2011 DOE Hydrogen and Fuel Cells and Vehicle Technologies Programs Annual Merit Review

Low Cost Titanium – Propulsion Applications

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Project ID#
PM 006

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Overview

Timeline

Project start date: October 2008
Project end date: October 2012
Percent complete: 20%

Barriers

- Material limits
- Lack of investment in improving the traditional reciprocator platform
- Cost of advanced materials and their processing

Budget

Total project funding:

- DOE – $650 K
- Cost Share – 75%

Funding FY11: $360 K

Partners

Industrial CRADA Participant:
Cummins Inc.
- Dr. Yong-Ching Chen

Supplier Development:
ADMA Products Inc.
- Dr. Vladimir Moxson

Support:
- Dr. PK Mallick University of Michigan at Dearborn

Goal

- The goal of this project is to expand the use of titanium in automobiles thereby reducing mass, increasing fuel efficiency and reducing green house gas emissions.
  - This goal will be met by producing titanium alloys of interest to engine manufacturers using very low cost feed materials and processing to produce components that meet or exceed performance requirements.

Objectives of Project

Reduce the cost to manufacture titanium components for reciprocating and rotating applications

- Evaluate the capability of an emerging low cost titanium powder metallurgy production technology for use in fatigue rated applications
  - Currently, high cost wrought processed titanium is used in low volume high performance propulsion systems
  - By reducing the cost of titanium and the associated processing the performance benefit can be applied to more engine platforms thereby impacting US fuel consumption
- Assess the efficiency gain possible with increased use of titanium in propulsion systems

Deliverables – FY11

- Strain-controlled fatigue data from press/sintered/HIP and press/sintered/forged Ti6Al4V fabricated from TiH_2 powder
- An initial assessment of the efficiency gains possible with titanium used in rotating and reciprocating components
- Rotating beam fatigue from press/sintered and rod-rolled Ti1Al8V5Fe fabricated from TiH_2 powder
- Technical cost model of titanium components produced from TiH_2

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Efficiency Improvements

- Large number of analysis performed over many years with respect to titanium and fuel efficiency
  - Ranges from 20 to 60% and is dependent on engine and vehicle system
    - Single component mass savings of 60% in suspension and chassis reported General Motors and Timet
    - PNNL reported mass savings of 21% on FC vehicle
- It is understood that Ti can reduce mass, increase operating temperatures and improve efficiency
  - 14 OEMs have made limited titanium component production runs
- What stops titanium from large impact is cost
  - This project is focused on improving cost of titanium so that benefits can be realized

Technical Approach

- **Technology Development**
  - **This is a highly leveraged activity applying technology developed by a Department of Energy Global Initiative for Proliferation Prevention (DOE/GIPP) project performed in the Ukraine**
    - Fabricate test bars from low cost TiH_2 powder using low cost high yield powder metallurgy methods
      - Press, sinter, HIP
      - Press, sinter and forge
      - Press, sinter and rod-roll
    - Fatigue test samples machined from test bars using a strain controlled fatigue test that has been used to qualify titanium materials in propulsion systems
    - Develop cost model for process deployment

- **Technology Deployment**
  - The test methods are to be selected from procedures used by Cummins Inc. to qualify titanium materials and should be readily applicable to speed up the qualification
  - Test bars are to be fabricated at the commercialization partner of the DOE/GIPP project, ADMA Products Inc.
    - ADMA has been producing approximately 35,000 lbs of TiH_2 powder per year in the Ukraine
  - US TiH_2 powder production now being performed in small quantities
    - Large vessel being installed

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Technical Progress

- Fabrication of high bars by rod rolling was completed
  - Heat treatment studies and tensile test characterization was completed
    - RBF and strain controlled fatigue samples to be fabricated
- Ti6Al4V
  - New hot forming and heat treatment schedule to improve microstructure for fatigue resistance
- Ti1Al8V5Fe
  - New alloy developed to enhance ductility without strength decrease
    - Reduced oxygen and different forming process
- Contract at University of Michigan at Dearborn - modeling of titanium impact on efficiency
  - Dr. PK Mallick
- Initiated cost models based ADMA US based powder production
  - Prior work was performed with powders produce in Ukraine

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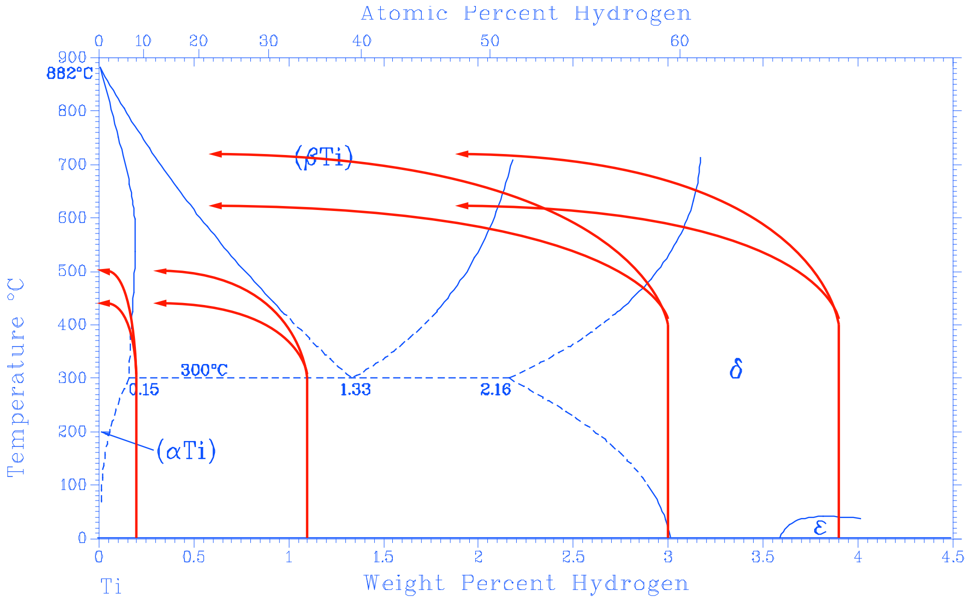
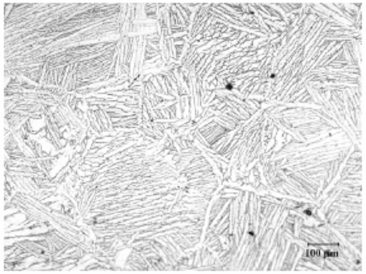
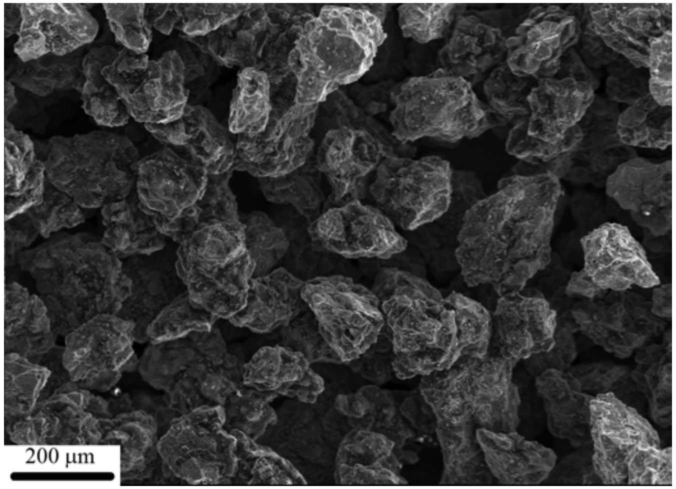
Low Cost Titanium Hydride Processing

