Recent Research Progress in Grain Refinement of Cast Metals

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ARC Centre of Excellence for Design in Light Metals, Australia

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

ARC Centre of Excellence Design in Light Metals

- **Australian Research Council (ARC) Centre of Excellence for Design in Light Metals, established in 2005. $3.0 million fr.om ARC each year**
- **6 participation institutions, Headquarter is based at Monash University.**
- **17 CIs, 9 PIs, over 60 full-time researchers, over 100 postgraduates**
- **Research activities include:**
  - *Alloy design*
  - *Process design*
  - *Hybrid materials*
  - *Surface engineering*
  - *Mg, Al and Ti alloys, including light metal based BMG and composite*

Outline

- The best grain refiners for light alloys and the established theories of grain refinement.
- The edge-to-edge matching crystallographic model and its applications to grain refinement.
- The roles of peritectic reaction and growth restrict factor in grain refinement.
- What is beyond us in understanding the mechanisms of grain refinement?

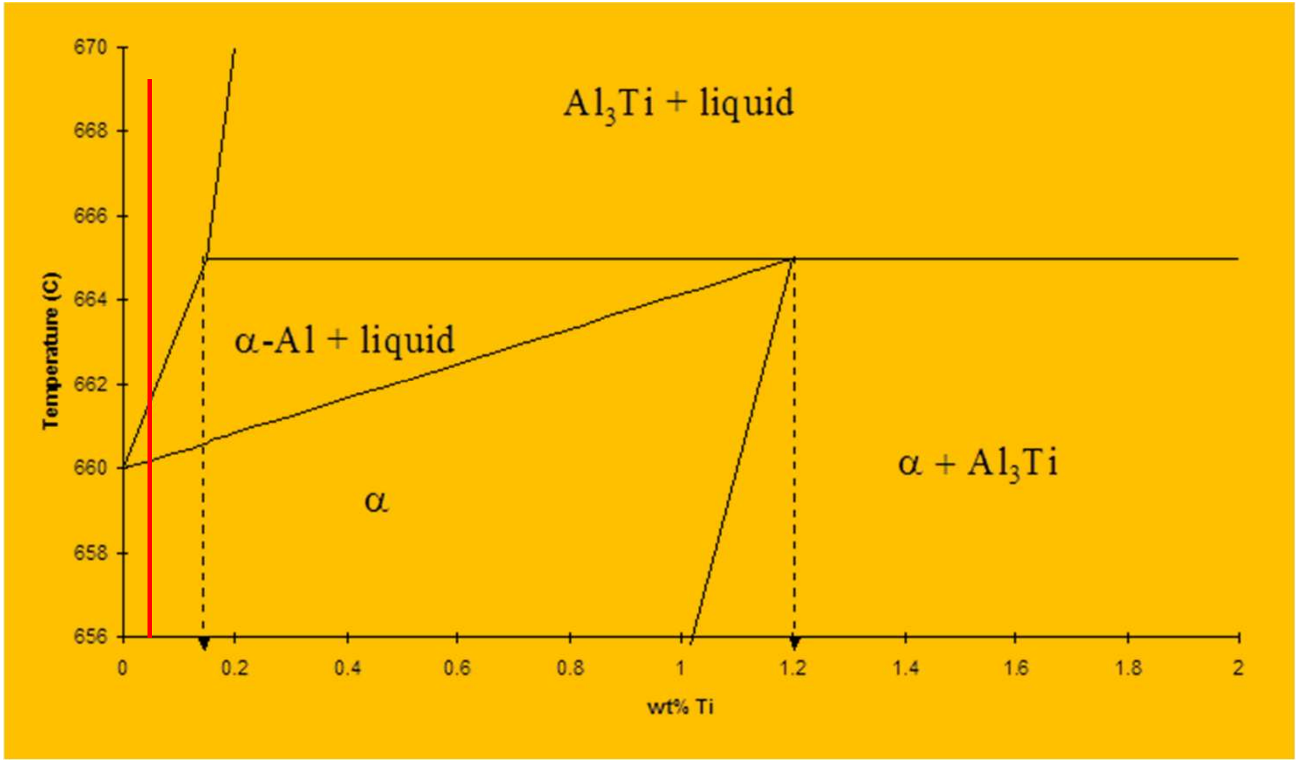
Established Work

The most effective grain refiners

- $Al_3Ti/TiB_2/TiC$ for Al alloys
  - Al_3Ti is the most effective one
  - Peritectic reaction
  - Large growth restrict factor – Q value
- Zr for Al/Mn/Si-free Mg alloys
  - Peritectic reaction
  - Large growth restrict factor – Q value

Major accepted theories/model

- **Peritectic reaction**



Addition of boron has little effect on the Al-Ti phase diagram

Actual grain refinement start at 0.05wt%Ti addition, which is far below the maximum solid solubility, Thus, it is considered there is no peritectic reaction and this hypothesis is discarded

Major accepted theories/model

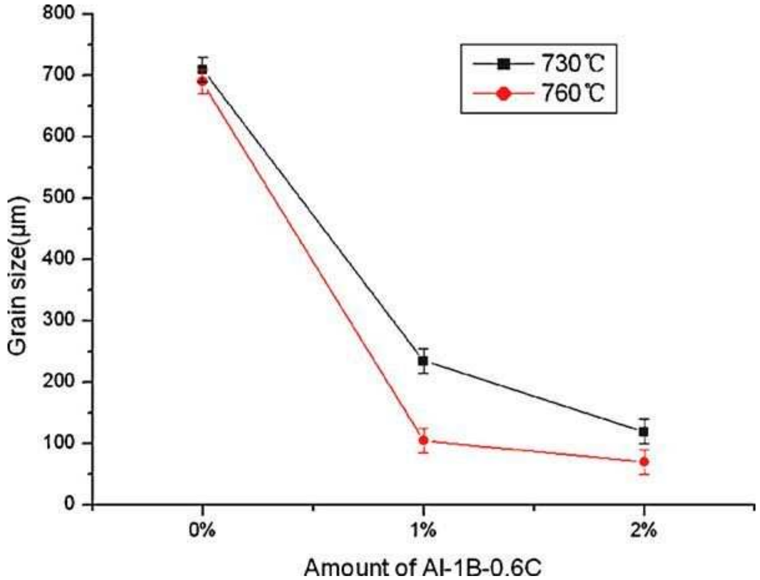
- **Duplex nucleation theory**
  - Formation of Al_3Ti shell on TiB_2 (Vader et al and Bäckerud et al)
  - Ti segregates to TiB_2 (Mohanty et al, Schumacher and Greer)
- **Solute theory – growth restrict factor**
  - Johnsson, and then StJohn and Easton
  - $Q = mc_0(k\text{-}1)$ (c_0: concentration; m: gradient of the liquidus; and $k = c_s/c_l$)
  - The higher the Q value, the smaller grains

Major accepted theories/model

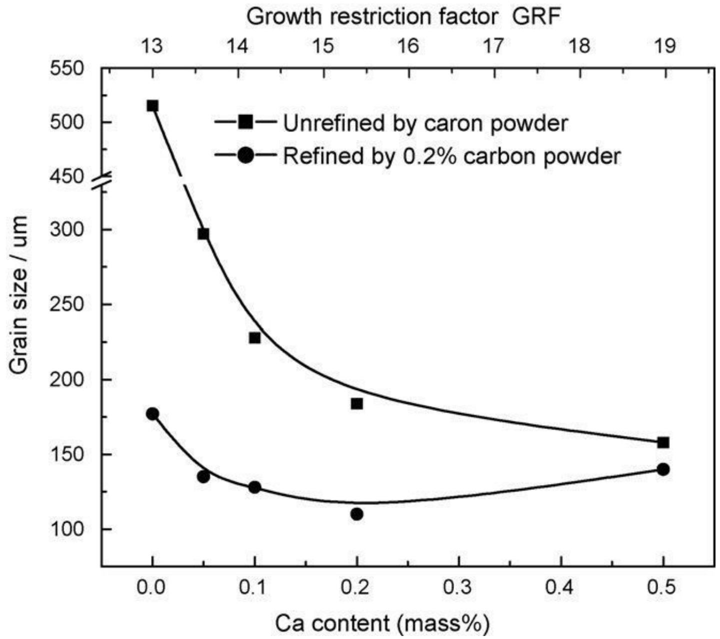
- **Classic heterogeneous nucleation**
  - **Development of more effective grain refiners and the associated master alloys**
- **The edge-to-edge matching model**
  - **To minimize the interfacial energy between the nucleants (the heterogeneous nucleation sites) and the solidified primary solids.**

New grain refiners for cast Mg alloys

- **The carbon group – Al_4C_3 or Al_2CO**
  – **Kurfamn, Yano et al, Tamura et al, Lim's team, X Liu and J Du**



