RADIKAL - Ressourcenschonende Werkstoffsubstitution durch additive & intelligente FeAl-Werkstoff-Konzepte für angepassten Leicht- und Funktionsbau

MatRessource

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Projektträger Jülich
Forschungszentrum Jülich

Additive Manufacturing of Intermetallics: Microstructures and Mechanical Properties of Iron Aluminides Processed by SLM and LMD

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NANOVAL

Outline

- Iron aluminides and investigated Fe–Al–X alloys
- Microstructures
  - Misorientations within individual grains
  - Influence of preheating temperature, scan strategy, annealing
- Mechanical properties: yield strength, creep, ductility
- Chemically graded Fe–Al and Fe–Al/steel samples

Motivation

- Fe-base materials with low density 5.7 - 6.7 g/cm^3 vs. 7.85 (steel)
- Excellent corrosion resistance (metal dusting, steam, molten salts…)
- High wear resistance
- Progress in increasing strength at high temperatures
- Limited ductility at ambient temperatures (0.5–1.5% elongation at RT)
- Cheap material (materials costs, no strategic elements & production)

⇨ **Possible replacement for Cr steels and Ni & Co base alloys**

AM processing is of specific interest for the production of intermetallic parts because their high hardness and brittleness makes near net-shape production desirable.

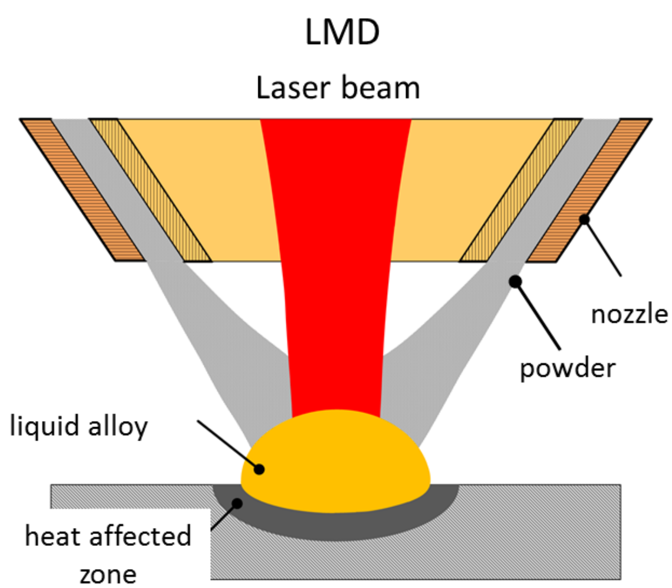
Why additive manufacturing (AM) of Fe–Al?

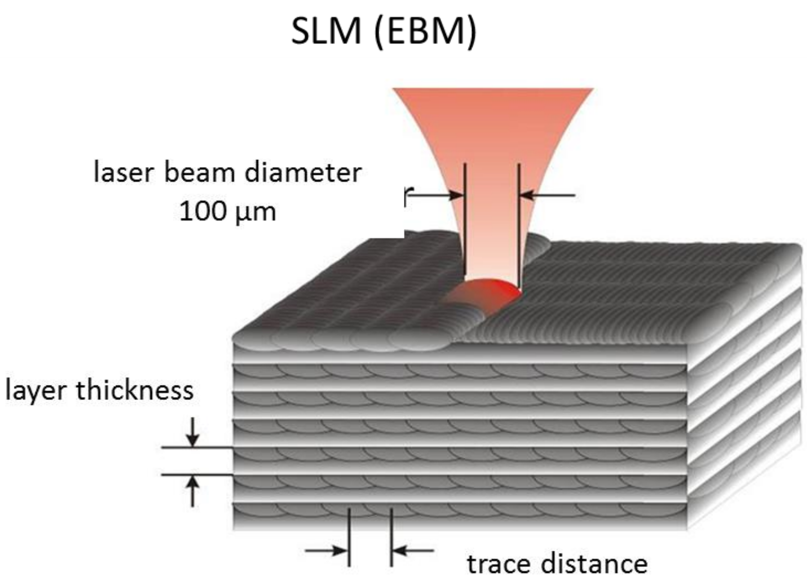
- Alternative processing route to casting
- Near net-shape processing ⇨ minimum of machining
- High cooling rates ⇨ fine microstructure ⇨ higher ductility
- Highly exothermic reaction between Fe and Al
  ⇨ build up from elemental powders ✓
- Possibility to build chemically graded steel/Fe–Al parts?

Employed AM processes

1. Laser Metal Deposition **LMD**
2. Selective Laser Melting **SLM**
3. (Electron Beam Melting **EBM**)

Fraunhofer ILT





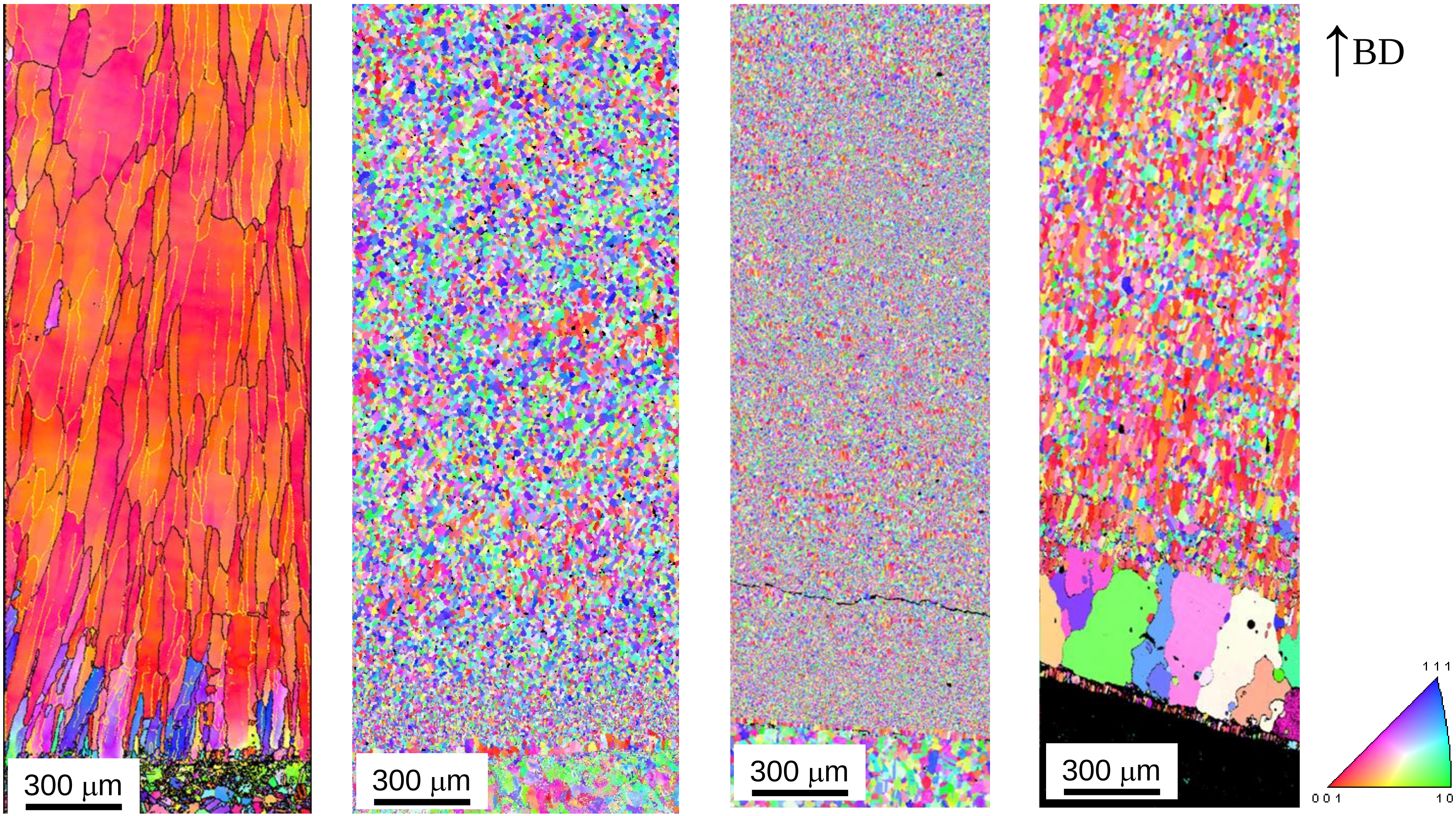
Build up on various preheated substrates: Fe, Fe–Al, 1.4301, 1.1730, P92…

Reaction zone between substrate and iron aluminide ≤1 mm

Investigated Fe–Al–X alloys

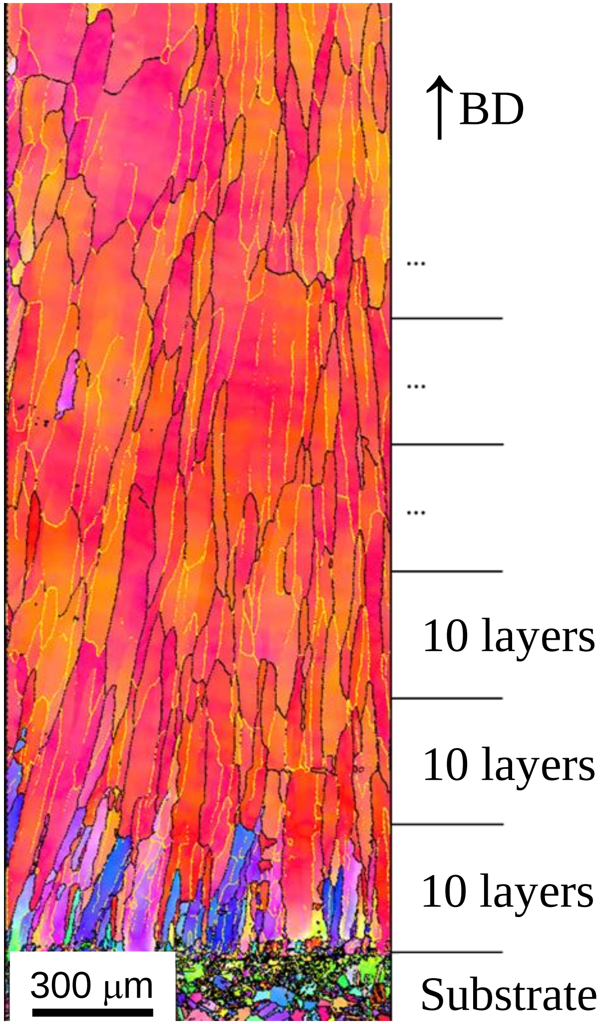
Fe–28Al	Fe–30Al–10Ti	Fe–30Al–5Ti–0.7B	Fe–22Al–5Ti
“Demo”	Increase of $L2_1 \leftrightarrow B2$	Precipitation of borides	Coherent $A2 + L2_1$

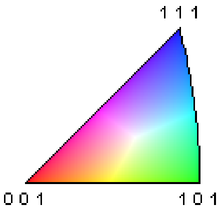
EBSD (SLM)



Fe–28Al

"Demo"





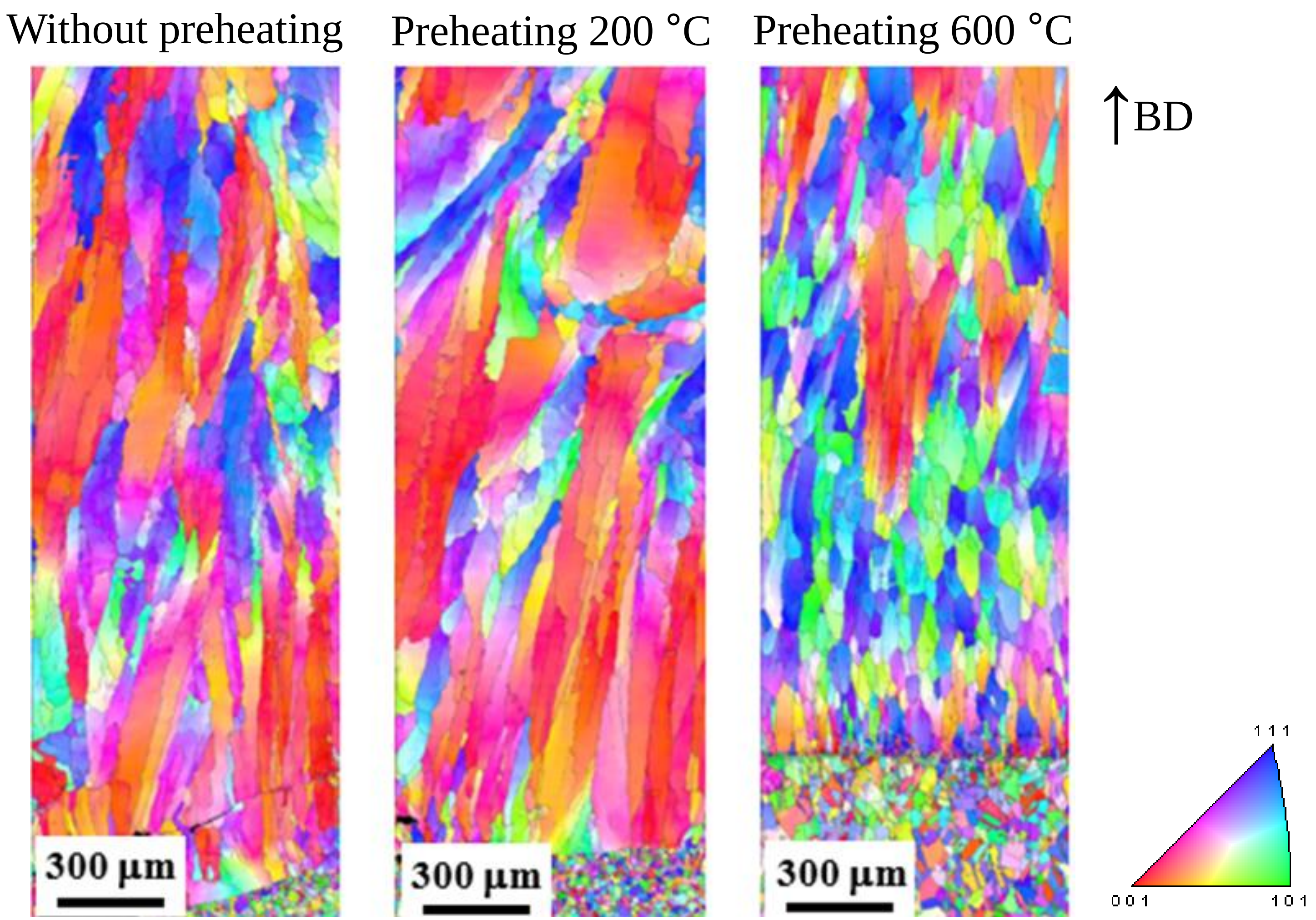
Defect free samples by preheating at 200 °C (LMD) and 600 °C (SLM)

