



Microstructural Characterization of Ti-6Al-4V Deposited via Electron Beam Freeform Fabrication

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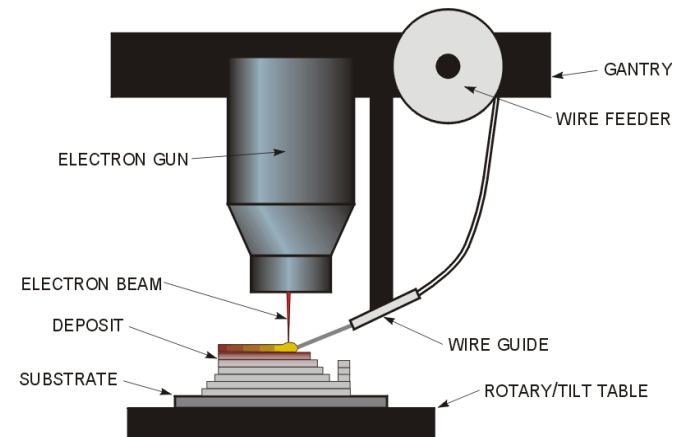
*National Aeronautics and Space Administration
Langley Research Center, Hampton, Virginia, USA*

Introduction – Electron Beam Freeform Fabrication



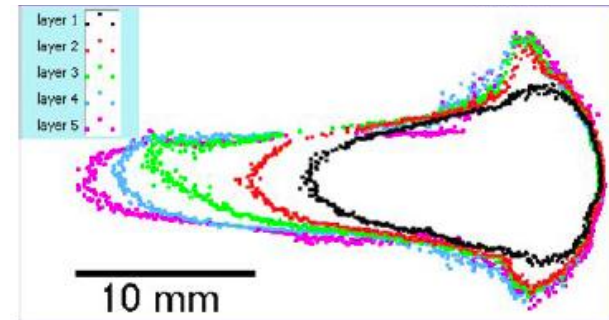
Additive manufacturing is a family of processing methods that selectively add material in order to directly create a three-dimensional part directly from a computer model

NASA Langley Research Center is currently investigating electron beam freeform fabrication (EBF³) as a means for making large scale components (>1 m) for a variety of aerospace applications

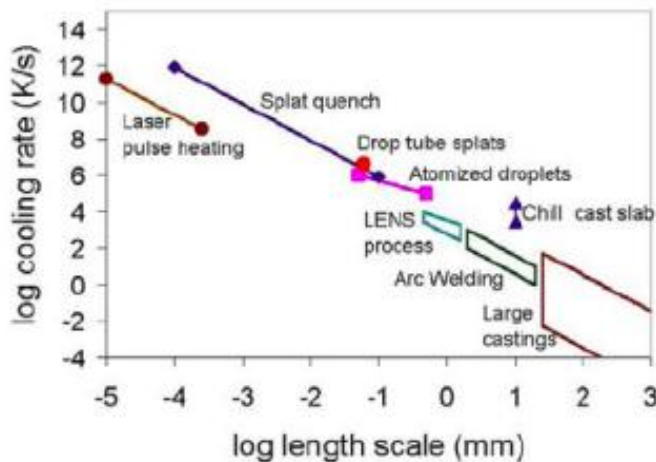


Molten pool dimensions change as thermal conditions change

- residual heat accumulates in substrate
- thermal path changes (2D vs 3D heat flow)



Hofmeister et al, Materials Science & Technology Conference 2005, Pittsburgh, PA



Hofmeister et al, JOM, Sept 2001, pp 30-34.

Cooling rate linearly dependent on molten pool dimension

- consistent molten pool size should result in repeatable microstructure
- consistent microstructure should result in reproducible properties

Thermal Input – Constant vs Controlled



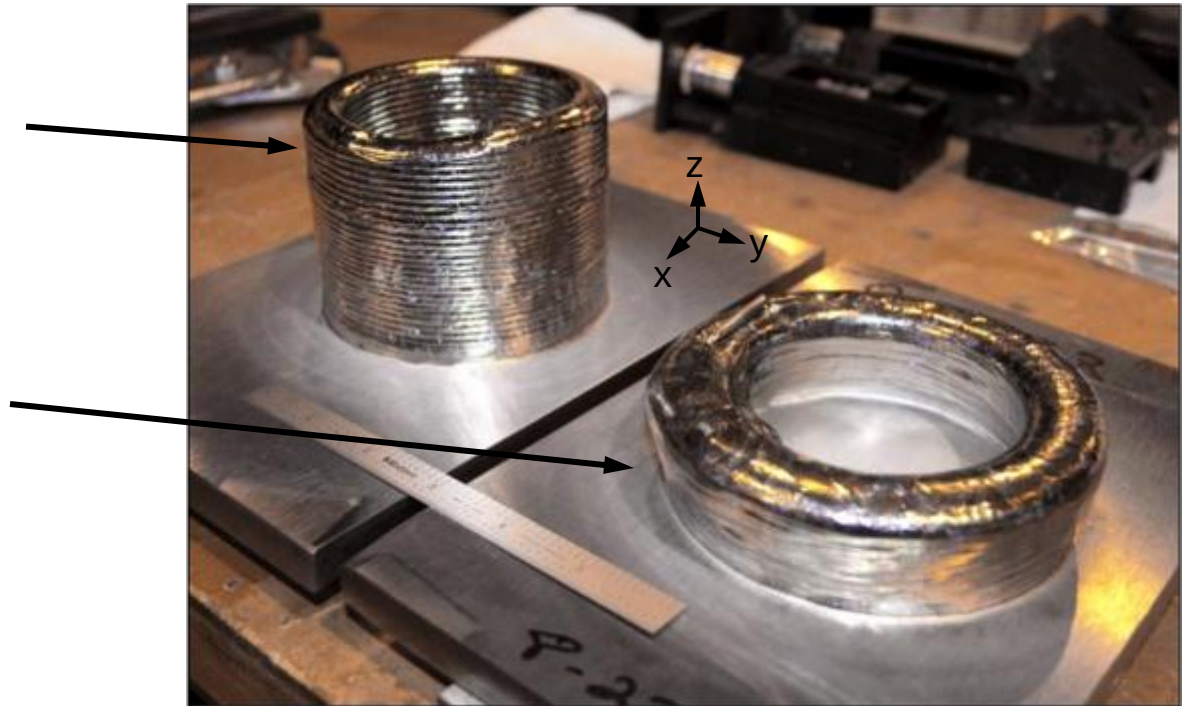
Geometrical differences between controlled and uncontrolled samples are obvious:

Closed-loop Controlled

- variable beam power
- uniform wall thickness

Uncontrolled

- constant beam power
- wall thickness continuously increasing
- stopped due to the molten pool “falling” off the top of the deposit



How do the microstructural features compare?