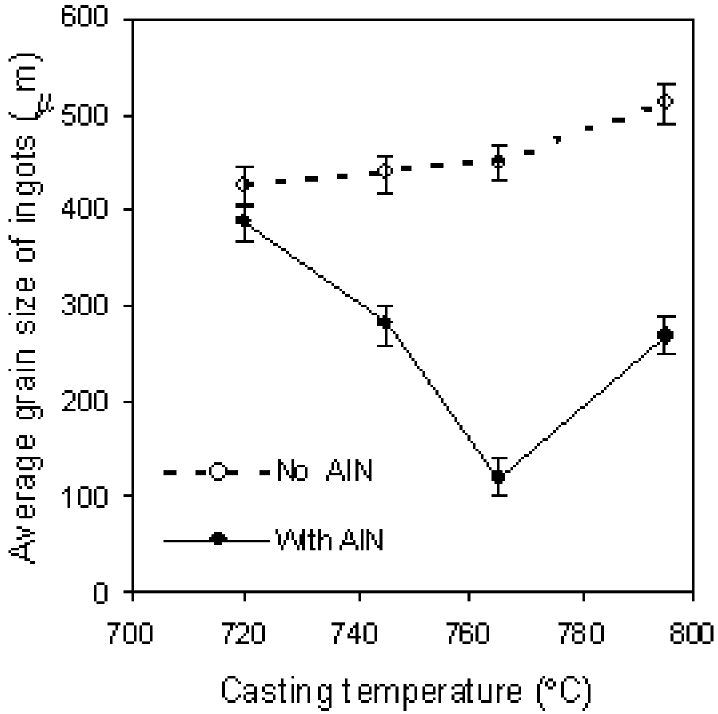
G Ma et al: J. Alloys Compd. 491 (2010) 165

