Kevin L. Klug ***and*** **Joseph R. Pickens**

Damage Tolerance of Low-Cost Titanium Alloys

Materials Congress 2006
Wednesday, 5 April 2006

Acknowledgments

- **Concurrent Technologies Corporation**
  - Christine Slippy, Mustafa Guclu, Ibrahim Ucok, Mehmet Gungor, Hao Dong, Wm. Troy Tack, Lawrence Kramer
- **(US) Naval Surface Warfare Center**
  - Ernie Czyryca
- **ATI / Wah Chang**
  - Larry Martin
- **PCC Structurals**
  - James Ault
- **TIMET**
  - James Grauman
- **RTI / RMI**
  - Oscar Yu

- **U.S. Office of Naval Research** (ONR)
- **M777 Lightweight Howitzer Joint Program Management Office** (JPMO)

Outline

- Titanium’s benefits
- Titanium’s limitations
- Cost reduction strategies
- Damage tolerance data
- Summary

The case for titanium

- Titanium and its alloys offer
  - High strength to weight ratios
    - 100–160 ksi yield strengths
      - 55% of the density of steel
  - Corrosion resistance, including marine environments
  - Fully processed cast product mechanical properties comparable to wrought forms

Limitations

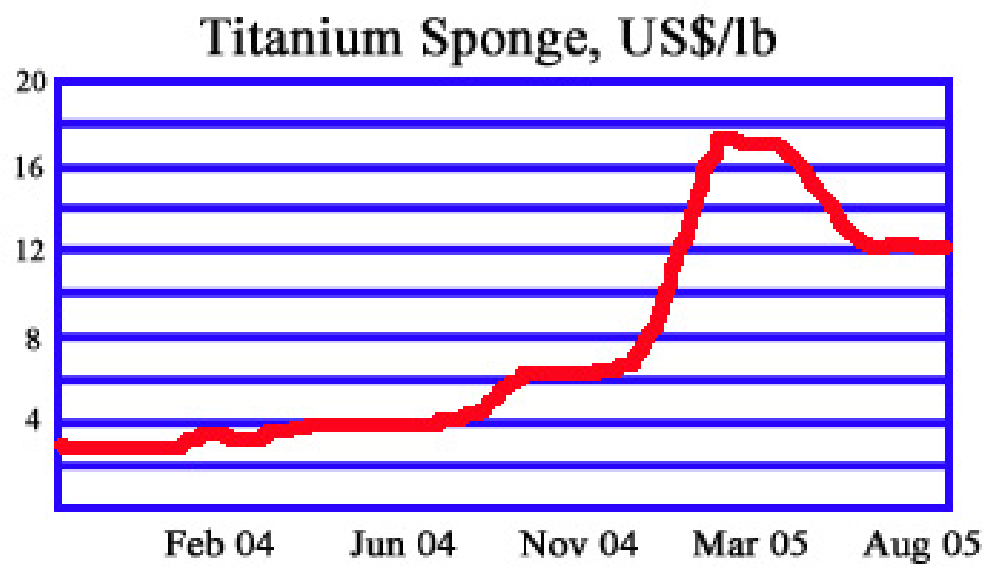
- Inferior wear resistance compared to steels with comparable hardness
  - May be addressed through coating or other approaches
- Relatively high cost
  - Kroll process
    - Labor-intensive
    - Batch
  - Multiple melting
  - Fabrication

“Titanium sponge prices, producers' backlogs up”

(Frank Haflich, American Metal Market, 10 February 2005)

“Titanium price increases and shortages may affect JSF programme”

James Murphy, Jane’s Defence Industry, 28 February 2006



Adapted from Metalprices.com

“Rising demand for titanium drains supply as prices soar”

Polly Yam, The Standard – “China’s Business Newspaper,” 8 June 2005

Factors affecting titanium damage tolerance

- Many factors combine to affect the damage tolerance exhibited by titanium alloys
  - Thermomechanical process history
  - Subsequent heat treatments
  - Crystallographic texturing
  - Interstitial and substitutional constituents
  - Presence of defects and inclusions
- Complex effect of each factor can lead to apparently conflicting results!

