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"Grain Refinement of Al-Si Alloys by Nb-B Inoculation. Part 1: Concept Development and Effect on Binary Alloys. Part 2: Application to Commercial Alloys"

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Grain refinement of Al-Si alloys by Nb-B inoculation

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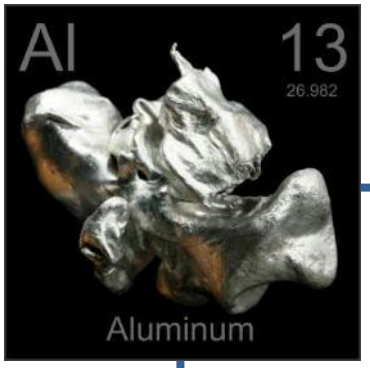
Outline

- Grain refinement in Al alloys with Al-5Ti-B
- Concept development
- Application to Al-Si cast alloys
- Al-Nb-B master alloy
- Comparative study between Al-Nb-B and Al-5Ti-B master alloys

ALUMINIUM ALLOYS



PROPERTIES

- LOW DENSITY, 2.7 g/cc
- GOOD MECHANICAL PROPERTIES
- HIGH CORROSION RESISTANCE
- HIGH THERMAL CONDUCTIVITY
- LOW ELECTRICAL RESISTIVITY

ALLOYS

WROUGHT

CAST (Al-Si)

GRAIN REFINEMENT

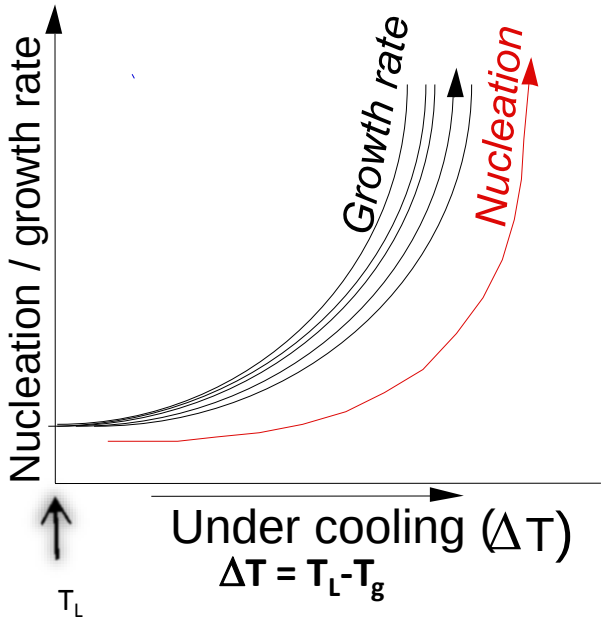
IMPROVEMENT

FLUIDITY/CASTABILITY
MECHANICAL PROPERTIES
MACHINABILITY
SURFACE QUALITY
CHEMICAL HOMOGENEITY
REDUCED SHRINKAGE POROSITY

Factors determining grain size in as cast microstructure

Nucleation & Growth

Heterogeneous nucleation
Homogeneous nucleation



Growth Kinetics

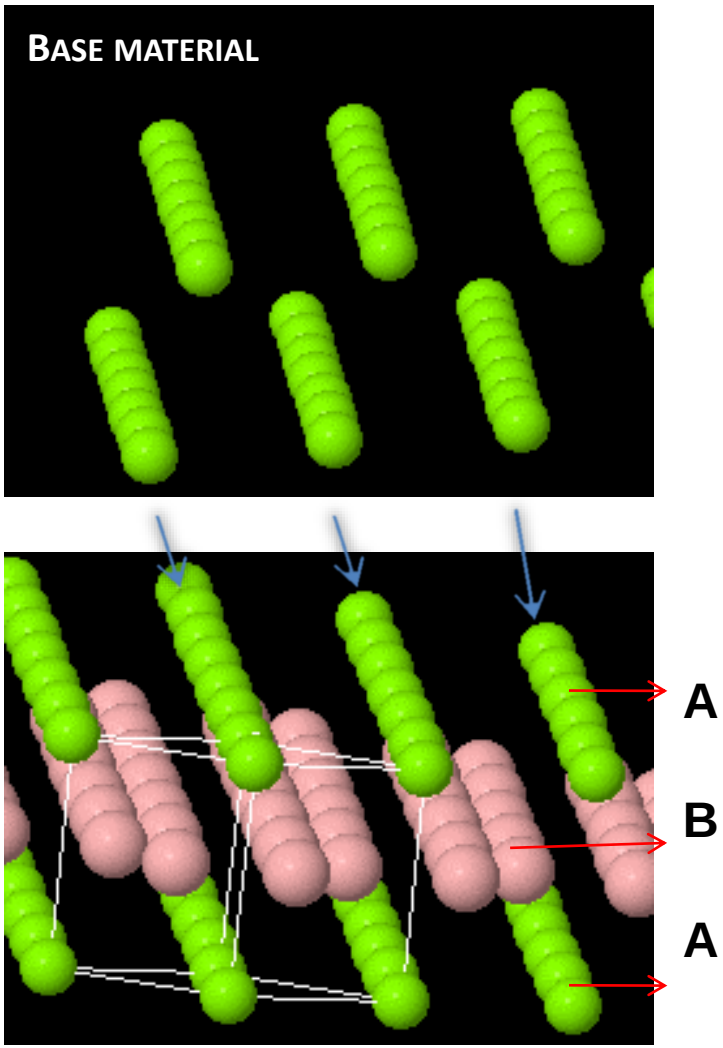
- Temperature
- Atmosphere/Pressure
- Growth restriction
- Fragmentation
- Cooling rate

Efficient Heterogeneous Nucleation Sites

1. High melting Temp

2. Low lattice mismatch
   (atom position matching)

3. Chemical stability
   (should not react with alloying elements)



N. Hari Babu et al., Nature Materials 2005;4:476

GRAIN REFINERS IN ALUMINIUM INDUSTRY

GRAIN REFINEMENT: Al-Ti-B

Al-Ti-C

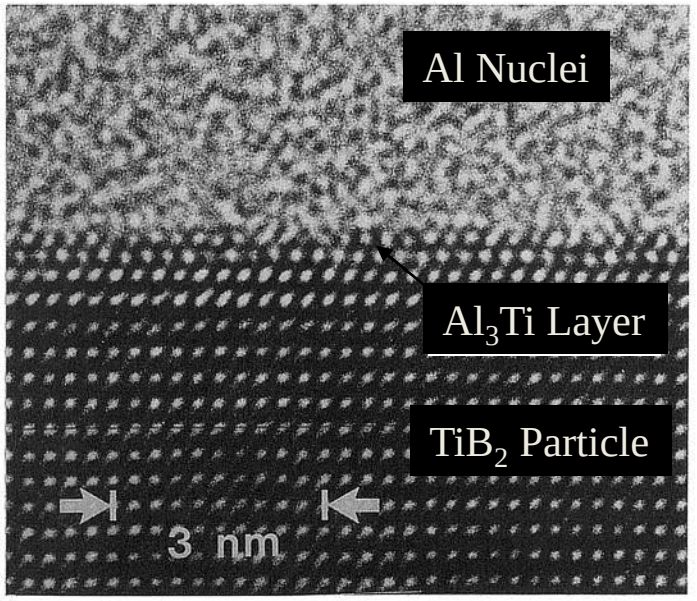
TiB_2 & Al_3Ti

- Orientation Relationships

{111}Al//{112}Al_3Ti//{001}TiB_2

<110>Al//<201>Al_3Ti

<110>Al_3Ti//<110>TiB_2



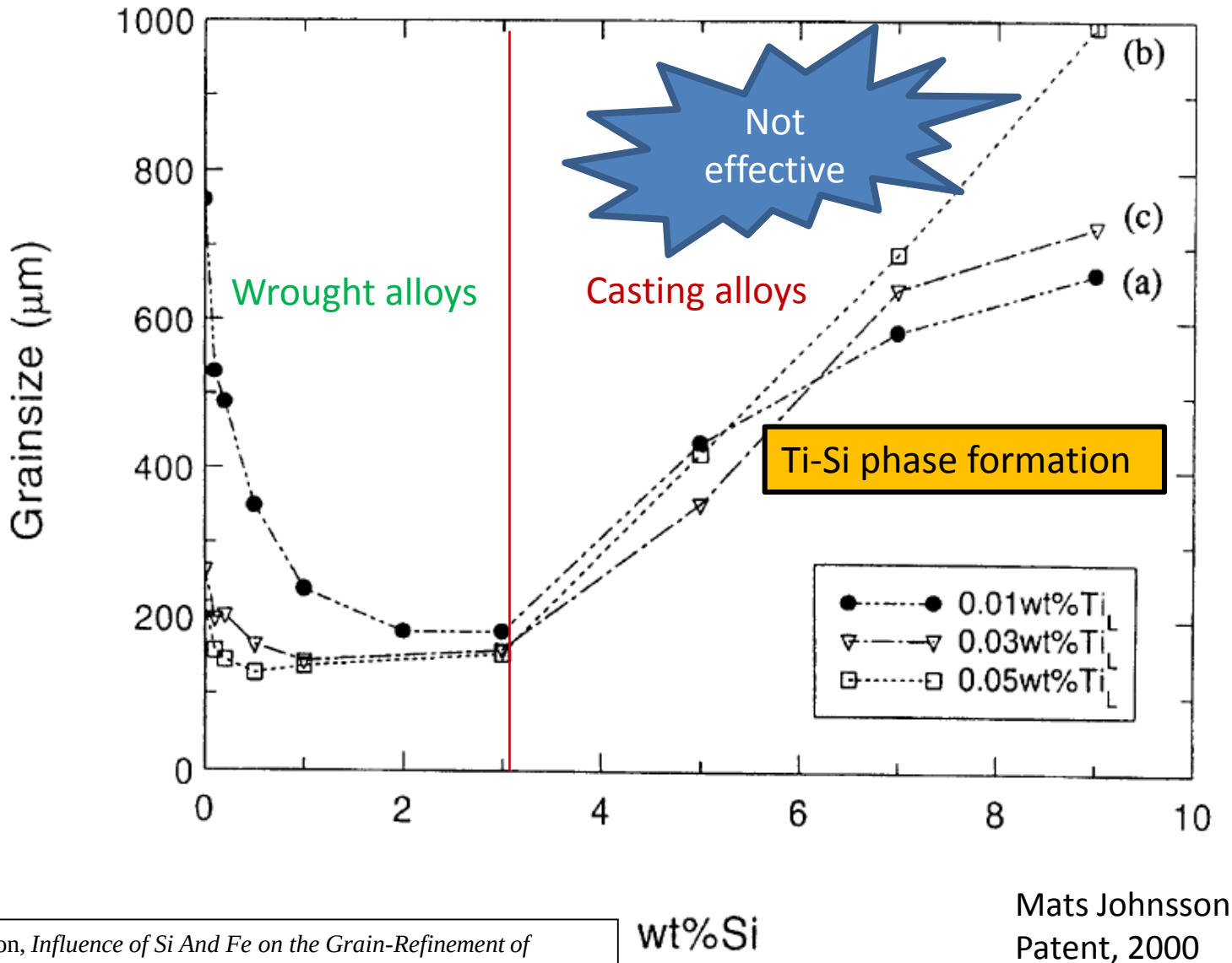
HREM image of $Al/Al_3Ti/TiB_2$ interface

Source: B. J McKay

MODIFICATION: Sr modification of the Si morphology

P to nucleate the primary Si particles

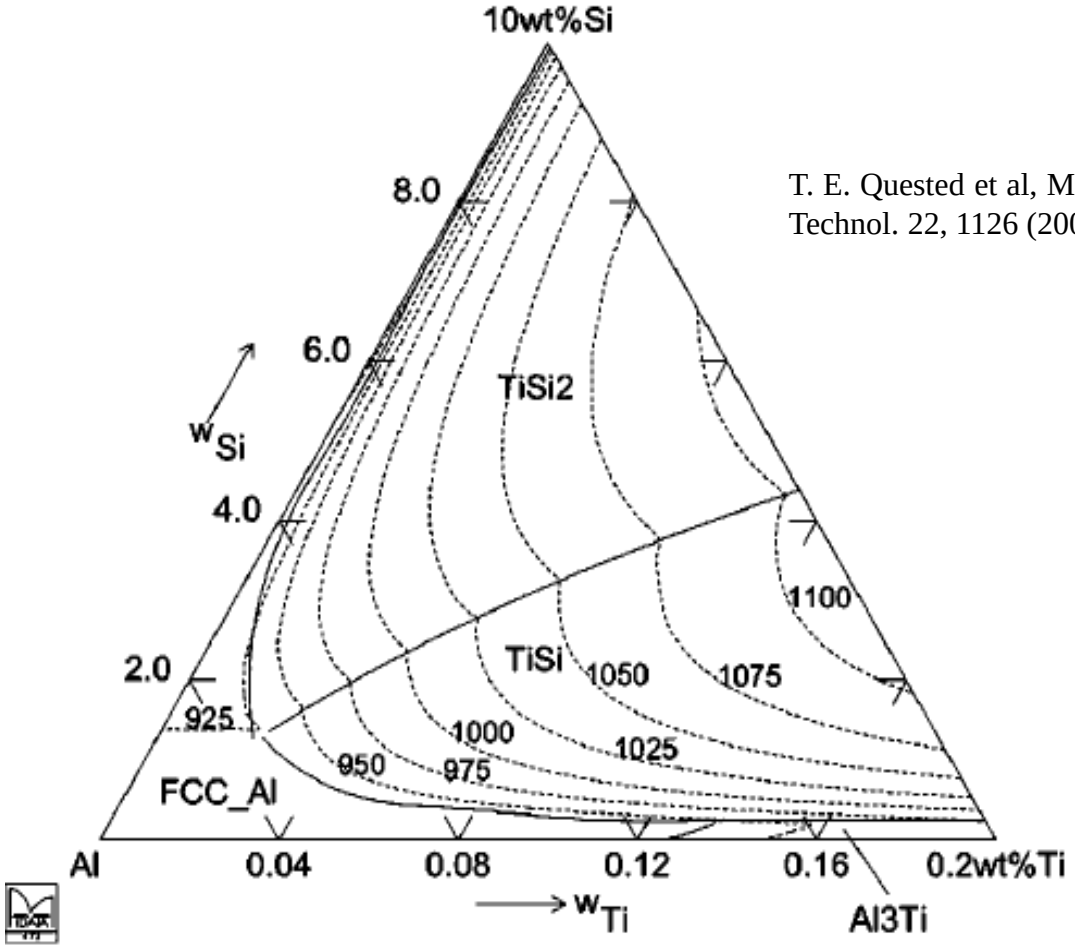
Influence of Al-Ti-B grain refiner for Al-Si alloys



Mats Johnsson
Patent, 2000

M. Johnsson, *Influence of Si And Fe on the Grain-Refinement of Aluminum*, Zeitschrift für Metallkunde, 85 (1994), 781-785

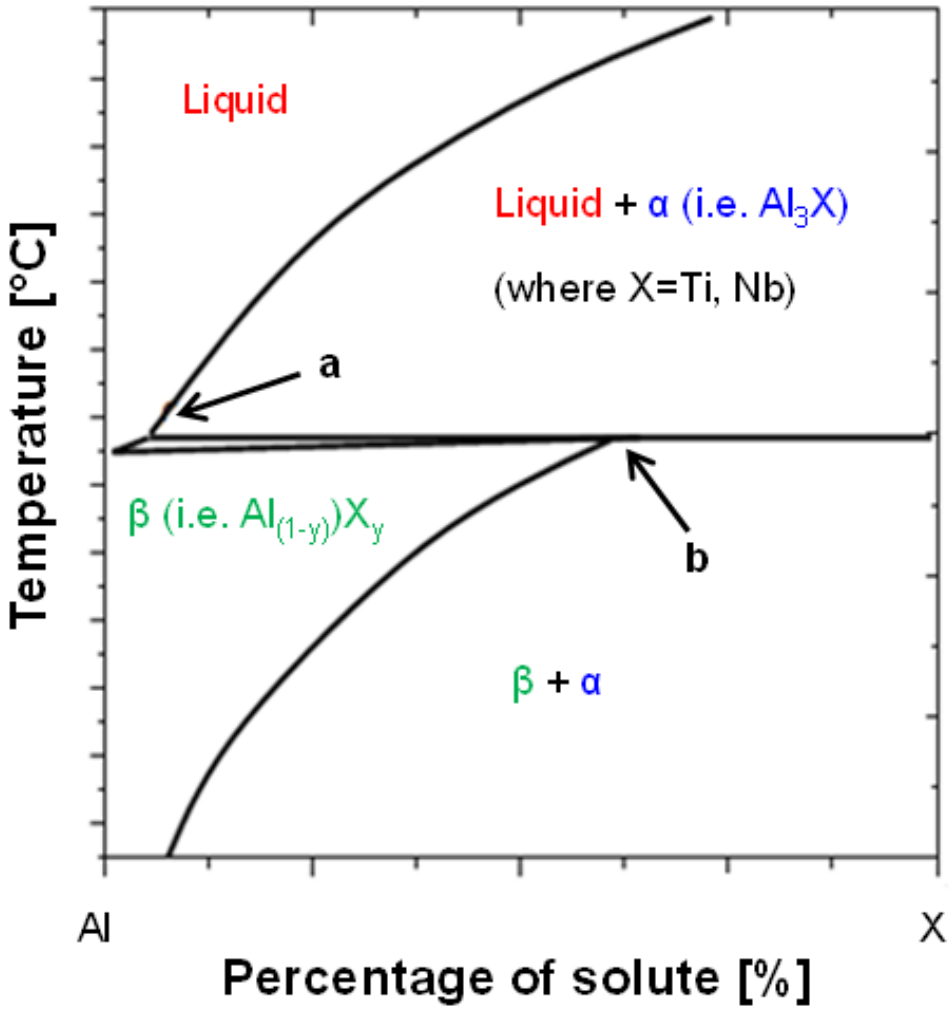
Ti reaction with Si in Al-Si alloys



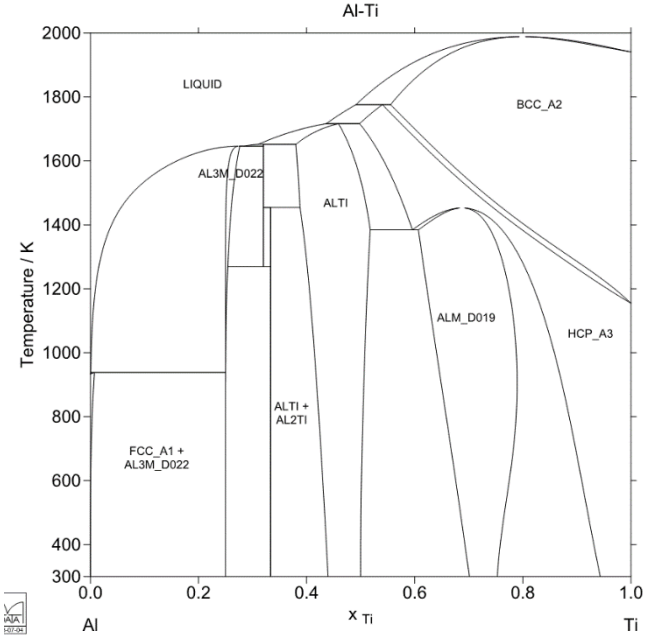
T. E. Quested et al, Mater. Sci. Technol. 22, 1126 (2006)

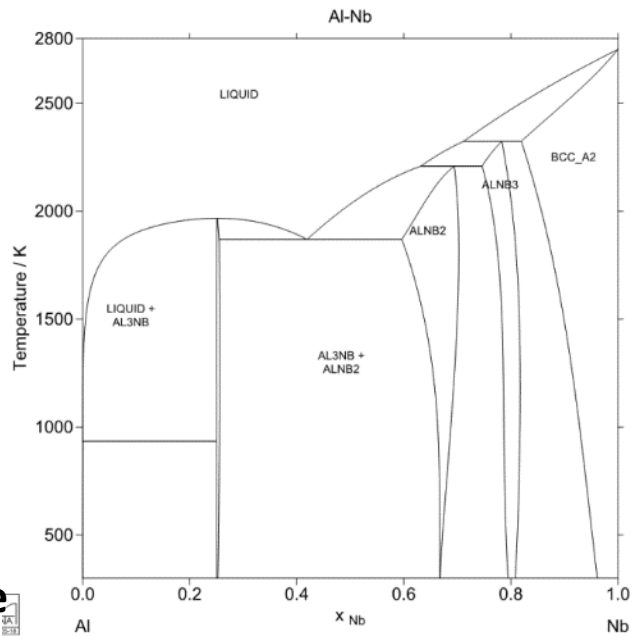
Ti is consumed by the formation of $TiSi_2$ and TiSi

Analogy between Al-Ti & Al-Nb phase diagrams



Al_3Ti
Al_3Nb

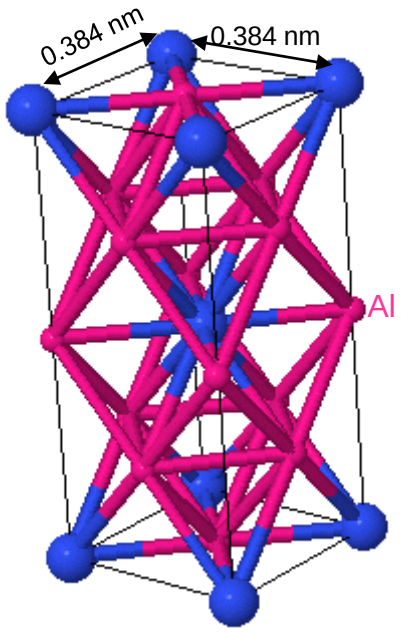


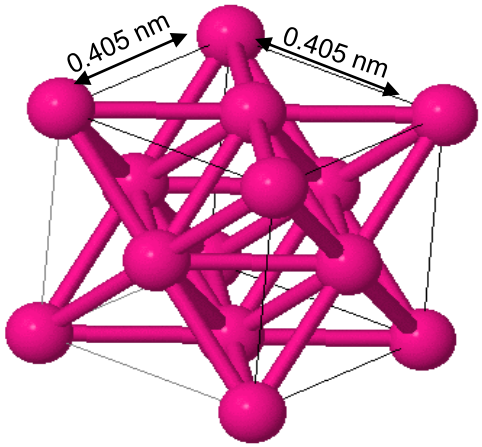


LATTICE MISMATCH

Element	Phase	Melting Point [°C]	Density [g/cm^3]	Lattice structure	Lattice parameter
Aluminium	Al	660	2.70	Face-Centred Cubic	a = 4.050 Å
Titanium	Ti	1668	4.51	Hexagonal	a = 2.950 Å, c = 4.683 Å
	Al_3Ti	1350	3.36	Tetragonal	a = 3.848 Å, c = 8.596 Å
	TiB_2	3230	4.52	Hexagonal	a = 3.023 Å, c = 3.220 Å
	TiC	3160	4.93	Face-Centred Cubic	a = 4.330 Å
Niobium	Nb	2468	8.57	Body-Centred Cubic	a = 3.300 Å
	Al_3Nb	1680	4.54	Tetragonal	a = 3.848 Å, c = 8.615 Å
	NbB_2	3036	6.98	Hexagonal	a = 3.102 Å, c = 3.285 Å
	NbC	3490	7.82	Face-Centred Cubic	a = 4.430 Å

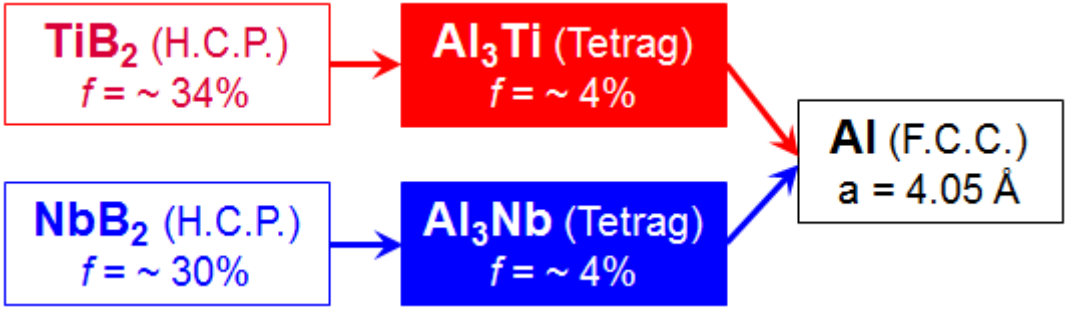
Al_3Nb

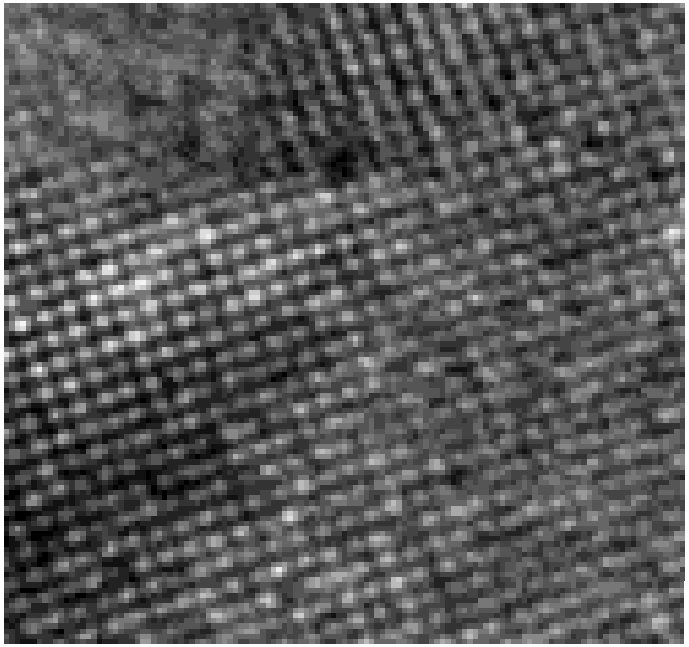


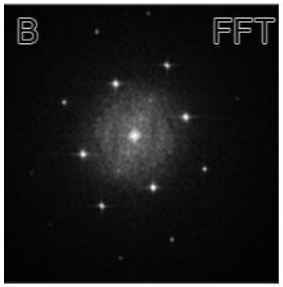


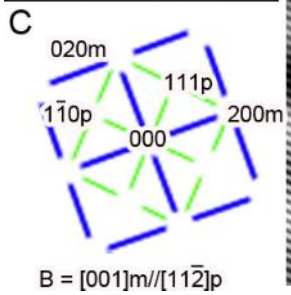
Al (face centred cubic)

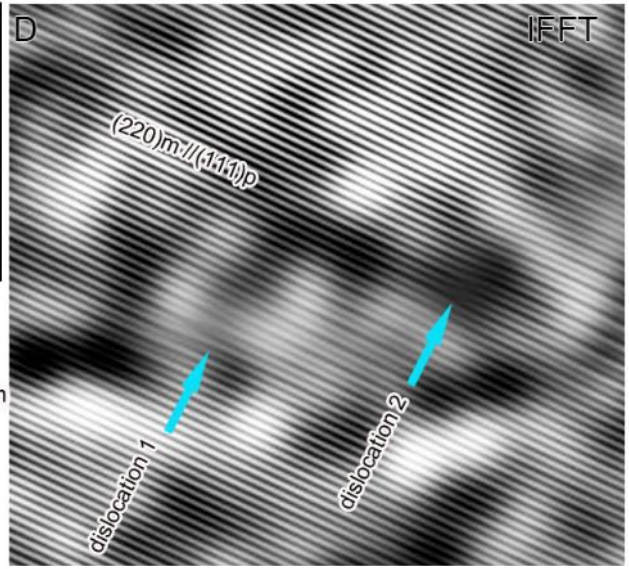
Low Lattice Mismatch – Coherent Interface