Quantitative microstructural characterization of $\alpha + \beta$ titanium alloys:

- Tiley et al, *Mater Sci & Eng A* 372 (2004) 191-198
- Searles et al, *Meas Sci Tech* 16 (2005) 60-69

Two dimensional stereological methodology in order to measure and quantify three-dimensional features in complex two phase microstructures

**Features of interest
for transformed β
microstructures**

- 1. Thickness of Widmanstätten α laths
- 2. Volume fraction retained β
- 3. Colony size
- 4. Width of grain boundary α
- 5. Volume fraction grain boundary α
- 6. β grain size

Additional analysis:

- Microhardness for mechanical property estimation
- Differential Scanning Calorimetry for β transus determination
- Texture Analysis via Electron Backscatter Diffraction



Comparison of properties relative to coarse or fine microstructures in transformed β lamellar microstructures

(+ indicates better, – indicates worse)

Property	Fine	Coarse
Strength	+	–
Ductility	+	–
Fracture Toughness	–	+
Fatigue Crack Initiation	+	–
Fatigue Crack Propagation	–	+
Creep Strength	–	+
Oxidation Behavior	+	–

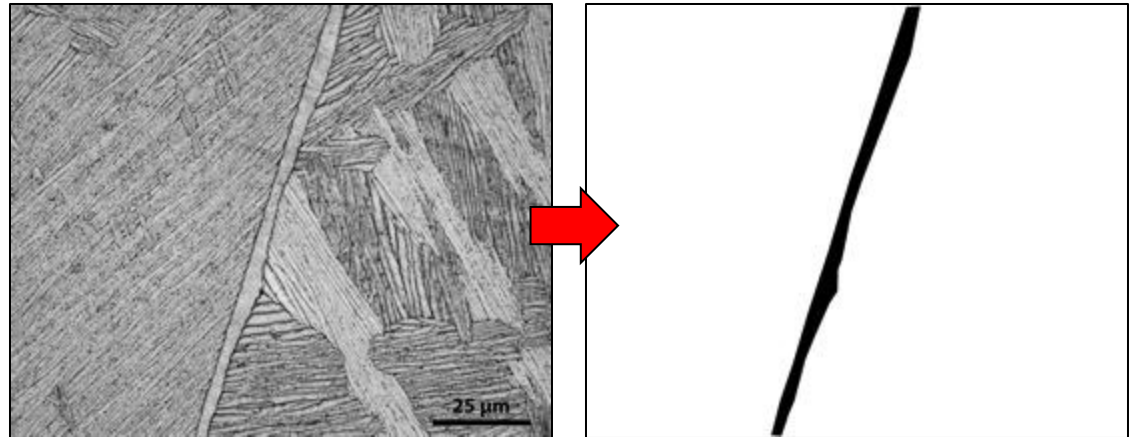
*adapted from: C. Leyens and M. Peters eds, *Titanium and Titanium Alloys*, Wiley VCH 2006.

Grain Boundary α Lath Thickness



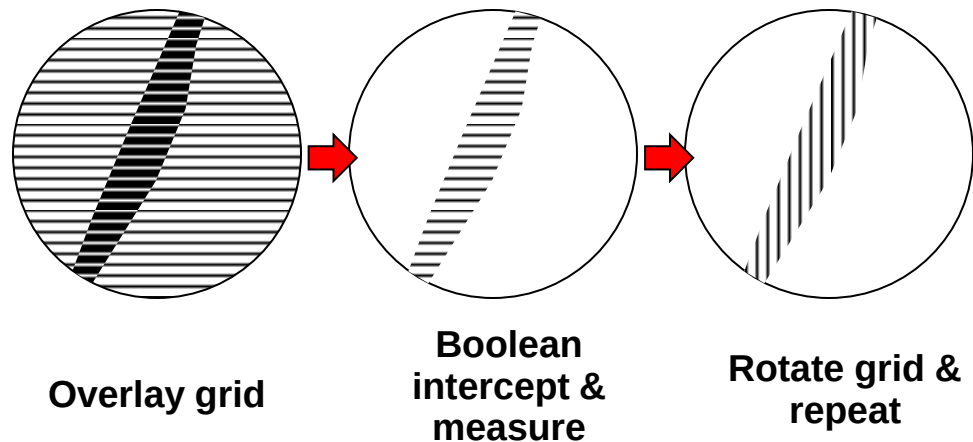
Steps:

1. Low magnification optical image
2. Calibrate (pixels/unit length)
3. Threshold grain boundary α
4. Overlay parallel lines
5. Boolean AND between lines and grain boundary α
6. Measure intercept distance
7. Rotate grid and repeat



Result is mean intercept length (λ_{mean}) and it is related to thickness by:

$$Thickness = \frac{1}{1.5 \left[\frac{1}{\lambda_{mean}} \right]}$$

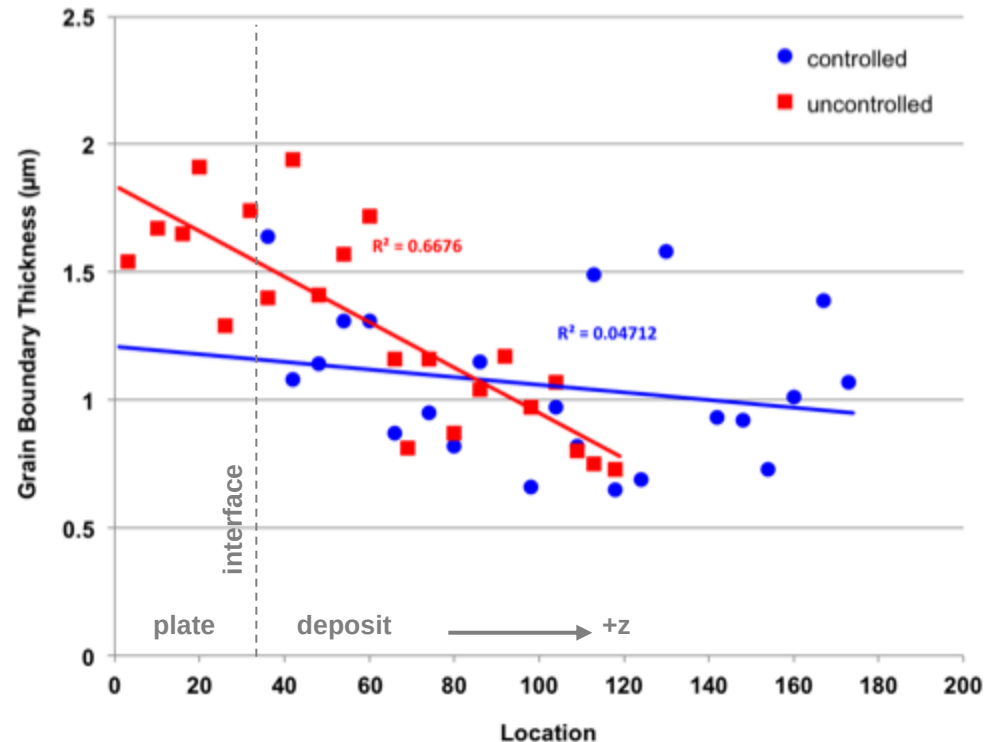


Grain Boundary α Lath Thickness Results



Measurements made from optical micrographs in ≈ 3 mm increments along z-axis direction