Data and processes of interest

Current presentation is confined to Ti-6Al-4V

Process/material variants

- Powder processing
- Single melt processing
  - Electron beam cold hearth melting
  - Plasma arc cold hearth melting
- Near-net-shape processing
  - Castings
  - Forgings
  - Flowforming
- Relaxed composition
  - Elevated oxygen

Damage tolerance properties

- Fracture toughness
- Low and high cycle fatigue S/N behavior
- Fatigue crack growth rate
- Stress corrosion cracking
- Impact toughness
  - Charpy V-notch
  - Dynamic tear

Cost reduction innovations must be accompanied by mechanical test data to support implementation

Fracture toughness – products

Ingot Practice	Form	Heat Treatment	Oxygen (wt %)	Ref
EBCHM - used an ingot made from 31.6% Ti sponge, 62.4% Ti-6-4 turnings and the balance aluminum shot and Al-V master alloy - from Titanium Hearth Technologies (THT) Remelted by TIMET	2.5" plate	Initial breakdown was in beta range Rolling was in alpha/beta (1725 °F) First anneal was 1725 °F for 2 hr Final mill anneal was at 1400 °F for 1 hr Statement that heat treatment was to optimize ballistic properties, not fatigue (which suffered slightly)	0.176	1
Melting not specified, but processing listed as standard at that time (~1976), so likely 3XVAR	1" plate	Ingots were "produced according to current [1976] mill practice". Ingot breakdown was in beta phase field, followed by alpha/beta cross-rolling, beginning at 1850 °F.	0.07; 0.09; 0.10; 0.12	2
Melting not specified, but processing listed as standard at that time (~1976), so likely 3XVAR	Rammed graphite casting	Believed to be as-cast, although not specified	0.09; 0.11; 0.18	2
Investment cast EFV track blocks Electrode was 80% plasma consolidated revert + compressed sponge briquettes + Al-V master alloy Single VAR melt prior to casting	Investment casting	Chemical milled HIPped in pure argon, 1650 +/- 25 °F and 15 ksi for 2 hr min Annealed at 1300 +/- 25 °F for 2 hrs, furnace cooled to 1000 °F, then air cooled to RT	0.19; 0.25	3
Not specified	Rammed graphite cast plates	HIPped at 1650 °F, 15 ksi, 2.25 hr Annealed at 1350 °F, 2.25 hr, furnace cooled to below 1000 °F, and then air cooled to room temp	0.17; 0.21	4