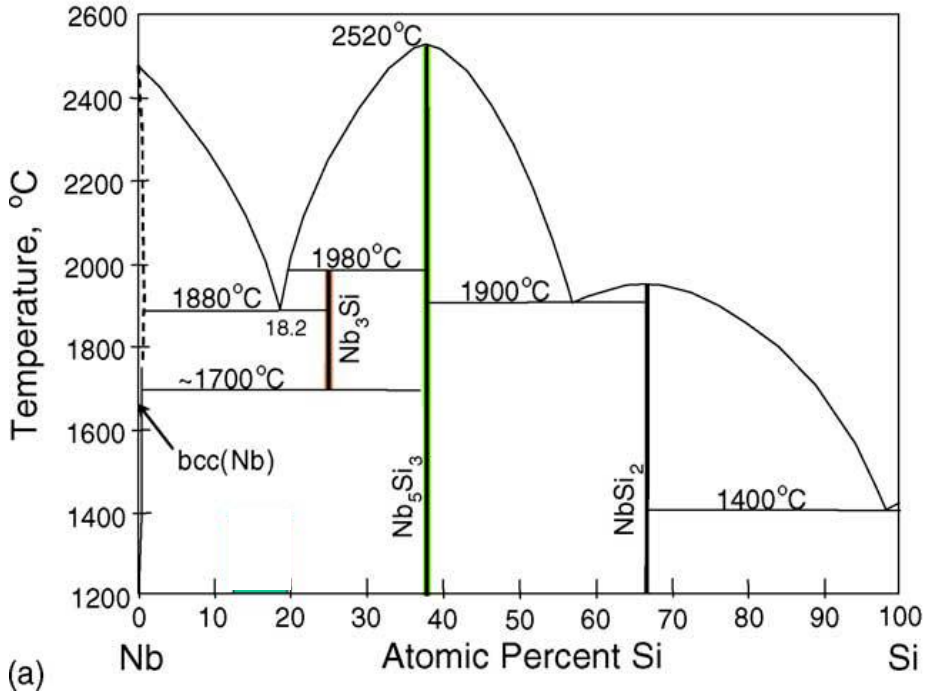




Lattice mismatch ~0.9%

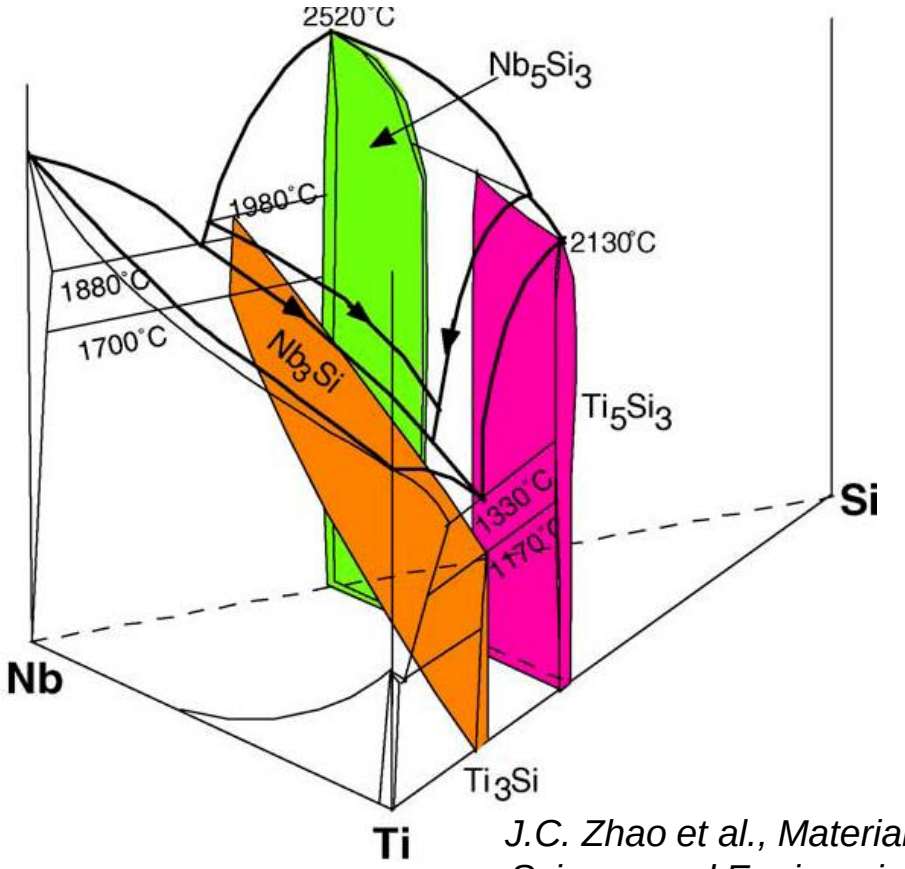
Nb chemical stability with Si

Nb–Si binary phase diagram



J.L. Muray and A. J. Alister, Bulletin of Alloy Phase Diagrams 1984;5:74

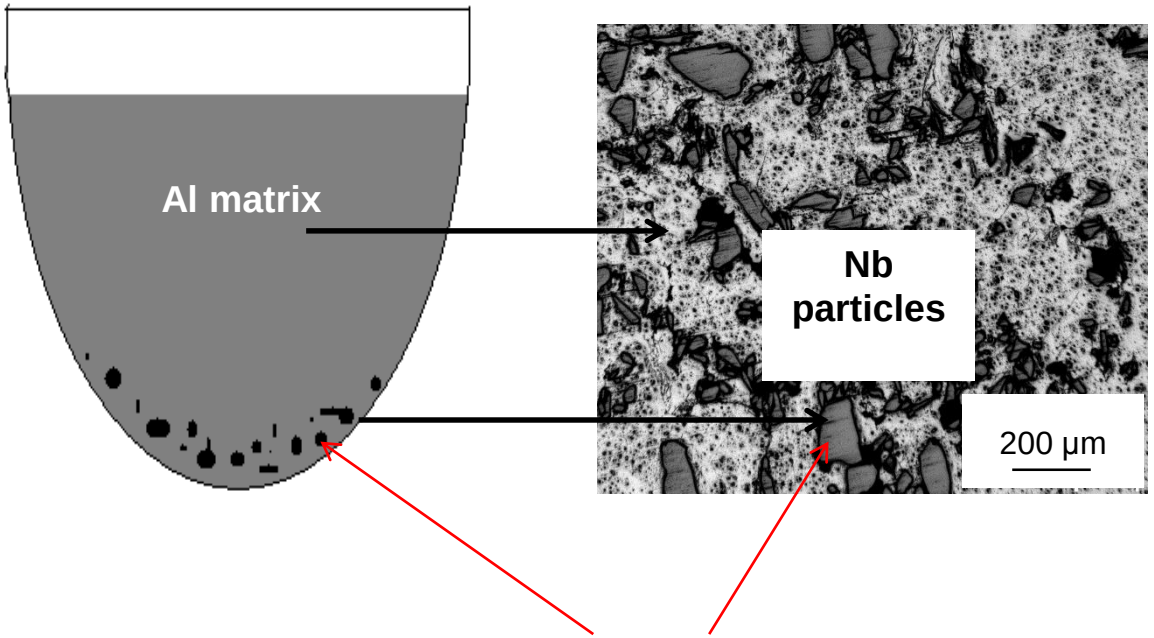
Nb–Ti–Si ternary system



J.C. Zhao et al., Materials Science and Engineering A 2004;372:21

Nb silicides form at higher temperature than Ti silicides thus preventing poisoning

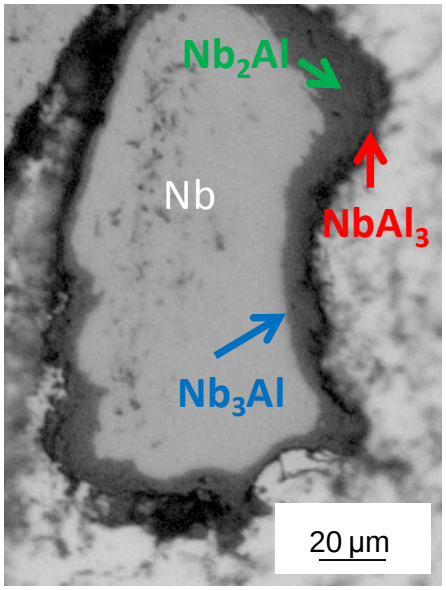
Addition of Nb metal powder to liquid Al

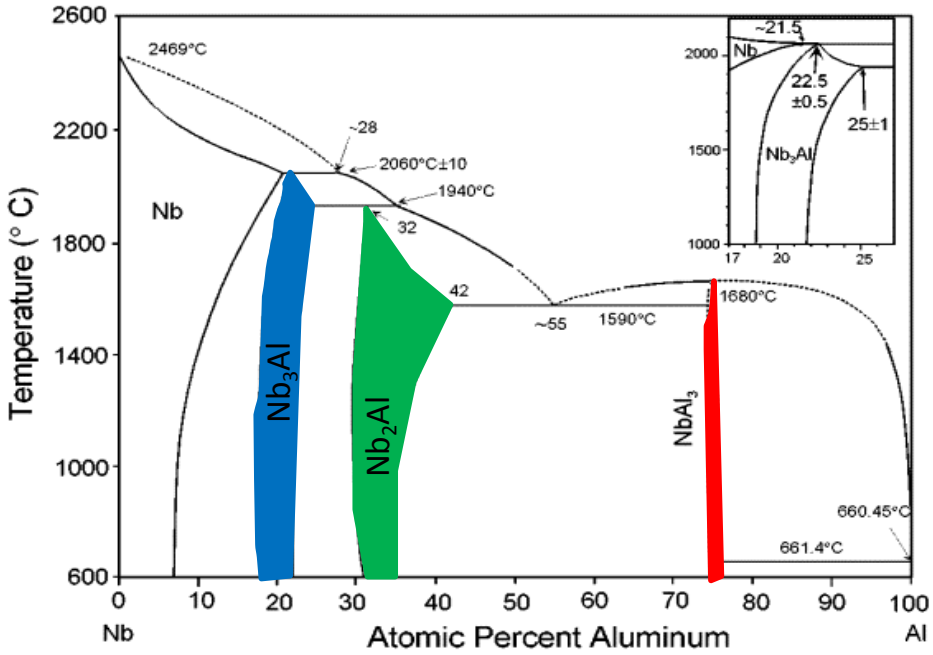


750 - 800 C

Unreacted Nb metallic particulates

Poor dissolution of Nb in liquid Al



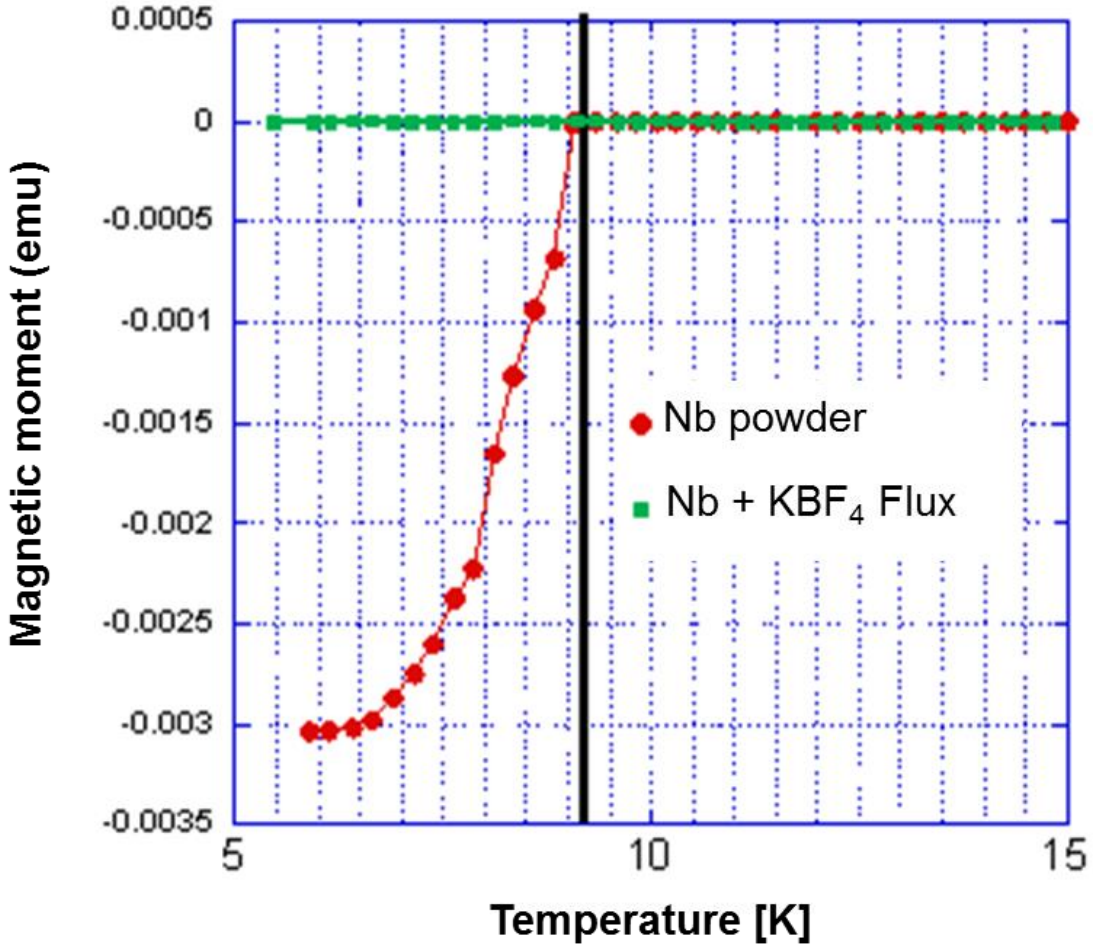


	T [°C]			
	700	750	800	850
Solubility, K [wt.%]	0.020	0.034	0.057	0.10
Dissolution rate constant, K_1 [m/s]	4.60	5.10	6.20	6.80
Coefficient of diffusion, $D \cdot 10^9$ [m^2/s]	1.61	1.86	2.49	2.89

$$C = C_S\left[1 - \exp\left(-\frac{k \cdot s \cdot t}{v}\right)\right]$$

Requires high temperature for larger Nb particles and high concentrations

Addition of Nb fine metal powder to liquid Al



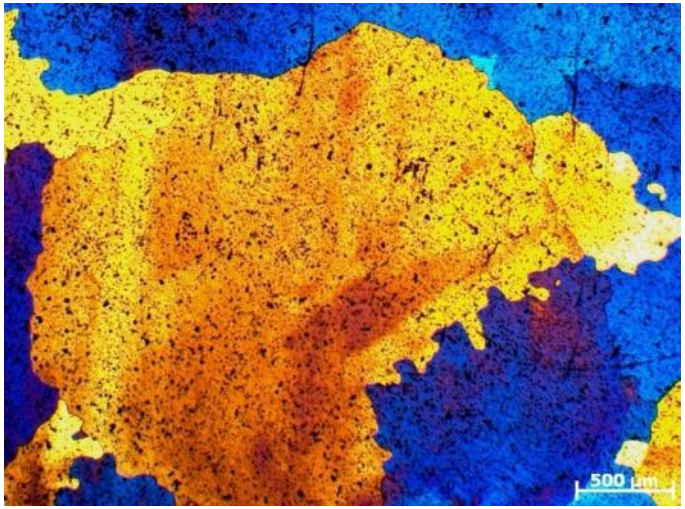
Nb- Superconductivity – 9K

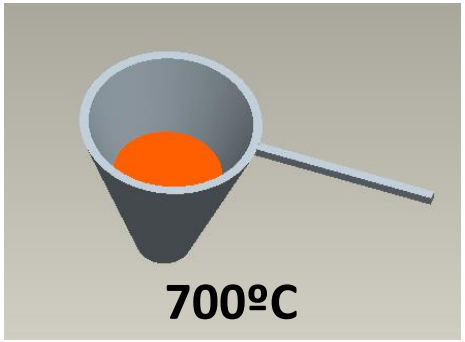
To verify the Nb dissolution, magnetic moment vs temperature measured

<45 μm

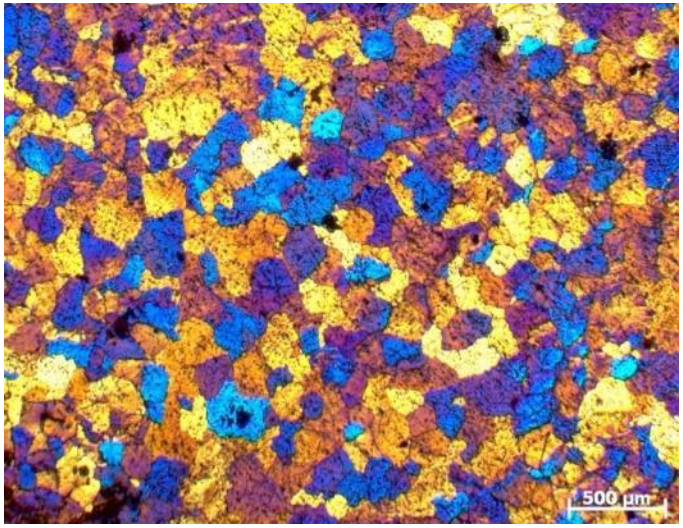
EFFECT OF Nb on CP Al

CP-Aluminium

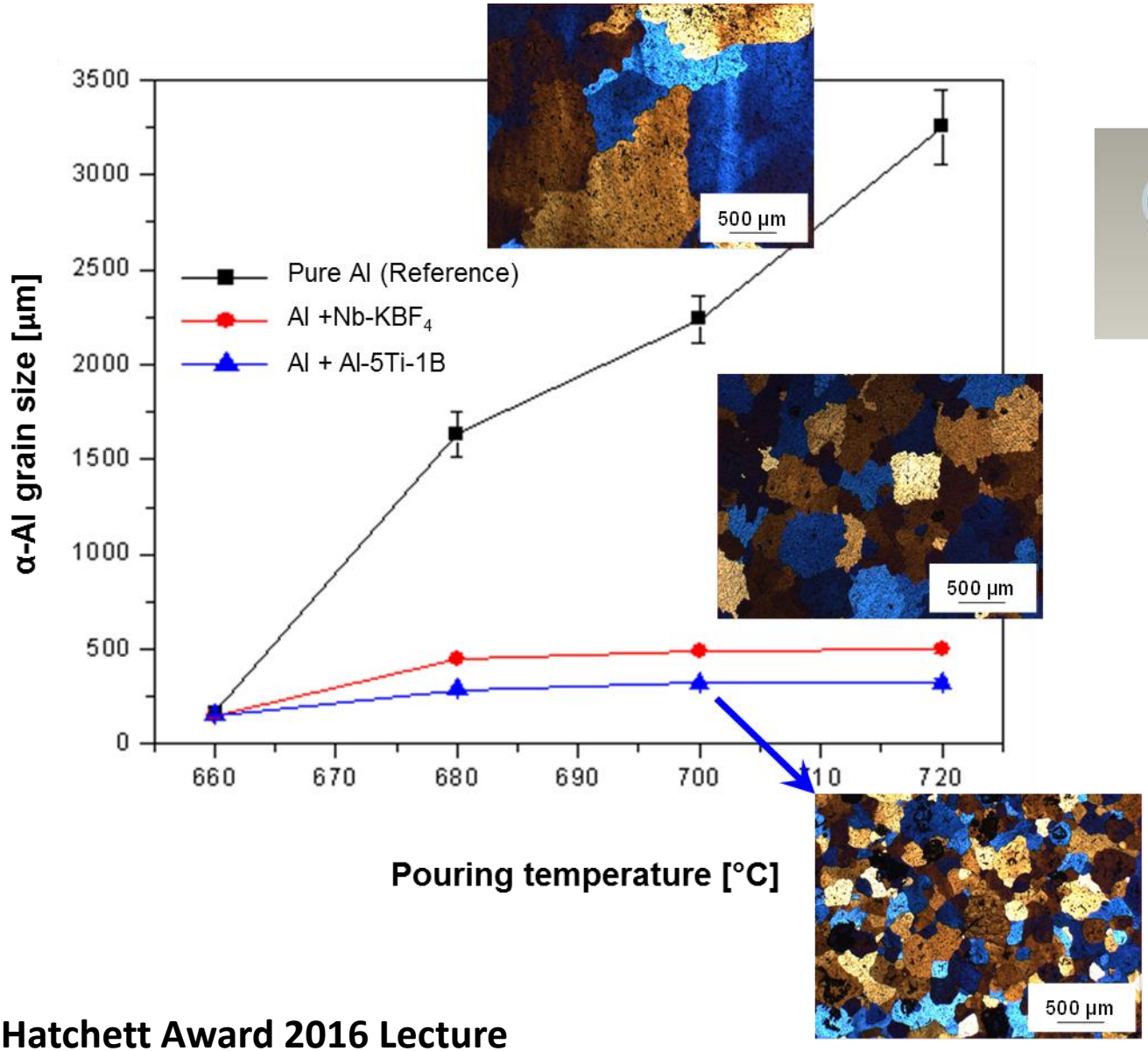


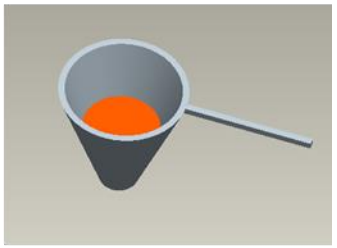


Al with Nb-B

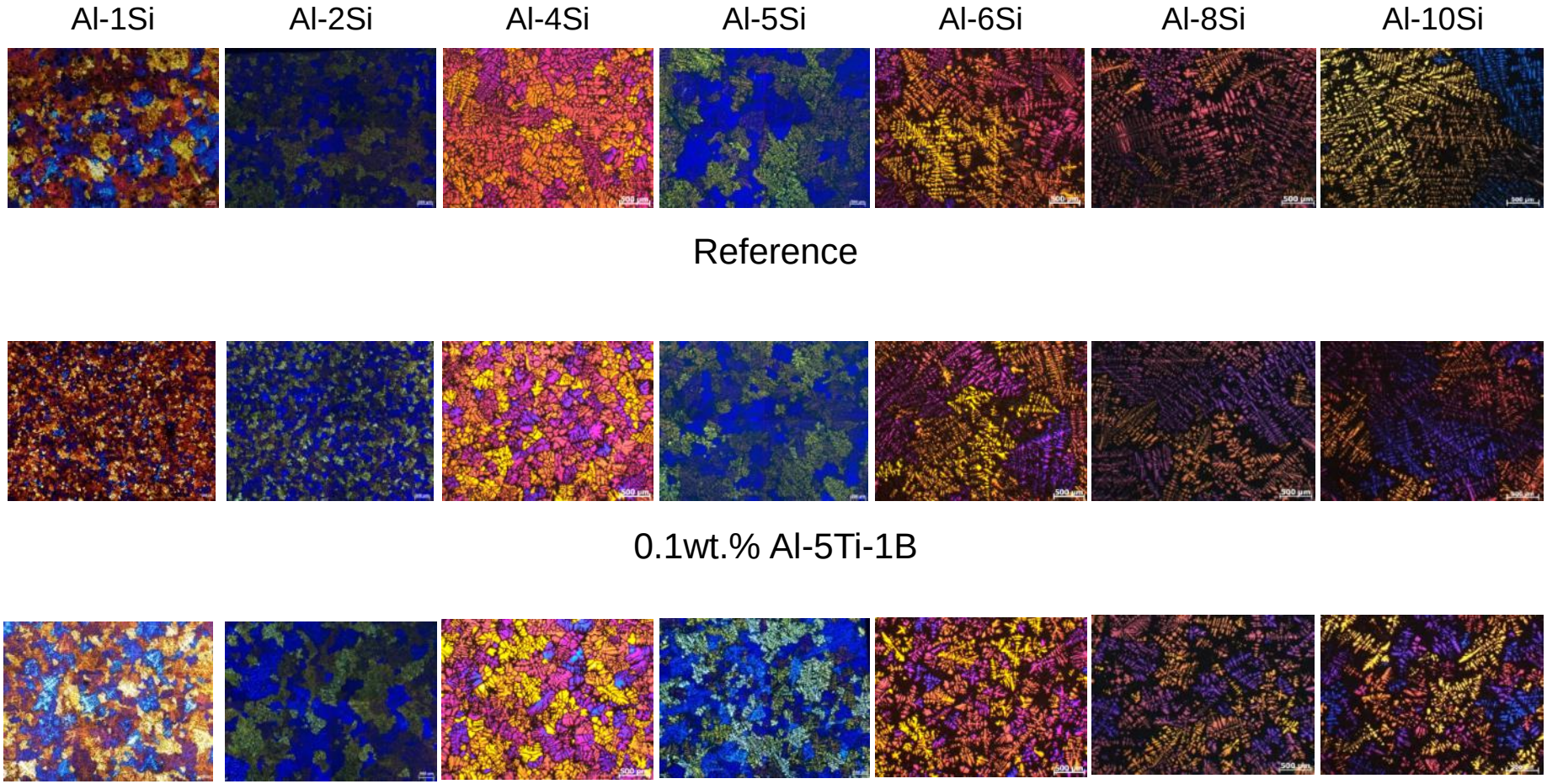


COMPARISON OF Al-Ti-B AND Nb-B ON CP Al





Comparison of Al-Ti-B and Nb-B to Hypoeutectic Binary Al-Si Alloys



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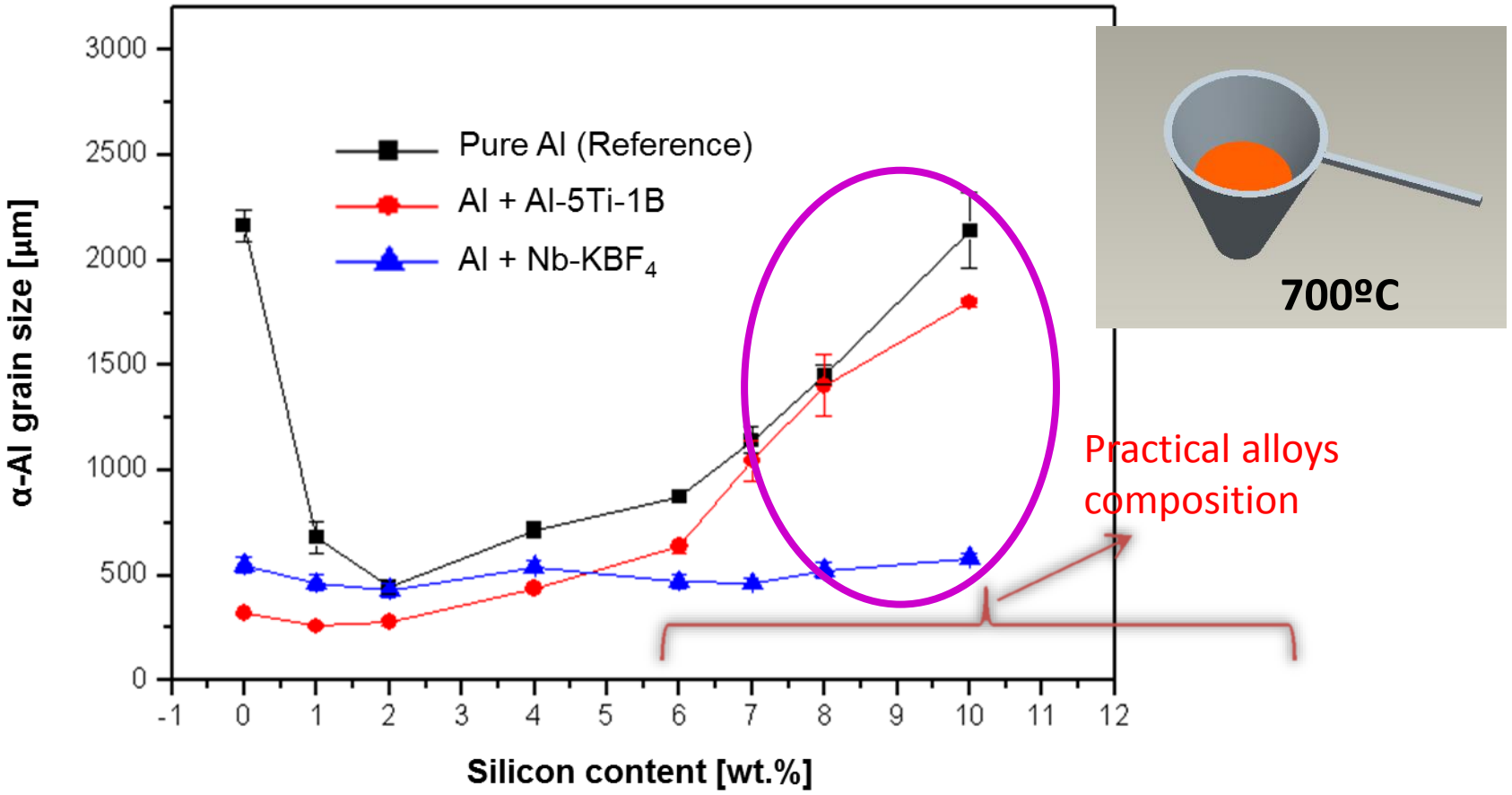
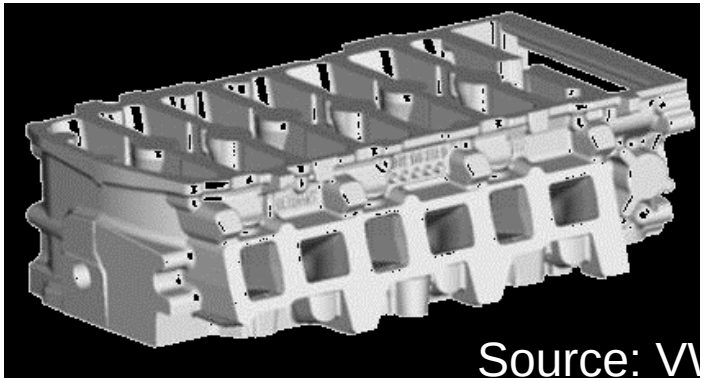
Comparison of Al-Ti-B and Nb-B to Hypoeutectic Binary Al-Si Alloys

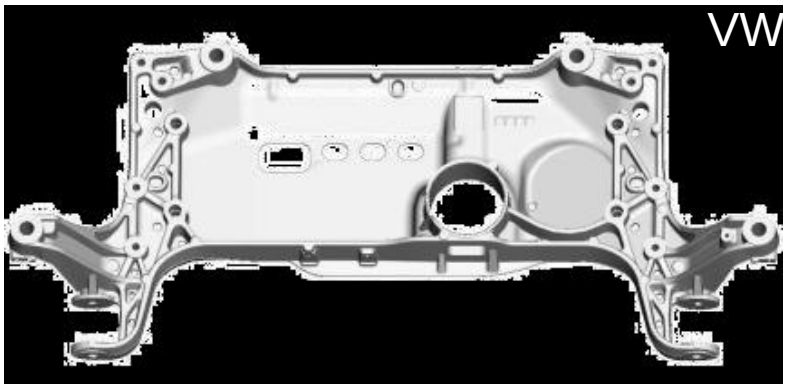


Al-Si alloys for automotive applications

Engine & transmission Components
Crankcases
Cylinder heads
Intake manifolds
Housings manual/automatic transmissions
Housings power transfer units



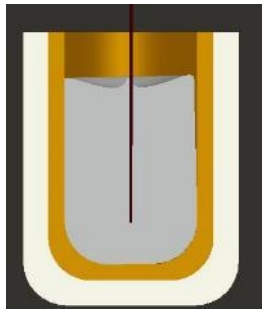
Chassis Components
Subframes Knuckles
Steering housings