- For uncontrolled sample, grain boundary α decreasing with z height
Linear correlation based on decision point analysis[†]
(DP = 0.423 for n = 22)
- No linear correlation for controlled data



Possible conclusions:

- Aluminum loss due to vaporization reduces α thermodynamic stability
- Longer dwell at higher temperature for the uncontrolled sample
- Epitaxial growth of the grains and the sampling technique used biased the results

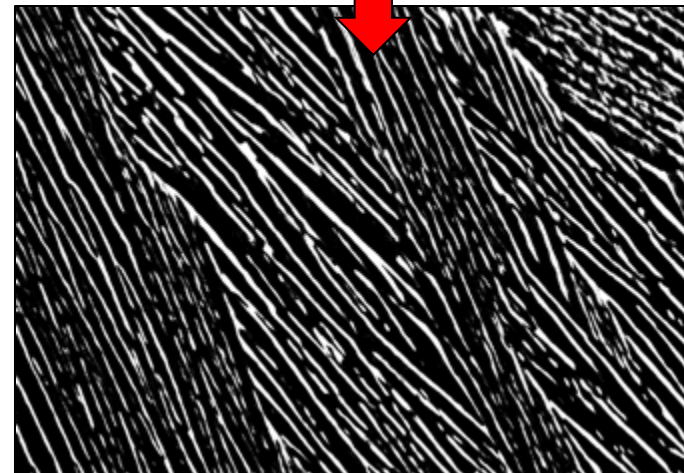
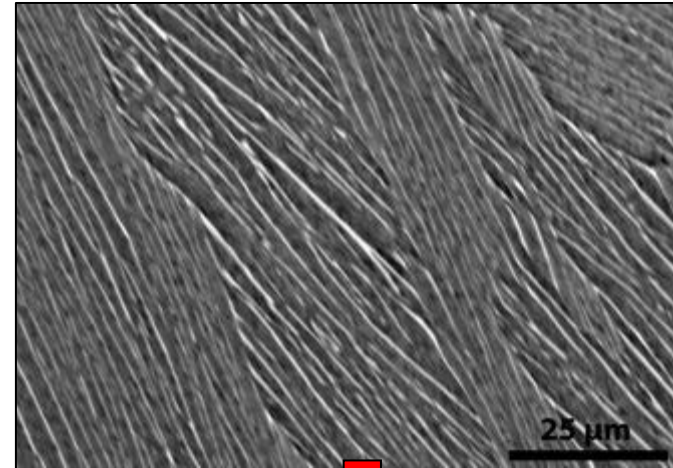
[†]<http://www.tc3.edu/instruct/sbrown/stat/decpts.htm>

α Lath Thickness



The image analysis steps taken for alpha lath thickness measurement:

1. Collect high magnification backscattered electron SEM image
2. Calibrate (pixels/unit length)
3. Conduct image processing
4. Threshold & invert
5. Overlay parallel lines
6. Boolean AND between lines and α lath
7. Measure intercept distance
8. Rotate grid and repeat

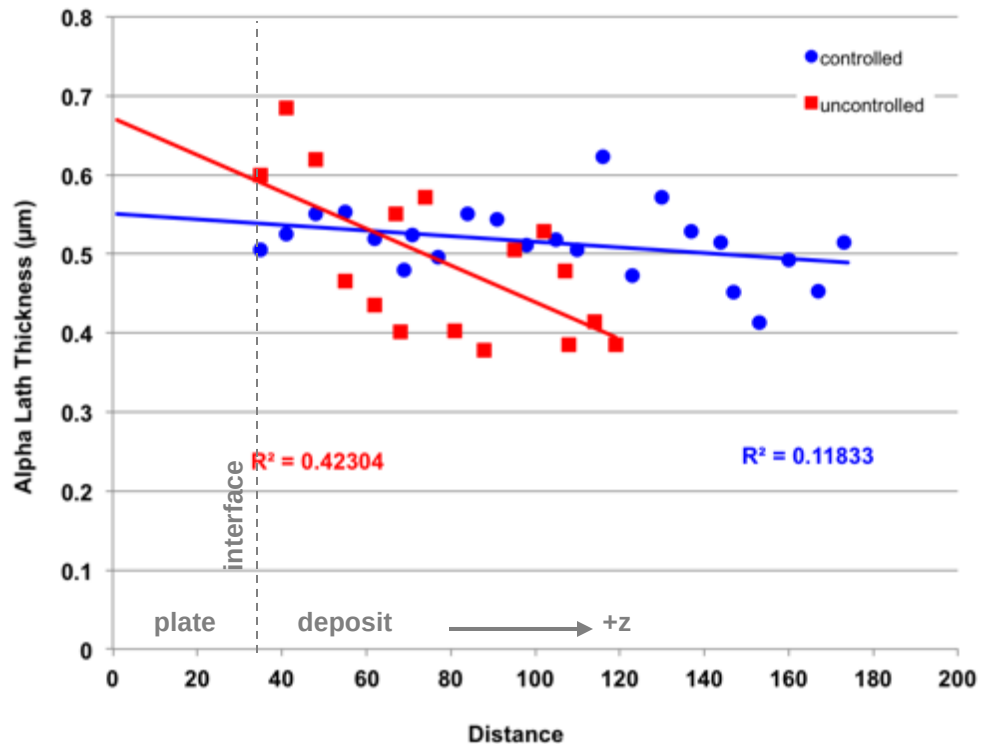


α Lath Thickness Results

Measurements made from optical micrographs in ≈ 3 mm increments along z-axis direction

- For uncontrolled sample, alpha lath spacing decreases with increasing z height
 - Linear correlation based on decision point analysis (DP = 0.497 for n = 16)
- No linear correlation for controlled data

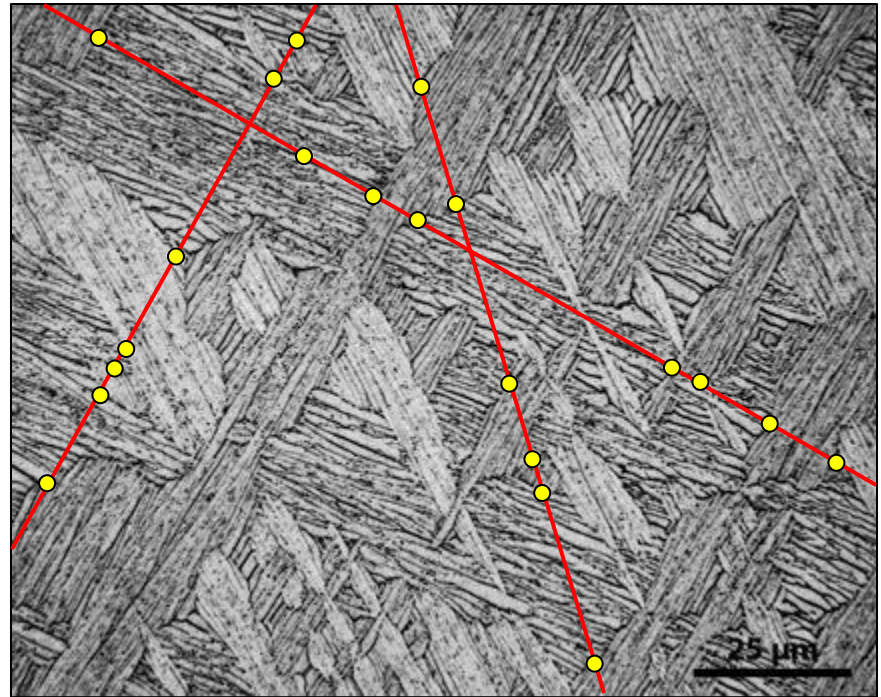
Result consistent with grain boundary α result