Compositions SLM: 27.2 ± 0.3 at.% Al
LMD: 27.8 ± 0.3 at.% Al
Powder: 28.3 at.% Al

Elongated grains up to mm (as cast several 100 μm)

Growth preferentially in [001] direction (direction of the highest heat flow in α-Fe,Al)

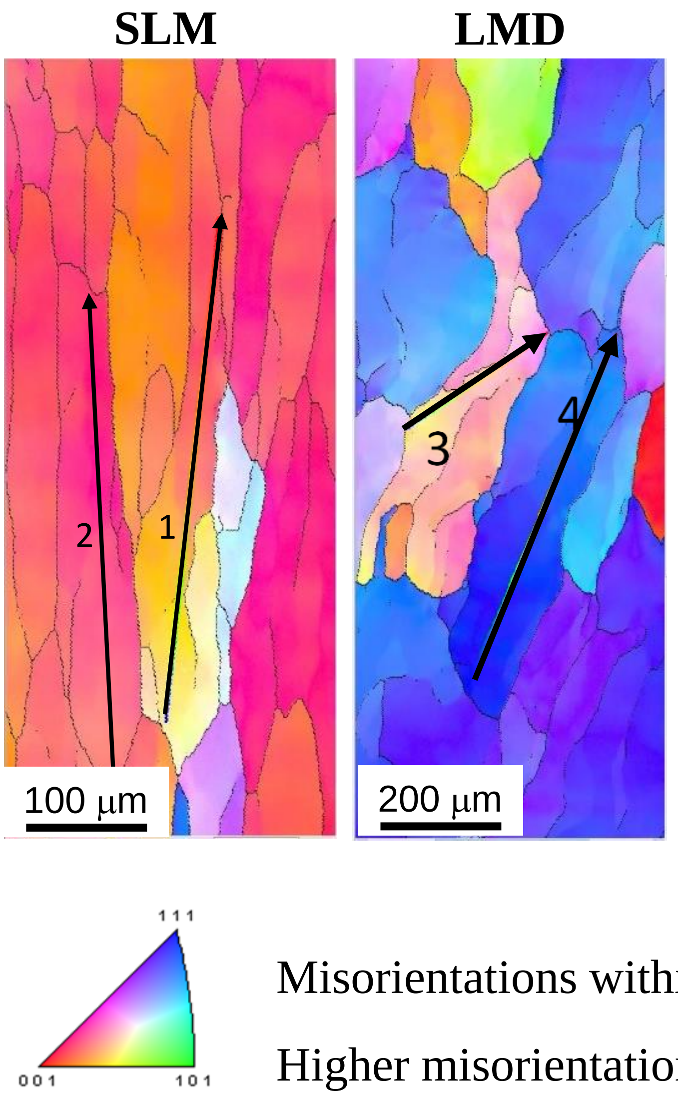
Fe–28Al: Effect of preheating temperature on grain size

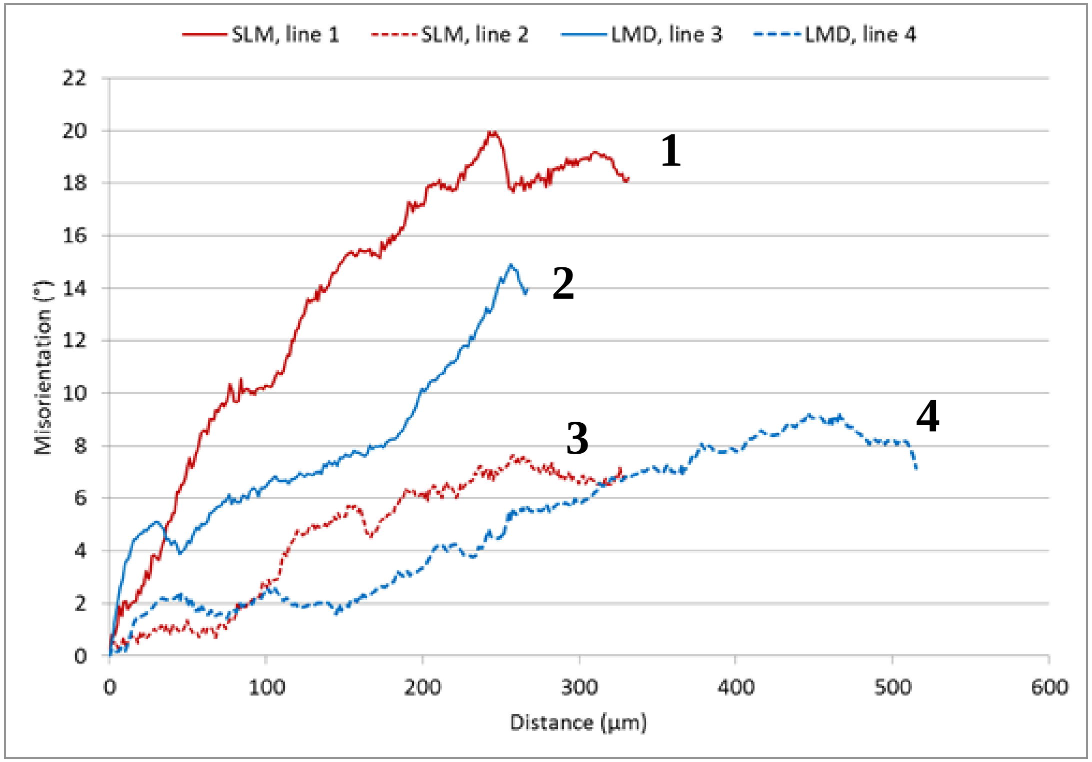


Grain size decreases with increasing preheating temperature

⇨ grain size increases with increasing temperature gradient

Fe–28Al: Misorientations within individual grains



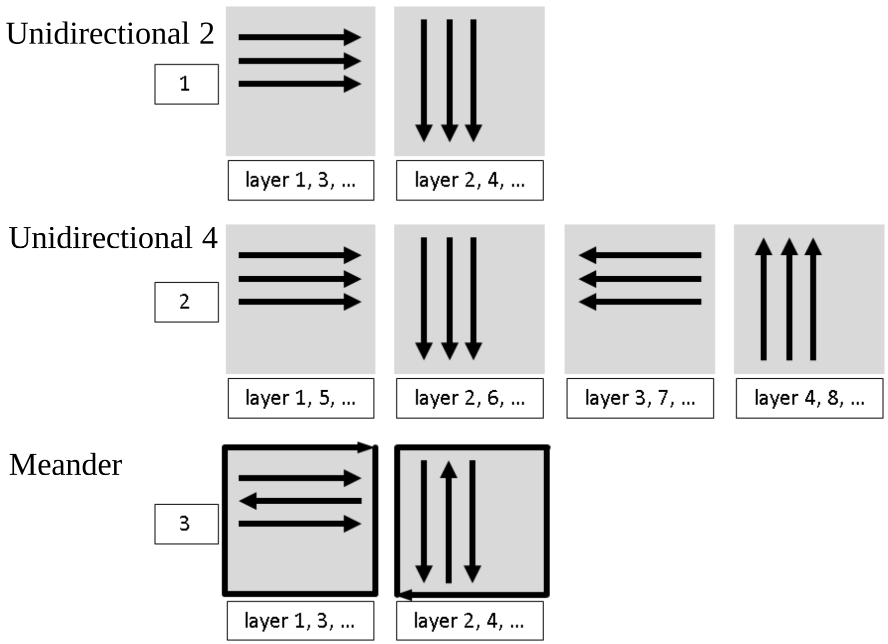


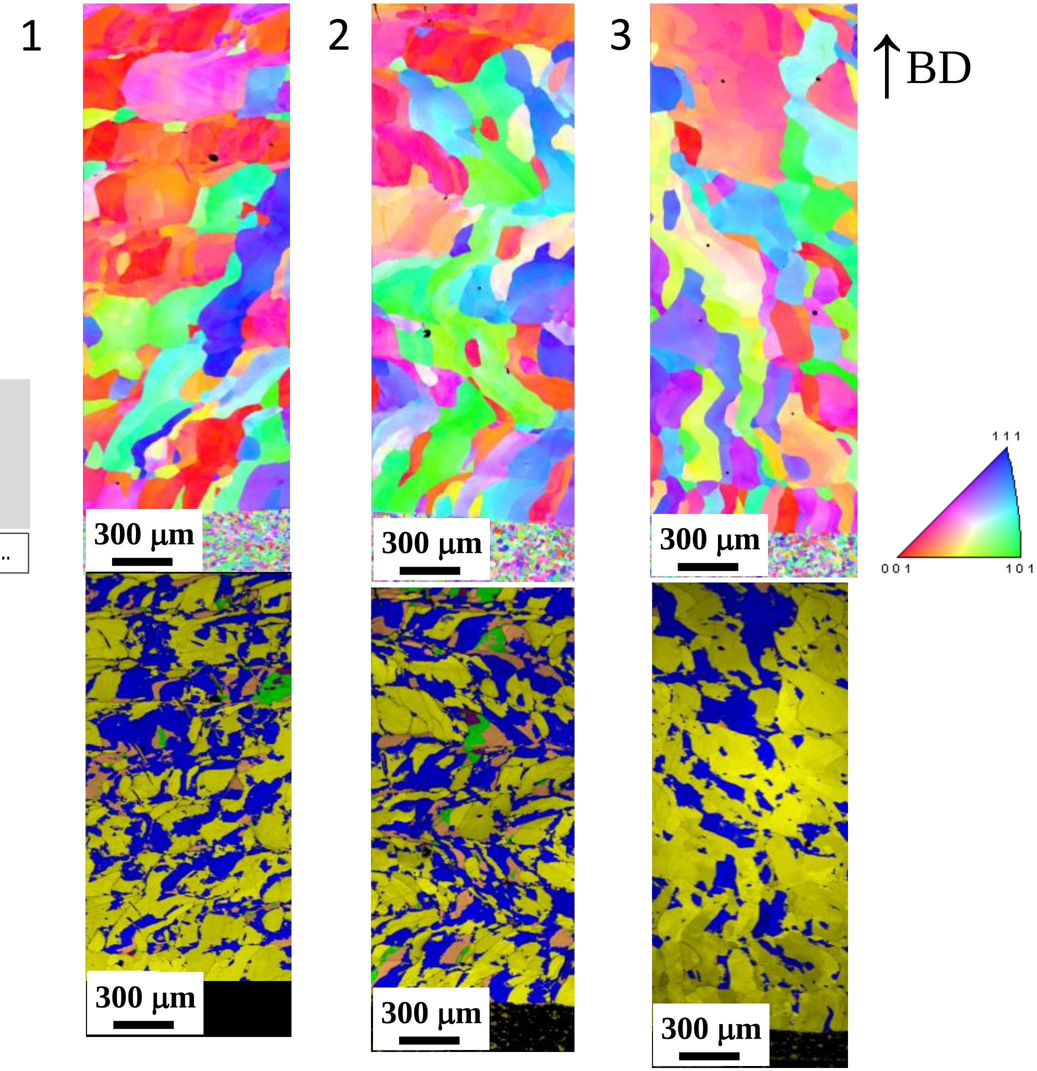
Misorientations within individual grains up to 20°

Higher misorientations in SLM compared to LMD (due to higher cooling rate)