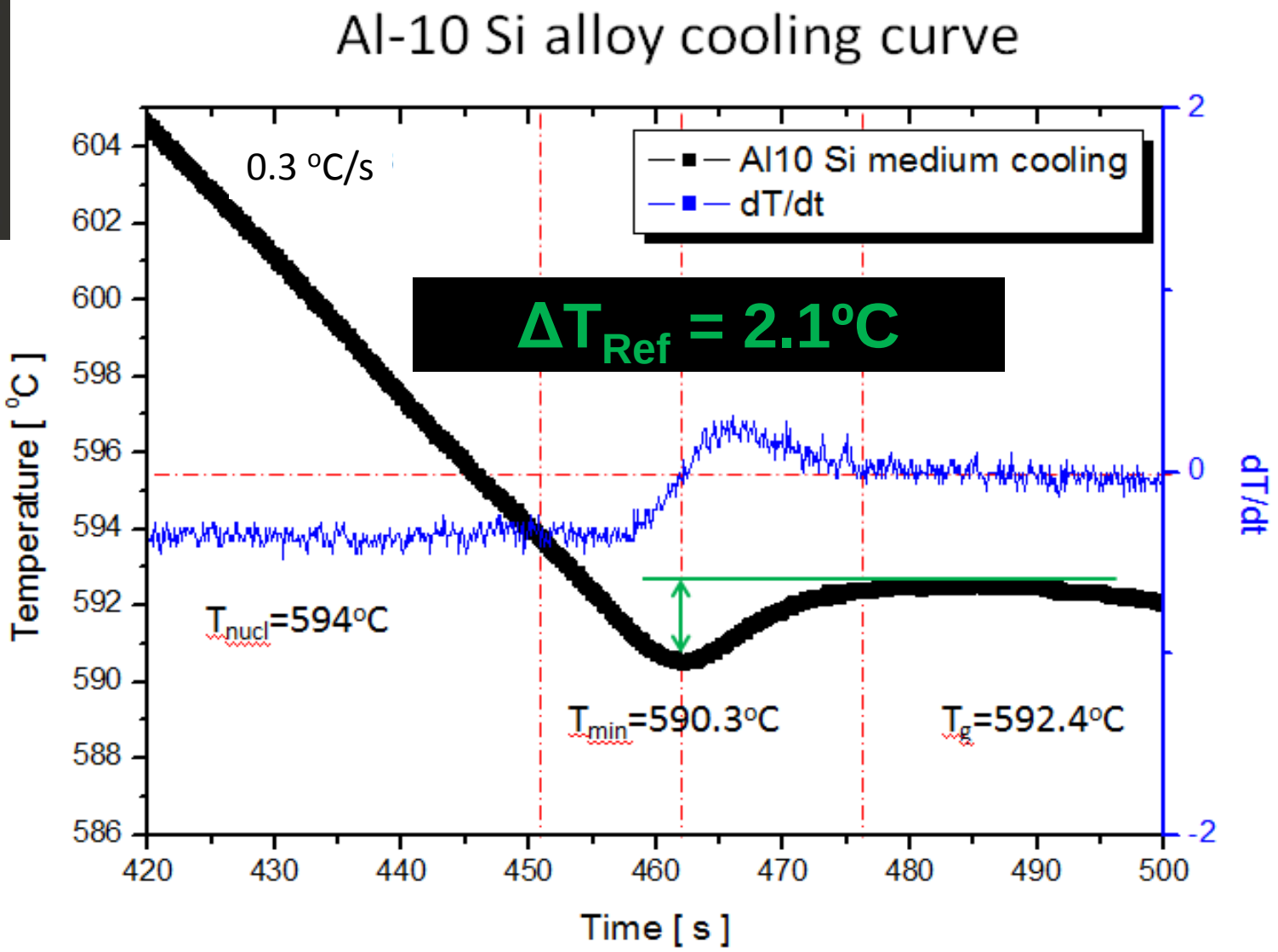


Structural Components
Body structures
Instrument panels
Door frames

Wheels

Undercooling for Al-10Si alloy





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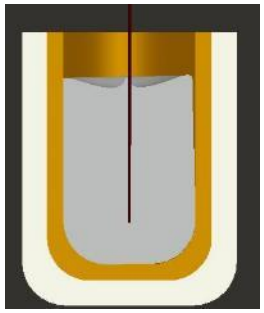
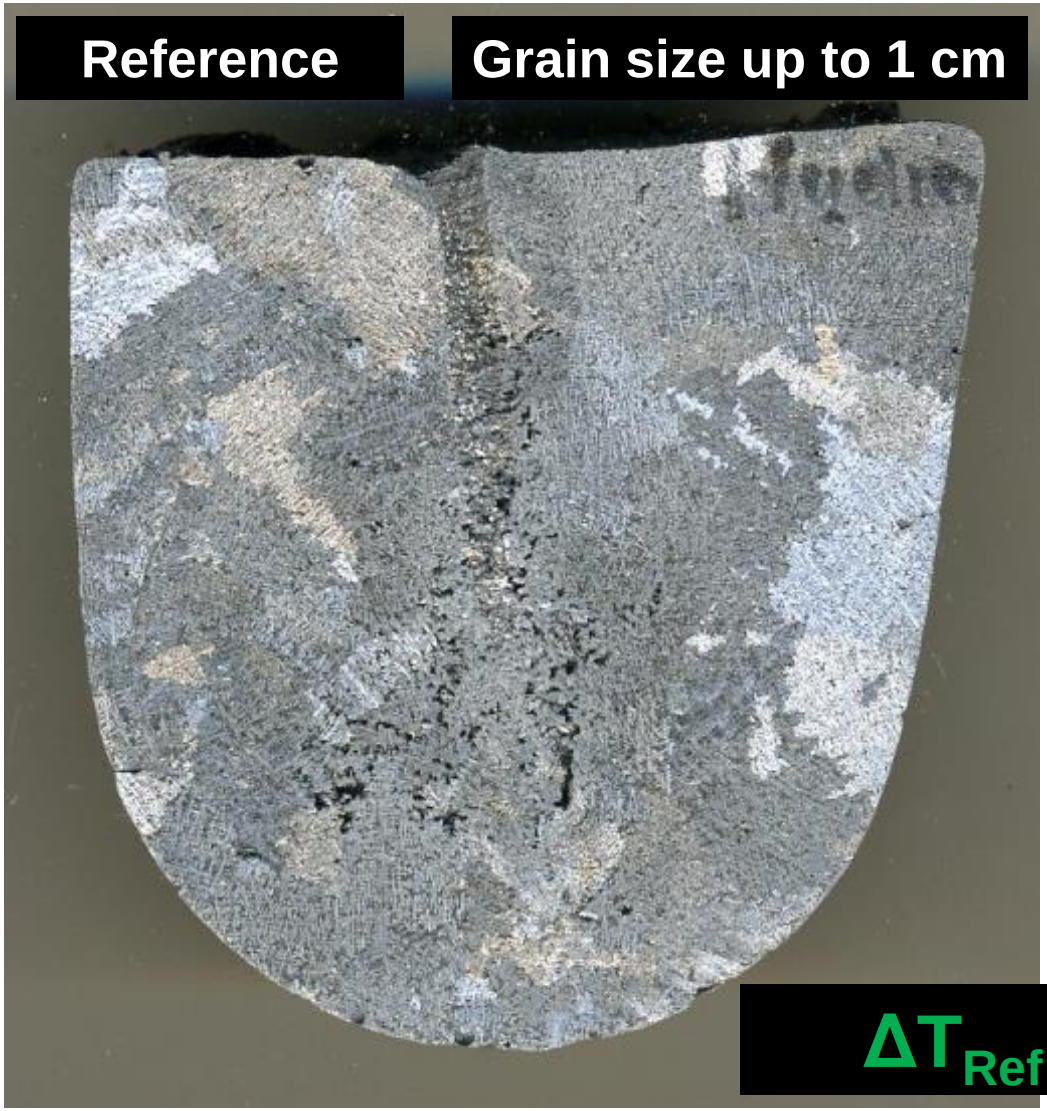
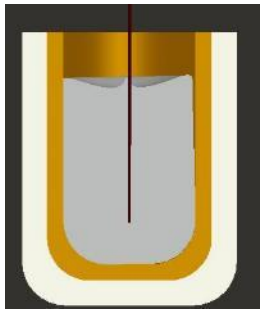
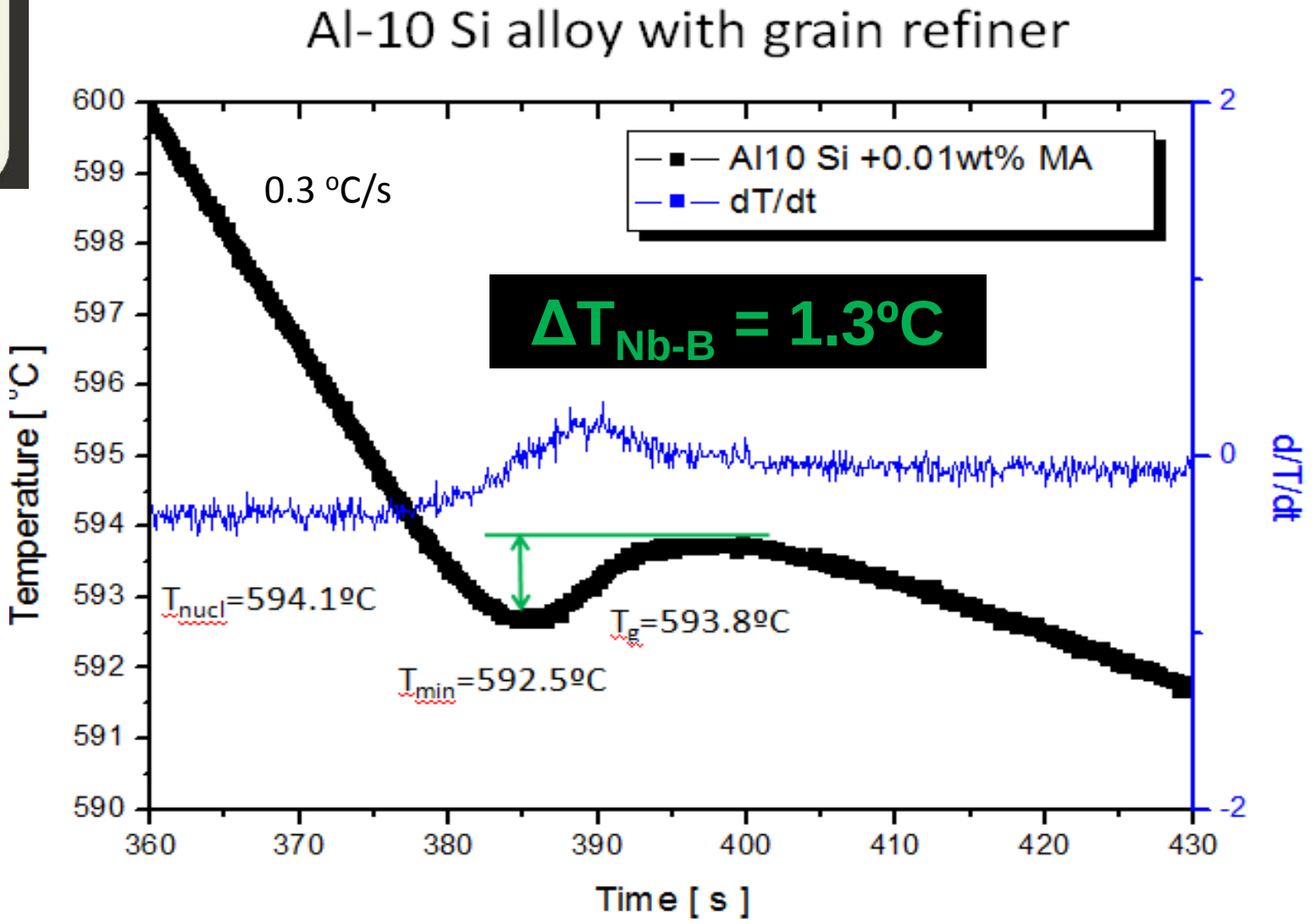


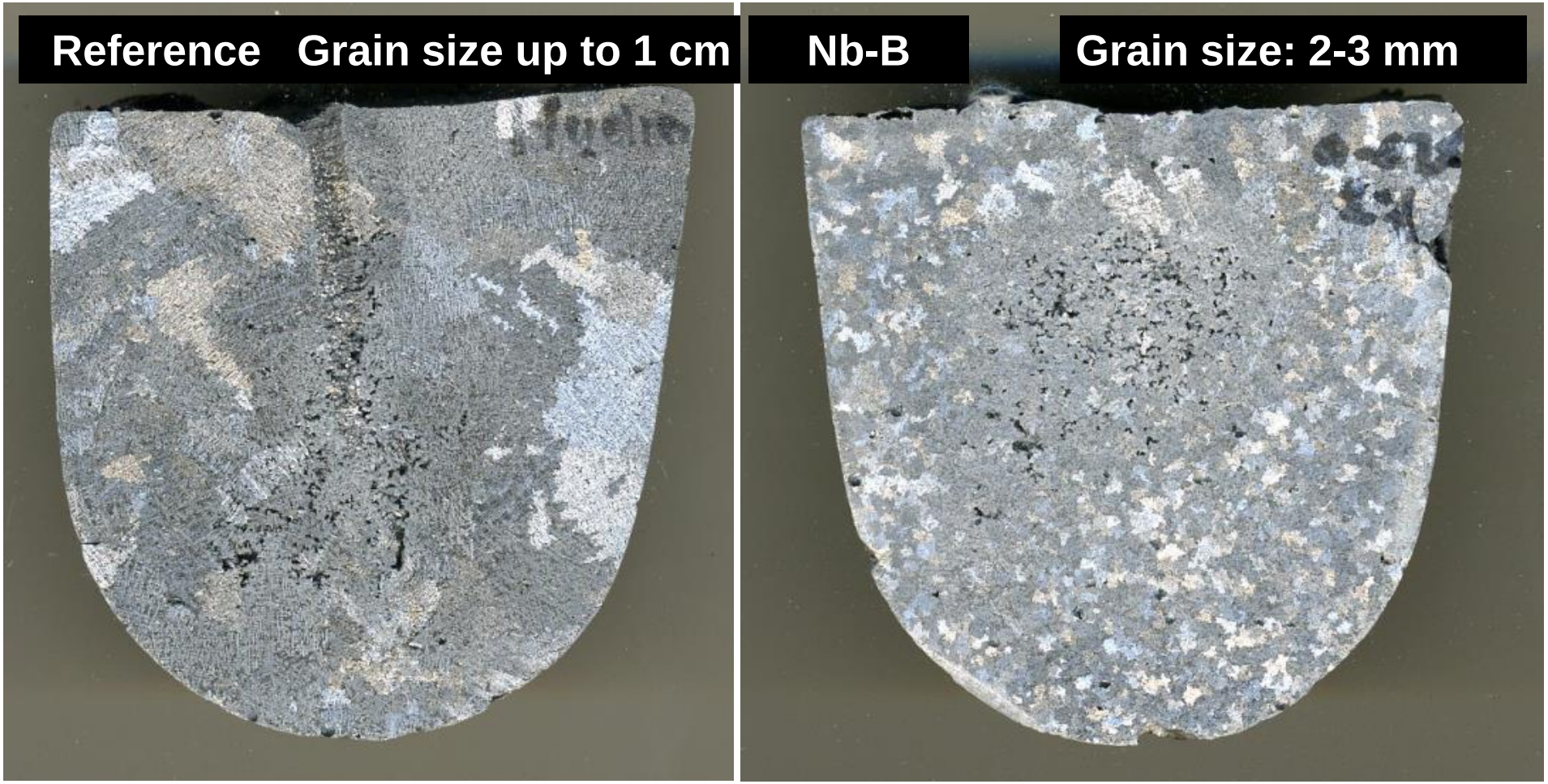

Reference
Grain size up to 1 cm
ΔT_{Ref} = 2.1ºC

Undercooling in the presence of NbB_2/Al_3Nb





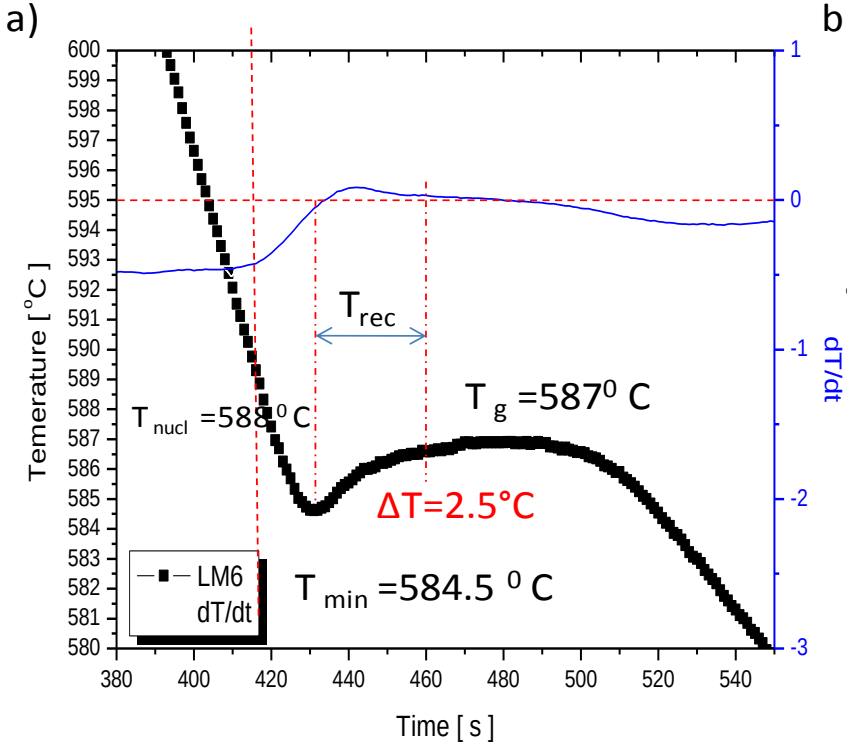
GRAIN STRUCTURE

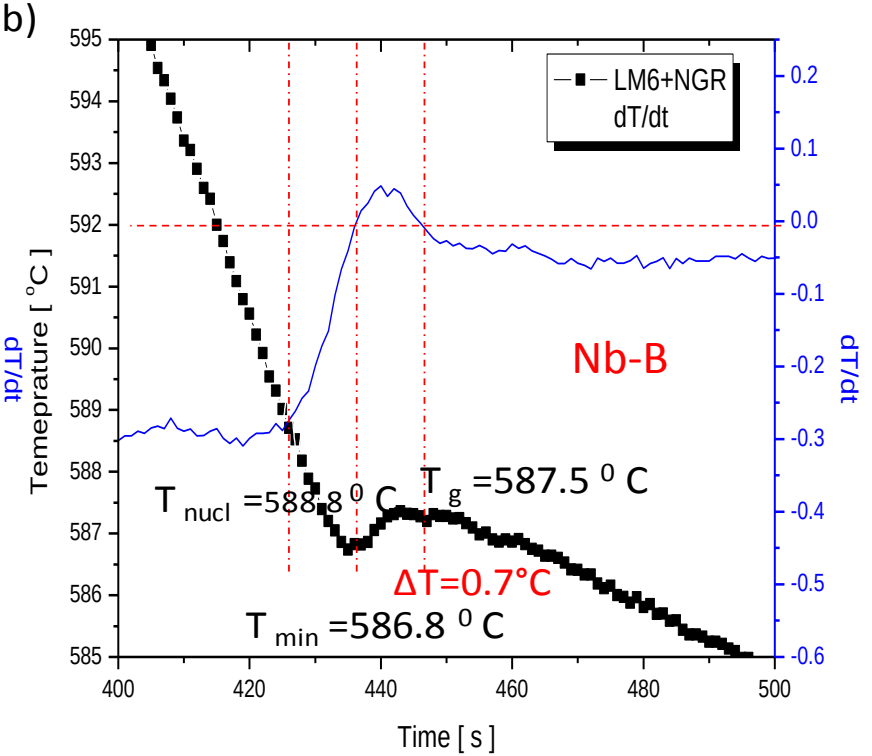


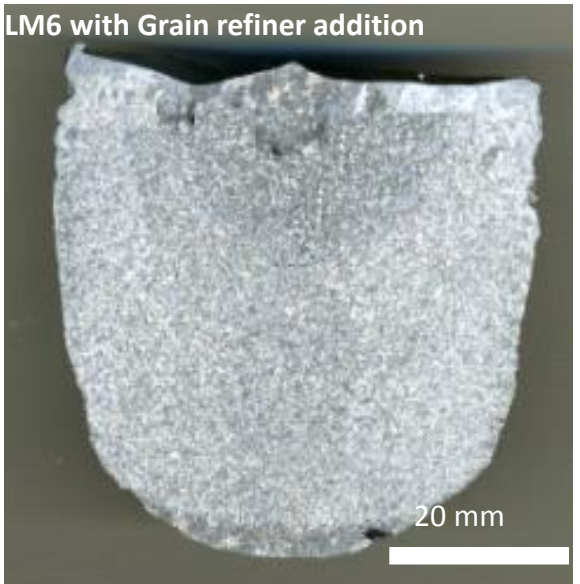
ΔT_{Ref} = 2.1ºC

$\Delta T_{Nb\text{-}B}$ = 1.3ºC

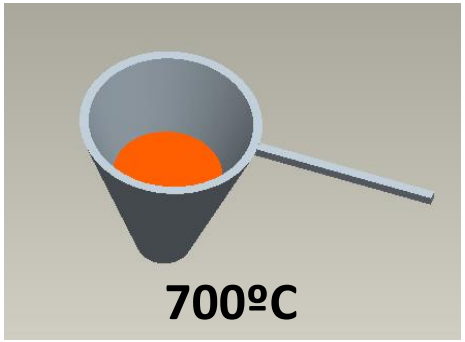
Cooling curves for Al-11Si (LM6) alloy



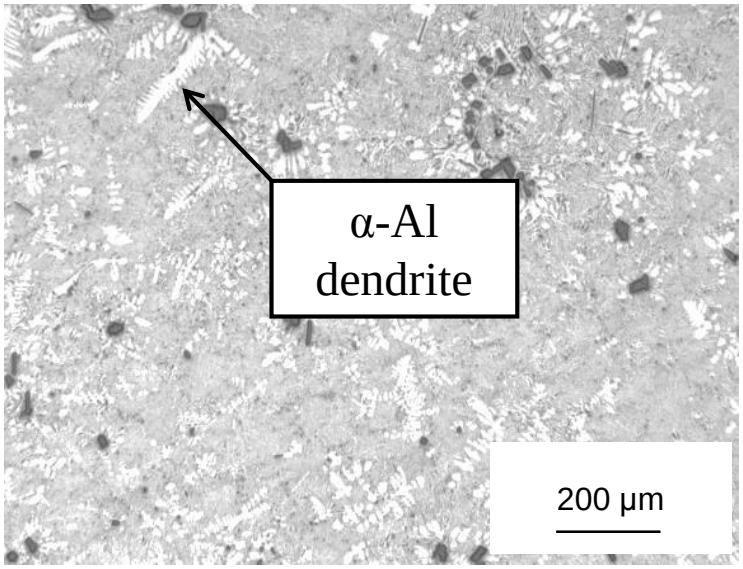


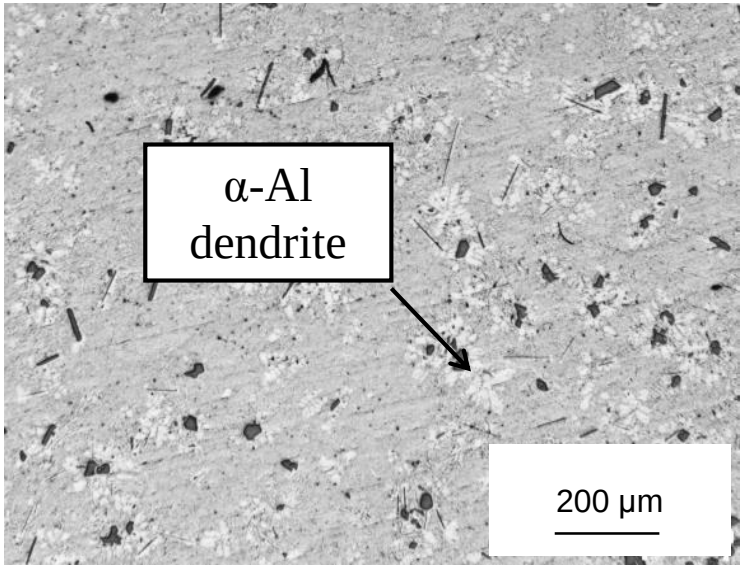


HYPEREUTECTIC BINARY Al-Si ALLOYS



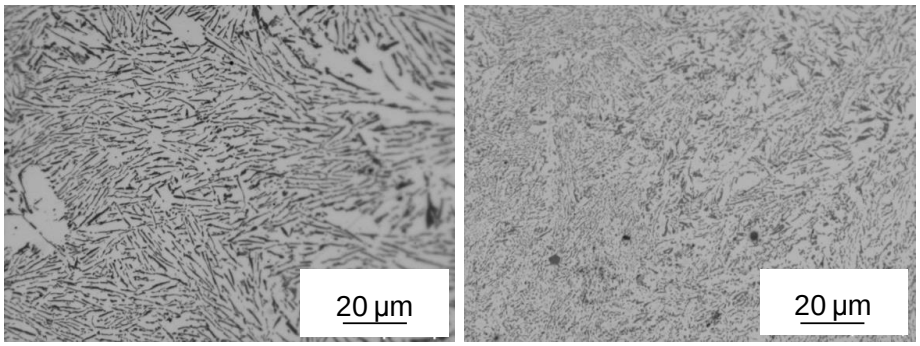
Al-14Si

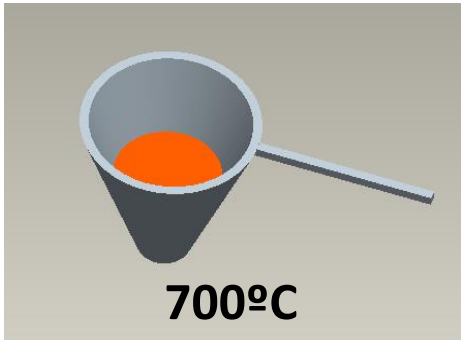




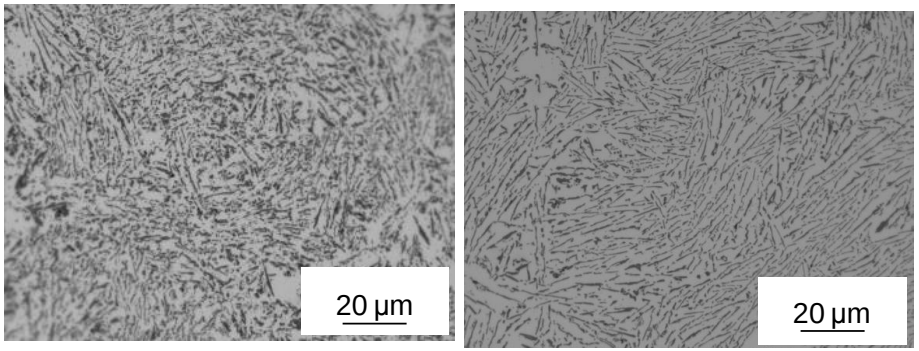
HYPEREUTECTIC BINARY Al-Si ALLOYS - EUTECTIC

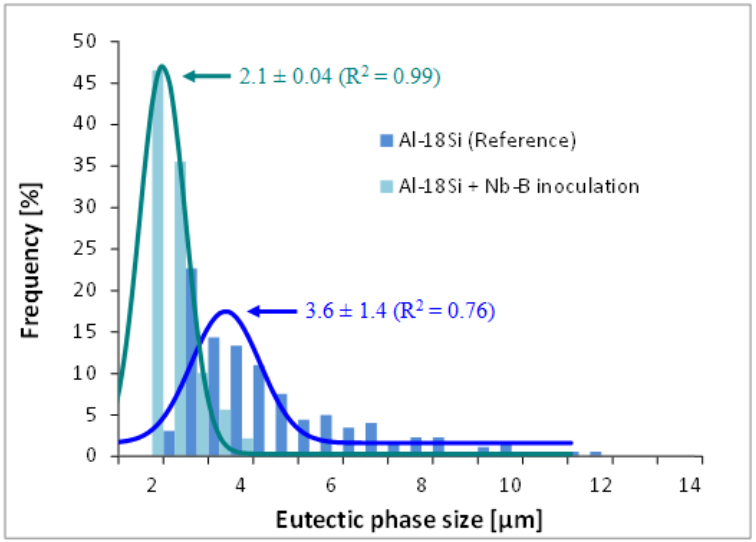
Al-16Si



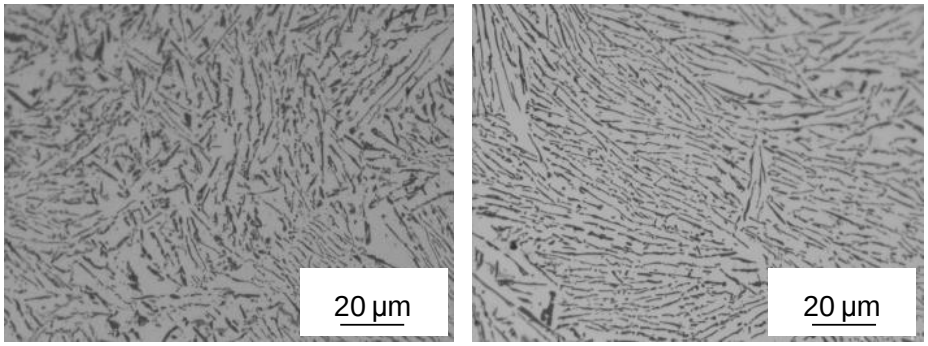


Al-18Si



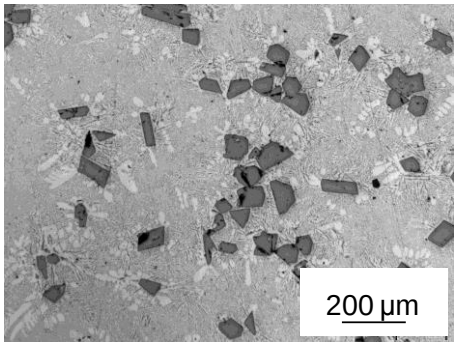


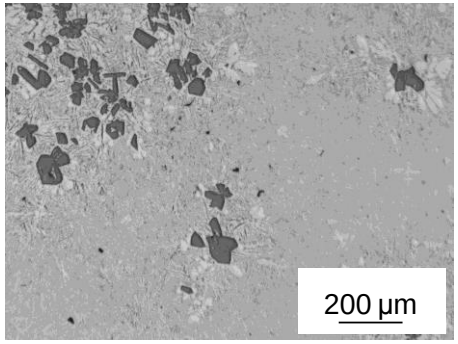
Al-27Si



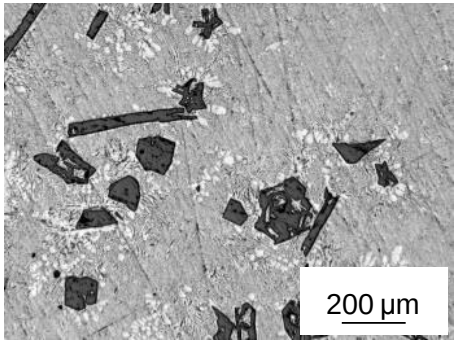
Hypereutectic Binary Al-Si Alloys – Primary Si

