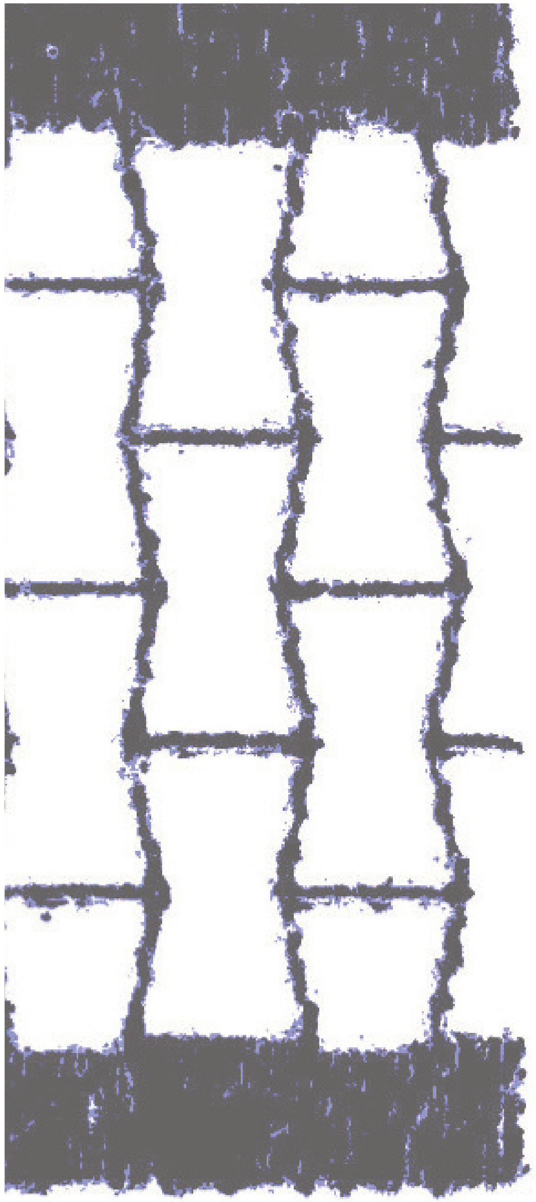

# Selective laser melting of Cu-based shape memory alloys


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# Acknowledgements



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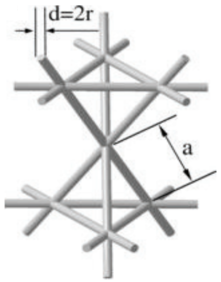
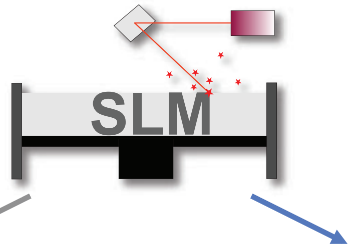
DFG Deutsche Forschungsgemeinschaft

CAPES

# SLM and metastability in metallic materials

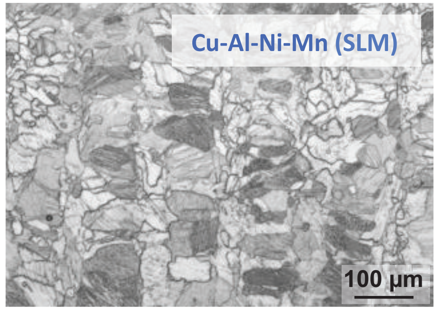





(i) Design + processing

(ii) Microstructure




## (i) Design + processing

- “Unlimited” design freedom, optimized topologies
- No need for dedicated tools/moulds

  → manufacturing of prototypes, …

*J.H. Zhu, Arch Computat Methods Eng 2015*

## (ii) Microstructure

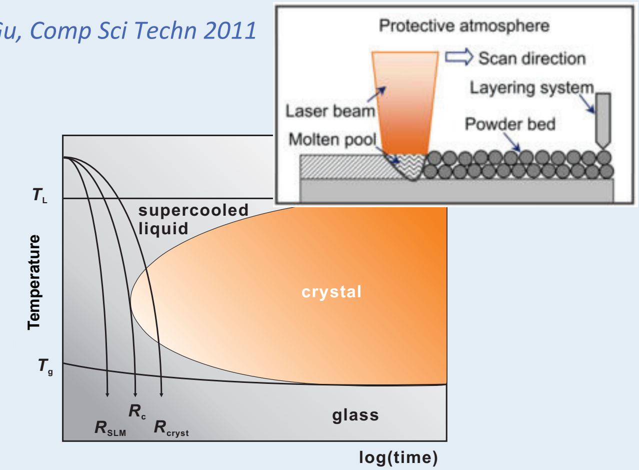
*D. Gu, Comp Sci Techn 2011*

- Fabrication split into multiple “casting steps”
- Small melt pool → high intrinsic cooling rates
- Supersaturation, grain refinement, metastable phases

  → metastable microstructures

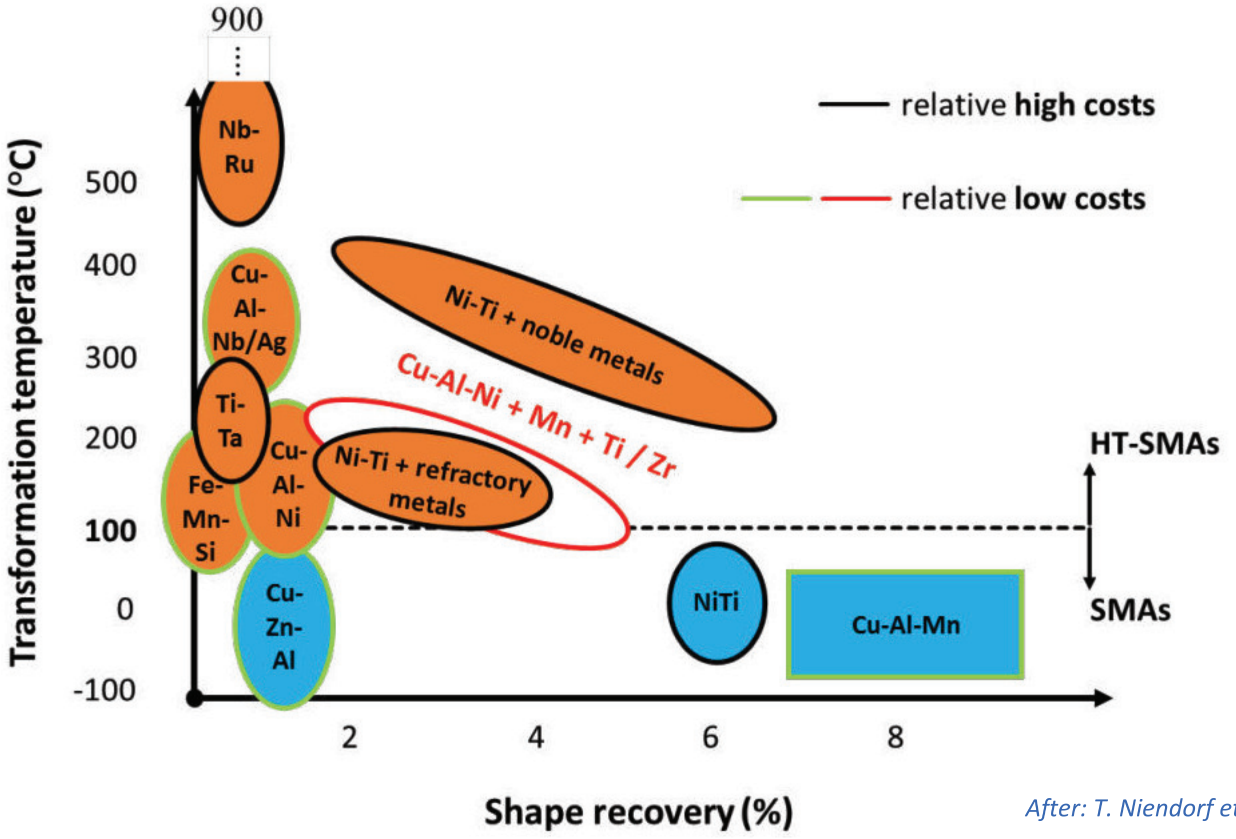
  → adjust microstructure locally (energy input, scan strategy, heating…)