Fe–28Al: Effect of scanning strategy on misorientations

SLM; processed at RT



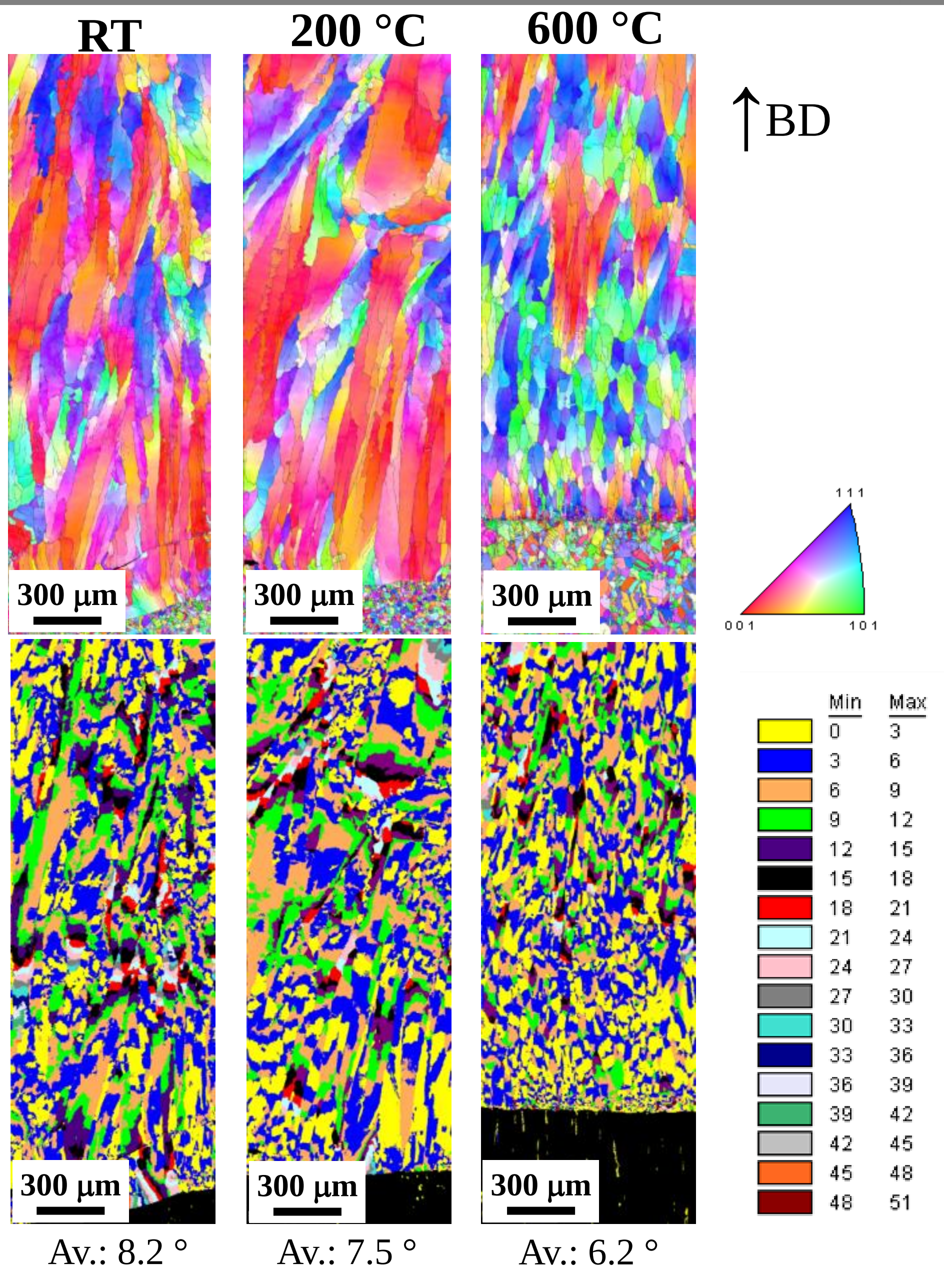


Max.: 15.2°
Av.: 3.2 °

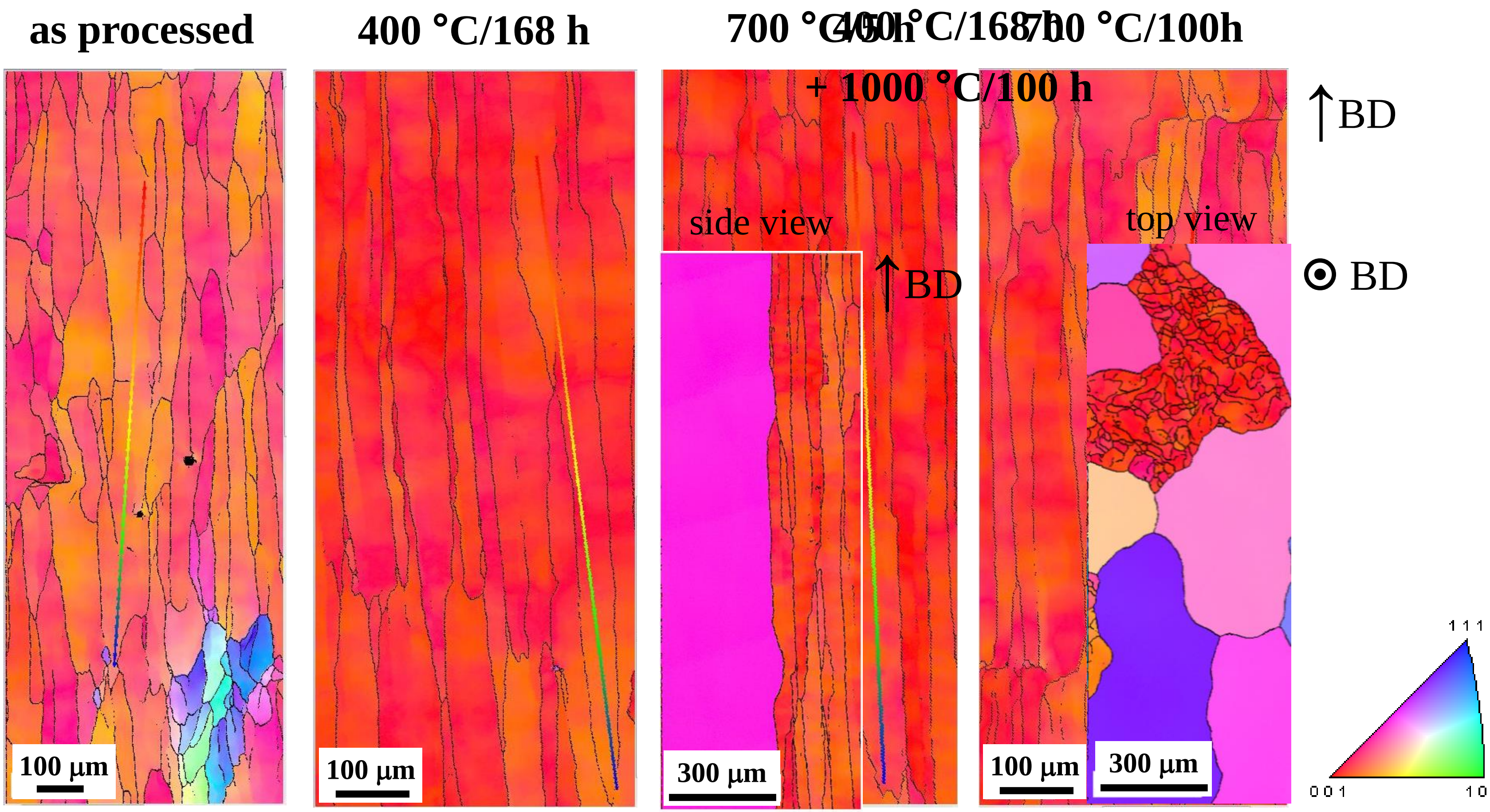
Max.: 16.9 °
Av.: 4.0 °

Max.: 11.9 °
Av.: 2.8 °

Scan strategy has a marked influence on misorientations



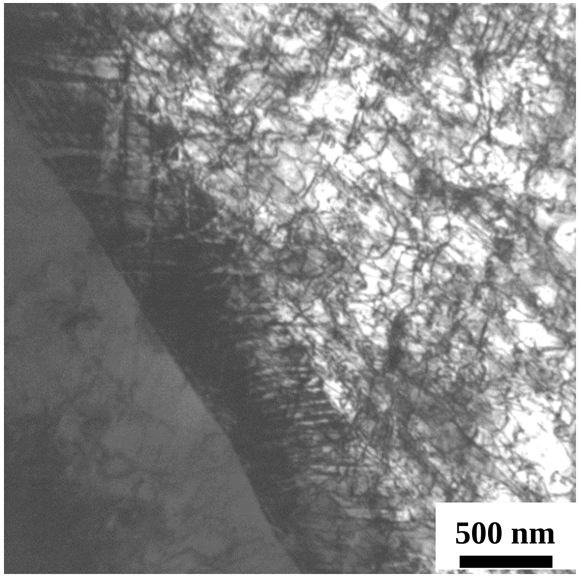
Misorientations decrease with increasing preheating temperature

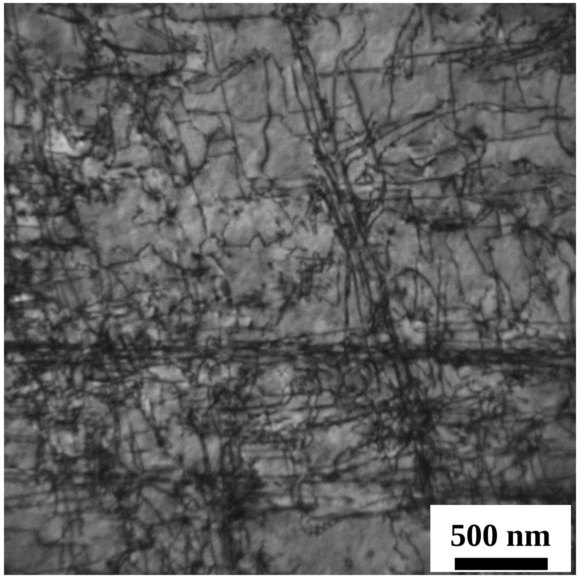


No recrystallization after various heat treatments

Fe–28Al: TEM analysis of the dislocation structure

TEM-BF





Sample	Dislocation density
As cast	3.8×10^{12} m^{-2}
LMD	2.0 x 10^{13} m^{-2}
LMD + 700 °C/5 h	5.8 x 10^{12} m^{-2}
SLM (KEG)	2.2 x 10^{14} m^{-2}
SLM (ILT)	3.5 x 10^{14} m^{-2}
SLM + 700 °C/5 h (ILT)	4.0 x 10^{13} m^{-2}

Very high dislocation densities

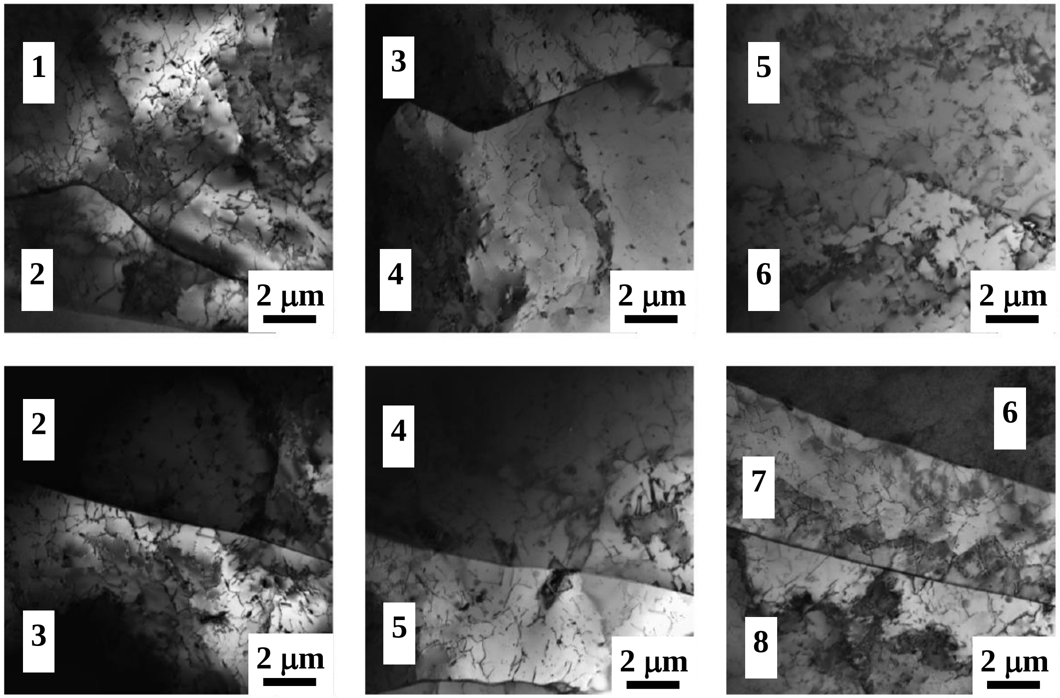
Subgrains are formed through formation of dislocation walls

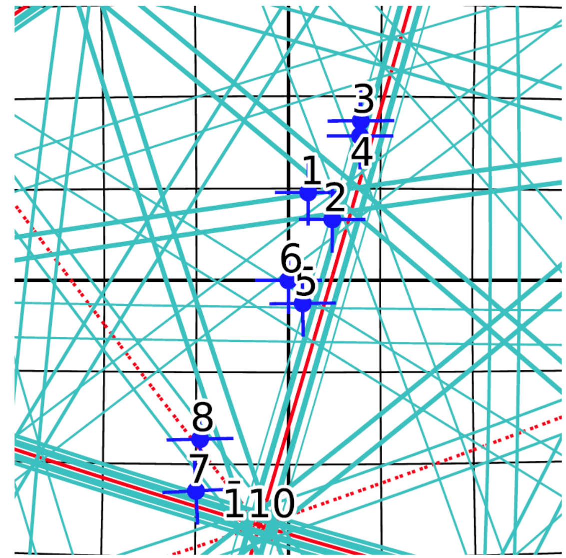
Dislocations are arranged in a network of parallel screw dislocations

Dislocation densities are about one magnitude higher in SLM samples than in LMD samples

Fe–28Al: TEM analysis of individual subgrains

TEM-BF



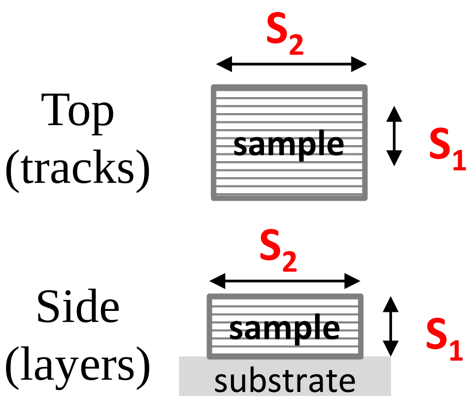


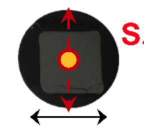
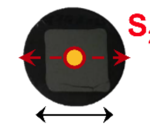
(Grid 5 x 5°)

Subgrains are located on common zone axes and are inclined by 1–2° against each other.

