Developments and Novelties in Thermal Management

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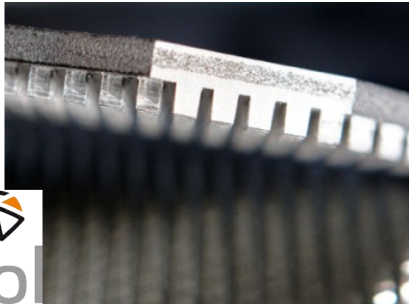
Thermal Management Materials Workshop,
6th of Nov 2015
CERN – EUCARD II

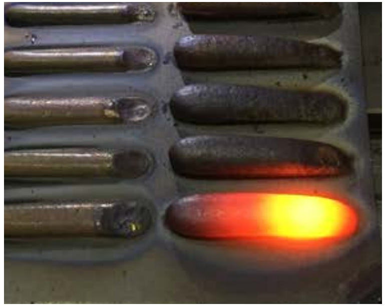
RHP-Technology GmbH Forschungszentrum A-2444 Seibersdorf, Austria

Short introduction to RHP

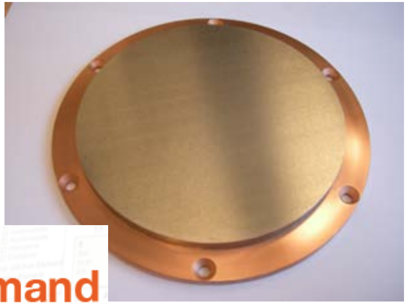
- **Advanced Materials** for functional applications



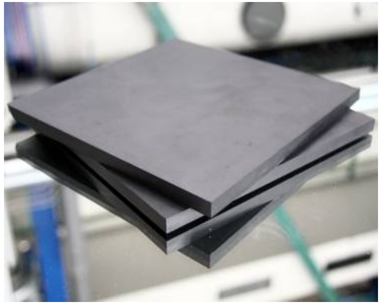
dia cool



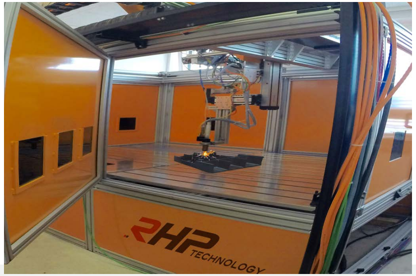
- **Sputtering Targets** on customized compositions



targets on demand



- **Research Solutions** by sintering, hot pressing, additive manufacturing and powder injection moulding

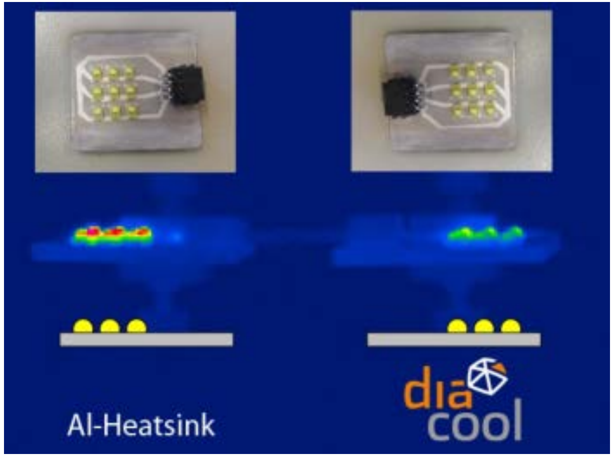


Content

Outline

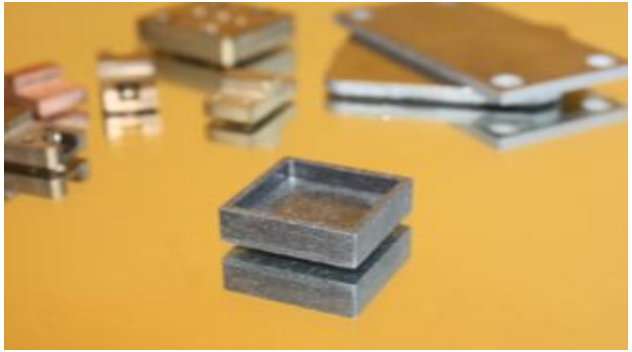
- Motivation and targeted thermal properties
- Materials and Concepts for Thermal Management
  - ☐ Starting materials, processing routes & their challenges
  - ☐ Diamond Composites (Metal & Ceramic Matrix)
  - ☐ Multilayer Materials
  - ☐ Channel Structures for Metals and Ceramics
- Summary

Overview on Materials

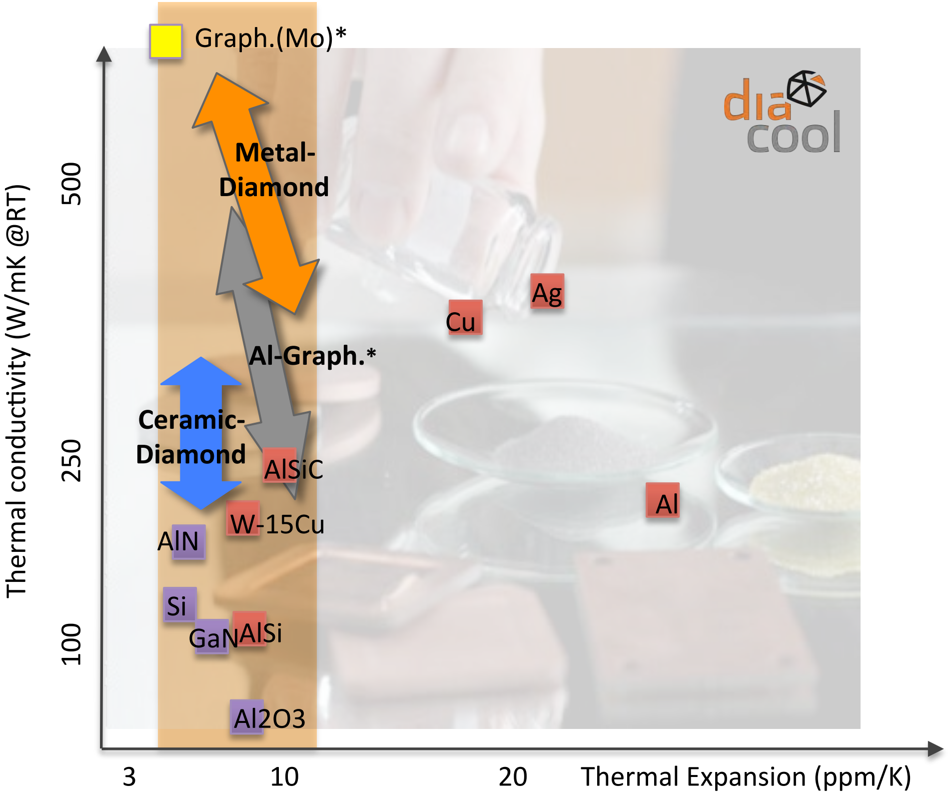


Main requirement to heat sink materials:
- High thermal conductivity
- Low coefficient of thermal expansion
- Low weight

Composite Materials:
- Metal-Diamond (Cu, Al, Ag)
- Ceramic-Diamond (AlN, Al2O3)
- Aluminium-Graphite
- Cu-W, Cu-Mo



Thermal properties



Matrix and Filler Materials:

- Diamonds (1500-2000W/mK)
- Graphite flakes (150-1000 W/mK*)
- Carbon fibres (up to 1000 W/mK*)

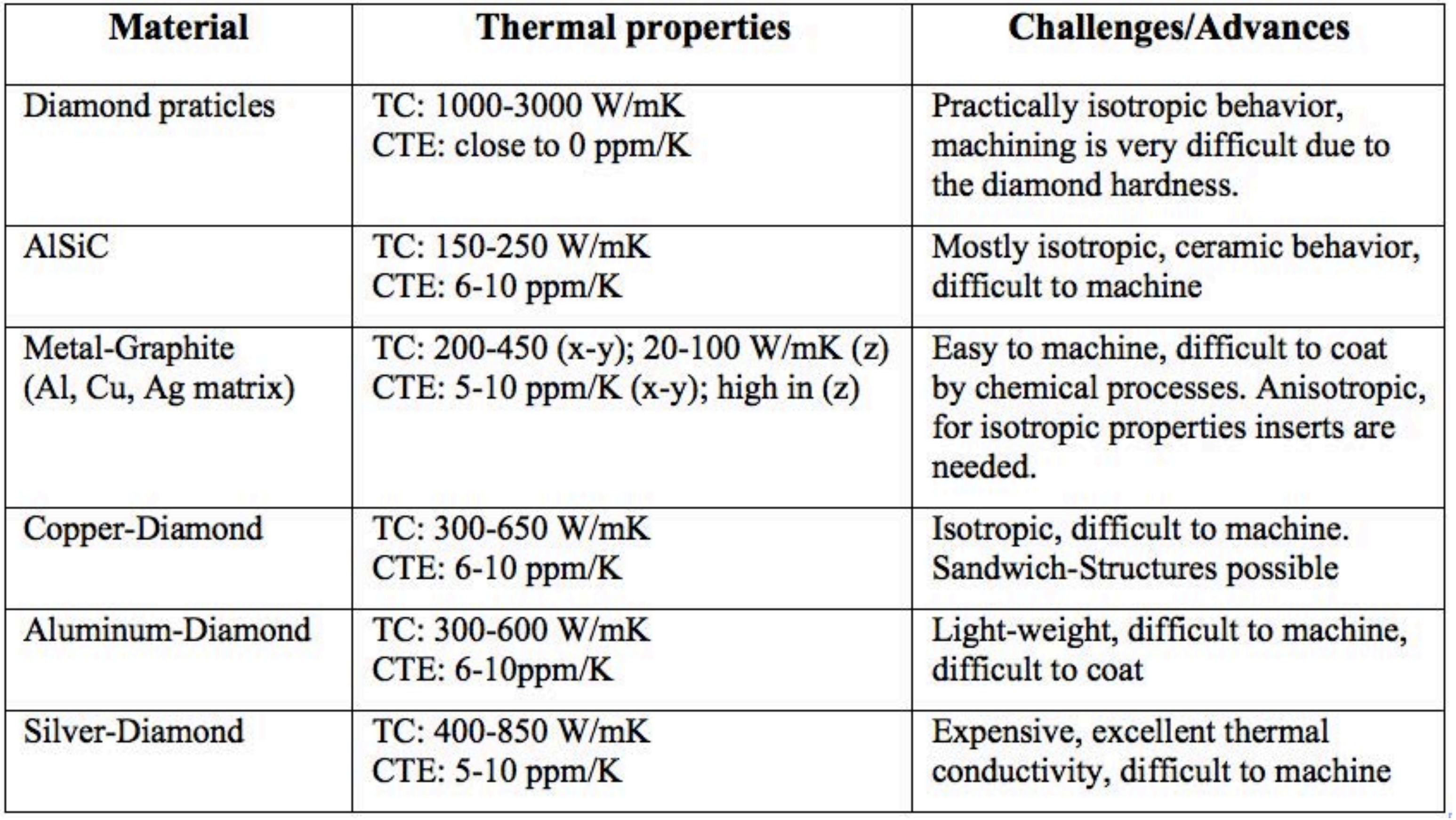
- Cu (400 W/mK) / Ag (420 W/mK) / Al (240 W/mK)
- AlN (180-230 W/mK) / Al2O3 (~20 W/mK)

Diamond Composites:

- Cu/Ag/Al-Diamond: 300-650 W/mK
- AlN-Diamond: ~300 W/mK
- Coeff. of thermal expansion: 4-10ppm/K

* anisotrop behavior (higher in-plane or in fibre axis)
values given at room temperature

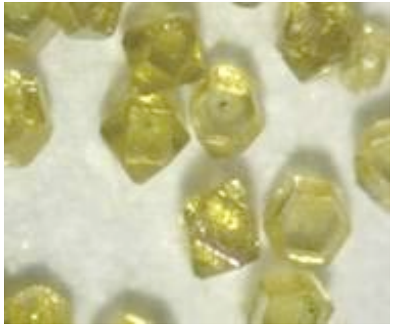
Thermal properties (cont‘d)

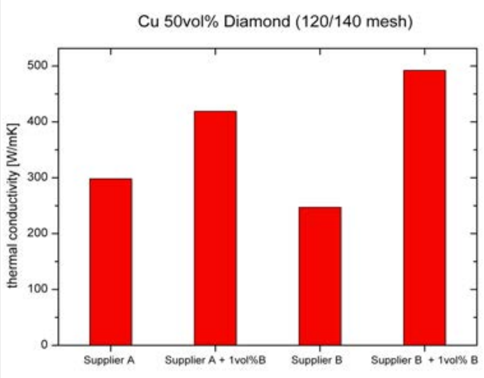


Material	Thermal properties	Challenges/Advances
Diamond praticles	TC: 1000-3000 W/mK CTE: close to 0 ppm/K	Practically isotropic behavior, machining is very difficult due to the diamond hardness.
AlSiC	TC: 150-250 W/mK CTE: 6-10 ppm/K	Mostly isotropic, ceramic behavior, difficult to machine
Metal-Graphite (Al, Cu, Ag matrix)	TC: 200-450 (x-y); 20-100 W/mK (z) CTE: 5-10 ppm/K (x-y); high in (z)	Easy to machine, difficult to coat by chemical processes. Anisotropic, for isotropic properties inserts are needed.
Copper-Diamond	TC: 300-650 W/mK CTE: 6-10 ppm/K	Isotropic, difficult to machine. Sandwich-Structures possible
Aluminum-Diamond	TC: 300-600 W/mK CTE: 6-10ppm/K	Light-weight, difficult to machine, difficult to coat
Silver-Diamond	TC: 400-850 W/mK CTE: 5-10 ppm/K	Expensive, excellent thermal conductivity, difficult to machine