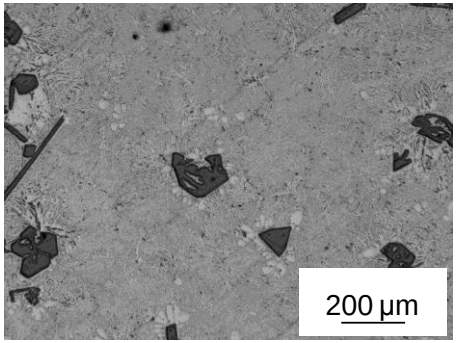
Al-16Si



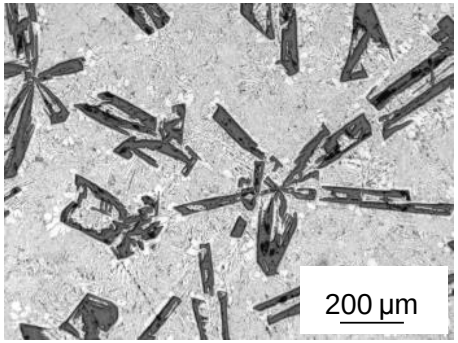


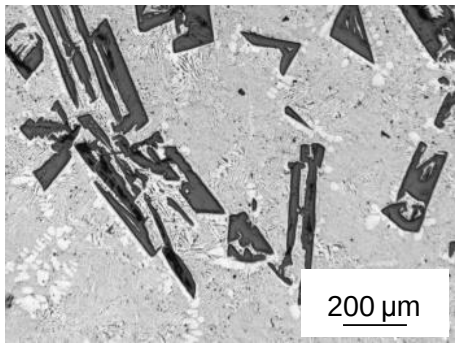
Al-18Si

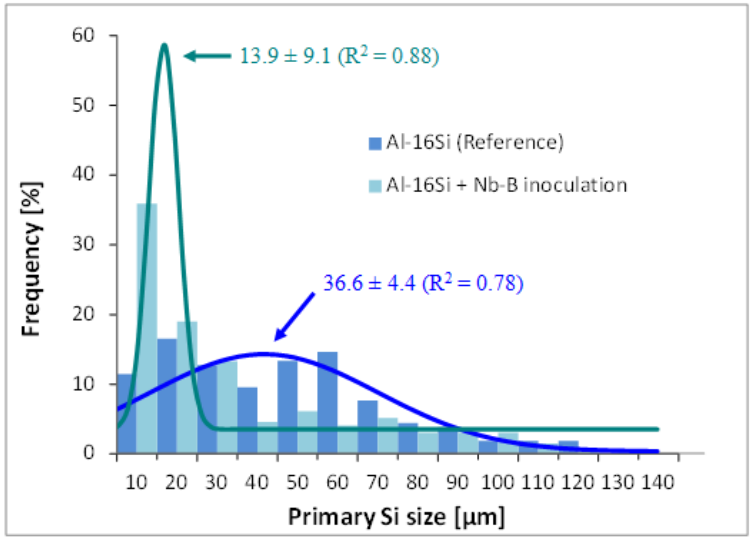


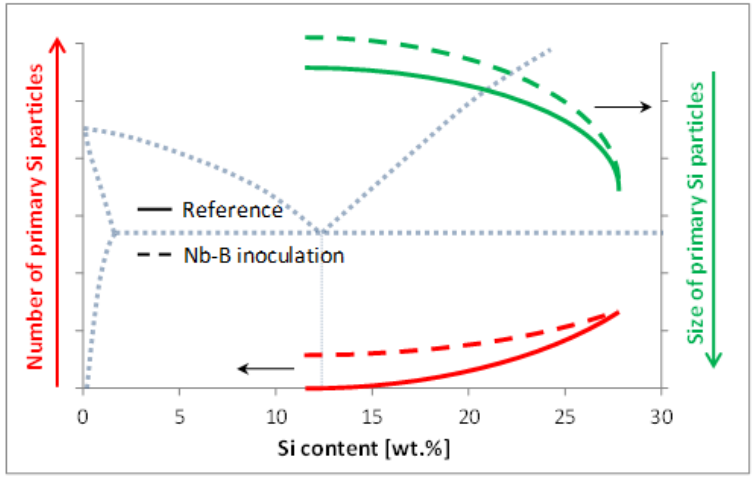


Al-27Si









Application of Nb-B grain refiner to Al-Si commercial alloys

The Charles Hatchett Award 2016 Lecture

Commercial alloys tested with Nb-B

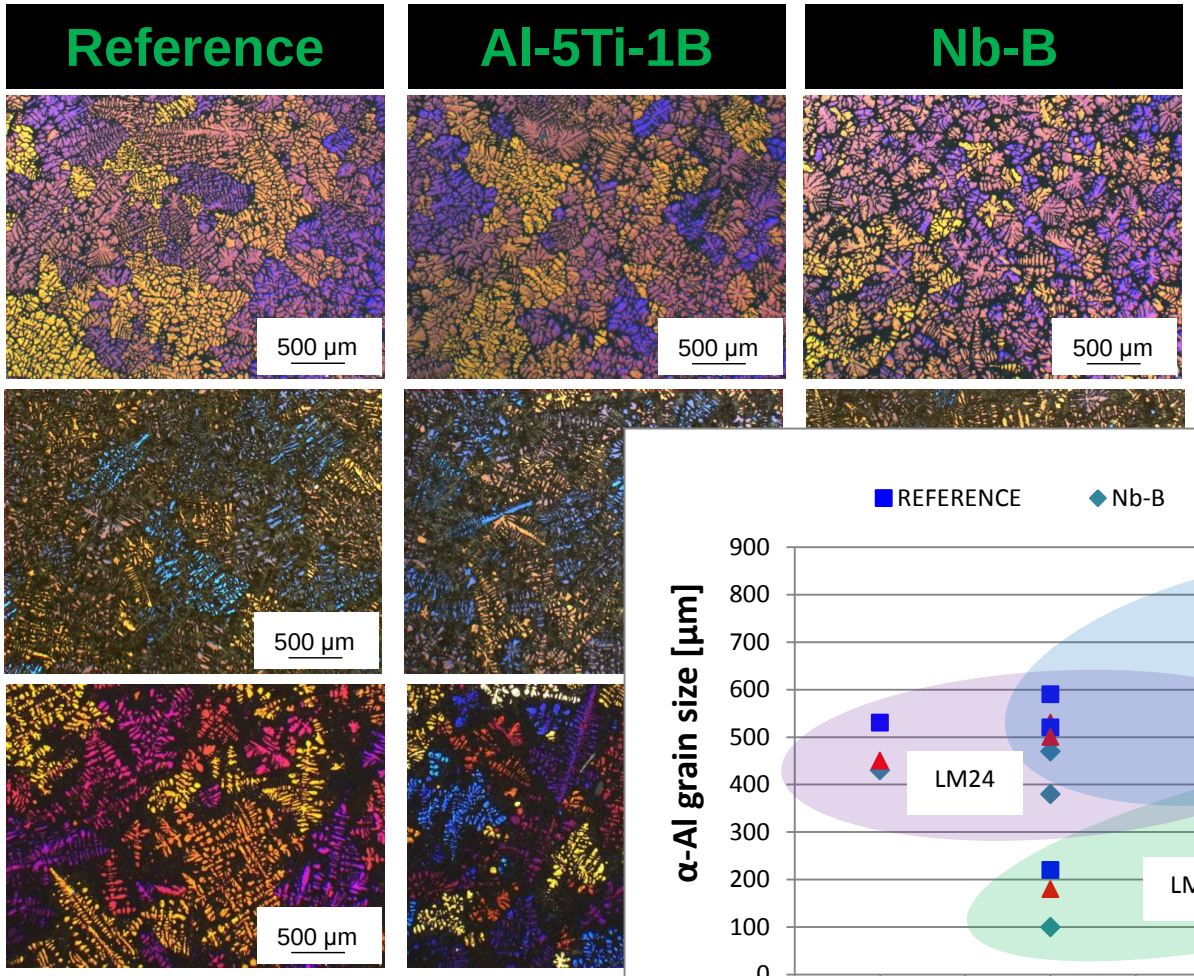
GB	USA	Si	Mg	Mn	Cu	Ni	Zn	Fe
LM6	A413	10.0-13.0	0.1max	0.5max	0.1max	0.1max	0.1max	0.6max
LM13	336	10.0-13.0	0.2-0.4	0.5max	0.7-1.5	1.5max	0.1max	1max
LM24	A380	7.5-9.5	3 max	0.5max	3.0-4.0	0.5	3	1.3max
LM25	A356	6.5-7.5	0.2-0.6	0.3	0.2	0.1	0.1	0.5
		9.99	0.005	0.005	0.0017	0.0044	0.005	0.09
		10.98	0.268	0.21	2.134	0.068	0.778	0.83
		6.06	0.275	0.265	2.725	0.0257	0.305	0.356
		11.9	0.8	0.005	3.7	2	0.003	0.12

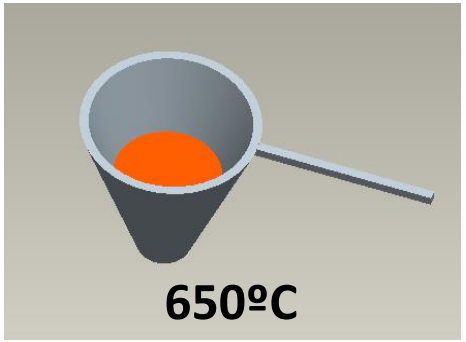
Nb-B Grain Refiner for Al-Si cast alloys

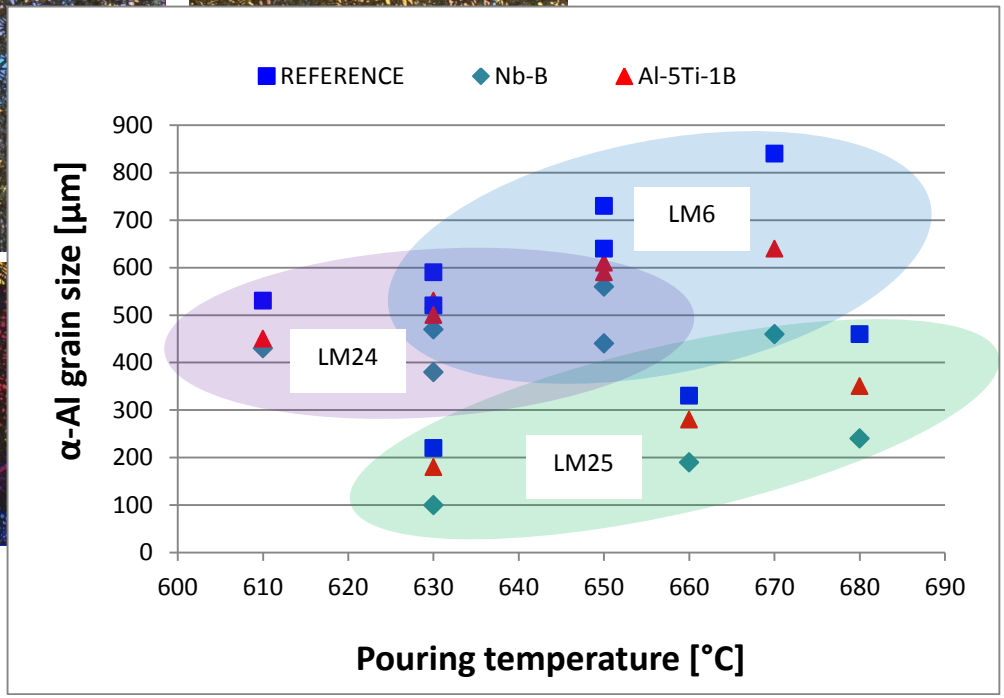
❑Highly effective for Al-Si alloys & Mg alloys

- ❑Fine & uniform grain structure
- ❑Grain size is less sensitive to cooling rate
- ❑Highly effective in sand casting cooling conditions
- ❑Reduced porosity & macro defects
- ❑Fine eutectic structure & intermetallics
- ❑Improved ductility & strength
- ❑Tolerant to Fe contamination
- ❑Recycling of Al-Si scrap

COMMERCIAL HYPOEUTECTIC Al-Si ALLOYS







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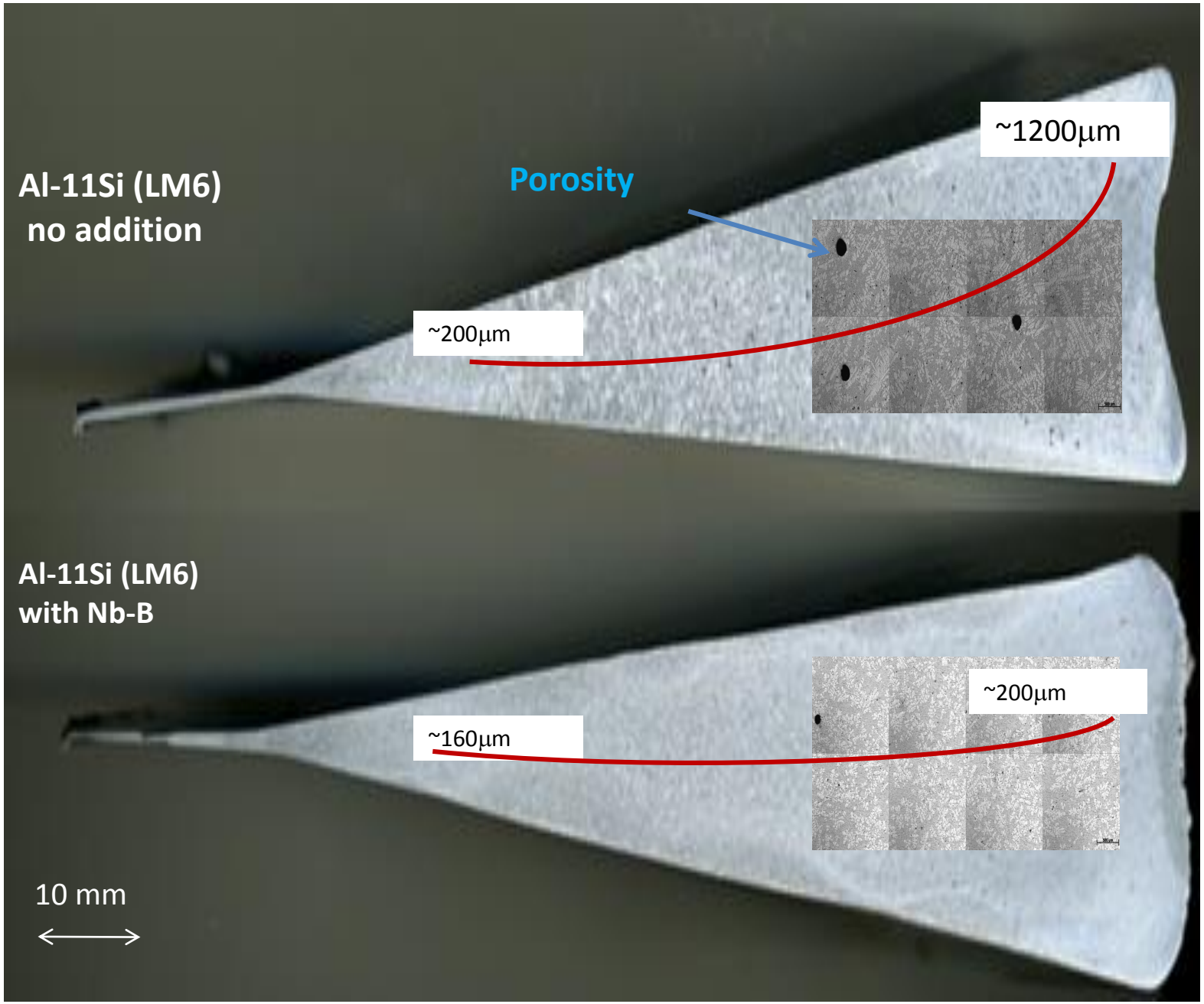
Al-11Si (LM6)
no addition
Porosity
~1200µm
~200µm
Al-11Si (LM6)
with Nb-B
~160µm
~200µm
10 mm

Al-Nb-B Grain Refiner for Al-Si cast alloys

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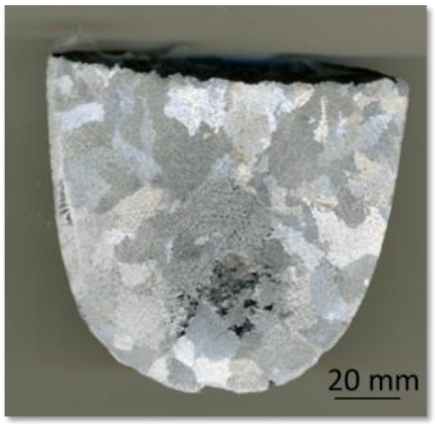
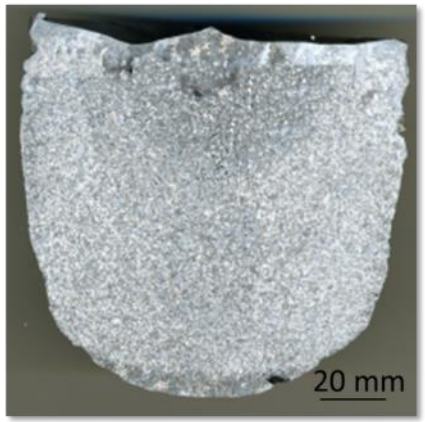
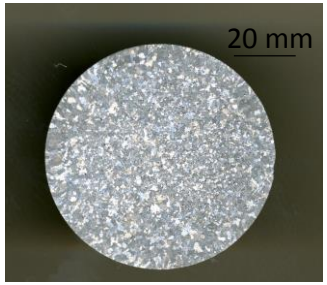
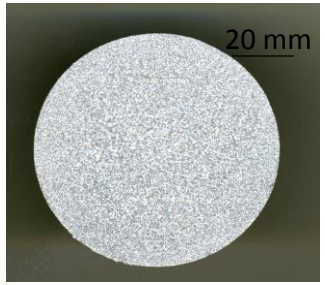
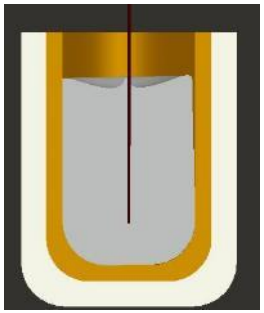
EFFECT OF COOLING RATE