Fe–28Al: XRD analysis of internal stresses

XRD: local stress measurements



Strategy		Stress S1 [MPa]		Stress S2 [MPa]
				
LMD 1, top	⊥ tracks	**130 ± 60**	ǁ tracks	**36 ± 67**
LMD 2, top	⊥ tracks	**82 ± 29**	ǁ tracks	**29 ± 70**
LMD 3, top	⊥ tracks	**109 ± 37**	ǁ tracks	**-10 ± 103**
LMD 1, side	⊥ layers	**- 101 ± 90**	ǁ layers	**84 ± 95**
LMD 2, side	⊥ layers	**- 148 ± 66**	ǁ layers	**- 65 ± 37**
LMD 3, side	⊥ layers	**24 ± 104**	ǁ layers	**16 ± 27**
SLM side (20 °C)	⊥ layers	**432 ± 172**	ǁ layers	**159 ± 45**
SLM side (200 °C)	⊥ layers	**378 ± 92**	ǁ layers	**187 ± 27**

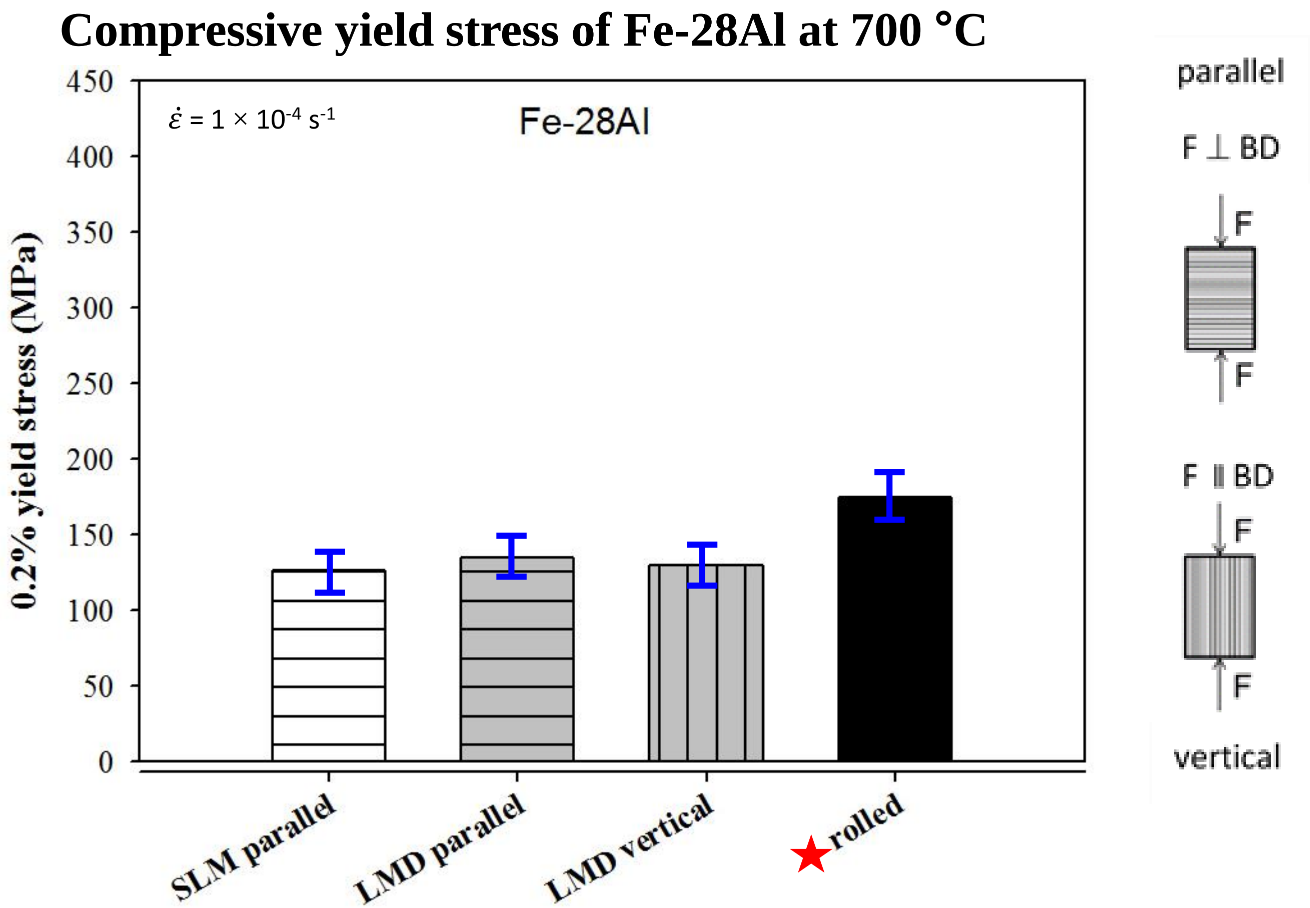
Local stress measurements show mixture of tensile and compressive stresses.

High tensile stresses vertical to individual tracks, low stresses along tracks.

Compressive stresses vertical to individual layers, low stresses along layers.

Stresses are higher in SLM than in LMD samples.

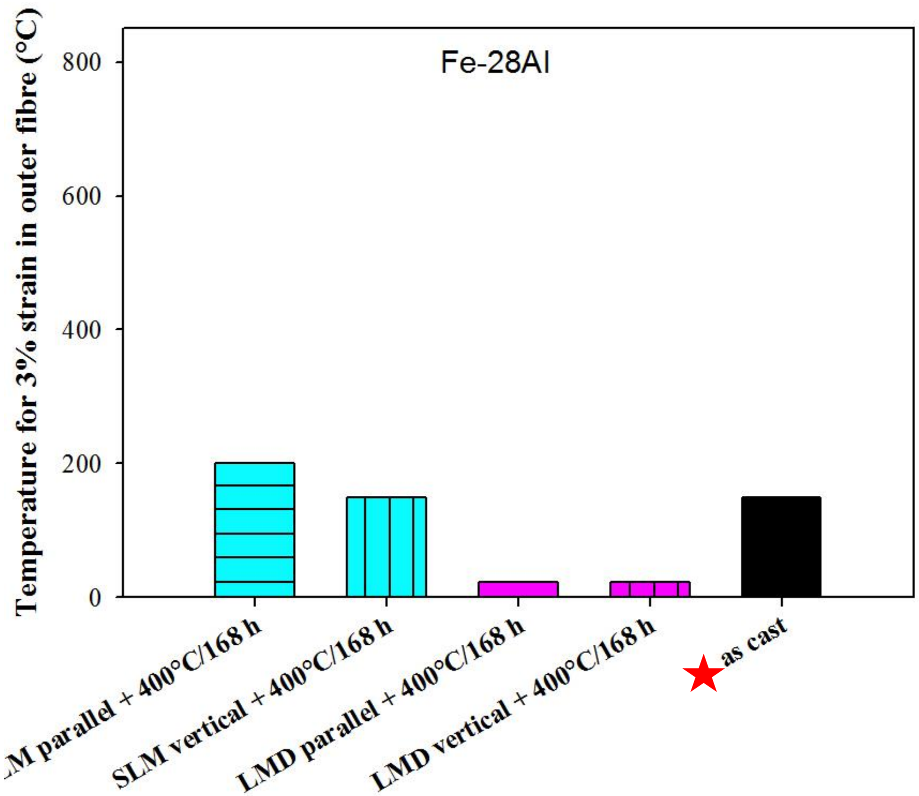
Fe–28Al: Compressive yield stress

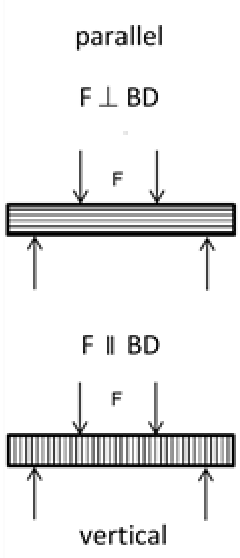


No marked difference in compressive yield strength between AM and as-cast samples or whether SLM and LMD samples are tested horizontal (parallel) or vertical to BD.

★ C.G. McKamey et al. ORNL Rep. 10793 (1988) 1-55

Ductility of Fe–28Al determined in 4-point bending





LMD samples show improved ductility compared to SLM and as-cast samples.

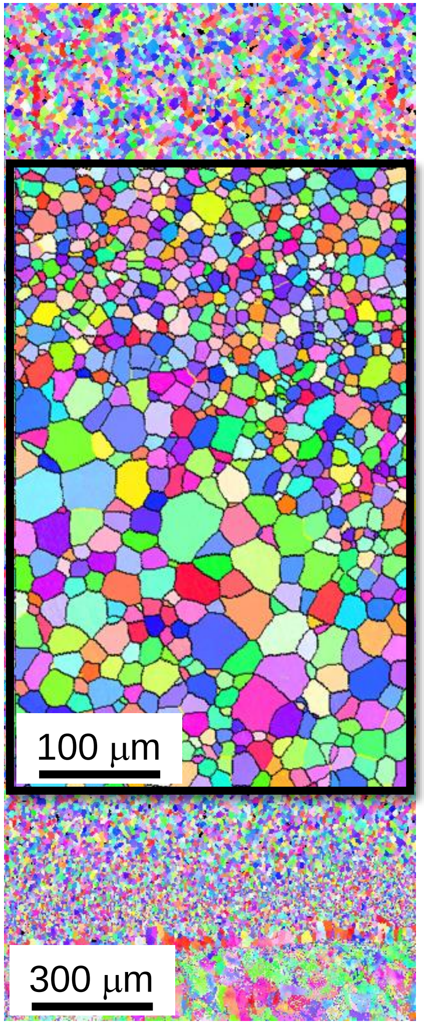
The strong crystallographic texture and high dislocation density have no influence on ductility.

★ D. Risanti et al.; Intermetallics 13 (2005) 1337

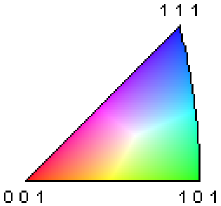
Fe–30Al–10Ti: Microstructure

Fe–30Al–10Ti

Increase of $L2_1 \leftrightarrow B2$



↑BD



Defect free samples by preheating at 700 °C (LMD) and 800 °C (SLM)

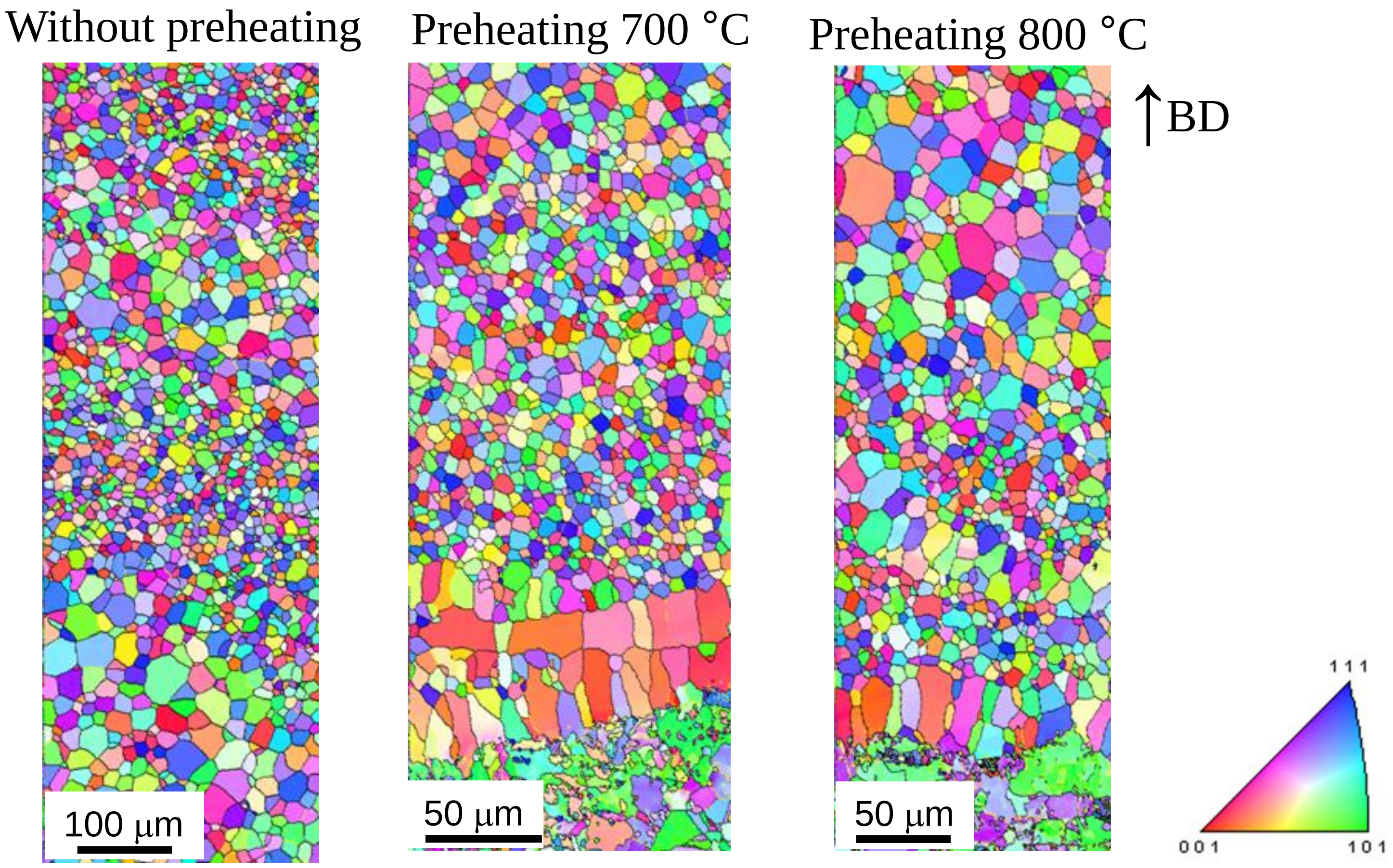
Equiaxed grains

Average grain size < 5 µm (as cast > 100 µm)