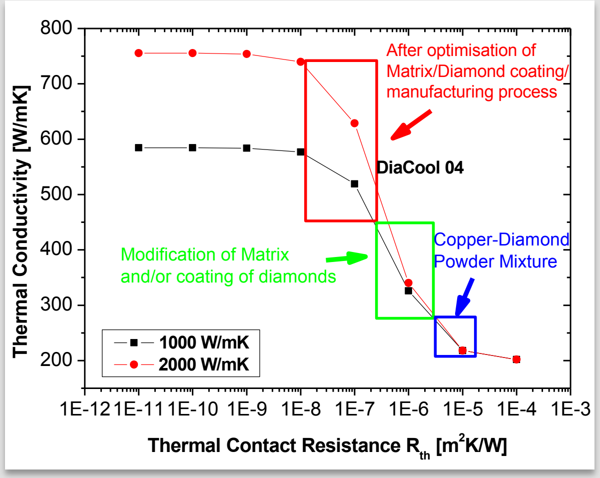
CHALLENGES IN MANUFACTURING

1) selection of raw materials



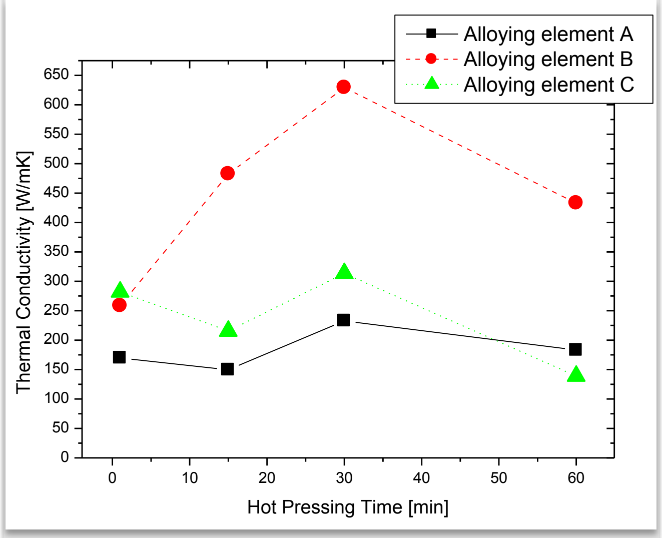


2) interface modification



- alloying elements
- thermal transfer

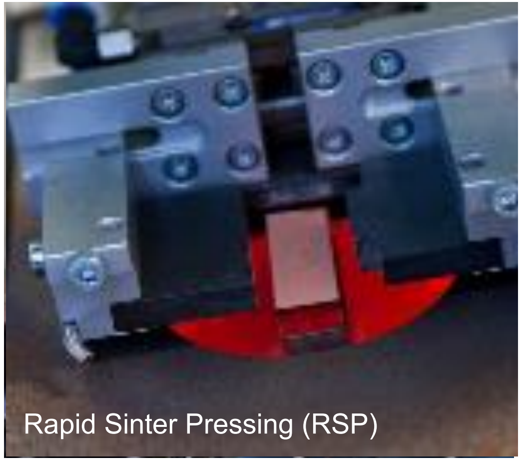
3) consolidation



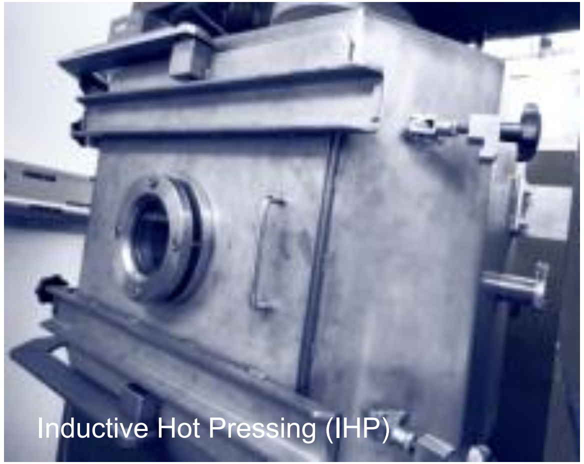
- filler degradation
- graingrowth
- movement of filler particles

4 Different Hot & Pressure Assisted Manufacturing Processes

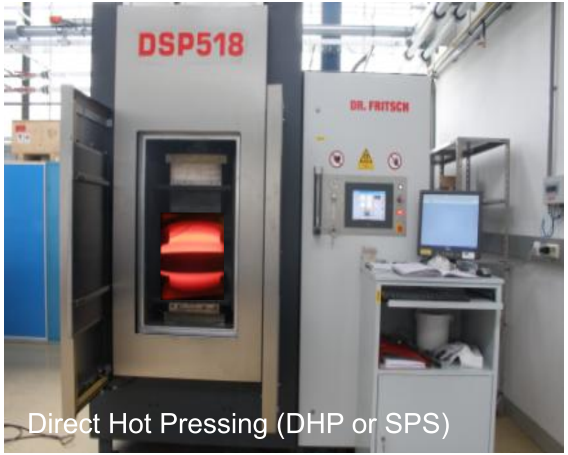
- **Conventional hot pressing:** graphite mould with powder mixture is indirectly heated via a graphite heating element (10 – 20 K/min)
- **Induction heated hot pressing:** The graphite mould with the powder mixture is heated via induction coil resulting in high heating rates (50 – 300 K/min)
- **Direct heated hot pressing:** high heating and cooling rates by using a AC or DC or pulsed current flowing through the sample for heating. (50 – 300 K/min)
- **Rapid Sinter Pressing:** uses a permanently heated pressing die made of steel or ceramic. Samples are heated with a rate of several thousand Kelvin per minute, up to 1000°C (3.000 – 4.000 K/min)



Rapid Sinter Pressing (RSP)

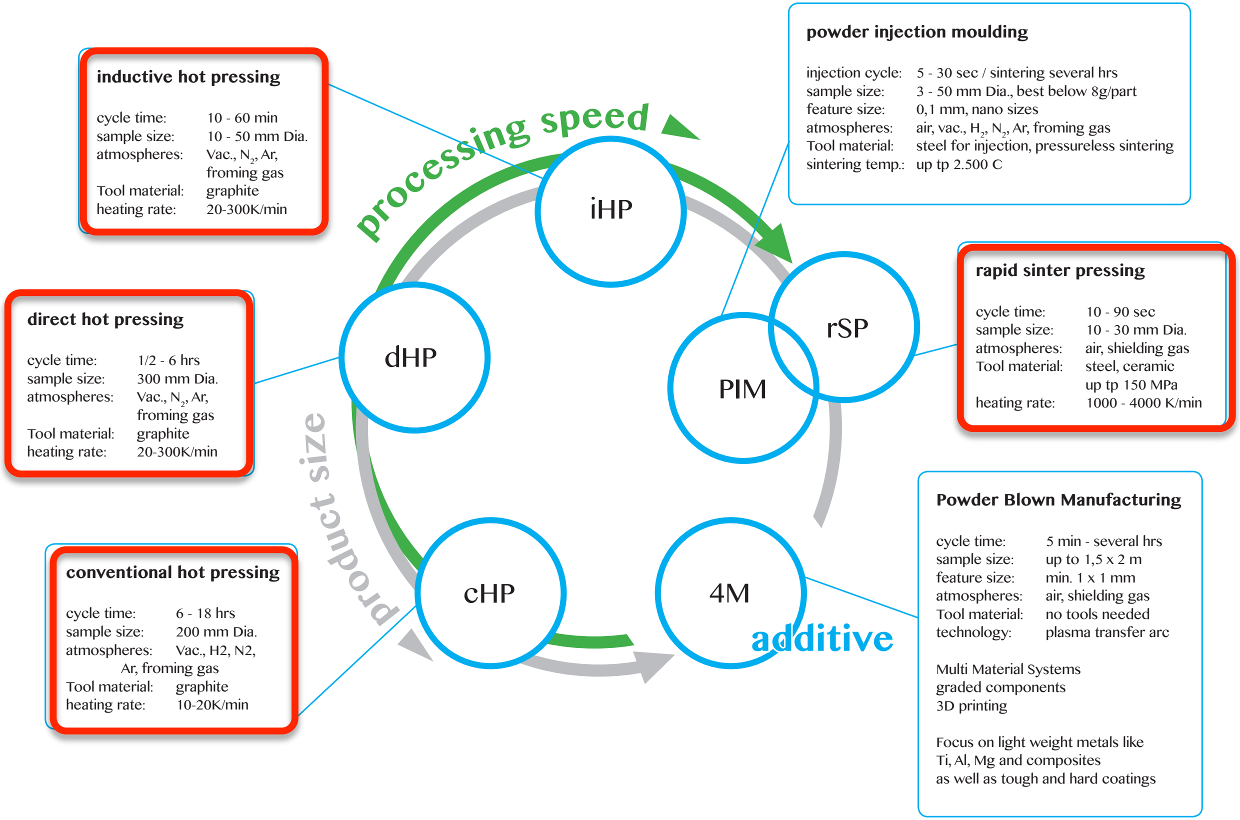


Inductive Hot Pressing (IHP)



Direct Hot Pressing (DHP or SPS)

Manufacturing Processes (cont‘d)



inductive hot pressing

cycle time:	10 - 60 min
sample size:	10 - 50 mm Dia.
atmospheres:	Vac., N_2, Ar, froming gas
Tool material:	graphite
heating rate:	20-300K/min

direct hot pressing

cycle time:	1/2 - 6 hrs
sample size:	300 mm Dia.
atmospheres:	Vac., N_2, Ar, froming gas
Tool material:	graphite
heating rate:	20-300K/min

conventional hot pressing

cycle time:	6 - 18 hrs
sample size:	200 mm Dia.
atmospheres:	Vac., H2, N2, Ar, froming gas
Tool material:	graphite
heating rate:	10-20K/min

powder injection moulding

injection cycle:	5 - 30 sec / sintering several hrs
sample size:	3 - 50 mm Dia., best below 8g/part
feature size:	0,1 mm, nano sizes
atmospheres:	air, vac., H_2, N_2, Ar, froming gas
Tool material:	steel for injection, pressureless sintering
sintering temp.:	up tp 2.500 C

rapid sinter pressing

cycle time:	10 - 90 sec
sample size:	10 - 30 mm Dia.
atmospheres:	air, shielding gas
Tool material:	steel, ceramic up tp 150 MPa
heating rate:	1000 - 4000 K/min

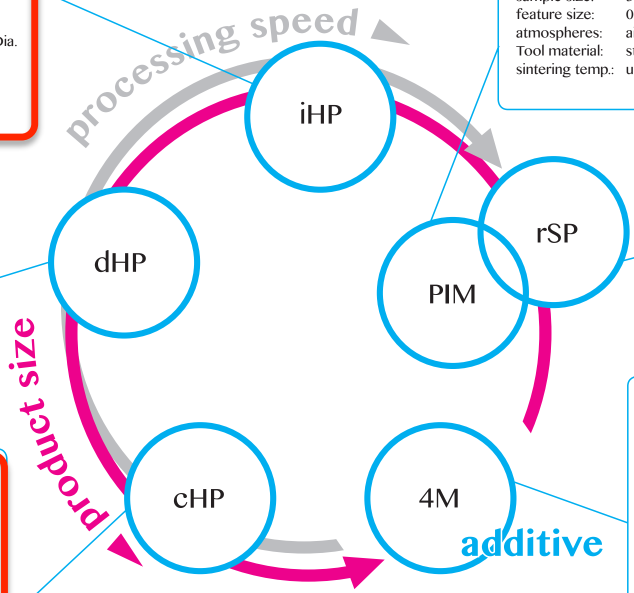
Powder Blown Manufacturing

cycle time:	5 min - several hrs
sample size:	up to 1,5 x 2 m
feature size:	min. 1 x 1 mm
atmospheres:	air, shielding gas
Tool material:	no tools needed
technology:	plasma transfer arc

Multi Material Systems
graded components
3D printing

Focus on light weight metals like
Ti, Al, Mg and composites
as well as tough and hard coatings

Manufacturing Processes (cont‘d)



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graded components
3D printing

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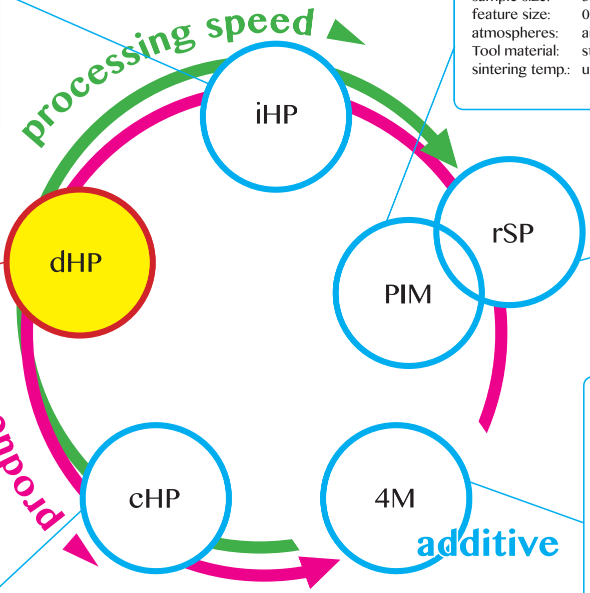

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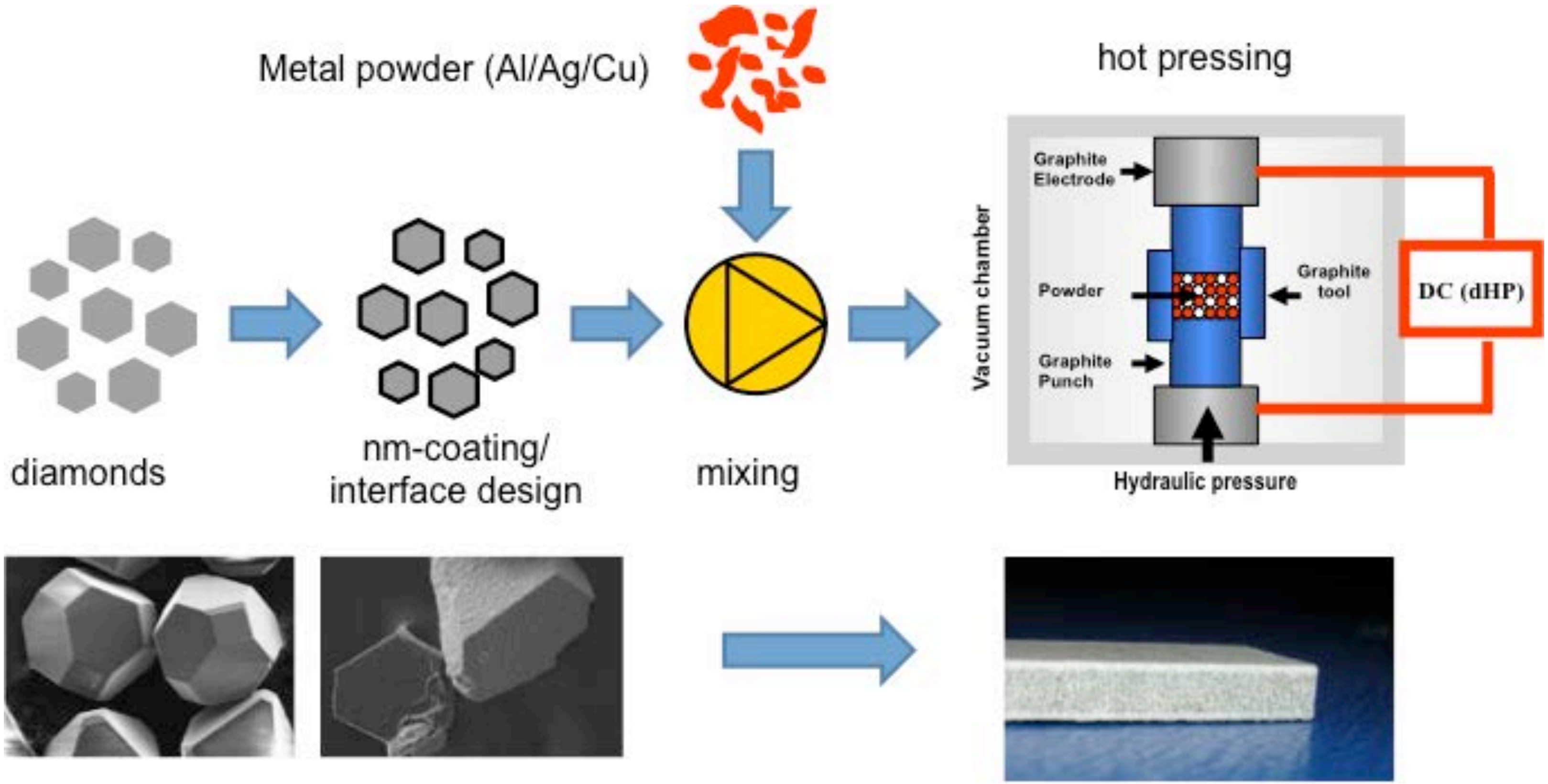
Manufacturing process – hot pressing