- TiH_2 Powder – direct press and sinter to reduce machining loss
  - Greater than 96% dense
  - Fine grain sizes observed in TiH_2 pressings may meet the fatigue requirements
  - Will have application in other components i.e. valves etc…





Fine as-sintered grain size

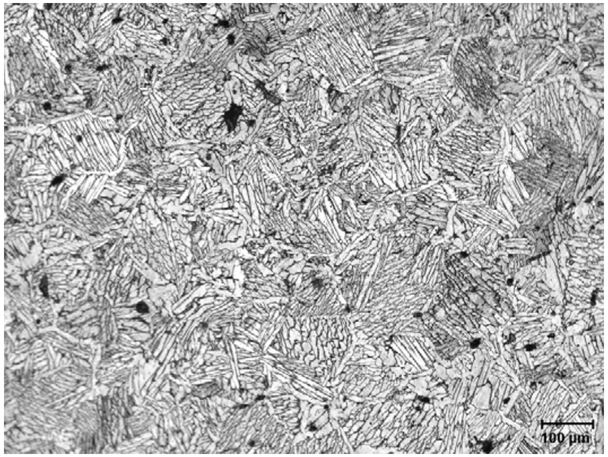


Press and Sinter Bars from TiH_2 Powder

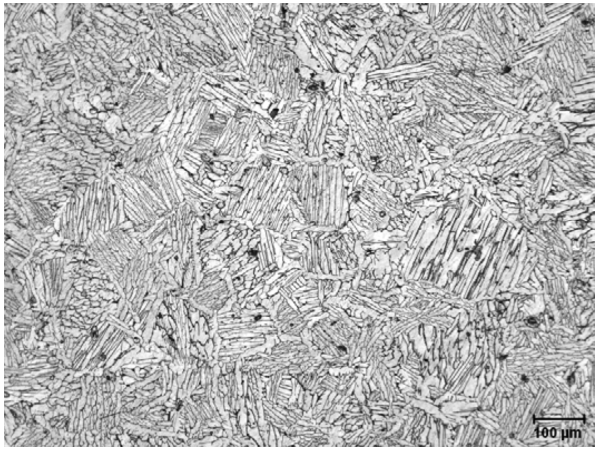
- Fabricated bars for tension testing to determine interstitial content
- Average bulk density greater than 98%
  - Core density is lower – new sintering parameters at ADMA focused on extrusion that did not require full density

Composition	C	O	N	H	Fe	Al	V	Oxygen equivalent
As-Received	0.001	0.192	0.022	0.0006	0.083	6.25	4.3	0.26976
Target 1	0.009	0.289	0.021	0.0006	0.130	6.18	4.4	0.37503
Target 2	0.009	0.176	0.022	0.0006	0.320	6.04	4.3	0.3028
Target 3	0.010	0.227	0.024	0.0004	0.200	6.3	4.3	0.33552
Target 4	0.010	0.249	0.023	0.0004	0.340	6.27	4.4	0.38275

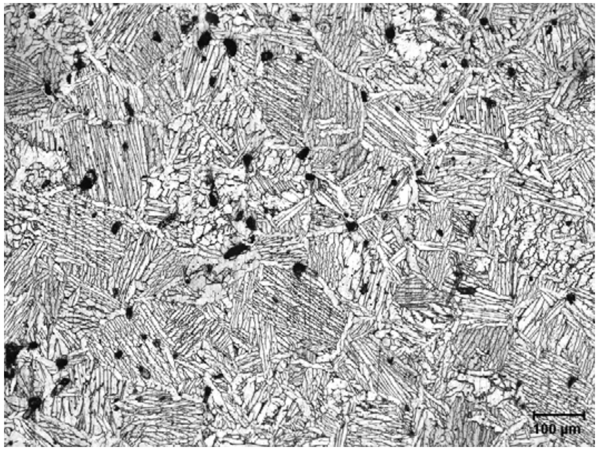
Microstructure of Sintered T6Al4V with varying Oxygen and Iron content