No preferred orientation of the grains

No misorientations within individual grains

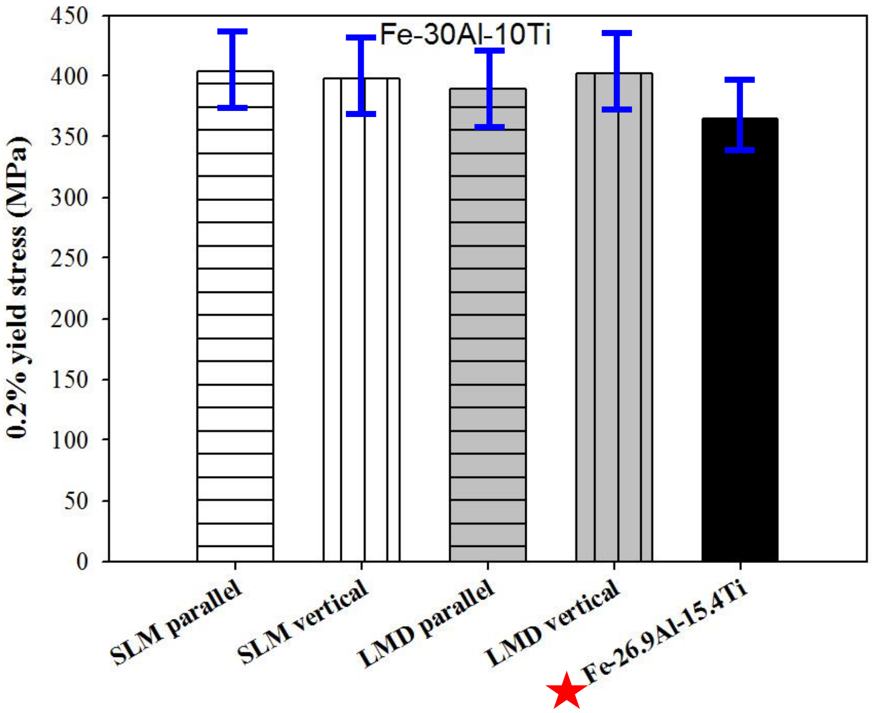
Fe–30Al–10Ti: Effect of preheating temperature on grain size



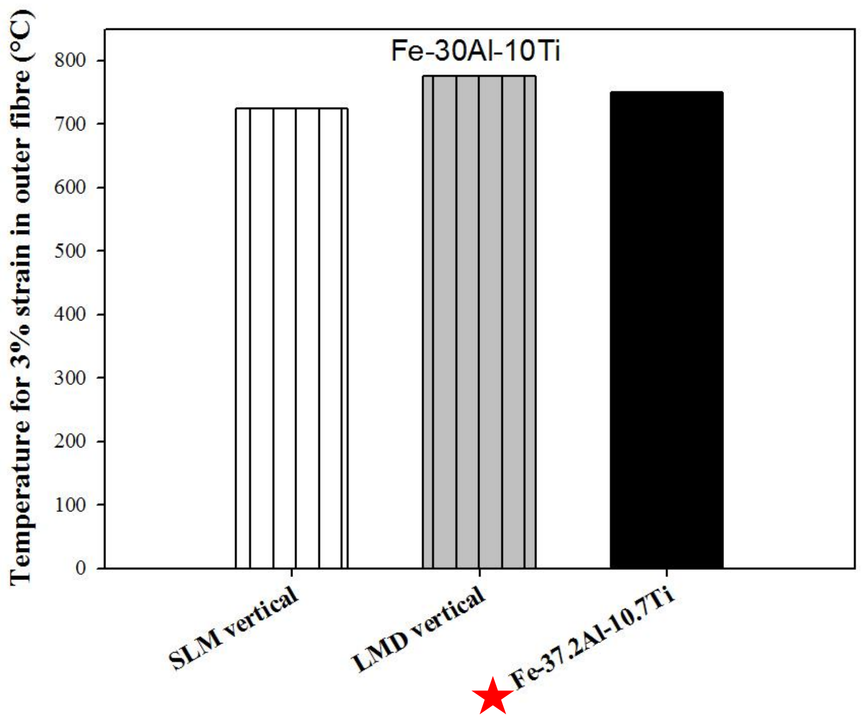
No effect of preheating temperature on grain size

Fe–30Al–10Ti: Yield stress and ductility

Compressive yield stress of Fe–30Al–10Ti at 700 °C



Ductility of Fe–30Al–10Ti determined in 4-point bending



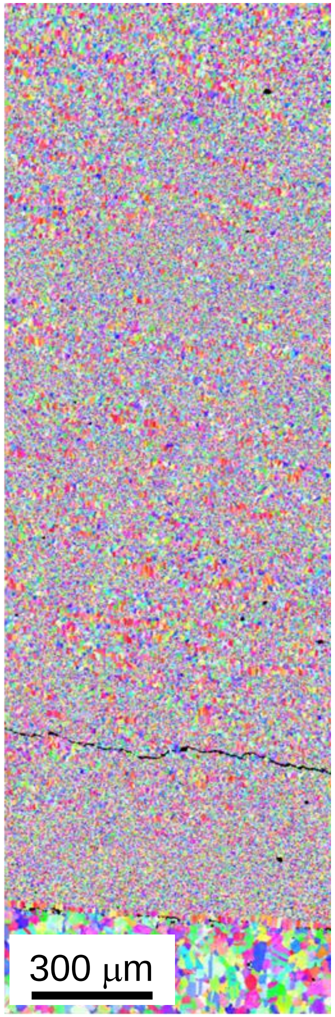
No marked difference in compressive yield strength and ductility between AM and as-cast samples or whether SLM and LMD samples are tested horizontal (parallel) or vertical to BD (yield stress).

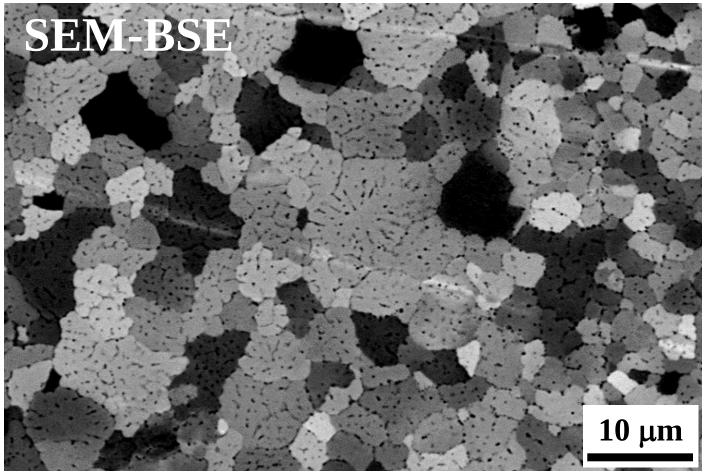
★ M. Palm, G. Sauthoff; Intermetallics 12 (2004) 1345

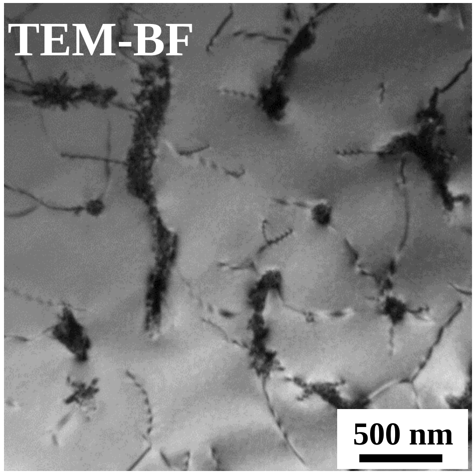
Fe–30Al–5Ti–0.7B: Microstructure

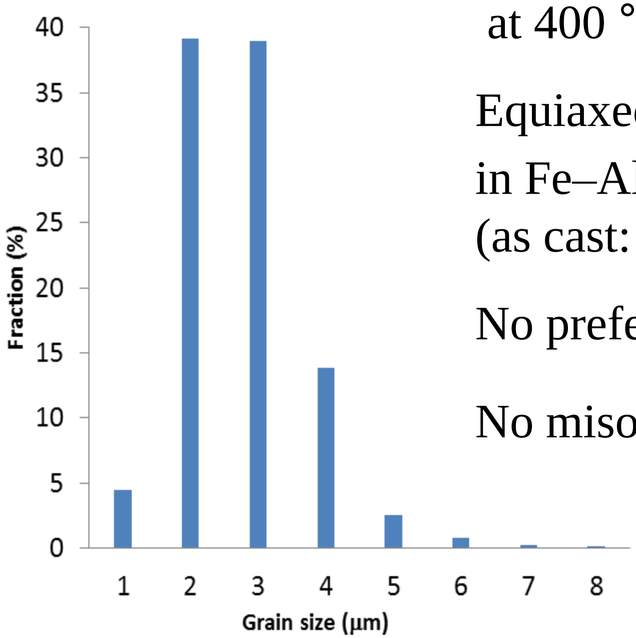
Fe–30Al–5Ti–0.7B

Precipitation of borides









Defect free samples by preheating at 400 °C (LMD) and 600 °C (SLM)

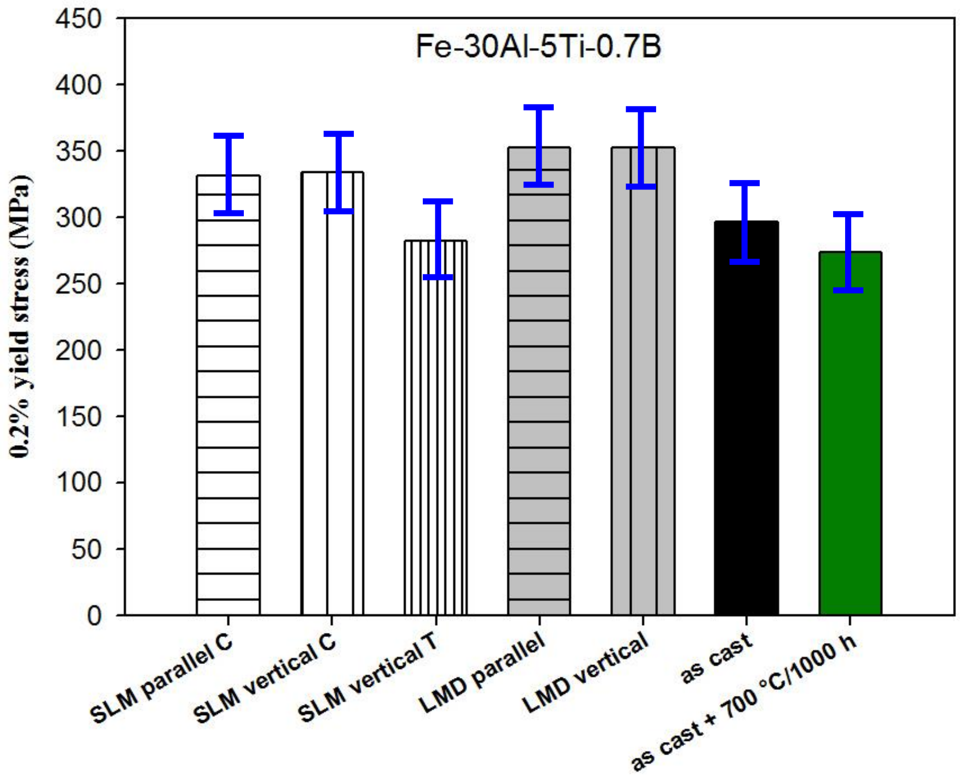
Equiaxed Fe–Al grains (< 5 µm) + TiB_2 (50 nm) in Fe–Al grains and at grain boundaries (as cast: Fe–Al (10 µm) + TiB_2 (100 nm) at GB)

No preferred orientation of the grains

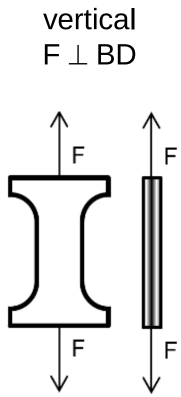
No misorientations within individual grains

Fe–30Al–5Ti–0.7B: Yield stress

Yield stress of Fe–30Al–5Ti–0.7B at 700 °C



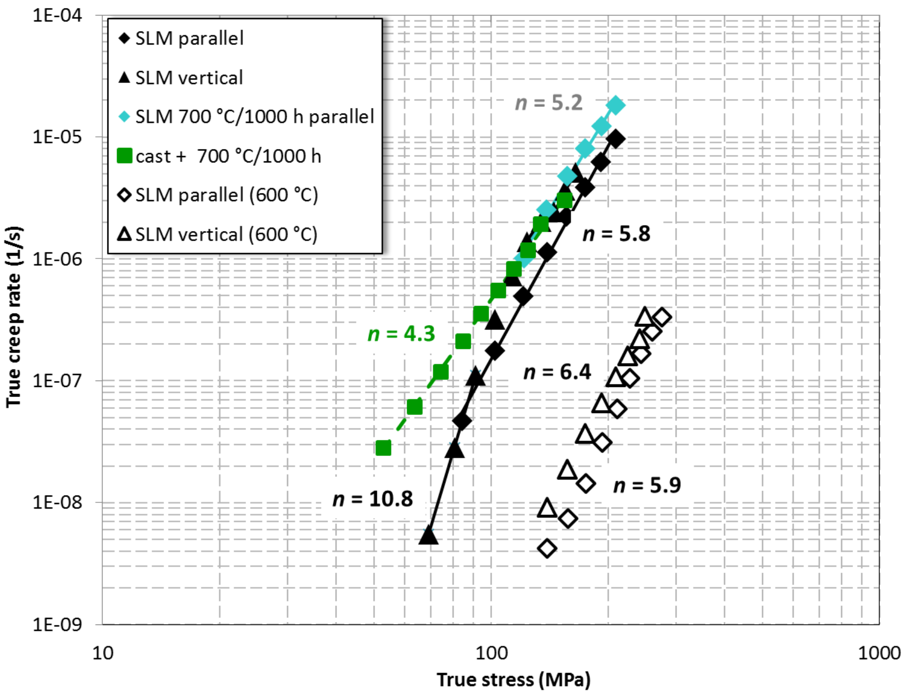
Orientation of the samples for tension (T) testing