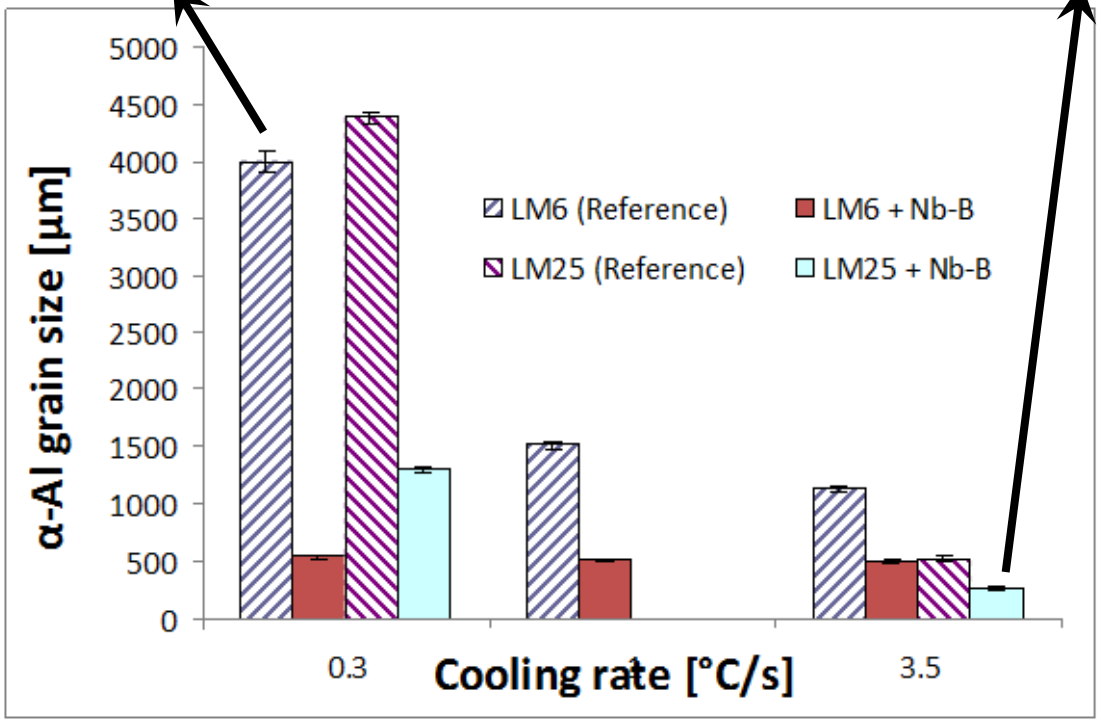




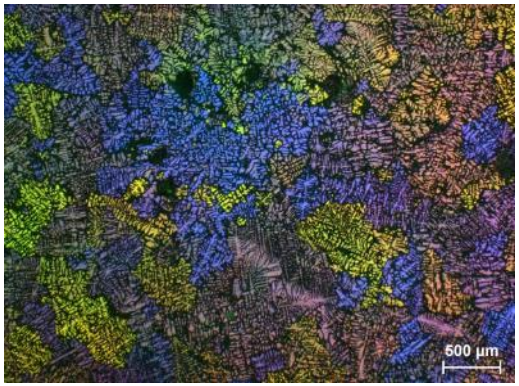


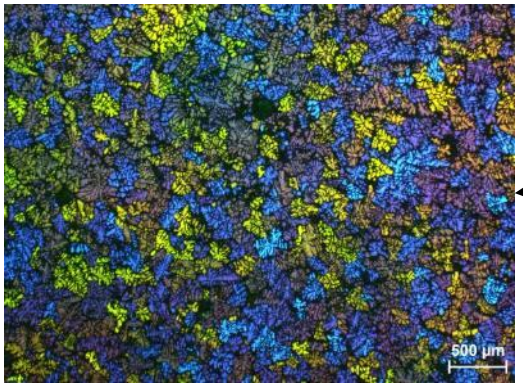


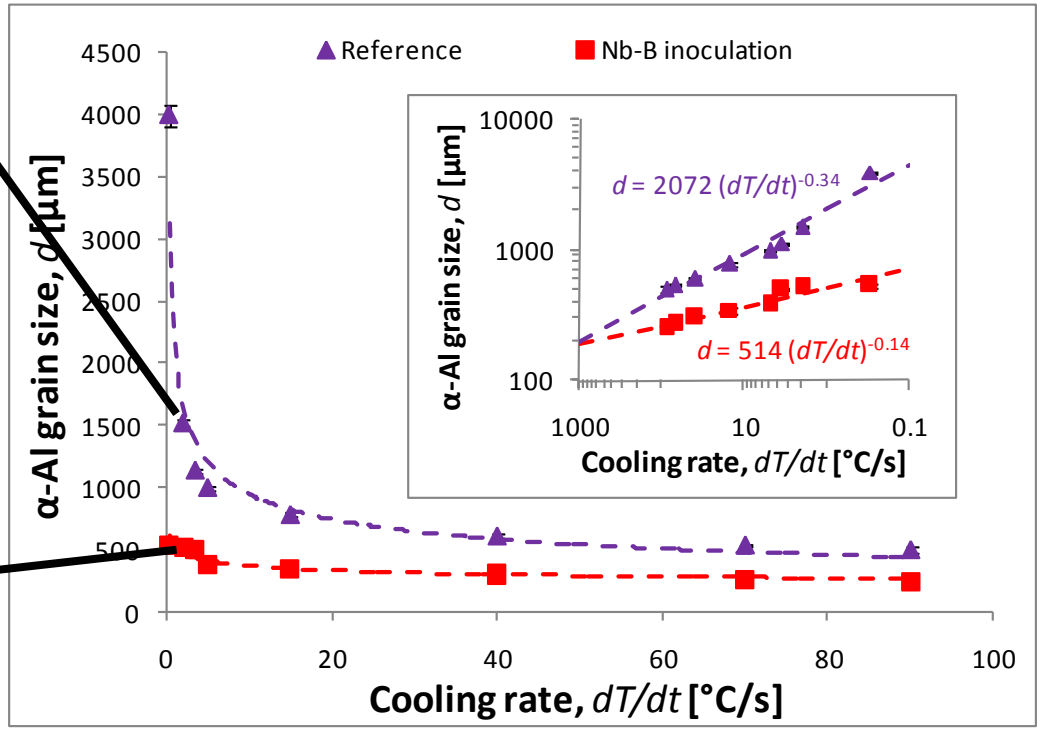




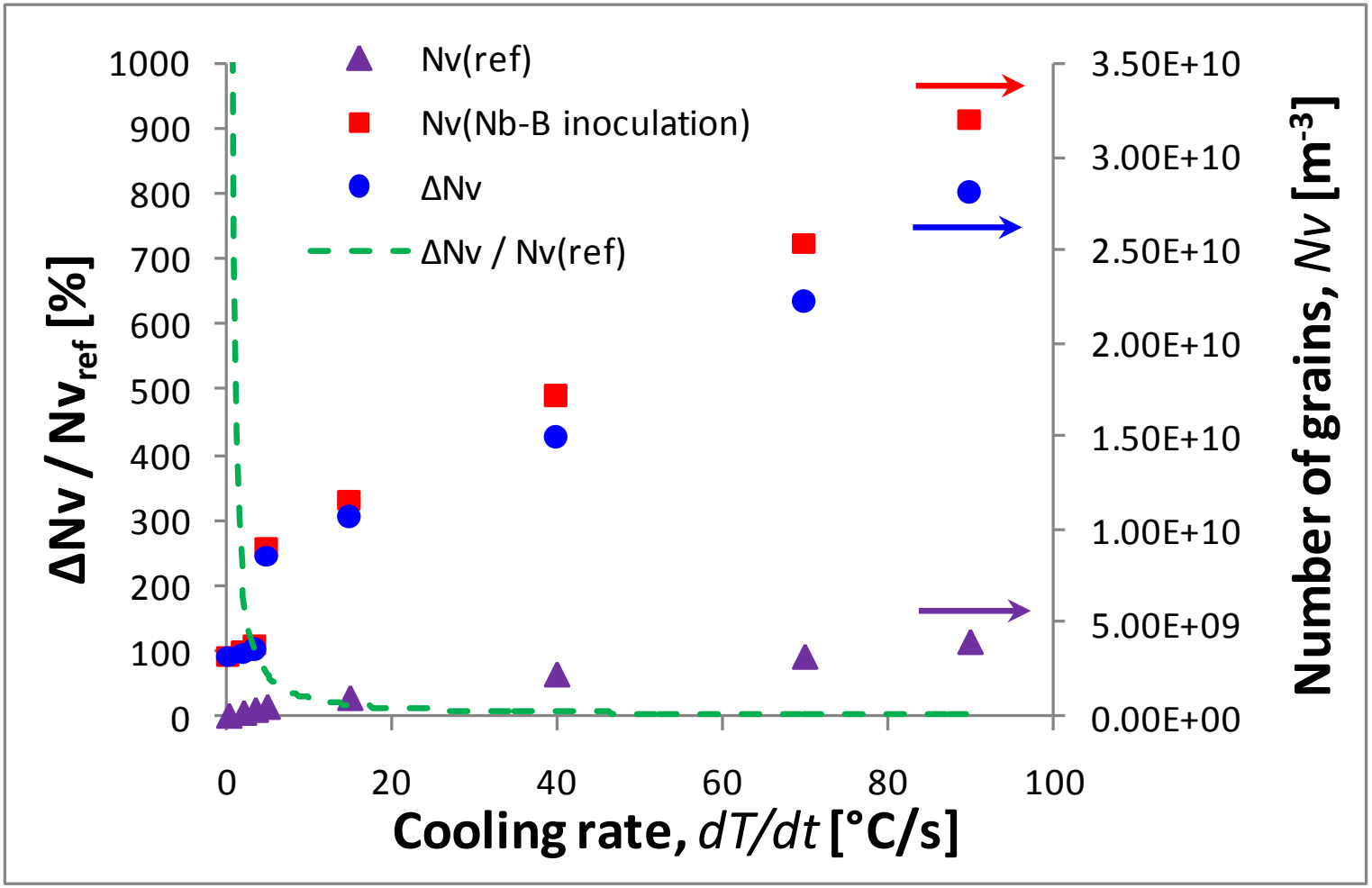
Effect of Cooling Rate







Effect of Cooling Rate



Nb-B Grain Refiner for Al-Si cast alloys

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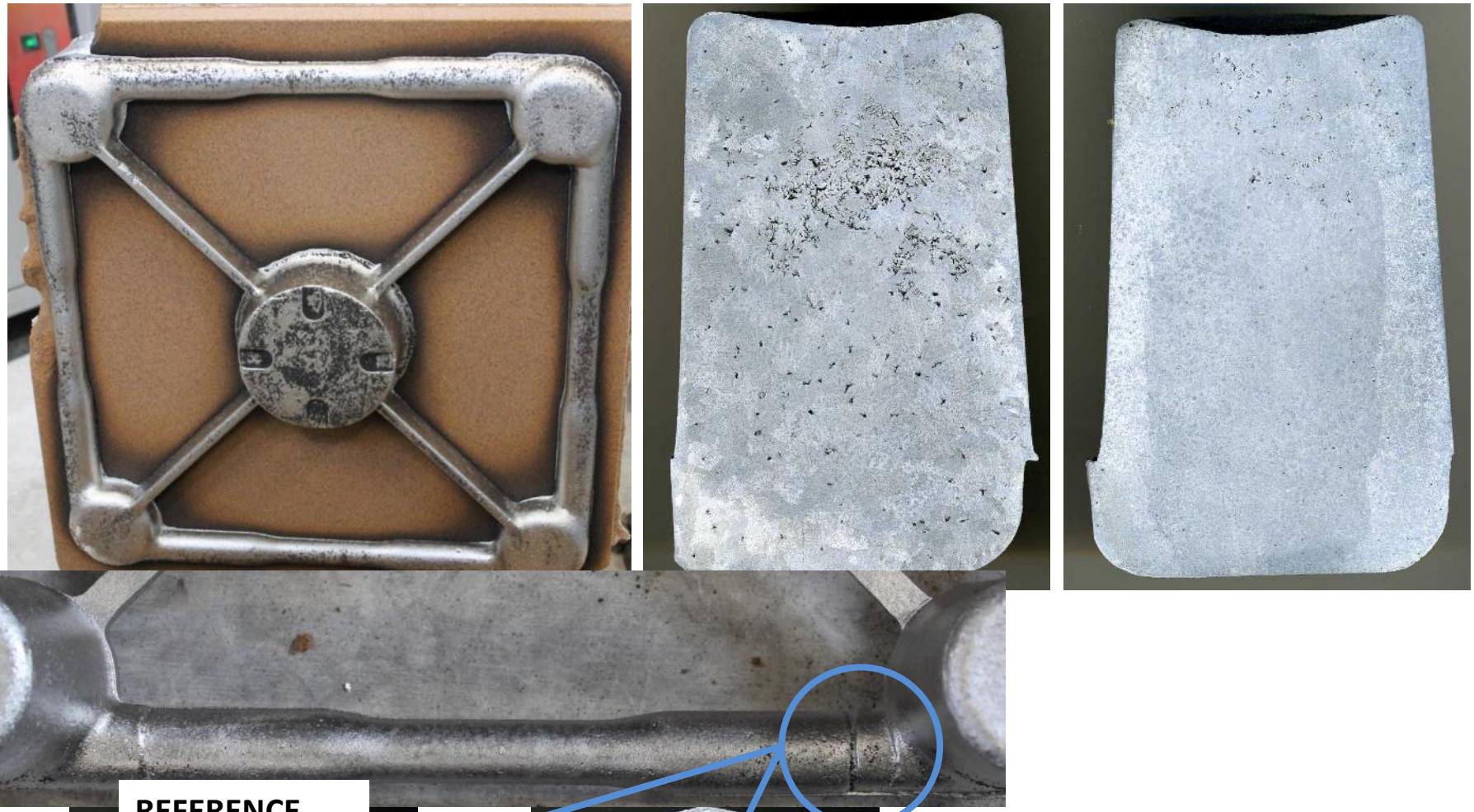
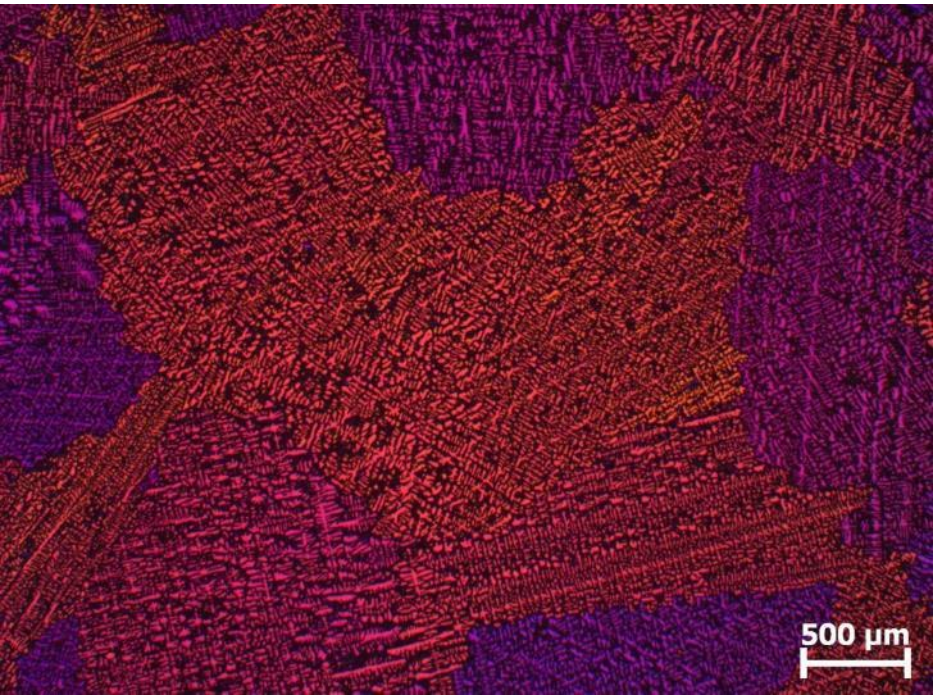
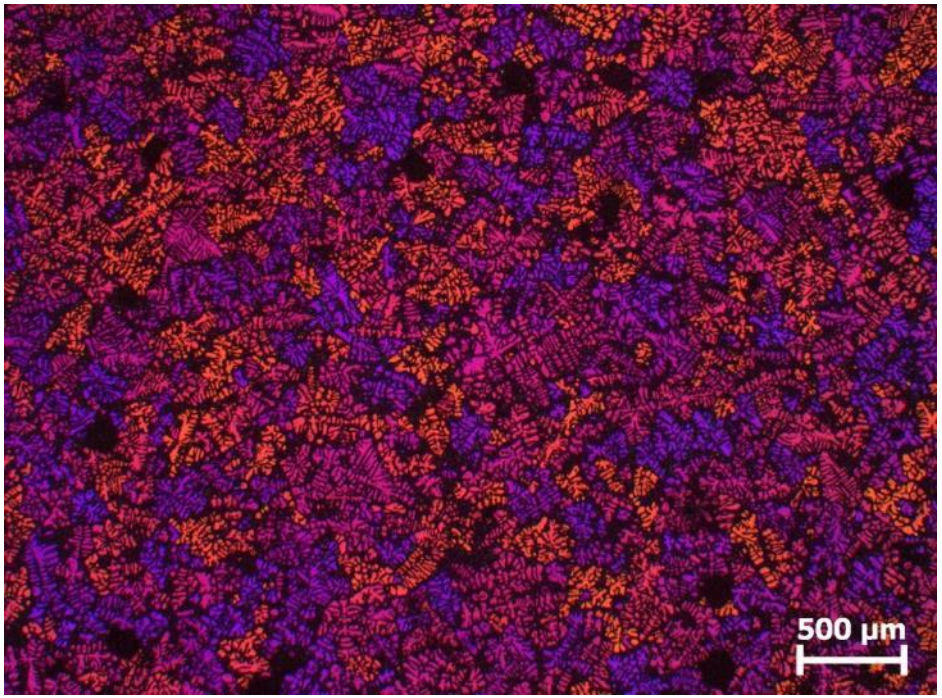
- Fine eutectic structure & intermetallics
- Improved ductility & strength
- Tolerant to Fe contamination
- Recycling of Al-Si scrap



Al-9Si-2Cu-0.7Mg-0.15Fe

A354





Alloy	Condn.	%Cu	%Mg	%Si	%Fe	%Mn	%Ni	%Zn	%Pb	%Sn	%Ti	%Sr
A354	CAST	1.60-2.0	0.50-0.60	8.6-9.44	0.154	0.05-0.10	0.054	0.10	0.014	0.054	0.10-0.154	0.02-0.030

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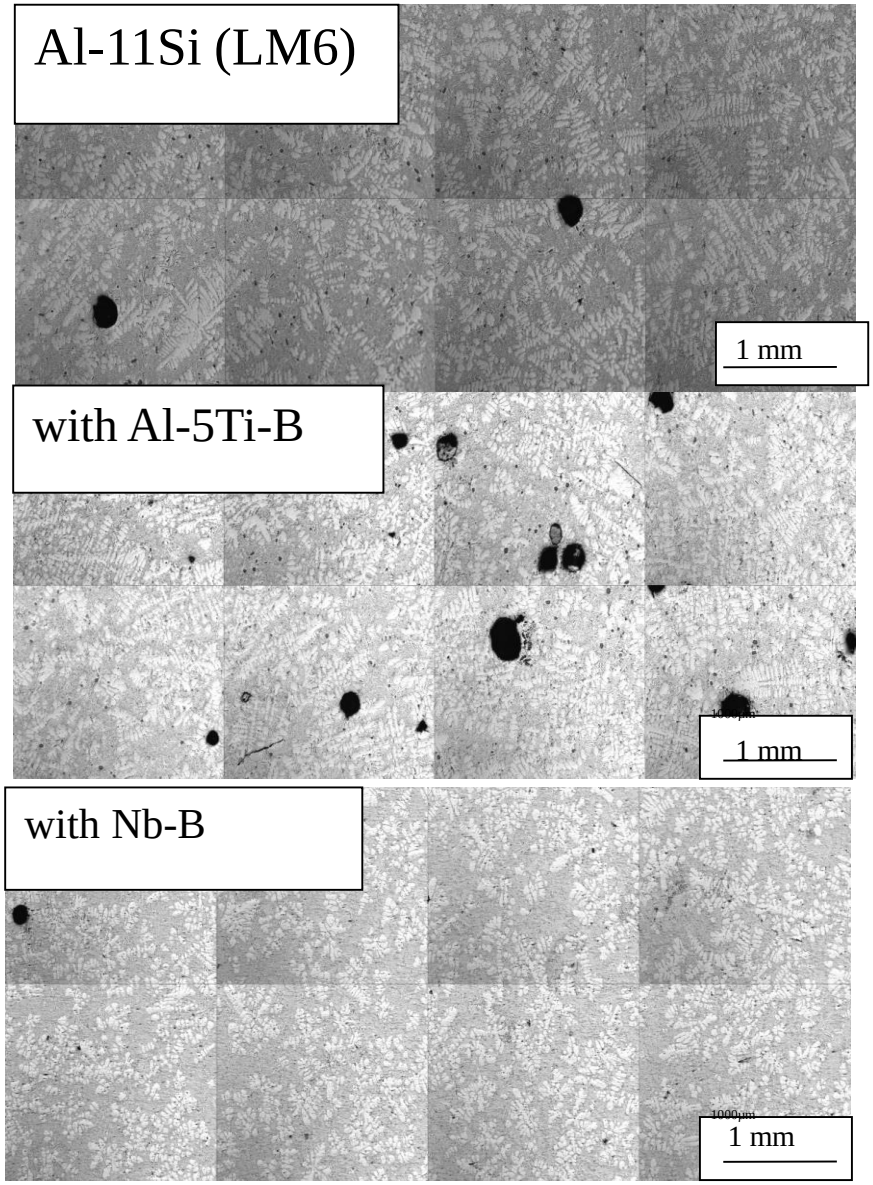
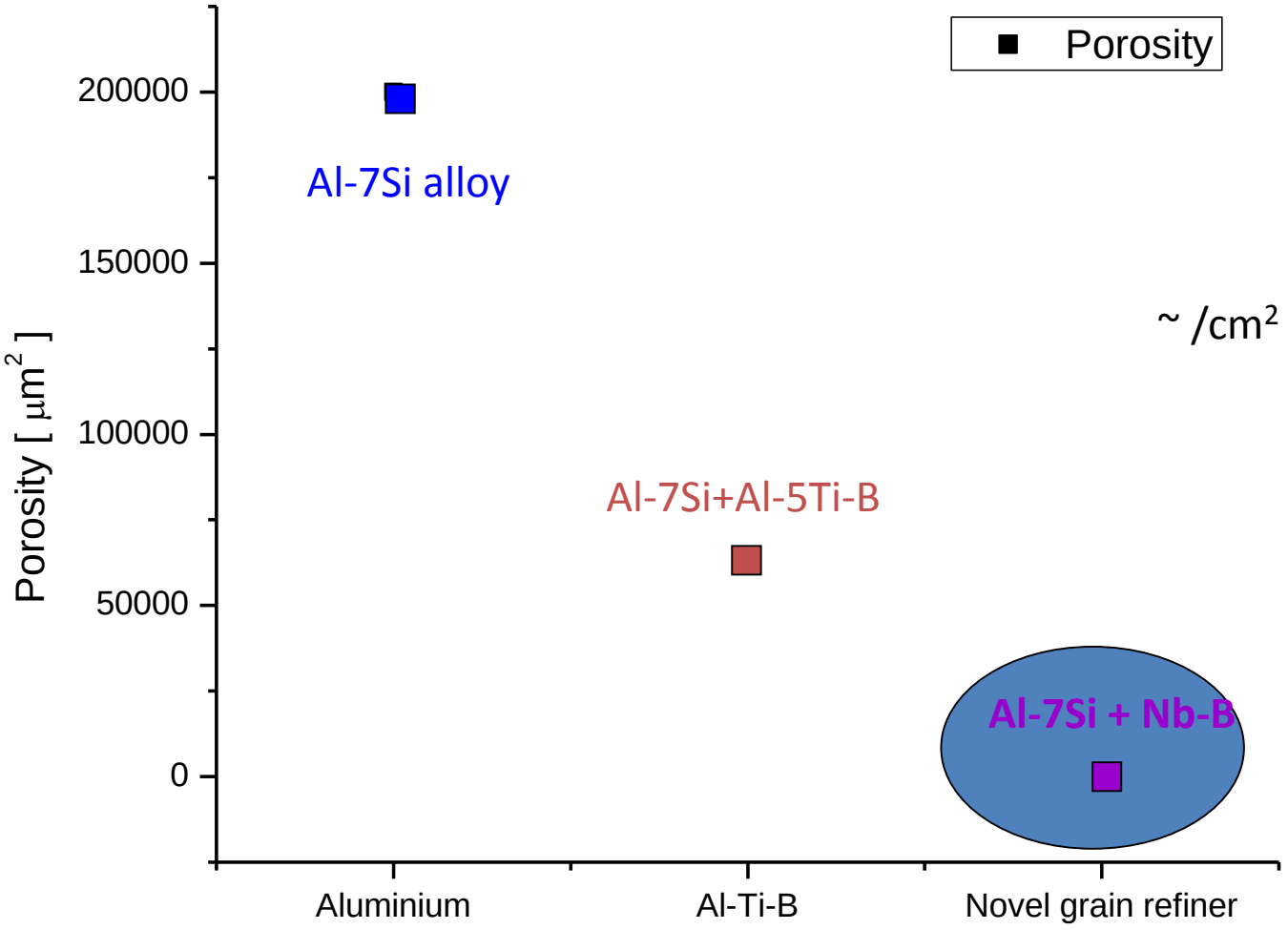
Reduced Macro-porosity with Nb-B



Porosity



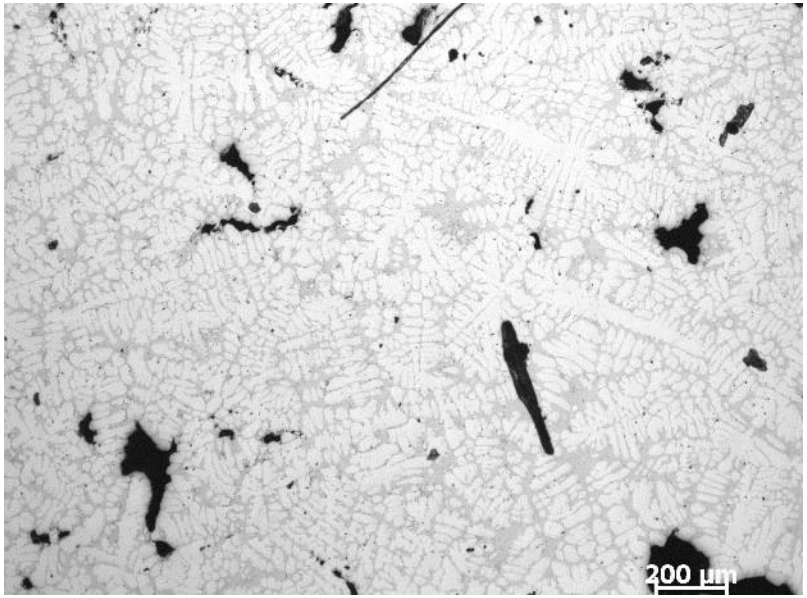
~ /cm²

Tp1 test
700 °C

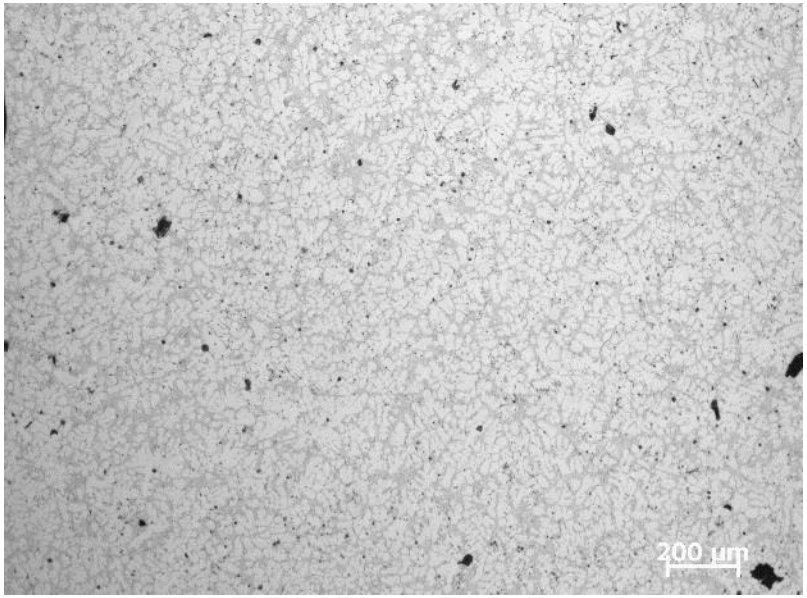
Reduced porosity in Nb-B grain refiner added castings

Al-7Si alloy

Without



With Nb-B addition



Fine grain structure
Reduced porosity

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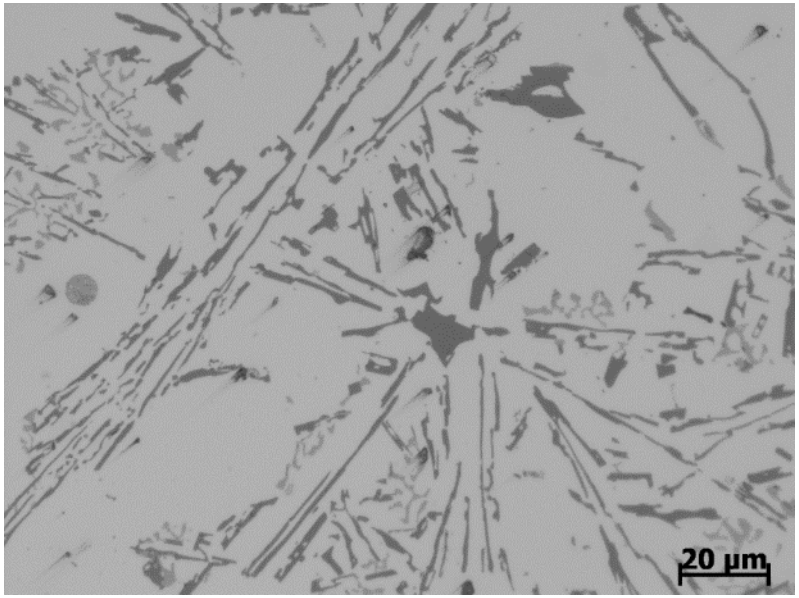
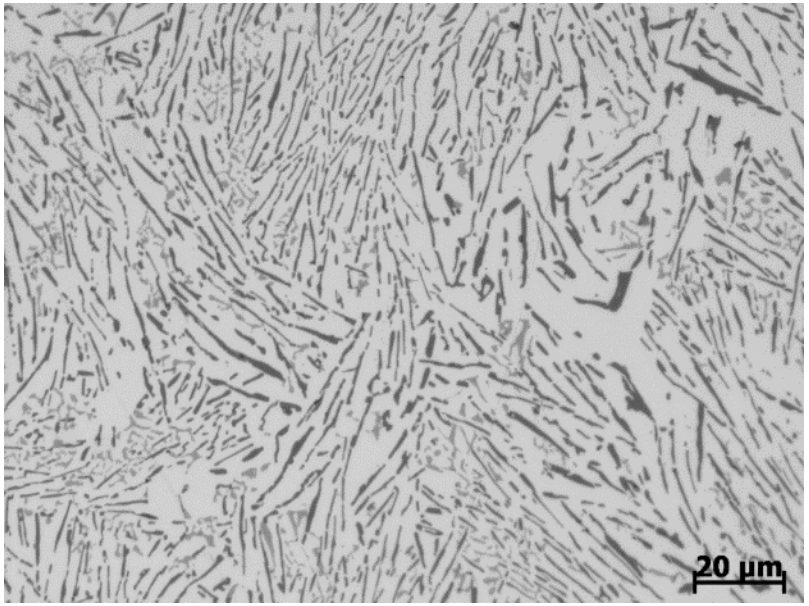
Fine eutectic structure

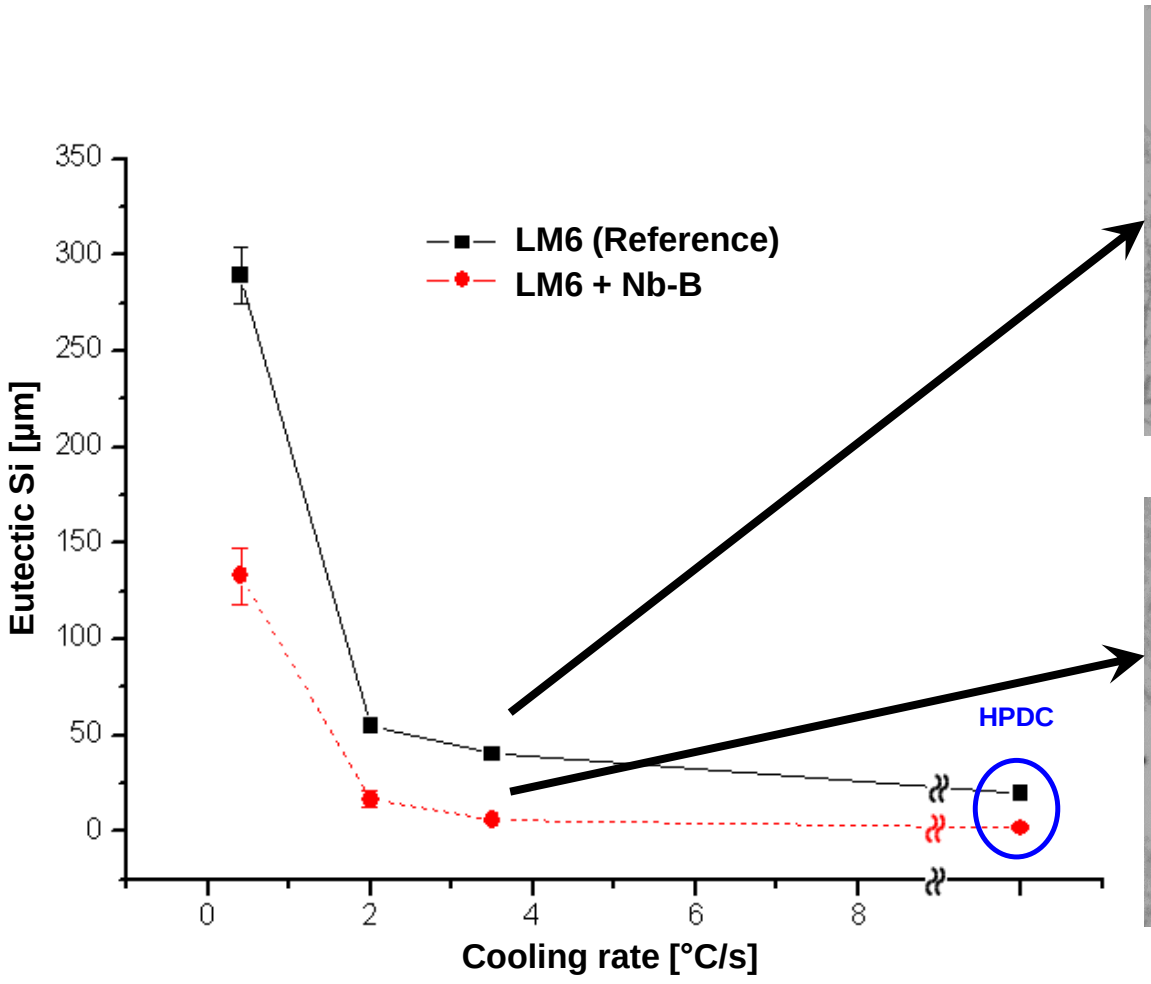


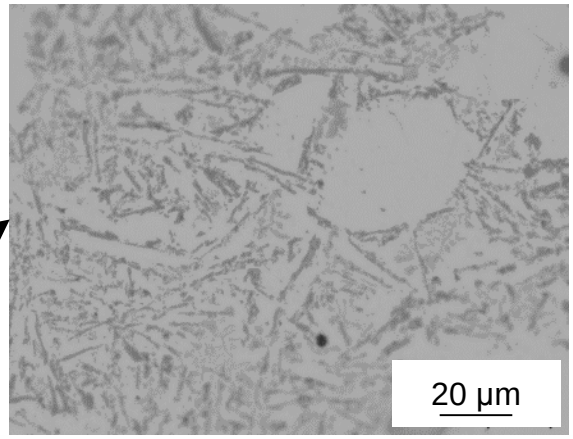
Al-11Si (LM6)

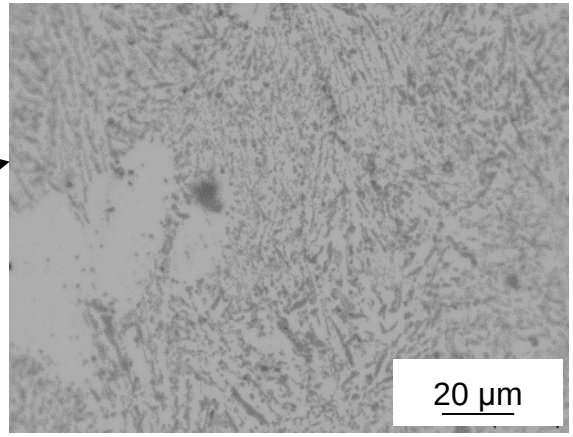


with Nb-B

Finer Eutectic Si - wider range of cooling rates

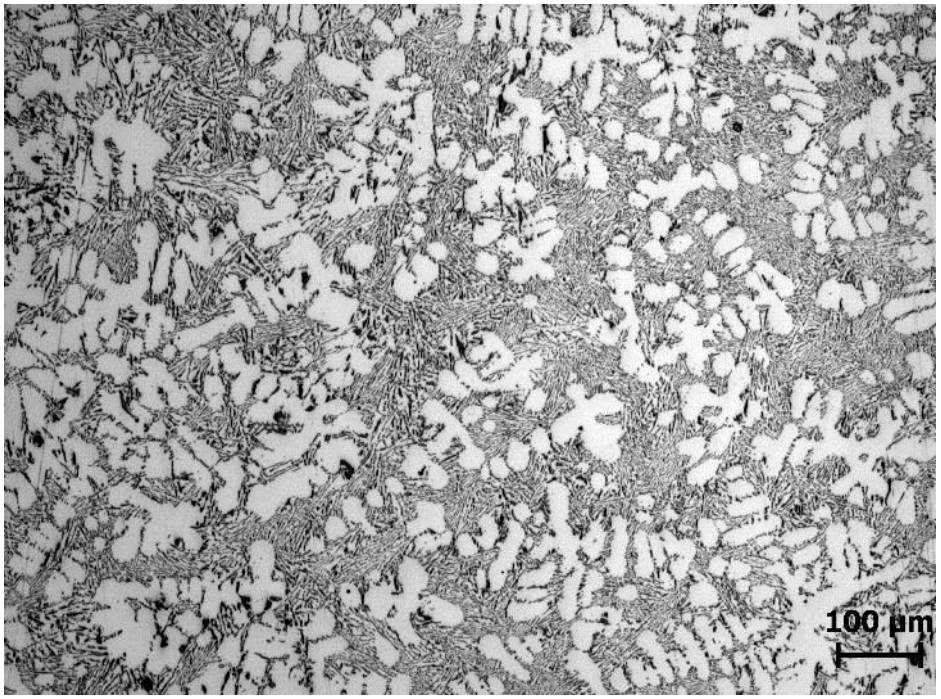






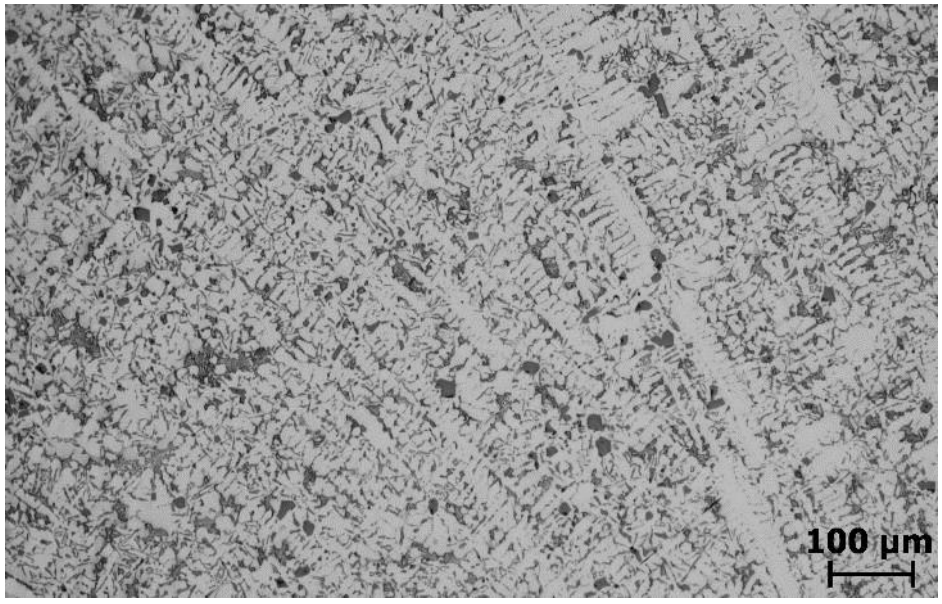
Al-10Si

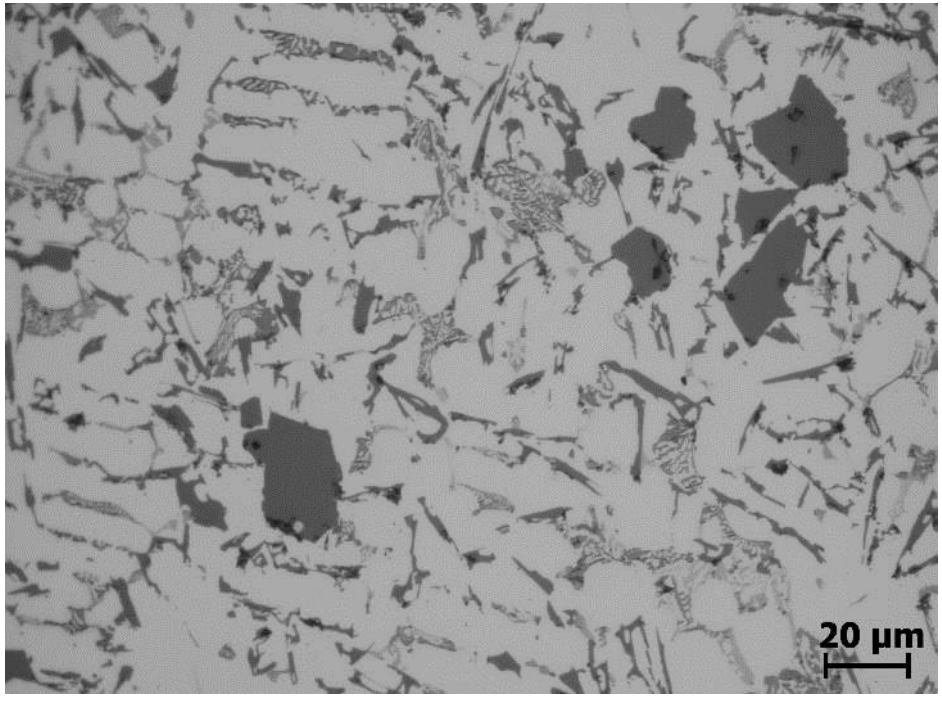
With Nb-B

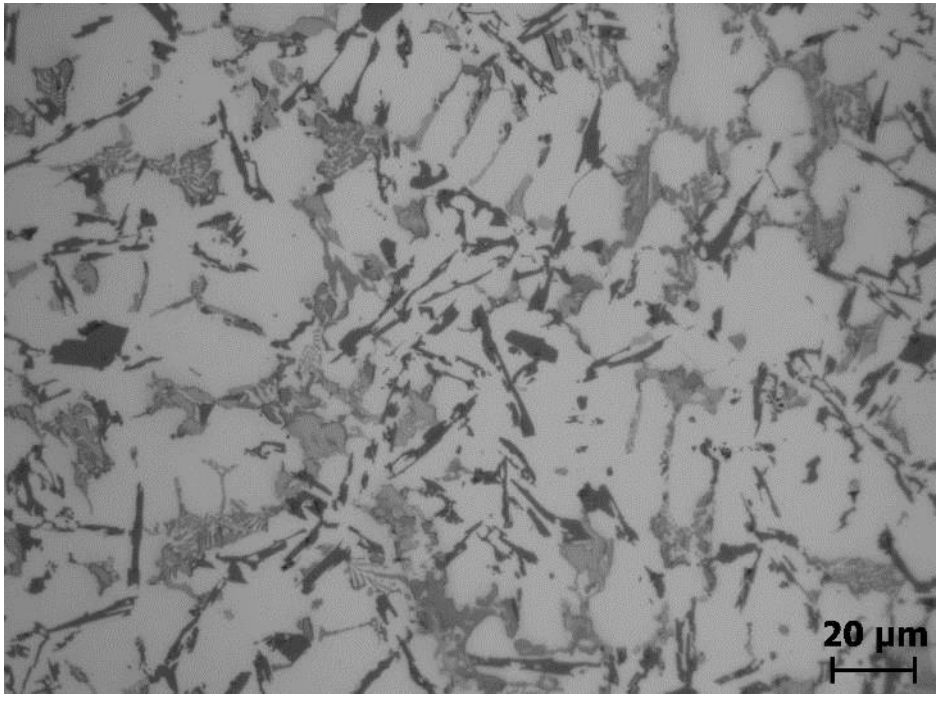


Reference (Al-13Si)