  → metastable microstructures at large scales



# Shape-memory alloys (SMAs)






After: T. Niendorf et al. Acta Mater 2015

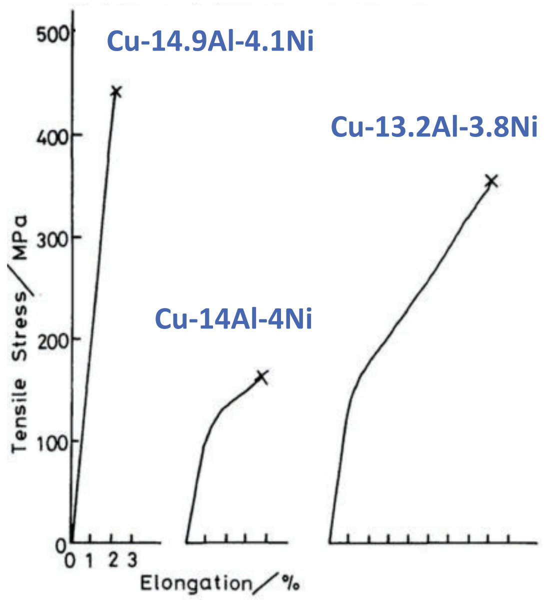

J. Mohd Jani et al. Mater Des 2014

**Cu-based SMAs:**

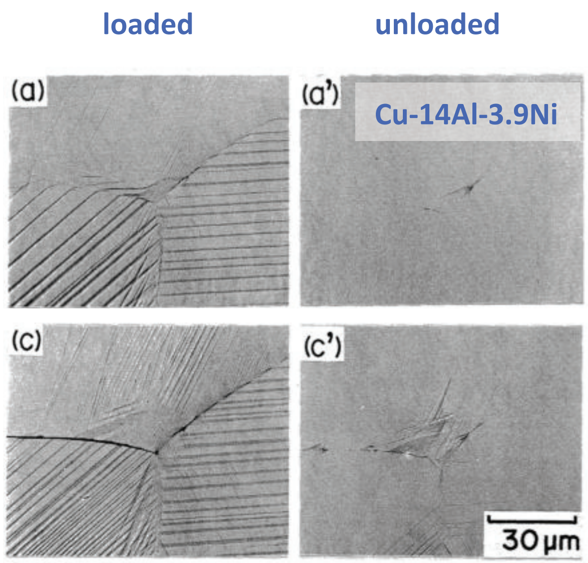
- **Cu-Zn-Al, Cu-Ni-Al**
- **Cost-efficient**

- **Good processability**
- **Good shape memory properties**
- **Transformation temperatures relatively high**

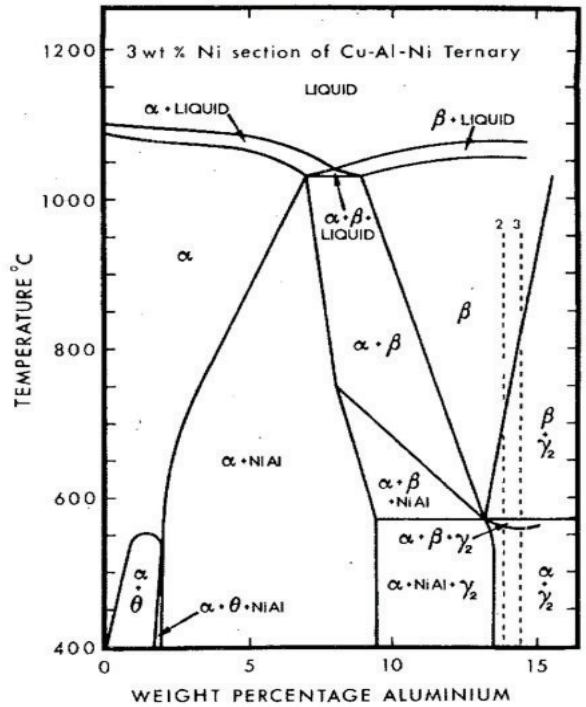
# Cu-based shape memory alloys




*H. Sakamoto et al. Trans JIM 1982*




*S. Miyazaki et al. Trans JIM 1981*




*D.P. Dunne et al. Metals Forum 1981*

- **Coarse-grained Cu-based SMAs are intrinsically brittle**
- **Elastic anisotropy → transgranular fracture**
- **Grain refiners (e.g. Ti, Zr, B, …), thermo-mechanical treatment, cooling rate ↑**
- **Avoid formation of eq. phases: α, $\gamma_2$ and NiAl**

# Outline



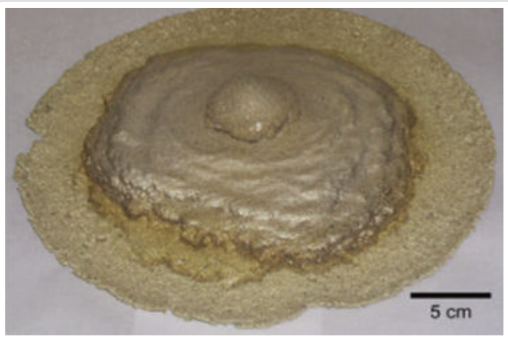
- Two compositions: Cu-11.85Al-3.2Ni-3Mn

  Cu-11.35Al-3.2Ni-3Mn-0.5Zr

- Effect of SLM parameters and SLRM on SME → tune properties

  → for comparison: spray forming and Cu-mould casting (+ annealing)

  → phase formation, grain size and ordering on SME




spray forming (SF)

Ø: 70 mm
h: 120 mm

induction casting (IC)

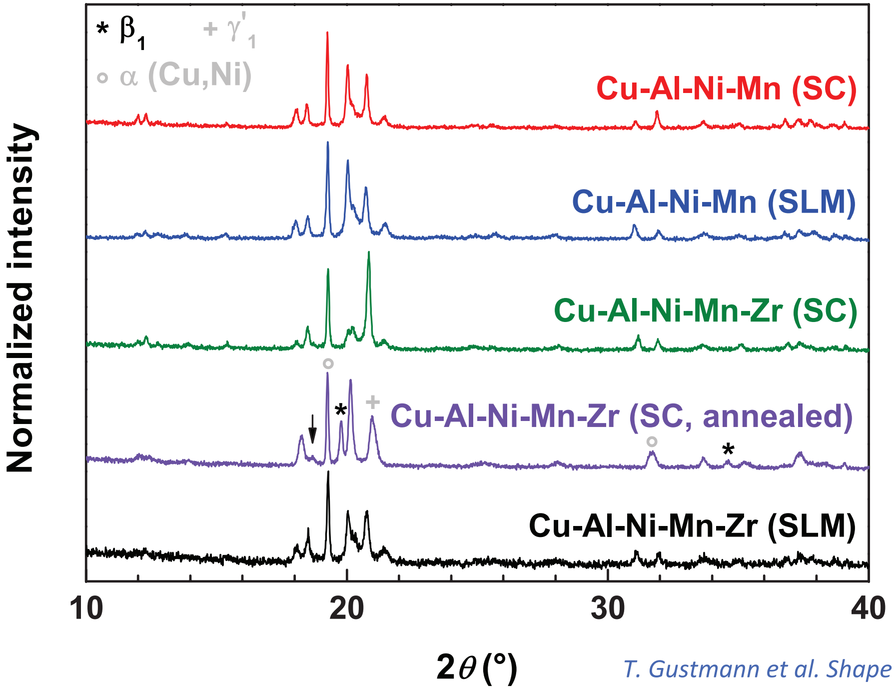
Ø: 3 mm
h: 80 mm

suction casting (SC)

