Quality & reliability – prerequisites for industrial 3D printing in Al ➔ “a big bang” that will (can) start in 2017 ?!

Monthly colloquium

19. May. 2016, AMAP Center, Aachen

Frank Palm – Airbus Group Innovations

AIRBUS GROUP

At a glance

1. Who is standing in front of you ?
2. What can you expect from me & my presentation ?
3. What is my expectation from you ? (➔ post lecture discussion)
4. The technical challenge (of 3D-printing in Al)
5. Just more than a summary ➔ Any particular consequences to the current state of 3D-printing in Al ?
6. Your questions & my answers ⇔ my questions & (hopefully) your answers

Who is standing in front of you ?

1. 55 years old tool maker
2. Technical University of Munich (TUM) ➔ Mechanical Engineering
3. With a high affinity to material science & processes
4. Working since more than 26 years in the aerospace industry at Airbus Group Innovations (the corporate research & technology of Airbus Group (since MBB-Zentrallabor))
5. Since 2005 as a Senior Expert for welding & additive manufacturing (incl. failure analysis (company-wide))

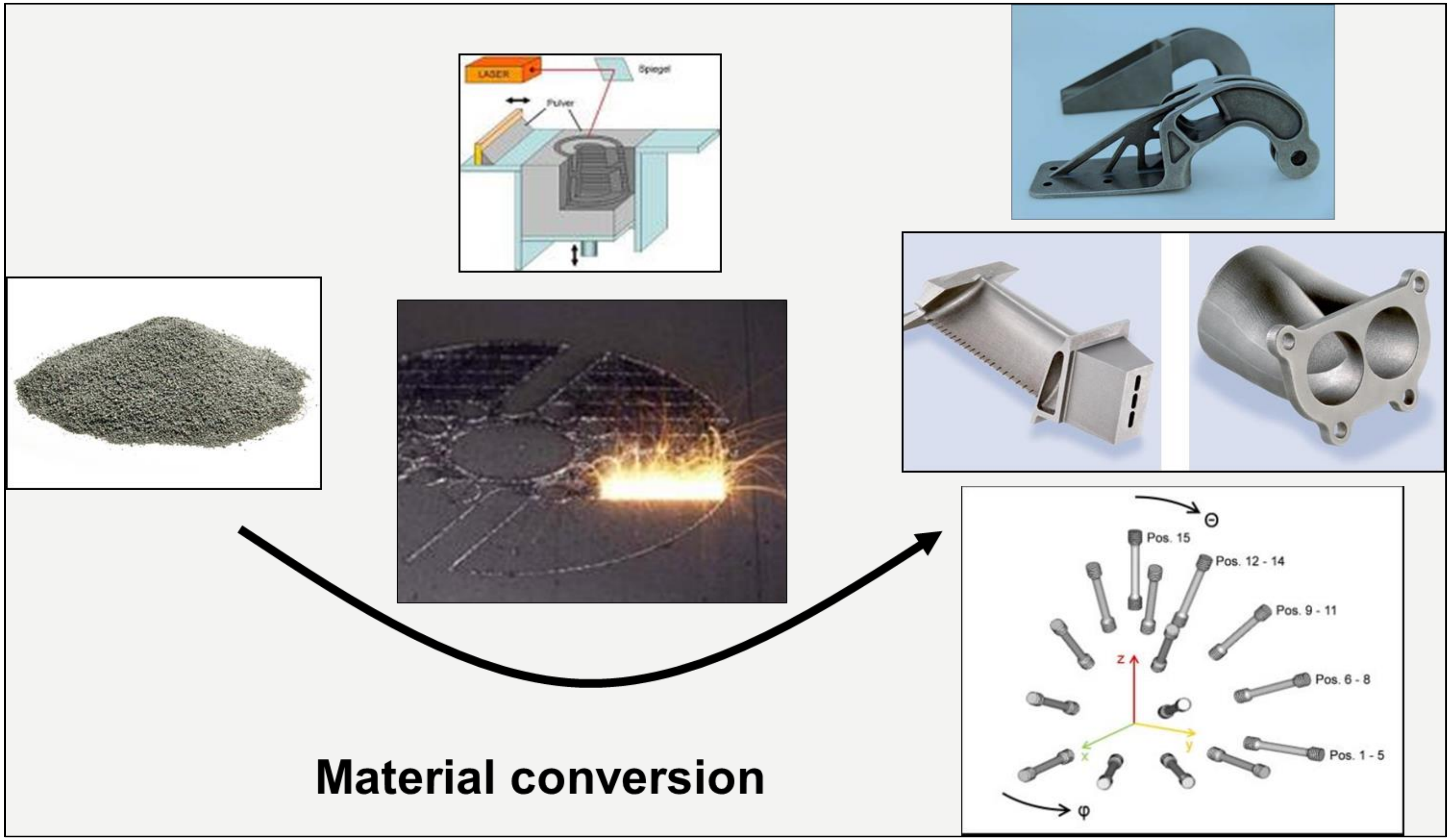
What can you expect from me & my presentation ?

1. My personal perspective on 3D printing in general
2. In particular my perception of the technology state on **laser powder-bed melting** on Al-alloys
3. Some information about our Airbus Group position on 3D-printing
4. Core information how to assess & improve Al-based 3D printing (where secrecy would be contra-productive)
5. However, by far not the comprehensive solution & answers how you can do (painless) industrial 3D-printing in Al

What is my expectation from you ?

1. An audience that is following my speech carefully and with curiosity
2. A high level discussion coupled with the willingness to exchange experiences
3. Hopefully some answers to particular questions & issues I´m carrying on since many month without finding the expected (required) information
4. May some new contacts for future technical exchange or collaboration

Laser powder-bed melting (LPBM) of Al based materials



= Laser beam welding of Al alloys with Al-powder as filler material using a particular LPBM platform!

The technical challenge (of 3D-printing in Al)

Stage 1
AM Design

Stage 2
Process & postprocess

Stage 3
Quality assurance

End of life

Part concept design | **AM process select-ion** | **Detailed design, optimi-zation, DFM** | **Build design & preparation** | **Pre-material production & qualification** | **AM process** | **Part Heat & pressure treat-ment** | **Part removal from plate** | **Machin-ing and smooth-ing** | **Surface treat-ment** | **Destru-ctive testing of traveler** | **NDT** | **Finished part** | **Validation testing** | Customer feedback | **Repair** | **Recycle**

Environmental life-cycle assessment
eco-design & optimisation

Powder re-use (control of degradation)

Closed-loop material re-use

Pre-material
↓
Al-powder

Additive layer manufac-turing process

Part heat & pressure treatment

Core process:

- ➔ (direct) material manufacturing
- ➔ Strength properties
- ➔ Ductility & toughness
- ➔ Fatigue & damage accumulation
- ➔ Corrosion
- ➔ Surface protection & function
- ➔ ……

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The technical challenge (of 3D-printing in Al)

1. The company which is doing the 3D-print must be aware that they will be **material manufacturer !**
2. Material manufacturing for HQ applications implies a bunch of requirements & standards / qualifications & certifications
3. More than 100 years of experience in Al base material production defines our current material quality level (in terms of strength, material cleanliness (oxides, other impurities, hydrogen etc.)