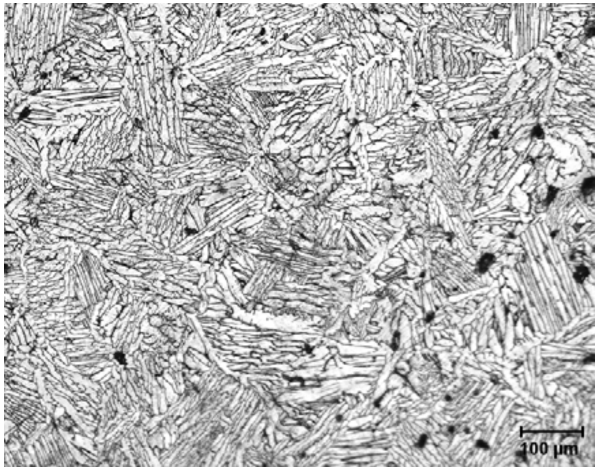
As Received Powder



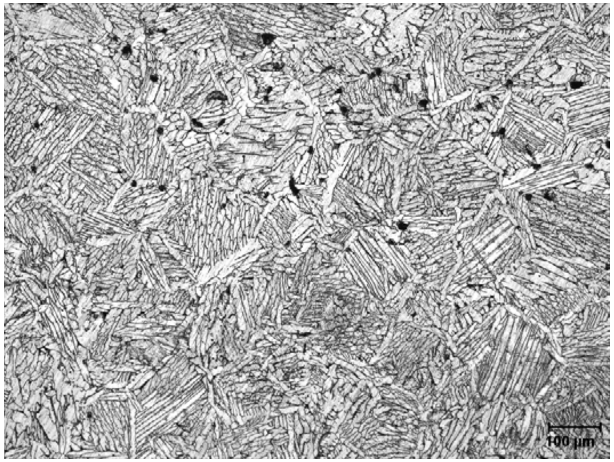
Target 1



Target 2



Target 3



Target 4

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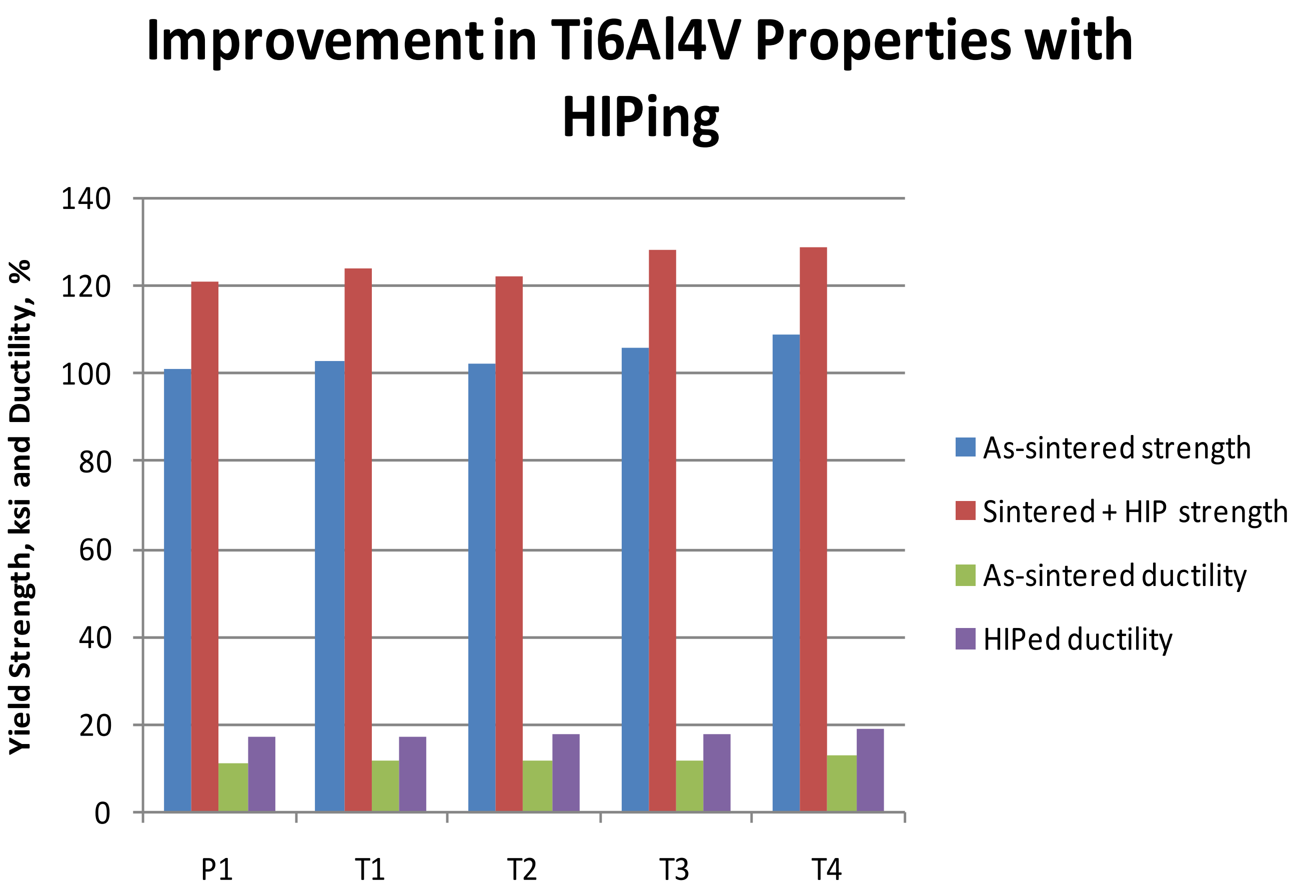
Preliminary Tensile Test Results

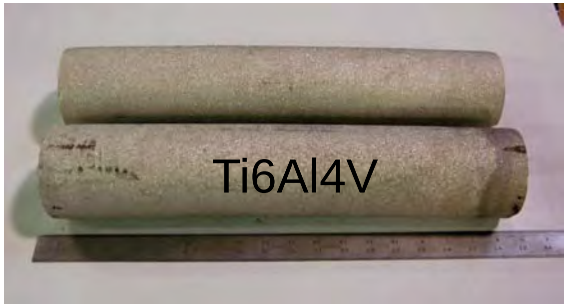
- Interstitial content from Target Composition 4 produced highest strength and ductility and will be used for future development
  - 2400 ppm oxygen and 3400 ppm Fe

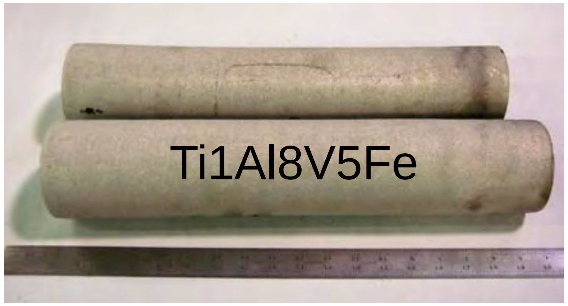


Semi-finished bar stock

- There has been some effort in beta alloy development from other emerging low cost titanium powders however all have used CIP/sinter and extrusion or vacuum hot pressing and extrusion
  - For the automotive industry round bar is a more useful semi-finished product and is most cost-effectively produced by rod-rolling
- Selected a beta alloy and Ti6Al4V to be consolidated by CIP/Sinter and rod rolling
  - Ti6Al4V – to be used to compare consolidation process with extrusion
  - Ti1Al8V5Fe – a low cost alloy developed in 1950's and dropped due to Fe segregation that occurs during melt
- Rod Rolling Trials completed
  - Ti6Al4V and Ti1Al8V5Fe Billets sintered to greater than 97% dense
  - Rolled to 16mm

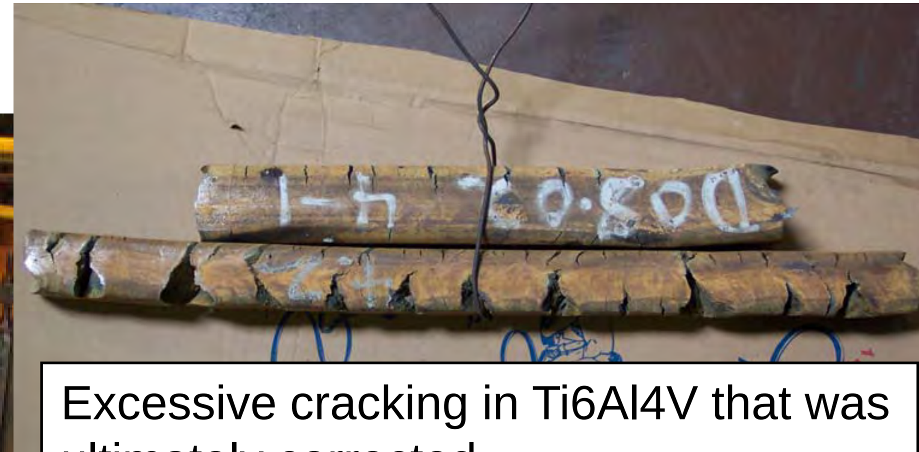
90 mm Rod Rolling Billets





Rod Rolling

Successful rod rolling of solid state processed Ti1Al8V5Fe beta alloy



Excessive cracking in Ti6Al4V that was ultimately corrected

Ti6Al4V and Ti1Al8V5Fe bars rolled from CIP/Sinter billets

Virtually 100% yield from starting billet (prior to peel)