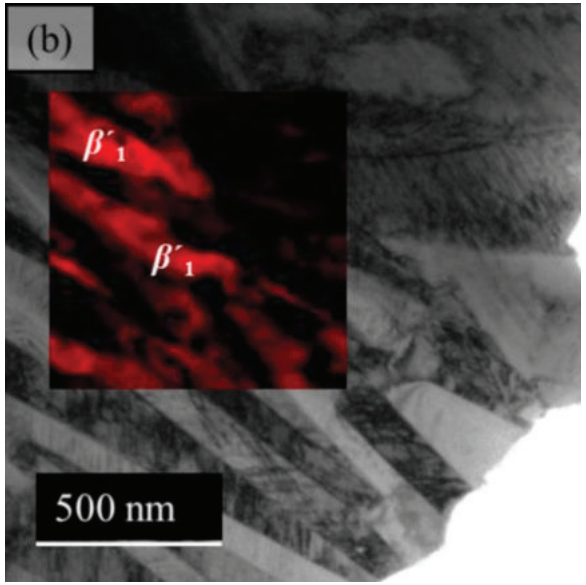
# Phase formation

Cu-11.85Al-3.2Ni-3Mn

Cu-11.35Al-3.2Ni-3Mn-0.5Zr




Cu-11.85Al-3.2Ni-3Mn, SLM




*T. Gustmann et al. Shape Mem Superelast 2016*

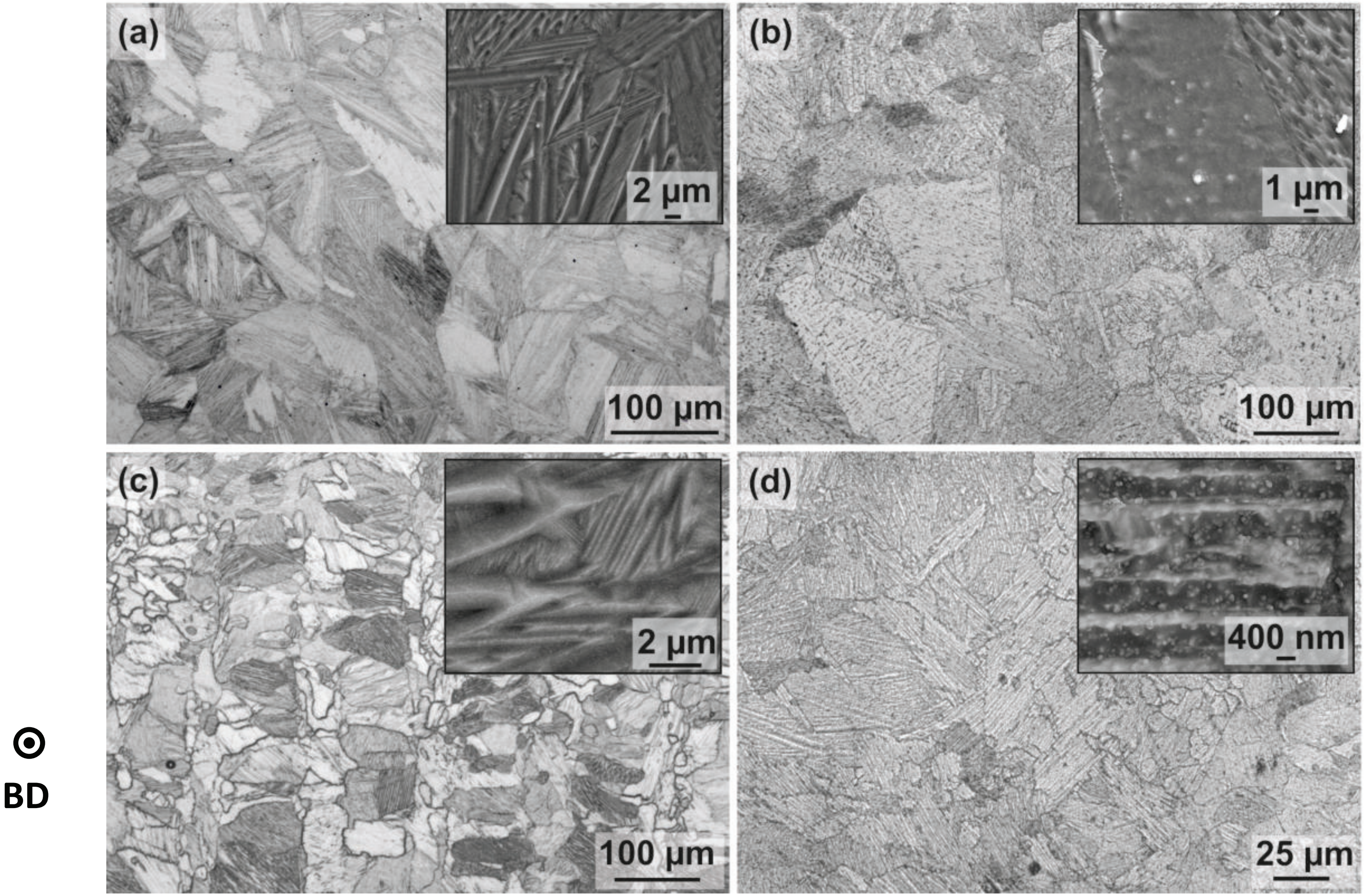
- $\beta_1$' martensite
- Phase identification difficult: broad peaks, multitude of phases
- Annealing: 10 mins @ 850 °C + water quenching + 60 mins @ 300 °C + slow cooling
- After annealing: $\beta_1$, α(?) and $\gamma_1$'(?) and additional phase (↓)

→ EDX + EBSD

# Phase formation and microstructure

Cu-11.85Al-3.2Ni-3Mn (cast, centre)

Cu-11.35Al-3.2Ni-3Mn-0.5Zr (cast, centre)




Cu-11.85Al-3.2Ni-3Mn (SLM)

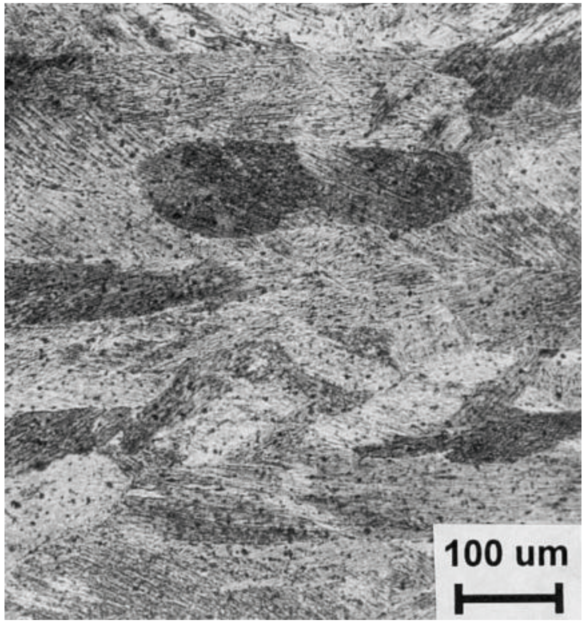
Cu-11.35Al-3.2Ni-3Mn-0.5Zr (SLM)

