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Microstructural Characterization of Electron Beam Additively Manufactured (EBAM) and Wire Arc Additively Manufactured (WAAM) Ti-6Al-4V

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Motivation

- Two common wire directed energy deposition processes are electron beam additive manufacturing (EBAM) and wire arc additive manufacturing (WAAM).
- EBAM and WAAM often produce different chemical and microstructural characteristics, resulting in variable mechanical properties
- In this poster, we present our efforts to characterize and assess the microstructural and chemical influences on the resulting tensile properties for EBAM and WAAM processed Ti-6Al-4V

Methods

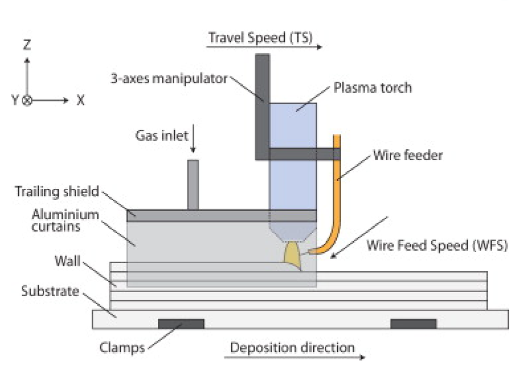


Figure 1. Sample schematic a WAAM system [1]

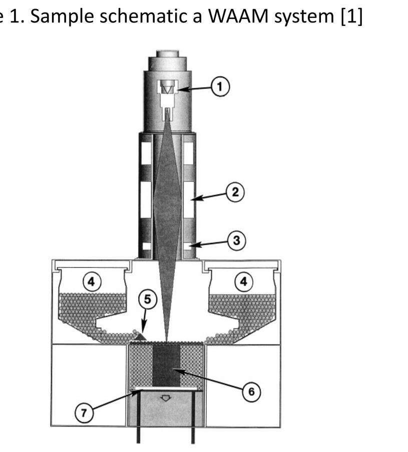


Figure 2. Sample schematic of a typical EBAM system, note that that system uses power feed but wire feed was used in this study[2]

WAAM

- Wire feed is melted by a plasma
- Relatively high solidification rates
- Process takes place in an Ar atmosphere

EBAM

- Wire feed is melted by an electron beam
- Relatively low solidification rates
- Process takes place in vacuum, which can lead to low melting point elements (such as Al) to evaporate during processing

- Three types of Ti-6Al-4V samples were prepared:(1) Wrought (2) WAAM and (3) EBAM
- A subset of both WAAM and EBAM samples were exposed a beta anneal (HT-01) and alpha anneal (HT-02) heat treatment. All samples were exposed to an overage anneal. (see fig. 3)
- All samples were tensile tested, and characterized with electron backscatter diffraction (EBSD), scanning electron microscopy (SEM), and electron probe microanalysis (EPMA).

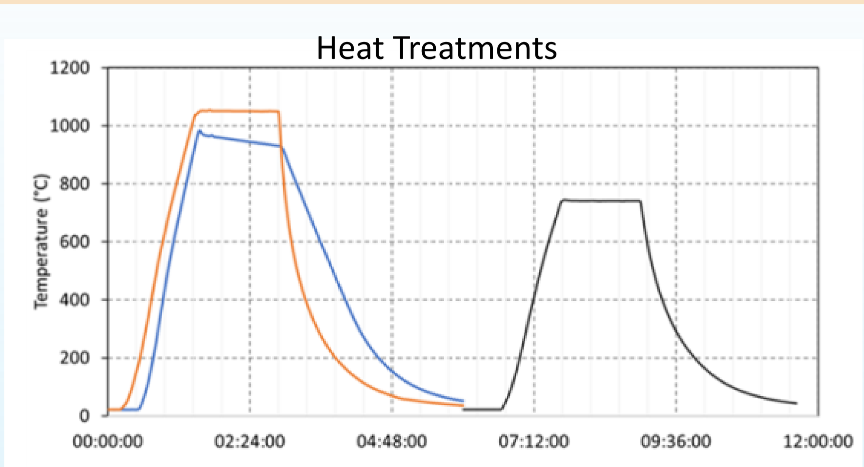


Figure 3. Heat treatments used for WAAM and EBAM samples. Beta anneal/HT-01 (orange), alpha anneal/HT-02 (blue), and overage anneal (black).