Fracture toughness – references

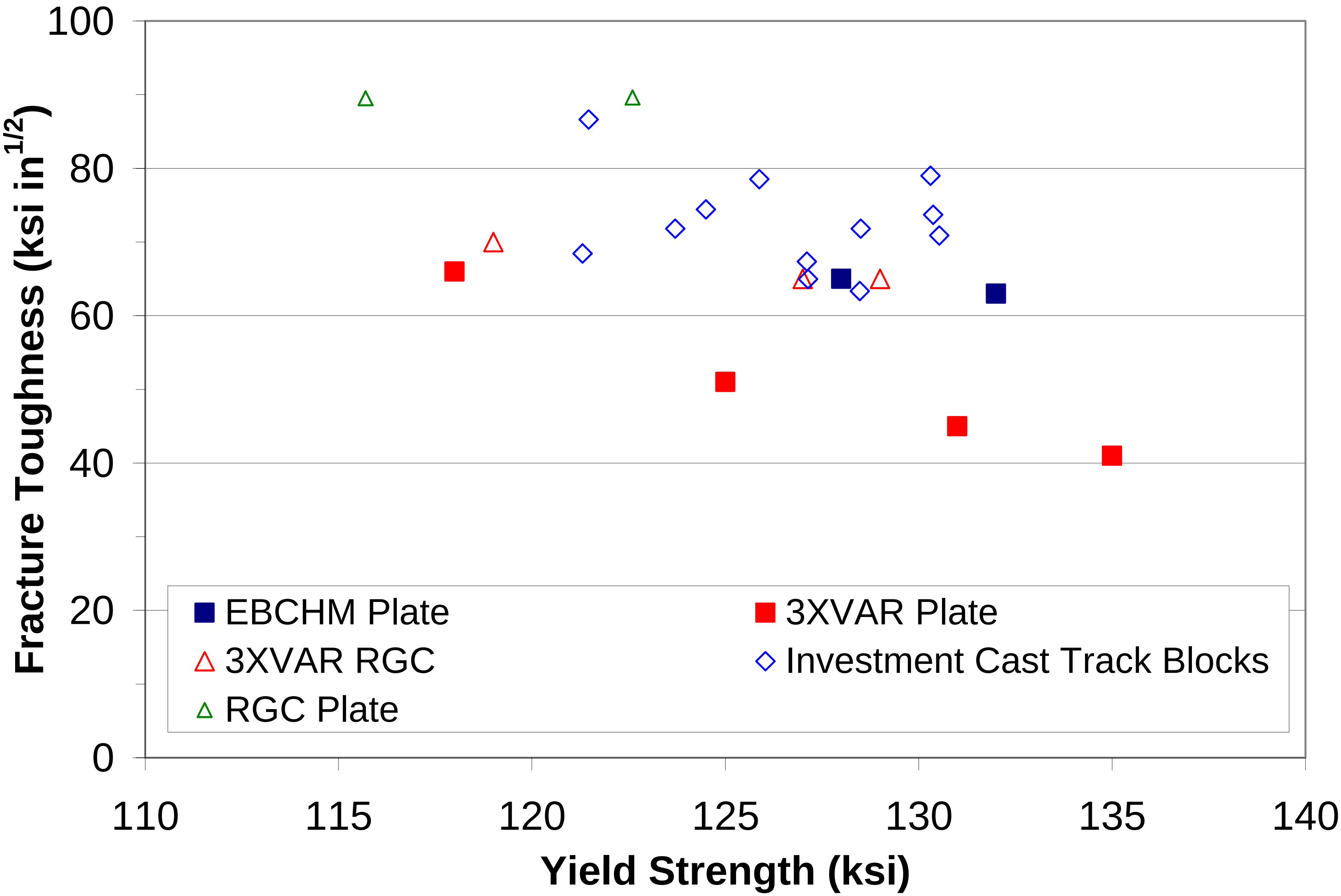
1) "The Mechanical and Ballistic Properties of an Electron Beam Single Melt of Ti-6Al-4V Plate," M. Burkins et al., ARL report (ARL-MR-515) Note: Listed as "Approved for public release; distribution is unlimited."

2) "Ti-6Al-4V for Marine Uses," G. Sorkin, I.R. Lane Jr. and J.L. Cavallaro, from Titanium & Titanium Alloys Scientific and Tech Aspects, Vol 1, Ed J.C. Williams and A.F. Belov, Plenum Press, 1976.