The image analysis steps taken for colony size measurement:

1. Collect low magnification optical image
2. Calibrate (pixels/unit length)
3. Overlay random line pattern of known length
4. Manually mark where line intercepts colony boundary
5. Report as “colony size factor” – not true length

*colony defined as >3 similarly aligned laths

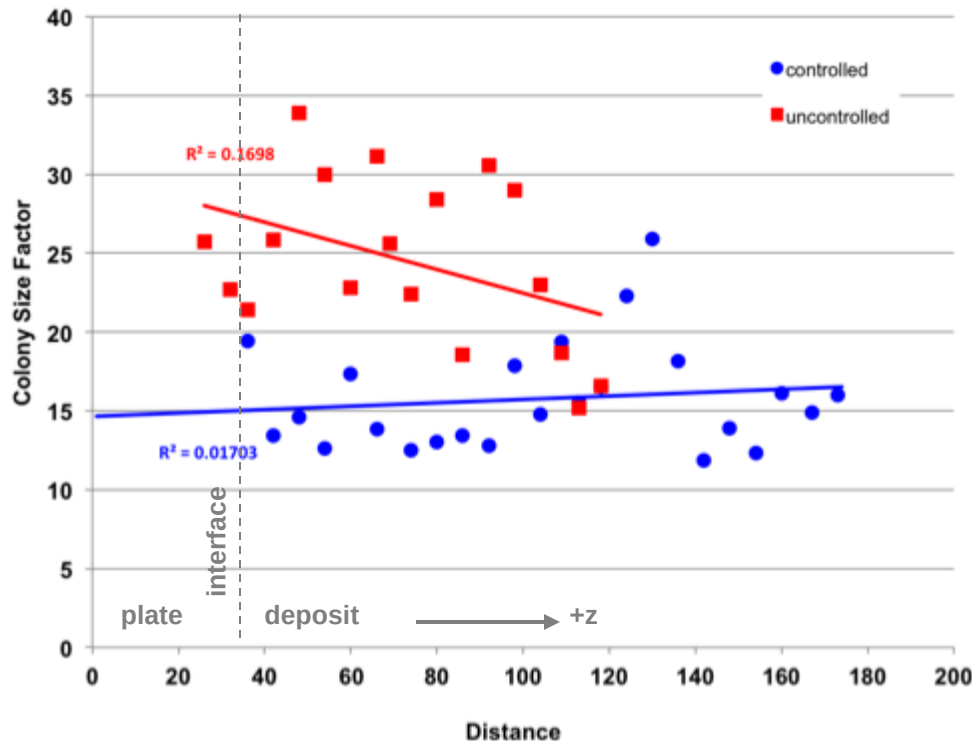


Colony Size Results



Colony size factor significantly influenced by thermal input

- Size factor directly related to length but due to complex shape of colonies, not a true measure of colony size
- *For the same alloy processed at the same deposition rate, critical properties could be significantly different*



**trend lines are not linearly correlated to data using decision point analysis*

Prior β Grain Size Factor

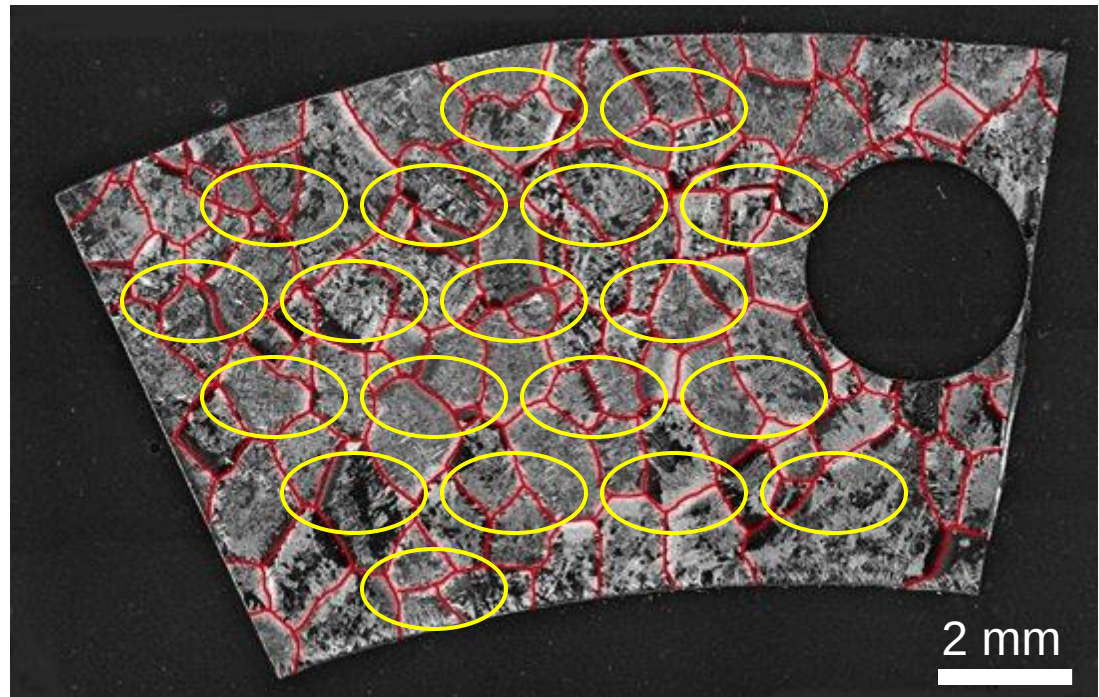


The image analysis steps taken for prior β grain size factor measurement:

1. Collect low magnification optical image (stitched montage)
2. Calibrate (pixels/unit length)
3. Manually decorate beta grain boundaries (red)
4. Overlay cycloid grid of known total distance (yellow)
5. Measure number of intercepts

$$P_L = \frac{\# \text{ intersection points}}{\text{total length of cycloids}}$$

$$S_V = 2P_L = \frac{\text{surface area of prior } \beta \text{ grain}}{\text{grain per unit volume}}$$