Metal powder (Al/Ag/Cu)

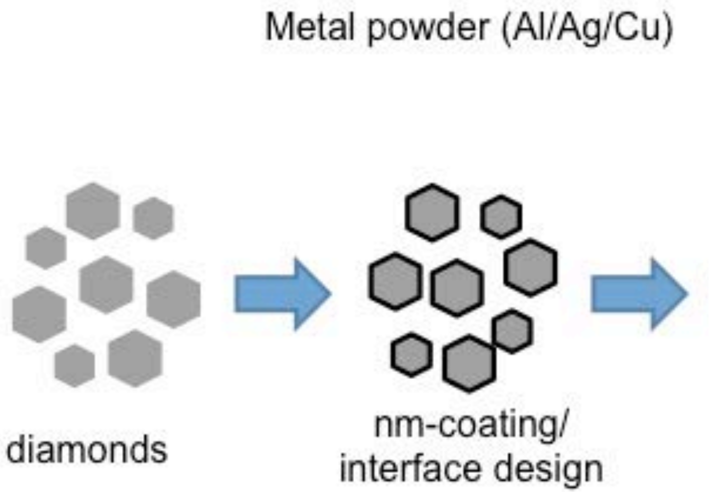
hot pressing

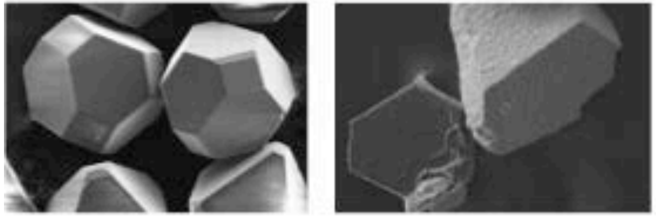
diamonds

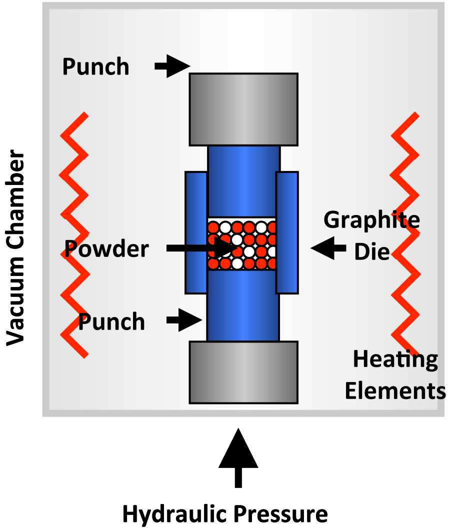
nm-coating/ interface design

mixing

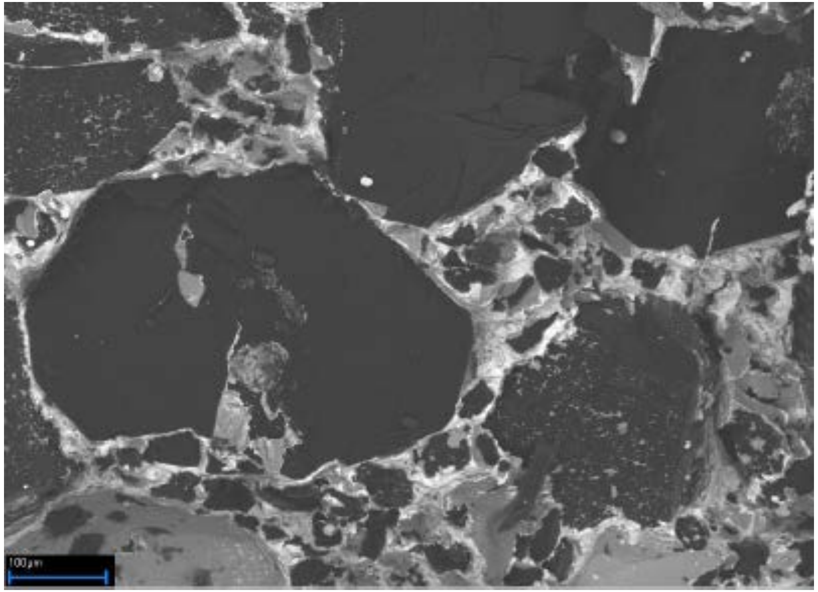
Manufacturing process – infiltration



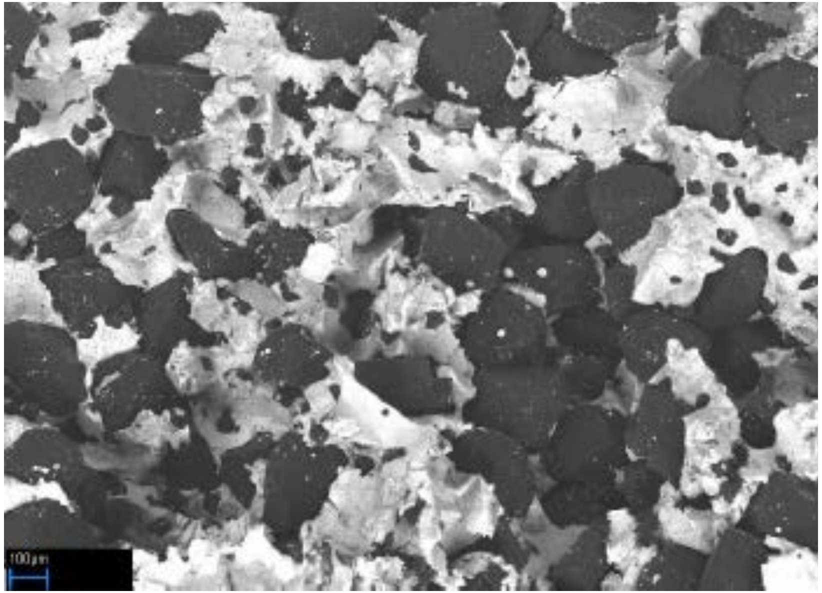




Metal-Diamond Composites



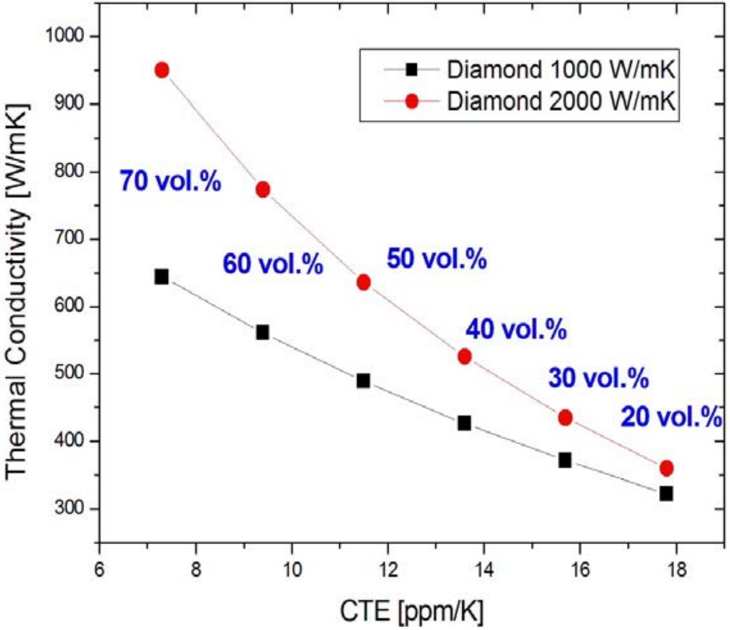
Fracture surface of a liquid metal infiltrated sample

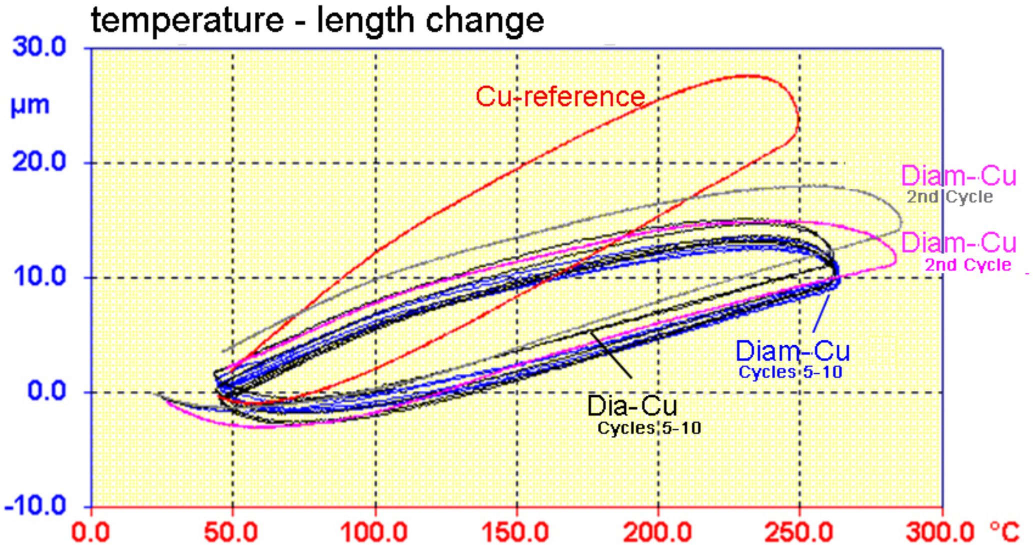


Fracture cross section of a hot pressed sample

Coefficient of thermal expansion

Copper-Diamond Composites – changing volume fraction

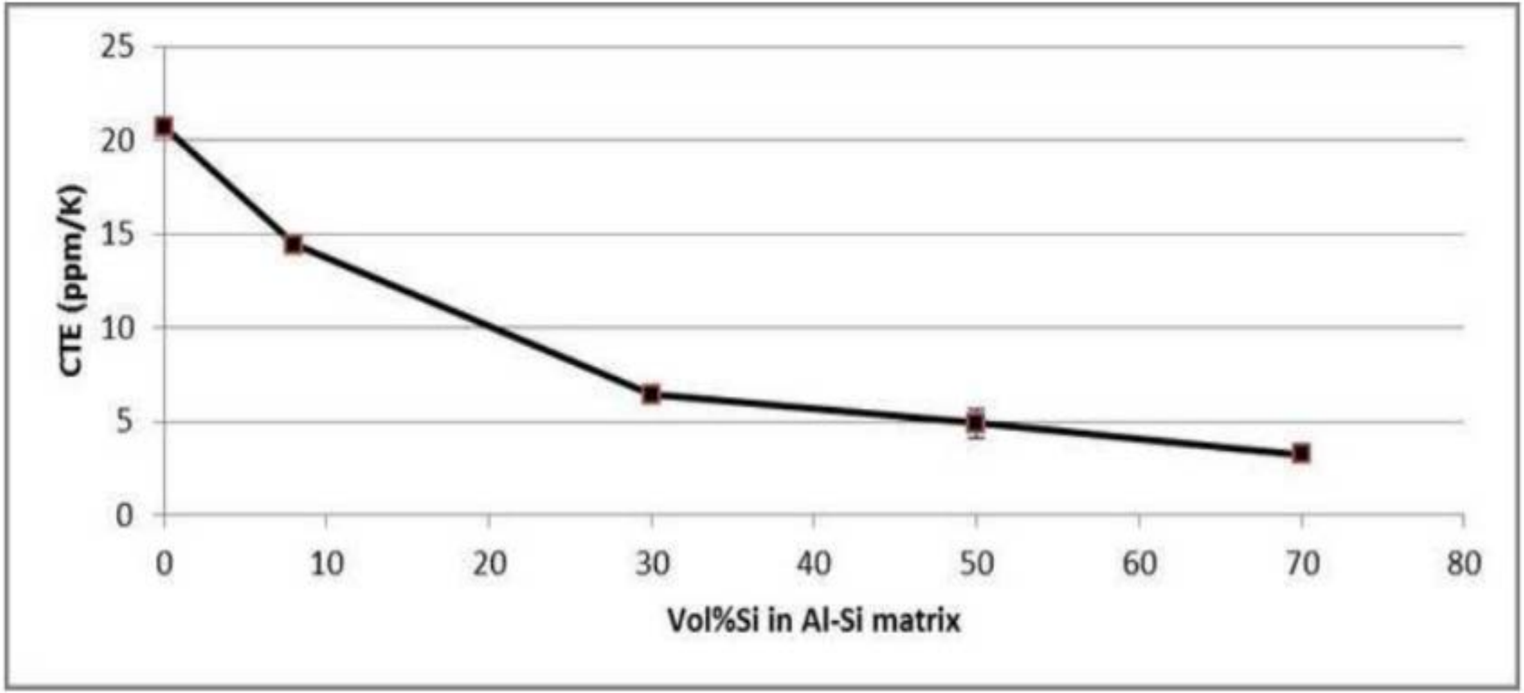




The Coefficient of thermal Expansion (CTE) mainly follows the rule of mixture regarding the diamond volume content. Thermal cycling behavior depends on the stability of the Matrix-Filler interface.