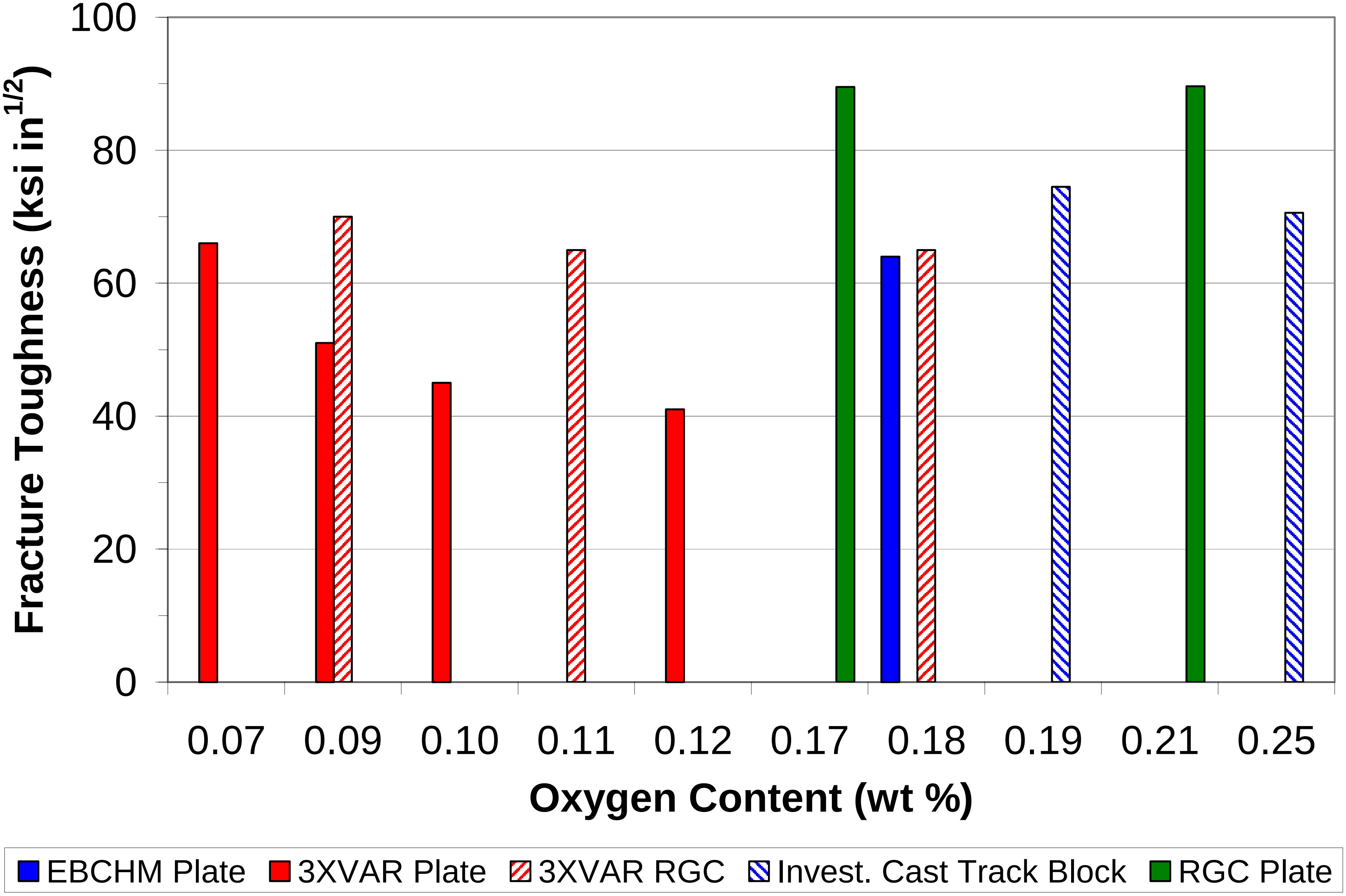
3) "Effect of Oxygen Content on Properties of Cast Alloy Ti-6Al-4V," Mustafa Guclu, Ibrahim Ucok and Joseph R. Pickens, Proceedings of 2004 TMS Annual Meeting, Charlotte, NC, 2004, pp. 135–143.

4) "Effect of Oxygen Content and Processing on Ti-6Al-4V Alloy Combat Vehicle Components" (presentation), Mustafa Guclu, Ibrahim Ucok, Urban DeSouza and Joseph R. Pickens, TMS 2003 Annual Meeting and Exhibition.