with Nb-B







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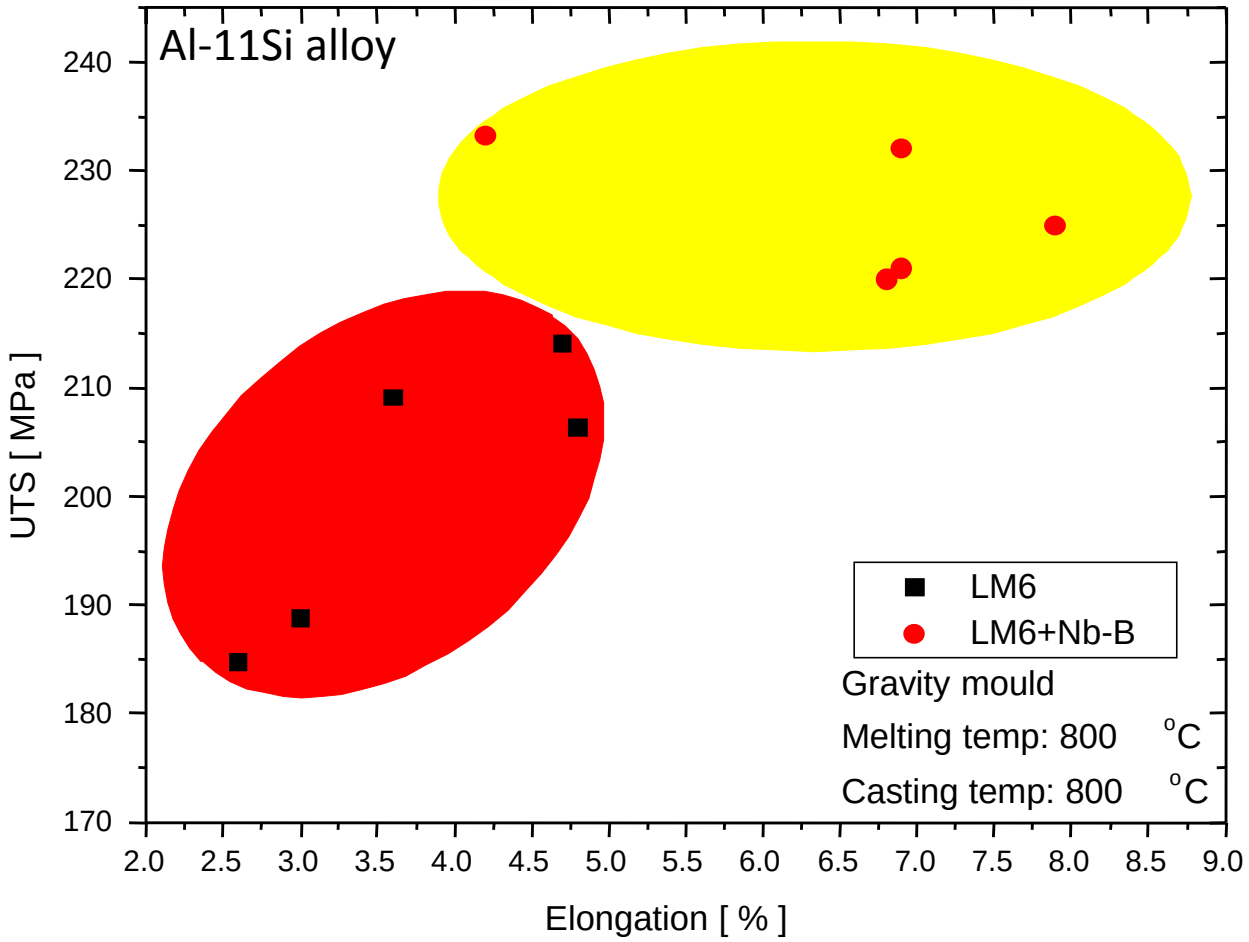
- **❑Improved ductility & strength**
- ❑Tolerant to Fe contamination
- ❑Recycling of Al-Si scrap

Improved strength & ductility

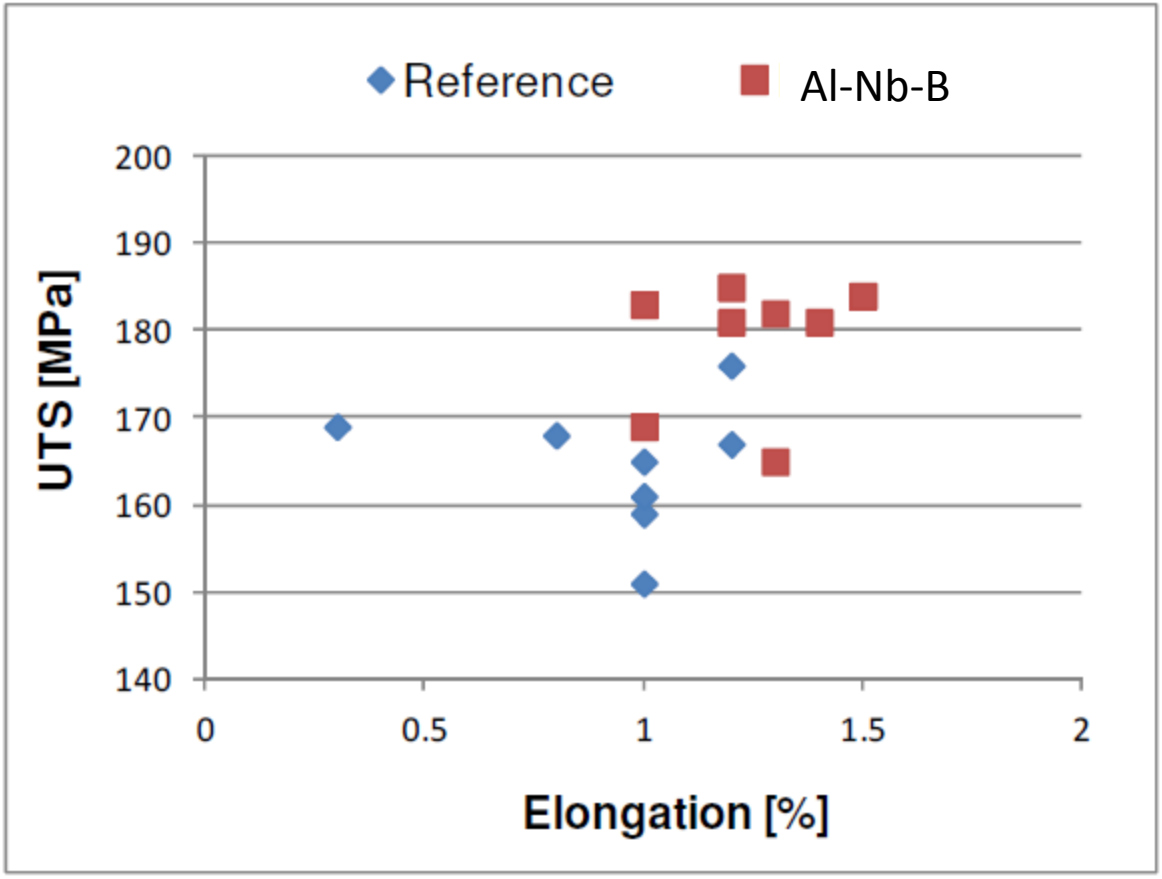


Machined from cast bars

Improved
- Crash performance
- Fatigue performance

yield
82.4 Mpa → 102 Mpa

Al-13Si piston alloy



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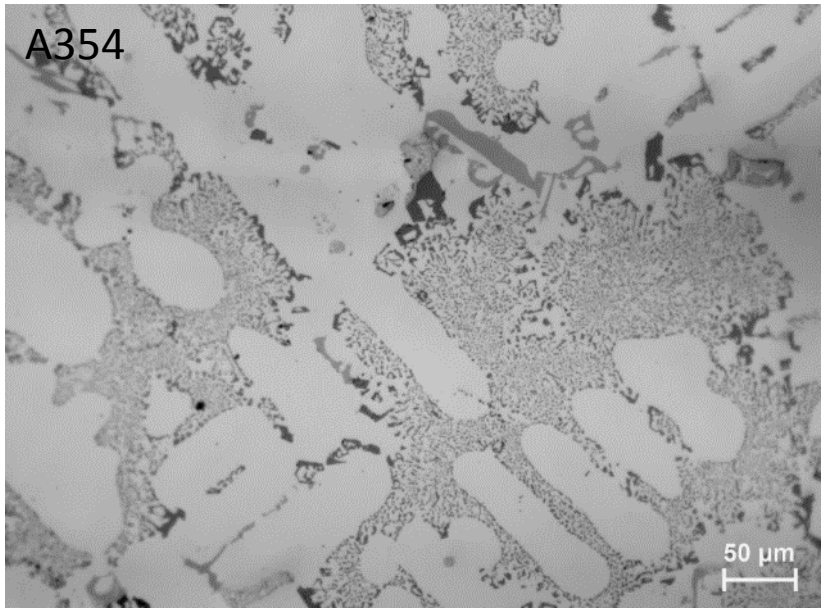
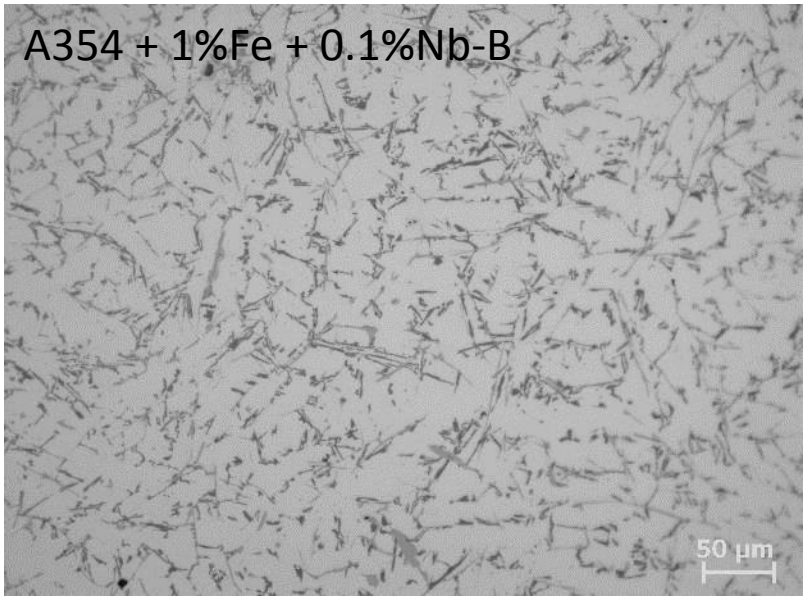
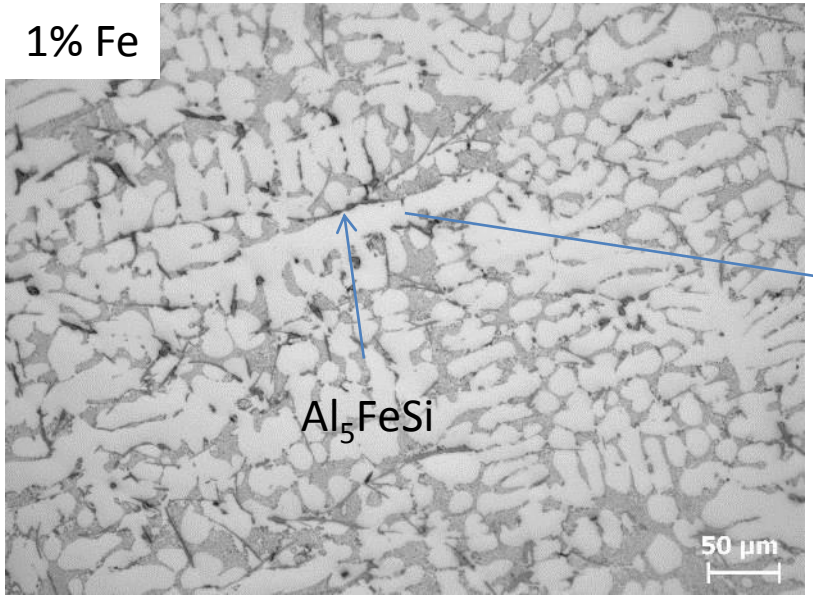
Control of Fe-intermetallics in Al scrap



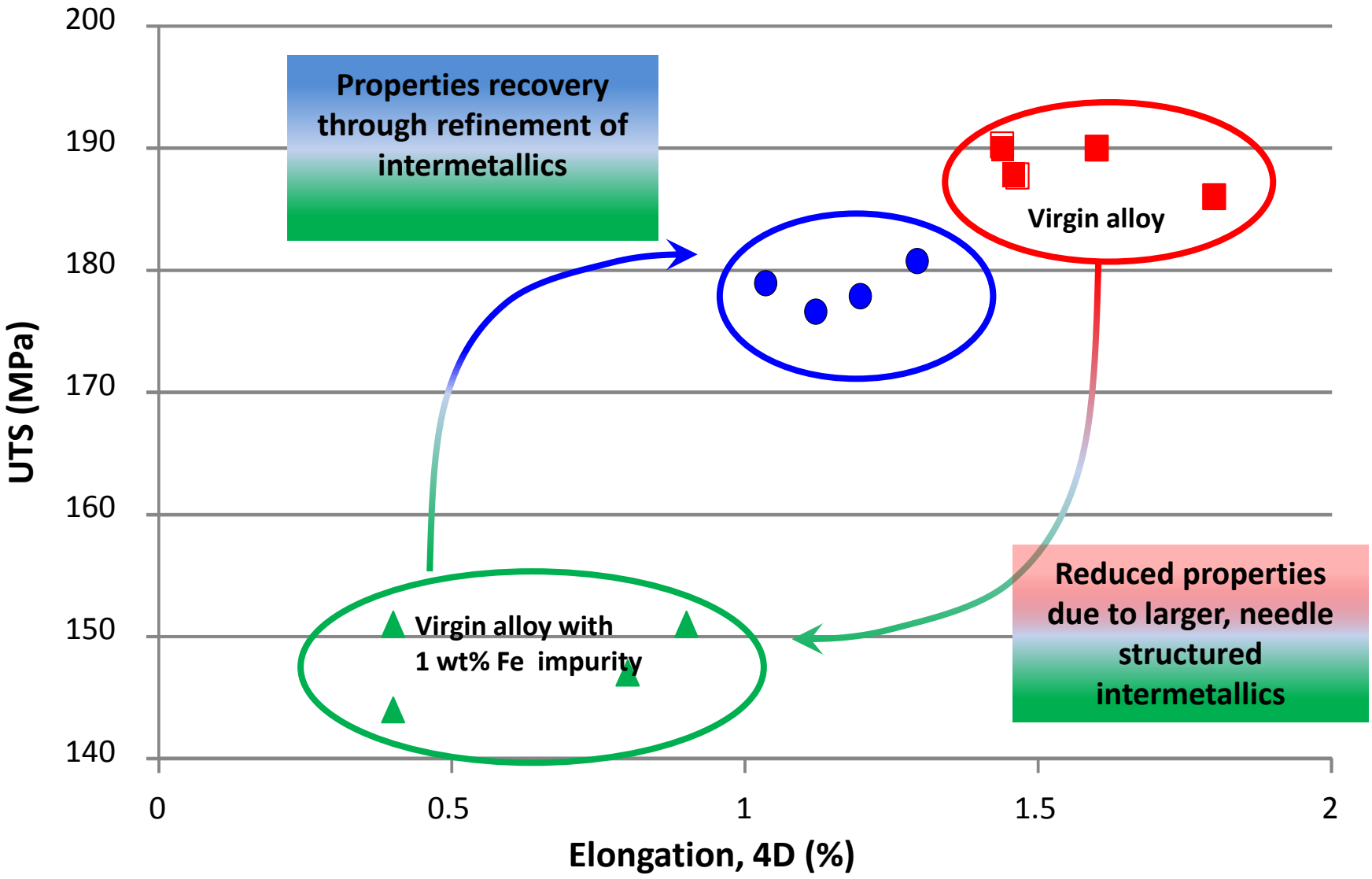




Grain refiner to control
Al-Fe-Si intermetallics

Al-Fe-Si large needle structure
detrimental to mechanical properties

Recovery of properties in Fe-rich aluminium scrap



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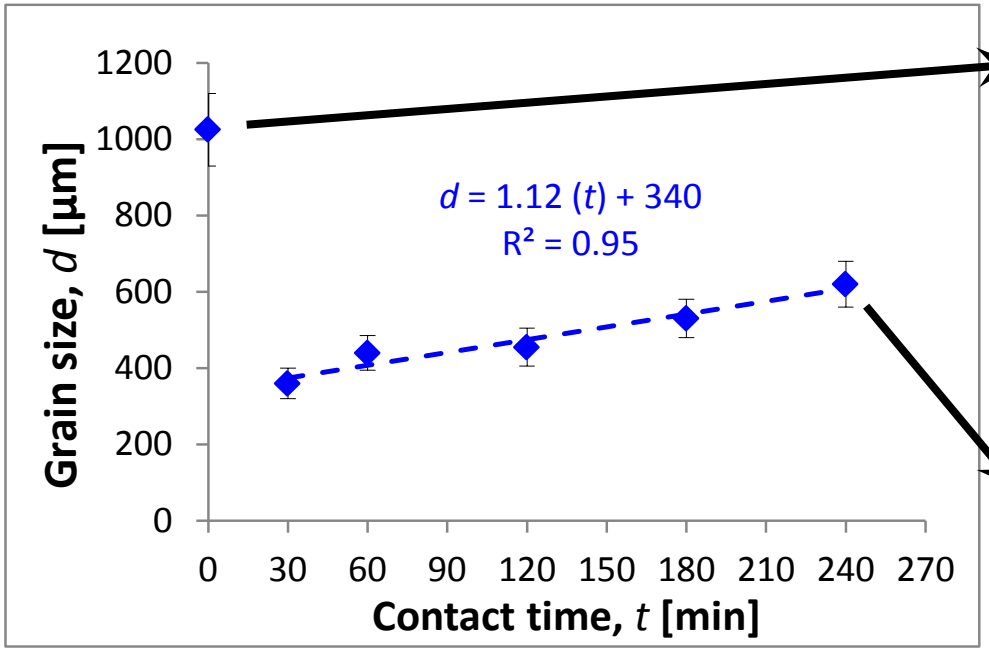
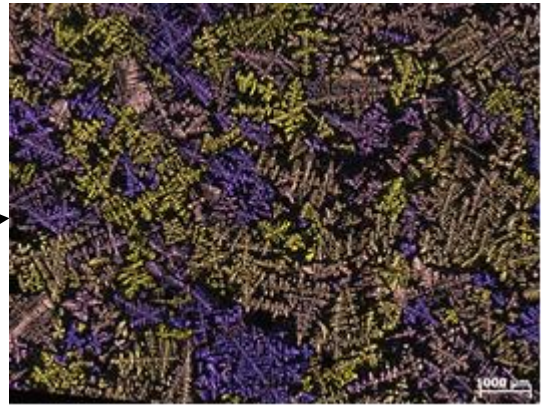
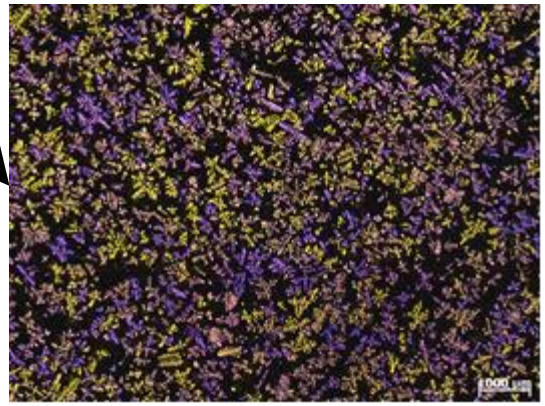
- **❑Re-melting & Fading study**