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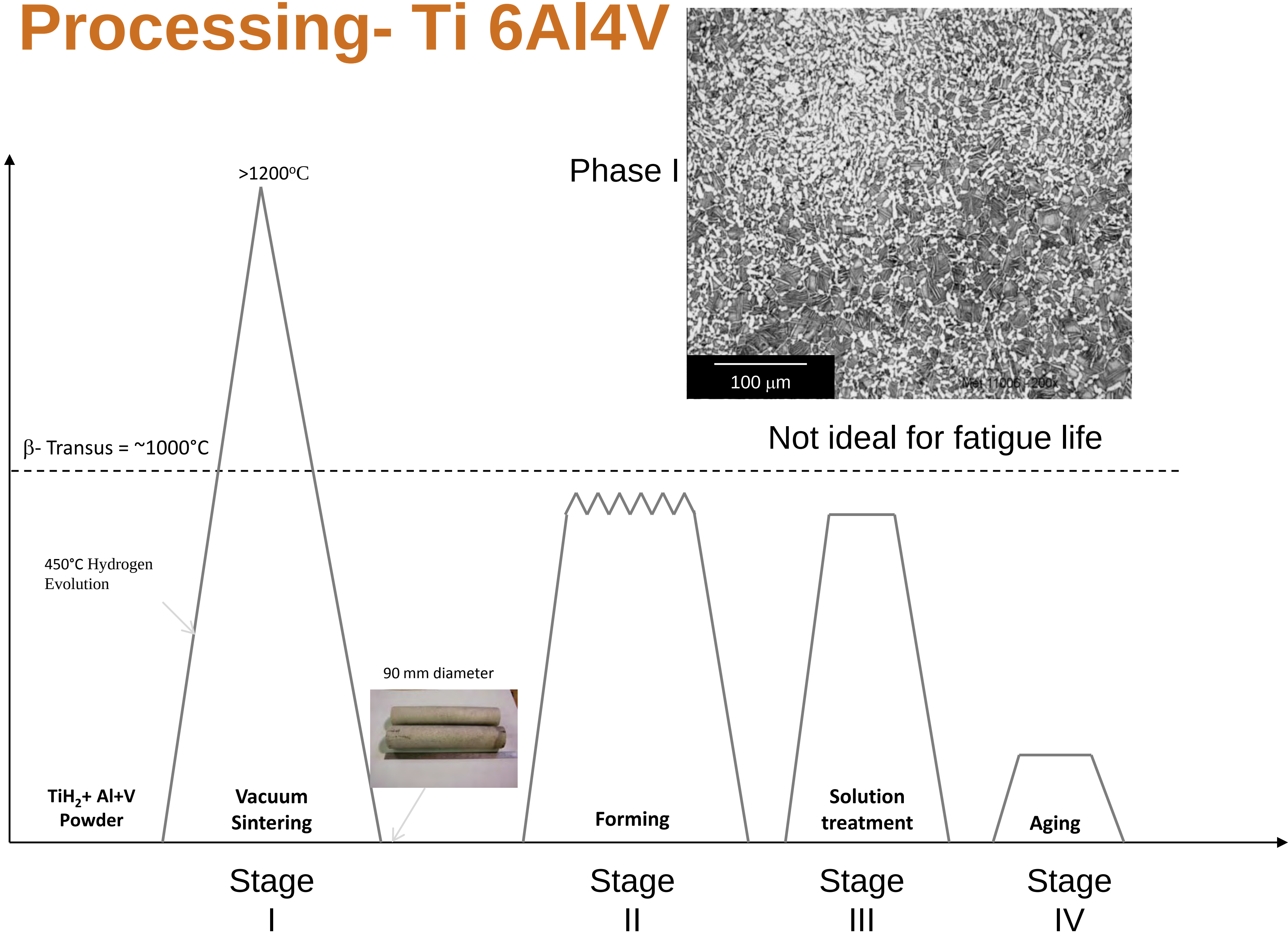
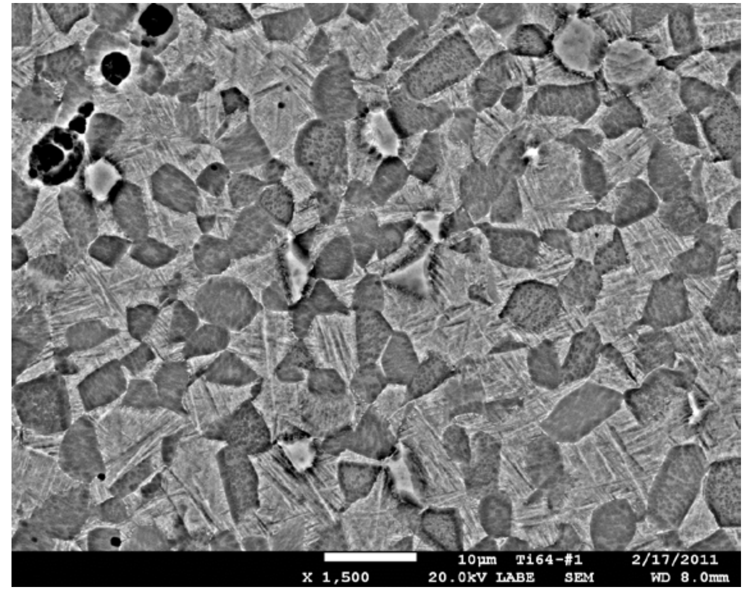
Processing- Ti 6Al4V