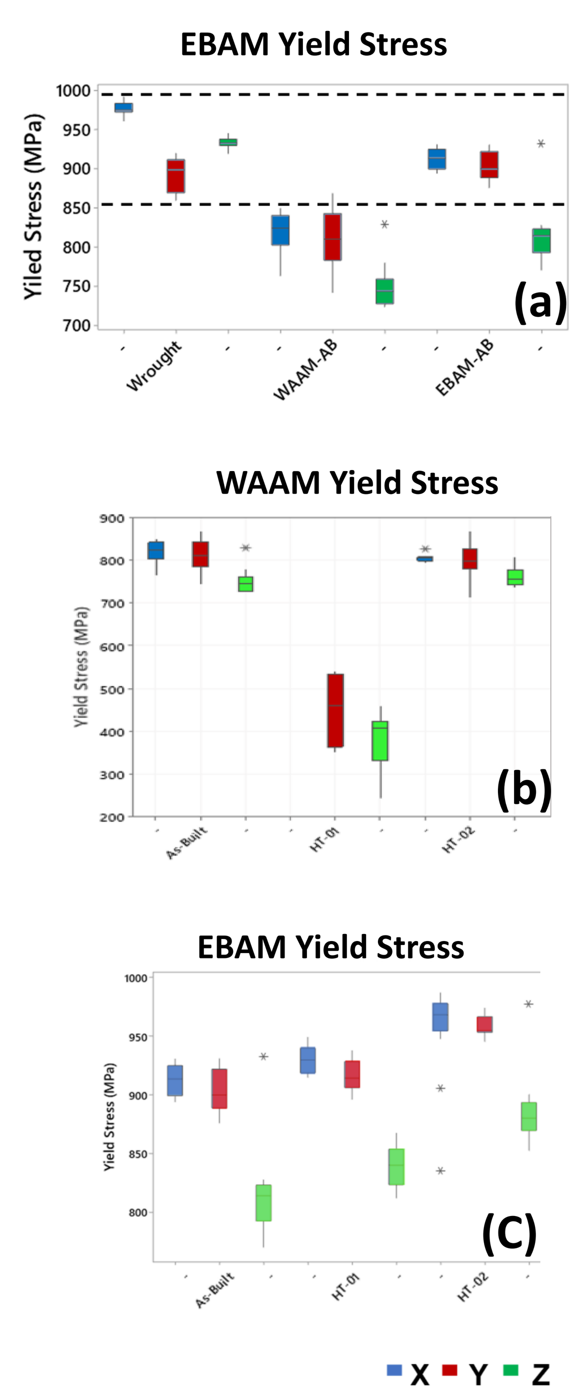
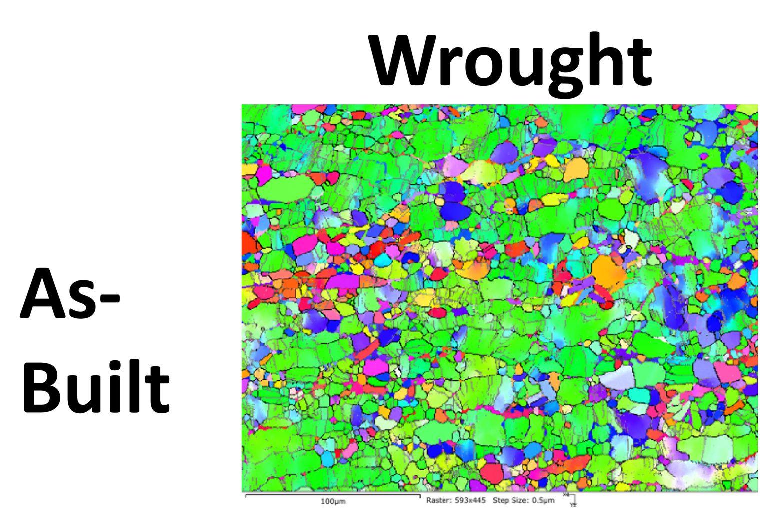