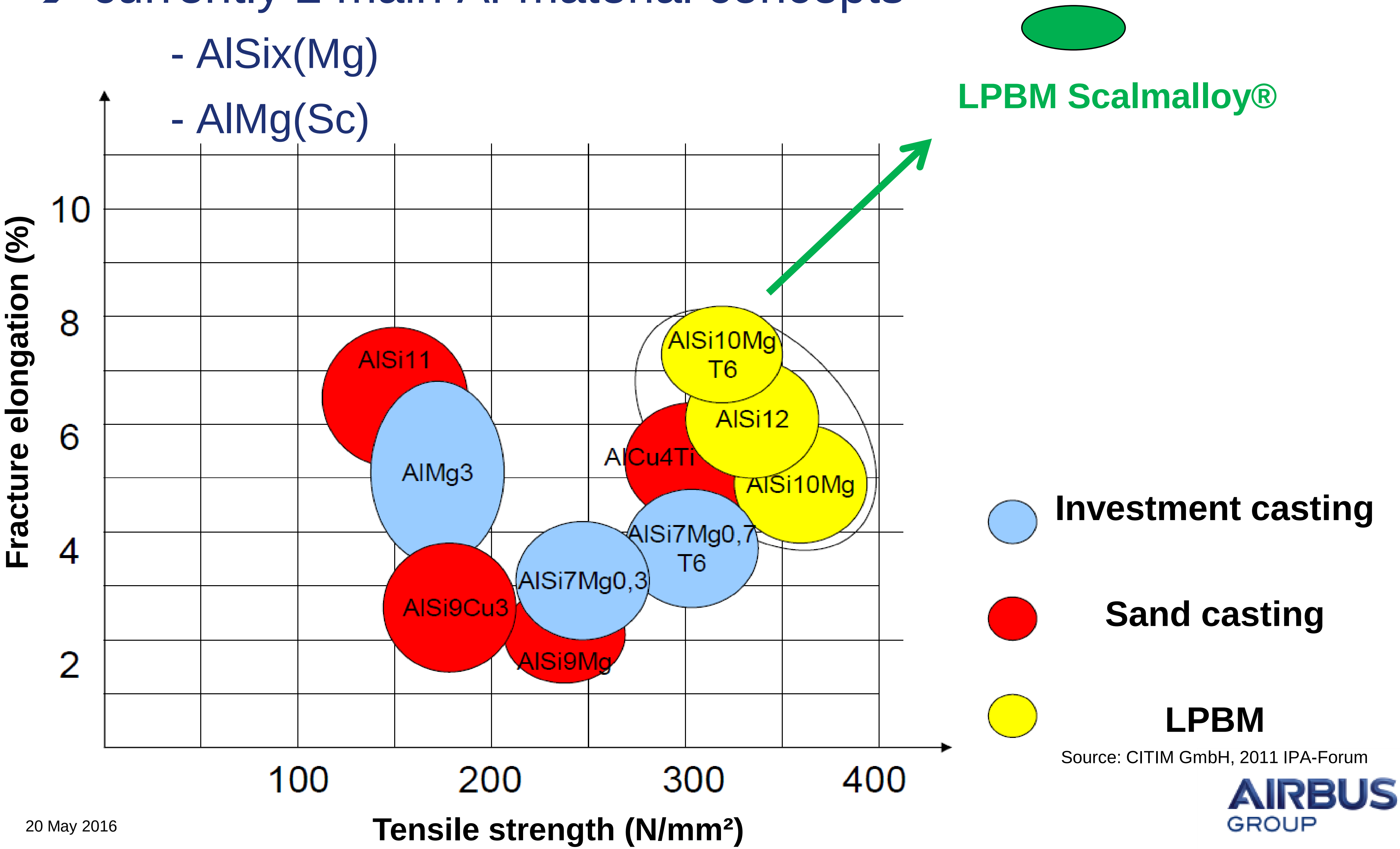
The technical challenge (of 3D-printing in Al)

1. In order to produce reliable material quality you have to know (to master)
   a. What is defining your material strength (where does your strength come from) ?
   b. What is limiting & influencing the generated material ductility ?
   c. Why & how is a post build-up heat treatment necessary and can contribute in a tailored manner to assure material quality

The technical challenge (of 3D-printing in Al)

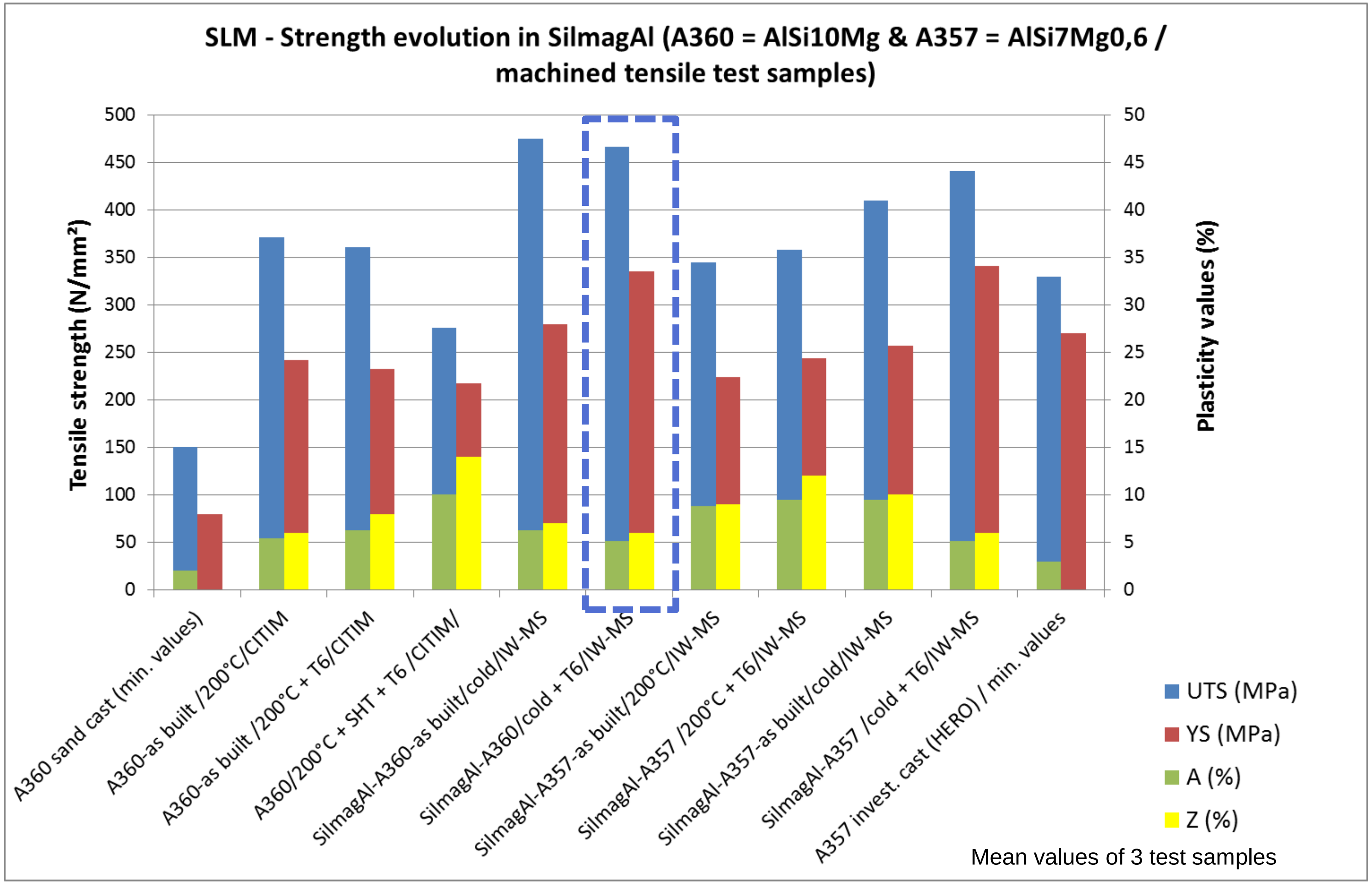
➔ currently 2 main Al-material concepts

- AlSix(Mg)
- AlMg(Sc)



Source: CITIM GmbH, 2011 IPA-Forum

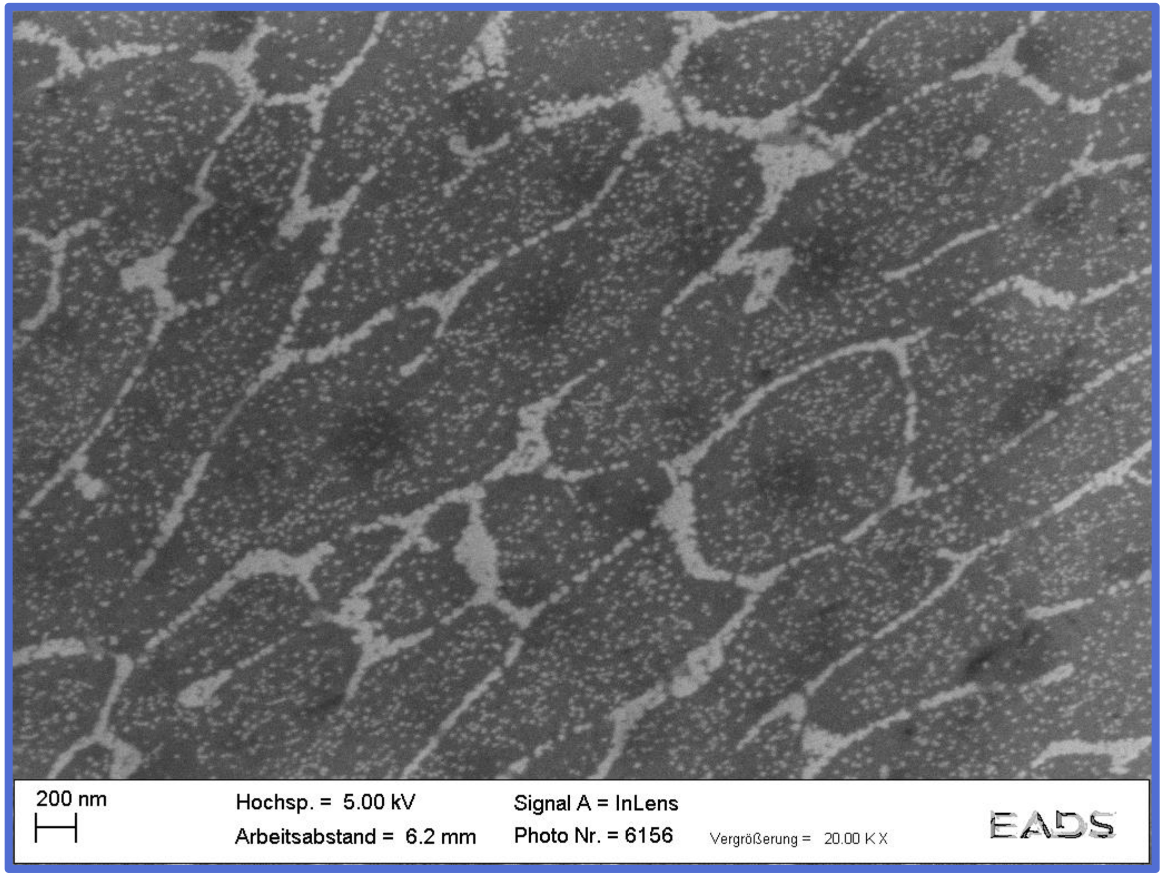
The technical challenge (of 3D-printing in AlSix(Mg))