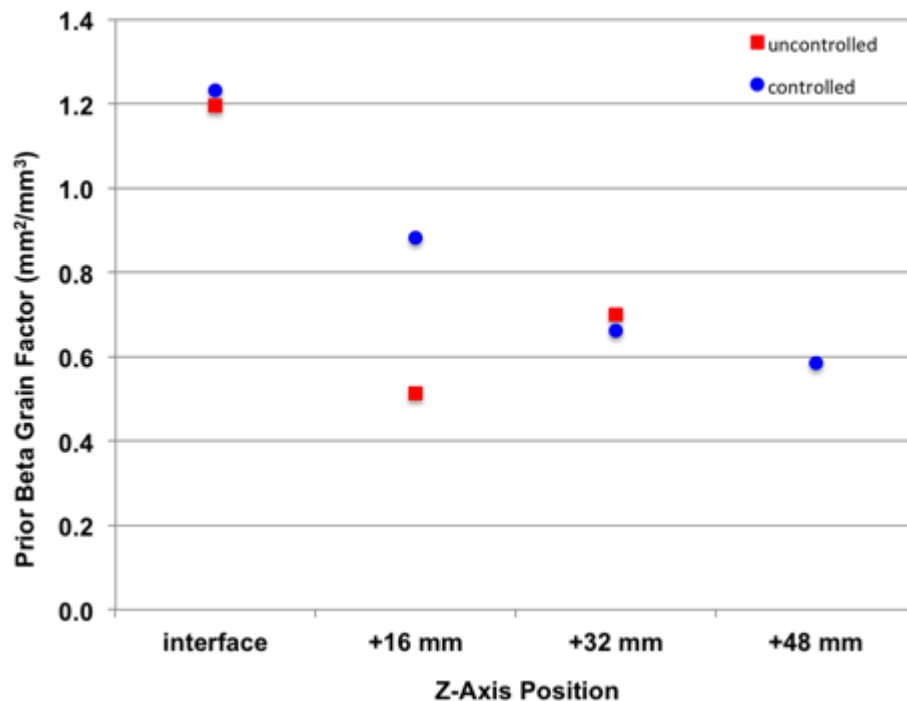


Prior β Grain Size Results

Prior β grain size increases with height for both samples

- The larger the β grain factor, the smaller the grain size

Larger prior β grains reduces tensile strength (weak correlation)

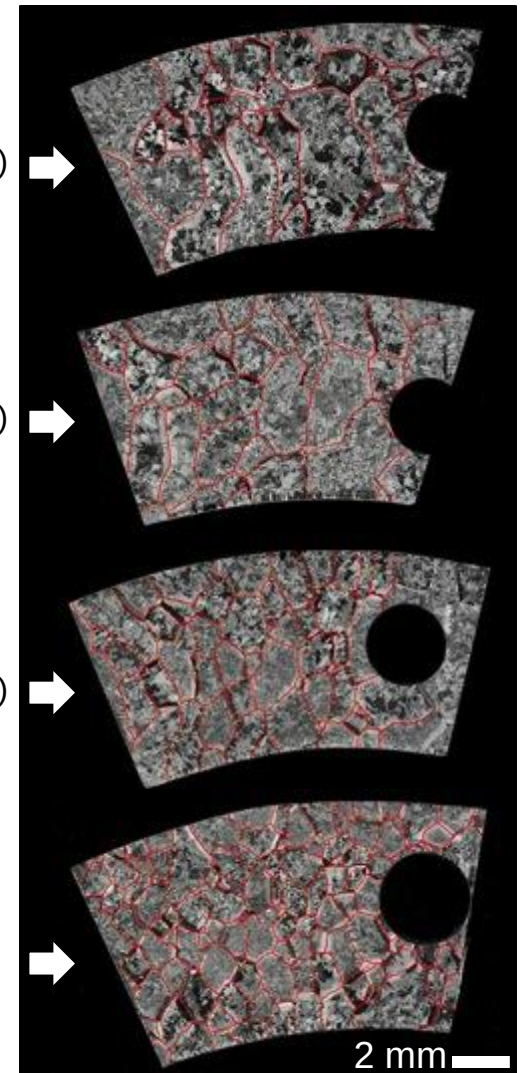


+ 48 mm (Z axis)

+ 32 mm (Z axis)

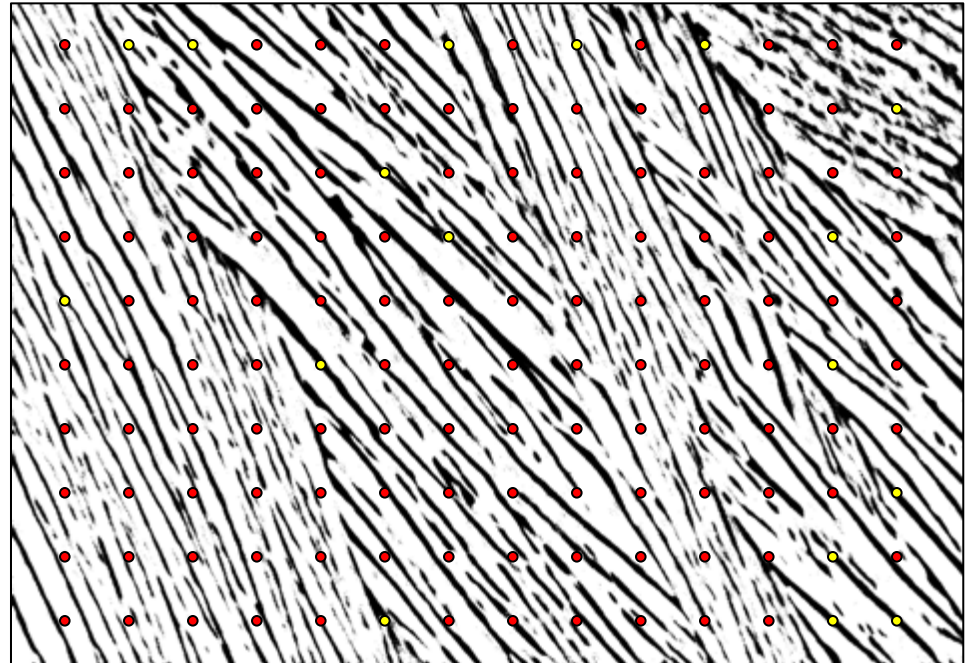
+ 16 mm (Z axis)

near
substrate/plate
interface



The image analysis steps taken for β volume fraction measurement:

1. Collect high magnification backscattered electron SEM image
2. Image processing (sharpen, invert, etc)
3. Overlay point grid
4. Count number of points lying within each phase
 β – yellow, α – red