Figure 4. Box and whisker plots showing the yield stresses in the x, y, and z direction for (a) wrought, as-built WAAM, and as-built EBAM, (b) as-built WAAM, and both heat treated WAAM samples , and (c) as-built EBAM, and both heat treated EBAM samples.

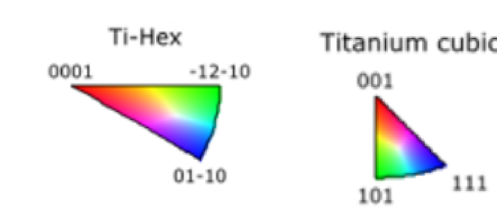
- Wrought samples had the highest yield stress as compared to EBAM and WAAM samples
- WAAM samples had the lowest yield stress in the as-built state, while EBAM had high anisotropy, with the Z direction having the lowest yield.
- WAAM HT-01 resulted in lost ductility
- Neither WAAM nor EBAM seem to benefit from a beta and alpha anneal.

Results

- EBSD Inverse Pole Figure (IPF) colored maps show that the two processes produce much different microstructures than the traditional, wrought sample
- The high cooling rate of WAAM lead to an acicular microstructure, while the slower cooling EBAM process produced large, martensitic grains
- Large grains in as-built EBAM sample explain the observed anisotropy in the yield stress
- After heat treatments WAAM and EBAM microstructures did not appear to be similar



- EBAM samples that underwent HT-01 (beta anneal) resulted in large martensitic structures, however this microstructure was not expected, we would have expected an acicular structure similar to EBAM HT-02