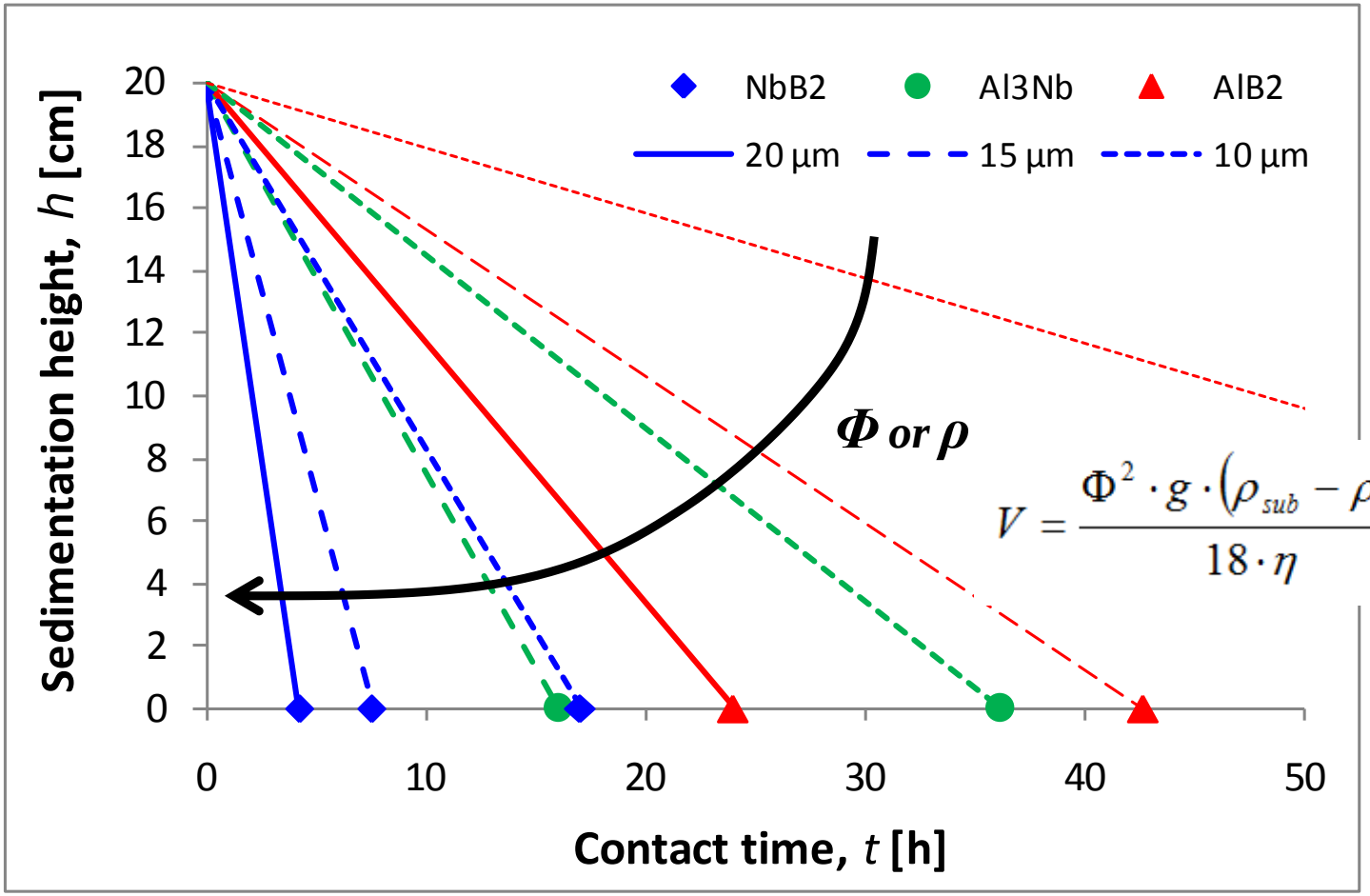
FADING STUDY





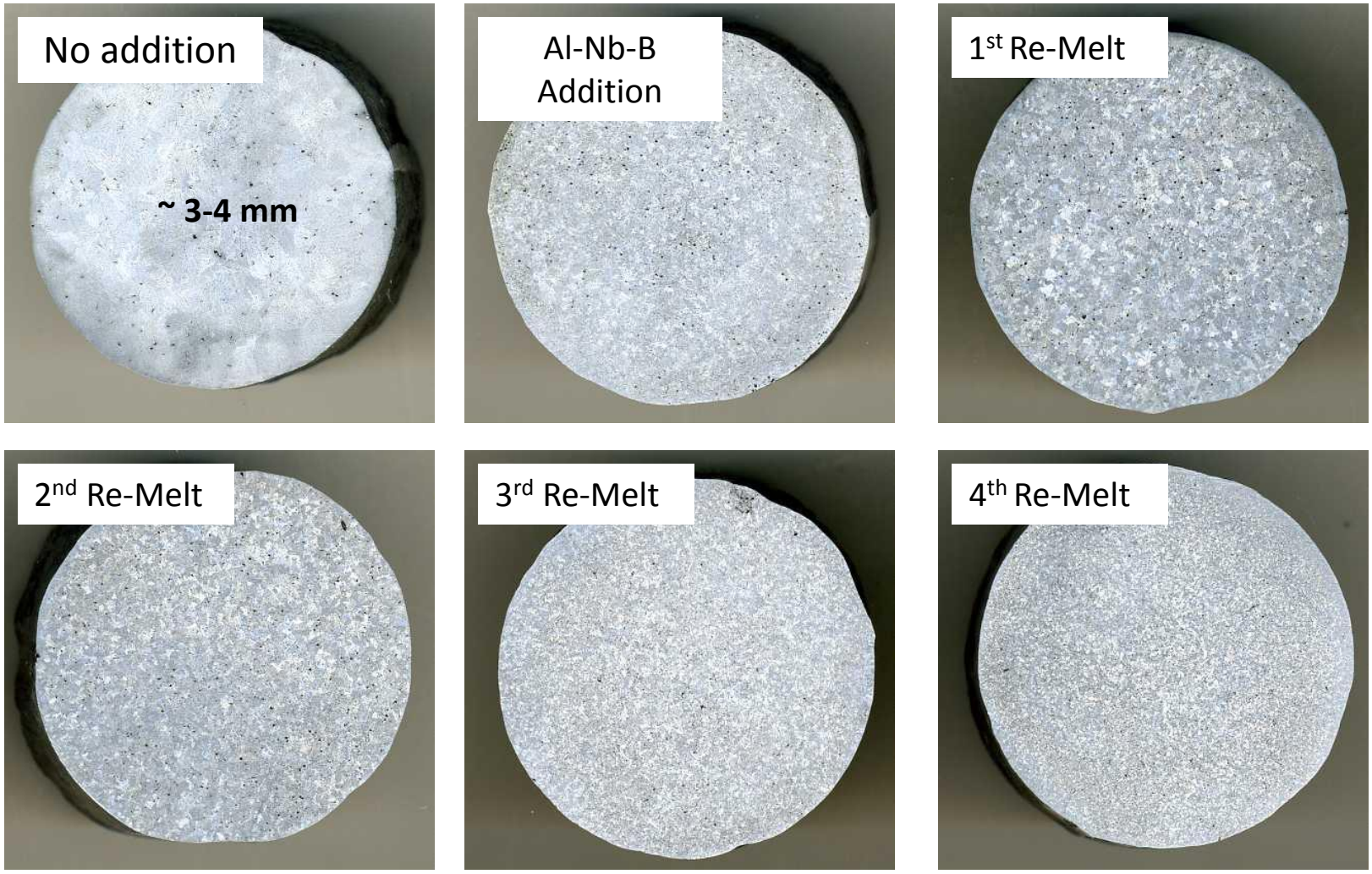


REQUIRED TIME TO SEDIMENT/FADE



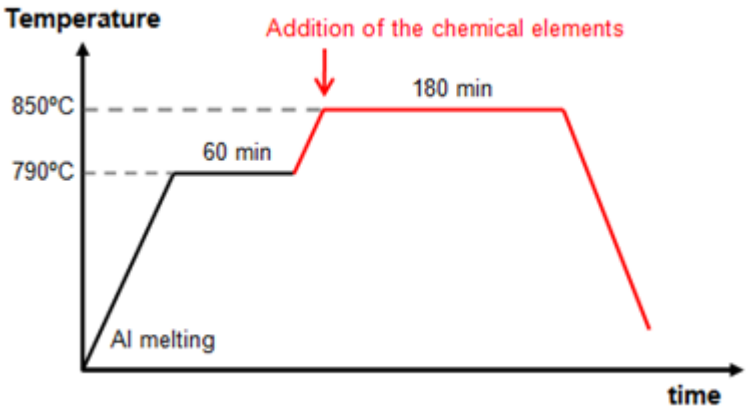
Remelting

Al-9Si-1.5Cu-0.6Mg-0.15Fe / RE-MELT



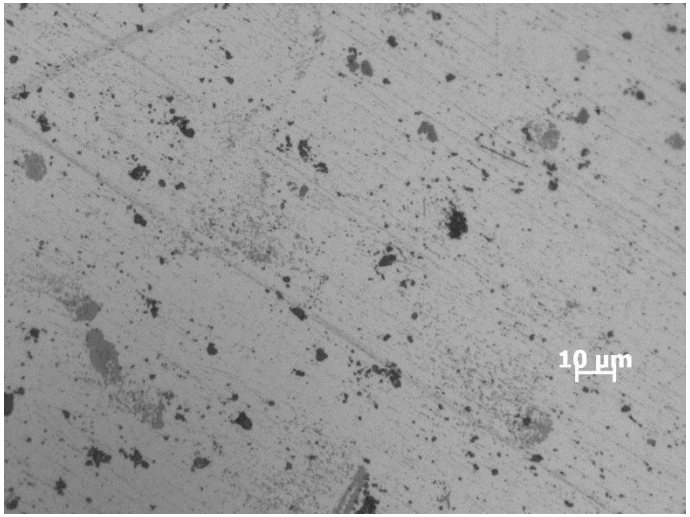
MASTER ALLOY DEVELOPMENT

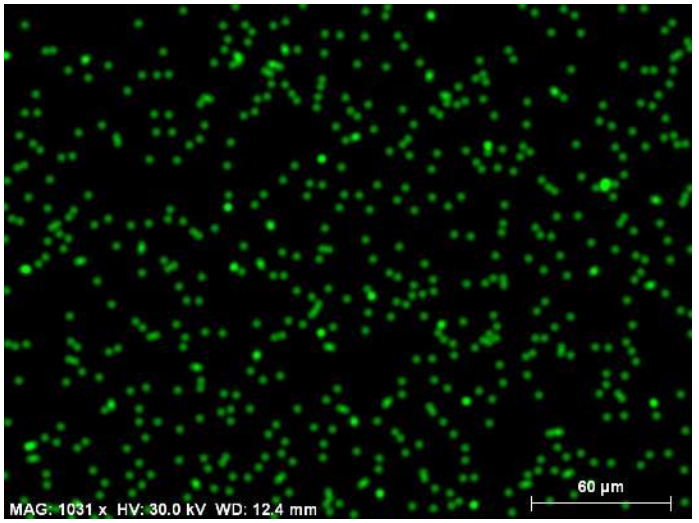
Al-Nb-B Master Alloy



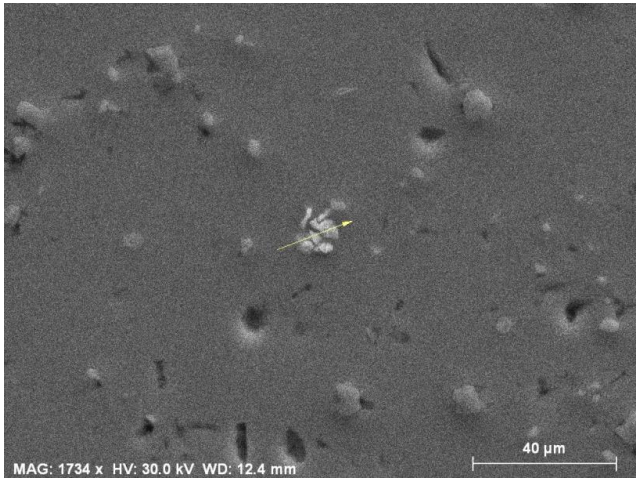
1. Nb metallic powder
   + KBF4

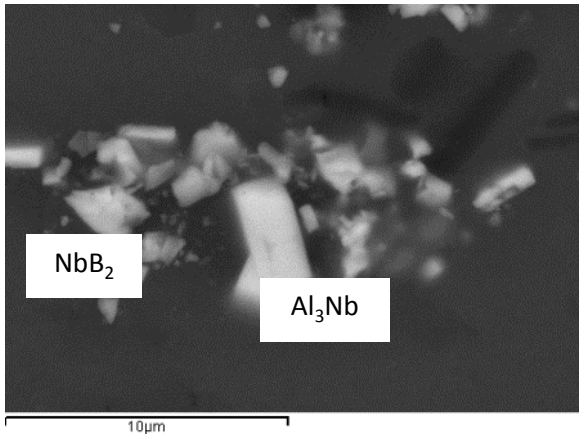
2. Addition of Nb metallic powder to diluted Al-B master alloy

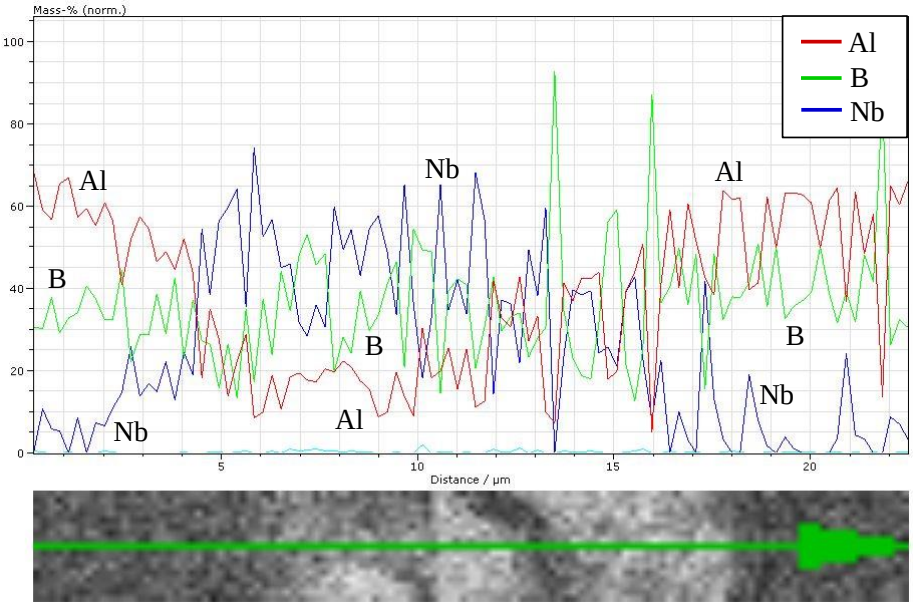


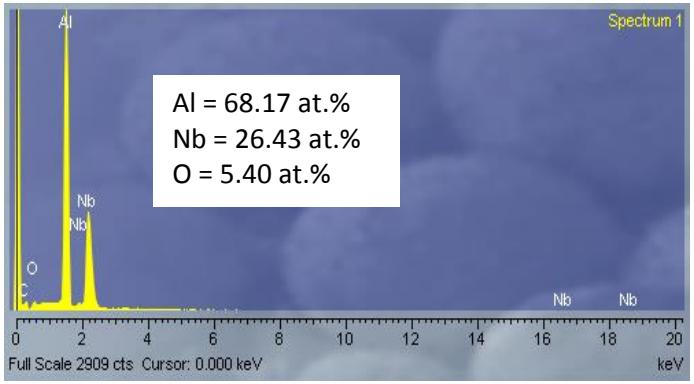


MASTER ALLOY (METHOD 1)









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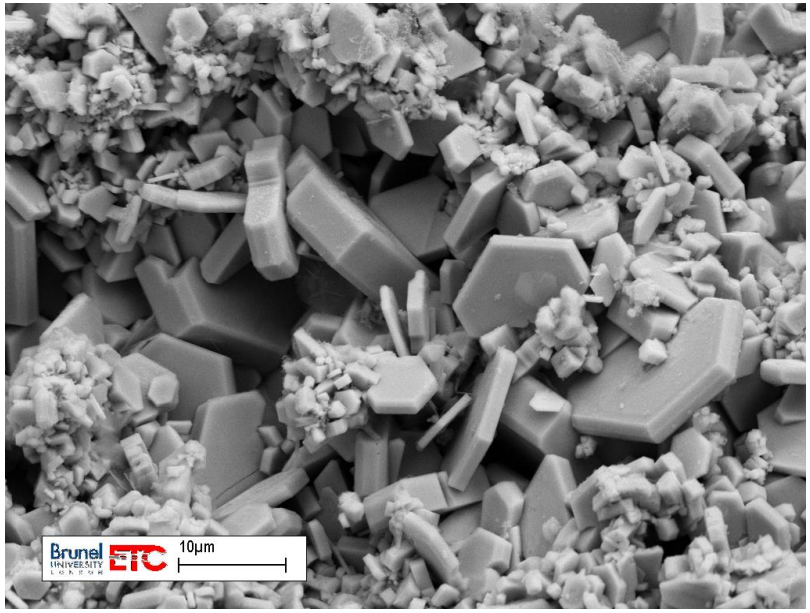
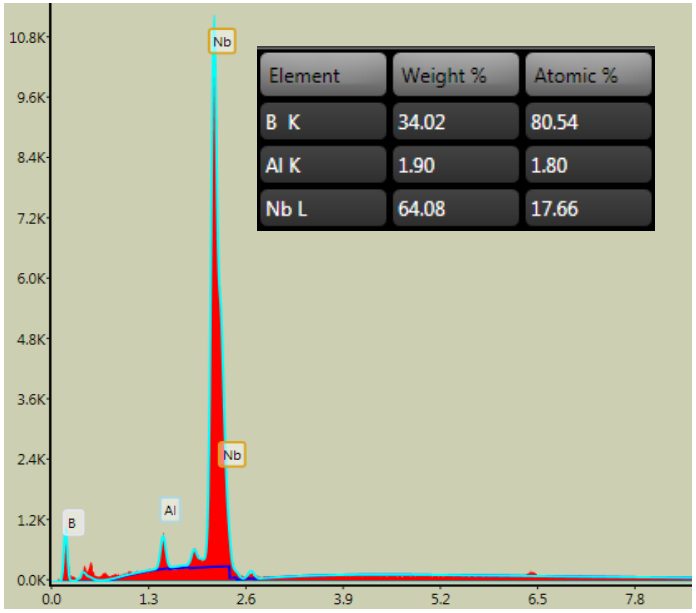
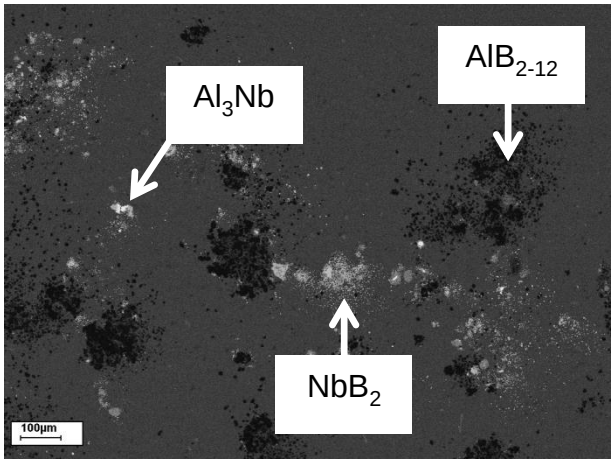
Al-2Nb-2B (Method 2)

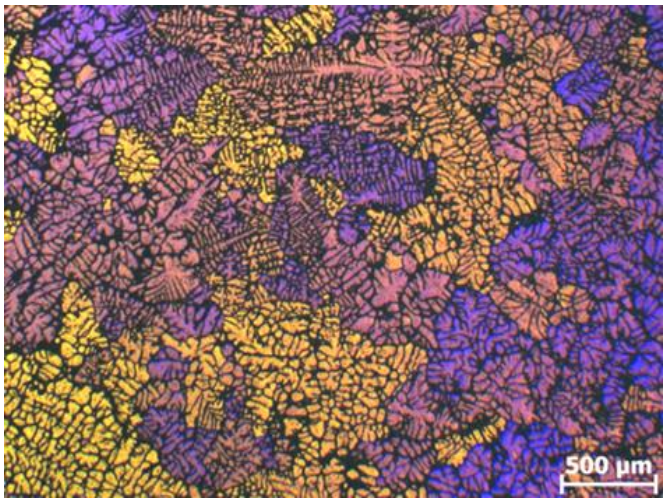


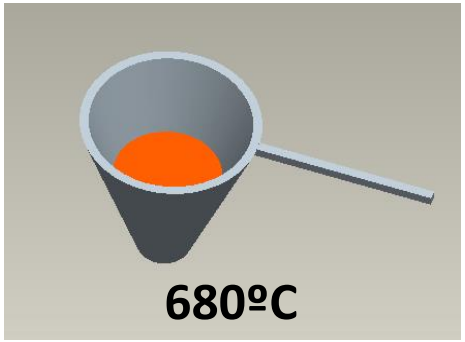


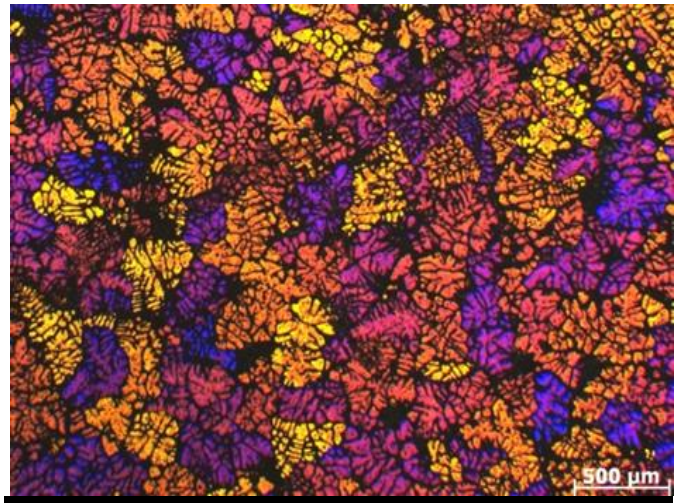


Al-4Nb-1B ON LM25

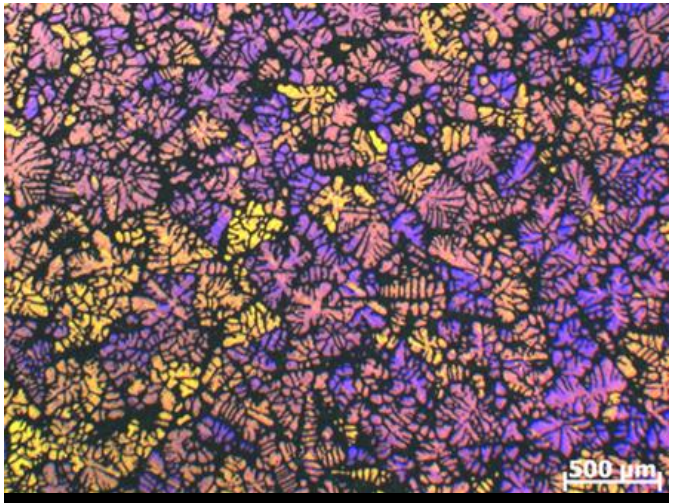
Reference





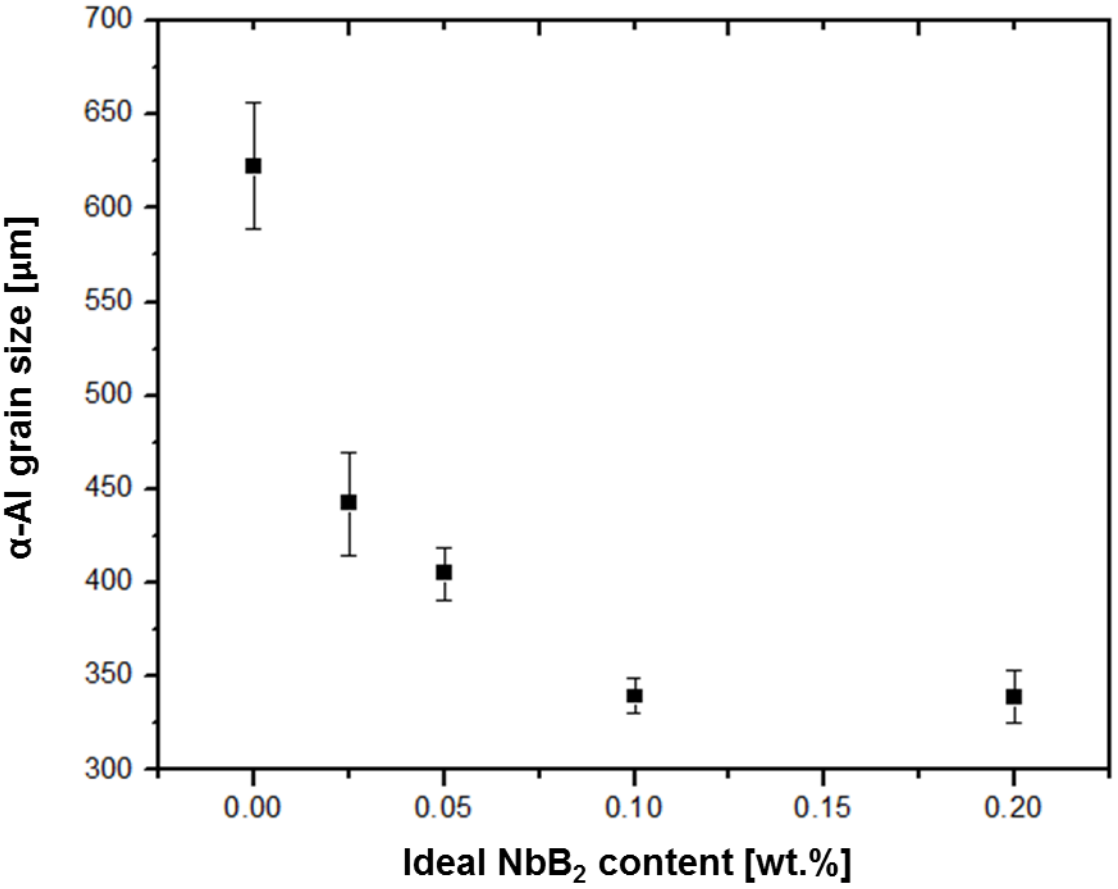


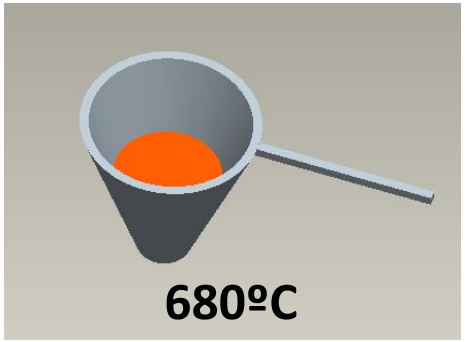
Nb-B (M.A.)



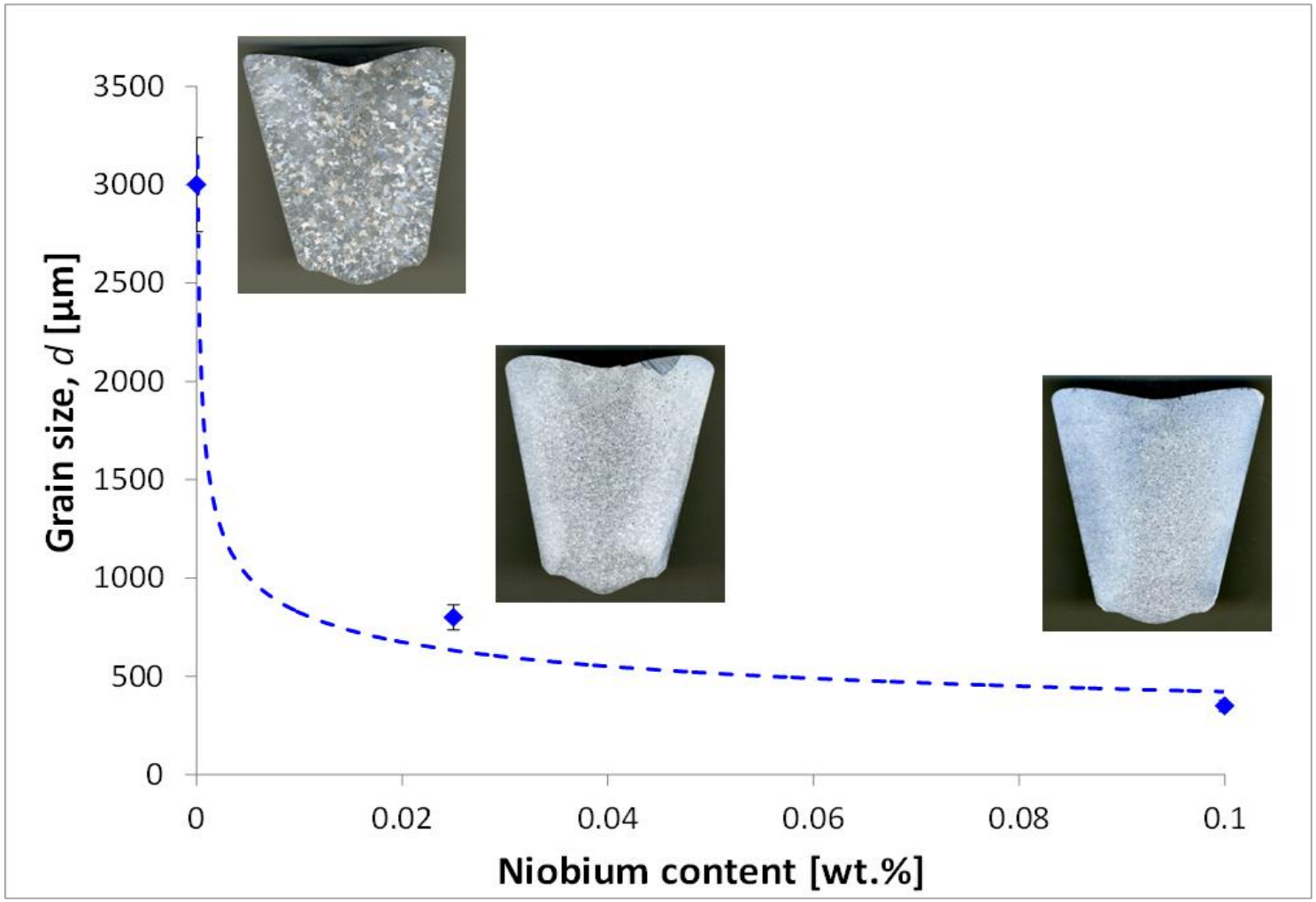
Al-Nb-B (powders)

Al-4Nb-1B ON LM6

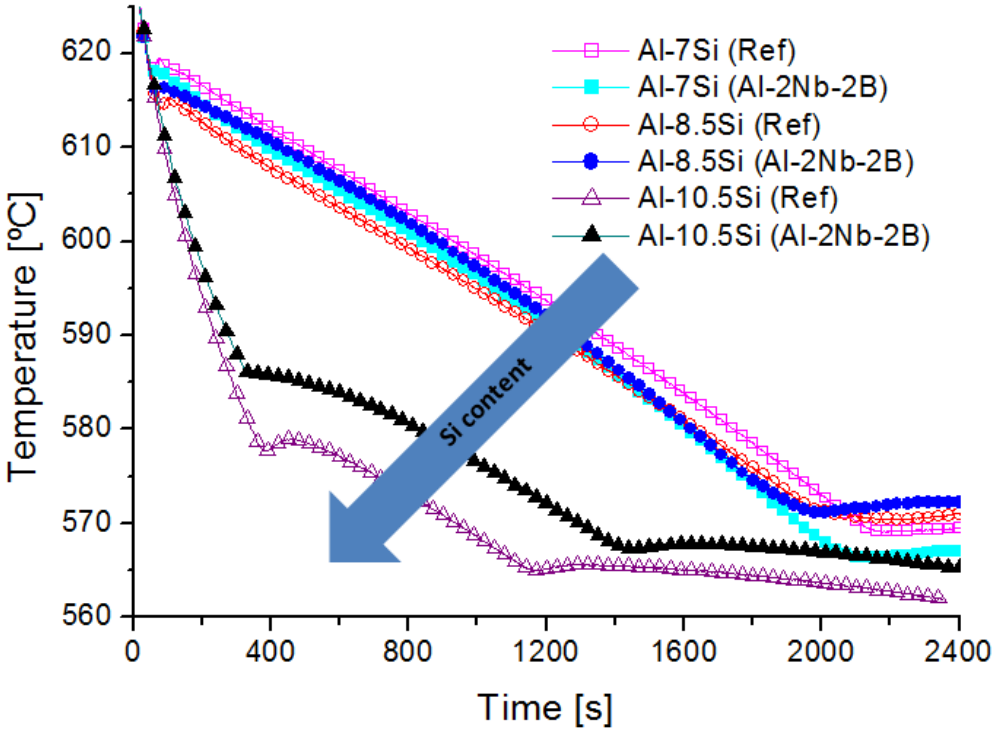




Al-2Nb-1B ON Al-10Si

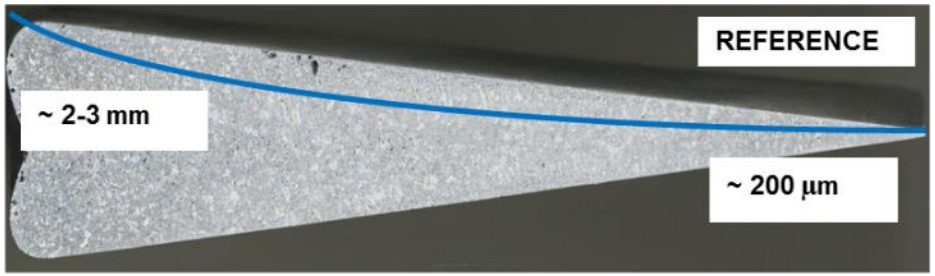


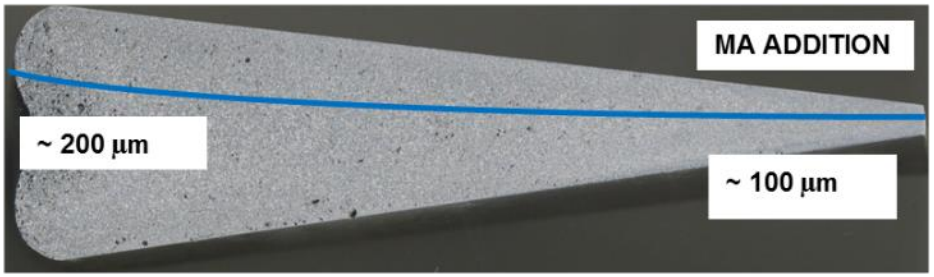
EFFECT OF Al-2Nb-2B ON UNDERCOOING FOR COMMERCIAL Al-Si ALLOYS

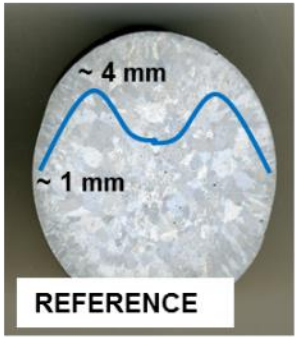


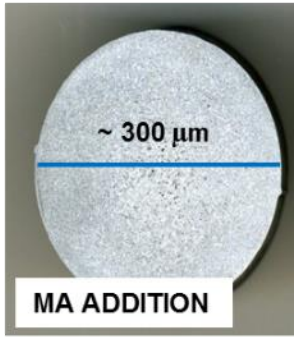
Material		Si content [wt. %]		
		7	8.5	10.5
Reference	ΔT_{α}	1.7	1.4	1.4
	ΔT_{eu}	1.4	1.8	0.9
Al-2Nb-2B master alloy addition	ΔT_{α}	0.6	0.3	0.4
	ΔT_{eu}	1.1	1.3	0.7