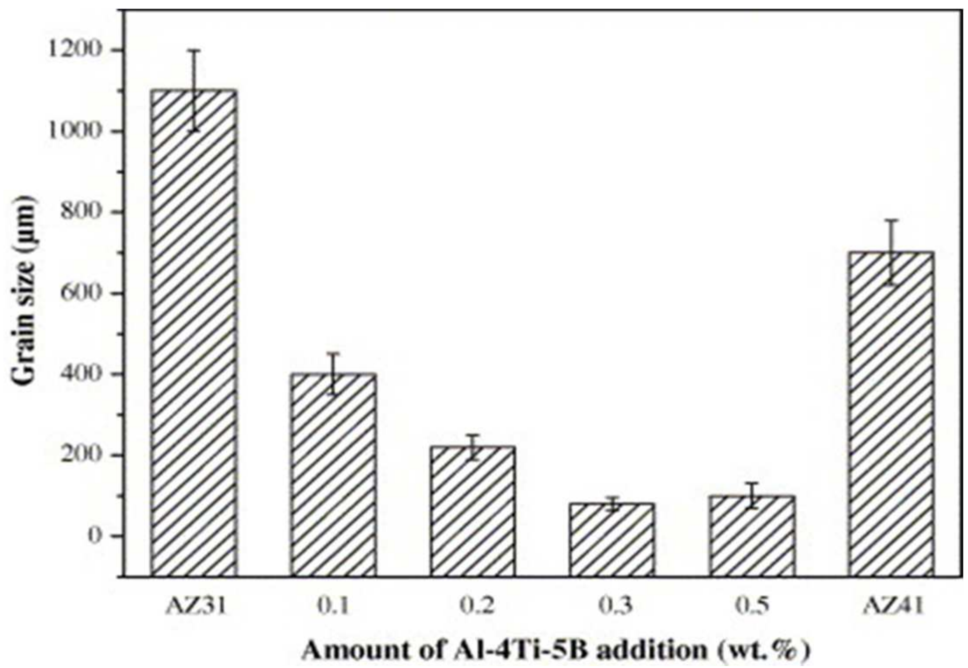


J Du et al: J. Alloys Compd. 470 (2009) 134

New grain refiners for cast Mg alloys

- Others – AlN, TiB_2, SiC, ZnO, Al_2Gd and RE



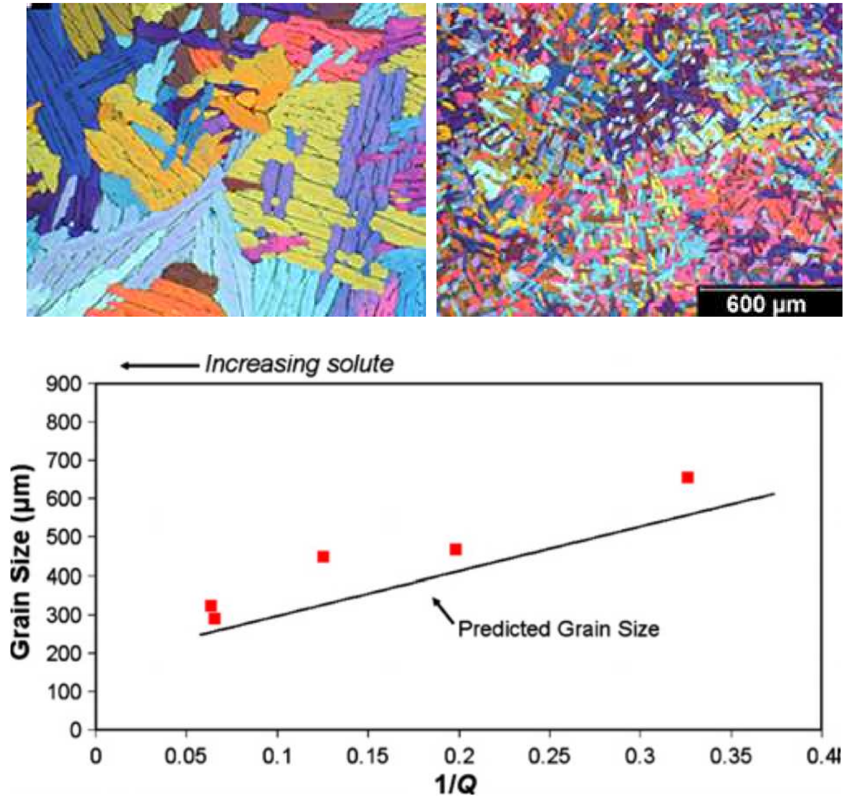


H Fu et al: J. Alloys Compd. 478 (2009) 809

Y Wang et al: Scripta Mater. 54 (2006) 269

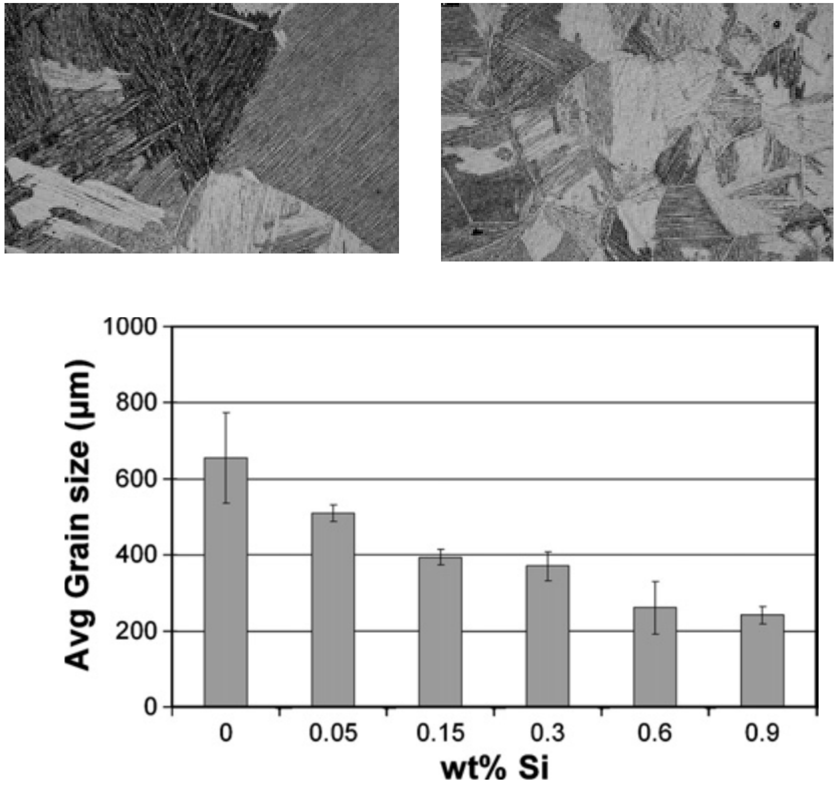
New grain refiners for cast Ti alloys

- **TiB**



M Bermingham et al: Scripta Mater. 59 (2008) 538

- **Si**



M Bermingham et al: Scripta Mater. 58 (2008) 1050

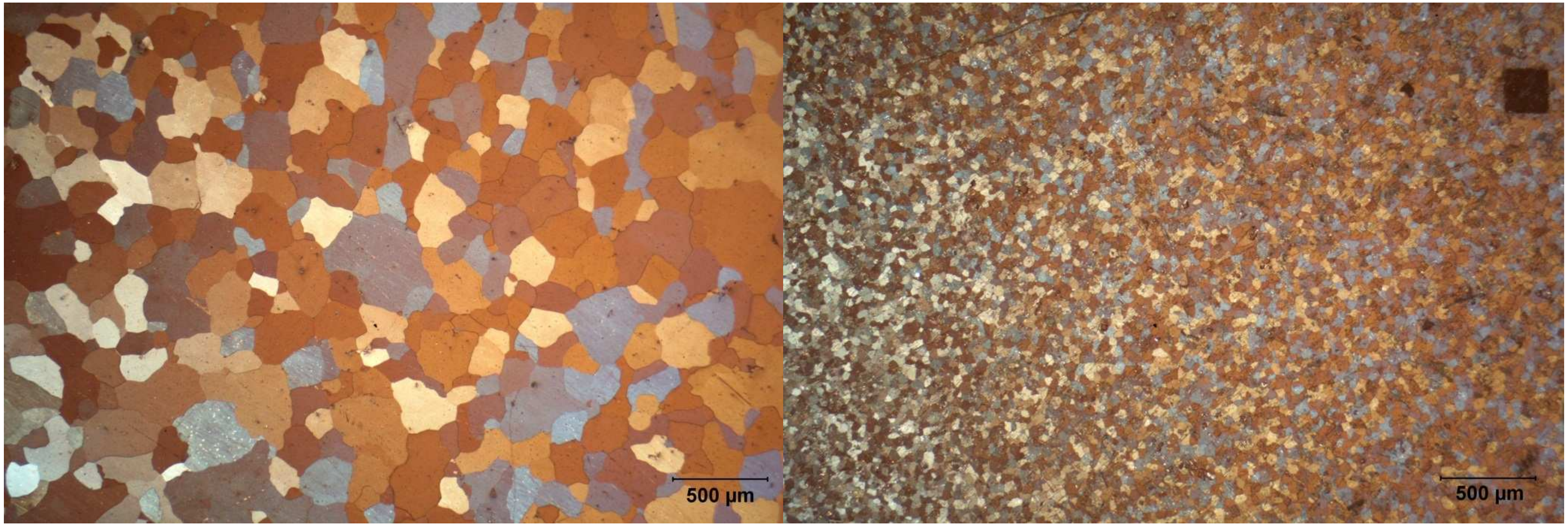
Efficiency

- None of them is as efficient and good as Al_3Ti and TiB_2 in Al alloys and as Zr in Mg alloys.
- Why?

The Edge-to-edge Matching (E2EM) Model and Its Applications

The most successful case

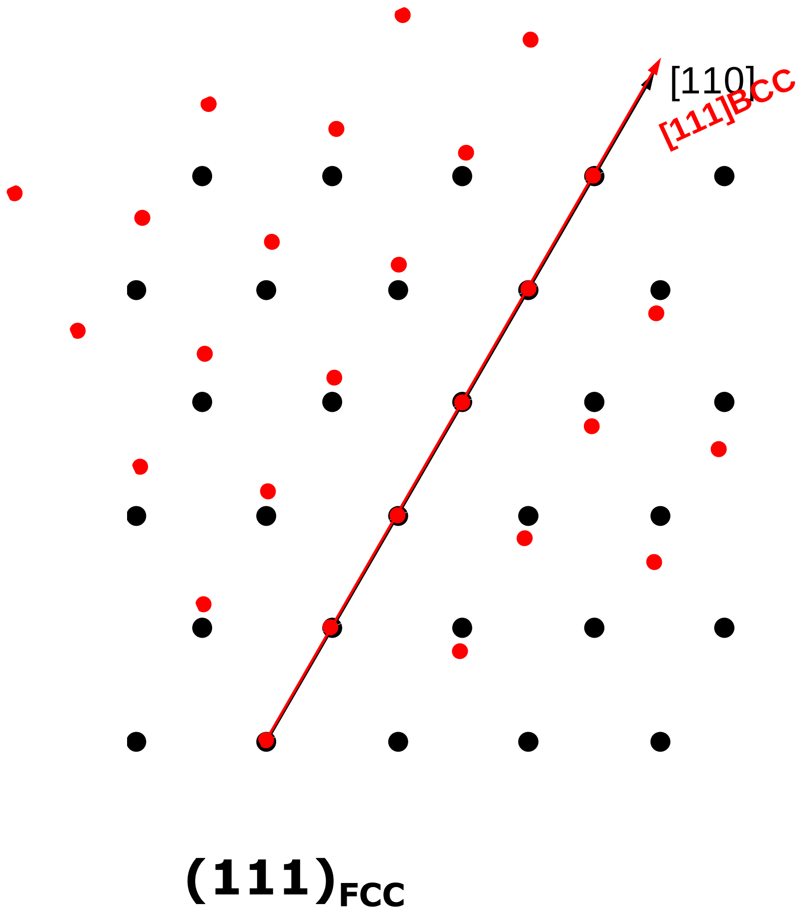
In the past years, the most successful grain refiner is the Al_2Y in Mg alloys developed by the E2EM model.