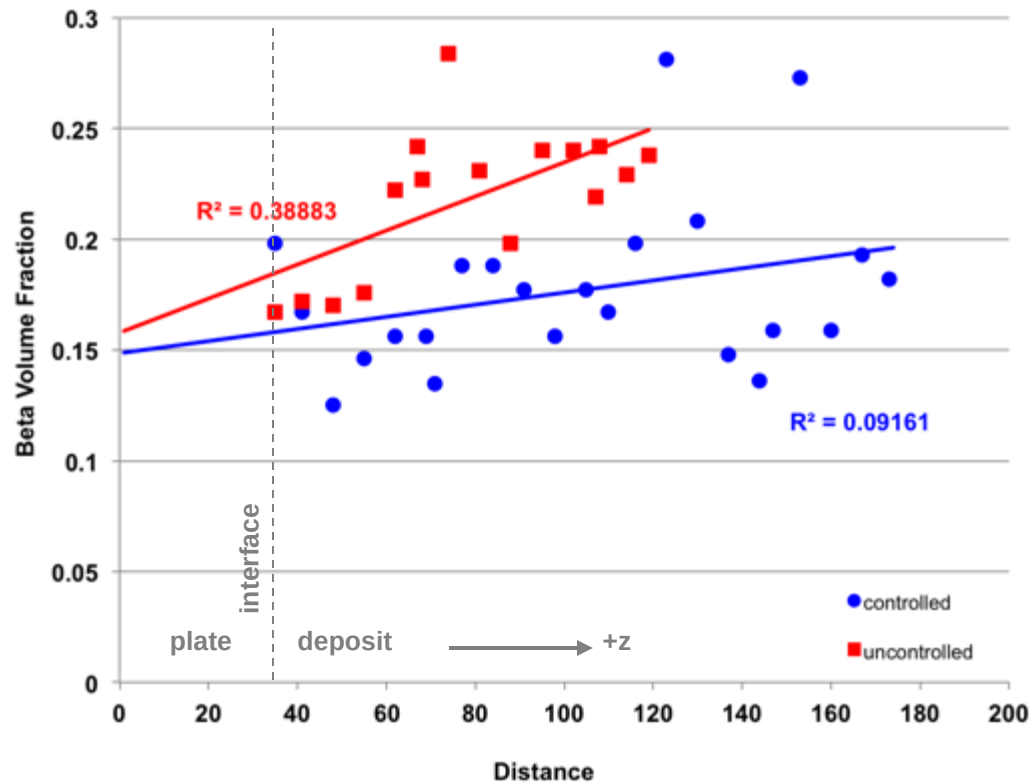
β Volume Fraction Results



Measurements made from SEM micrographs in ≈ 3 mm increments along z-axis direction

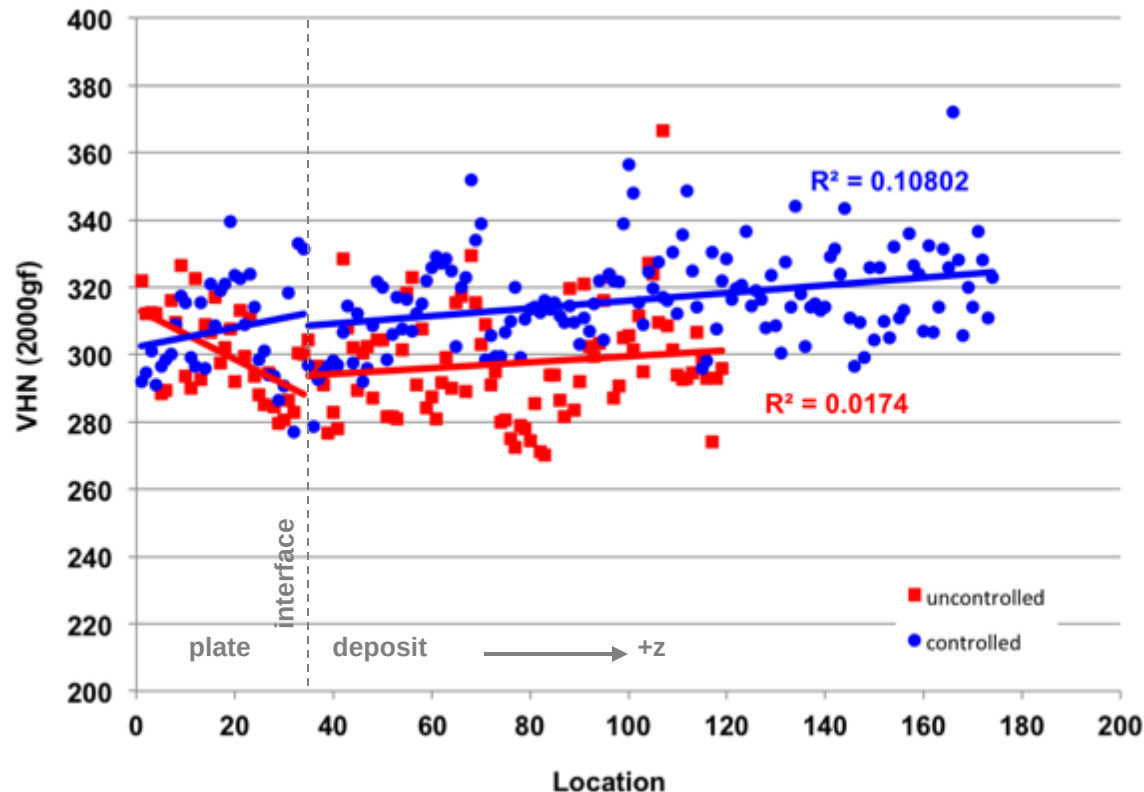
- For uncontrolled sample, β volume fraction increases with increasing z height
 - Linear correlation based on decision point analysis (DP = 0.497 for n = 16)
- No linear correlation for controlled data

Aluminum loss due to preferential vaporization likely a key factor in β volume increase



Microhardness traces performed on each sample from bottom of substrate to top of deposit

- Controlled sample shows linear correlation based on decision point analysis
- Uncontrolled data is random