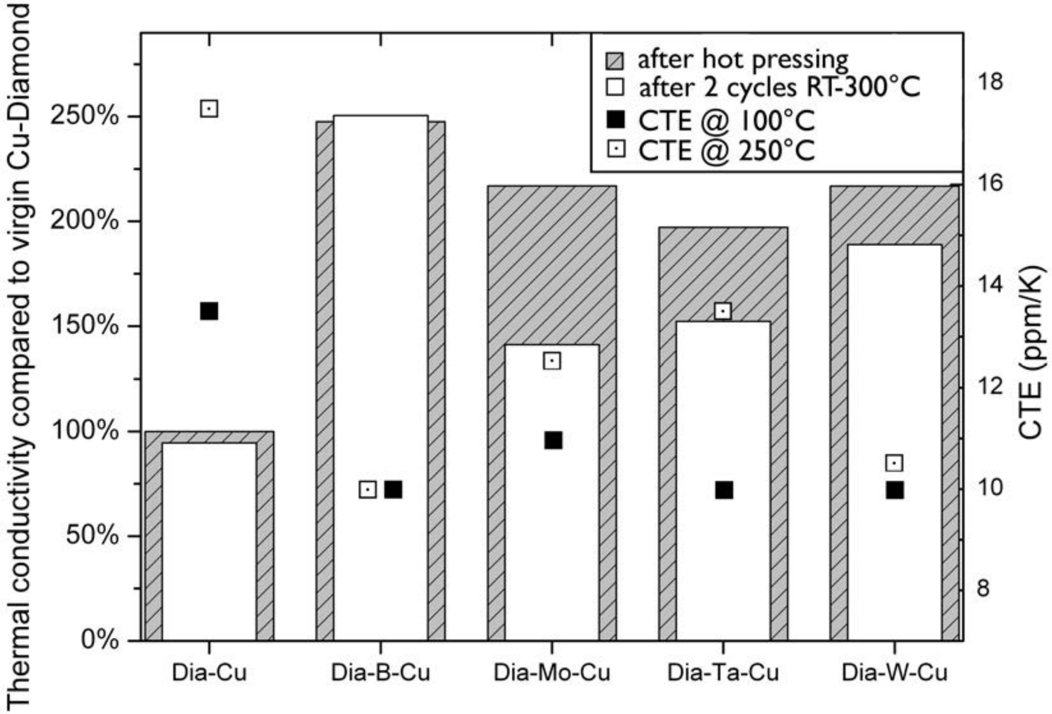
Coefficient of Thermal Expansion of Al-Si

Changing the CTE of the Matrix



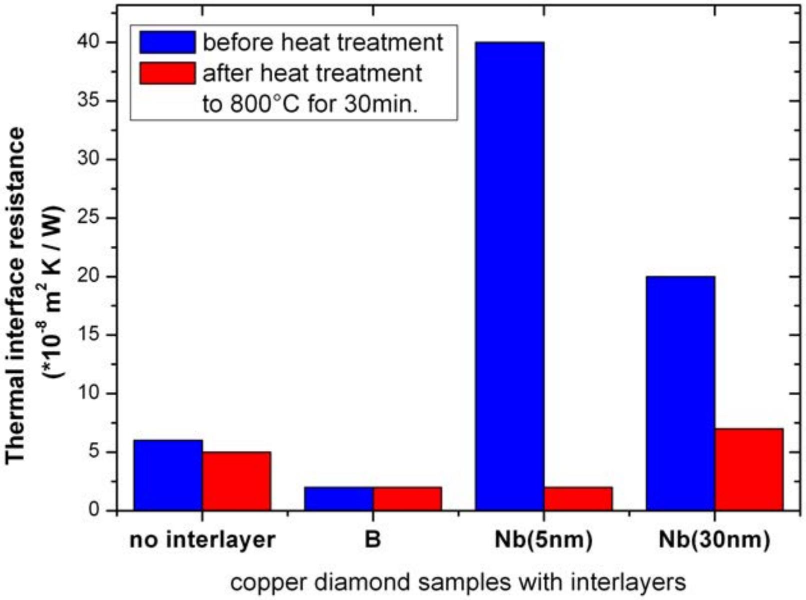
Thermal effect of additives/interlayers

Copper-Diamond Composites (50vol% Diamond)



Thermal Interface Resistance

Copper-Diamond Composites



- 5nm Niob – Kupfer – Schicht

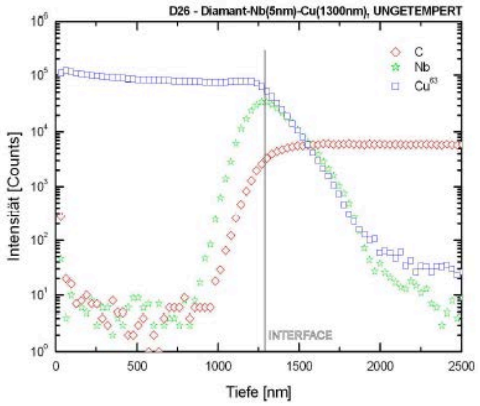


Abb. 67: D26 – UNGETEMPERT

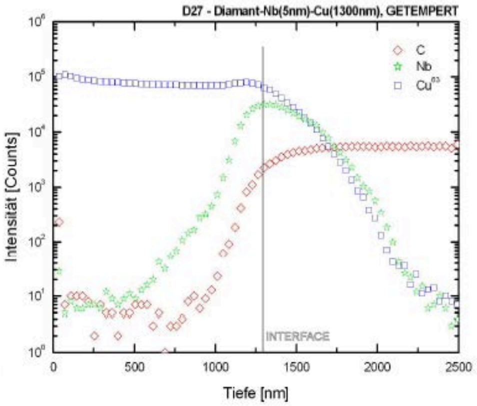
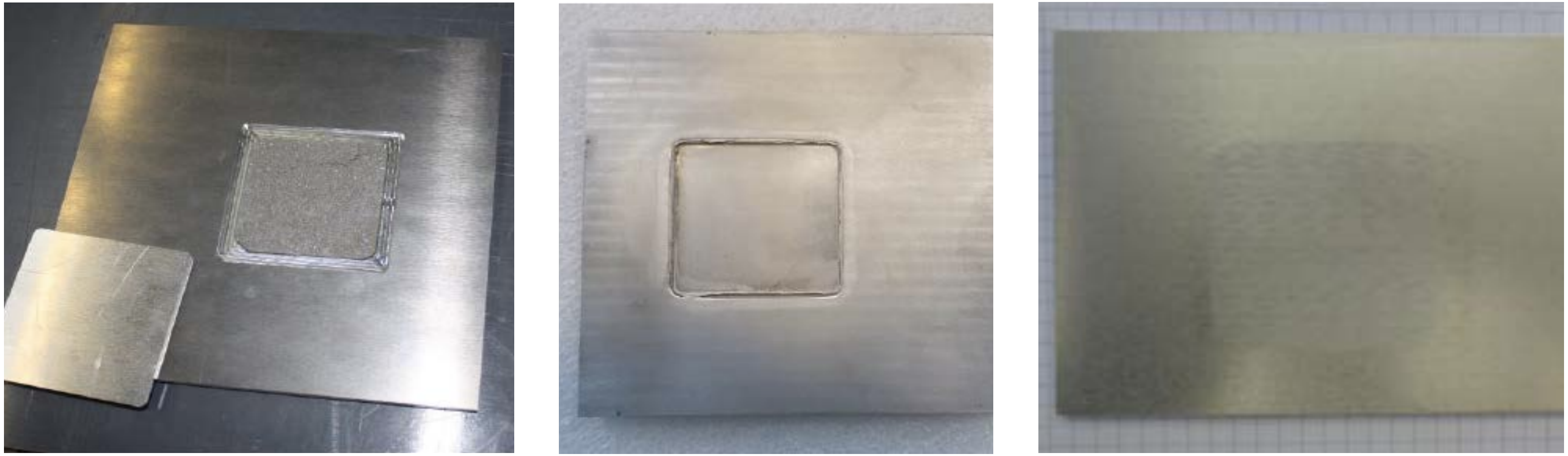


Abb. 68: D27 – GETEMPERT

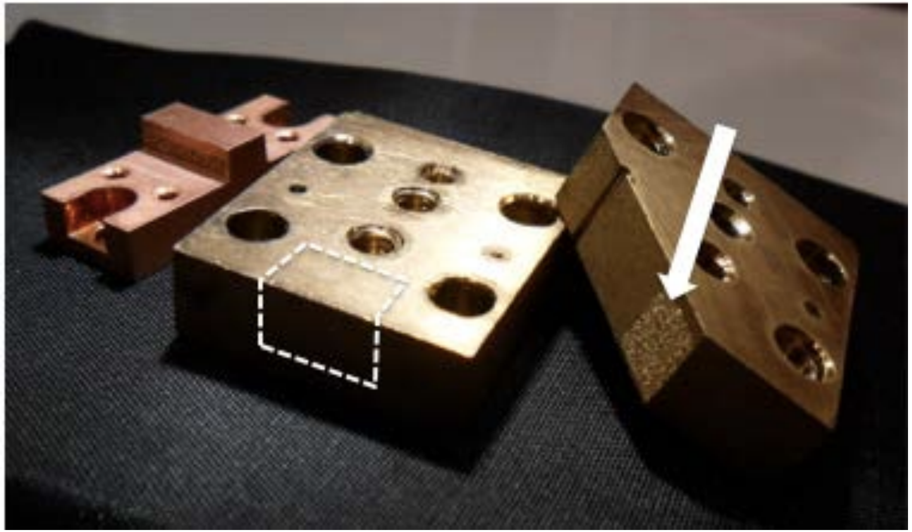
Local inserts

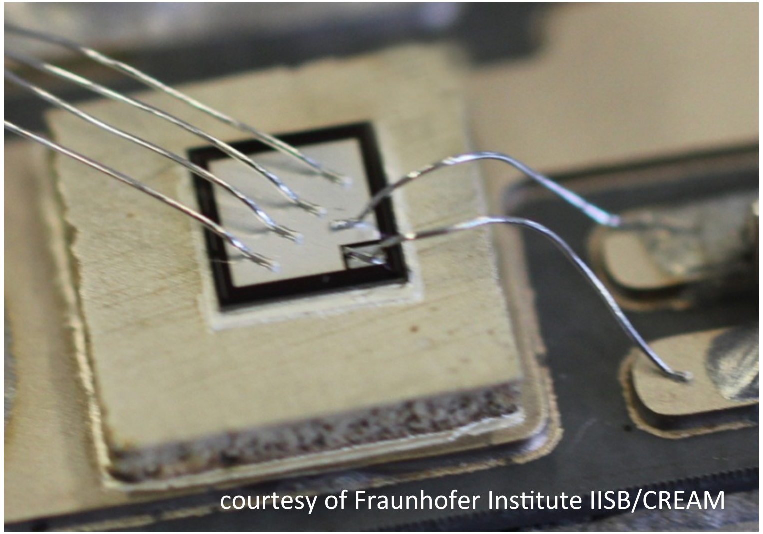
Aluminium-Diamond

Local Inserts (see below 50x50mm) can be directly implemented into a pure metal base plate (e.g. Al).



Local inserts (cont‘d)

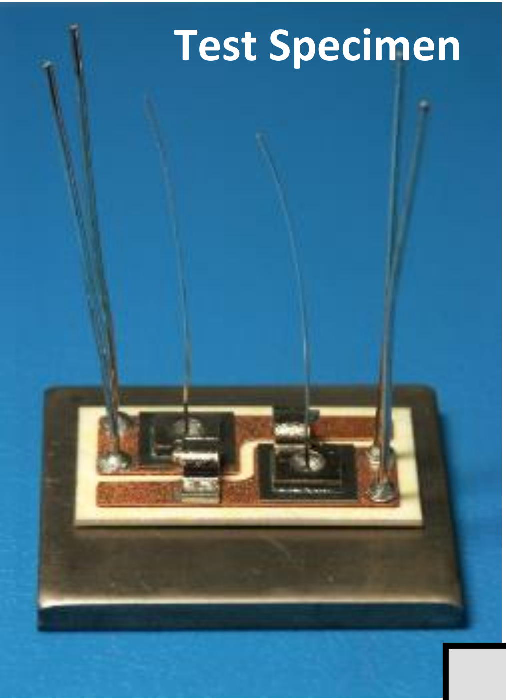



courtesy of Fraunhofer Institute IISB/CREAM

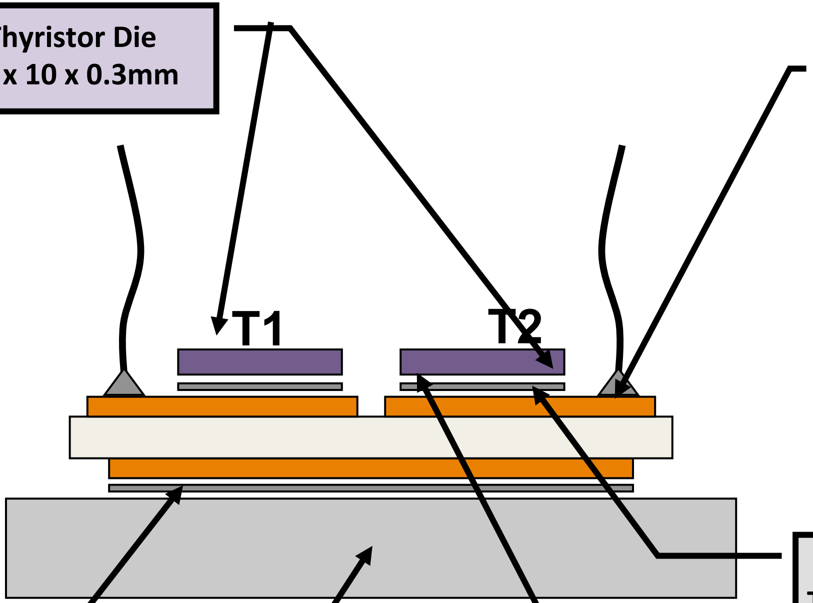
CTE matching:
Low thermal conductivity submounts are not needed any more. Direct bonding of the chip to the heat sink is possible.

Heat spreader:
High thermal conductivity makes the composite an efficient heat spreader to avoid hot spots.