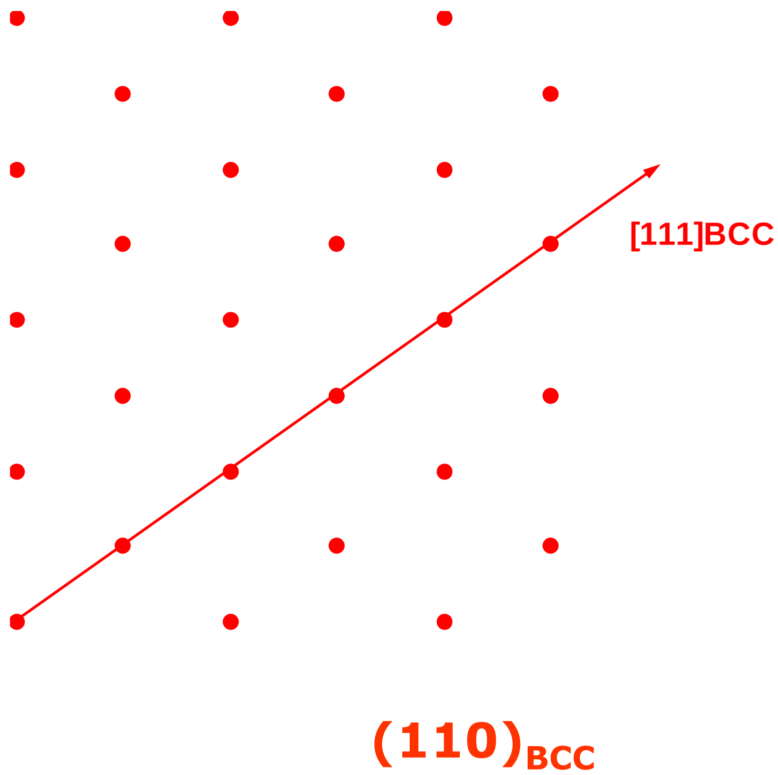


Without addition **With addition**

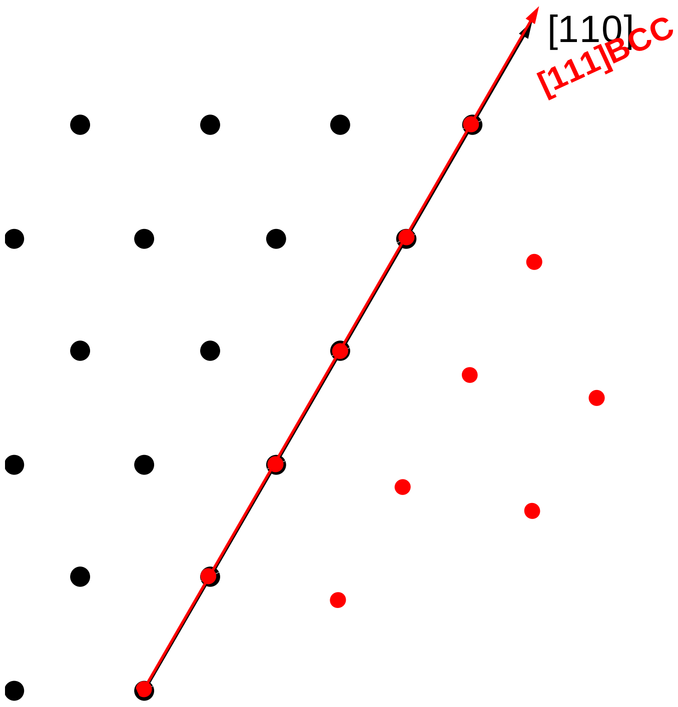
Edge-to-edge matching model

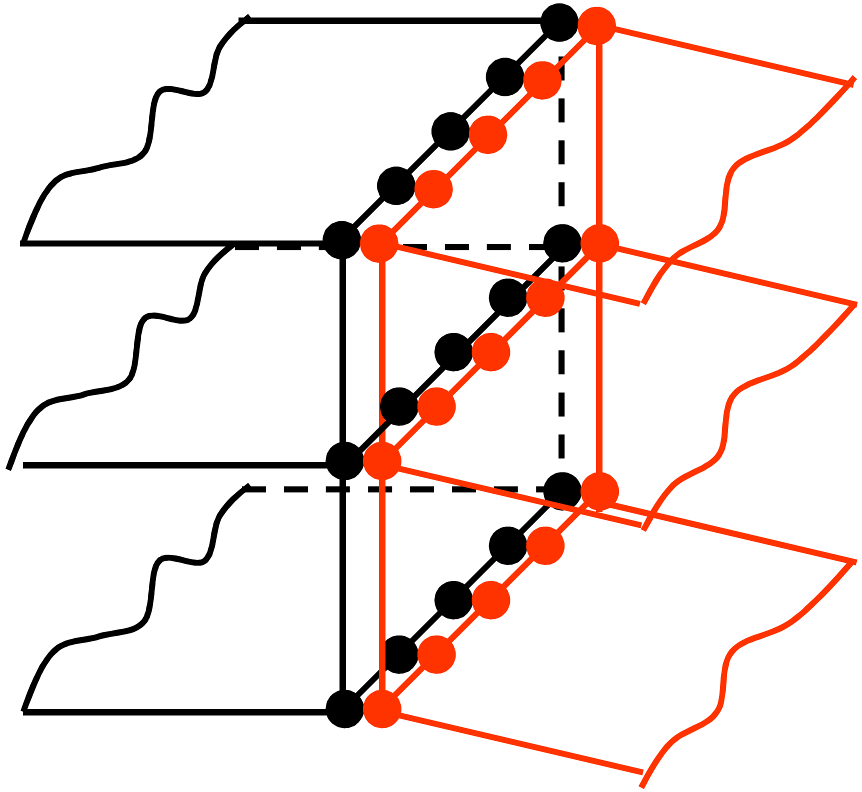
Plane-on-plane matching





Edge-to-edge matching model





$(111)_{FCC}$ $(110)_{BCC}$

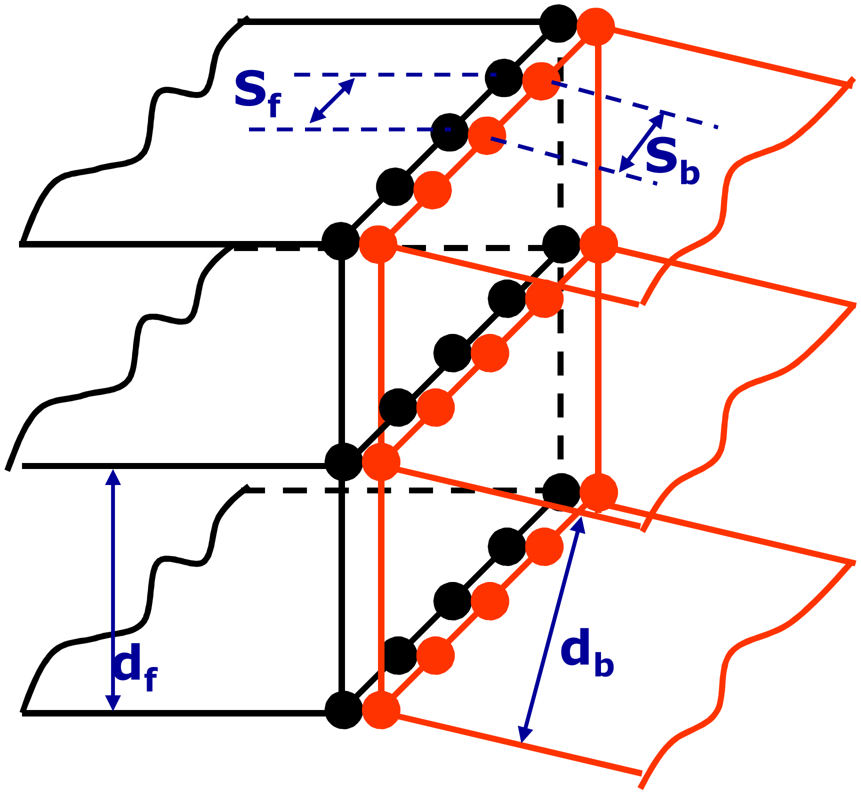
Edge-to-edge matching model

Interatomic spacing misfit =

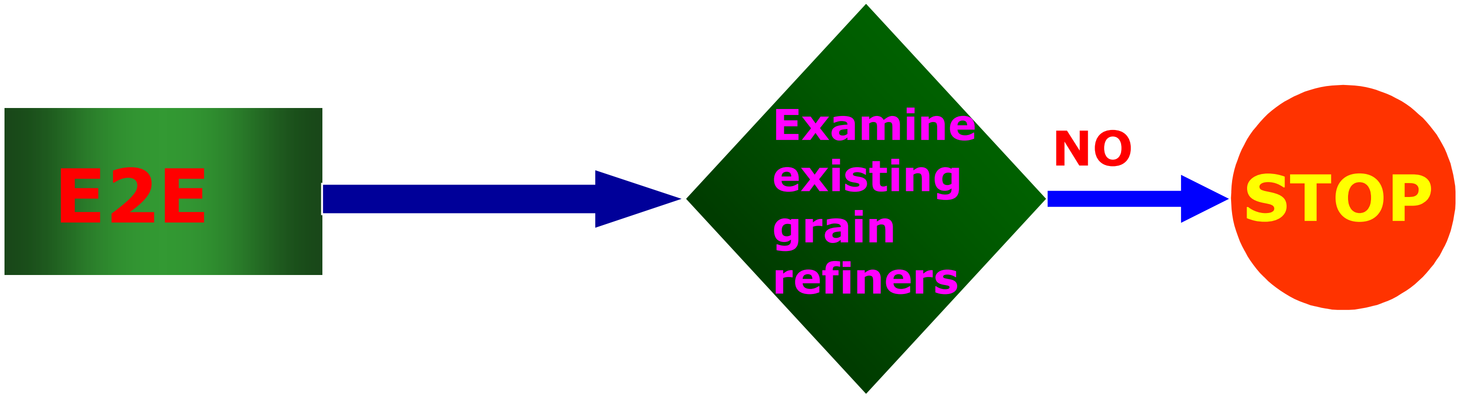
$$f_i = \frac{S_f - S_b}{S_f} \times 100\% < 10\%$$

Interplanar (d-value) mismatch =

$$f_d = \frac{d_f - d_b}{d_f} \times 100\% < 10\%$$



Application of the E2EM to grain refinement



Application of the E2EM to grain refinement

- **M-X. Zhang, P. M. Kelly, M. A. Easton and J. A. Taylor, Acta Mater. 2005, 53, 1427.**
- **M-X. Zhang, P. M. Kelly, M. Qian and J. A. Taylor, Acta Mater., 2005, 53, 3261.**
- **D. Qiu, J.A. Taylor, M.-X. Zhang and P.M. Kelly, Acta Mater., 2007, 55, 1447.**
- **D. Qiu, M.-X. Zhang, J.A. Taylor, H.-M. Fu and P.M. Kelly, Acta Mater., 2007, 55, 1863.**
- **D. Qiu, M.-X. Zhang, H.-M. Fu , J.A. Taylor and P.M. Kelly, Phil. Mag. Letters, 2007, 87, 505.**