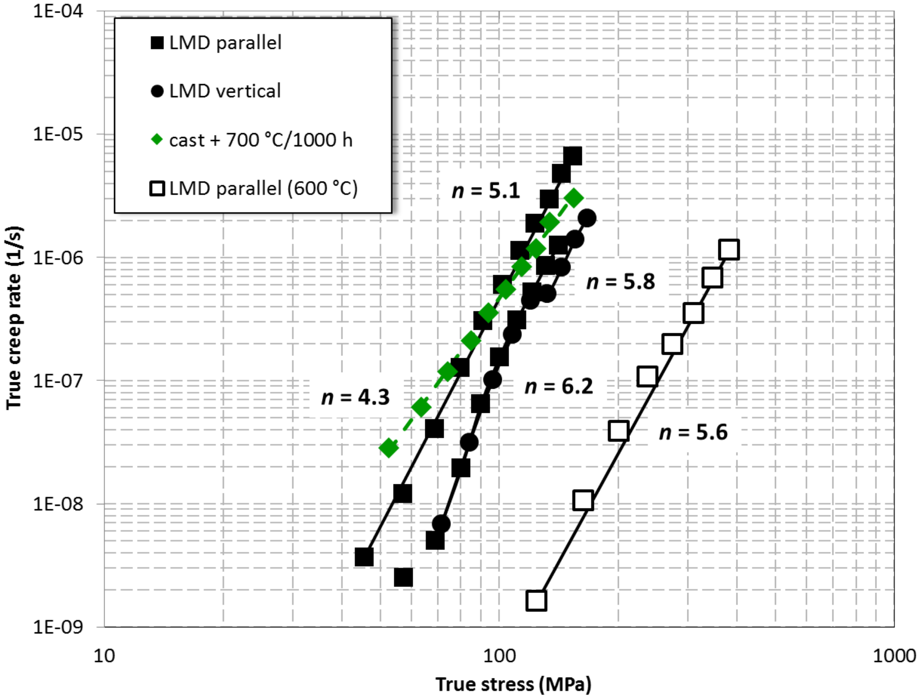


No marked difference in yield strength between AM and as-cast samples or whether SLM and LMD samples are tested horizontal (parallel) or vertical to BD.

Fe–30Al–5Ti–0.7B: Creep strength

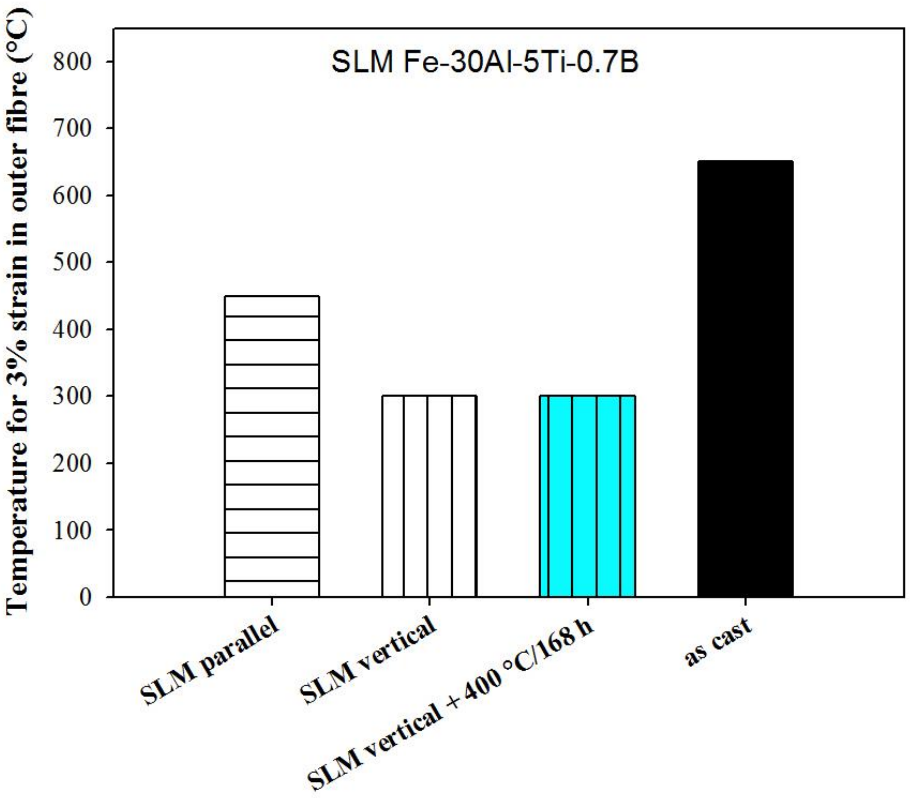
Secondary creep of SLM and LMD samples of Fe–30Al–5Ti–0.7B at 600 °C and 700 °C established in compression by stepwise increasing the load

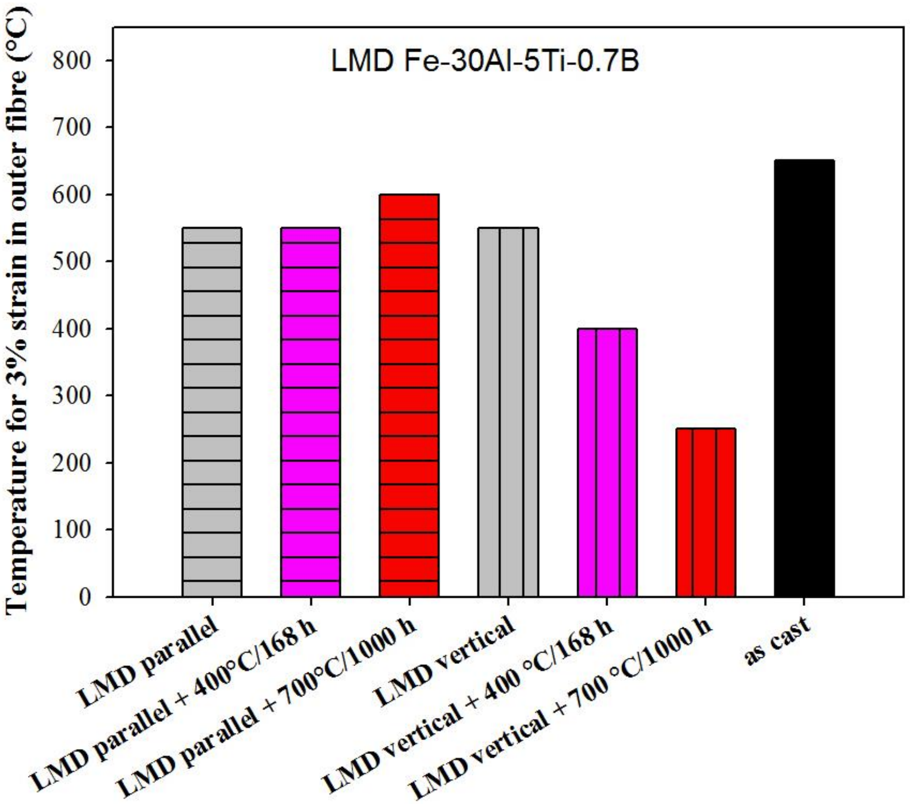




No marked difference in compressive creep strength between AM and as-cast samples or whether SLM and LMD samples are tested horizontal (parallel) or vertical to BD.

Ductility of Fe–30Al–5Ti–0.7B determined in 4-point bending

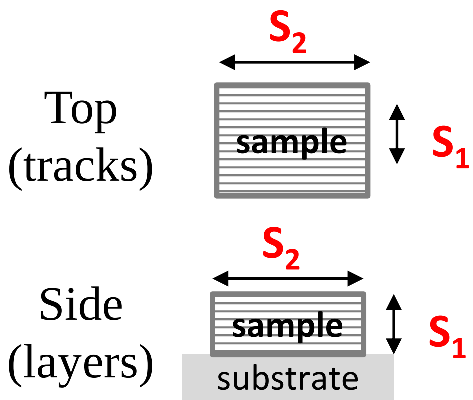


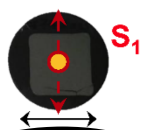
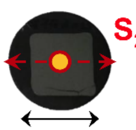


Marked difference in ductility between SLM and LMD or as-cast samples, whether SLM samples are tested horizontal (parallel) or vertical to BD and if LMD samples are annealed.

Fe–30Al–5Ti–0.7B: Ductility

XRD: local stress measurements



Material/condition		Stress S_1 (MPa)		Stress S_2 (MPa)
				
LMD top, as processed	⊥ tracks	114 ± 12	ǁ tracks	-32 ± 11
LMD side, as processed	⊥ layers	- 109 ± 36	ǁ layers	5 ± 8
LMD top (700 °C/1000 h)	⊥ tracks	-22 ± 2	ǁ tracks	-36 ± 2
LMD side (700 °C/1000 h)	⊥ layers	-73 ± 5	ǁ layers	-69 ± 6
SLM top, as processed	⊥ tracks	- 87 ± 4	ǁ tracks	38 ± 4
SLM side , as processed	⊥ layers	79 ± 9	ǁ layers	8 ± 10
SLM top (700 °C/1000 h)	⊥ tracks	- 4 ± 9	ǁ tracks	10 ± 6
SLM side (700 °C/1000 h)	⊥ layers	- 46 ± 3	ǁ layers	- 35 ± 3

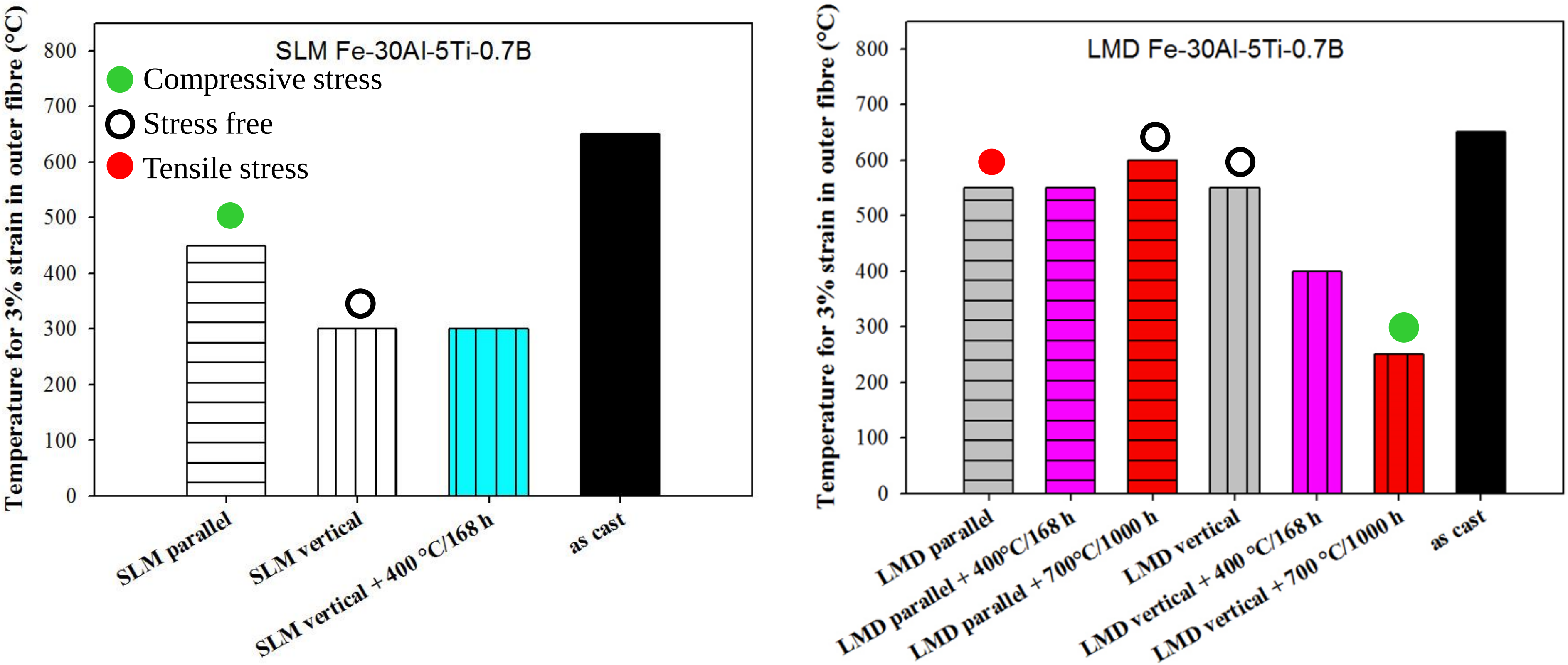
Local stress measurements show mixture of moderate tensile and compressive stresses.

Tensile or compressive (SLM) stresses vertical to individual tracks, low stresses along tracks.

Compressive stresses vertical to individual layers, low stresses along layers.

Fe–30Al–5Ti–0.7B: Ductility

Ductility of Fe–30Al–5Ti–0.7B determined in 4-point bending

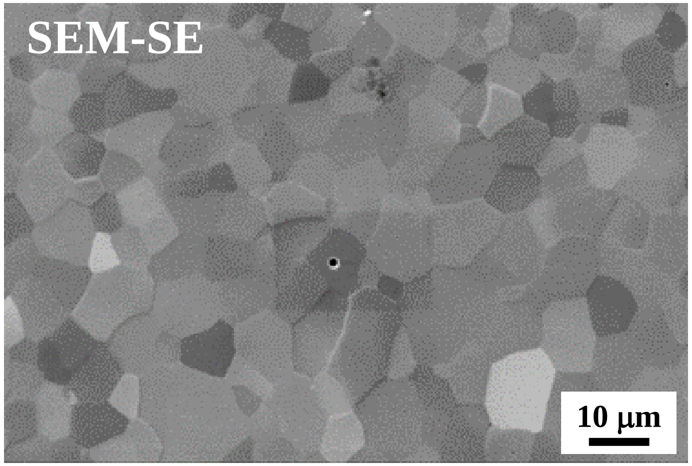


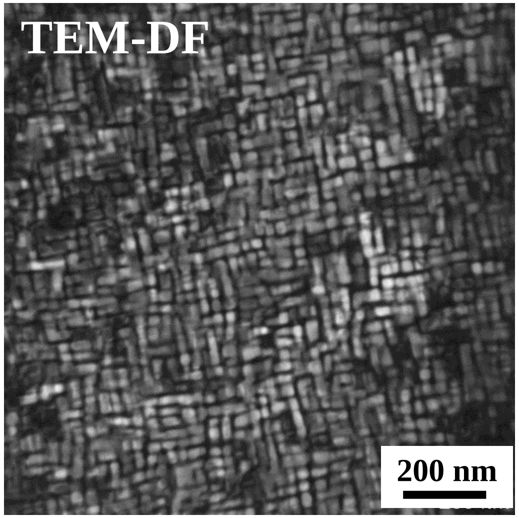
No direct relation between internal stresses and ductility of the samples.