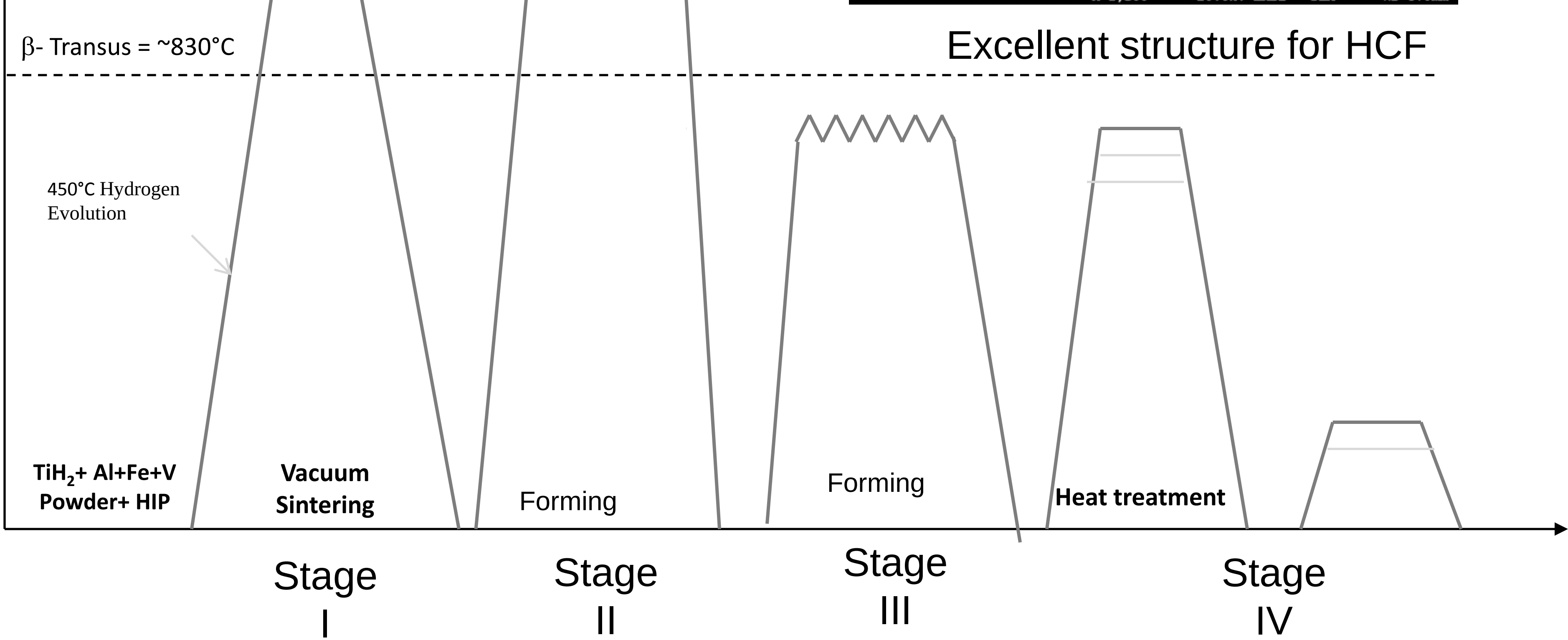


Processing- Ti 64

Phase II

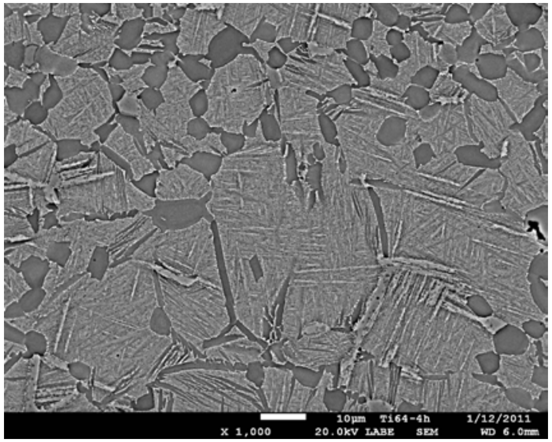


Excellent structure for HCF

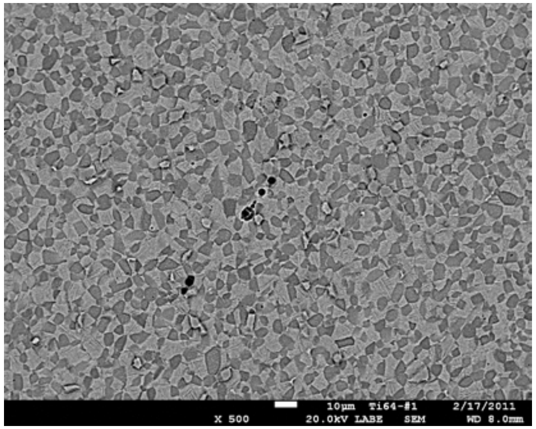


Ti6Al4V Tensile Properties

- As-formed properties of Ti6Al4V
  - Yield strength 130 ksi (900 MPa) and ductility close to 20%
    - Increase in yield strength and ductility
  - Material should have very good fatigue life previous structures would not



Previous microstructure



New microstructure

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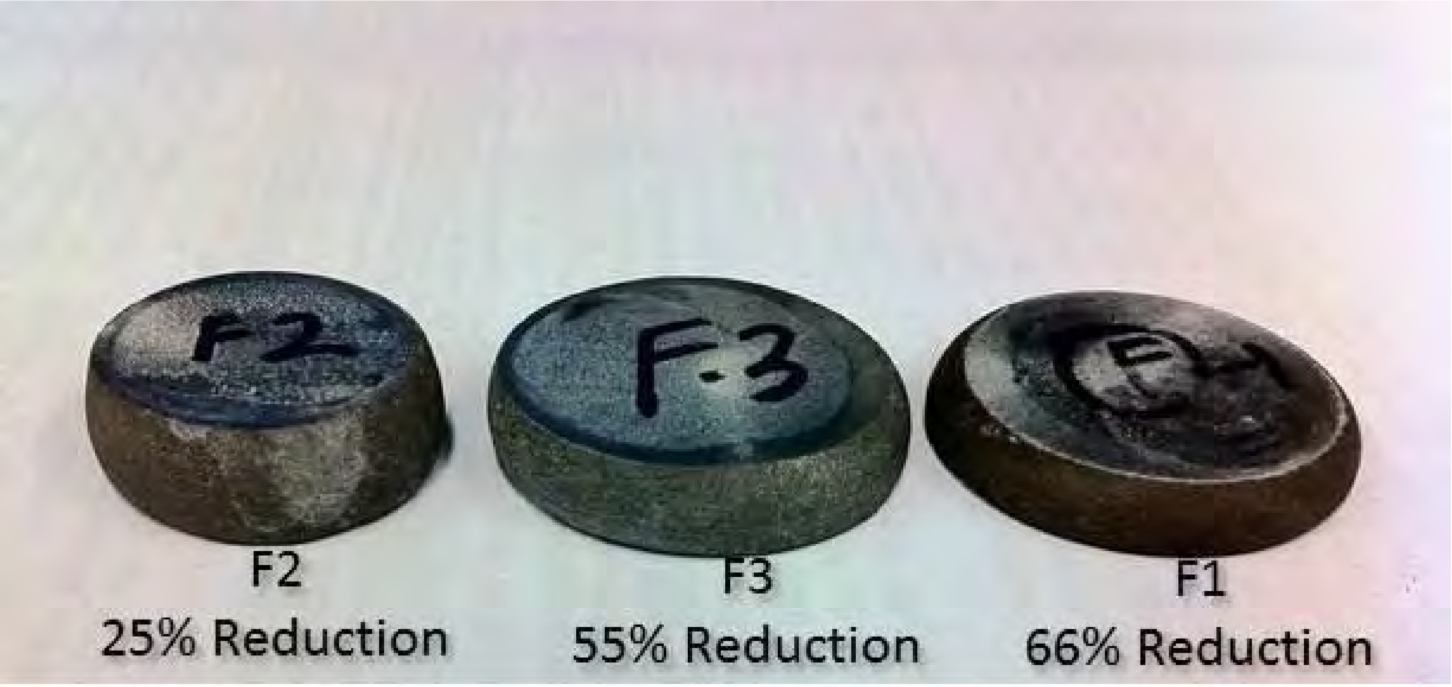
Forging to Blanks for Cummins Use



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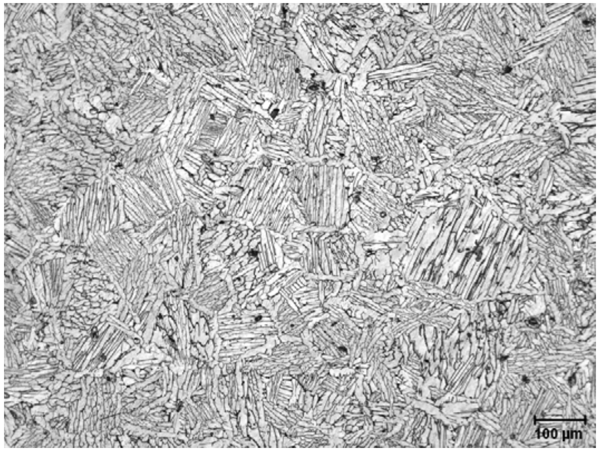
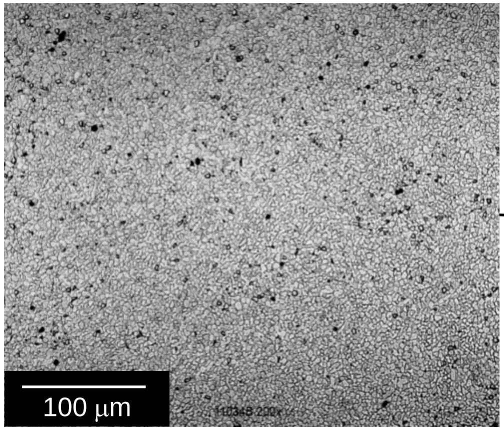
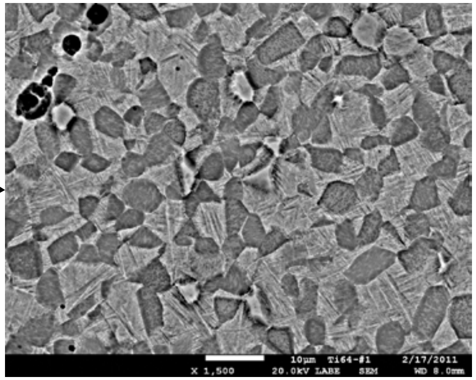
Ti6Al4V from Low Cost TiH_2 Powder