- AlSix(Mg) powders from different sources !
- Testing was done at AGI
- SLM process parameter based on recommendations of SLM Solutions or self developed

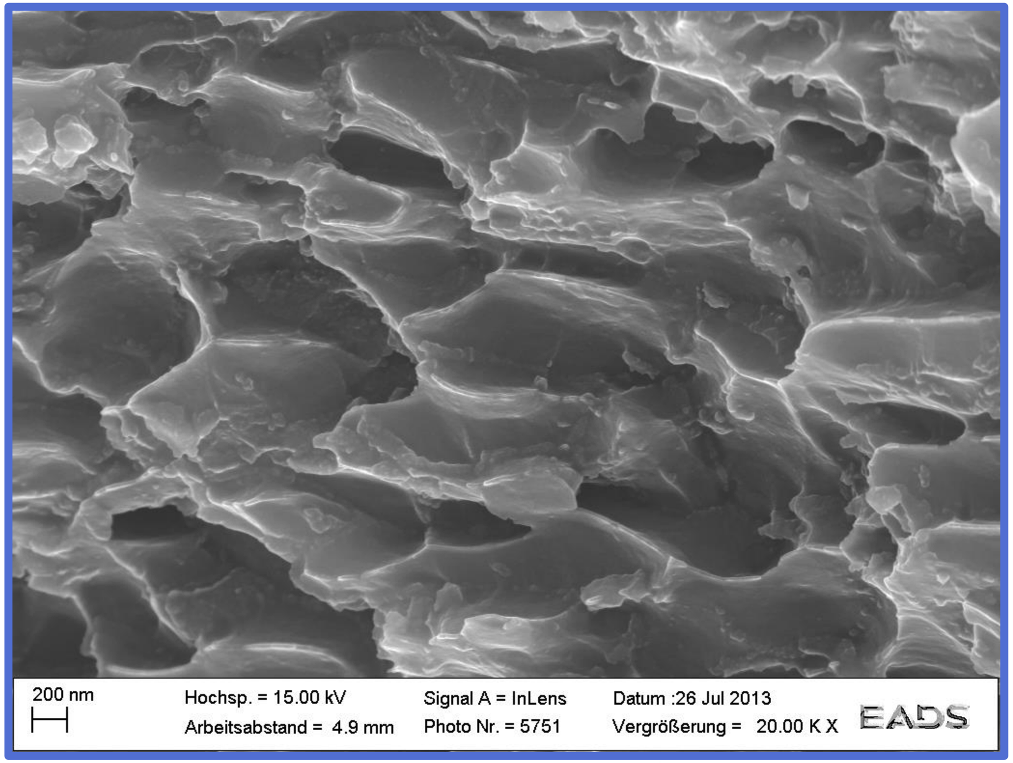
- Fully machined surfaces / very high strength with cold (RT) build parameter ➔ rapid solidification enables super solid solution of Mg_2Si ➔ precipitation possibility !
- Improved ratio of strength versus ductility for AlSi7Mg0.6

The technical challenge (of 3D-printing in AlSix(Mg))

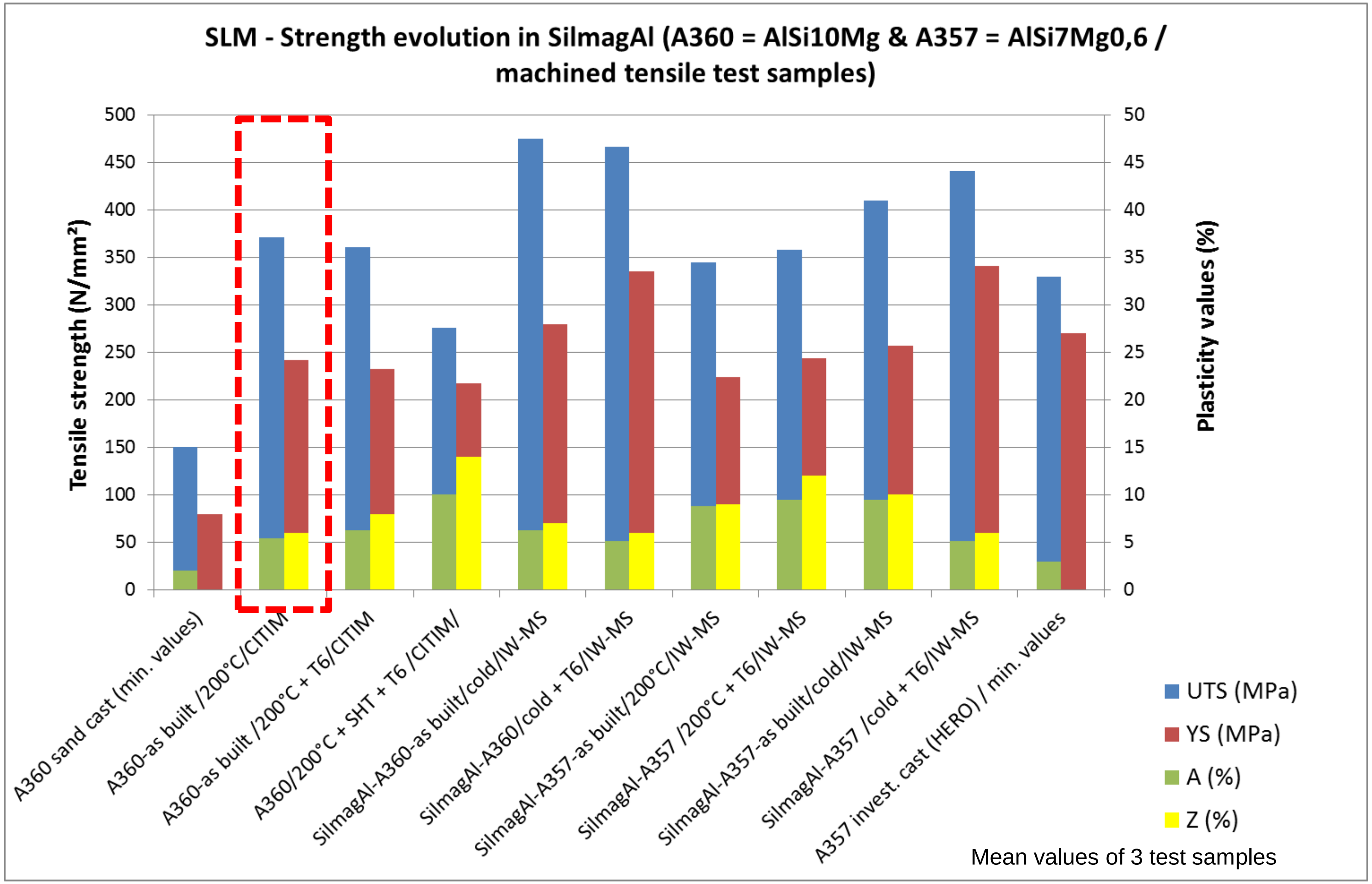


- Precipitation hardening by Mg_2Si-phase can contributes with about 30 – 50 MPa to the entire material strength provided a cold build-up process parameter was used
- The coarser the Si-phase the lower the strength