Fracture toughness vs. yield strength



Fracture toughness vs. oxygen content



High cycle fatigue – products & data

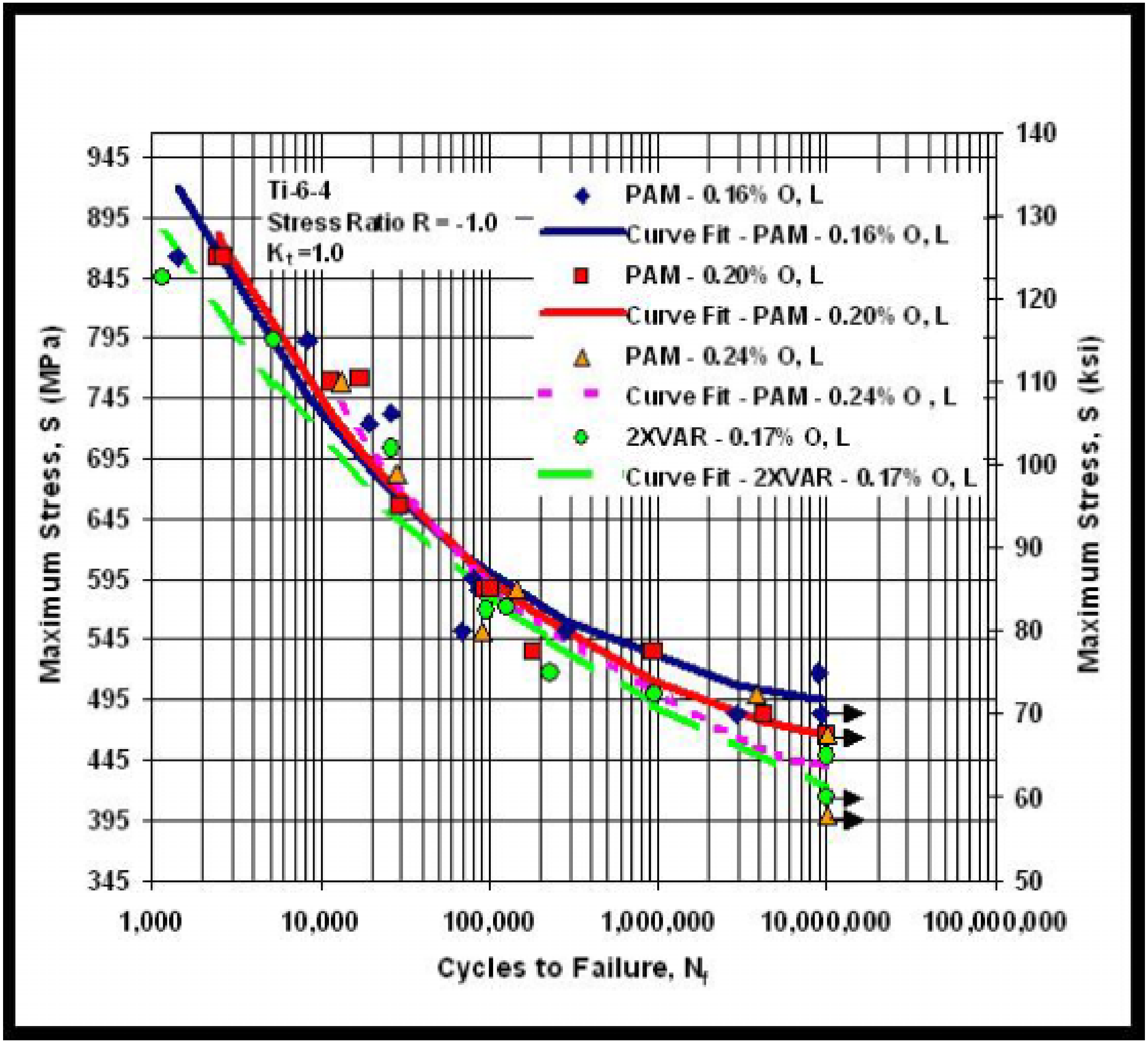
Ingot Practice	Form	Heat Treatment	Structure	Orientation	(Calculated) Fatigue Strength at 10^7 cycles (ksi)	Oxygen (wt %)	Ref
Single-melt PAM Upset forging was in beta field (2070 °F) Press forging in beta field (2070 °F) Final forging in alpha/beta (1750 °F) Billet cropped and turned to size Billet forged into bell housing in alpha/beta (1750 °F) in three major steps	Forging	Mill Anneal at 1350 °F for 3 hours, furnace cooled to 1000 °F and air cooled to RT	bimodal	L	71.7	0.16	5
					67.4	0.2	
					63.7	0.24	
2XVAR Upset forging was in beta field (2070 °F) Press forging in beta field (2070 °F) Final forging in alpha/beta (1750 °F) Billet cropped and turned to size Billet forged into bell housing in alpha/beta (1750 °F) in three major steps					61.1	0.17	
3XVAR investment cast	Investment casting	HIPped at 1650 °F/15 ksi argon/2 hr Chemical milled Vacuum annealed 1550 °F/2 hr	lamellar	N/A	70.3	< 0.20	6, 7
Machine chip intensive input, single vacuum arc melt at casting					69.5		
Machine chip and revert intensive ingot, single vacuum arc melt at casting					69.1		