Thermal Performance of MMC in Power Switching Applications



Test Specimen



Thyristor Die
10 x 10 x 0.3mm

Copper
Thickness 0.3mm

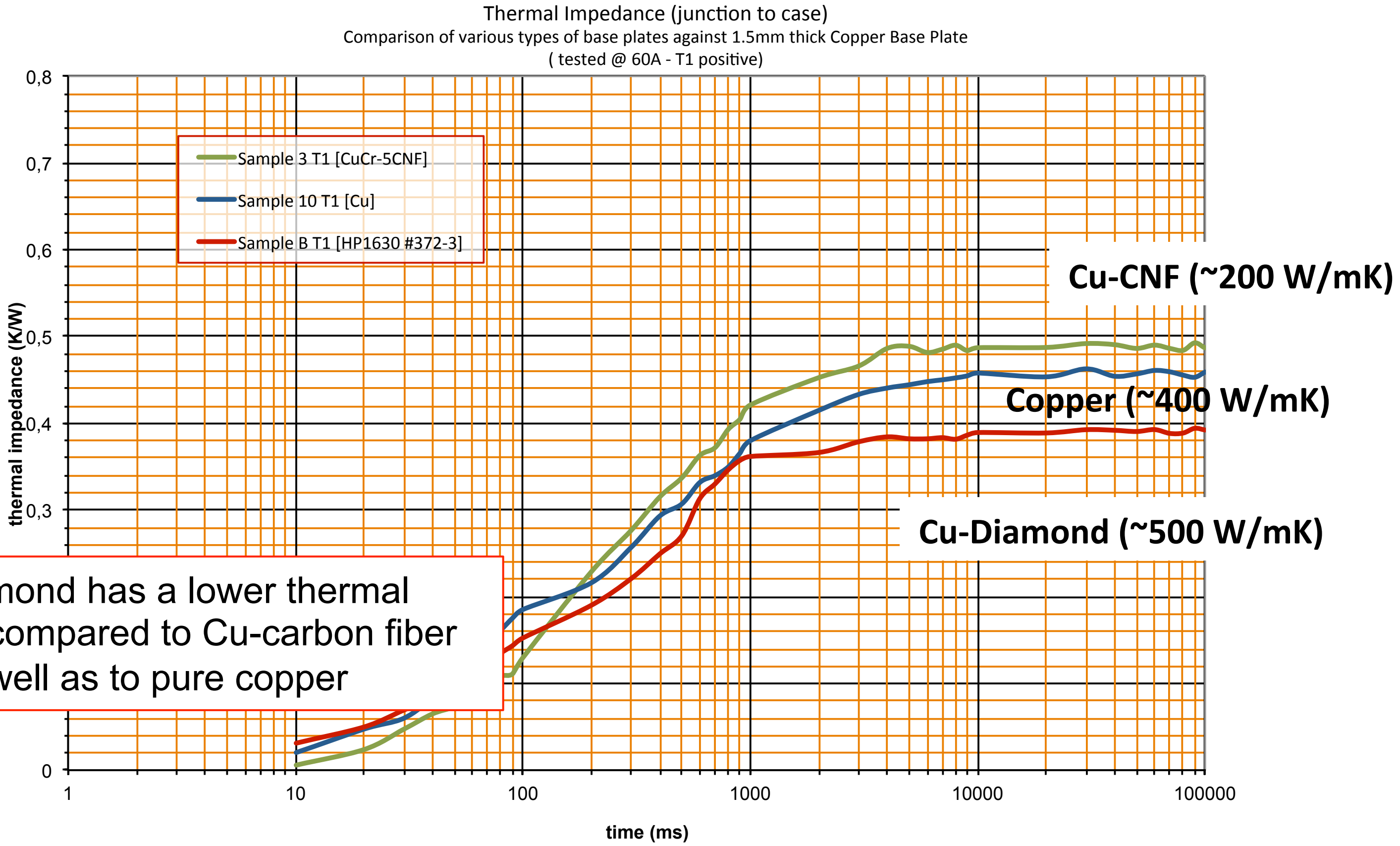
Solder
Thickness ~ 50µm

Solder
Thickness ~ 80µm

Nickel plated Base plate
39 x 42 x 1.5mm

Direct Copper Bonded
(DCB) ceramic substrate
35 x 21 x 1.2mm

Metal-Diamond in Power Switching Applications



Cu-CNF (~200 W/mK)

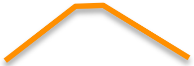
Copper (~400 W/mK)

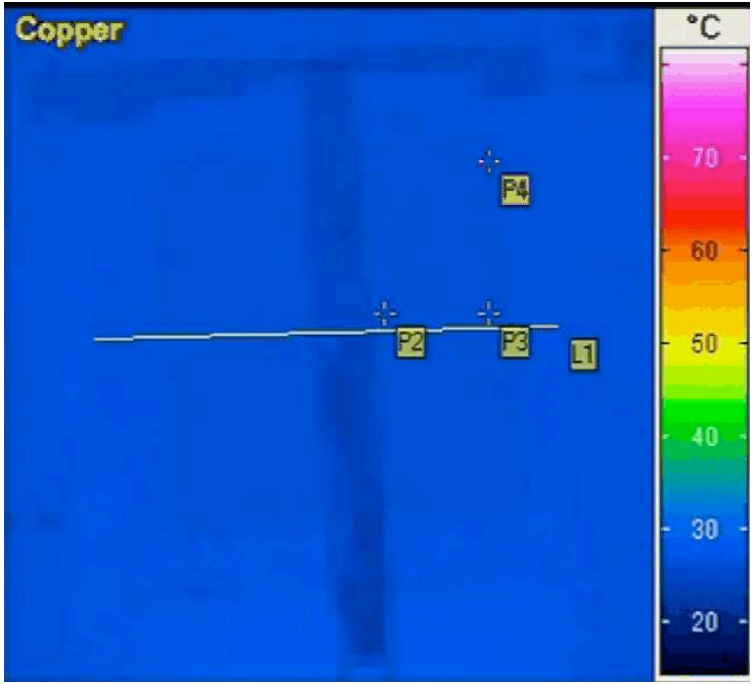
Cu-Diamond (~500 W/mK)

Copper-Diamond has a lower thermal impedance compared to Cu-carbon fiber material as well as to pure copper

Performance test of Metal-Diamond in comparison to pure Copper

Copper





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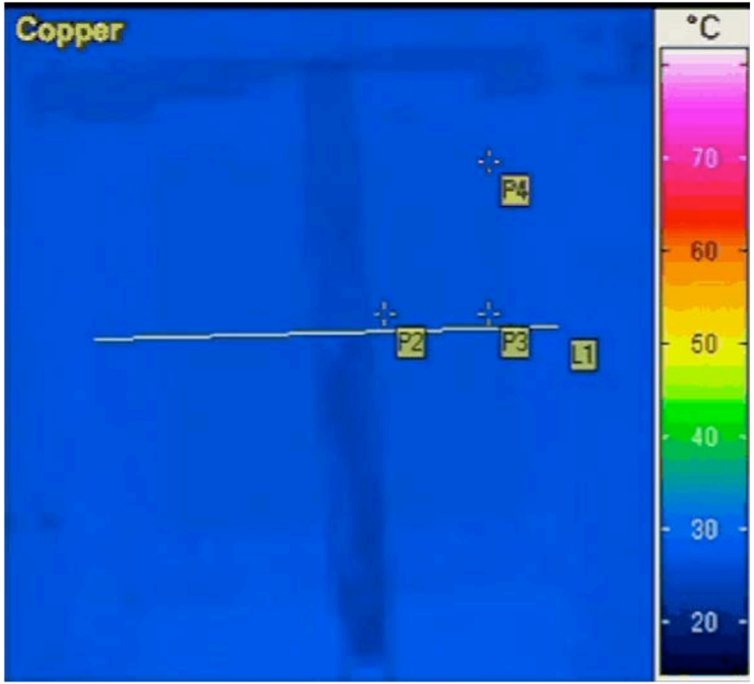

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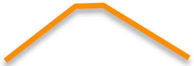
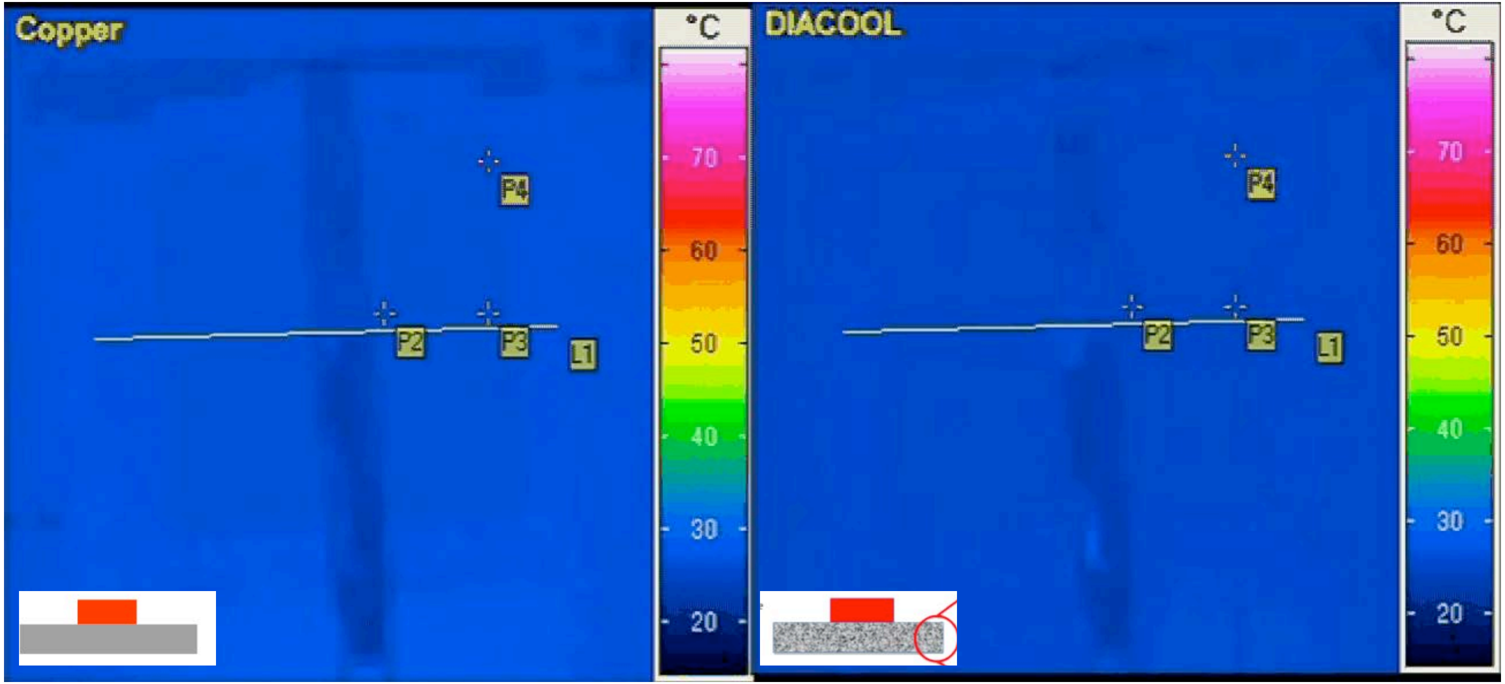


Copper-Diamond



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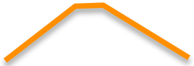
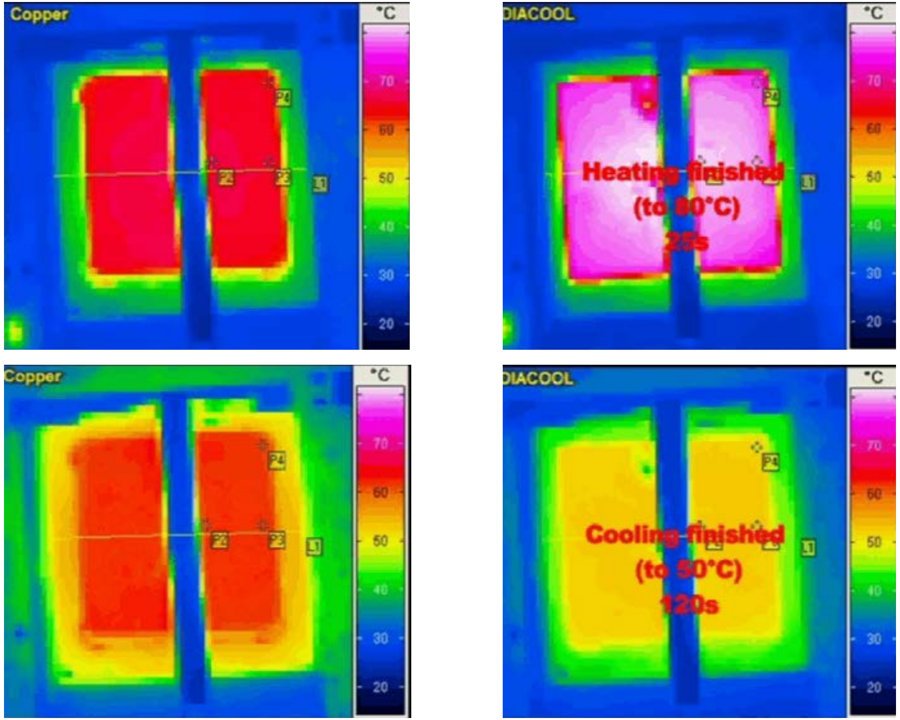