Fe–22Al–5Ti : Microstructure

Fe–22Al–5Ti

Coherent A2+ $L2_1$



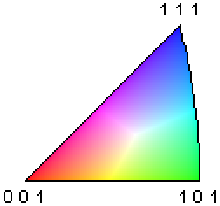


Defect free samples by preheating at >800 °C ~~(LMD)~~ and 800 °C (SLM)

Equiaxed grains (10 µm) with coherent A2 + $L2_1$ microstructure (30 nm) (comparable to as-cast microstructure)

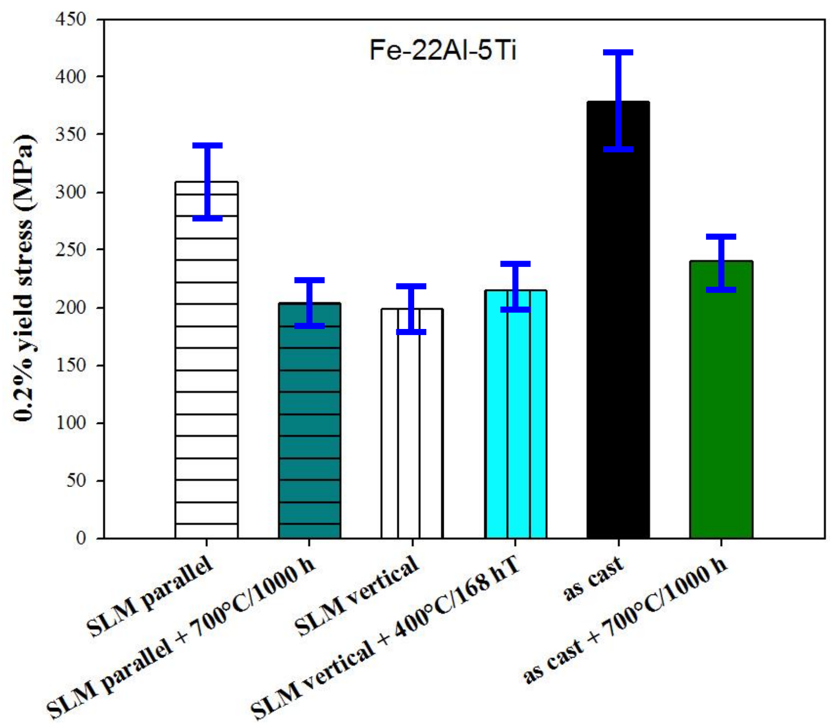
No preferred orientation of the grains

No misorientations within individual grains



Fe–22Al–5Ti: Yield stress

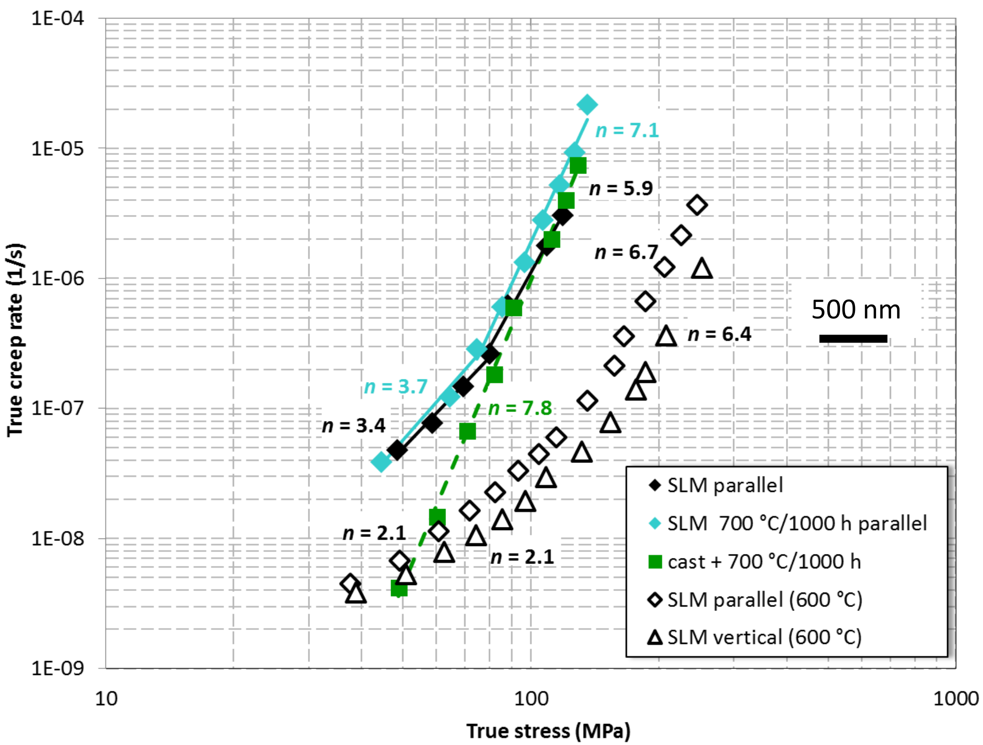
Compressive yield stress of Fe–22Al–5Ti at 700 °C



Marked difference whether SLM samples are tested horizontal or vertical to BD.

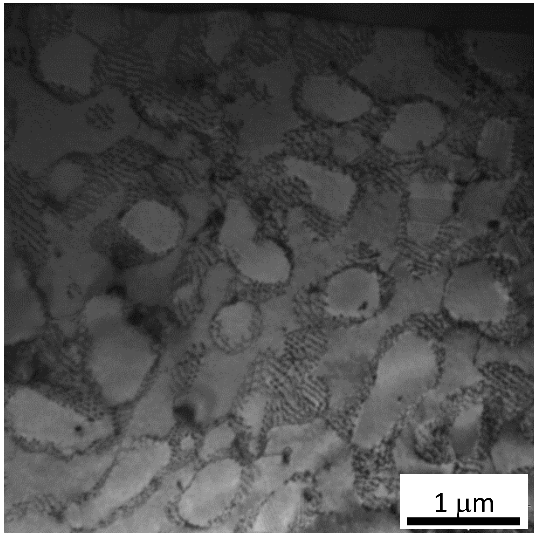
Reduction of yield strength after annealing at 700 °C due to coarsening of coherent microstructure.

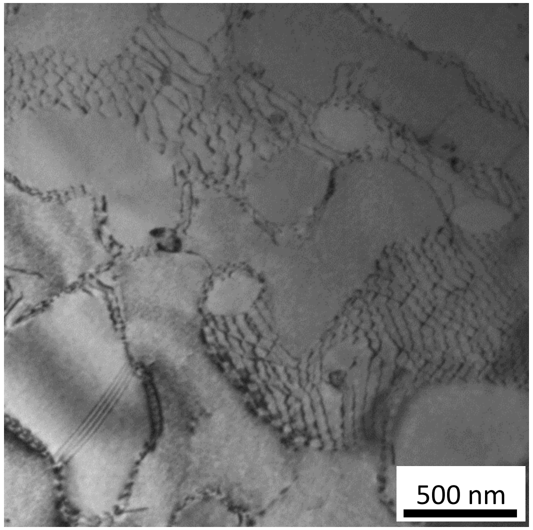
Secondary creep of SLM samples of Fe-22Al-5Ti at 600 °C and 700 °C established in compression by stepwise increasing the load



No marked difference in compressive creep strength between SLM and as-cast samples or whether SLM samples are tested horizontal (parallel) or vertical to BD.

700 °C/ 100 h (TEM-BF)

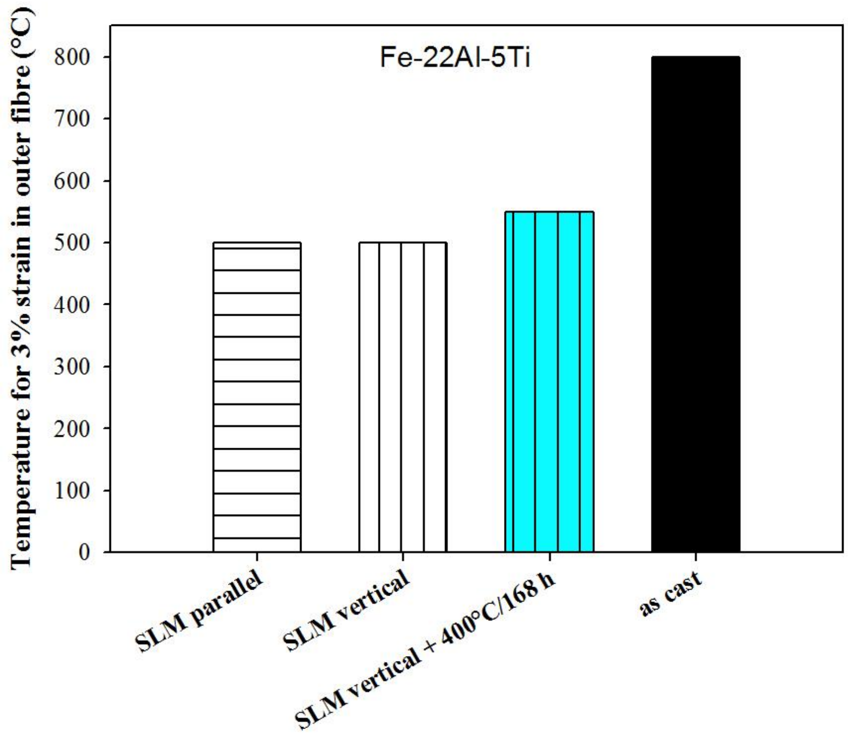




Formation of dislocation networks

Fe–22Al–5Ti: Ductility

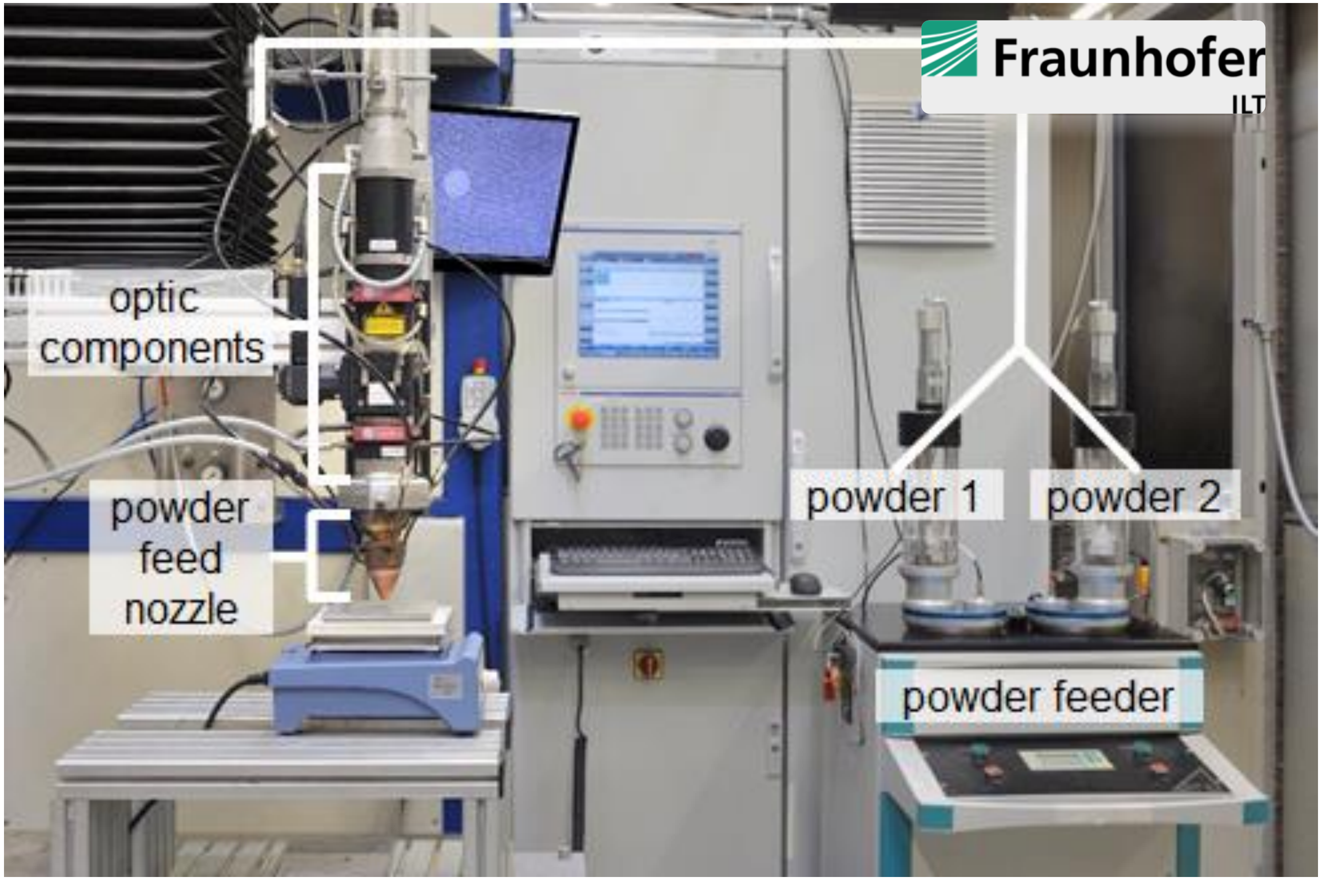
Ductility of Fe–22Al–5Ti determined in 4-point bending



SLM samples show improved ductility compared to as-cast samples.