- Very high strength in AlSi(Mg) **LPBM** material is caused by nano-sized primary solidified Si-particles at & in the fine cell boundaries (MMC effect)
- Fracture morphology also reflects this observation



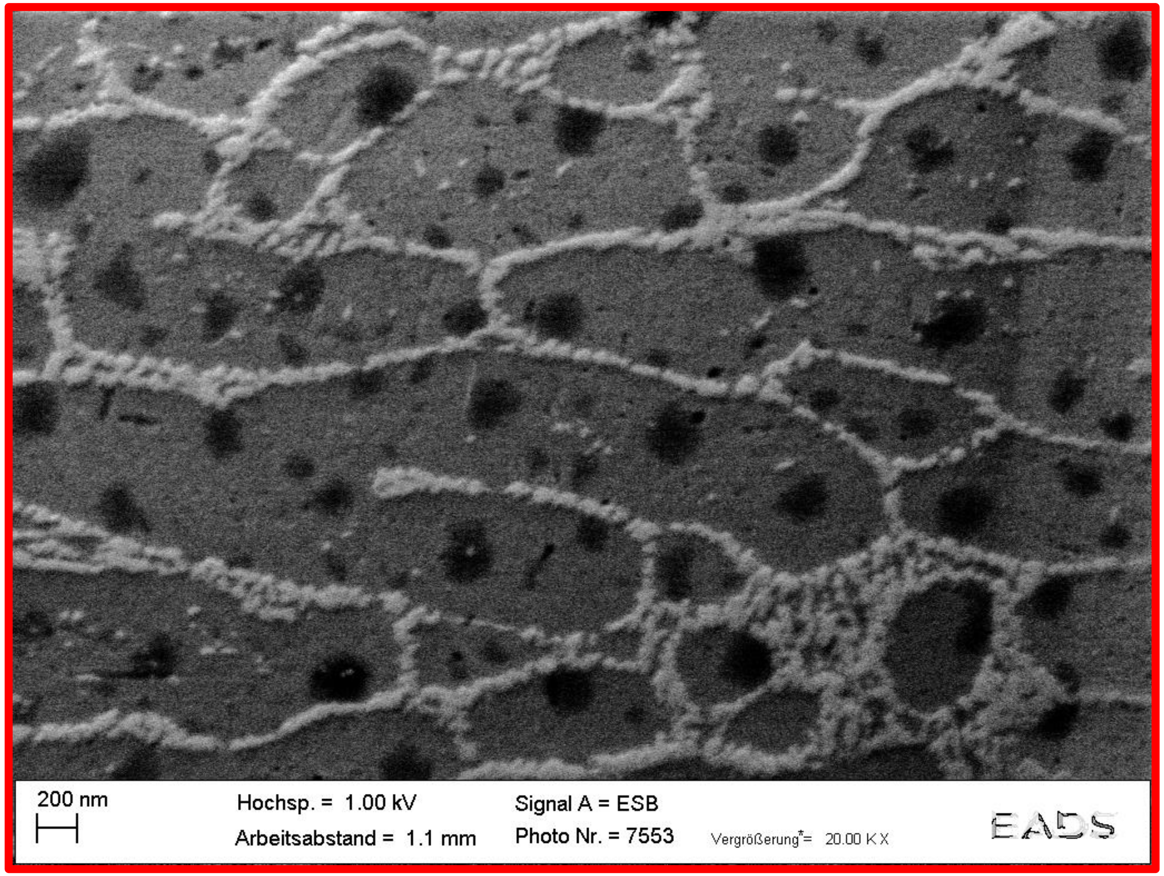
The technical challenge (of 3D-printing in AlSix(Mg))



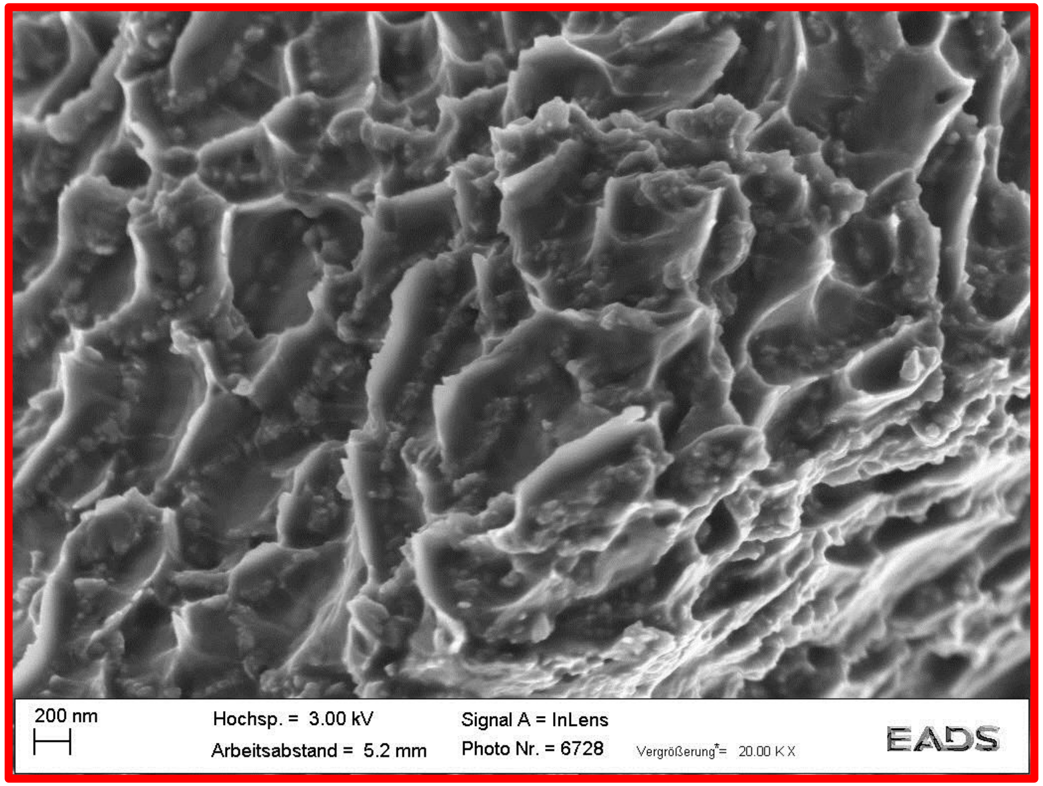
- AlSiMg powders from different sources !
- Testing was done at AGI
- SLM process parameter based on recommendations of SLM Solutions

- Fully machined surfaces / very high strength with cold (RT) build parameter ➔ rapid solidification enables super solid solution of Mg_2Si ➔ precipitation possibility !
- Improved ratio of strength versus ductility for AlSi7Mg0.6

The technical challenge (of 3D-printing in AlSix(Mg))