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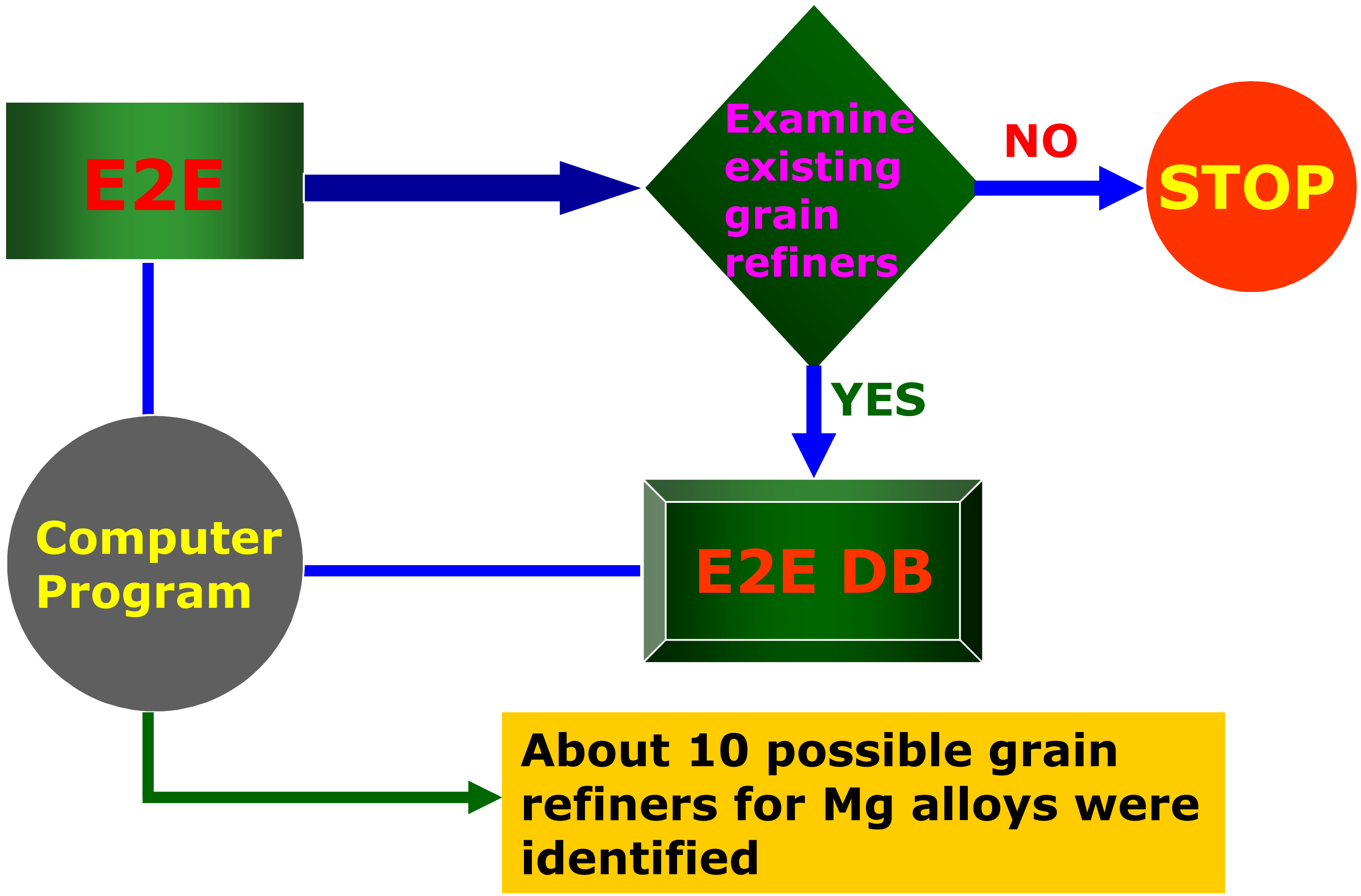
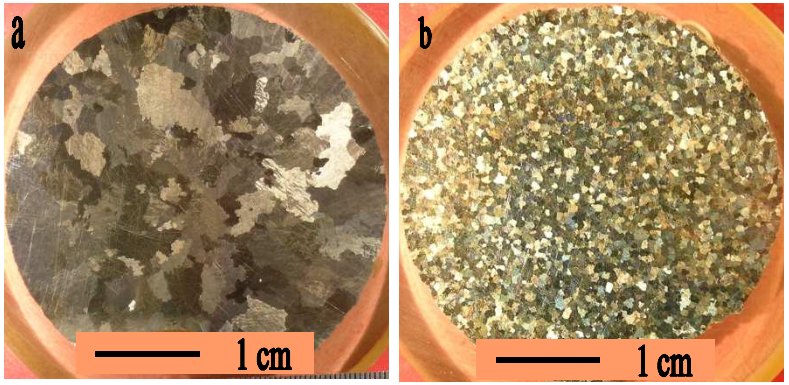
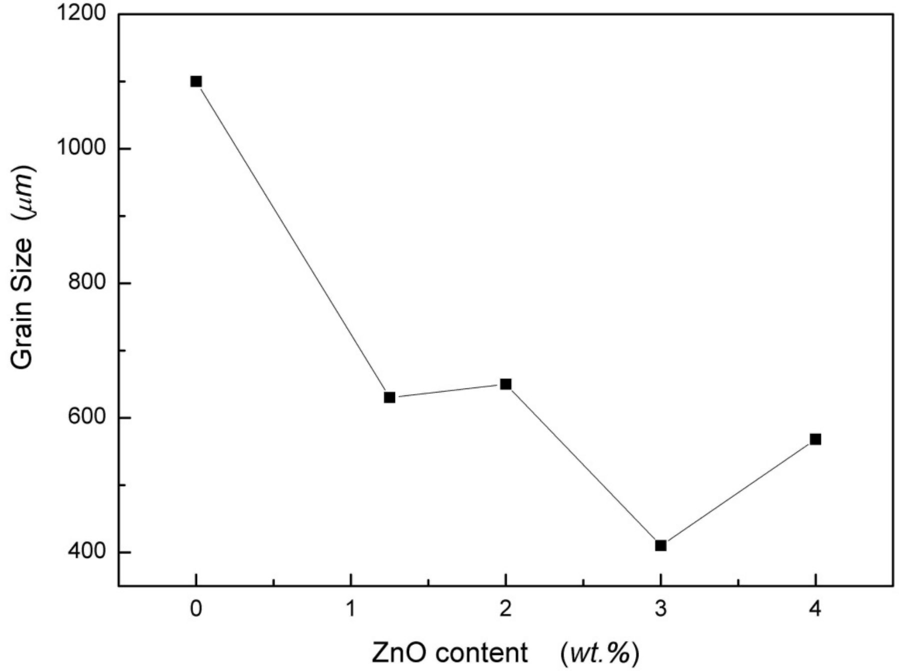


Application of the E2EM to grain refinement

- **Reduce the number to 4.**
  - ZnO (new), AlN, Al_2Y (new) and Al_2Ca (new)
- **All have good edge-to-edge matching**

