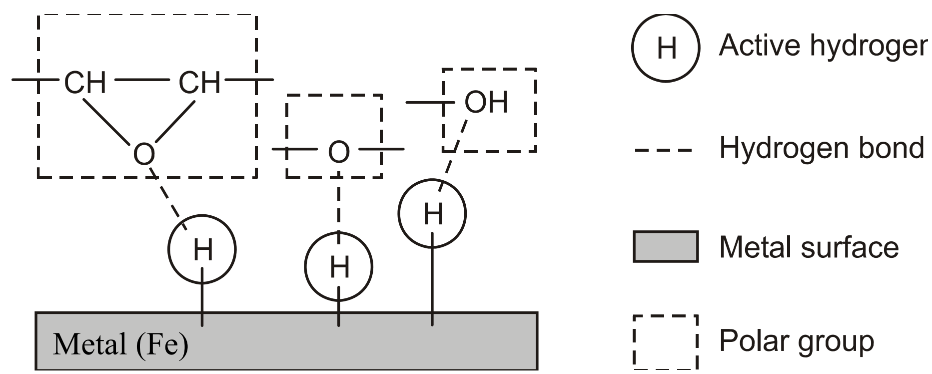


Part after
infiltration with
polyurethane

Polymers 6: Others (polymer blends, thermosets)

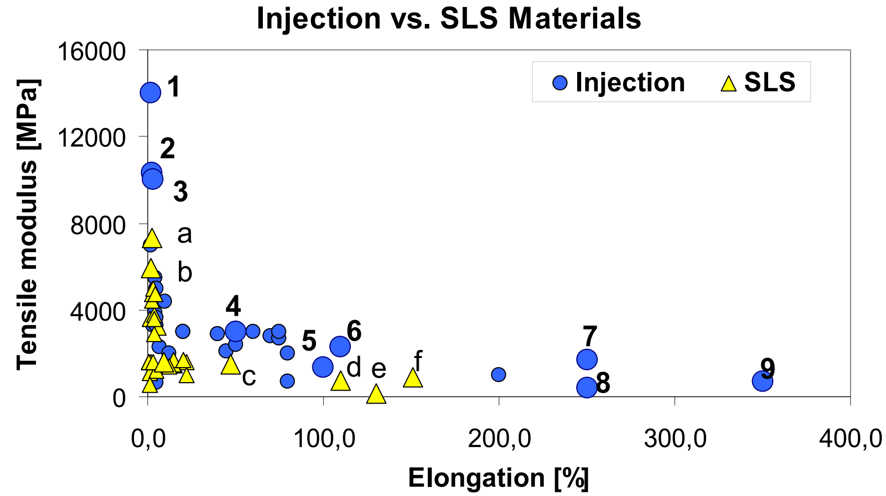
- **Polymeric blends**: Partial melting
  - Multiphase materials → tuned microstructure!
  - Example 1: mixed PA – HDPE (80/20, 50/50, 20/80 wt%)
  - Example 2: polymer 1 coated with low melting (thermoplastic) polymer 2 (T_m<70°C, e.g. polyvinyl acetal, heptadecanoic acid,…)

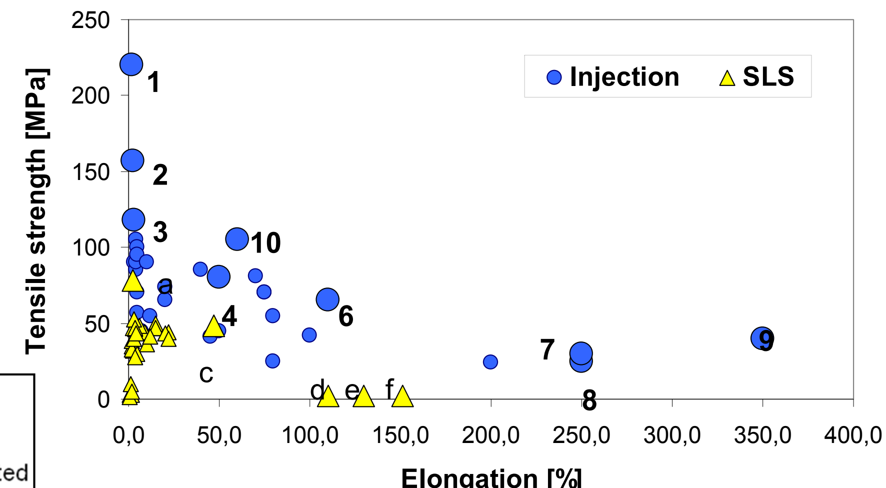
- **Thermosetting materials**: Chemical binding
  - E.g. mixture epoxy-iron
  - Hydrogen bounds between polar O^- from resin and H^+ on iron surface



Polymers: Conclusion

- **Different classes of polymers covered**
  - Semi-crystalline
  - Amorphous
  - Debindable
  - Filled polymers
  - Elastomeric
  - Polymer-polymer blends
  - Thermosetting
- **Scope of applicable polymers still limited**
  - Still mainly PA (plain or filled)
- **Good, but no extreme properties**





INJECTION				SLS			
1	Grivory HTV	6	PC	a	Windform PROB	d	DuraForm Flex
2	Peek c	7	ECTFE a	b	DuraForm GF	e	SOMOS 201
3	Peek b	8	PTFE	c	DuraForm Ex	f	DuraForm Flex infiltrated
4	PA 6	9	PEUHMW				
5	PP a	10	PEI				

Metals

Metals

Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
  - 2.1 different binder and structural materials
    - 2.1.1 separate structural and binder particles
    - 2.1.2 composite particles
    - 2.1.3 coated grains particles
  - 2.2 no distinct binder and structural materials
    - 2.2.1 single phase material partially molten
    - 2.2.2 fusing powder mixture
- **3. Full Melting**
  - 3.1 single component single material
  - 3.2 single component alloyed material
  - 3.3 fusing powder mixture
- **4. Chemically Induced Binding**

Steel

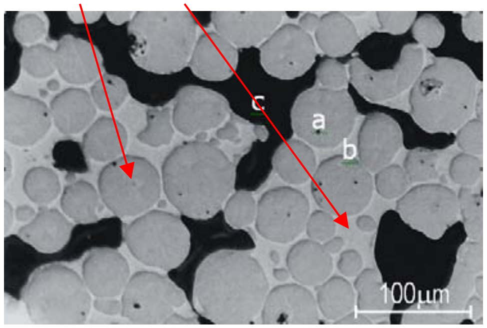
Titanium

Metals 1: Liquid Phase Sintering (different materials)