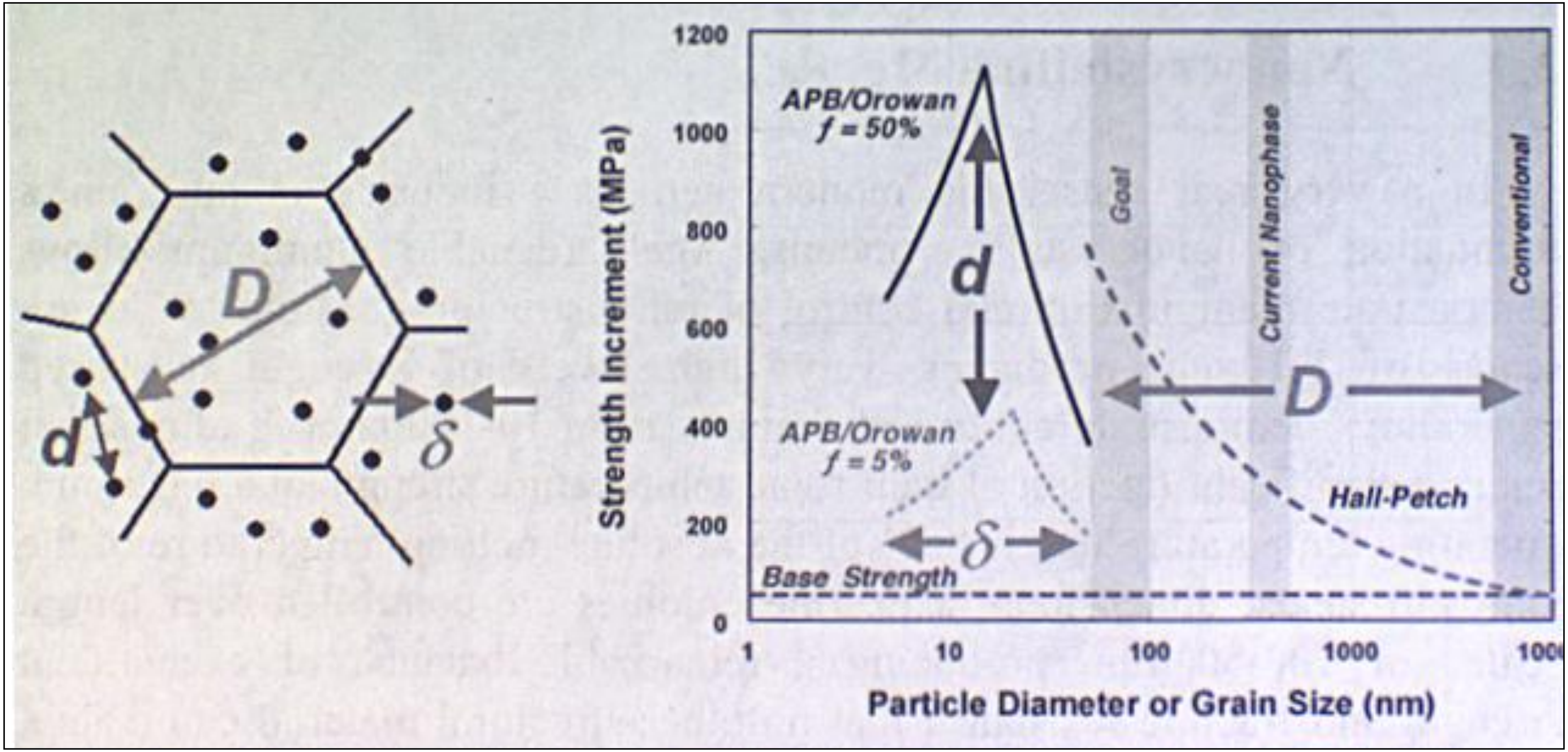


- Strength decrease (MMC effect is almost lost due to absence of very fine Si-primary particles)
- Fracture morphology also reflects this observation partially



- Base plate temperature of about 200°C (= reduced rapid solidification) suppresses supersaturation & leads to Si-primary phase coarsening
- Post heat treatments at high T are “critical”

The technical challenge (of 3D-printing in AlSix(Mg))



- Hall-Petch (fine grain) hardening ➔ improving strength + ductility
- Particle hardening (MMC - effect) ➔ damaging ductility
- Precipitation hardening ➔ ideal mix of strength & ductility

The technical challenge (of 3D-printing in AlMg(Sc))

Al-Mg structure material EN-AW5083 (AlMg4,5Mn) +Sc/Zr

| 100 MPa ---------- 425 MPa ---------- 850 MPa |

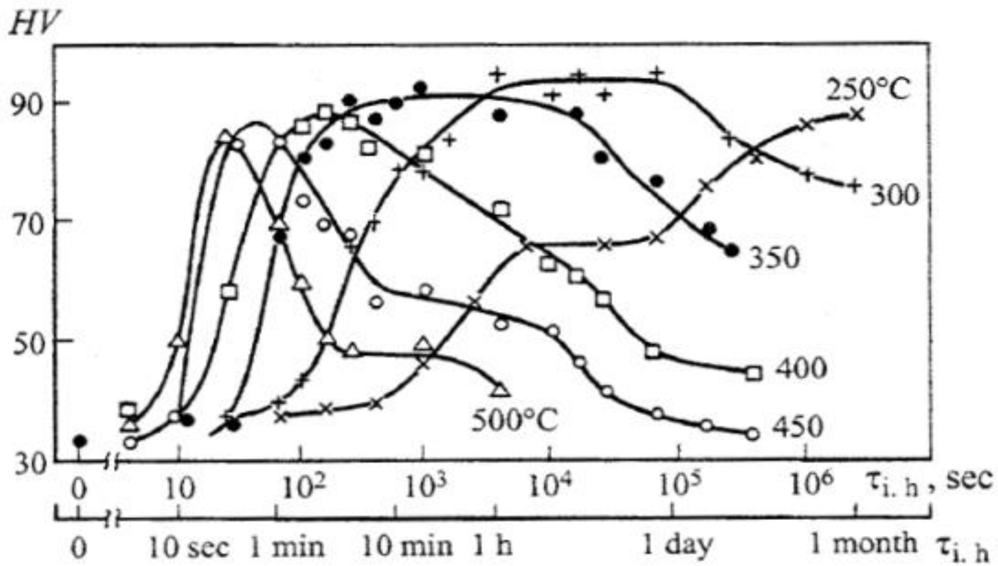
5083 "cast"

+ 100% !!

5083 + 0,8%Sc + 0,3%Zr

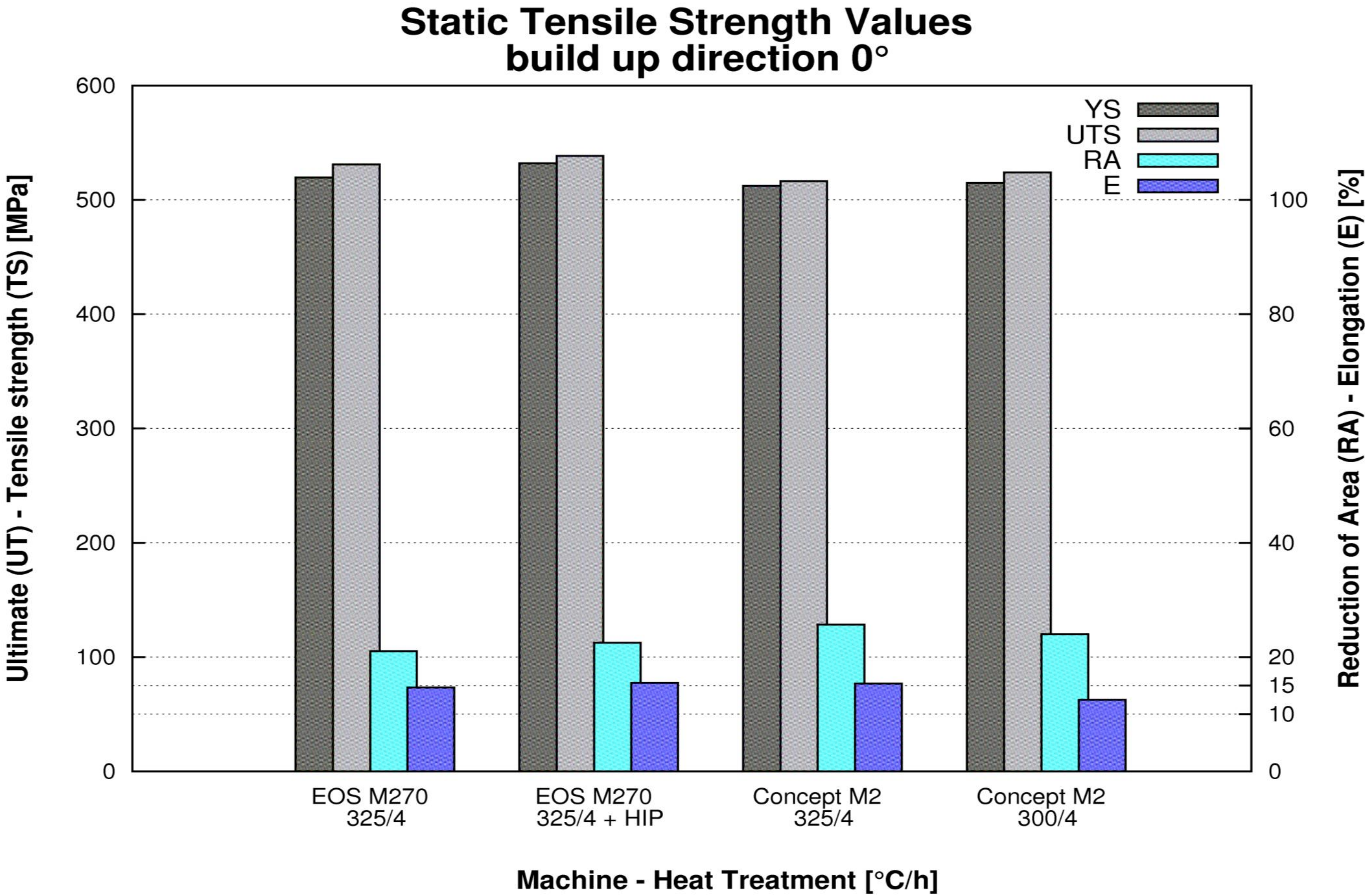
Scalmalloy®

- ✓ **Residual stress annealing**
- ✓ **Precipitation hardening**
- ✓ **Post built-up consolidation with iso-static pressure (HIP)**