EBSD IPF maps coloring key

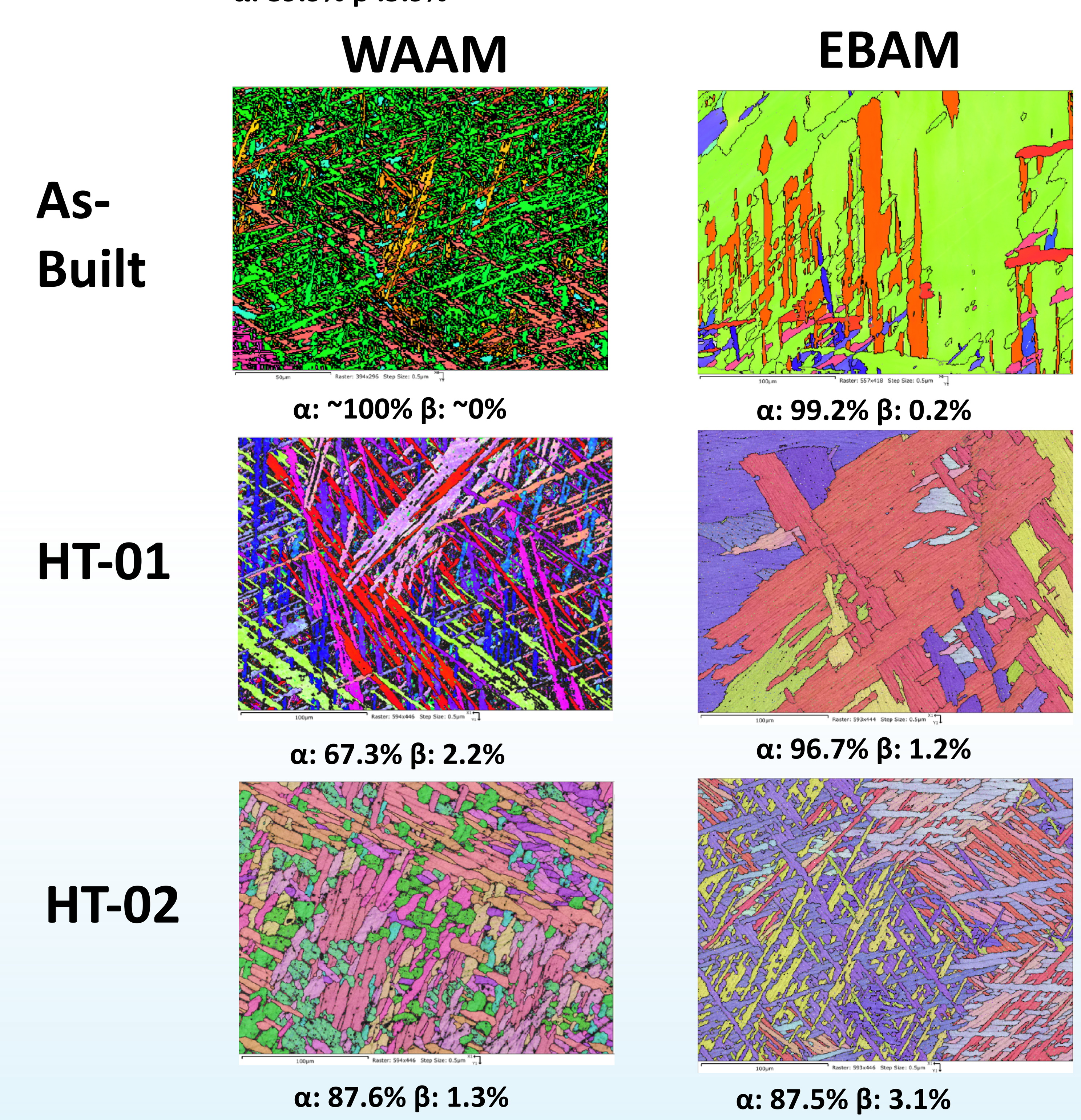


Figure 5. EBSD Inverse Poe figure (IPF) colored showing the microstructure of the wrought, WAAM and EBAM samples. EBSD maps contain box alpha phase (hexagonal Ti) and beta phase (cubic Ti). Each map is colored according to they Key

Discussion

- Chemical variation between EBAM and WAAM could explain the resulting microstructures after the heat treatments
- Equivalent Mo (beta stabilizer) and Al (alpha stabilizer) values were calculated for both samples, showing that there is a large difference in Al equivalent elements
- Although EBAM has a higher alpha stabilizer content, it still does not explain the resulting microstructure of EBAM HT-01

	WAAM	EBAM
$[Mo]eq$	2.8%	3.1%
$[Al]eq$	7.6%	9.3%

Table 1. Mo equivalent values and Al equivalent values for WAAM and EBAM samples. Data is semi quantitative.

- EPMA was conducted on one of the EBAM HT-01 samples to understand the distribution of elements across boundaries, particularly for any of interstitial oxygen
- EPMA results were inconclusive and showed no major trends in any of the elements, however the Oxygen levels were quite high (2.0 wt%), leading us to believe the samples may have captured oxygen during sample prep or while waiting to be analyzed.