Effect of ZnO

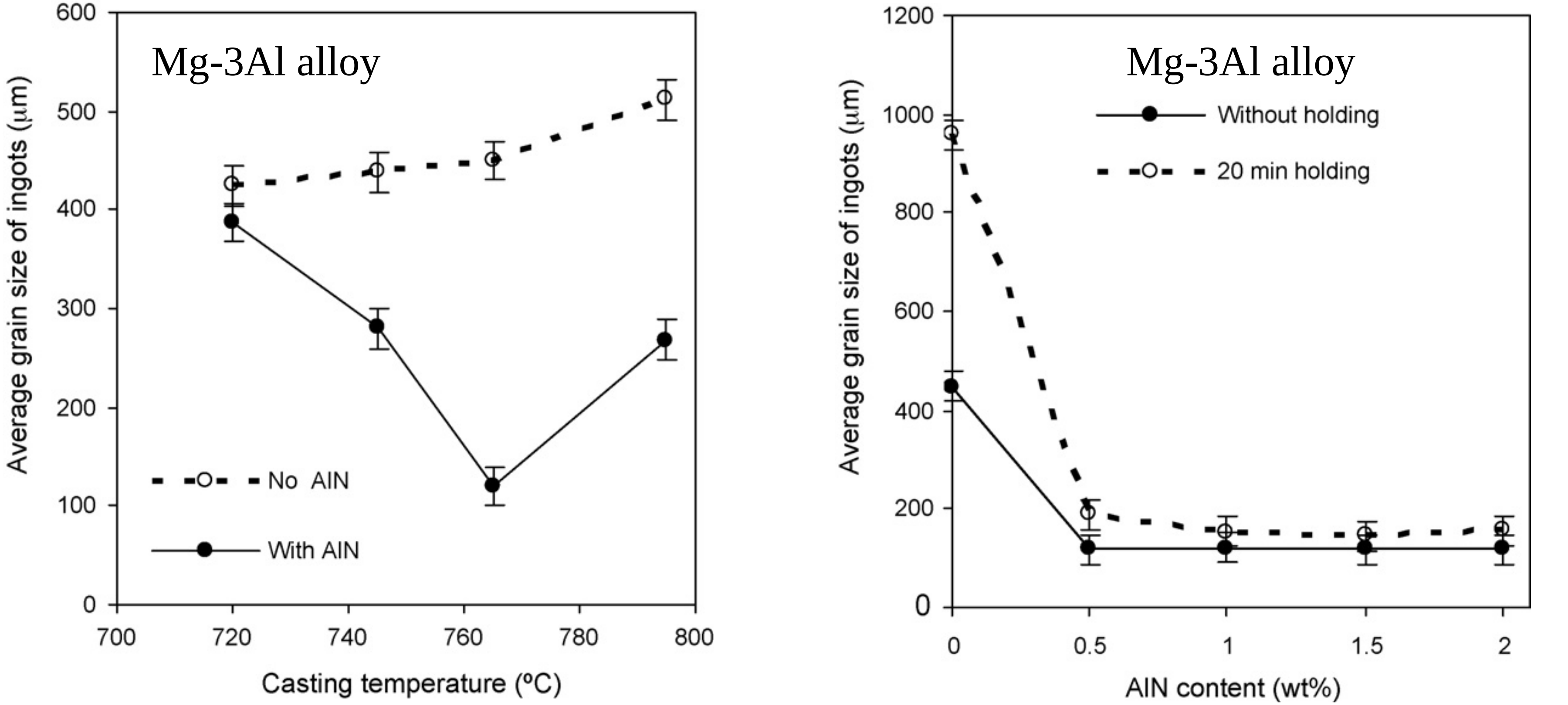




For pure Mg

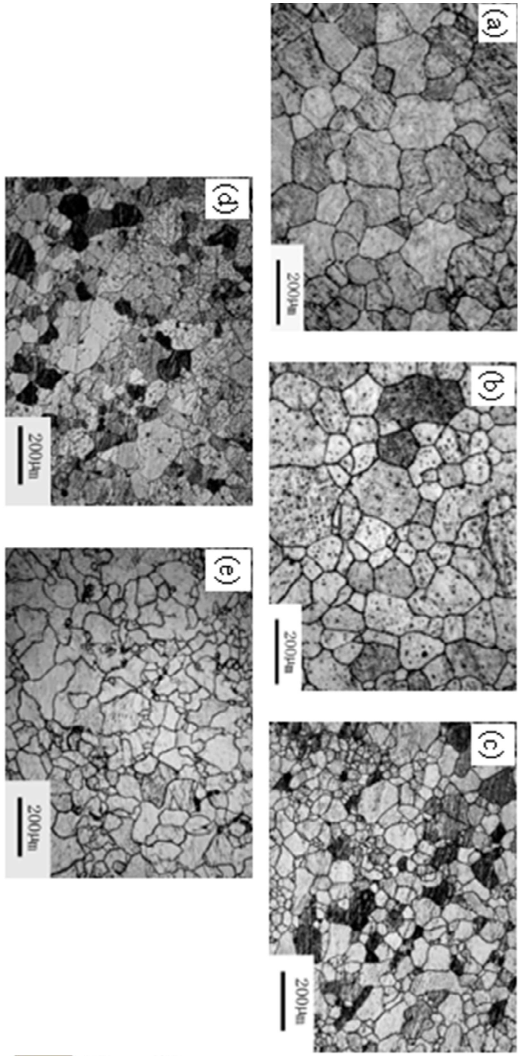
H Fu et al: J Alloys Compd. 456 (2008) 390

Effect of AlN

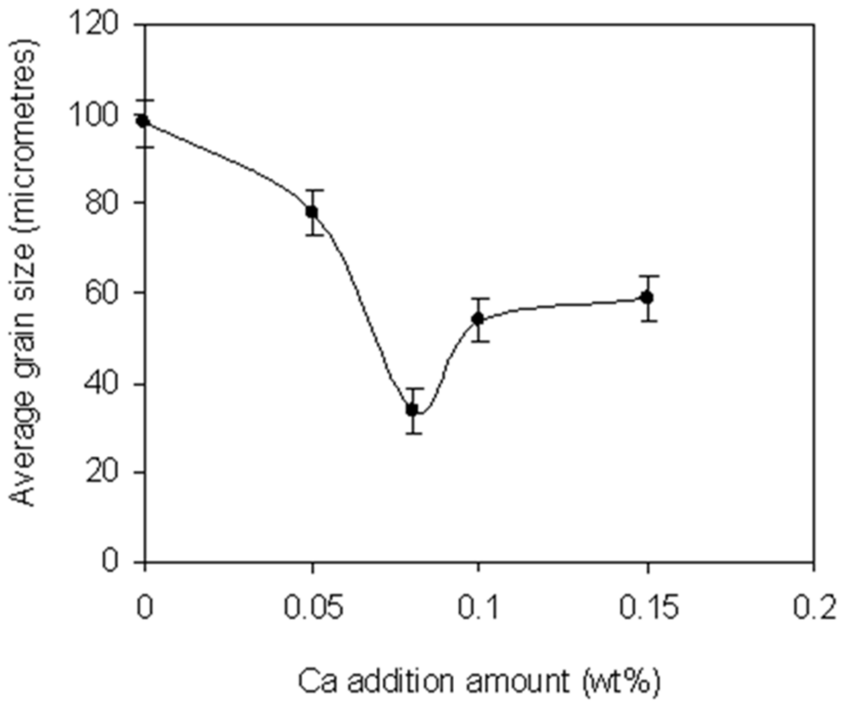


H Fu et al: J Alloys Compd. 478 (2009) 809

Effect of Al_2Ca

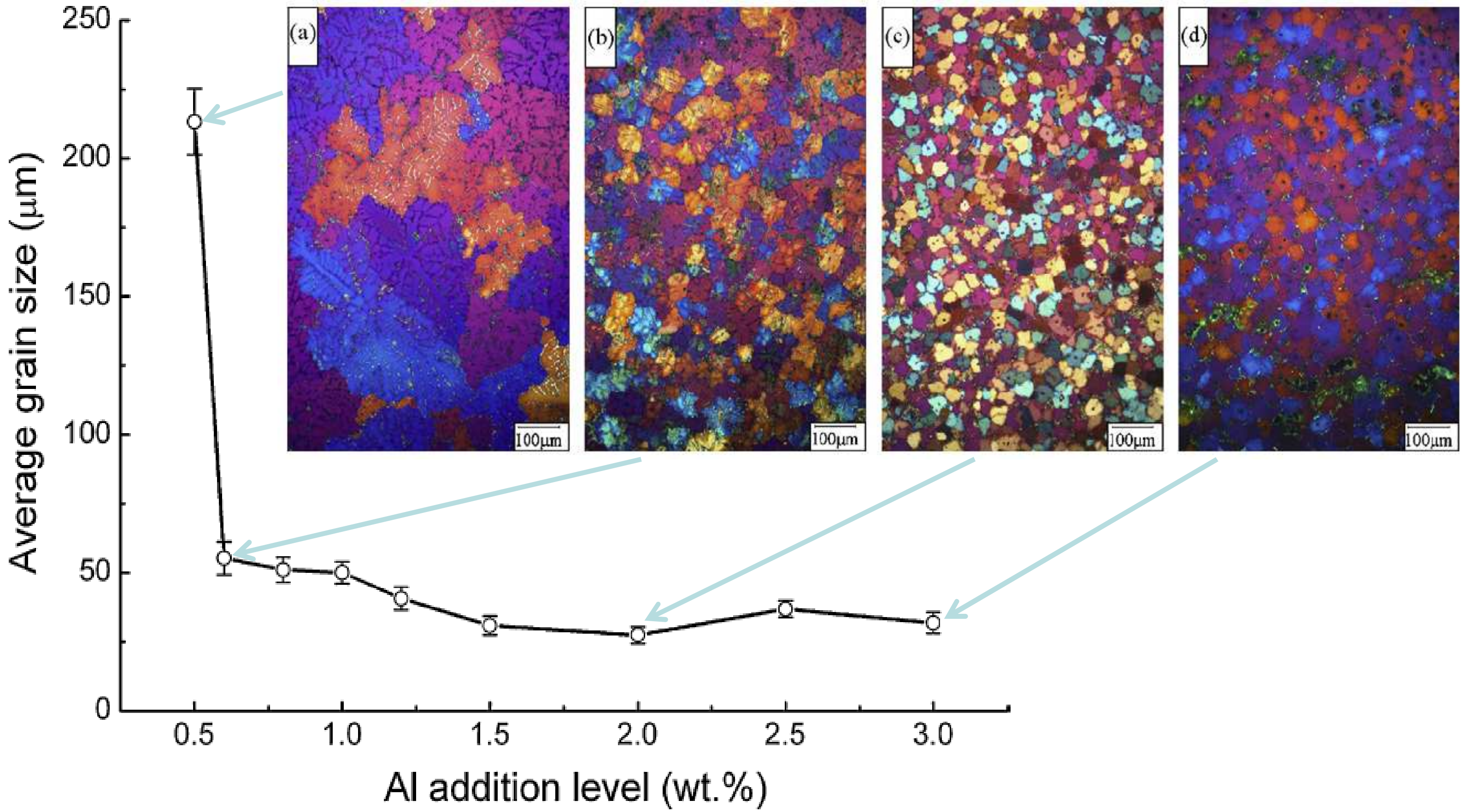


AZ31 – twin rolled casting



B Jiang et al: Mater Chem. Phys. 133 (2012) 611

The most successful case – Al_2Y



The most successful case – Al_2Y

- D. Qiu, M-X. Zhang, Metall Mater Trans A. 2012, accepted.
- D. Qiu, M-X. Zhang, Metall Mater Trans A., 2010, 41A, 3412.
- D. Qiu, M-X. Zhang, J Alloy Compd., 2009, 488, 260.
- D. Qiu, M.-X. Zhang, Scripta Mater., 2009, 61, 312.
- D. Qiu, M.-X. Zhang, Acta Mater., 2009, 57, 3052.