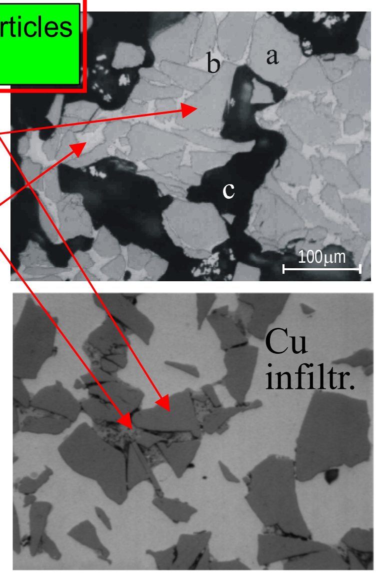
Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
  - 2.1 different binder and structural materials
    - 2.1.1 separate structural and binder particles
    - 2.1.2 composite particles
    - 2.1.3 coated grains particles
  - 2.2 no distinct binder and structural materials
    - 2.2.1 single phase material partially molten
    - 2.2.2 fusing powder mixture
- **3. Full Melting**
- **4. Chemically Induced Binding**

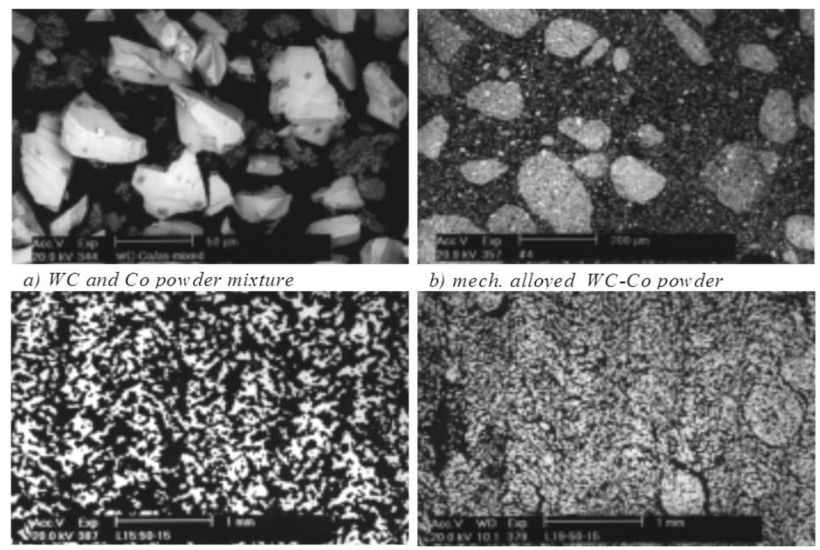
Steel + Cu



WC + Co



WC + Co



a) WC and Co powder mixture

b) mech. alloyed WC-Co powder

c) sintered powder mixture

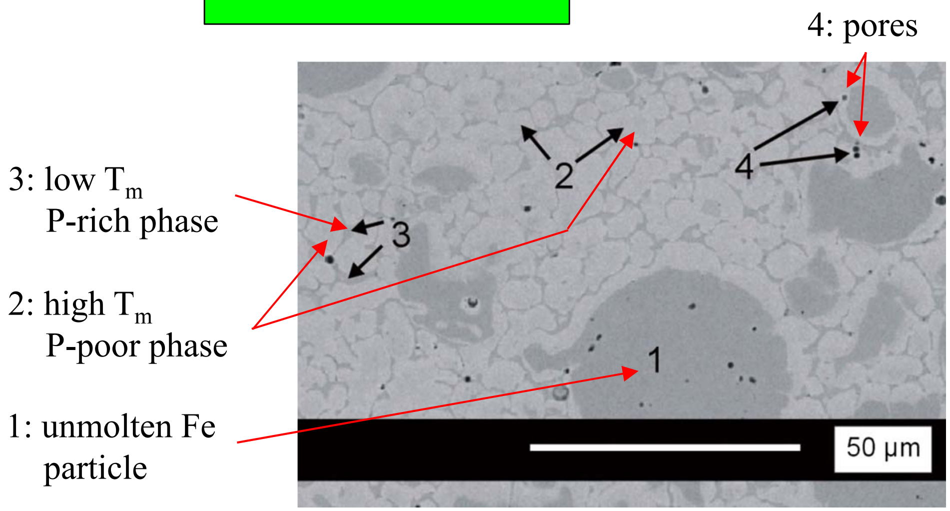
d) sintered mech. alloyed WC-Co powder

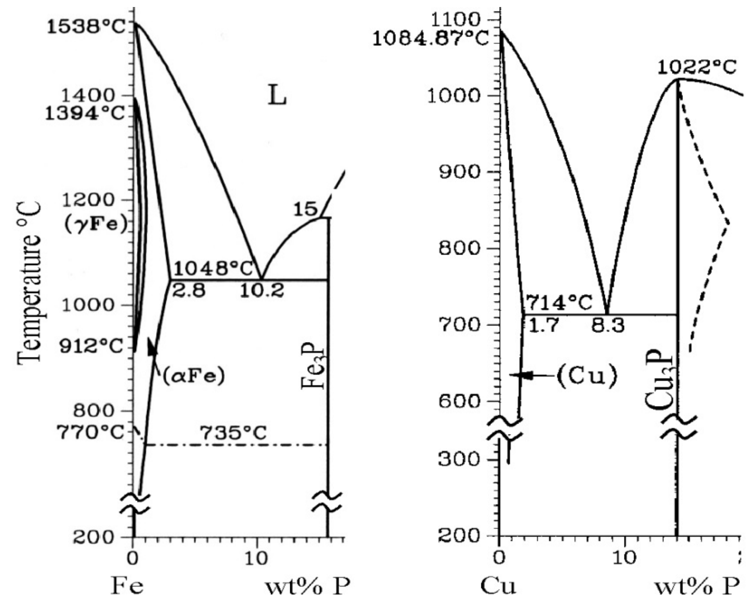
Metals 2: LPS / Partial melting (no distinct materials)

Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
  - 2.1 different binder and structural materials
    - 2.1.1 separate structural and binder particles
    - 2.1.2 composite particles
    - 2.1.3 coated grains particles
  - 2.2 no distinct binder and structural materials
    - 2.2.1 single phase material partially molten
    - 2.2.2 fusing powder mixture
- **3. Full Melting**
- **4. Chemically Induced Binding**