Chemically graded Fe–Al samples produced by LMD

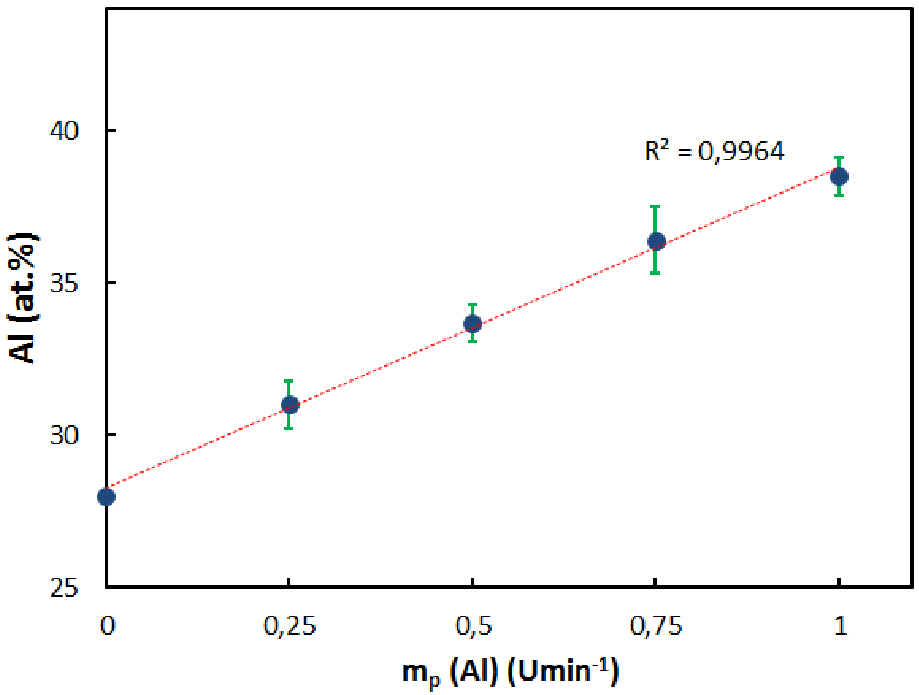
Experimental setup at ILT



- YAG-Laser: 2000 W
- Fe-28Al: powder particle size 45 – 90 µm
- Chemical composition varied by the rotation speed m_p ($Umin^{-1}$) of the feeder

Production of binary Fe–Al samples by varying the speed (m_p) of the Al feeder

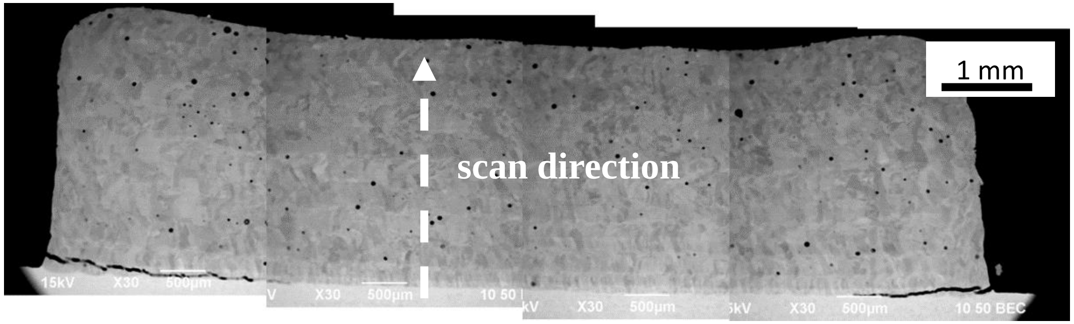
m_p Al ($Umin^{-1}$)	Al (at%)
0.25	31.0 ± 0.8
0.50	33.7 ± 0.6
0.75	36.4 ± 1.1
1.00	38.5 ± 0.6



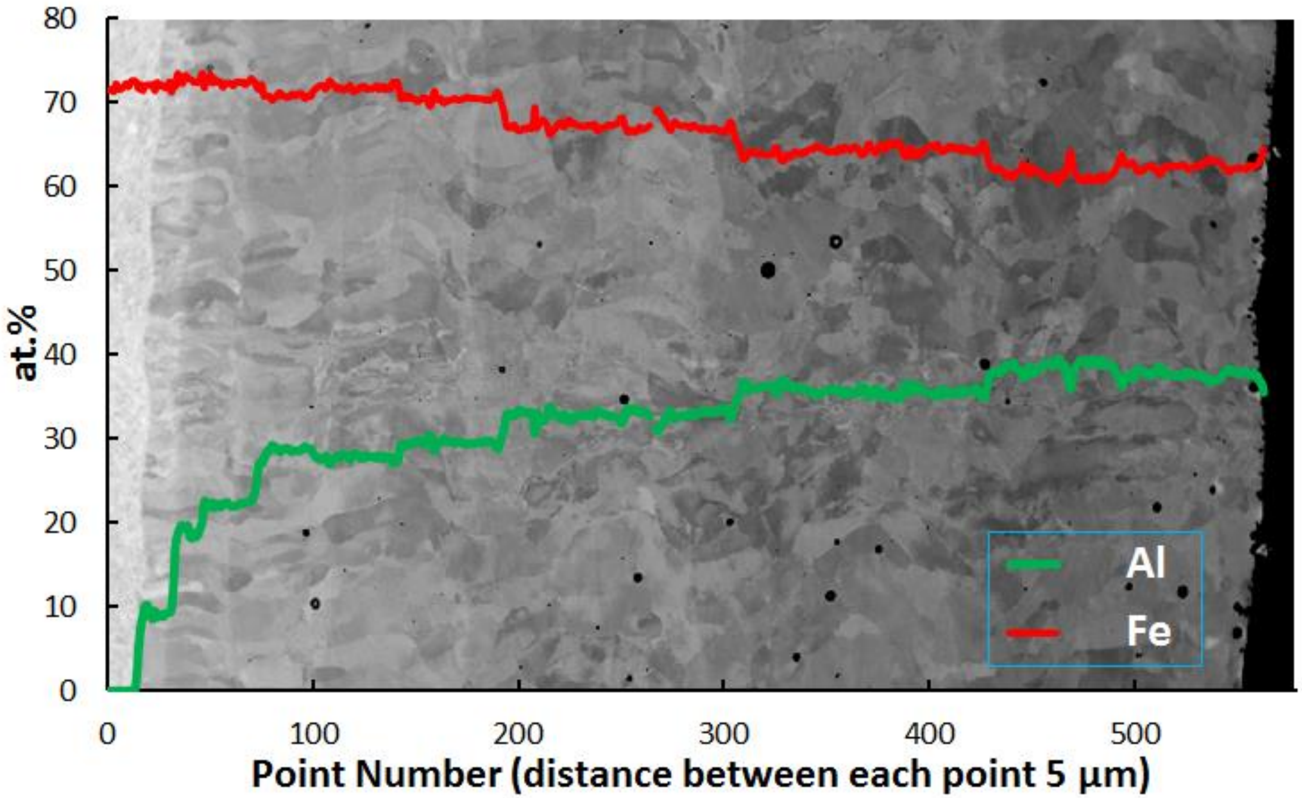
Linear dependence between rotation speed of the feeder and obtained composition.

⇨ Production of LMD samples with defined composition gradients possible

Chemically graded Fe–Al sample



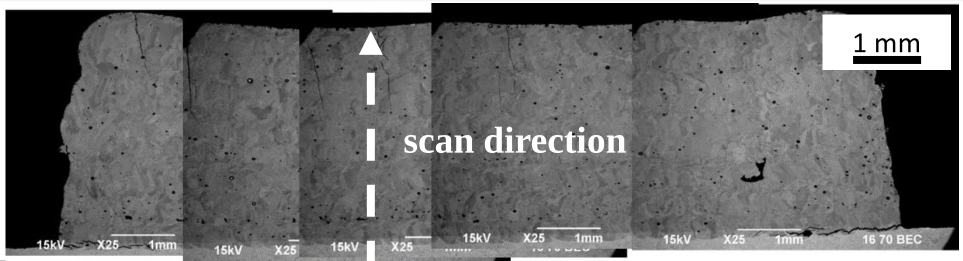
SEM-EDS

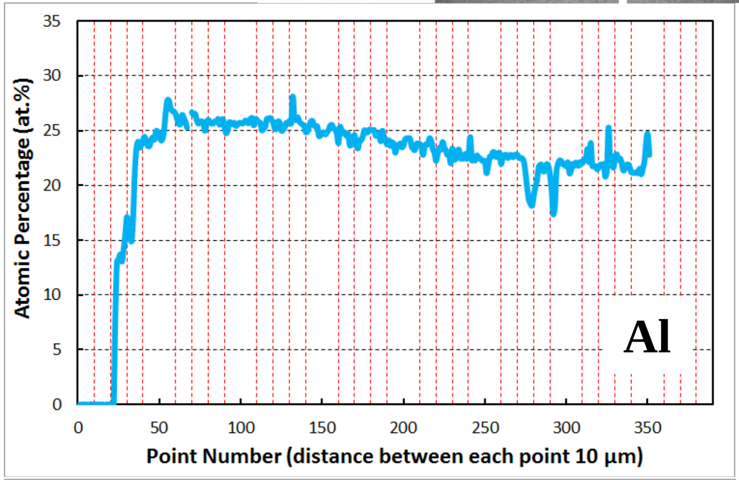


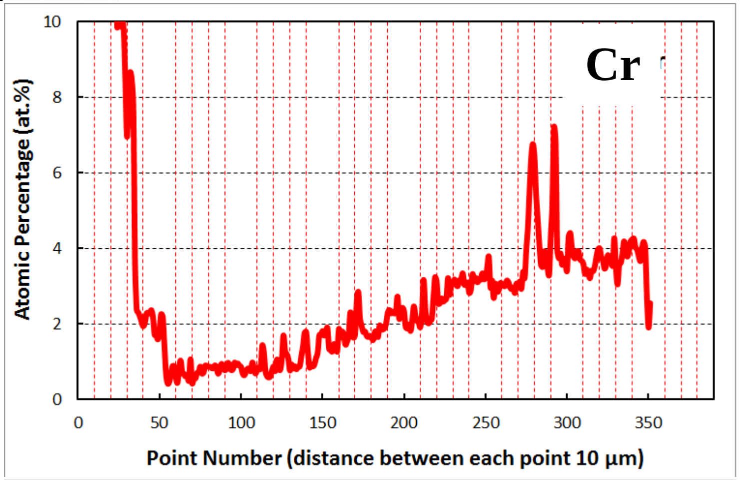
Production of chemically graded Fe–Al samples by LMD is possible.

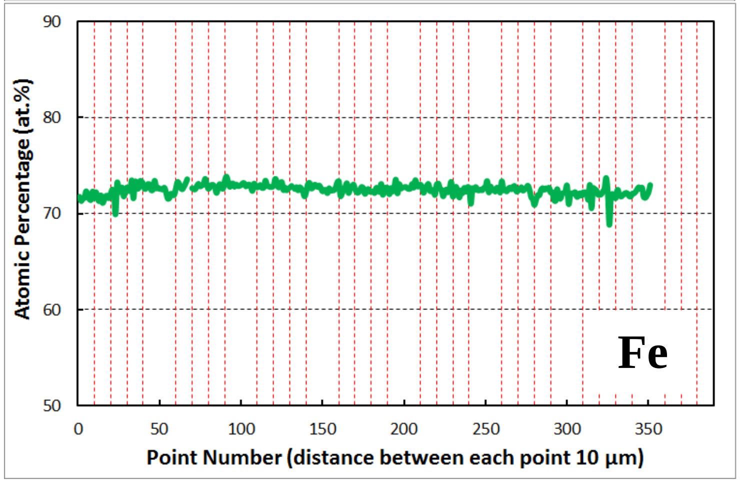
Chemically graded Fe–Al/ steel 316L sample

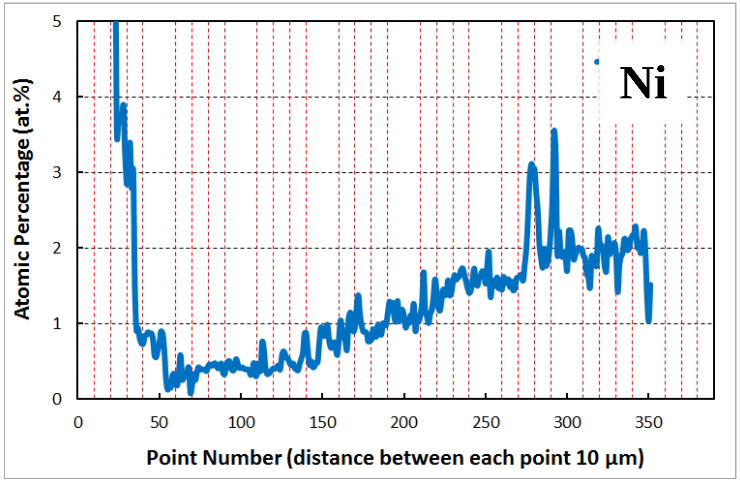
EPMA (WDS)











Production of chemically graded Fe–Al/steel samples by LMD is possible.

Conclusions

- Intermetallic Fe–Al alloys can be processed by SLM and LMD
- Fe–Al alloy concepts developed for casting can be transferred to AM
- Yield strength and creep strength are comparable to that of as cast alloys
- Partly improvement of ductility (through internal stresses (?) not through reduction of grain size)
- Chemically graded Fe–Al samples with defined concentration profiles can be manufactured by LMD

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