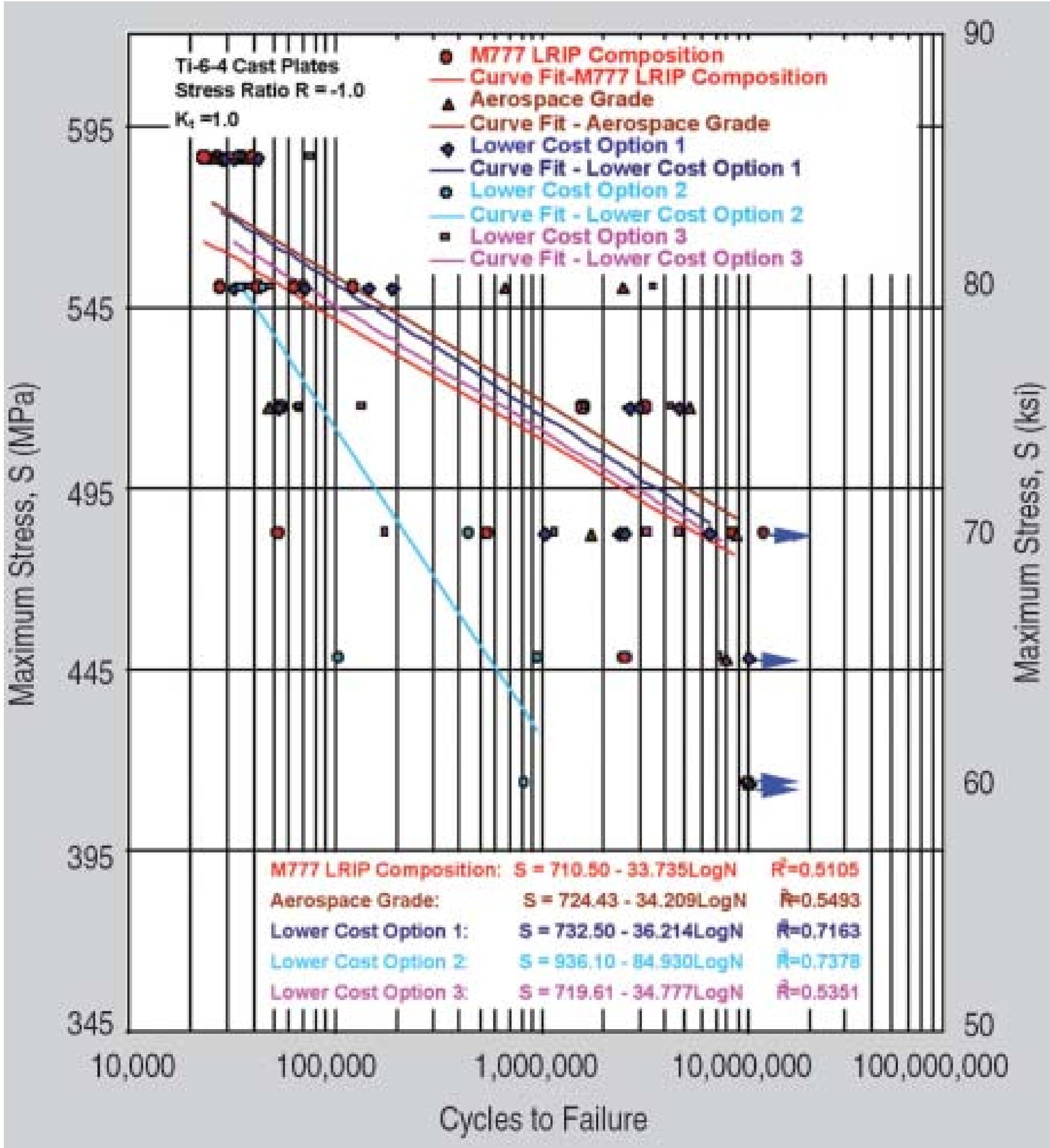
High cycle fatigue – references

5) "Effect of Oxygen Content on Fatigue Properties of Single-Melt PAM Processed Forged Ti-6Al-4V Bell Housings for Lightweight 155mm Howitzer," M. Guclu, I. Ucok, H. Dong and C. Hatch, Proceedings of 6th Global Innovations Symposium on Materials Processing, TMS 2005 Annual Meeting, San Francisco, CA, 2005, pp. 267–280.

6) "The Near-Net-Shape Manufacturing of Affordable Titanium Components for the M777 Lightweight Howitzer," Kevin L. Klug et al., JOM, November, 2004, p. 35.

7) "Affordable Ti-6Al-4V Castings," Kevin Klug et al., presented at the 2004 TMS Annual Meeting.


Ti-6-4
Stress Ratio R = -1.0
K_t=1.0
PAM - 0.16% O, L
Curve Fit - PAM - 0.16% O, L
PAM - 0.20% O, L
Curve Fit - PAM - 0.20% O, L
PAM - 0.24% O, L
Curve Fit - PAM - 0.24% O , L
2XVAR - 0.17% O, L
Curve Fit - 2XVAR - 0.17% O, L
Maximum Stress, S (MPa)
945
895
845
795
745
695
645
595
545
495
445
395
345
Maximum Stress, S (ksi)
140
130
120
110
100
90
80
70
60
50
1,000
10,000
100,000
1,000,000
10,000,000
100,000,000
Cycles to Failure, N_f


Ti-6-4 Cast Plates
Stress Ratio R = -1.0
K_t =1.0
M777 LRIP Composition
Curve Fit-M777 LRIP Composition
Aerospace Grade
Curve Fit - Aerospace Grade
Lower Cost Option 1
Curve Fit - Lower Cost Option 1
Lower Cost Option 2
Curve Fit - Lower Cost Option 2
Lower Cost Option 3
Curve Fit - Lower Cost Option 3
M777 LRIP Composition: S = 710.50 - 33.735LogN R^2=0.5105
Aerospace Grade: S = 724.43 - 34.209LogN R^2=0.5493