*T. Gustmann et al. Shape Mem Superelast 2016*

# Phase formation and microstructure



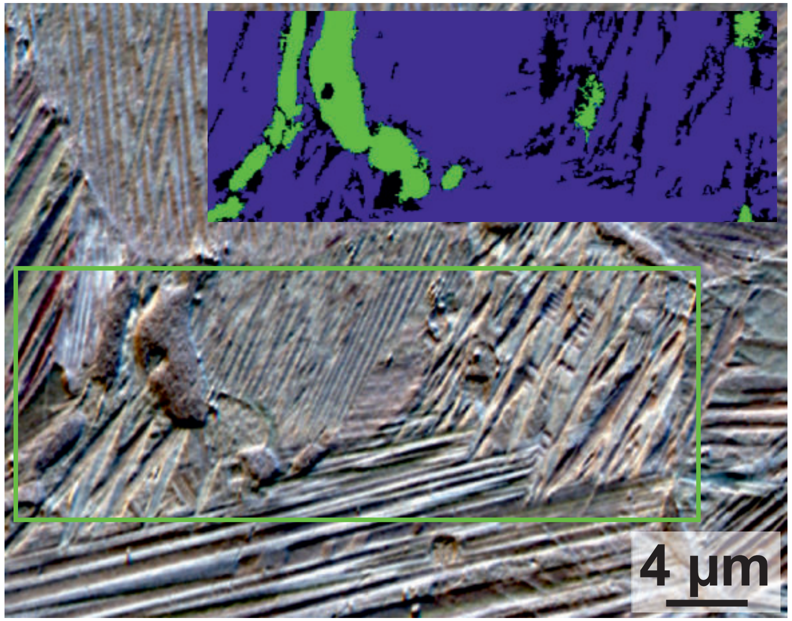
**Cu-11.4Al-2.5Ni-5Mn-0.4Ti**




*J. Dutkiewicz et al. MSEA 1999*

**cast Cu-11.35Al-3.2Ni-3Mn-0.5Zr, annealed**

$Cu_2AlZr$
$\beta_1'$




*T. Gustmann et al. Shape Mem Superelast 2016*

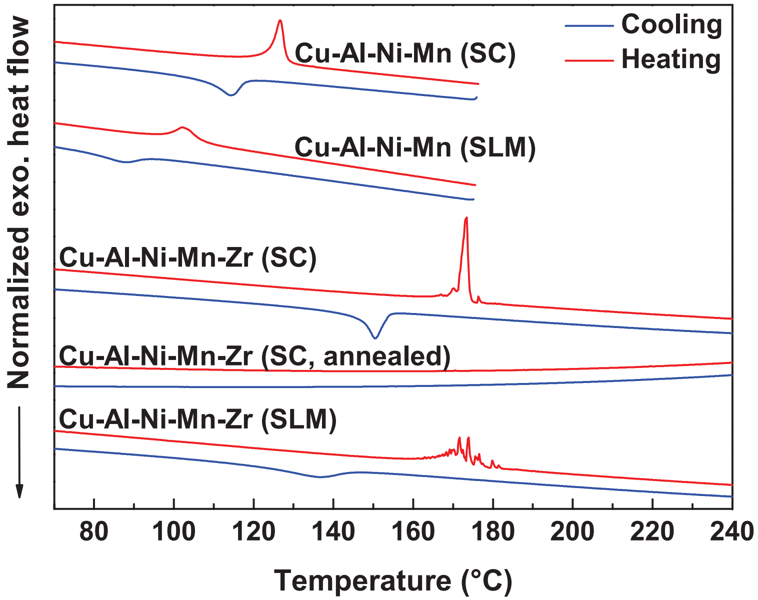
- **$Cu_2AlTi$ (X phase) in Cu-Al-Ni-Mn-Ti**
- **$Cu_2AlZr$ (Y phase, isomorphous to the X phase)**
- **Y phase very fine in as-prepared state**
- **No hints of $\alpha$, $\gamma_2$ or NiAl**