Fe-Fe_3P-Ni-Cu powder mixture

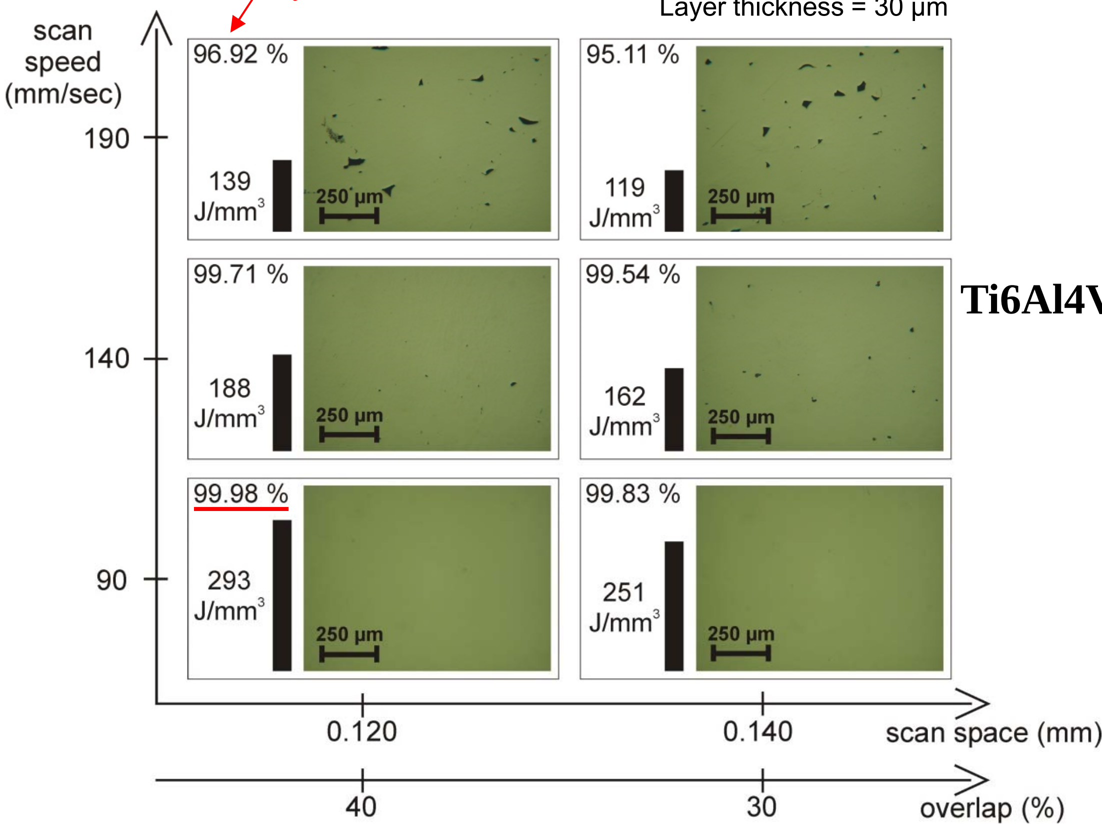




Metals 3: Full Melting (e.g. Titanium)

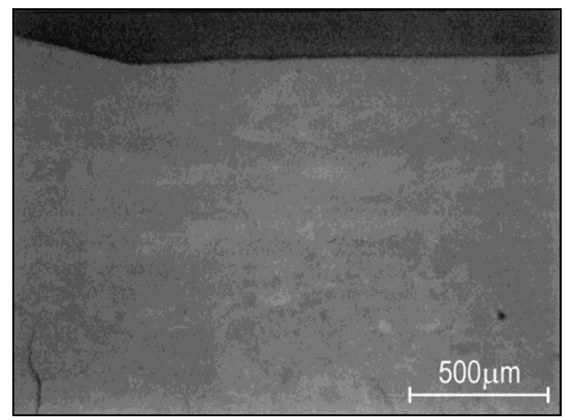
Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
- **3. Full Melting**
  - 3.1 single component single material
  - 3.2 single component alloyed material
  - 3.3 fusing powder mixture
- **4. Chemically Induced Binding**



Ti6Al4V

Pure Ti (CP Ti)



Metals 3: Full Melting (e.g. Titanium)

Binding mechanism classification

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  - 3.1 single component single material
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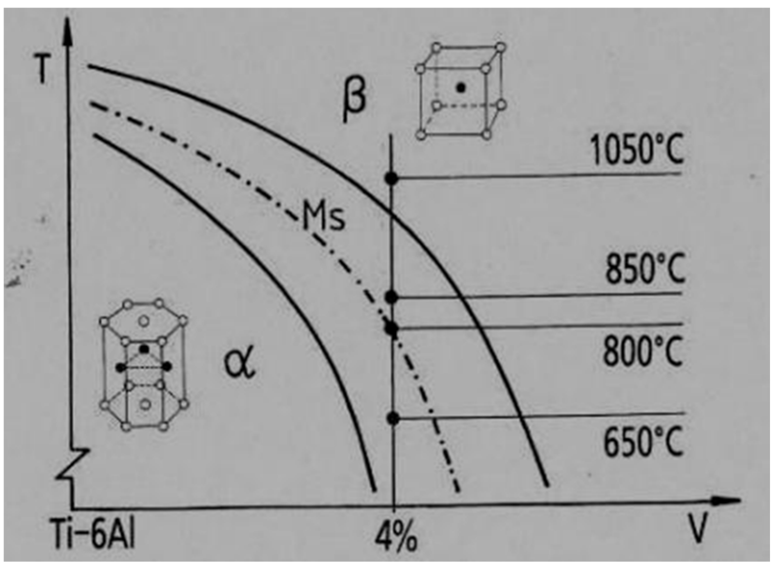
  - 3.3 fusing powder mixture
- **4. Chemically Induced Binding**



Ti6Al4V

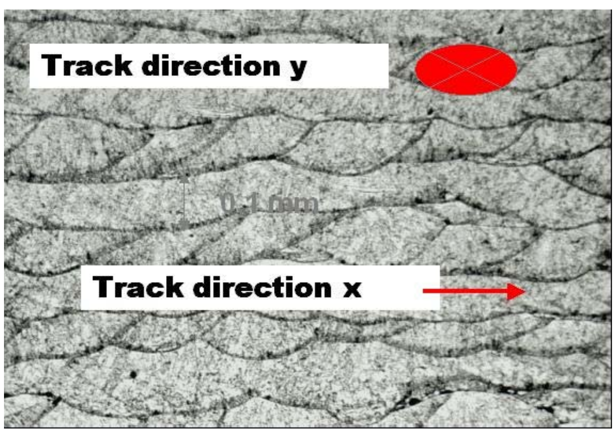
Ti6AlV4	SLM		Bulk annealed
Density [kg/m^3]	4415	≈	4430
Hardness [Vickers]	405	>	350
Yields strength [MPA]	1125	>	1035
UTS [MPa]	1250	>	1035
Elongation [%]	6	<	11
E modulus [GPa]	94	<	114

Metals 3: Full Melting (e.g. Fe alloys)