- Development of Fatigue Life
  - Microstructure for LCF different than HCF
    - Two processing paths developed from ideal microstructure







As-sinter plus HIP

Hot forming plus heat treat structure

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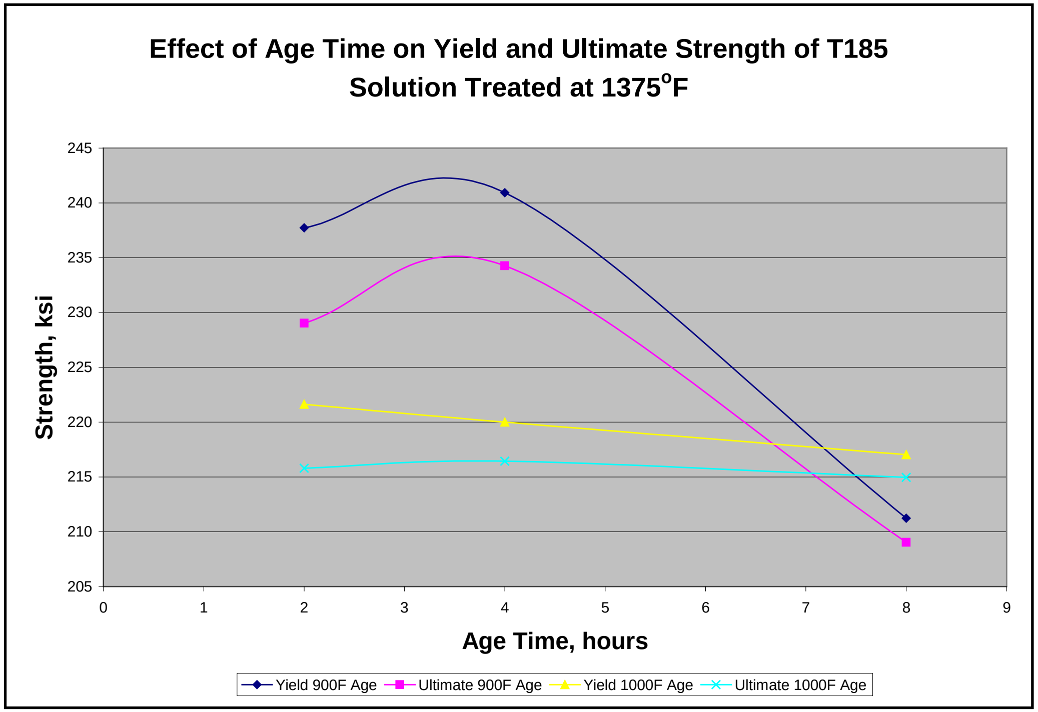
High Strength Ti1Al8V5Fe

- Ti185 can benefit from heat treatment like other beta alloys
  - Precipitation of fine alpha
  - In our peak condition the alloy exhibited
    - 230 ksi, 240 ksi, yield and ultimate strength, respectively with 5% elongation
    - Elongation is on the lower side; but not uncommon for high strength beta alloys such as “C” and 10-2-3
  - First iteration on the alloy and we added 0.32 weight percent oxygen to bring our total oxygen to 0.5

Typical Age Curve



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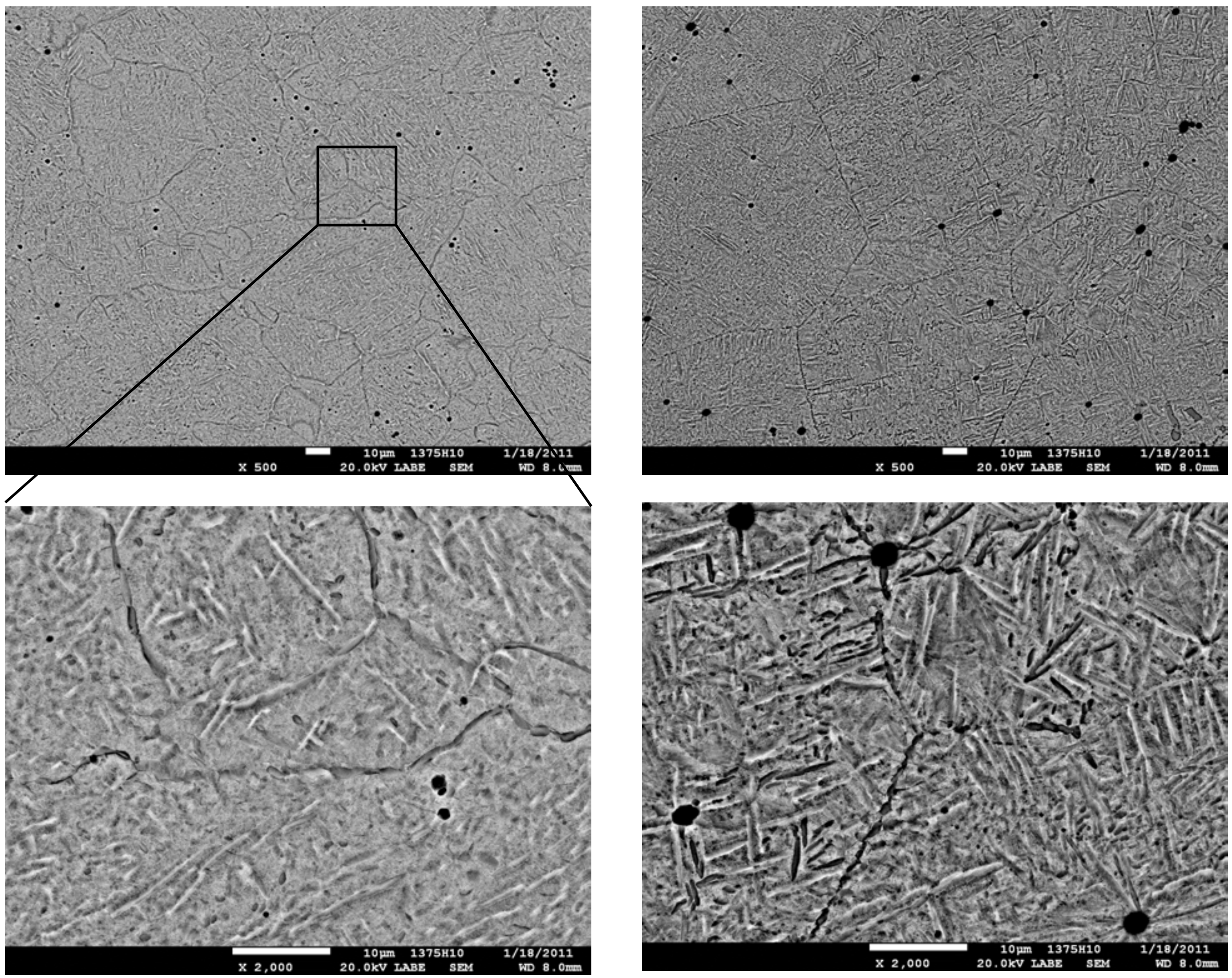
Ti1Al8V5Fe- Heat Treatment Microstructural Characterization