# Martensitic transformation

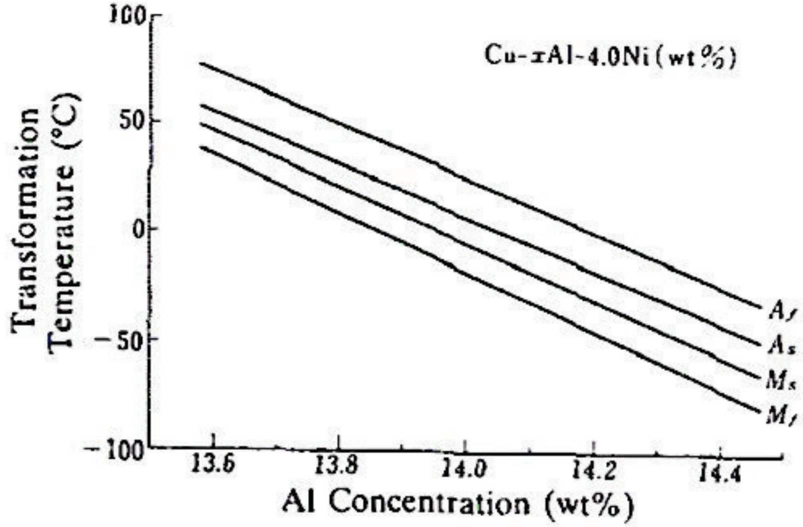


Cu-11.85Al-3.2Ni-3Mn

Cu-11.35Al-3.2Ni-3Mn-0.5Zr




*T. Gustmann et al. Shap Mem Superelast 2016*



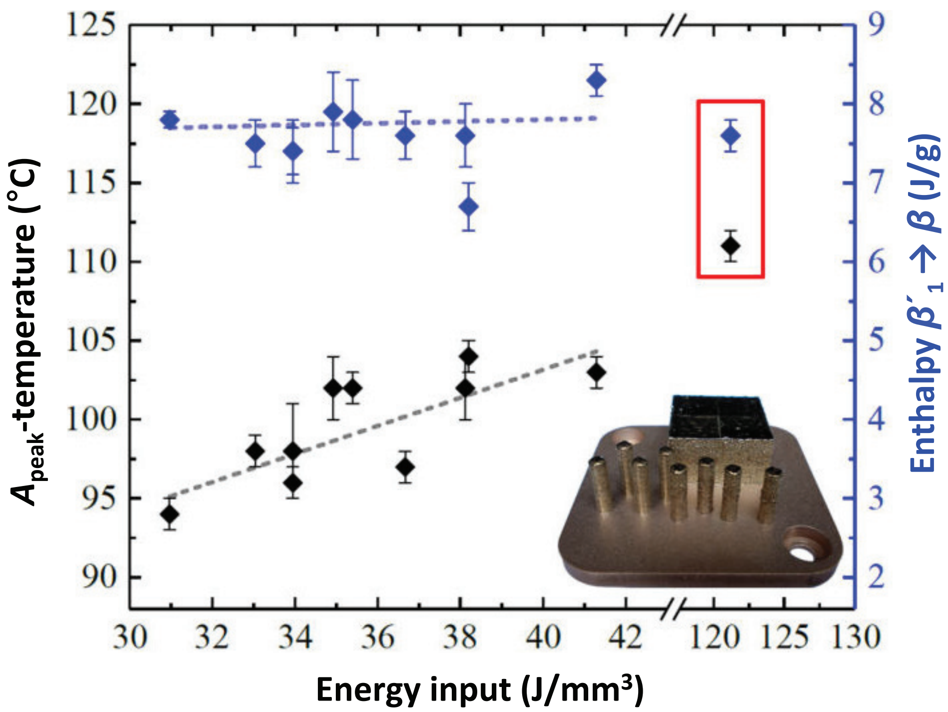

*T. Tadaki in Shape memory materials, 1998*

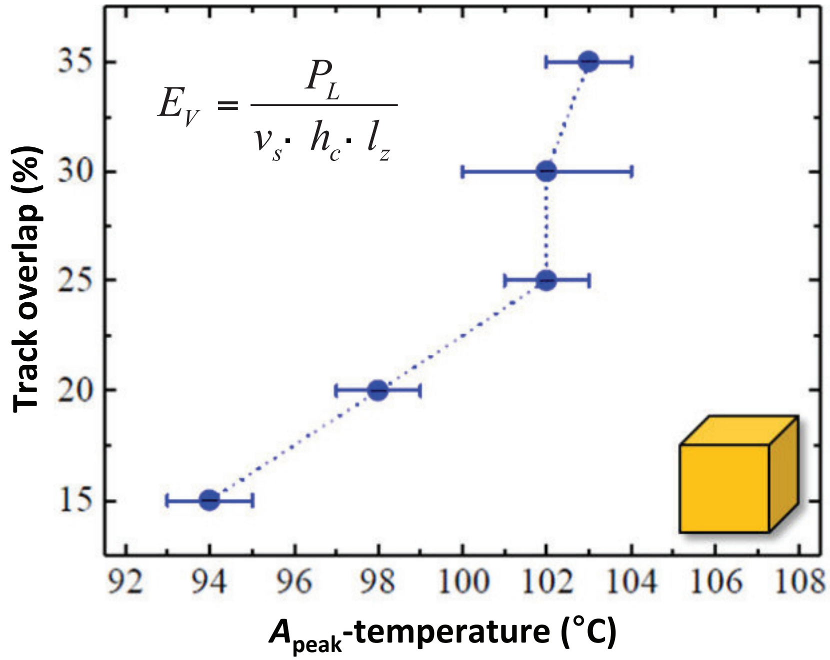
- **Transformation temperatures ↑ with Zr additions**
- **Fine Y phase: jerky transformation**
- **Fine Y phase: increase in MT temperatures**
- **Annealing: coarse Y phase at grain boundaries → no more MT**

**→ "switch off" SME locally in sample**

# Martensitic transformation and SLM parameters (Cu-11.85Al-3.2Ni-3Mn)

$P_L$ = 300 W ; $v_s$ = 500 mm/s ; 50 % track overlap ; $l_z$ = 50 µm



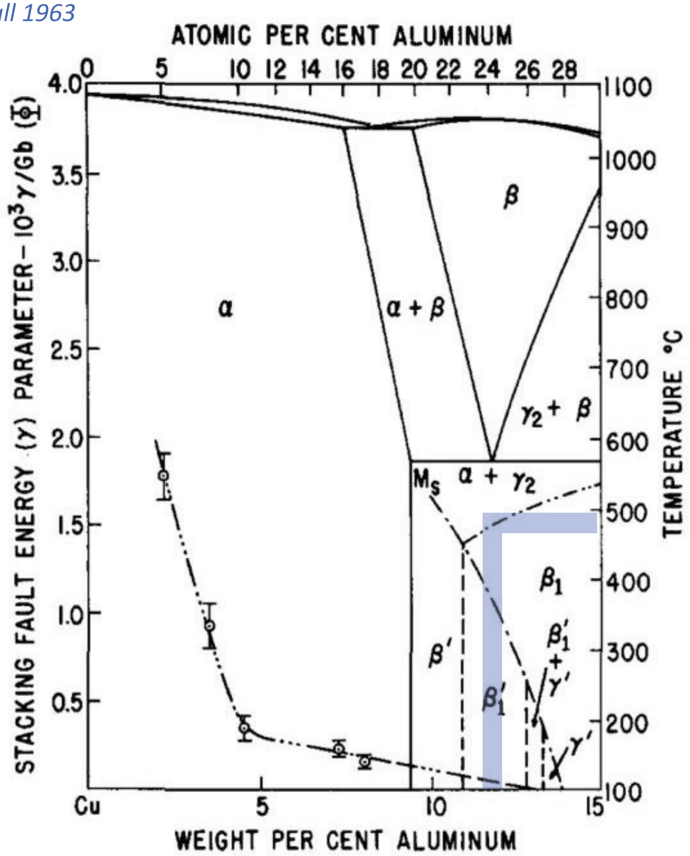



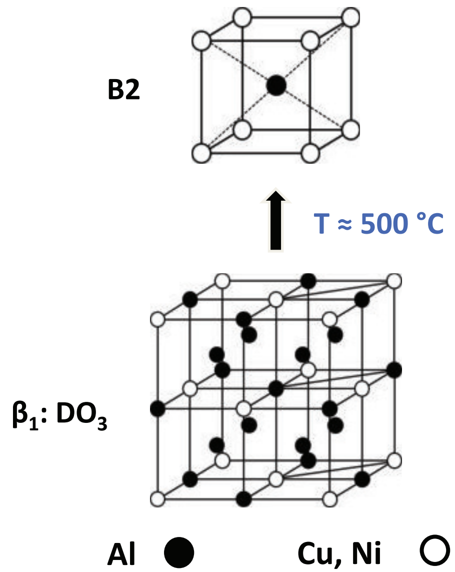

- **Transformation temperatures ↑ when energy input ↑ (no oxygen uptake)**
- **Temperature window: about 10 °C**
- **Local modification by changing the process parameters**