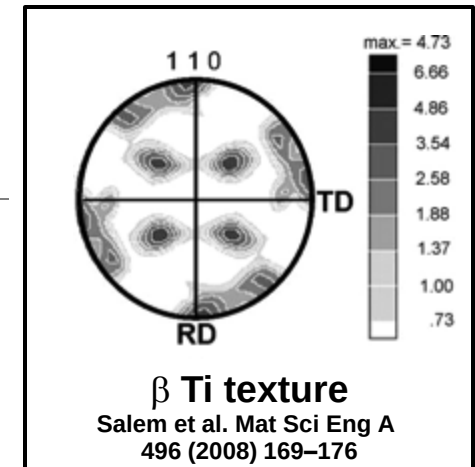
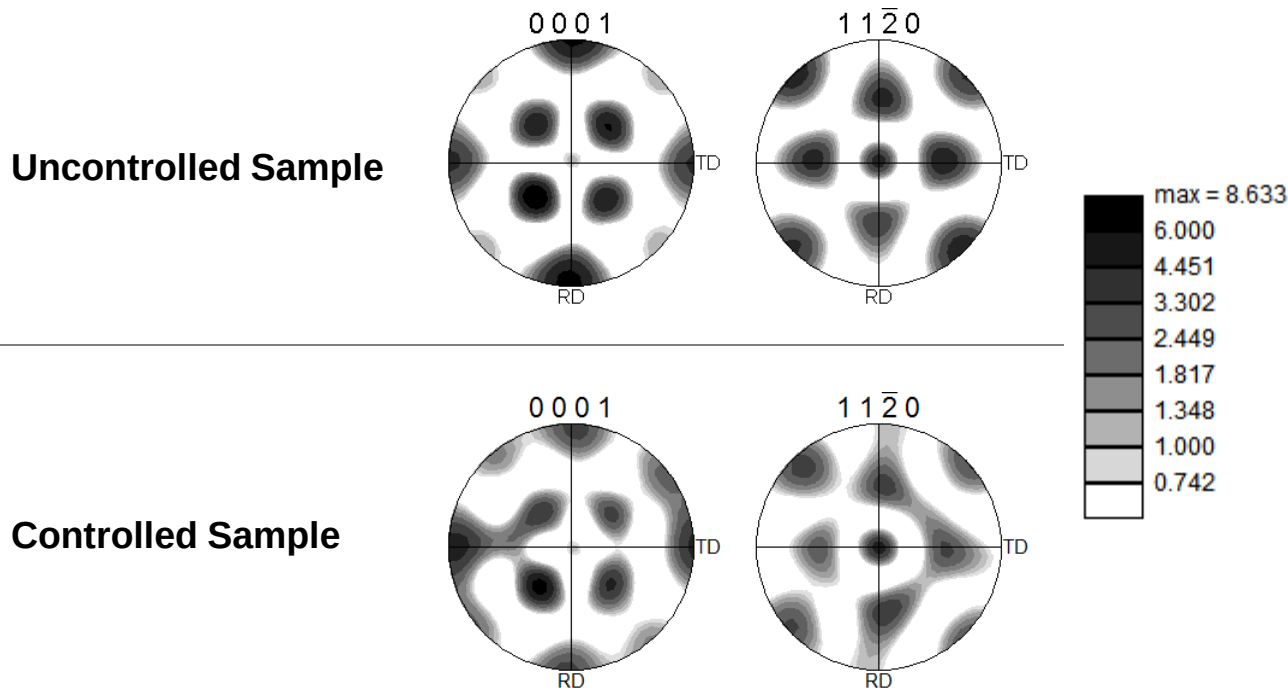
Texture Analysis – Pole Figures

Similar basal textures for α -Ti grains in uncontrolled vs. controlled conditions

- Slightly sharper texture in uncontrolled sample

Relationship to 'Cube' texture seen in literature for β phase (BCC) Ti-6-4

- Indicative of a Burgers relationship: $(110) \beta \parallel (0001) \alpha$

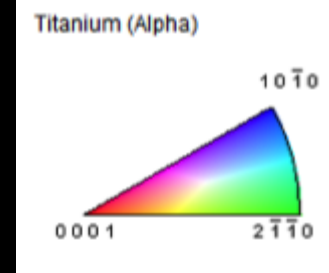
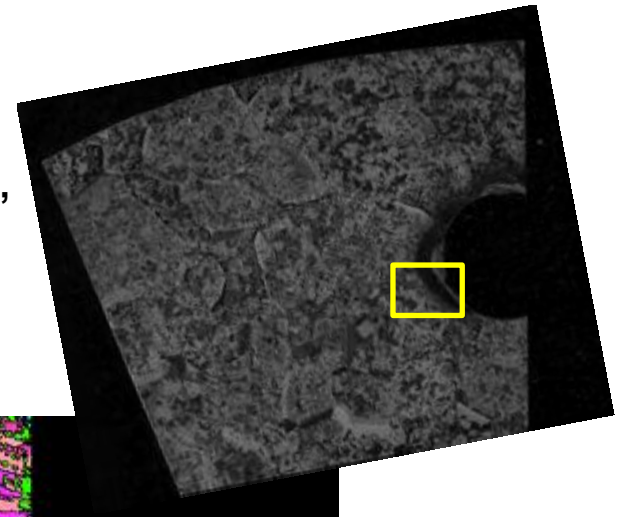


Texture Analysis – Inverse Pole Figure Map

Uncontrolled

- Variability in α colony size
- α colonies tend to be long and thin
- *Relatively a larger volume fraction of 0001 texture in the Uncontrolled compared to that in the controlled $\rightarrow$ higher number of softer grains in the uncontrolled*

'RD' $\uparrow$
'TD' $\leftarrow$



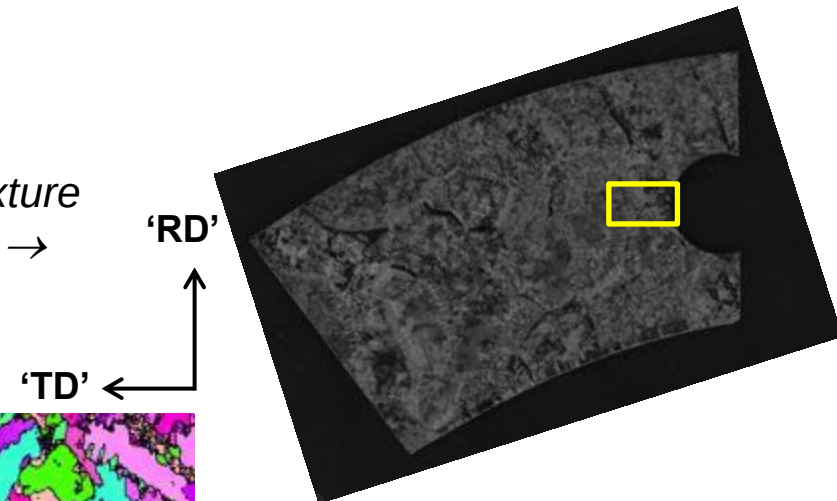
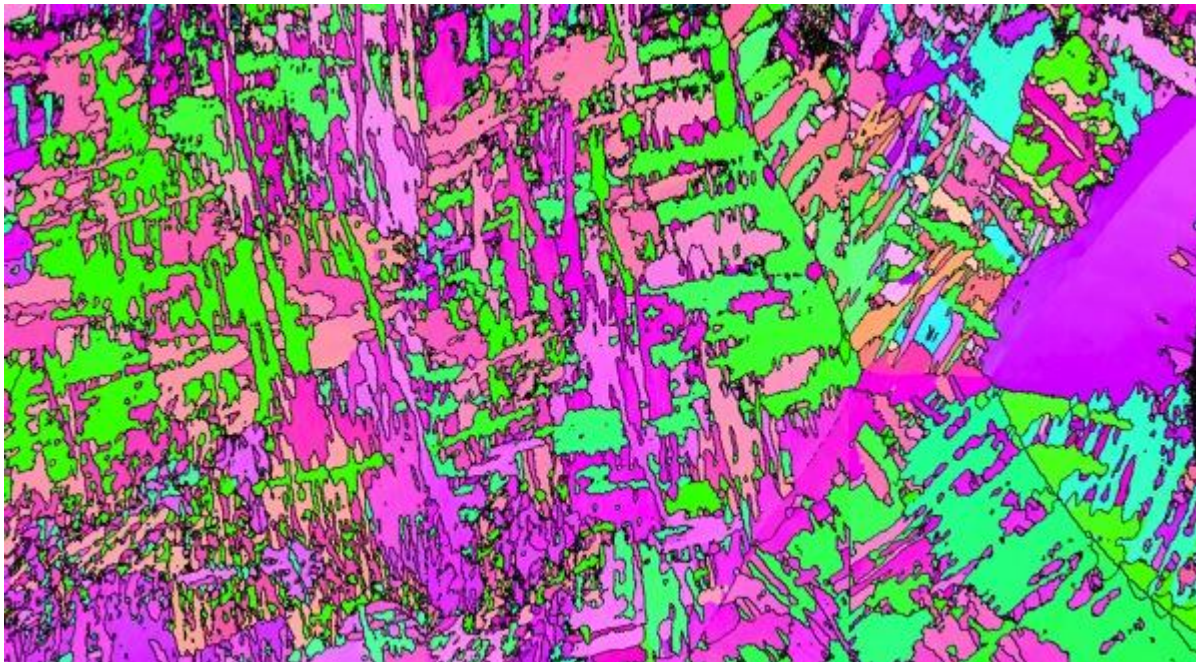
500 μm