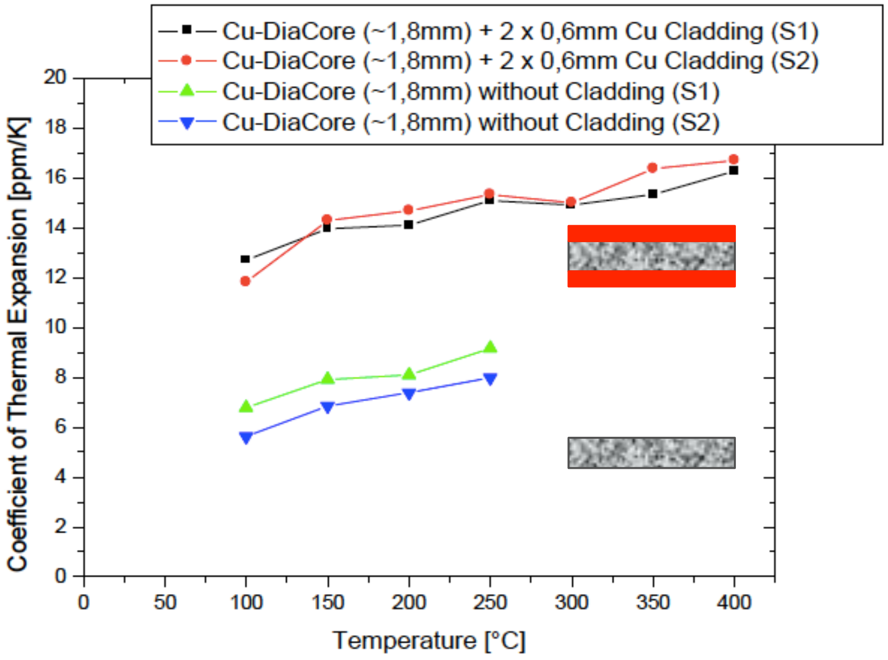
Cu-Diamond



Heating up to 80°C finished **in 25 s compared to 60 s** for copper

Cooling down to 50°C is finished **in 120s compared to 260 s** for copper

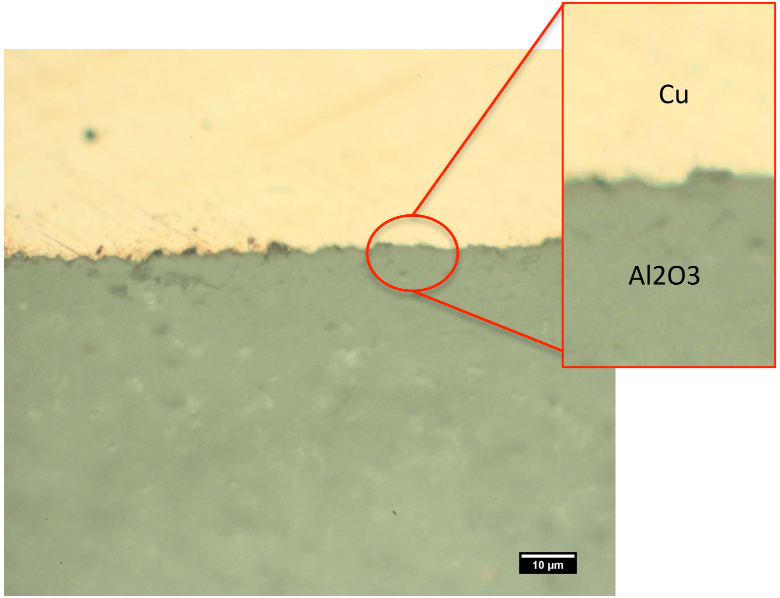
CTE and sandwich structures

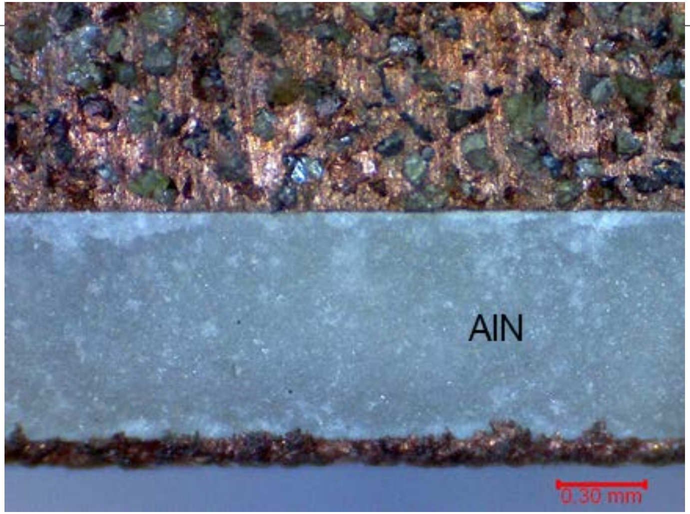


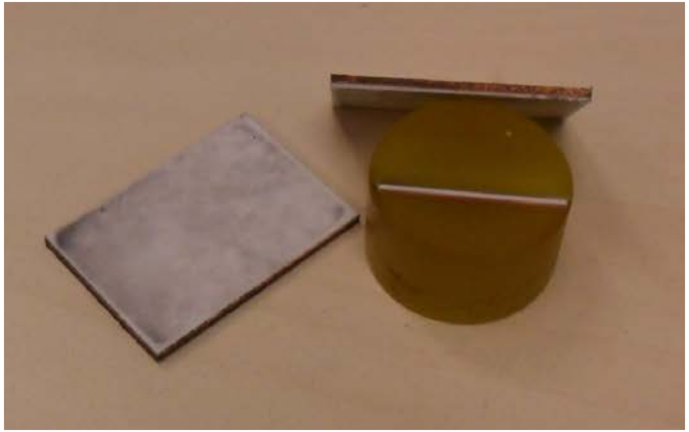
Copper-Diamond (rapid hot pressed):
for thin cladding layers compared to the composite core, the coefficient of thermal expansion is dominated by the one of the core. Obviously this is no longer true, when cladding layer and core have similar thicknesses.

MMC – Ceramic Compounds

- Bonding of Copper to Alumina Substrate
- At the same time bonding of the copper-Diamond composite to the Alumina Substrate.
- Also tested for AlN as Ceramic substrate.



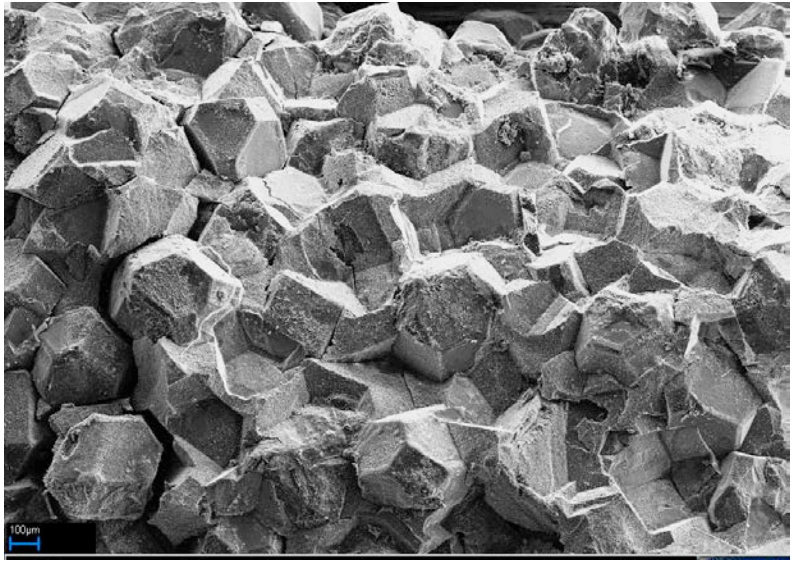




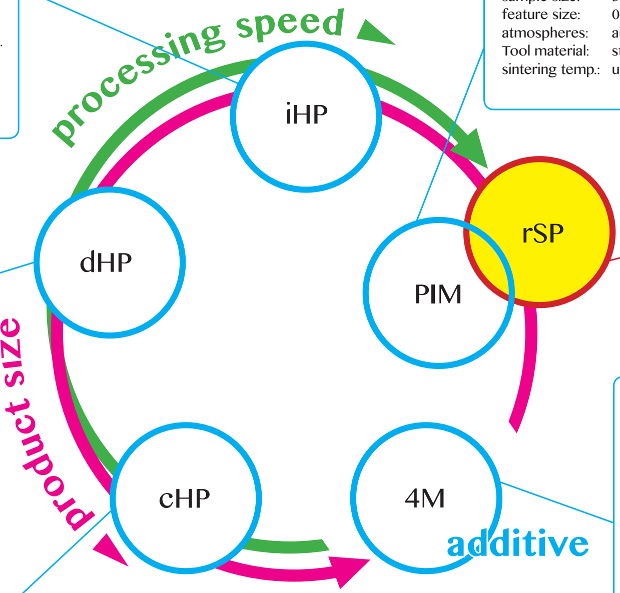
Diamond-Ceramic Composites

AlN (with additives) – Diamond Composite

On both sides of the Composite Core, ceramic cladding layers were added for machining to produce good surface quality. Thermal conductivites close to 300 W/mK can be achieved up to now.



Manufacturing Processes (cont‘d)



inductive hot pressing

cycle time:	10 - 60 min
sample size:	10 - 50 mm Dia.
atmospheres:	Vac., N_2, Ar, froming gas
Tool material:	graphite
heating rate:	20-300K/min

powder injection moulding

injection cycle:	5 - 30 sec / sintering several hrs
sample size:	3 - 50 mm Dia., best below 8g/part
feature size:	0,1 mm, nano sizes
atmospheres:	air, vac., H_2, N_2, Ar, froming gas
Tool material:	steel for injection, pressureless sintering
sintering temp.:	up tp 2.500 C

direct hot pressing

cycle time:	1/2 - 6 hrs
sample size:	300 mm Dia.
atmospheres:	Vac., N_2, Ar, froming gas
Tool material:	graphite
heating rate:	20-300K/min

rapid sinter pressing

cycle time:	10 - 90 sec
sample size:	10 - 30 mm Dia.
atmospheres:	air, shielding gas
Tool material:	steel, ceramic up tp 150 MPa
heating rate:	1000 - 4000 K/min

conventional hot pressing

cycle time:	6 - 18 hrs
sample size:	200 mm Dia.
atmospheres:	Vac., H2, N2, Ar, froming gas
Tool material:	graphite
heating rate:	10-20K/min

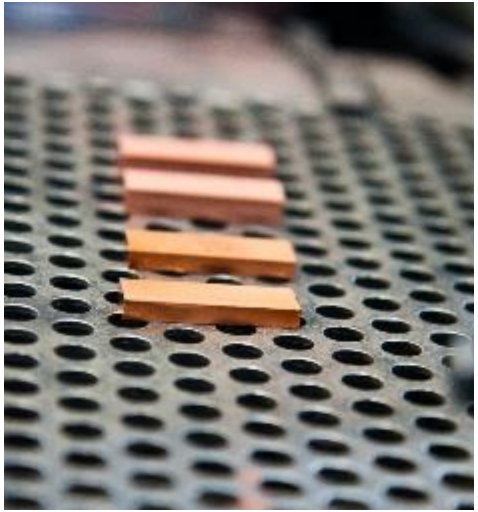
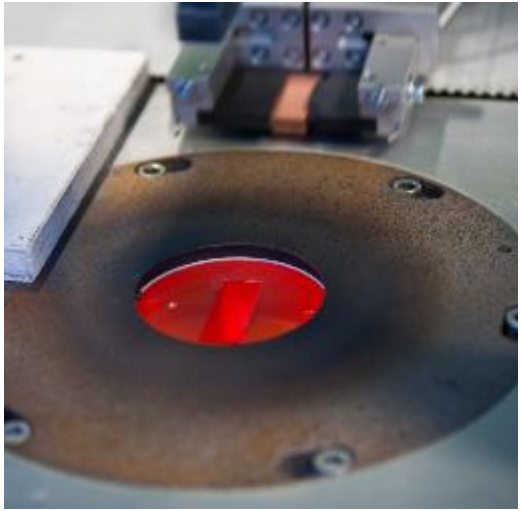
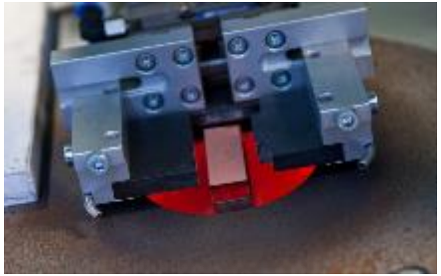
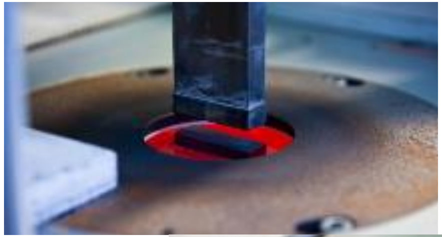
Powder Blown Manufacturing

cycle time:	5 min - several hrs
sample size:	up to 1,5 x 2 m
feature size:	min. 1 x 1 mm
atmospheres:	air, shielding gas
Tool material:	no tools needed
technology:	plasma transfer arc

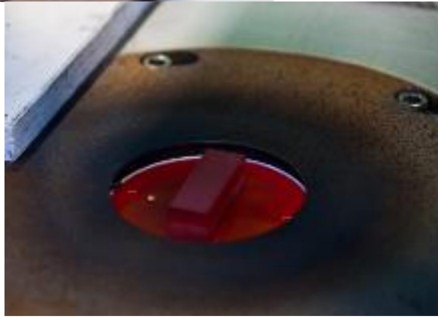
Multi Material Systems
graded components
3D printing

Focus on light weight metals like
Ti, Al, Mg and composites
as well as tough and hard coatings

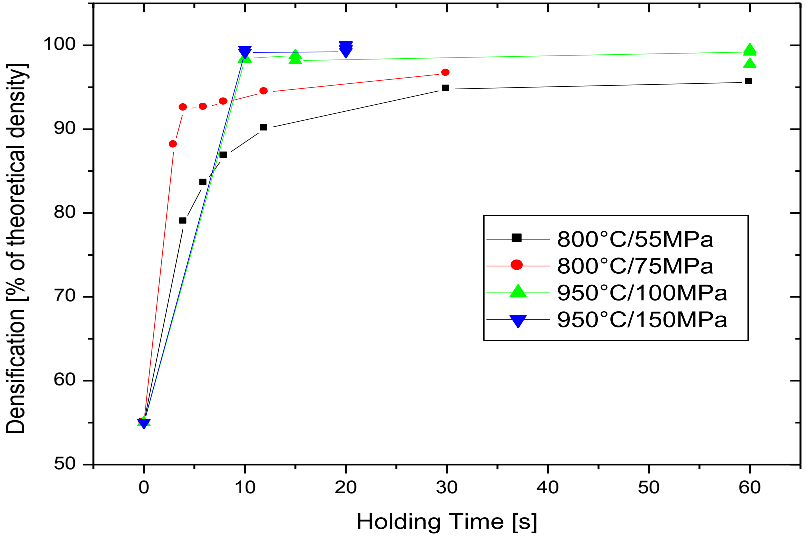
Processing steps of Rapid Sinter Pressing

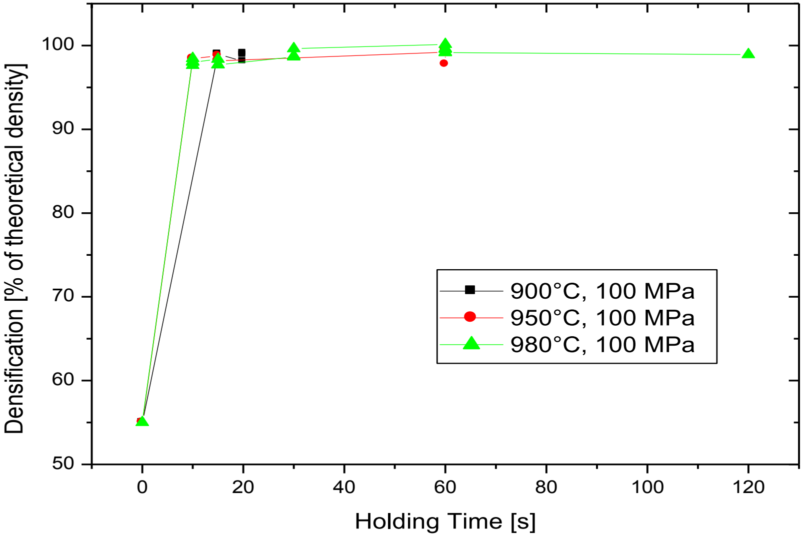





- RSP-Technology allows the densification of powders in seconds
- RSP uses a permanently heated cavity (e.g. up to 950°C) in which a compacted green part is inserted and densified by pressure (up to 150 MPa)
- RSP is a method which is suitable for the manufacturing of parts in large volume