Application of the E2EM to grain refinement

- **ZnO, AlN and Al_2Ca are not as good as Al_2Y.**
- **All have good matching**
- **Only difference is that Al_2Y involves peritectic reaction:**

$$Al_2Y + L \rightarrow \alpha\text{-}Mg$$

- **Peritectic may play a role**

The roles of peritectic reaction and growth restrict factor in grain refinement

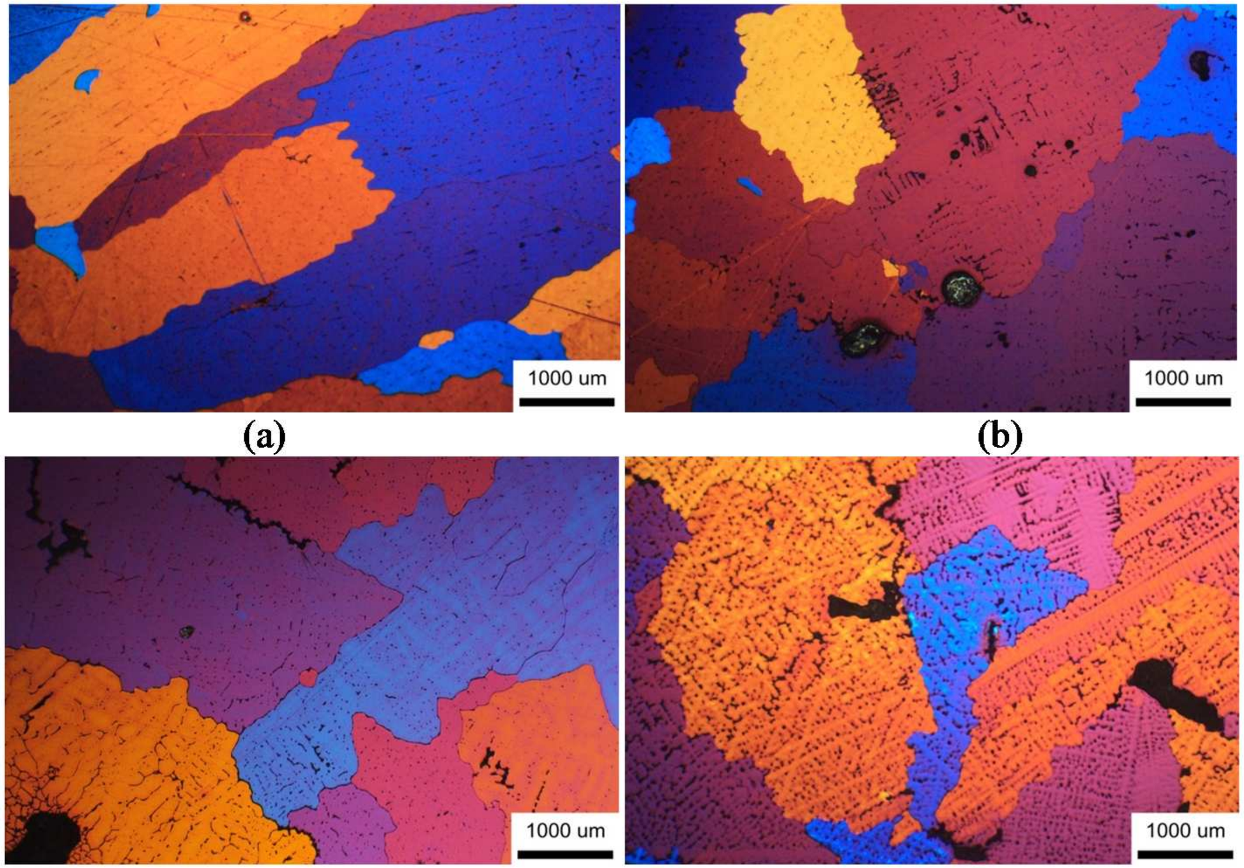
The role of peritectic reaction in grain refinement in cast Al

<table>
<tr><th></th><th colspan="2">Group 1
(approx. Q=12 k)</th><th colspan="2">Group 2
(approx. Q=5 k)</th><th colspan="2">Group 3
(approx. Q=2 k)</th><th colspan="2">Group 4
(approx. Q=1 k)</th></tr>
<tr><th>Solute</th><th>Nominal Addition Level</th><th>Growth Restriction Factor</th><th>Nominal Addition Level</th><th>Growth Restriction Factor</th><th>Nominal Addition Level</th><th>Growth Restriction Factor</th><th>Nominal Addition Level</th><th>Growth Restriction Factor</th></tr>
<tr><td>Ti</td><td>0.05</td><td>11.2</td><td>0.02</td><td>4.5</td><td>0.01</td><td>2.3</td><td>0.005</td><td>1.1</td></tr>
<tr><td rowspan="4">V</td><td rowspan="4">--</td><td rowspan="4">--</td><td>0.15</td><td>4.5</td><td rowspan="4">0.07</td><td rowspan="4">2.1</td><td rowspan="4">0.04</td><td rowspan="4">1.0</td></tr>
<tr><td>0.40</td><td>5.1</td></tr>
<tr><td>0.60</td><td>5.1</td></tr>
<tr><td>1.00</td><td>5.1</td></tr>
<tr><td rowspan="3">Nb</td><td rowspan="3">--</td><td rowspan="3">--</td><td rowspan="3">--</td><td rowspan="3">--</td><td rowspan="3">--</td><td rowspan="3">--</td><td>0.12</td><td>0.8</td></tr>
<tr><td>0.20</td><td>1.0</td></tr>
<tr><td>0.50</td><td>1.0</td></tr>
<tr><td rowspan="4">Zr</td><td rowspan="4">--</td><td rowspan="4">--</td><td rowspan="4">--</td><td rowspan="4">--</td><td rowspan="4">--</td><td rowspan="4">--</td><td>0.10</td><td>0.7</td></tr>
<tr><td>0.20</td><td>0.7</td></tr>
<tr><td>0.30</td><td>0.7</td></tr>
<tr><td>0.50</td><td>0.7</td></tr>
<tr><td>Cu</td><td>4.50</td><td>12.7</td><td>1.60</td><td>4.5</td><td>--</td><td>--</td><td>0.40</td><td>1.1</td></tr>
<tr><td>Mg</td><td>4.00</td><td>12.2</td><td>1.50</td><td>4.6</td><td>--</td><td>--</td><td>0.35</td><td>1.1</td></tr>
<tr><td>Si</td><td>--</td><td>--</td><td>0.80</td><td>4.7</td><td>0.35</td><td>2.1</td><td>0.20</td><td>1.2</td></tr>
</table>