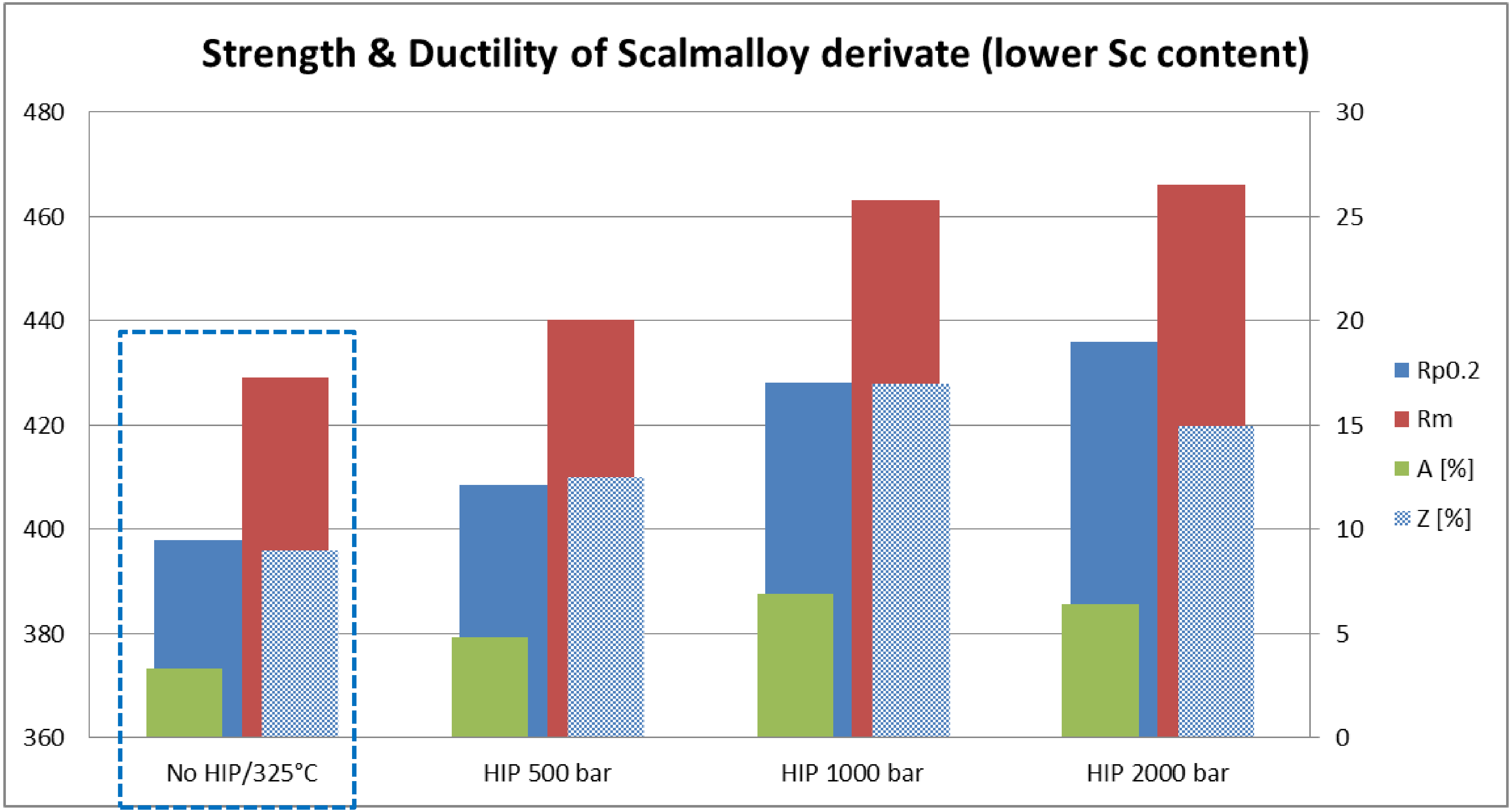


➔ **In one single (final) heat treatment material concept !**

The technical challenge (of 3D-printing in AlMg(Sc))



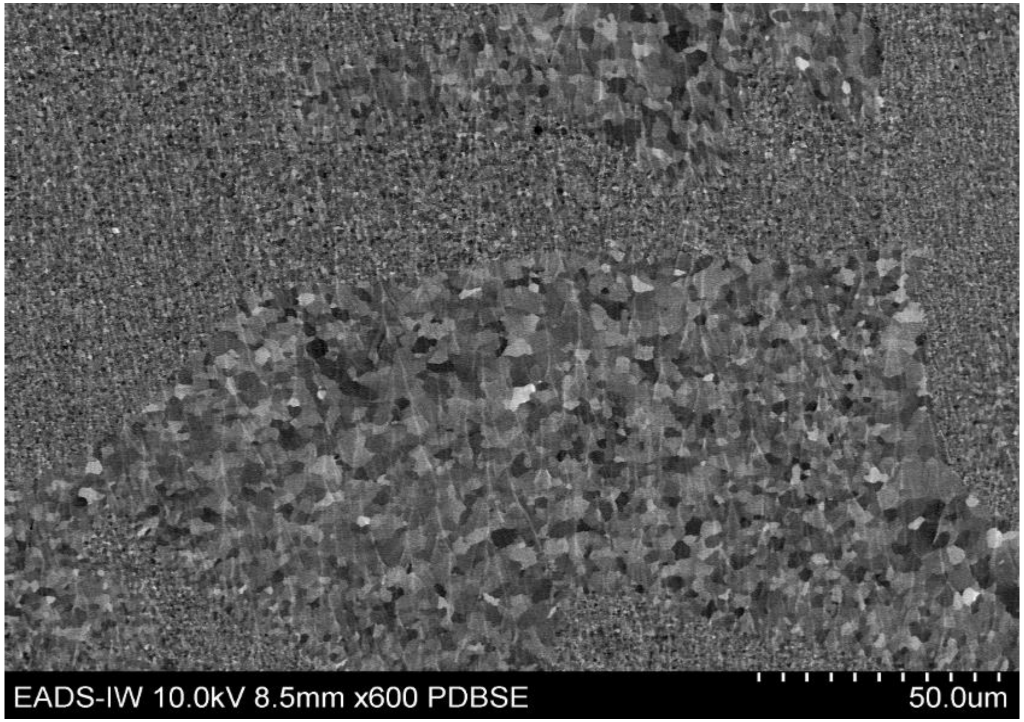
The technical challenge (of 3D-printing in AlMg(Sc))

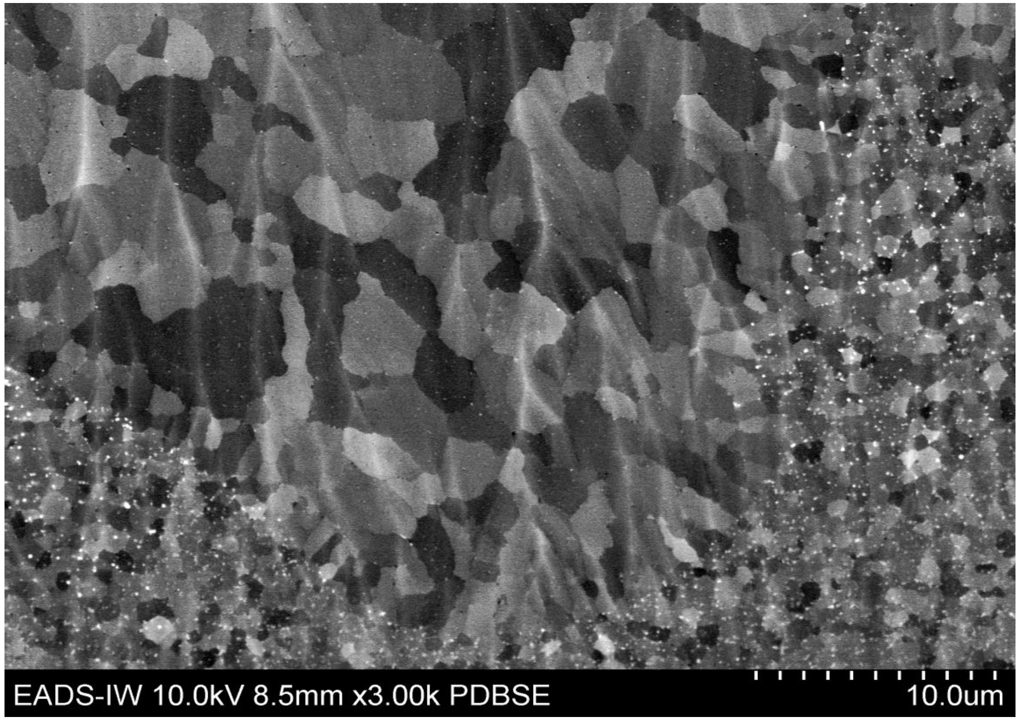


➔ „Repair capabilities“ in badly generated LPBM – AlMgSc material due to “Hipping”