  **→ graded transformation**
- **Ordering and grain size**

# Effect of ordering in Cu-Al(-Ni)

*P.R. Swann et al. Acta Metall 1963*

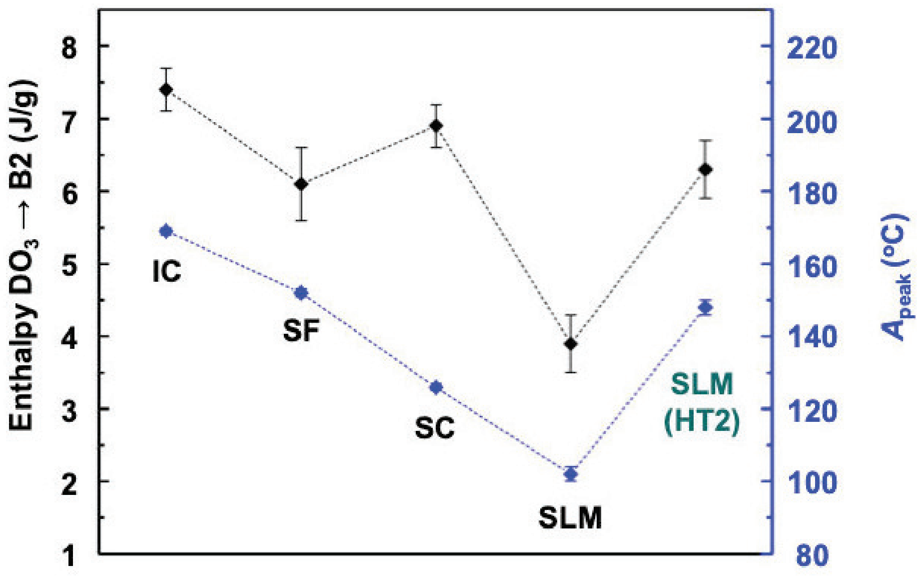


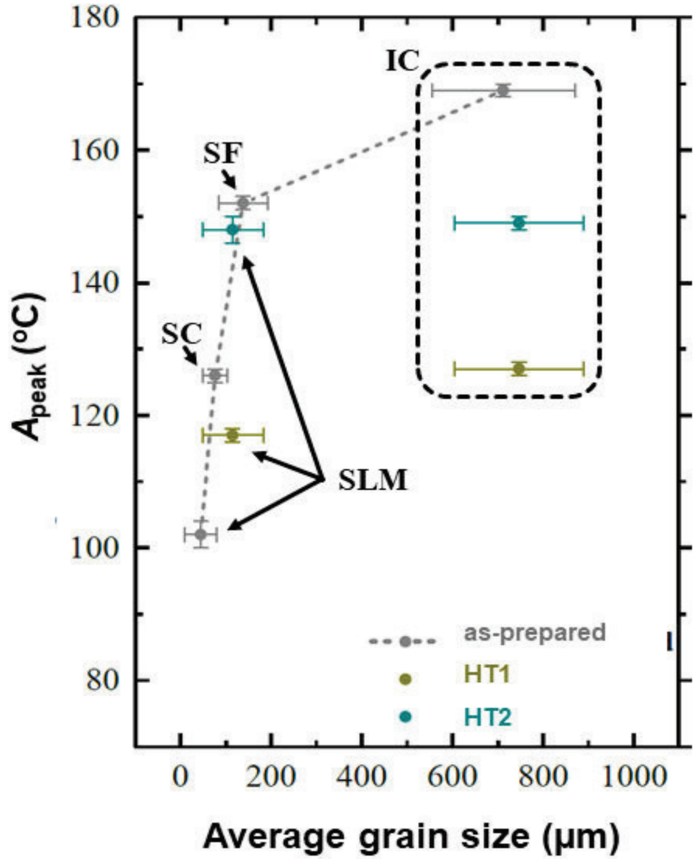

- $\beta_1$: $DO_3$ ordering, B2: ordered bcc (simple cubic)
- Variation of cooling rates
- Two heat treatments

# Effect of ordering in Cu-11.85Al-3.2Ni-3Mn






*T. Gustmann et al. unpublished*

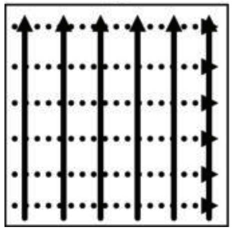



- HT1: 10 mins @ 850 °C + water quenching
- HT2: 10 mins @ 850 °C + water quenching + 60 mins @ 300 °C + slow cooling
- Suppression of $DO_3$-ordering → austenite stabilization
- Different processing: large transformation temperature window

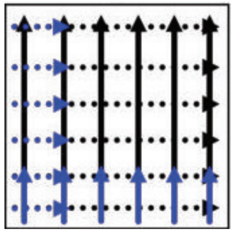
# Selective laser remelting (SLRM) of Cu-11.85Al-3.2Ni-3Mn

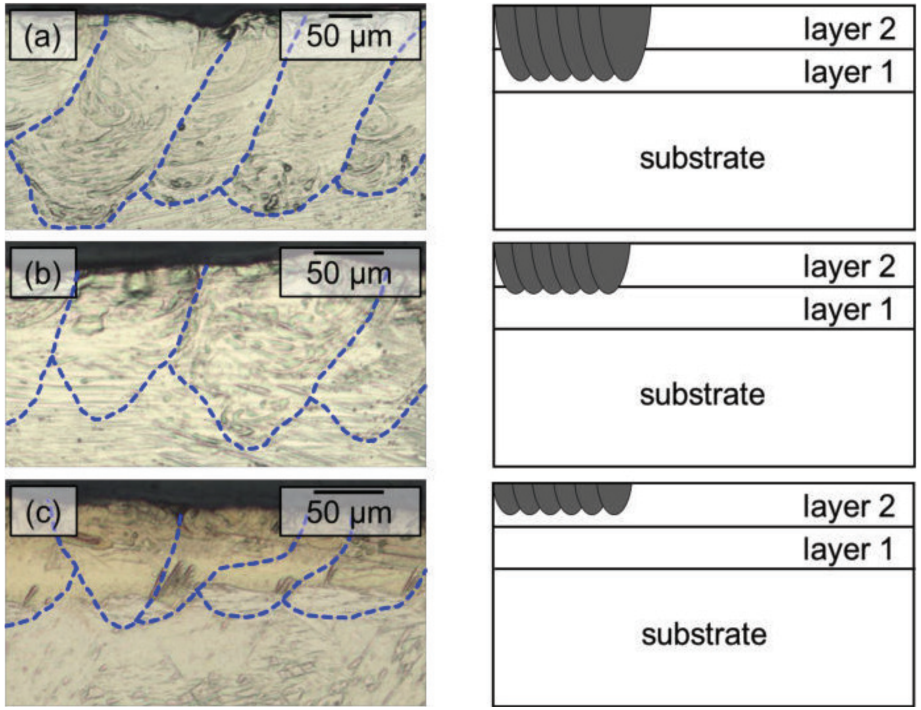


**SLM**



**SLM +**
**remelting (SLRM)**



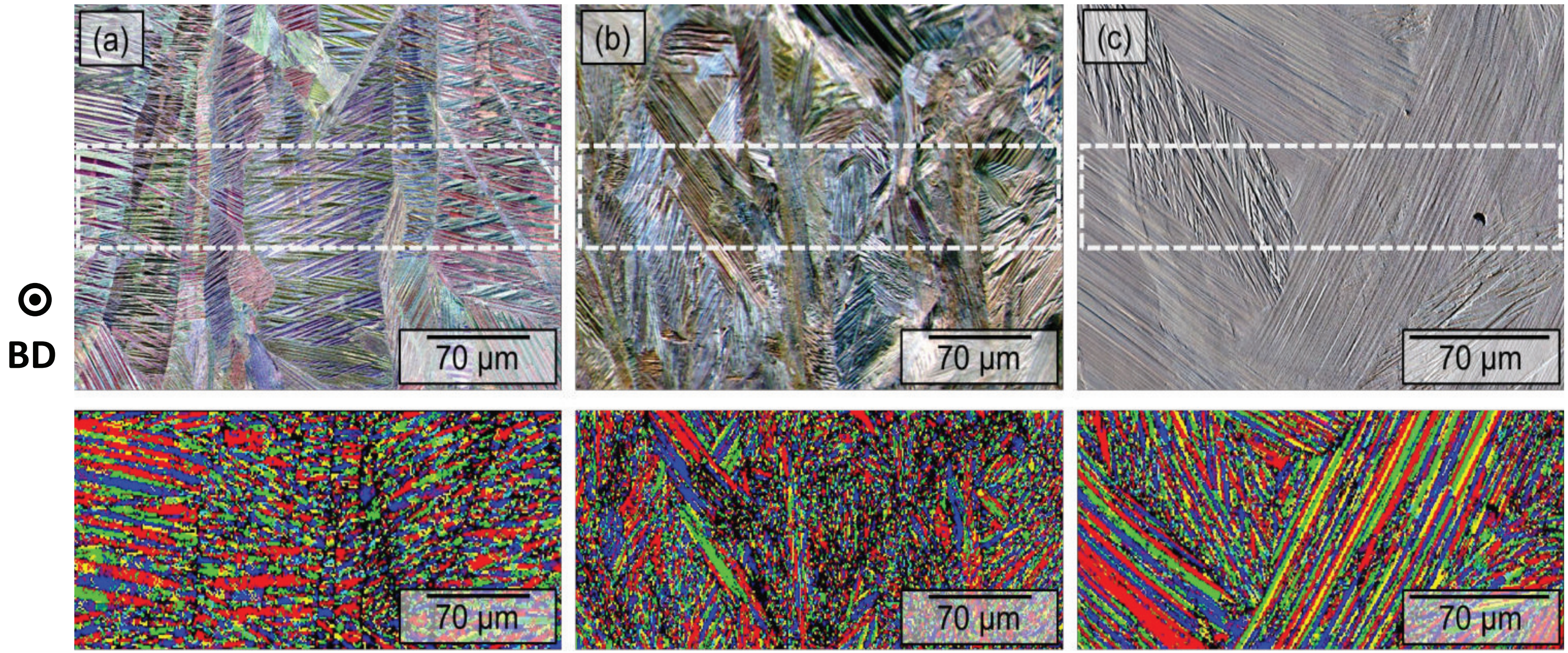



- **Increase in relative density (up to 99.5%)**
- **Systematic variation of energy input during remelting (30 – 250 J/mm³)**
- **Effect on microstructure?**
- **Influence on transformation properties?**