Solution Treatment
746°C for 1 hr + 4 hrs Aging at 900 F

0.7% O_2 | 0.35% O_2

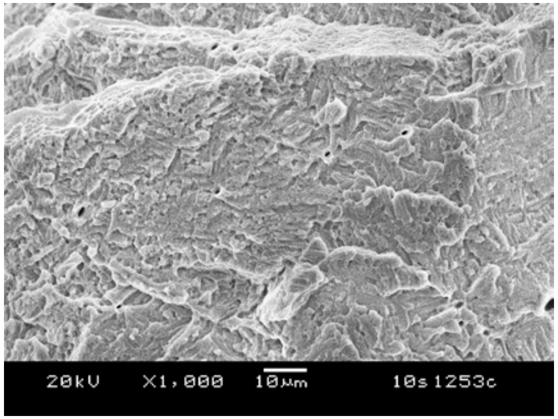


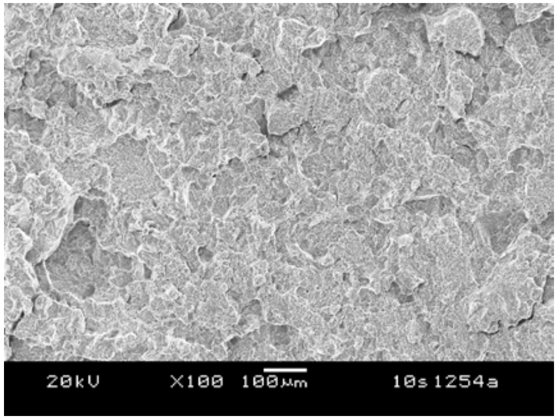
Fracture Surface Morphology After Tensile Testing

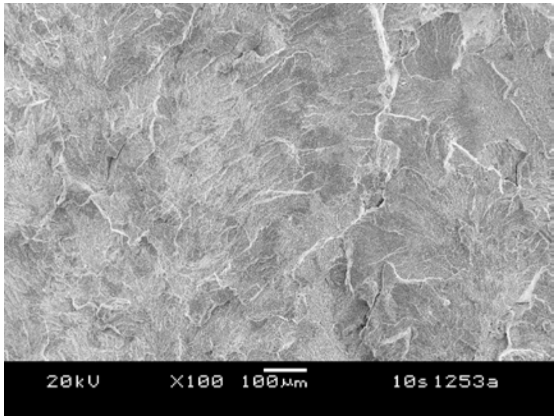
0.7% O_2

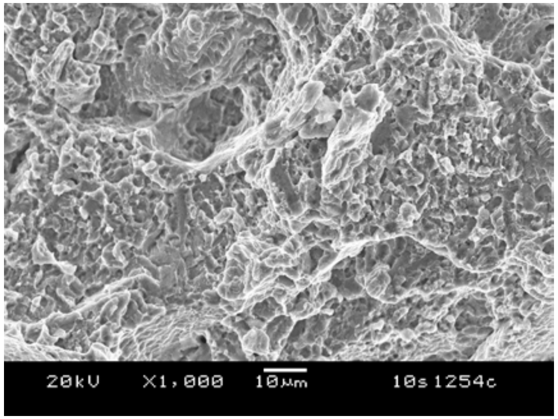
0.35% O_2

Solution Treatment
746°C for 1 hr + 4 hrs Aging at 900 F









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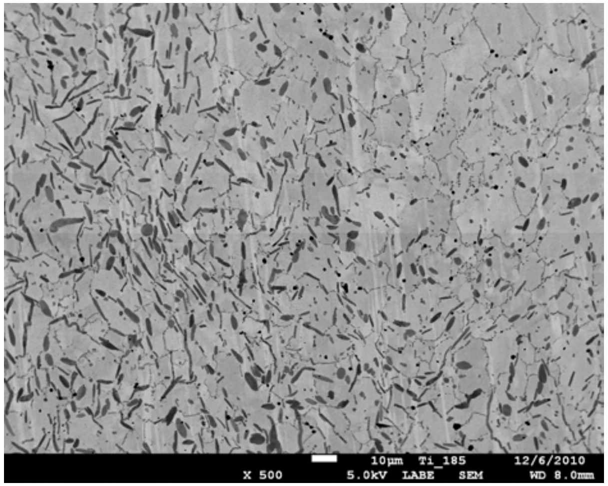
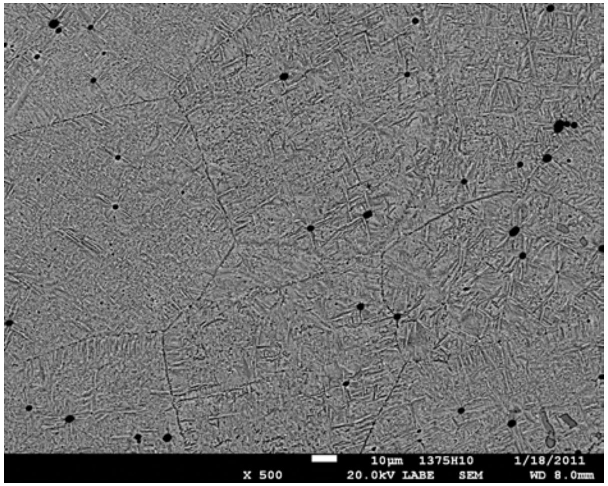
Ti185 New Alloy and Processing

- Strength levels maintained at excess of 240 ksi (1700 MPa) now with ductility over 12%
  - Better than conventional beta alloy properties

- Structure improved by processing and will be fatigue tested
  - New structure more homogeneous and without grain boundary alpha



Previous microstructure



New microstructure

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Engine Mass Analysis at UMD

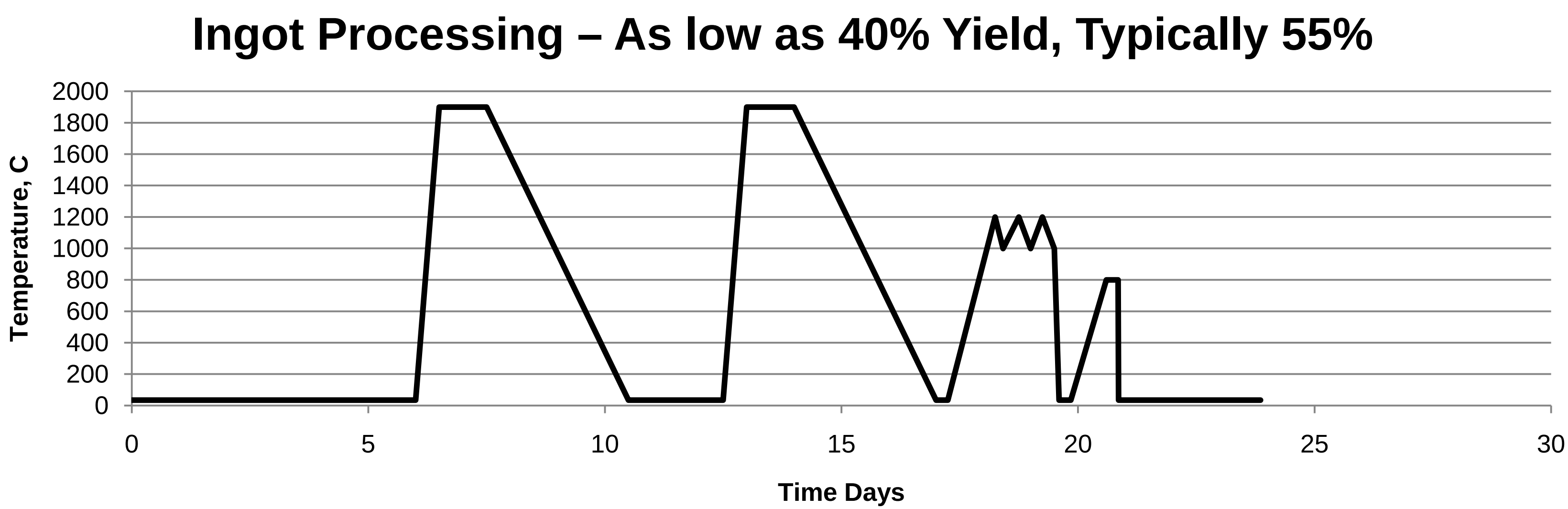
- UMD initiated analysis with Toyota Echo engine
- Cummins to provide diesel engine of interest