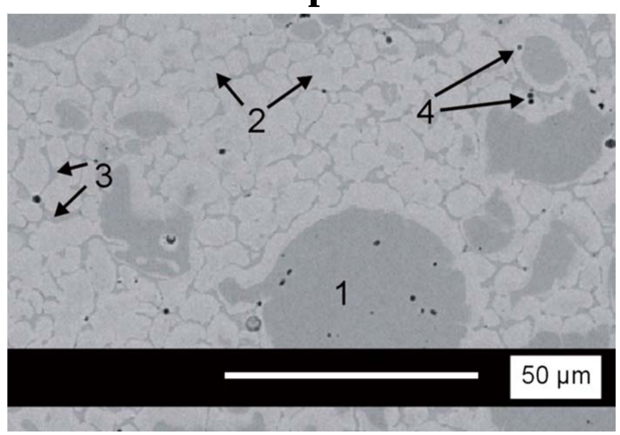
Binding mechanism classification

- 1. Solid State Sintering
- 2. Liquid Phase Sintering Partial Melting
- 3. Full Melting
  - 3.1 single component single material
  - 3.2 single component alloyed material
  - 3.3 fusing powder mixture
- 4. Chemically Induced Binding

Stainless steel 316



Fe-Fe3P-Ni-Cu powder mixture



Metals 4: Chemical binding (e.g. Al, reinforced Cu)

Binding mechanism classification

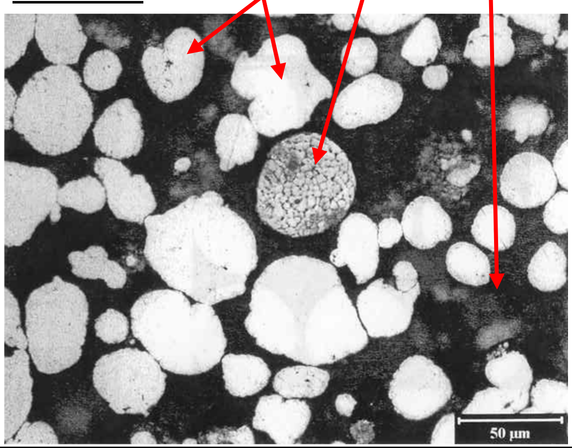
1. Solid State Sintering
2. Liquid Phase Sintering Partial Melting
3. Full Melting
4. Chemically Induced Binding

Cu-based composite:

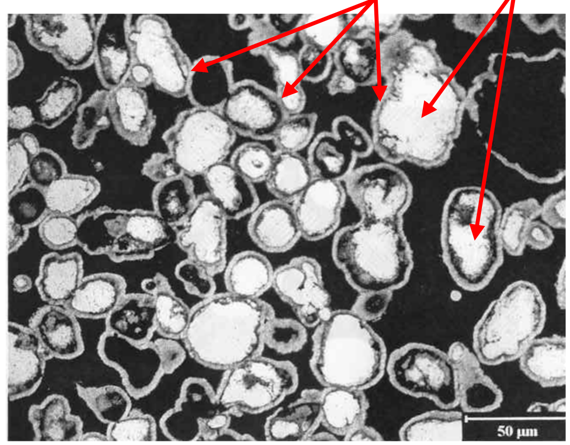
Cu + Ti + C → TiC + heat for fusing Cu

SLS of Aluminium:

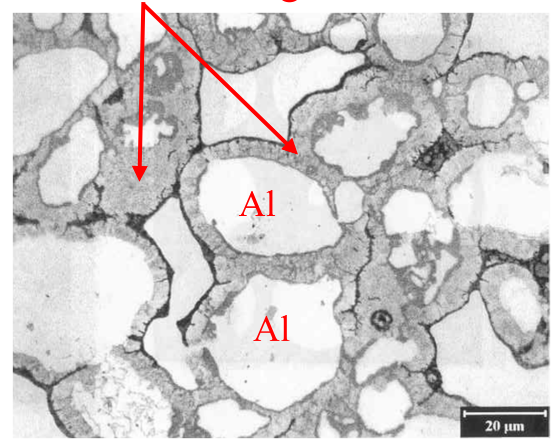
Powder: Al Mg Polymer binder



Chemically bounded skeleton in N_2 atmosphere: AlN Al



After infiltration with eutectic Al-13.8Si-4.7Mg infiltrant:



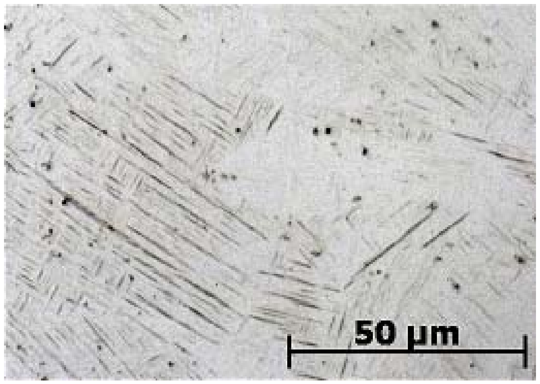
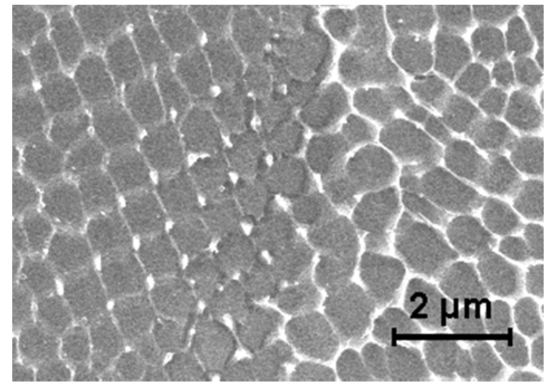
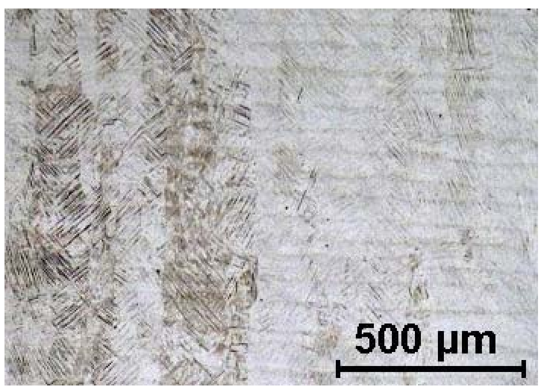
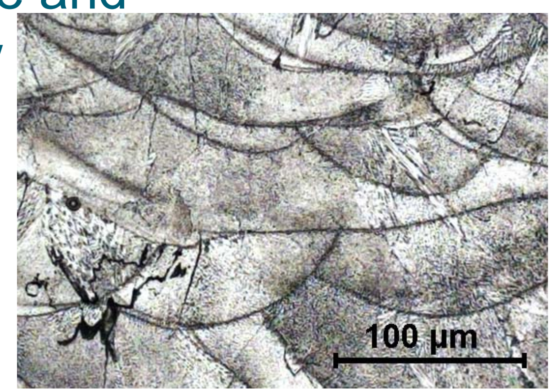
Mechanical properties of metals