EFFECT OF Al-2Nb-2B ON COMMERCIAL Al-Si ALLOYS

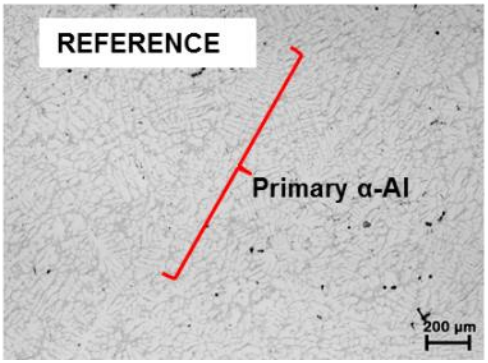


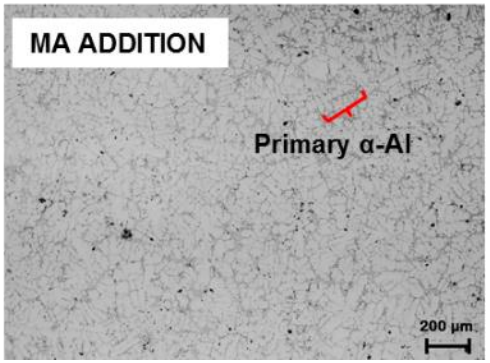






➢ **HYPO-EUTECTIC ALLOYS (LM24/25)**

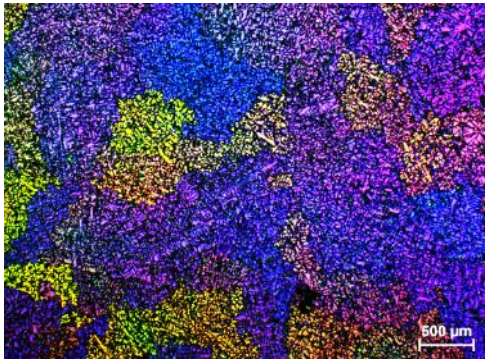


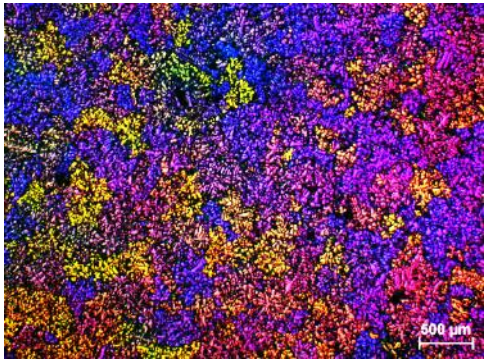


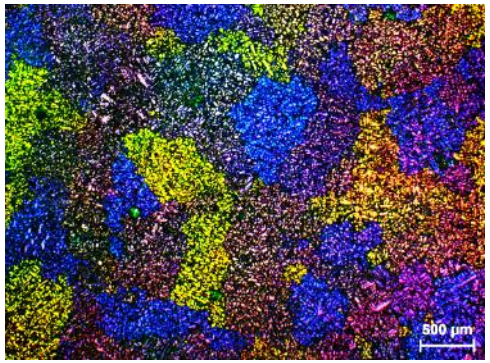
EFFECT OF Al-2Nb-2B ON COMMERCIAL Al-Si ALLOYS

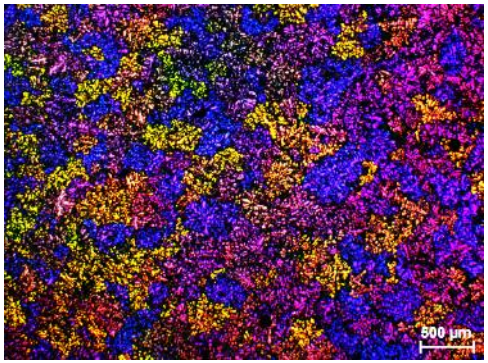
PISTON ALLOY (HYPER-EUTECTIC: 13 wt.% Si)

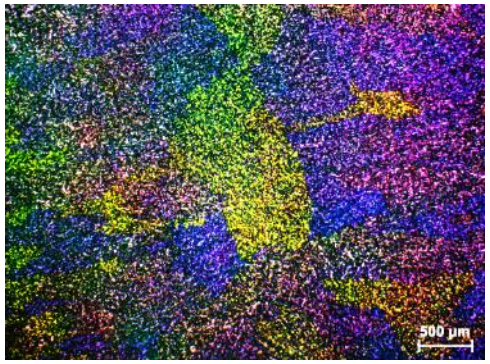
740°C

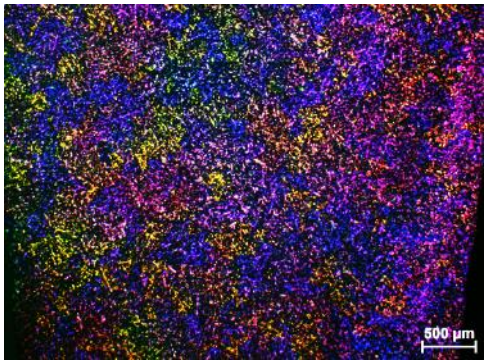




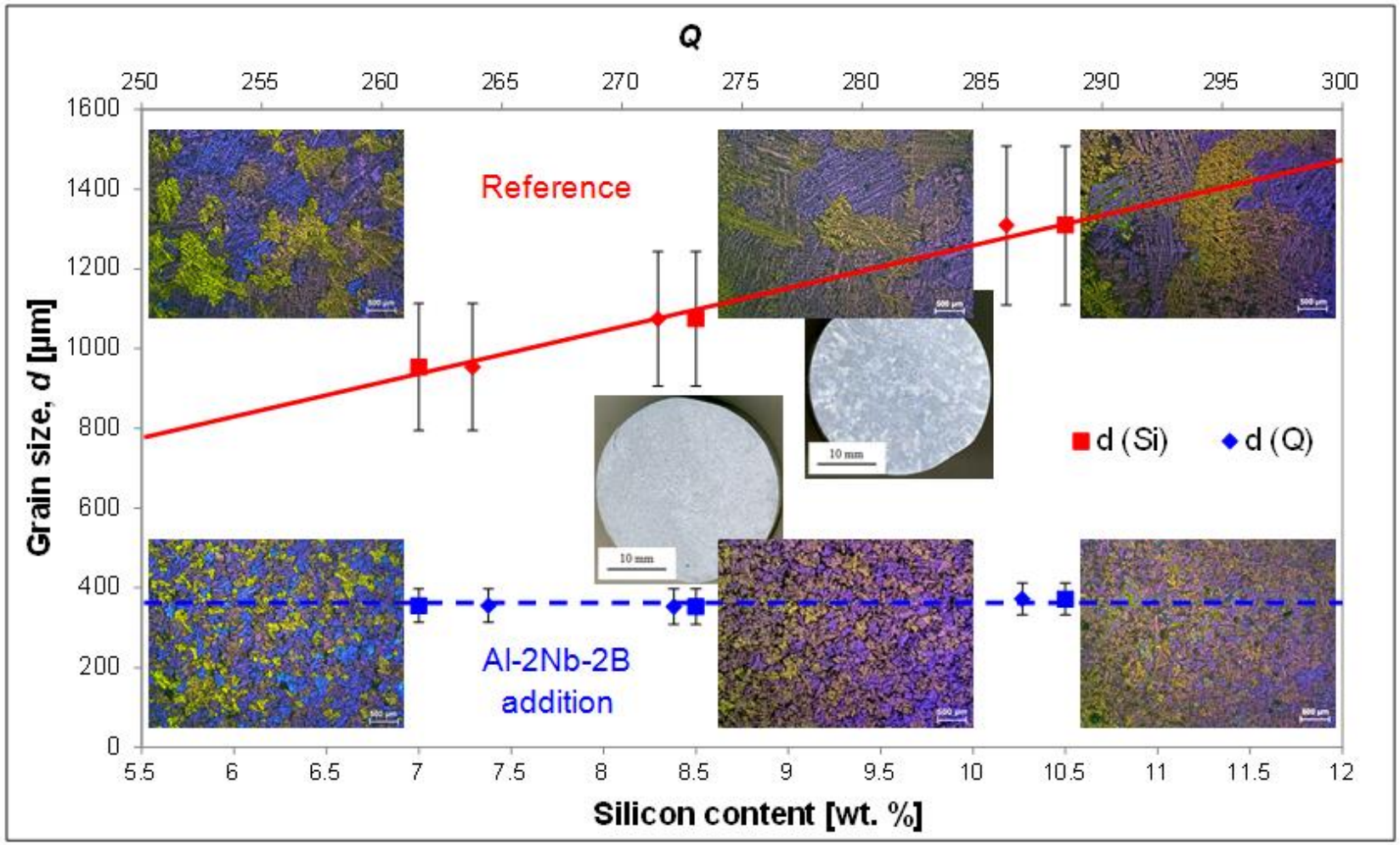






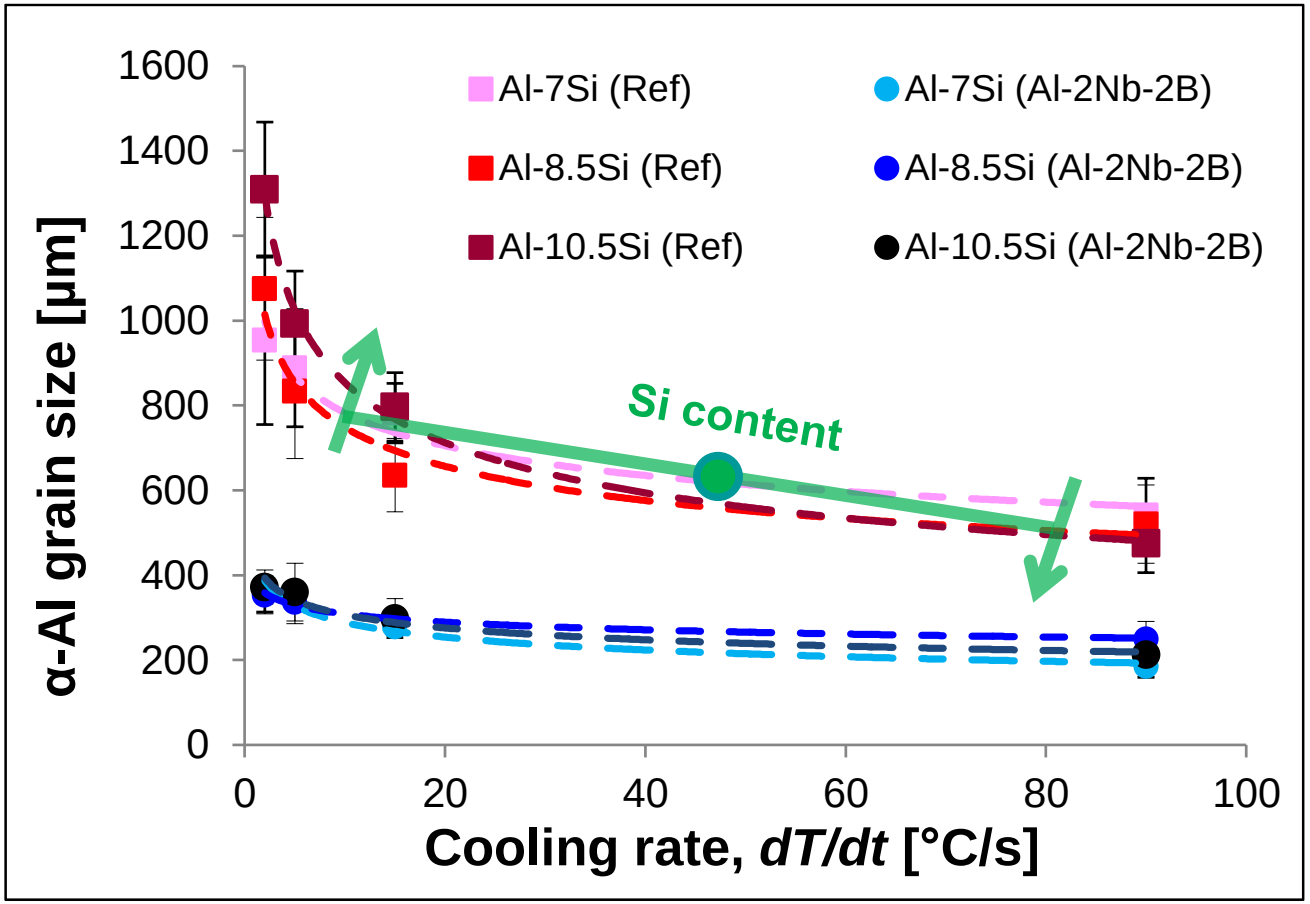


EFFECT OF Al-2Nb-2B ON COMMERCIAL Al-Si ALLOYS

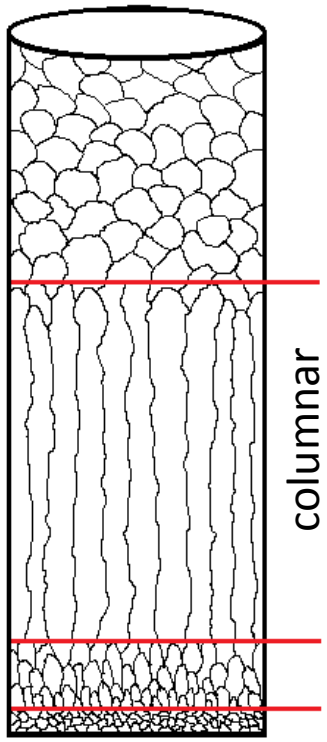


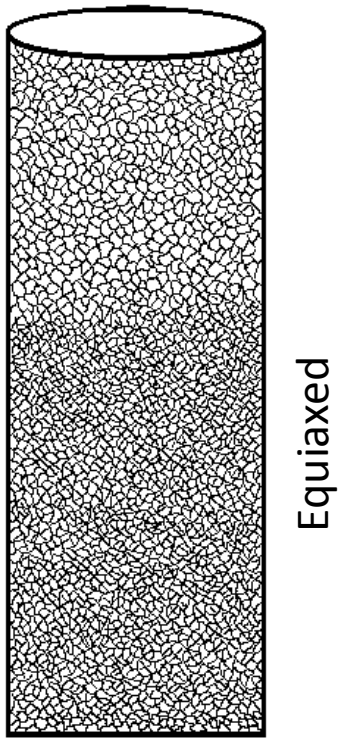
740 °C

EFFECT OF Al-2Nb-2B ON COMMERCIAL Al-Si ALLOYS

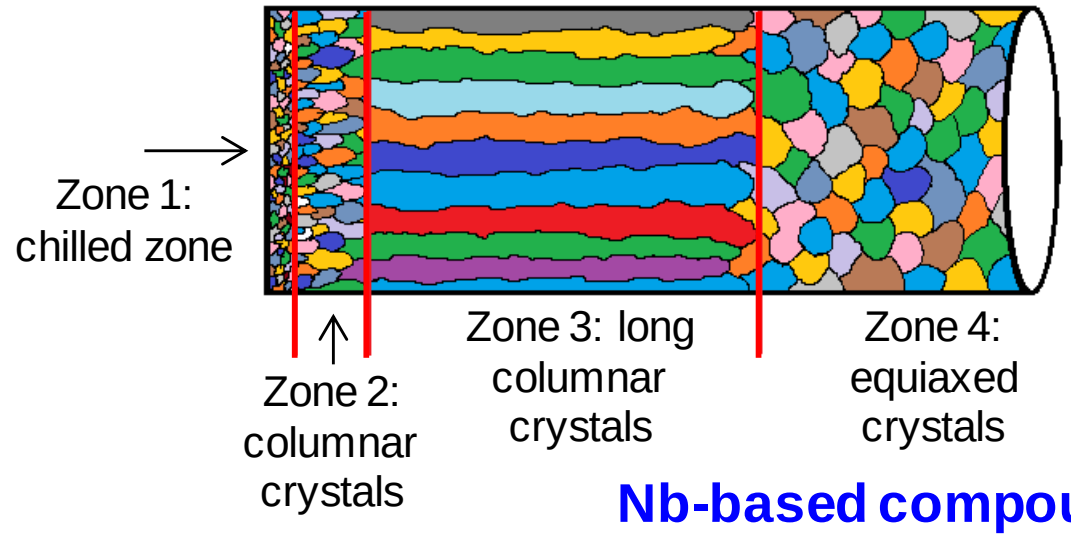


Al-10 Si alloy - Direct Chill Cast Billets





Al-10Si DC billets



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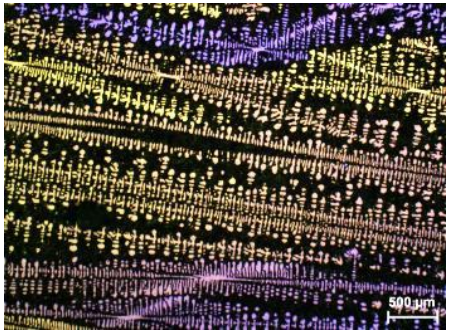
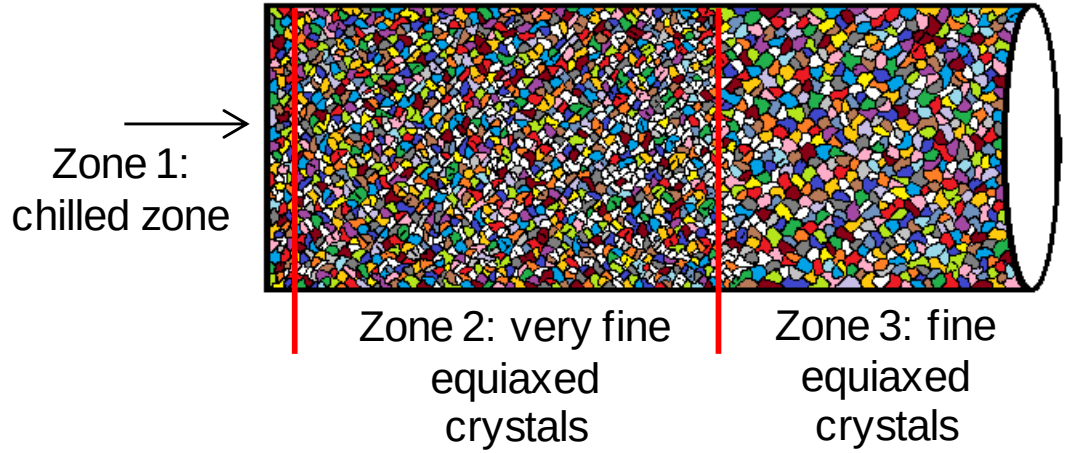
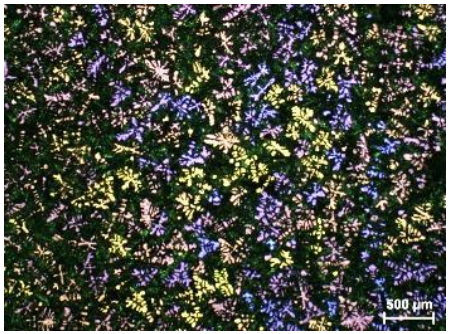
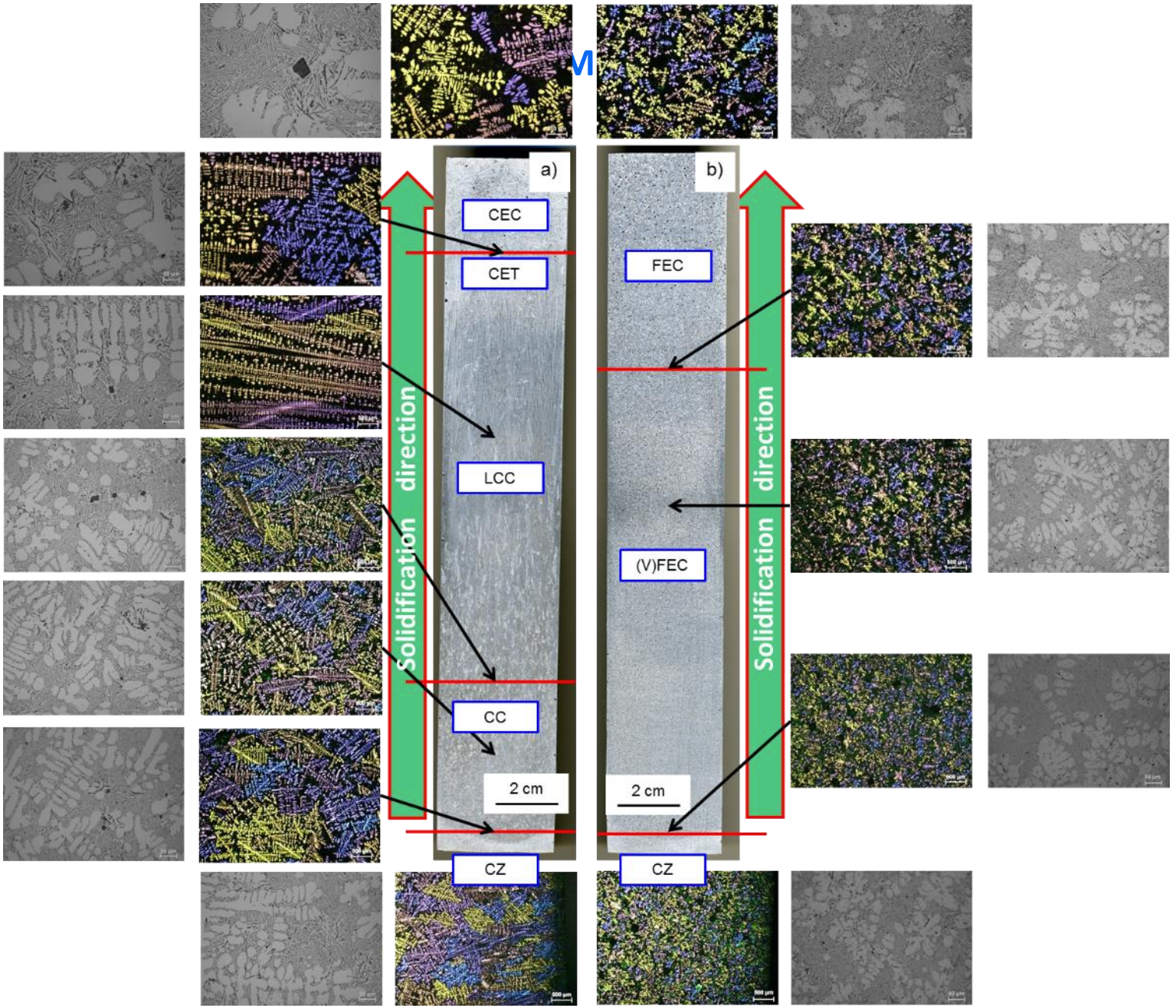


Nb-based compounds as heterogeneous nuclei



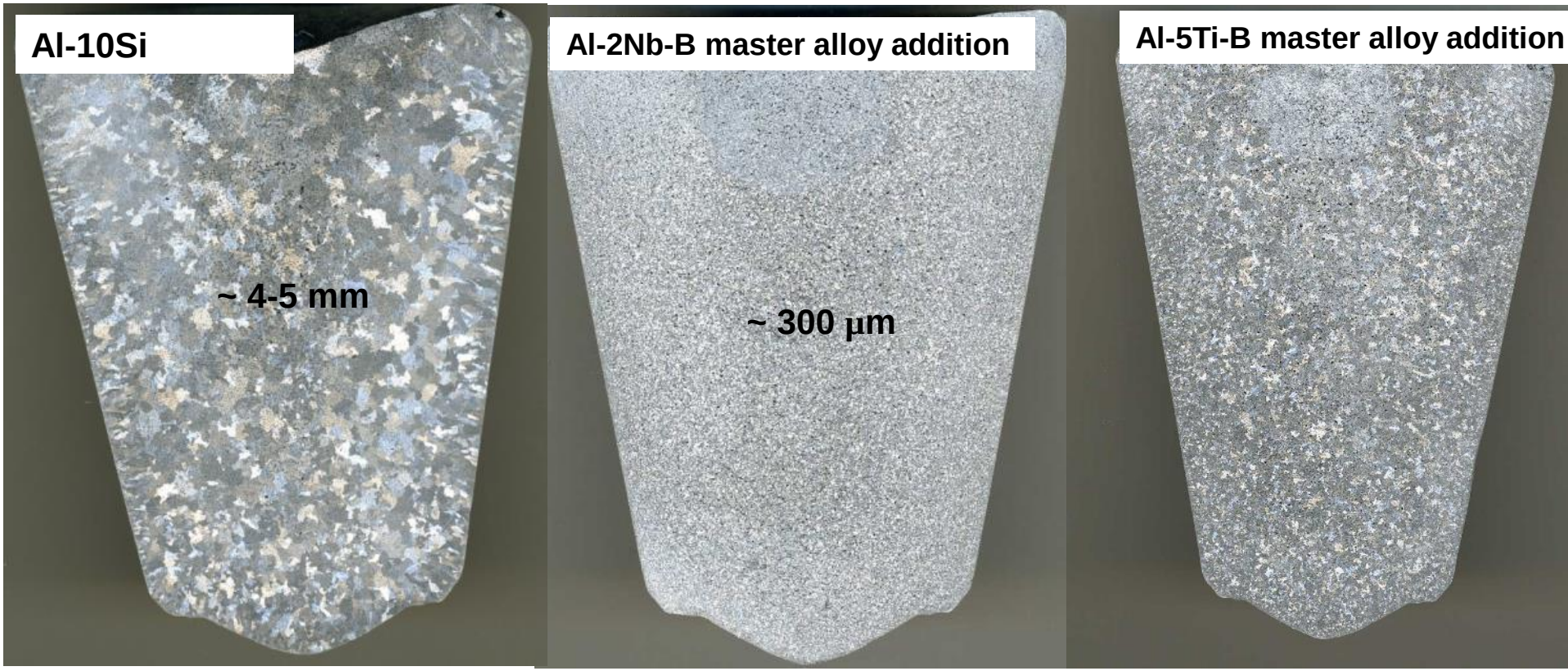
Inoculated




a)
b)
CEC
CET
LCC
CC
CZ
FEC
(V)FEC
CZ
Solidification direction
Solidification direction
2 cm
2 cm

Comparative study between Al-Nb-B and Al-5Ti-B master alloys

Comparison between Ti-B *and* Nb-B



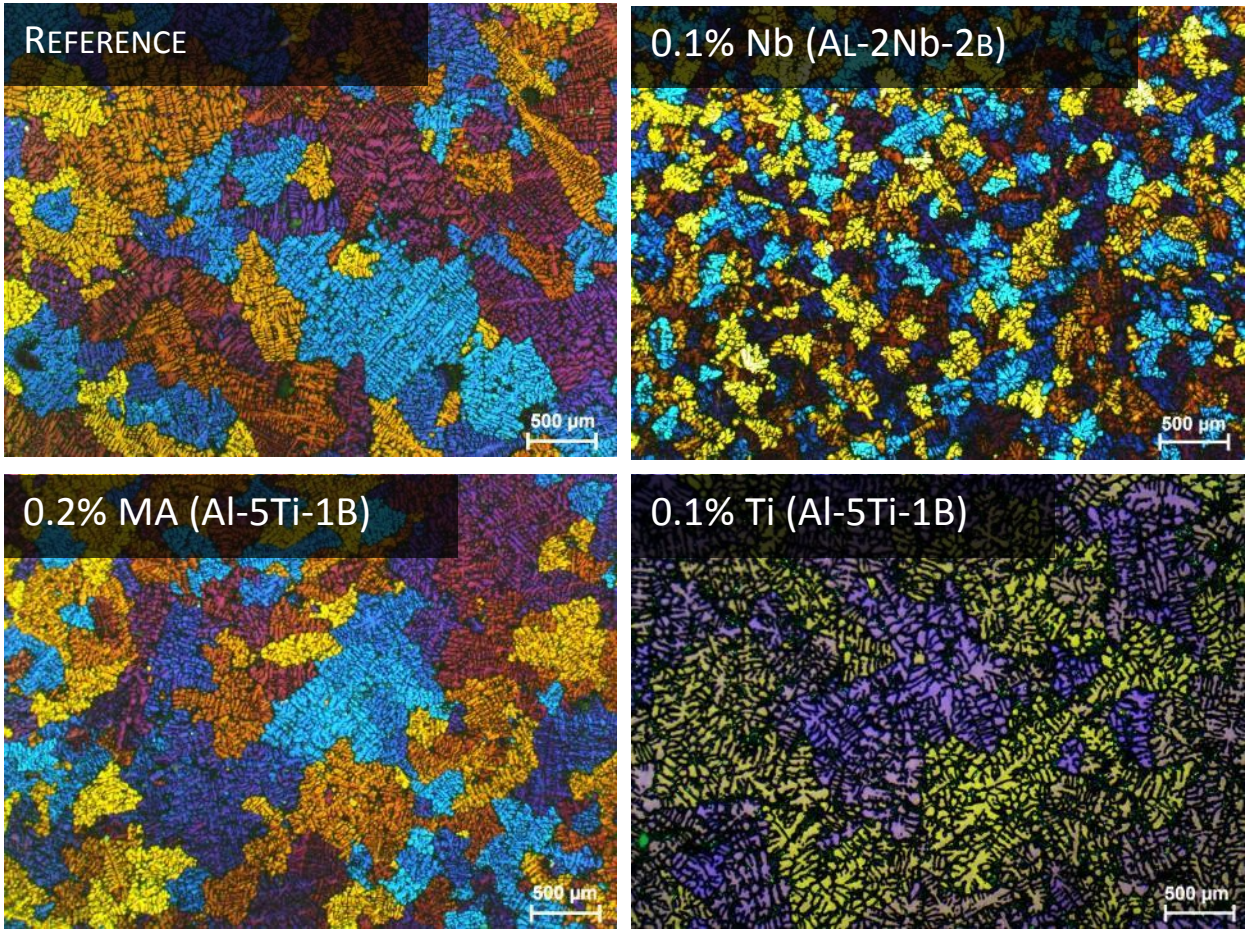
0.1% Nb

0.1%Ti

GRAIN REFINEMENT EFFICIENCY COMPARISON

WHEEL ALLOYS (HYPO-EUTECTIC: 7 wt.% Si)

740°C



Summary

- Nb-B addition to Al-Si melt refines the grain structure of casting

- End-user benefits:
  - Improved strength & ductility
    - ✓ Lighter/thinner structures
  - Homogeneous properties (thick & thin sections)
    - ✓ Complex structures
  - Tolerant to Fe contamination
    - ✓ Closed loop recycling of scrap containing higher Fe
  - Reduced shrinkage porosity - Improved soundness
    - ✓ Component rejection ratio can be minimised