Lower Cost Option 1: S = 732.50 - 36.214LogN R^2=0.7163
Lower Cost Option 2: S = 936.10 - 84.930LogN R^2=0.7378
Lower Cost Option 3: S = 719.61 - 34.777LogN R^2=0.5351
Maximum Stress, S (MPa)
595
545
495
445
395
345
Maximum Stress, S (ksi)
90
80
70
60
50
10,000
100,000
1,000,000
10,000,000
100,000,000
Cycles to Failure

The path forward…

- Maximum reduction in titanium cost will require:
  - A lower-cost, continuous method to win titanium
  - Direct consolidation of won titanium into useful products without traditional melting
- Incremental cost reduction possible via:
  - A lower-cost continuous method to win titanium as a substitute for sponge
  - Single melt processes
  - Relaxed compositional requirements
  - Near-net-shape processes
- All strategies require accompanying mechanical property data to support implementation

Summary

- Data supports the use of reduced cost titanium processes/compositions
  - Oxygen levels of up to 0.25 wt% may offer sufficient damage tolerance for select applications
- Predictable tradeoff between yield strength and fracture toughness
- For compositional variations of a product form with common process histories, fracture toughness generally decreases as oxygen content increases
- High cycle fatigue behavior of single-melt and elevated oxygen forged and cast Ti-6Al-4V comparable to 2XVAR and 3XVAR material

- Open request: assistance in populating this activity with relevant data to aid in the quest to increase implementation of lower cost of titanium