*T. Gustmann et al. Mater Design 2018*

# Selective laser remelting (SLRM) of Cu-11.85Al-3.2Ni-3Mn

SLM ($E_V$ = 38 J/mm$^3$) | SLRM ($E_V$ = 35 J/mm$^3$) | SLRM ($E_V$ = 204 J/mm$^3$)

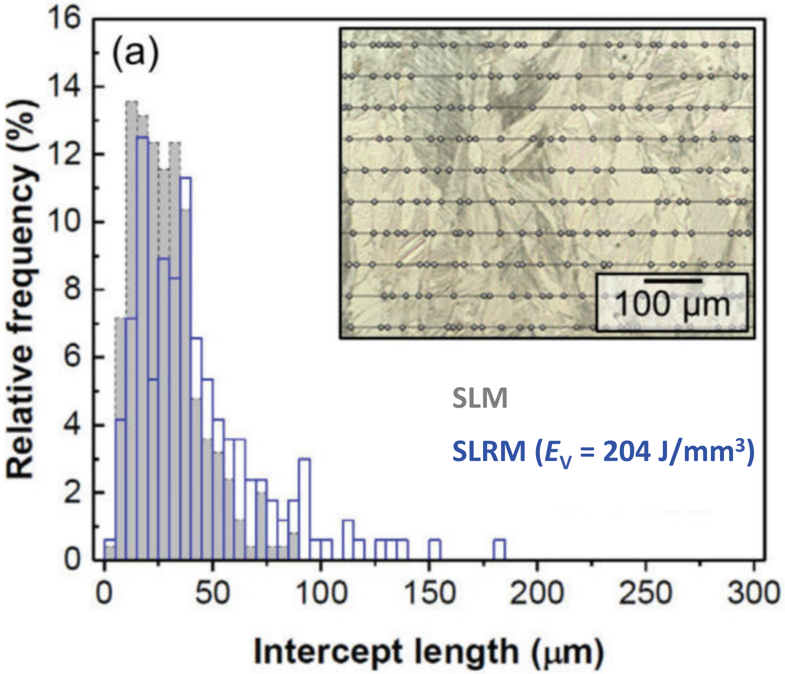


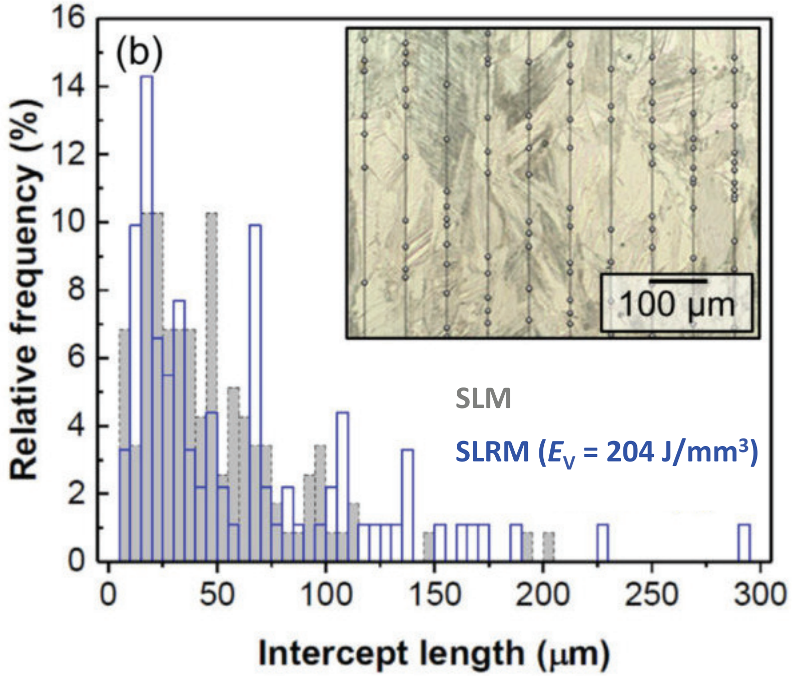

- Martensite variants become larger after remelting
- Reorientation of the variants

*T. Gustmann et al. Mater Design 2018*

# Selective laser remelting (SLRM) of Cu-11.85Al-3.2Ni-3Mn



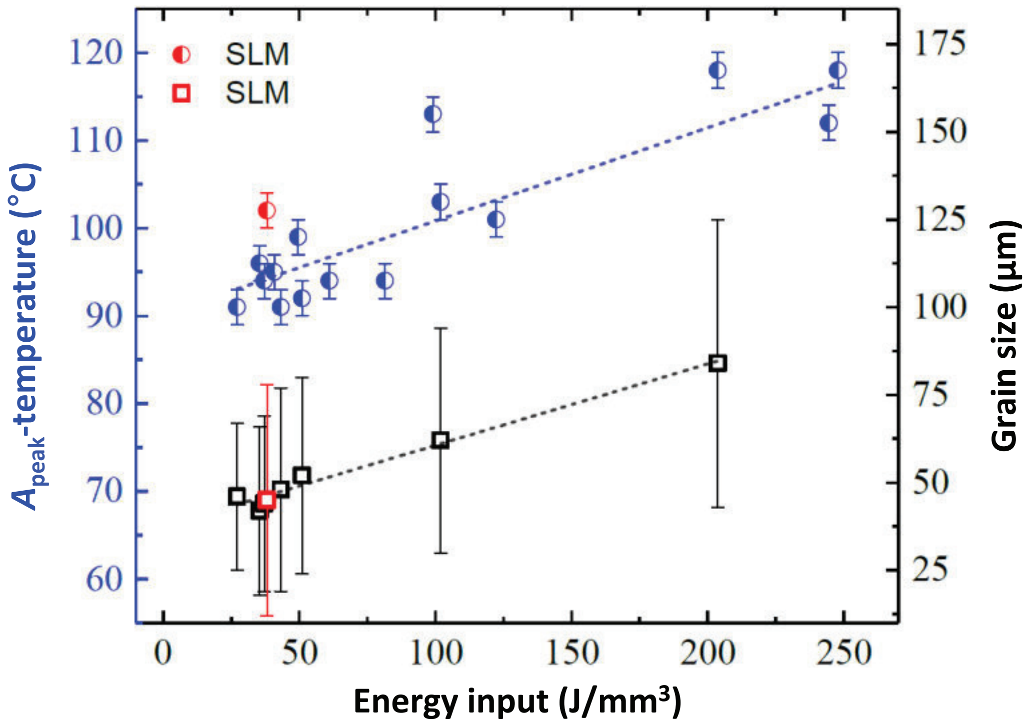



- **Grain size determined via intercepts**
- **Microstructure: difficult to quantify**
- **Energy input ↑ (remelting), grain size ↑**