Example I: Densification Experiment of Copper powders using RSP

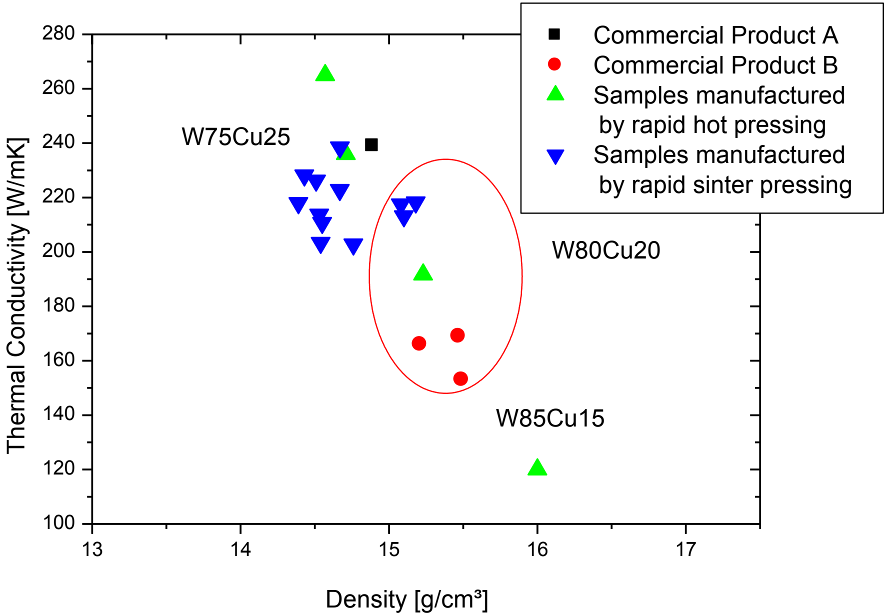


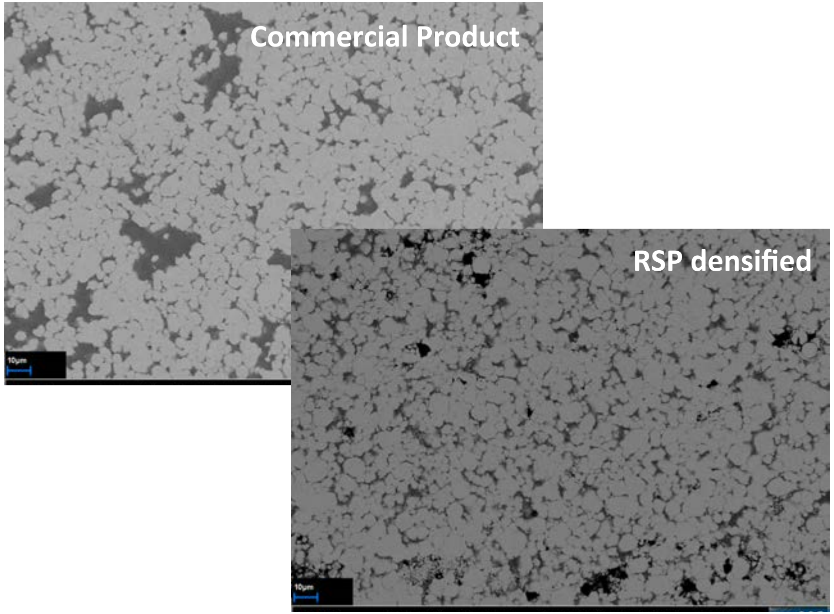


Densification as a function of different holding time and pressures

Example II: Tungsten-Copper

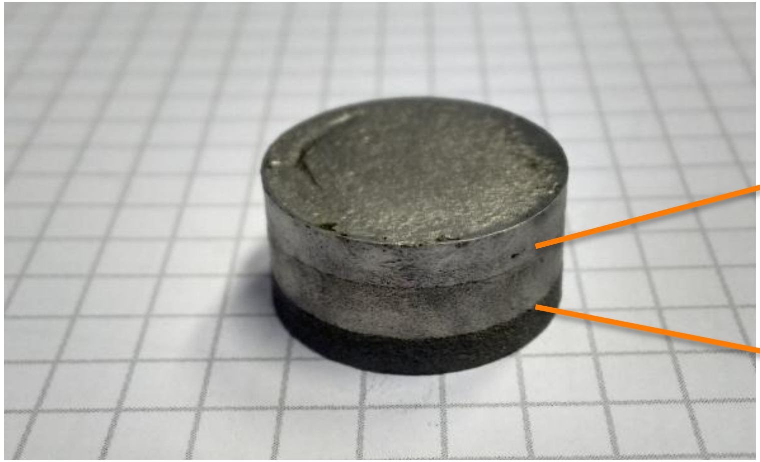
- Cu-W Composites with a W content >75 wt% are often produced by using a W-preform followed by infiltration
- **Question:** is it possible to obtain composites with a high densification at a W content of >75 wt% by using the RSP technology for consoldiation?

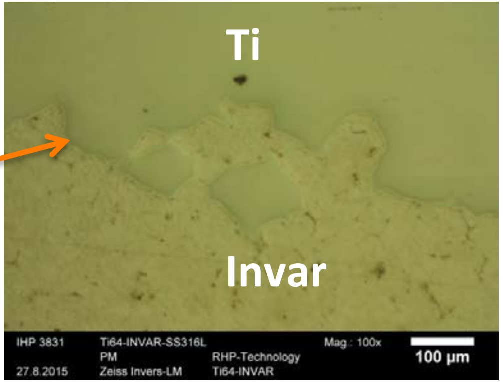


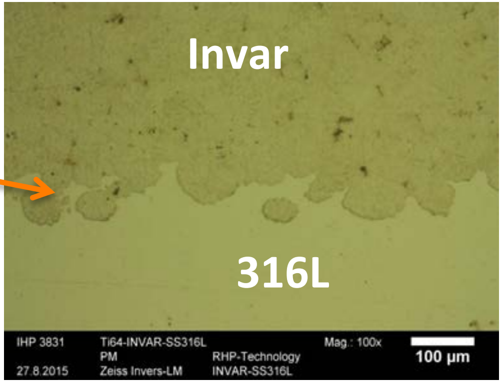


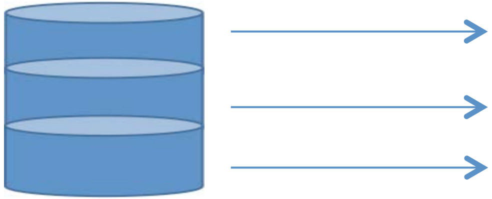
Example III: Multimaterial Structures

RSP allows to place the right material at the right position => made in less than 60 seconds from powders







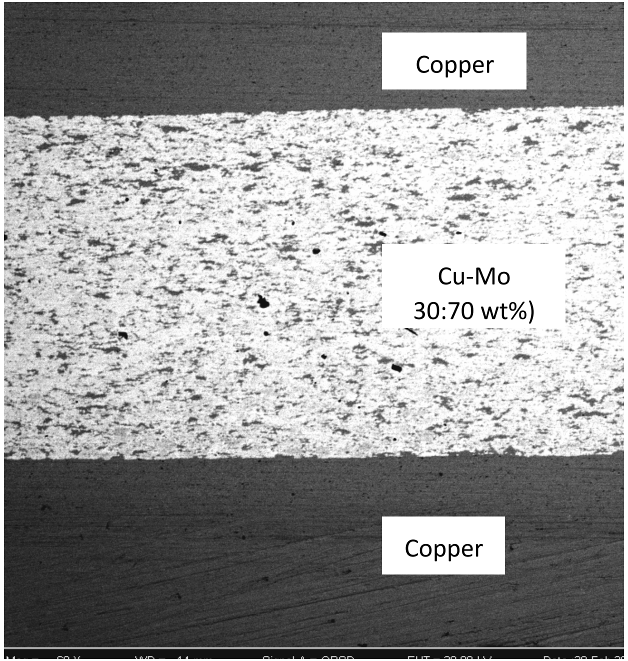


Layer that can withstand e.g. high operating conditions (thermal, chemical, wear etc.)

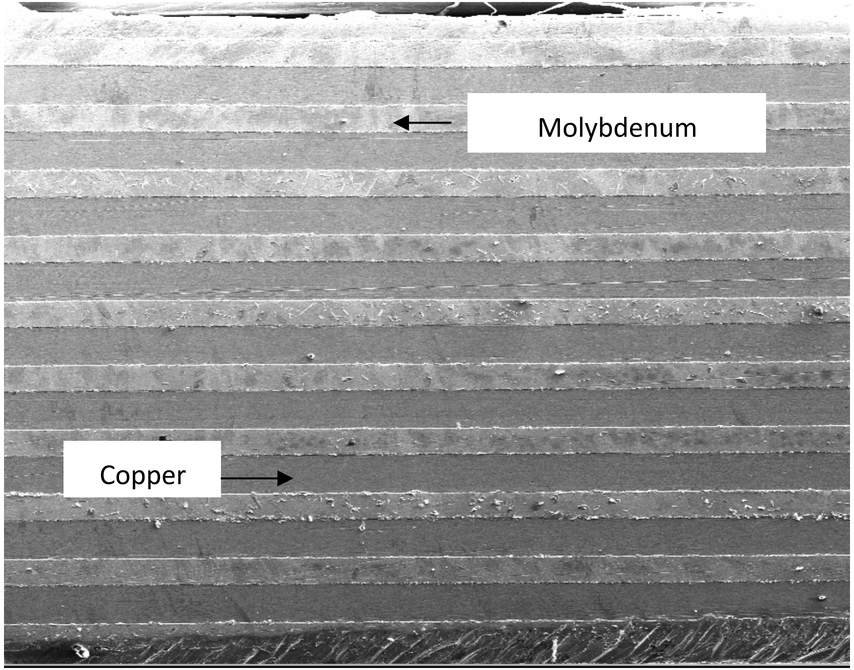
transition layer

Layer for joining to the rest of the system (steel for making threads, etc.)

Example IV: further „Design“ Possibilities

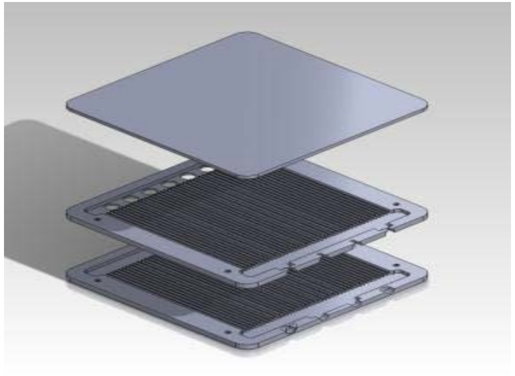


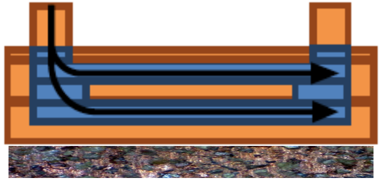
Sandwich Structure

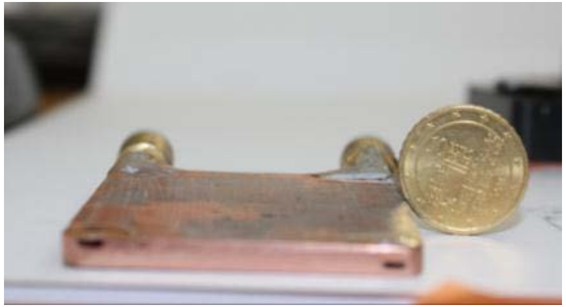


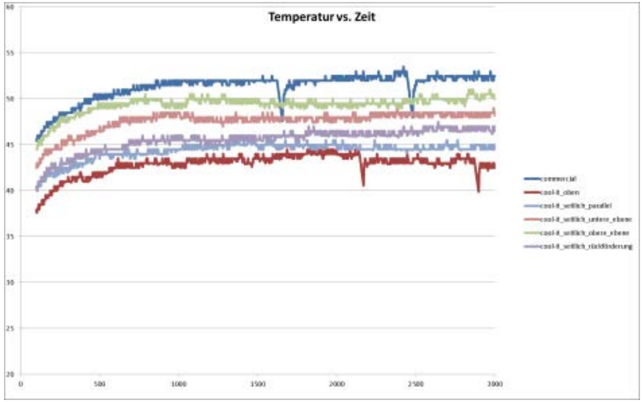
Multilayer Structure

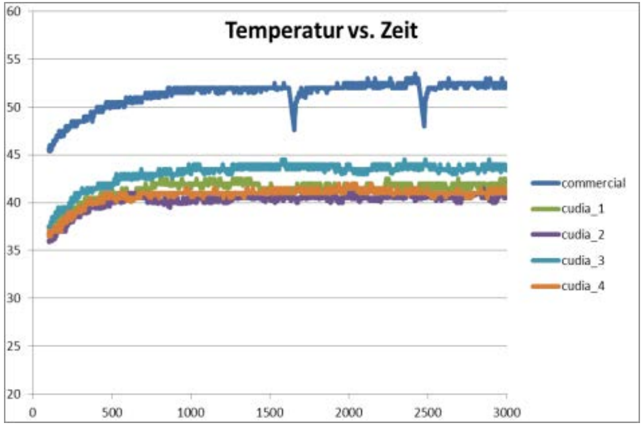
Multi Channel Cooler (with and without Diamond MMC)