() Conventional material (not heat treated)*

Alloy	Hardness	Charpy Impact	E-modulus	Tensile Strength	Elongation
Titanium alloy Ti6Al4V	410HV (396HV)*	11,5±0,5J (21J)*	96GPa (114GPa)*	1250MPa (1170MPa)*	6% (14%)
Stainless Steel 316L		59,2±3,9J (160J)*		719MPa (515MPa)*	51% (60%)
Maraging Steel 18Ni300	390HV (324HV)*	10,1±1,4J (18J)*	163GPa (180GPa)*	1290MPa (1000MPa)*	1,6% (12%)*
Aluminium alloy AlSi10Mg	127HV (86HV)*		56GPa (71GPa)*	396MPa (317MPa)*	2,75% (3,5%)*
Tool steel M2	760HV (250HV)*		110GPa (150GPa)*	300MPa (750MPa)*	0,35% (15%)*
Tantalum (Cold Worked)*	207HV (200HV)*		168GPa (186Gpa)*	513MPa (900MPa)*	29%
Cobalt Chroom	392HV (477HV)*		169GPa (207GPa)*	963MPa (925MPa)*	20% (5%)*

Other materials: Ni alloys (Inconel, Hastelloy), Pure CP-Ti, β-Ti, Nitinol, W, …

Mechanical properties: microstructure

	Ti6Al4V	CoCrMo
Micro	• Fine, needle-like martensitic α' • HCP  	• Fine, cellular α-Co • FCC 
Macro (side view)	• Elongated prior β grains in the build direction  	• Melt tracks clearly visible in both side and top view 

Mechanical properties – Heat treatments

- Heat treatments after SLM of Ti6Al4V

	T [°C]	t [h]	Cooling Rate	E [GPa]	σ_y [MPa]	UTS [MPa]	$\varepsilon_{failure}$ [%]
1	*540*	*5*	*WQ*	112.6 ± 30.2	1118 ± 39	1223 ± 52	5.36 ± 2.02
2	*850*	*2*	*FC*	114.7 ± 3.6	955 ± 6	1004 ± 6	12.84 ± 1.36
3	*850*	*5*	*FC*	112.0 ± 3.4	909 ± 24	965 ± 20	- (premature failure)
4	*1015* *followed by* *843*	*0.5* *followed by* *2*	*AC* *followed by* *FC*	114.9 ± 1.5	801 ± 20	874 ± 23	13.45 ± 1.18
5	*1020*	*2*	*FC*	114.7 ± 0.9	760 ± 19	840 ± 27	14.06 ± 2.53
6	*705*	*3*	*AC*	114.6 ± 2.2	1026 ± 35	1082 ± 34	9.04 ± 2.03
7	*940* *followed by* *650*	*1* *followed by* *2*	*AC* *followed by* *AC*	115.5 ± 2.4	899 ± 27	948 ± 27	13.59 ± 0.32
8	*1015* *followed by* *730*	*0.5* *followed by* *2*	*AC* *followed by* *AC*	112.8 ± 2.9	822 ± 25	902 ± 19	12.74 ± 0.56

Traditional Ti-6-4 treatments (treatments 5–8)

WQ = water quenching. AC = air cooling. FC = furnace cooling.

Treatment 6 to 8 are well known Ti6AL4V heat treatments [26].

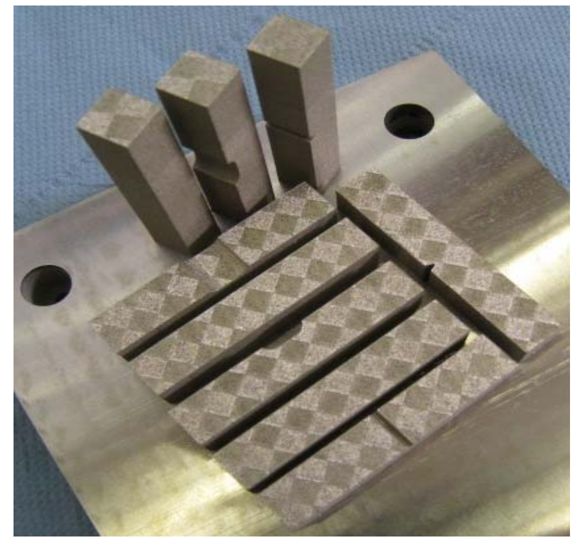
Samples for treatment 3 were built in a different batch: building errors led to premature failure of components.

Mechanical properties – Toughness and fatigue

Ti6Al4V: ductility, toughness & fatigue (without thermal treatment)

– Charpy V-notch: the roughness of SLM parts does NOT act as a stress concentrator.

	SLM	Investment cast	Wrought
Charpy V-notch [J]	11,5 ± 0,5	15-19	15-20

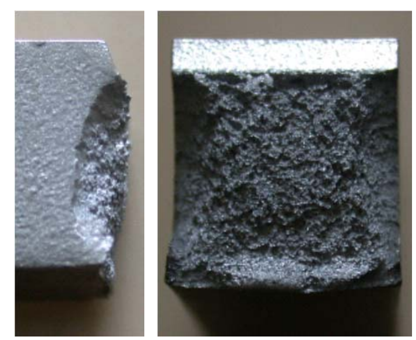


– Fracture toughness: (ongoing research)

	SLM	Cast	Wrought
K_{Ic} [MPa√(m)]	52	70-100	65-70

– Fatigue: (ongoing research)

(Unnotched, R=0 or 0,1)	SLM	Cast	Wrought
HCF limit [MPa]	>250	>200	>400



– Crack growth rate

Ceramics

Ceramics

Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
  - 2.1 different binder and structural materials
    - 2.1.1 separate structural and binder particles
    - 2.1.2 composite particles
    - 2.1.3 coated grains particles
  - 2.2 no distinct binder and structural materials
    - 2.2.1 single phase material partially molten
    - 2.2.2 fusing powder mixture
- **3. Full Melting**
  - 3.1 single component single material
  - 3.2 single component alloyed material
  - 3.3 fusing powder mixture
- **4. Chemically Induced Binding**

Alumina part

Examples:

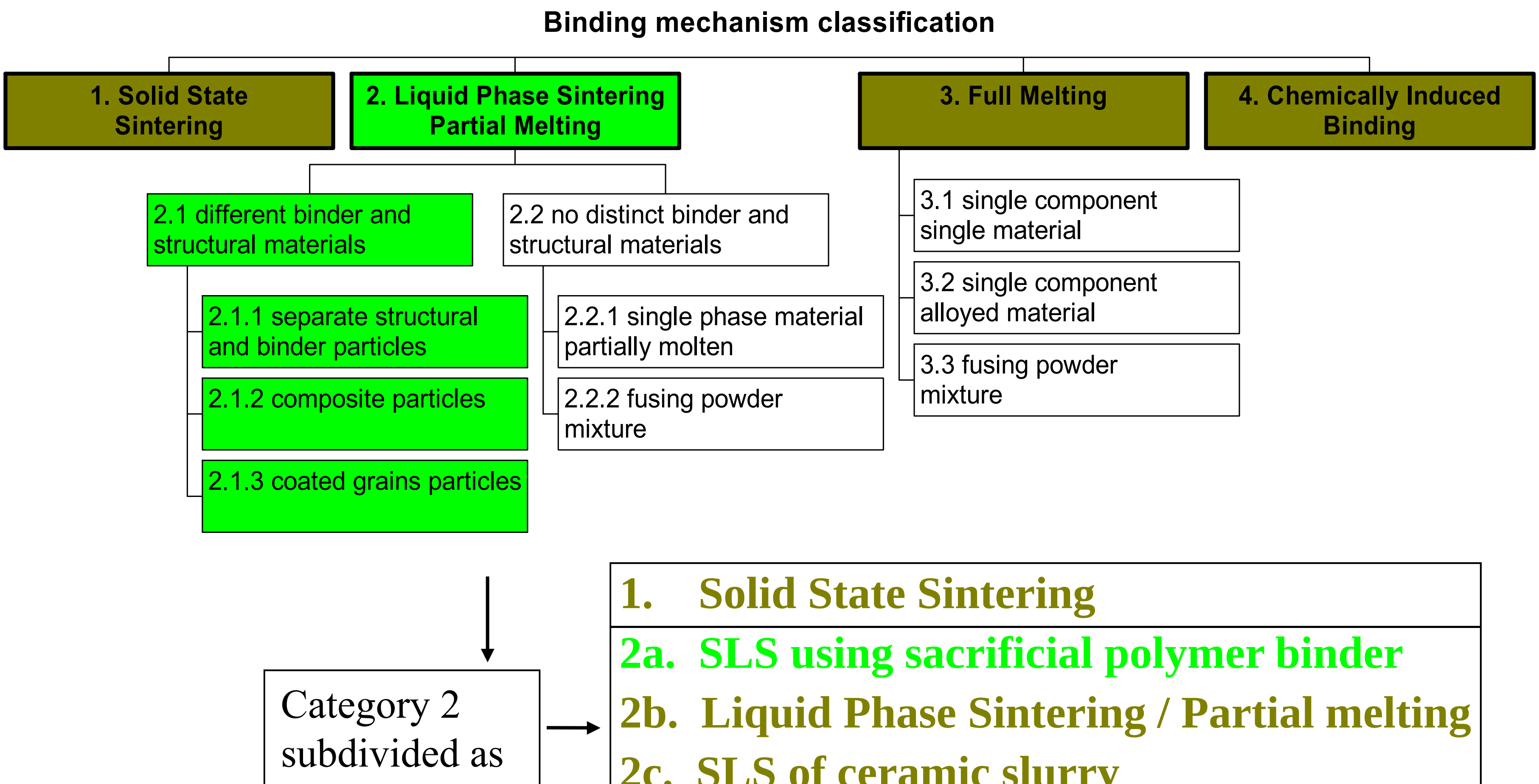
- Al_2O_3, ZrO_2, or eutectic mixture
- Micro SLS of SiC
- Transparent Ta_2O_5 dielectric ceramic
- SiO_2 investment casting shells
- HA biocompatible medical implants
- TCP/Glass biocompatible implants
- Bismuth-titanate ($Bi_4Ti_3O_{12}$) radiation detectors
- Bismuth-germanate ($Bi_4Ge_3O_{12}$)

Ceramics : Classification

Major distinction:

Ceramic type	Main Consolidation type
Silicate ceramics **Multi-phase material** made from clay, kaolin, silicate carriers (feldspar, soapstone) (+ Al_2O_3, $ZrSiO_4$)	• Liquid Phase Sintering • Partial Melting • Full melting
Oxide ceramics **90% single phase / single component metal oxides** (Al-oxide, Mg-oxide, Zr-oxide, Al-titanate, Piezo-ceramic)	• Solid State Sintering • Partial Melting • Full melting
Non-oxide ceramics **Si and Al, with N or C** • **Carbide ceramics** • **Nitride ceramics**	• Chemical Induced Binding • Partial Melting • Full melting

Ceramics : Classification



1. Solid State Sintering
2a. SLS using sacrificial polymer binder
2b. Liquid Phase Sintering / Partial melting
2c. SLS of ceramic slurry
3. Selective Laser Melting
4. Chemical or self-induced binding

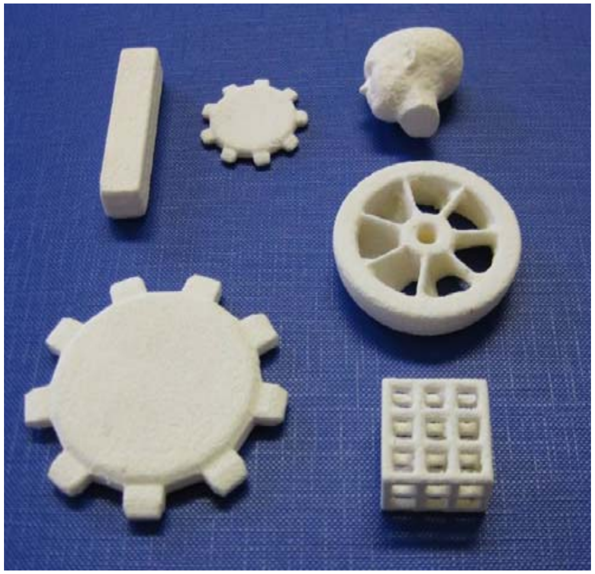
Selective laser processing of ceramics (e.g. Al_2O_3)

- ***In**direct* SLS of e.g. Al_2O_3 (partial melting of polym. binder)
- Densification strategies
  - infiltration of green/brown/final parts with highly loaded Al_2O_3 suspensions
  - isostatic pressing of green parts

Emblem statue of Brussels city

- Final Al_2O_3 densities after applying densification strategies
  - Carnauba wax: 75% => under investigation
  - PS: 66% => 85%
  - PA (ball milled): … => 94% (bad geometrical accuracy)
  - PA : 48% => 71%
  - PP: 48% => 82% (bending strength: 96 MPa)

It's only the begining.
Further improvements are expected!!