*T. Gustmann et al. Mater Design 2018*

# Selective laser remelting (SLRM) of Cu-11.85Al-3.2Ni-3Mn



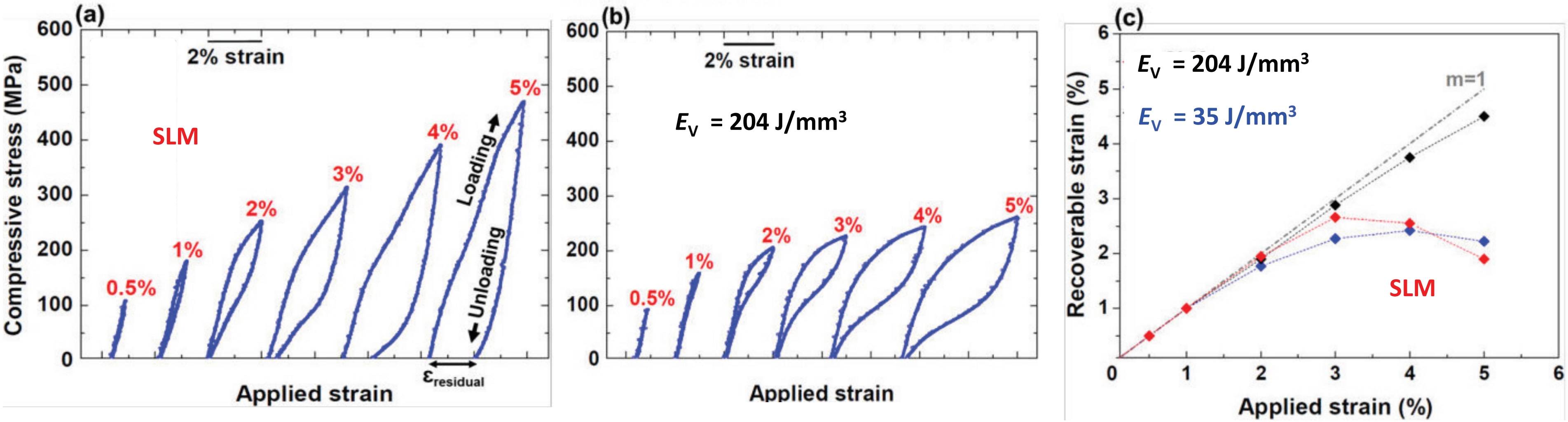

- **Transformation temperature increases with grain size**
- **Transformation temperature window about 30 °C**
- **Adjust transformation temperature through parameters**
- **SLRM: route to modify transformation temperatures even more**

*T. Gustmann et al. Mater Design 2018*

# Pseudoelasticity of Cu-11.85Al-3.2Ni-3Mn

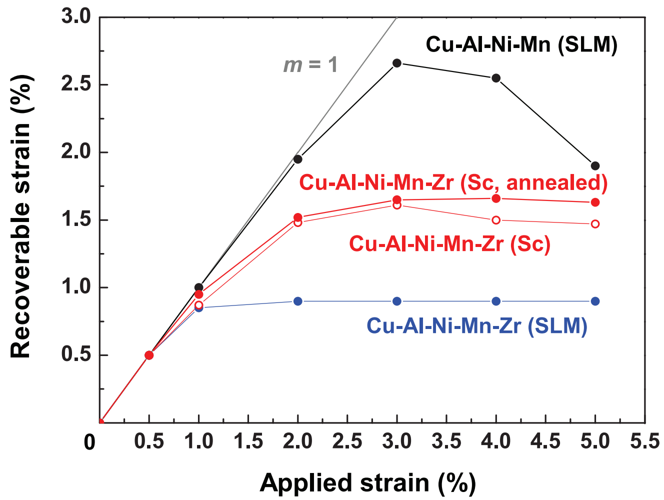
$T = A_f + 50$ °C

Recoverable strain = $\varepsilon_{appl} - \varepsilon_{res}$

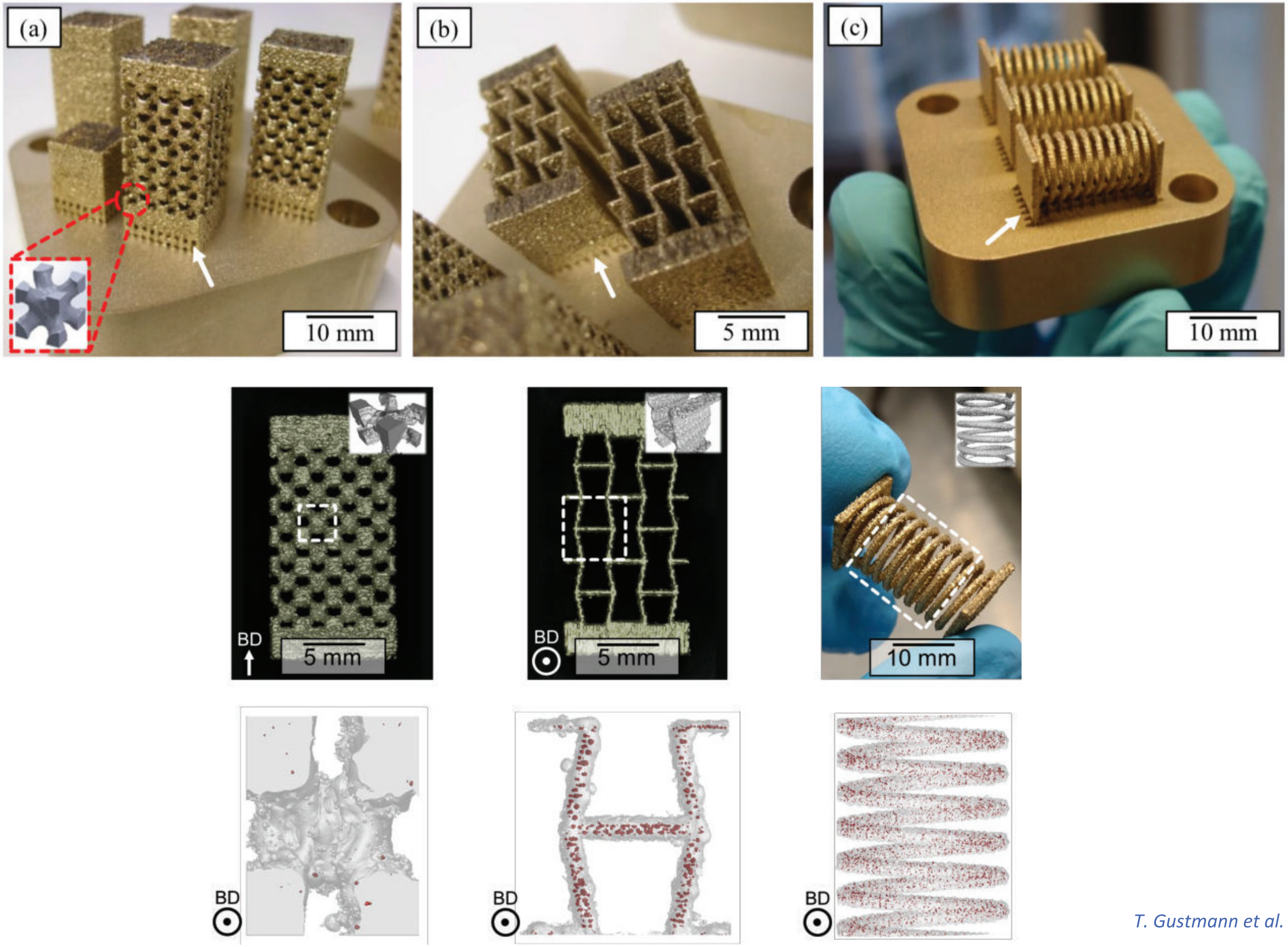



*T. Gustmann et al. unpublished*

- About 2% strain recovery for Cu-11.85Al-3.2Ni-3Mn (SLM)
- Remelting: strain recovery can be modified
- Almost 5% recoverable strain ($E_V$ = 204 J/mm$^3$)
  → exceptionally high
- Cu-Al-Ni-Mn-Zr: recoverable strain < 1%
- $Cu_2AlZr$ might be responsible



# Cu-based SMAs and SLM




*T. Gustmann et al. unpublished*

# Conclusions



**SLM of Cu-based SMAs allows:**

- **production of complex parts**
- **adjusting transformation temperatures**
- **optimizing shape memory properties**
- **local disabling of SME**
- **formation of graded material**

**→ Promising route to 4D printing**