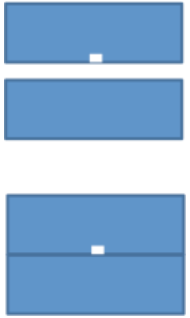






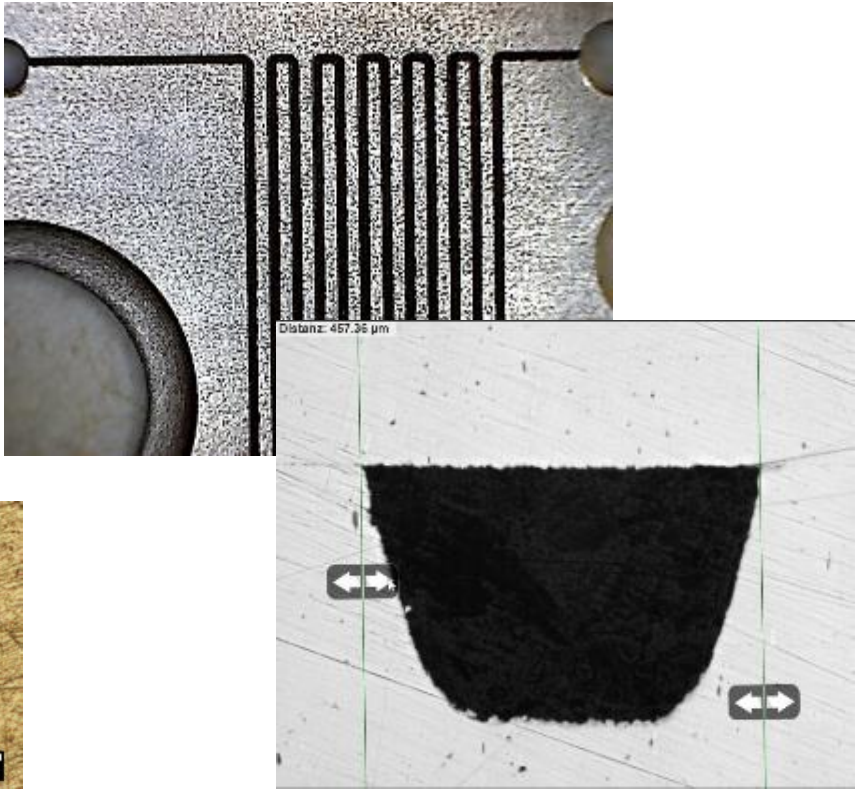


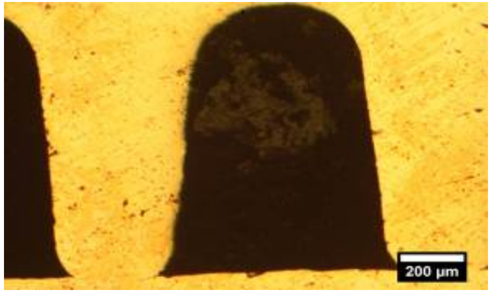
Channel Structures

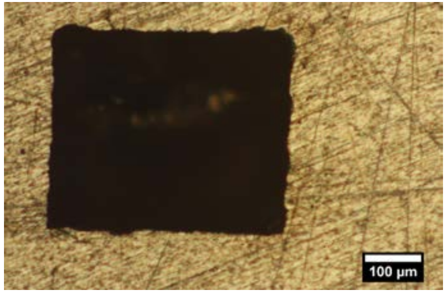


2D structured metals joined by diffusion bonding:

- Copper
- Aluminium
- Steel
- Titanium





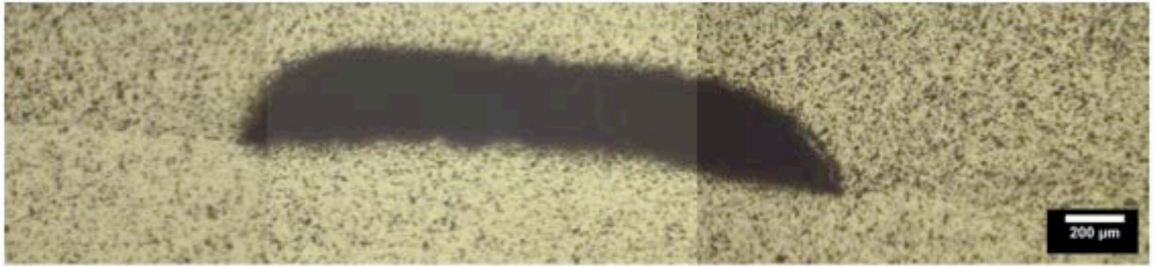


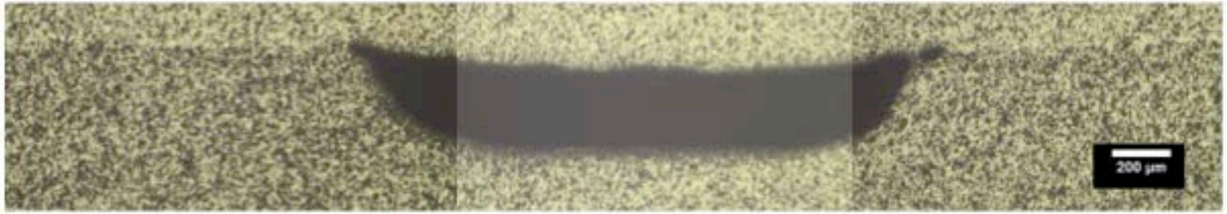
Joining of Ceramics - preliminary

2D structured ceramics joined by diffusion bonding

- AlN
- B4C

Up to now we have tested several ceramic materials, AlN and B4C showed very promising results. This is also possible for isotope enriched materials e.g. 10B-B4C





Wrap-up

Summary

- Thermal Properties strongly depend on raw materials and consolidation parameters leading to interface formations.
- Engineering approaches like using inserts broaden the application range.
- Fast techniques allow to combine hard to consolidate material systems.
- Different channel structures can be manufactured for metals and ceramics.

THANK YOU FOR YOUR ATTENTION

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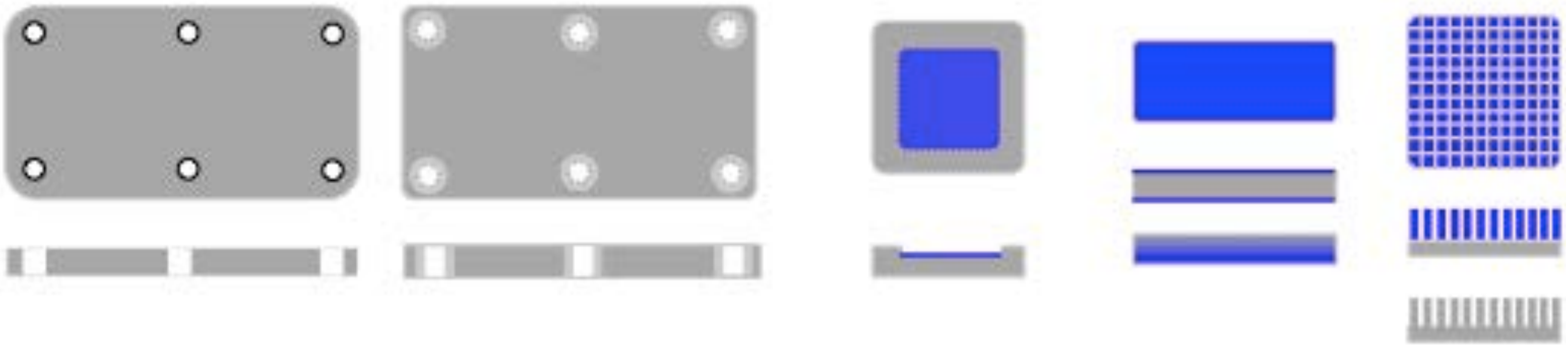
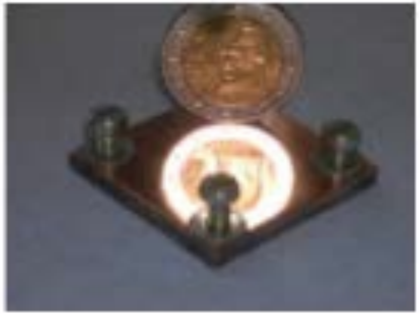
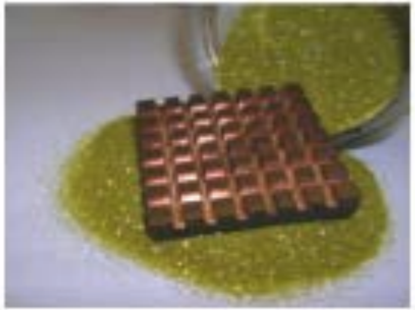
Backup Slides

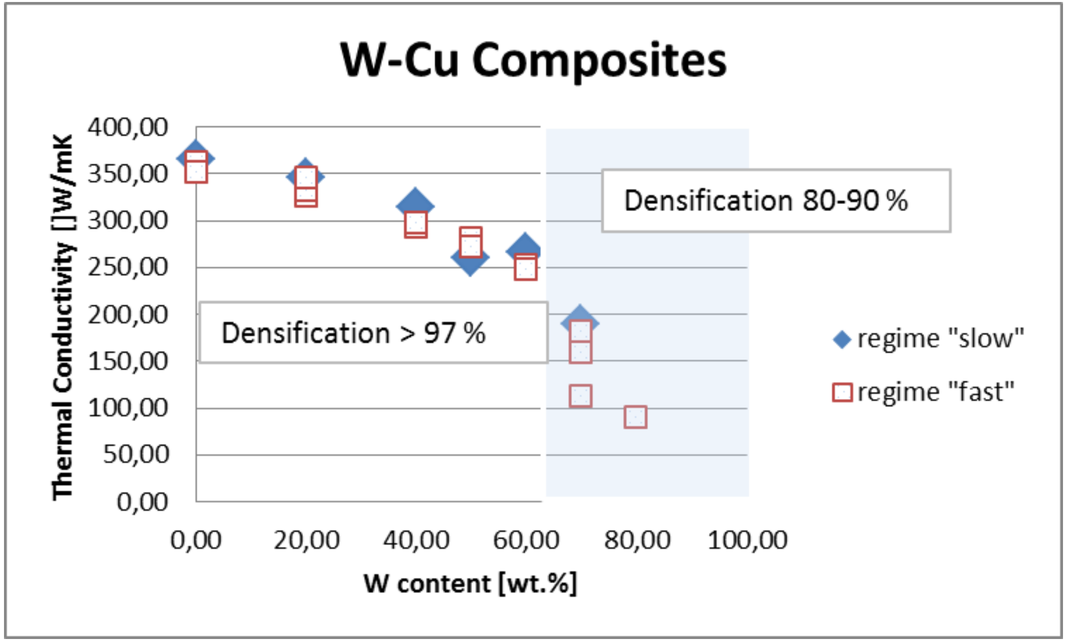
Design Possibilities

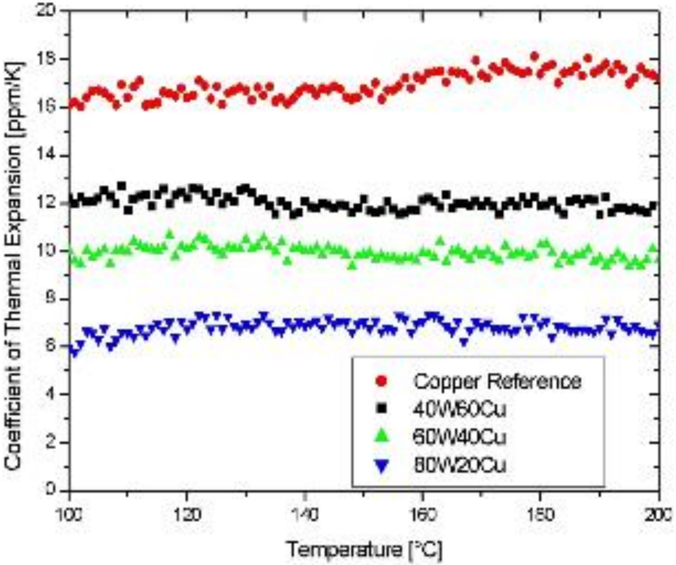






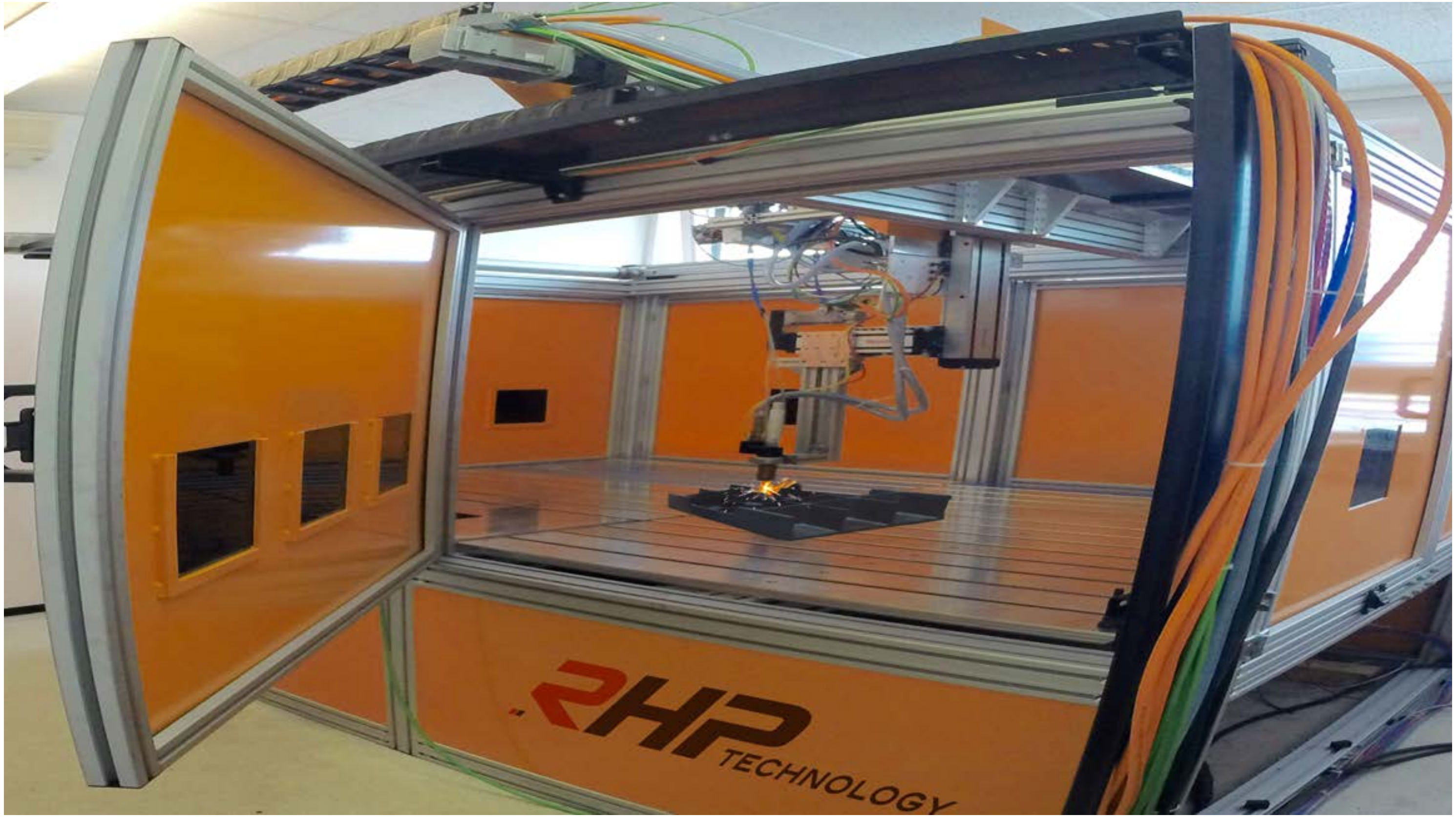
Manufacturing of W-Cu composites „fast“ vs. „slow“ processing





Thermal Conductivity of W-Cu composites as a function of the W content.

Coefficient of Thermal Expansion for W-Cu composites with different W concentration


RHP TECHNOLOGY

Parameter study on titanium