Selective laser processing of ceramics (e.g. Al_2O_3)

- E.g.:

powder synthesis (*40 vol% Al_2O_3, 60 vol% PP*) → SLS → debinding (deb.) & furnace SSS

SLS: *Green density: 48%*

Debinding & furnace SSS: *Density: 38%*

powder synthesis (*40 vol% Al_2O_3, 60 vol% PP*) → SLS → ***WIP*** *120°C* → debinding & furnace SSS

SLS: *Green density: 48%*

WIP: *Green density: 86%**

** 97% with carnauba wax*

Debinding & furnace SSS: *Density: 63%*

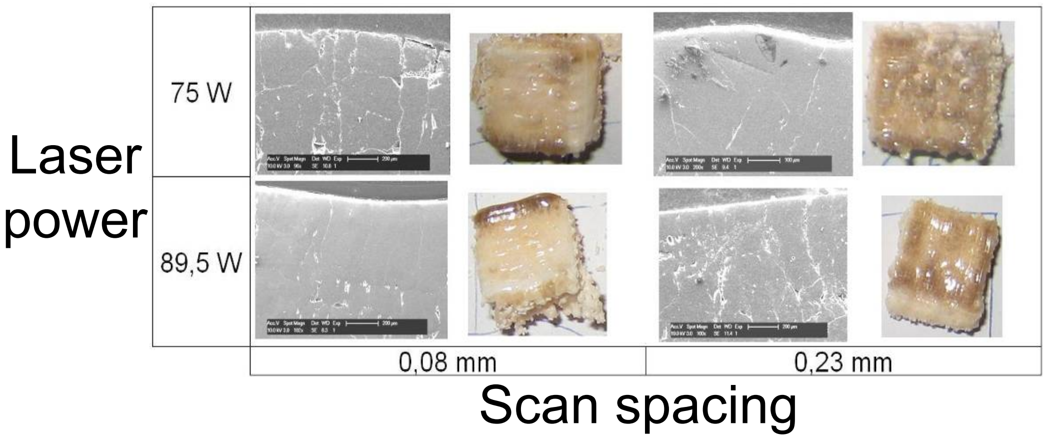
powder synthesis (*40 vol% Al_2O_3, 60 vol% PP*) → SLS → ***infiltration*** (*40 vol% Al_2O_3, 60 vol% ethanol*) → deb. → ***infiltration*** (*40 vol% Al_2O_3, 60 vol% ethanol*) → SSS

SLS: *Density: 48%*

SSS: *Density: 82%*

Selective laser processing of ceramics (e.g. Al_2O_3)

- Direct SLM of Al_2O_3 (full melting of ceramic itself, without polymer binder)



- DTM sinterstation 2000+
- v = 25 mm/s

Requirements:

- high packing density of sub micrometer particles (>50% Al_2O_3)
- preheating > 800°C
- no full melting

Experimental setup for direct SLS of Al_2O_3 under development…

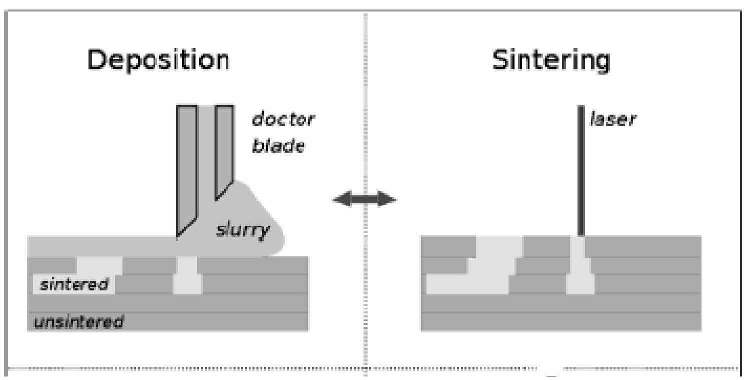
Ceramics: SLS of ceramic slurries

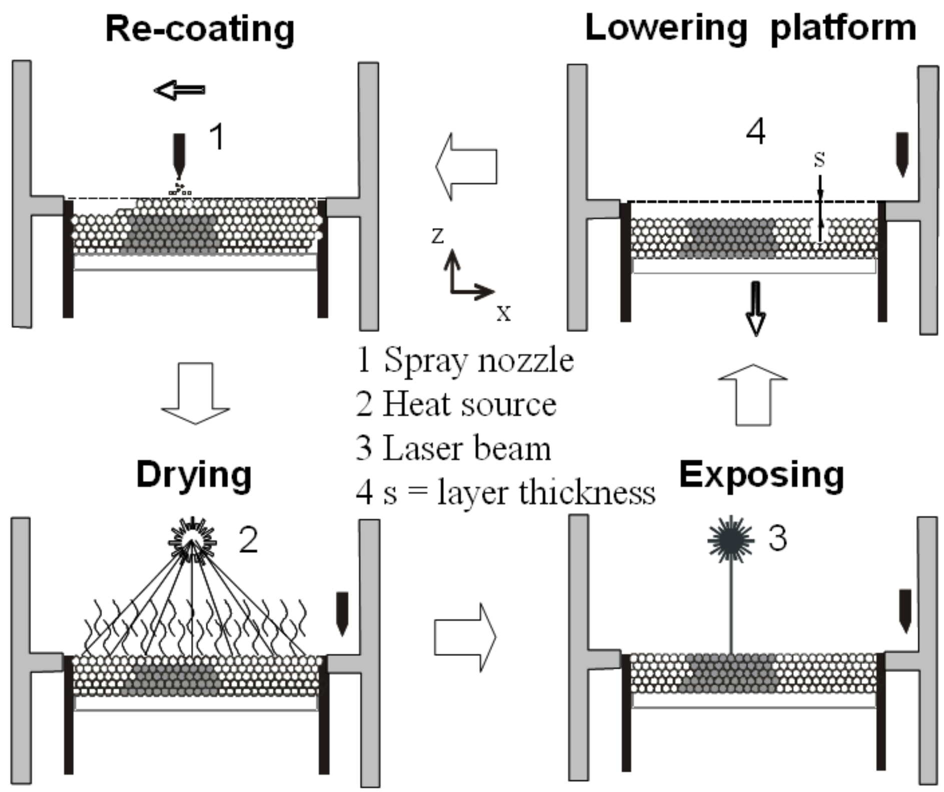
Principle:

- Replacing dry powder by slurry with smaller ceramic particles (high green density)
- Additional "drying" step, before "laser sintering": capillary forces increase packing

Example (Univ. Clausthal):

- **Hydroxyapatite + H_2O**
  (up to 66% solid loading)
- **Al_2O_3/SiO_2 + H_2O**
  - binder free, highly loaded slurry
    + drying + SLS
  - low melting SiO_2 + reaction sintering
    with Al_2O_3





Ceramics: Chemically and Self-induced binding

Principle:

- Induce chemical reaction that binds powder particles

Investment casting shell and cast impeller

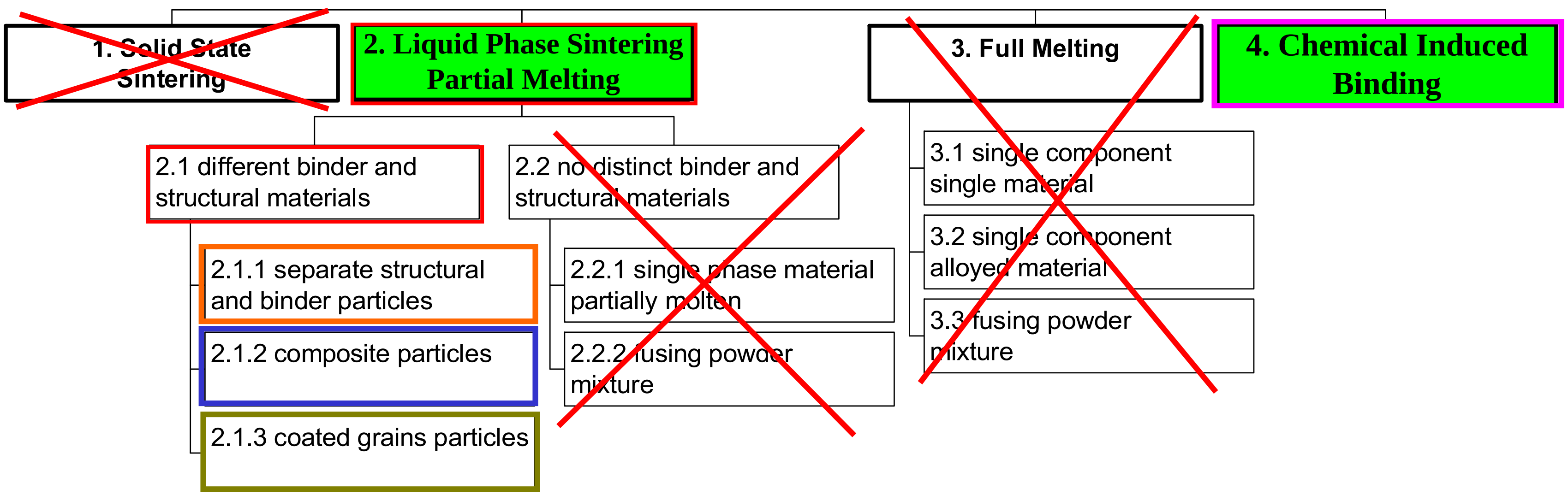
Examples:

- SiC $\Longrightarrow$ - disintegration SiC $\longrightarrow$ Si + C
  - Si + O_2 $\longrightarrow$ SiO_2 binder for SiC
  - infiltration with Si + reaction bounded
- CuO + Al $\longrightarrow$ Al_2O_3 + Cu
  - Heat comes from laser + exothermal reaction
  - Self propagation controlled by addition of Cu
- Ti + Al $\longrightarrow$ TiAl
  - Heat comes from laser + exothermal reaction
  - Self propagation controlled by addition of TiAl
- Also tested: TiC-Al_2O_3 (mixture of TiO_2, Al and C; self-propagating), $ZiSiO_4$, $MoSi_2$

Composites

Composites

Binding mechanism classification



SLS/SLM well suited for all kind of composites:

- polymer-metal (e.g. PA-Cu, PA-Al)
- polymer-ceramic (e.g. PE-HA, PCL-HA, PS-Al_2O_3)
- polymer-glass (e.g. PA-GF)
- metal-metal (e.g. Fe-Cu)
- metal-ceramic (e.g. WC-Co, Cu-TiC-TiB_2, Al_2O_3-Cu)
- …

mixed

coated (no agglomeration; uniform distribution)

composite powder (uniform; no agglomeration; possible problems with fibers)

Chemical binding from mixture of CuO and Al

Chemical binding from mixture of Cu, Ti and B_4C

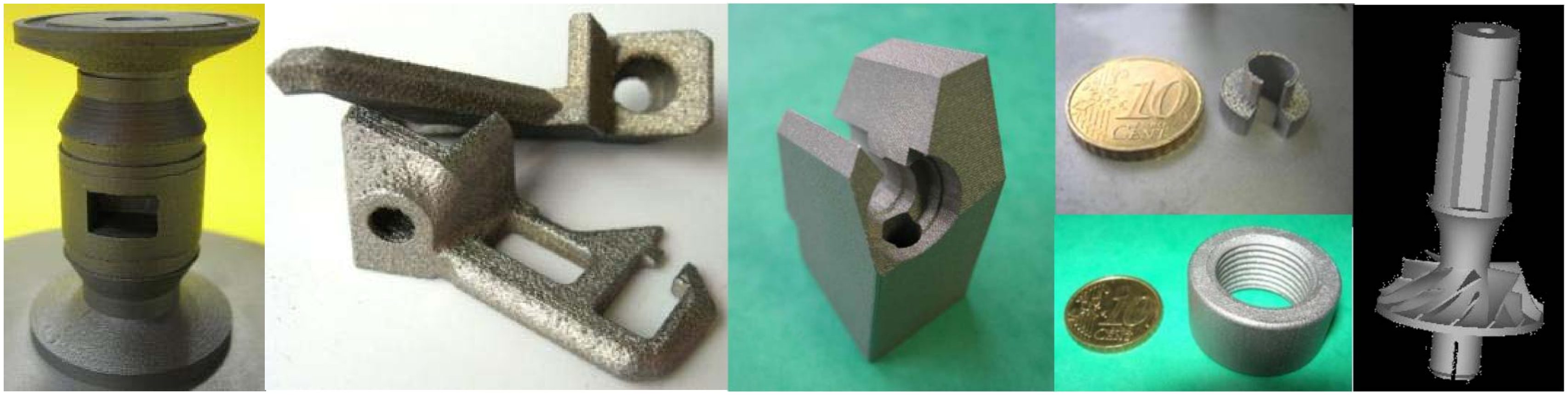
Liquid Phase Sintering

Conclusion

- **Laser powder-bed fusion is may be the most versatile AM technology**
- **It basically allows processing any material:**
  - **Polymers (semi-crystalline, amorphous, elastomeric, thermosetting)**
    - Although 20 years old, **still very limited pallet of polymers** (few semi-crystalline polymers)
    - Even with PA11-12, **density needs improvement** (still 5…8% porosity)
  - **Metal (ferro, non-ferro, reactive,…)**
    - **Pallet is increasing rapidly**
    - **Density mostly above 99 to 99.8%** (even up to 99.95% for several materials)
  - **Ceramics**
    - **Still under development**
    - **OK for porous parts** (filters and scaffolds), but **too low for structural parts** (94..97%)
  - **Composites** (polymer-metal, polymer-ceramic, metal-ceramics, metal-metal, reinforced)
    - **All kind of composites feasible** (see above)
    - **Technologically possible, but few industrial applications so far.**

Further developments may take decades, but this was also the case for subtractive and forming processes that have been developed for centuries.

Laser powder-bed fusion AM: SLS, SLM, …



Thank you for your attention