The role of peritectic reaction in grain refinement in cast Al

Pure Al

Addition of 0.35wt%Mg



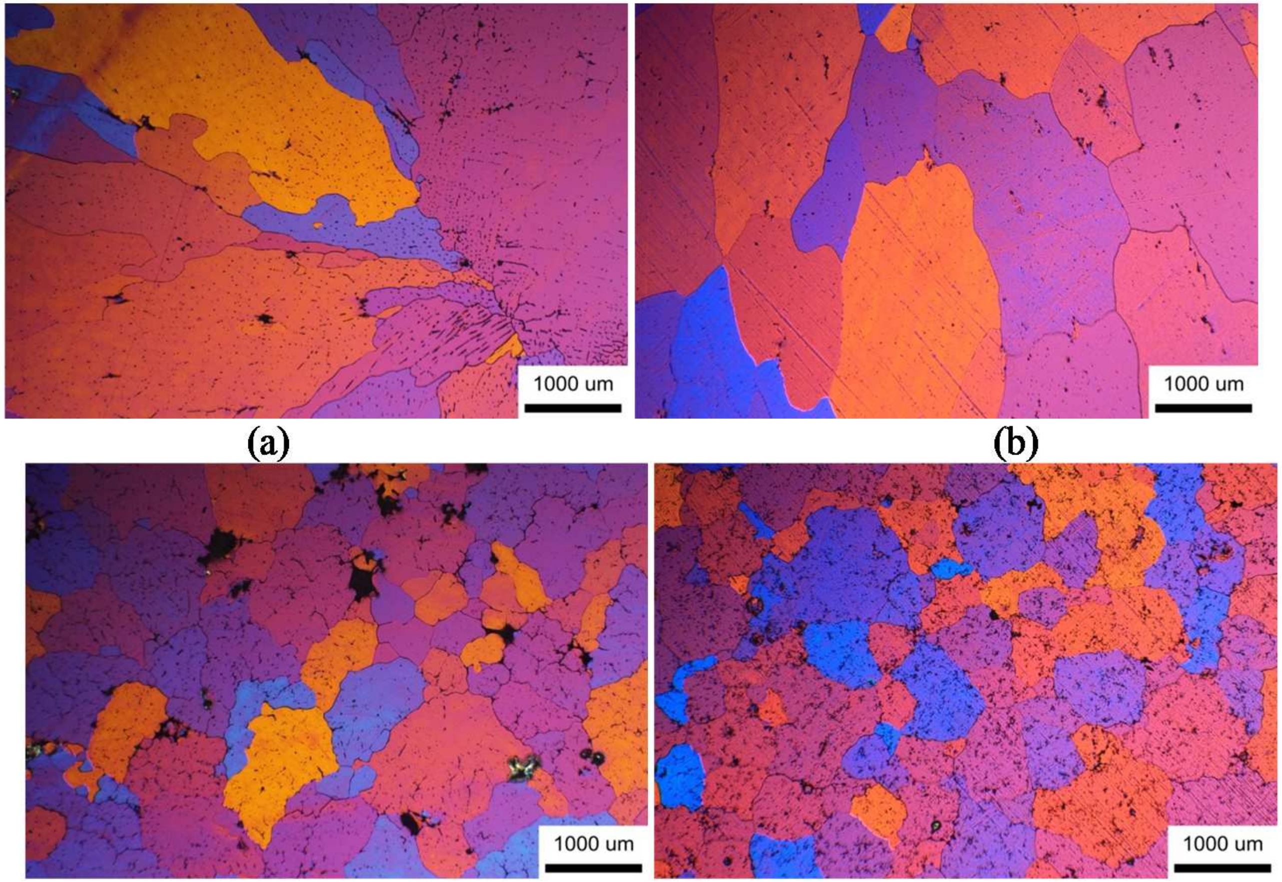
Addition of 1.5wt%Mg

Addition of 4.0wt%Mg

The role of peritectic reaction in grain refinement in cast Al

Pure Al

Addition of 0.1wt%Zr



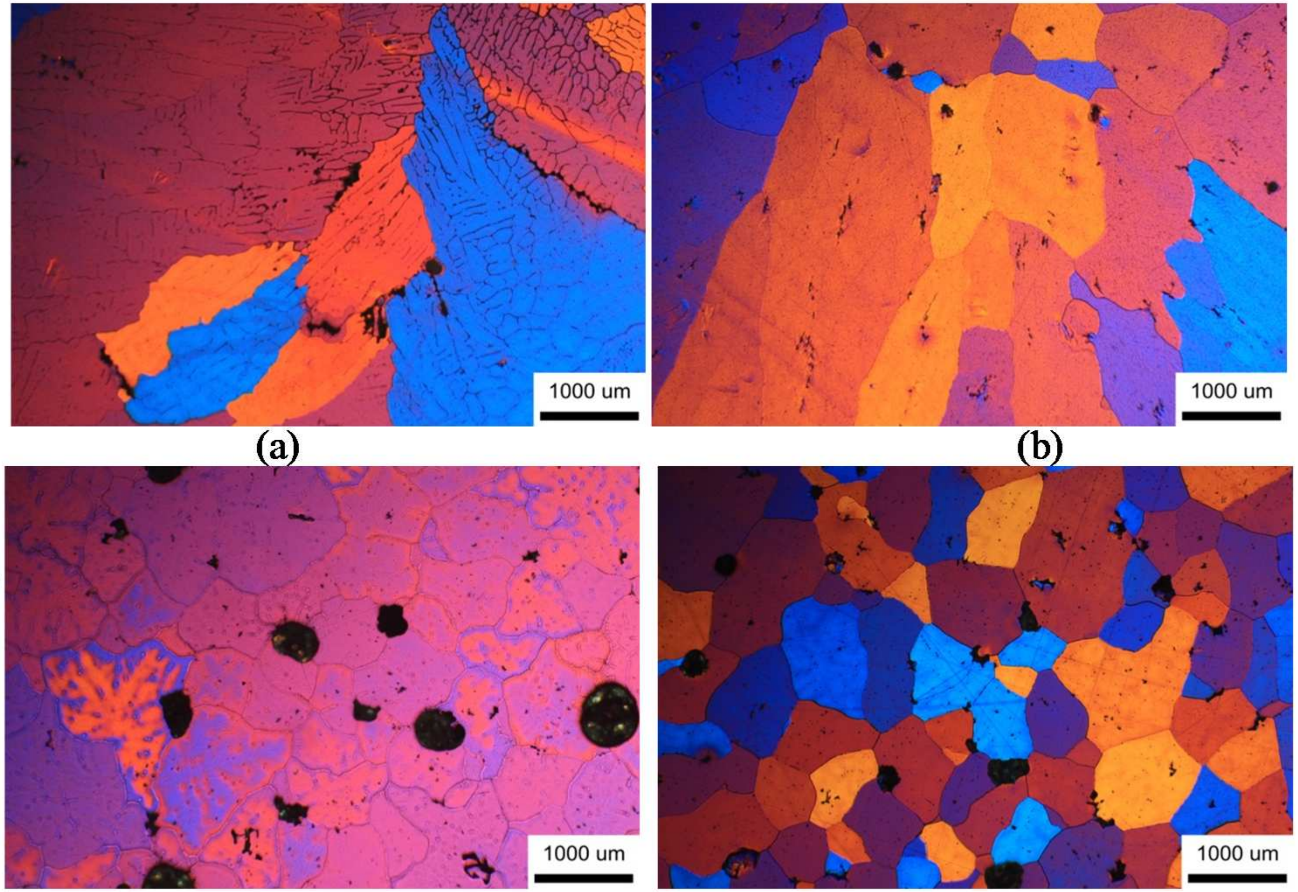
Addition of 0.2wt%Zr

Addition of 0.3wt%Zr

The role of peritectic reaction in grain refinement in cast Al

Pure Al

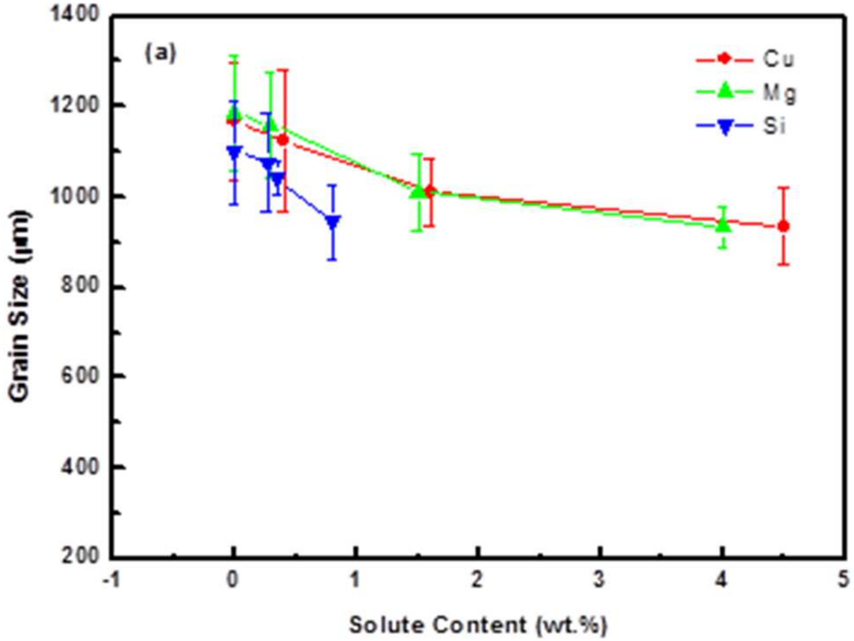
Addition of 0.12wt%Nb

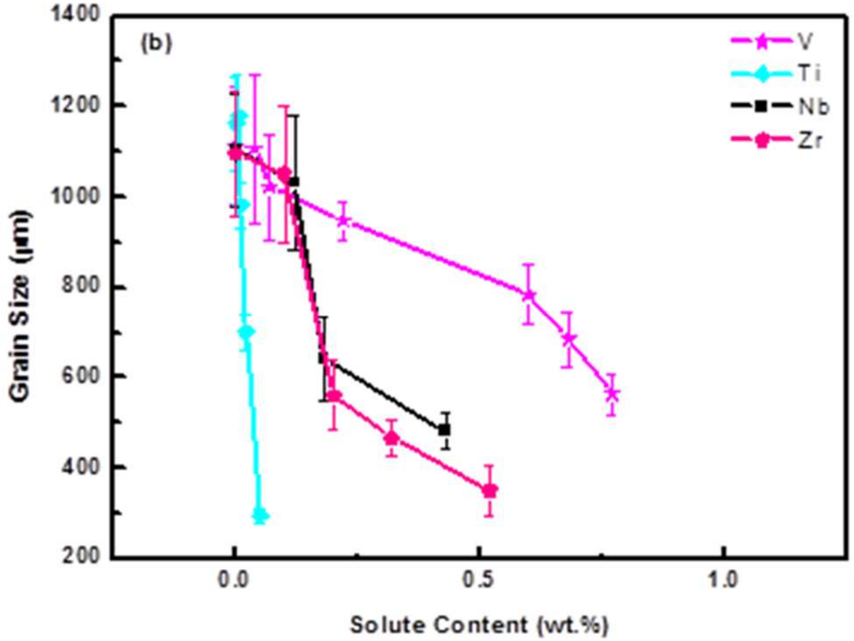


Addition of 0.2wt%Nb

Addition of 0.5wt%Nb

The role of peritectic reaction in grain refinement in cast Al





Addition of eutectic-forming alloying elements

Addition of peritectic-forming alloying elements

What are the key factors that govern the grain refinement in cast metals?

Possible answers

- Peritectic reaction
- Growth restrict factor
- Heterogeneous nucleation
- All of them
- What else?

Acknowledgement

- **Dr Dong Qiu – UQ**
- **A/Prof John Taylor – UQ**
- **Dr Mark Easton – Monash**
- **Mr Feng Wang – UQ**
- **Mr Zhilin Liu – UQ**
- **Dr Chun Li – UQ**
- **Australian Research Council (ARC)**