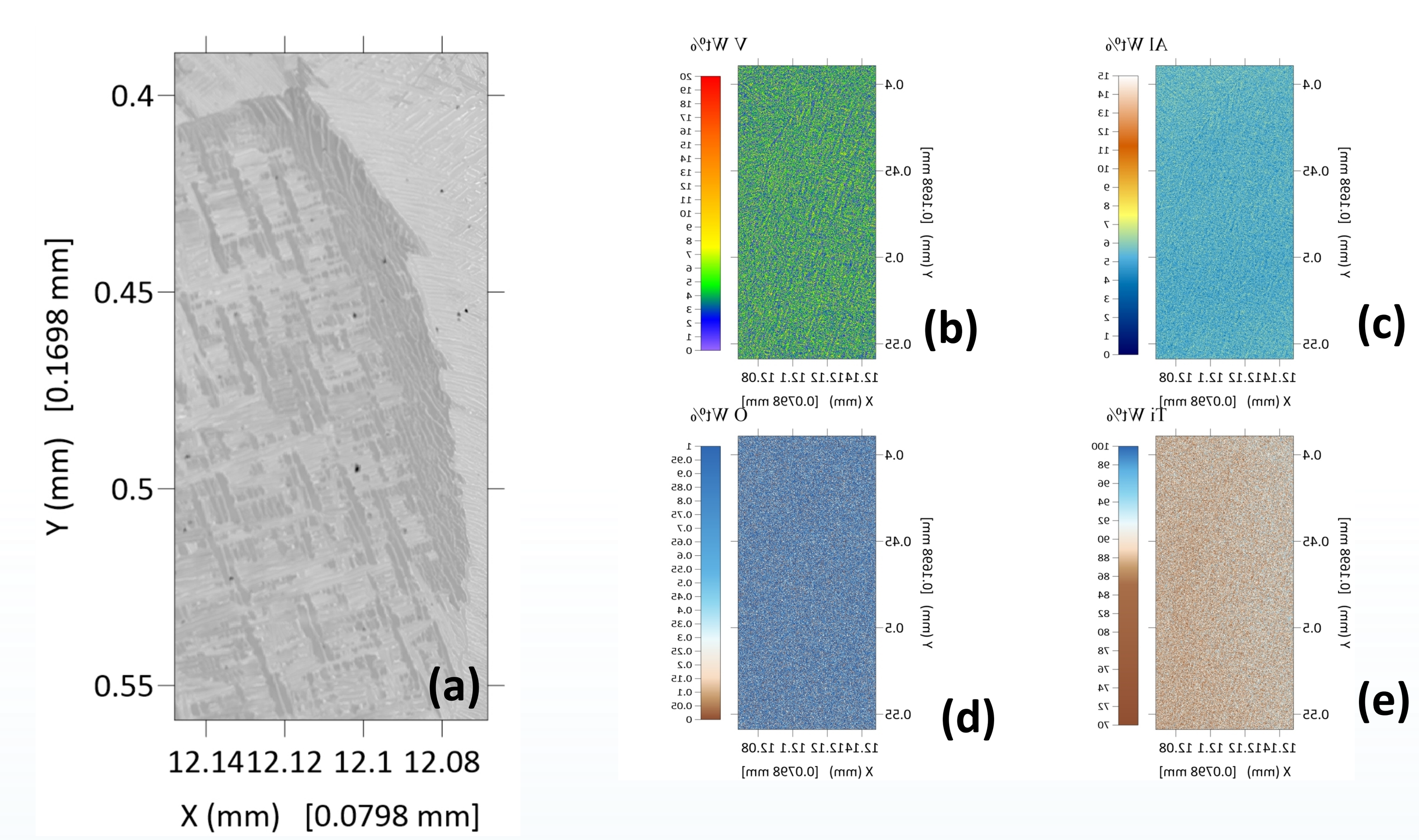


Figure 6. (a) back scatter electron image of EBAM HT-01 at a prior beta grain boundary. EPMA quant maps showing the distribution of, Aluminum (b), Vanadium(c) and Titanium(d) and oxygen(e) across the area imaged.

Conclusions

- Both WAAM and EBAM can produce Ti-6Al-4V with comparable yield stresses to wrought Ti-6Al-4V but very distinct microstructures
- There is no obvious benefit from heat treatment and in some cases (WAAM HT-01) yield stress is lowered
- Future work is needed to understand the resulting microstructures of the heat treated EBAM samples

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[1] **F. Martina et al.,** *Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V,* **2012**

[2] **L.E. Murr et al.,** *Microstructures and mechanical properties of electron beam-rapid manufactured Ti–6Al–4V biomedical prototypes compared to wrought Ti–6Al–4V*

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