Texture Analysis – Inverse Pole Figure Map

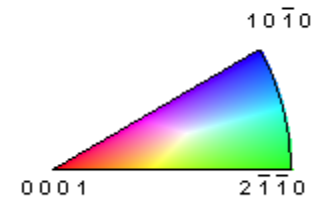


Controlled

- Slightly more uniform α colony size
- α colonies tend to be wider and shorter
- *Relatively a larger volume fraction of 2-1-10 prism texture in the controlled compared to that in the uncontrolled → higher number of harder grains in the controlled?*



Titanium (Alpha)

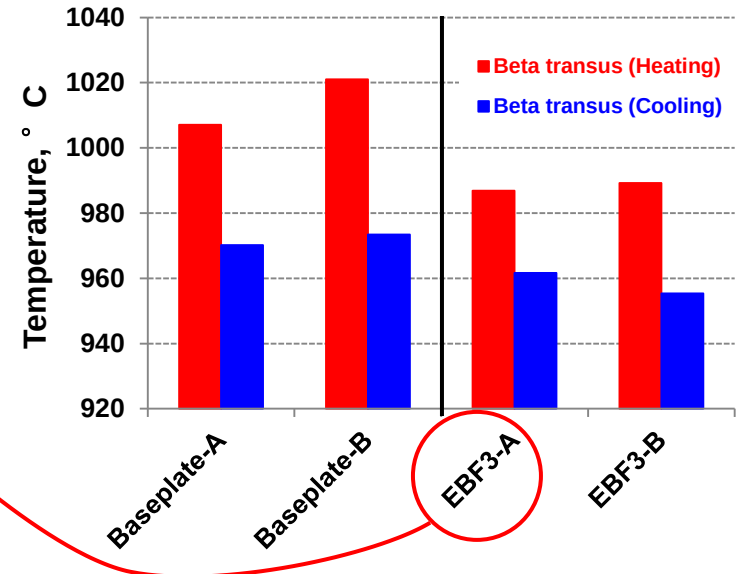
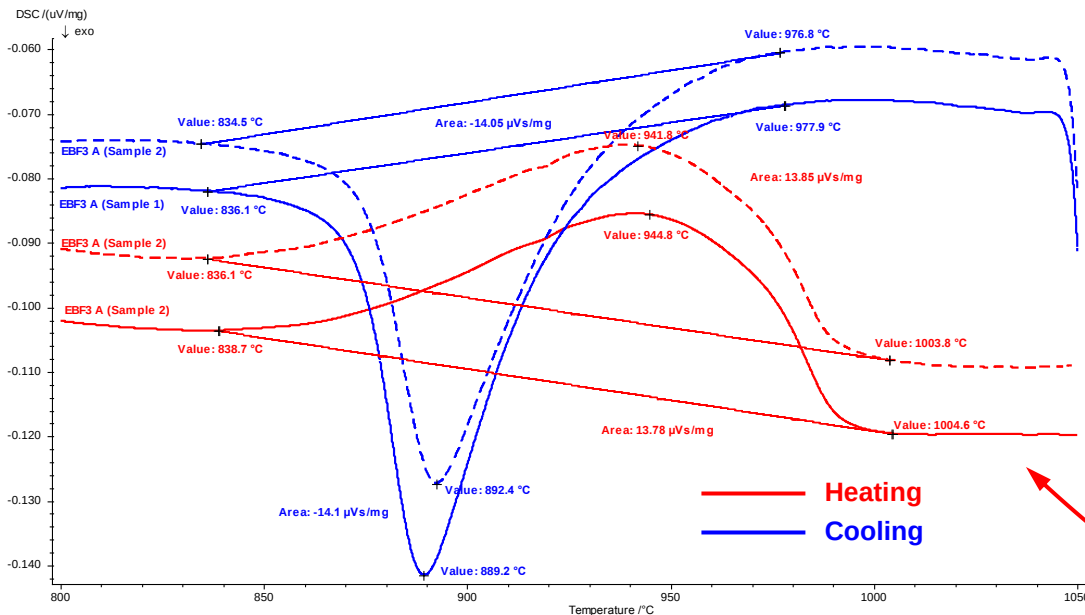


500 μm

Differential Scanning Calorimetry



- Higher the α -stabilizing element (e.g. Al) content, higher the β transus temperature.
- Al contents of both samples are significantly lower than those of their corresponding base plates. This is equivalent to significant Al losses during EBF³.
- For DSC analysis, Al loss appears to be nearly alike in both samples at the measurement location (≈ 30 mm in +z-axis direction)
- Hysteresis in β transus for heating versus cooling, is likely a measure of heterogeneity of $\alpha + \beta$ microstructures, and β grain size.



Beta Transus as Function of Aluminum Content



	β Transus (Heating), ° C	Estimated wt% Al
Base plate uncontrolled	1007.1 $\pm$ 1.3	5.85
Base plate controlled	1021 $\pm$ 4.5	6.53
EBF ³ uncontrolled	986.9 $\pm$ 0.2	4.89
EBF ³ controlled	989.2 $\pm$ 0.3	5.00

Assumptions:

β transus is ~ linear with Al content in the Ti-Al binary phase diagram.

β transus is not significantly affected by the V content in the Ti-Al-V system.*

**Materials Properties Handbook: Titanium Alloys, Editors, R. Boyer, G. Welsch, and E.W. Collings, 1994, p. 28.*

Comparison of the microstructural characteristics between the open-loop (uncontrolled) and closed-loop control samples shows distinct differences due to overall thermal input.

Preferential aluminum vaporization is significant in both deposited samples and likely contributes to the variation.

The open loop sample, with higher thermal input and reduced thermal gradient, exhibited significant variations in through-thickness microstructure.

The closed-loop control sample, where beam power was reduced in order to maintain consistent molten pool size, contained less microstructural variation.

Acknowledgements



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