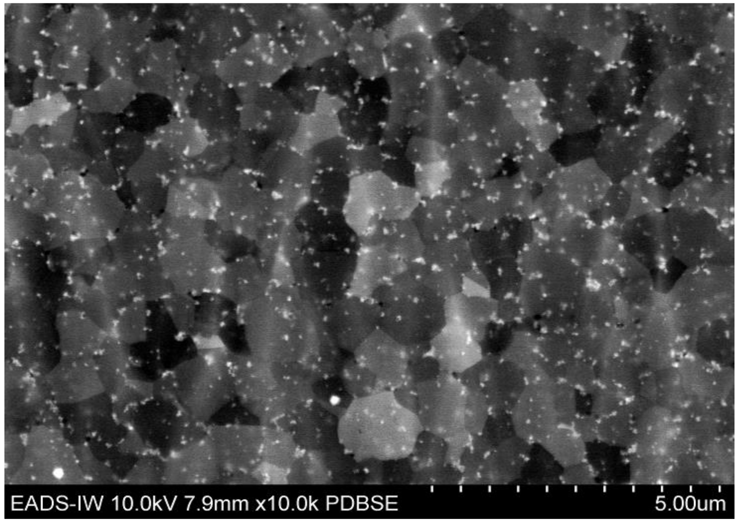
The technical challenge (of 3D-printing in AlMg(Sc))

➔ Ion etched – SEM-BSE contrast – perpendicular to build-up direction





Bi-modal micro-structure with equi-axed (cast) grains in z-build-up direction & equi-axed + elongated grains in the x-y plain



Grain sizes varies from 5 – 20 µm (equi-axed) & 25 - 100 µm (elongated) and 500 nm – 2 µm in the very fine equi-axed region

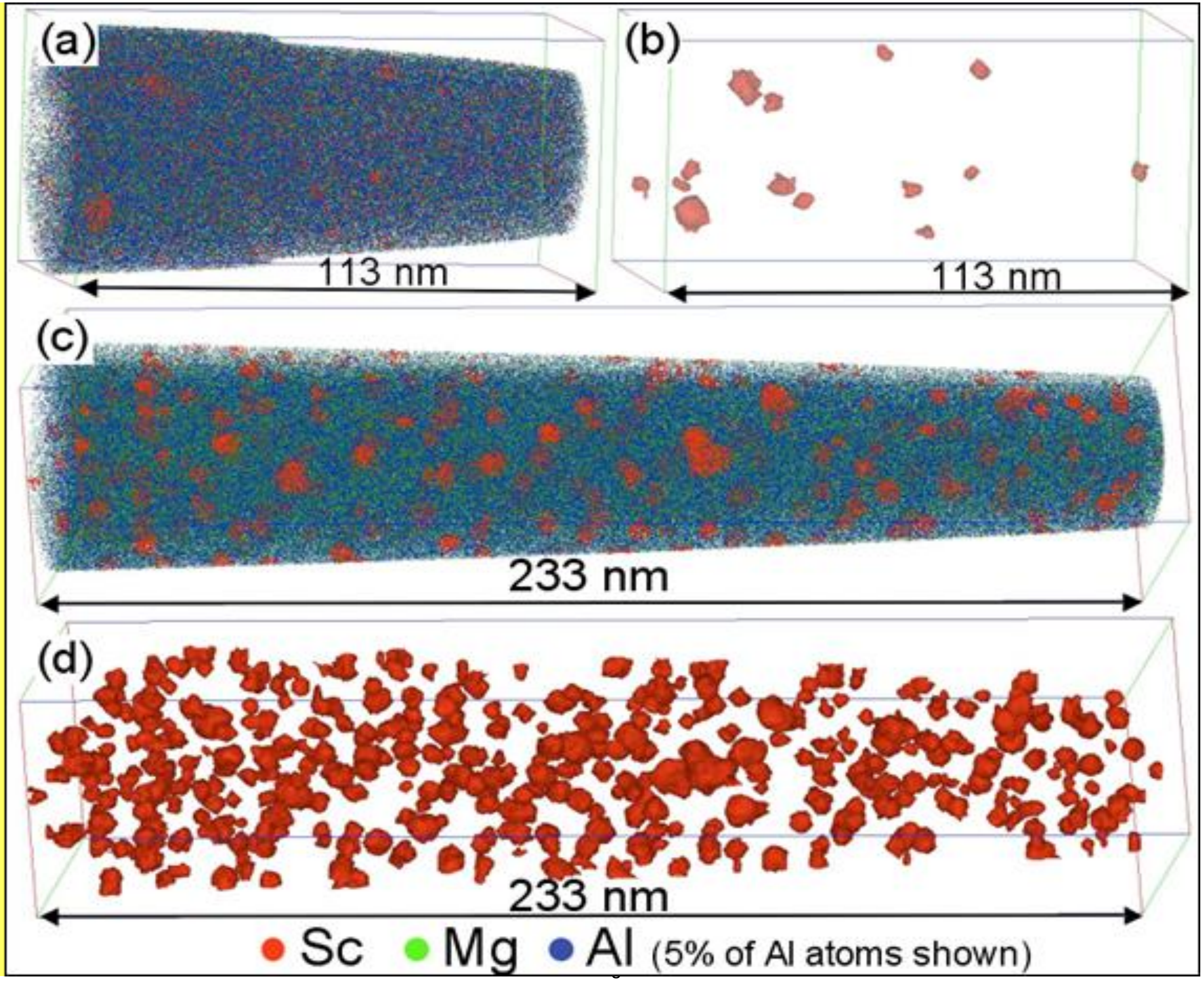
The technical challenge (of 3D-printing in AlMg(Sc))

➔ Precipitation hardening with Al_3ScZr ⇔ nano-sized ⇔ high density

As cast (= not aged)

Aged at 300°C/8 h

Aged at 300°C/8 h

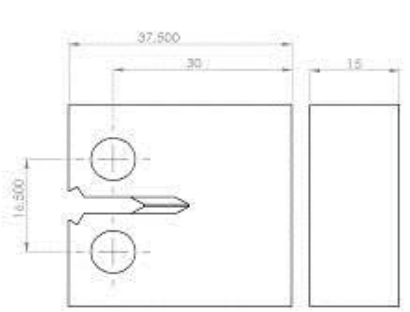


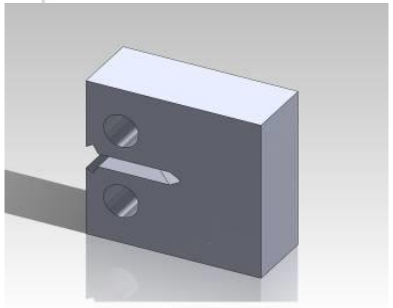
Al_3ScZr phase size about 4 – 10 nm with fully coherent lattice interface !!

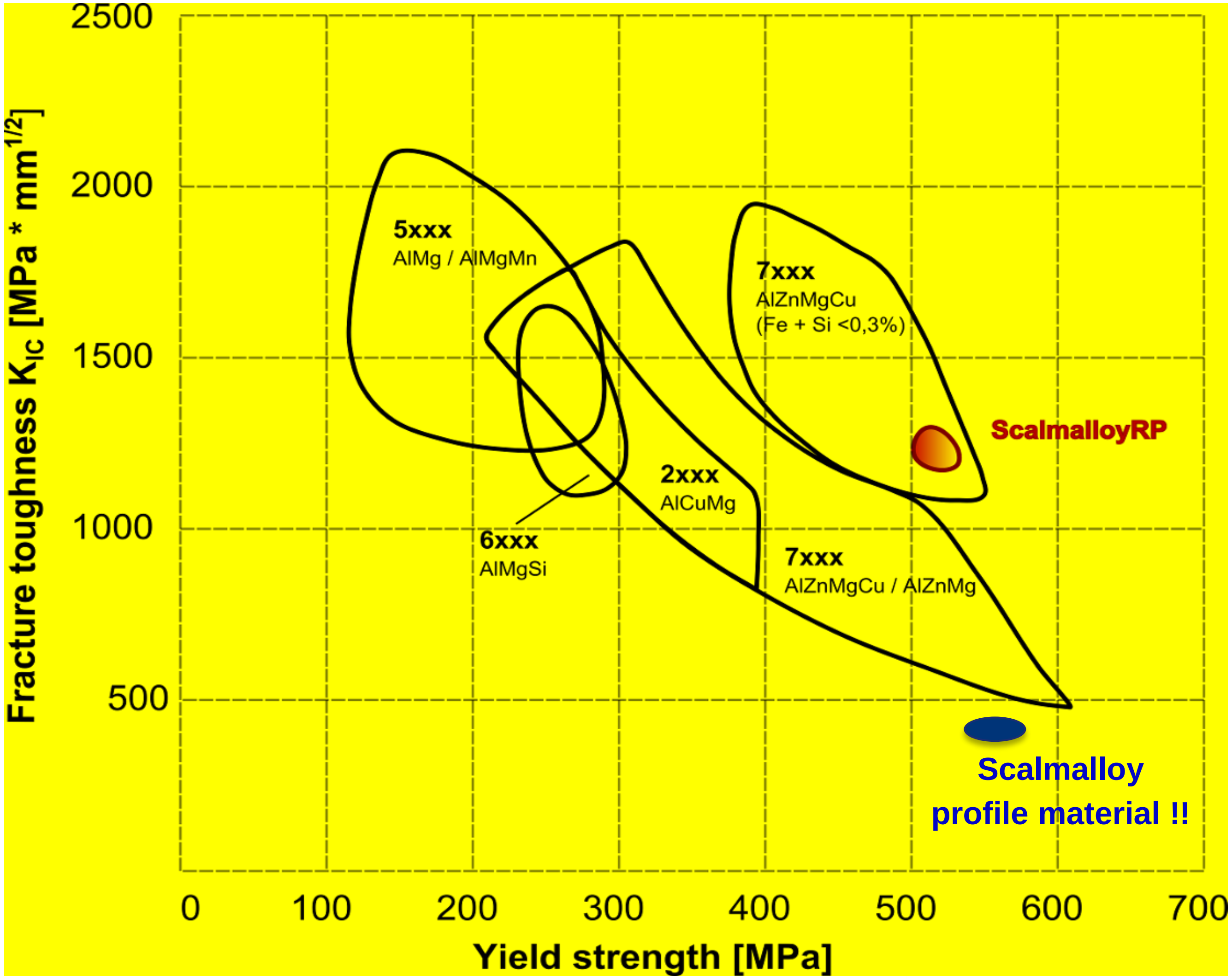
The technical challenge (of 3D-printing in AlMg(Sc))

➔ Relatively high fracture toughness K_{IC} in directly built & heat treated AlMgSc !!

- 3 samples per built direction (0° and 90°)
- tested according to ASTM E 1820





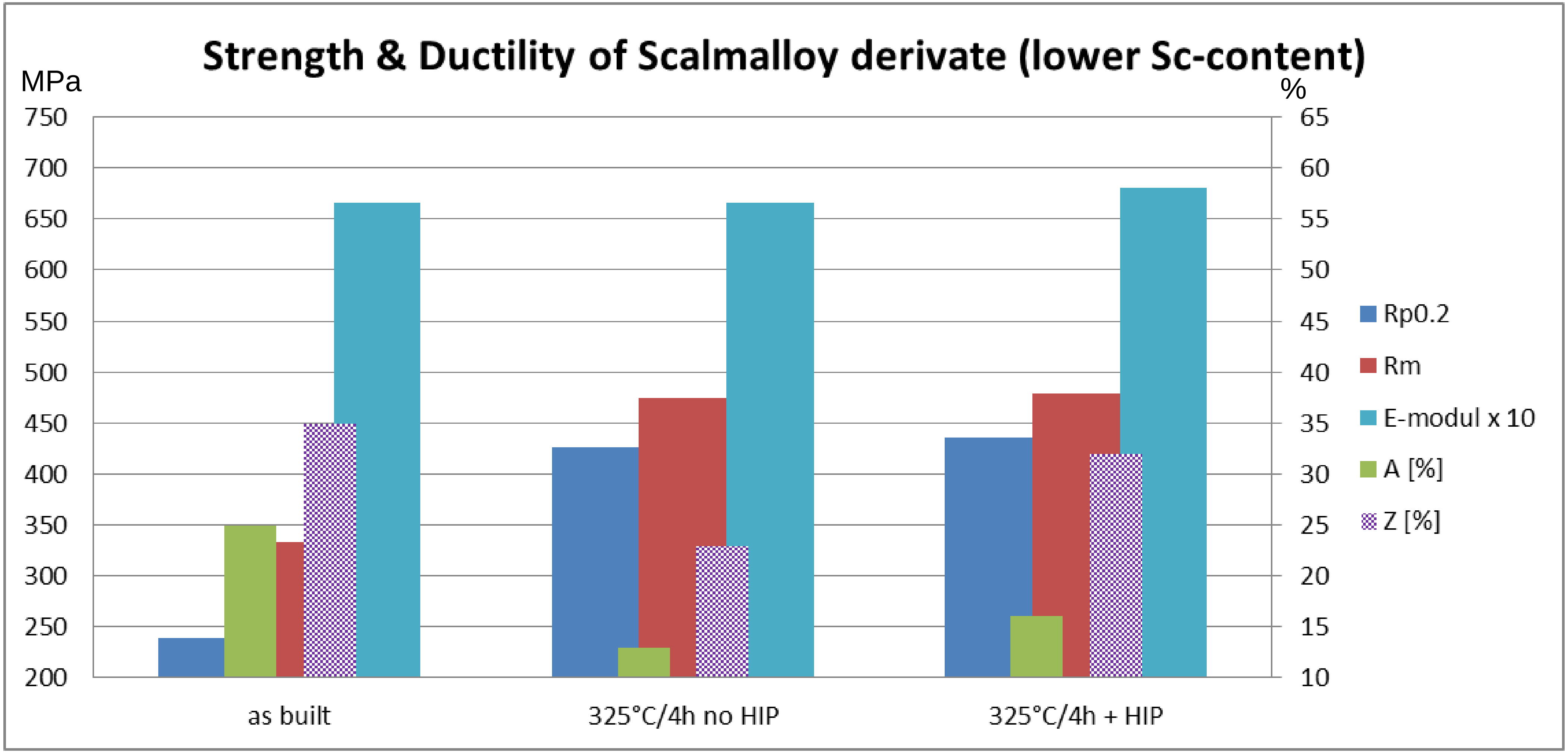


The technical challenge (of 3D-printing in Al)

How can I recognize whether my LPBM process parameter development is “finalized” (reaching the “saturated zone” of maximum strength versus ductility)?

- Difference between UTS & YS in horizontal and vertical build direction is ≤ ± 3 % (➔ means ± 15 N/mm² ⇔ 500N/mm²)
- Difference between A (fracture elongation) & Z (reduction in area at fracture) in horizontal and vertical direction is ≤ 25 %
- The measured Young´s modulus (deduced during tensile testing) is reaching the theoretical “limits”
- It will mean that the materials performance processing maxima (“saturation”) is achieved on which later you can build-up the base for “effect of defects” analysis etc.

The technical challenge (of 3D-printing in Al)



➔ Evolution of Scalmalloy® material performance parameter (reasonable process parameter) due to post built-up heat treatment (incl. HIP) with respect to UTS / YS / A / Z & Y-M

Just more than a summary

Qualified ("industrial") Al-materials have more or less **no** oxide inclusions and the hydrogen content is **less than 0.1 ppm** !!

- Even the Al-powder for LPBM displays oxide contents from 100 – 2000 ppm (there is a need for "passivated" powder due to security reasons !)
- Due to humidity & moisture coupled with powder handling the Al-powder displays 10 – 100ppm H_2 (H_2O) ➔ Clean room processing ??
- Obviously powder processing capabilities are affected by powder (O_2) cleanliness in an adverse manner (the cleaner the worse !)
- Heat treatments are a must ⇔ ideal fit (up to now) only for Scalmalloy®....... !
- Al-powder manufacturing & handling……one base for future LPBM success !

Just more than a summary ⇔ Any consequences ?

- Sufficient (“saturated”) Al material properties in LPBM require robust inherent process parameter & full process understanding
- 3D-printing product quality has to be directly generated (and cannot alternatively be restored by post process inspection or on-line process monitoring/control (➔ this will help however to secure the material generation !))
- Even in Al (strong & stable oxide-layer former) HIP is working (although the material generation process in running in an inert gas atmosphere !) ⇔ Why ?

- **Cleanliness & accuracy related to process parameter like powder, laser energy source, process chamber conditions are key topics to run future 3D-printing of HP aluminum on a commercial (value adding) base**

Thank you very much for your attention

Your questions – my answers

My questions – your answers