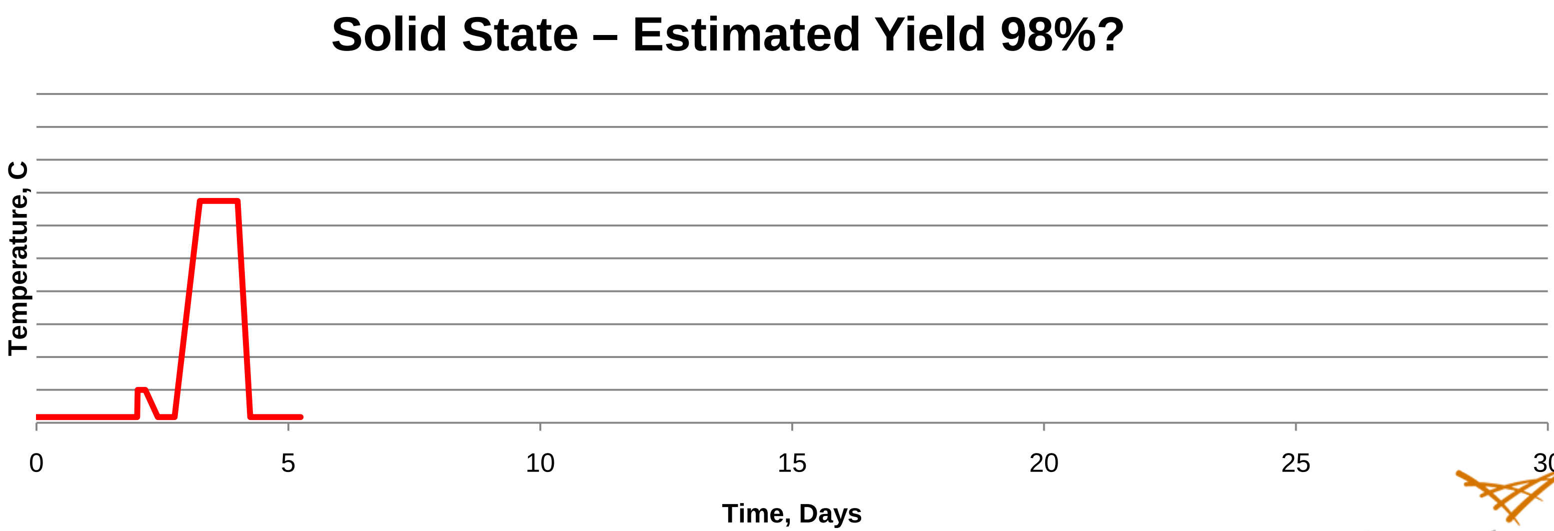
Engine Component	Weight per part (gm)	Number of parts in engine	Total Weight (gm)
Inlet Valve	34	8	272
Exhaust Valve	27	8	216
Valve Spring Retainer	8	16	128
Valve Spring	20	16	320
Valve Lifter	29	16	464
Inlet & Exhaust Common Bearing Cap	165	1	165
Piston(w rings)	236	4	944
Con-Rod	215	4	860
Wrist Pin	64	4	256
Con-Rod Bolt	18	8	144
Conrod-Cap	90	4	360
Conrod Cap Bearing (Each 8 gms)	16	4	64
Exhaust Camshaft	1664	1	1664
Intake Camshaft	2664.85	1	2664.85
Crankshaft	10177.5	1	10177.5
Timing Chain	371	1	371
Flywheel	6633.8	1	6633.8
Crankshaft Bearing Cap	344	4	1376
Crankshaft Bearing Cap (Center)	390	1	390
Crankshaft Bearing	18	8	144

Powder/Part Cost Analysis Being Performed

- Three groups
  - PNNL through an ITP project
  - ORNL through OVT
  - PNNL as part of this project
    - Specific application

Time and Temperature to Produce Wrought Ti6Al4V





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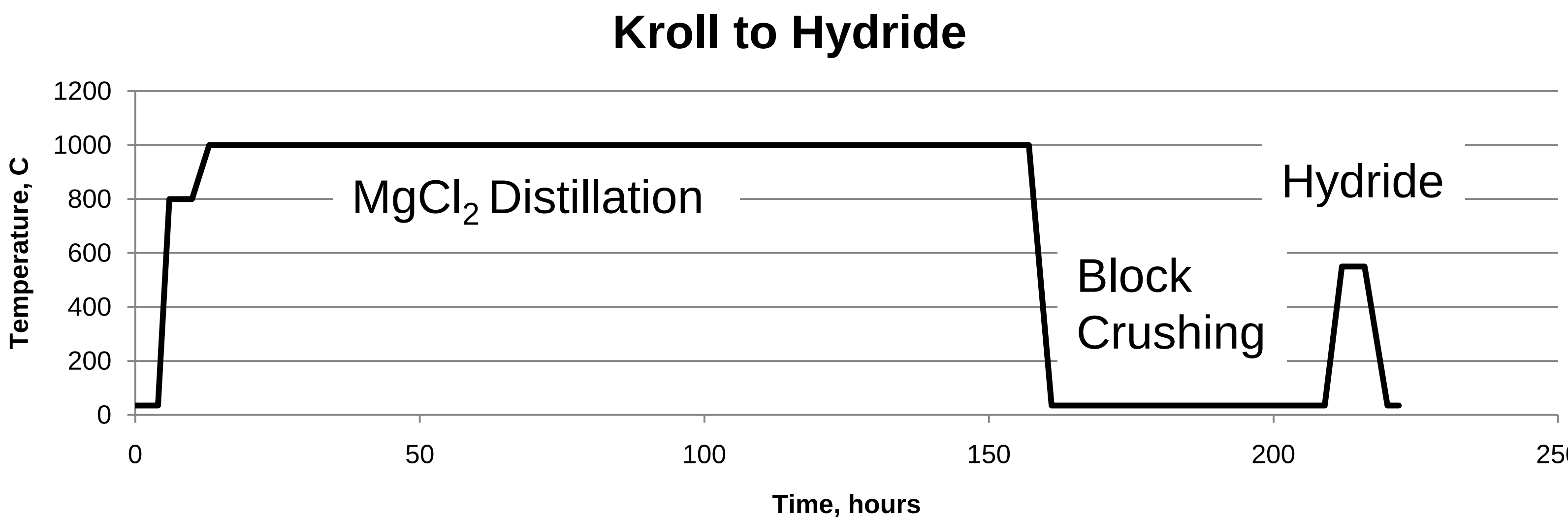
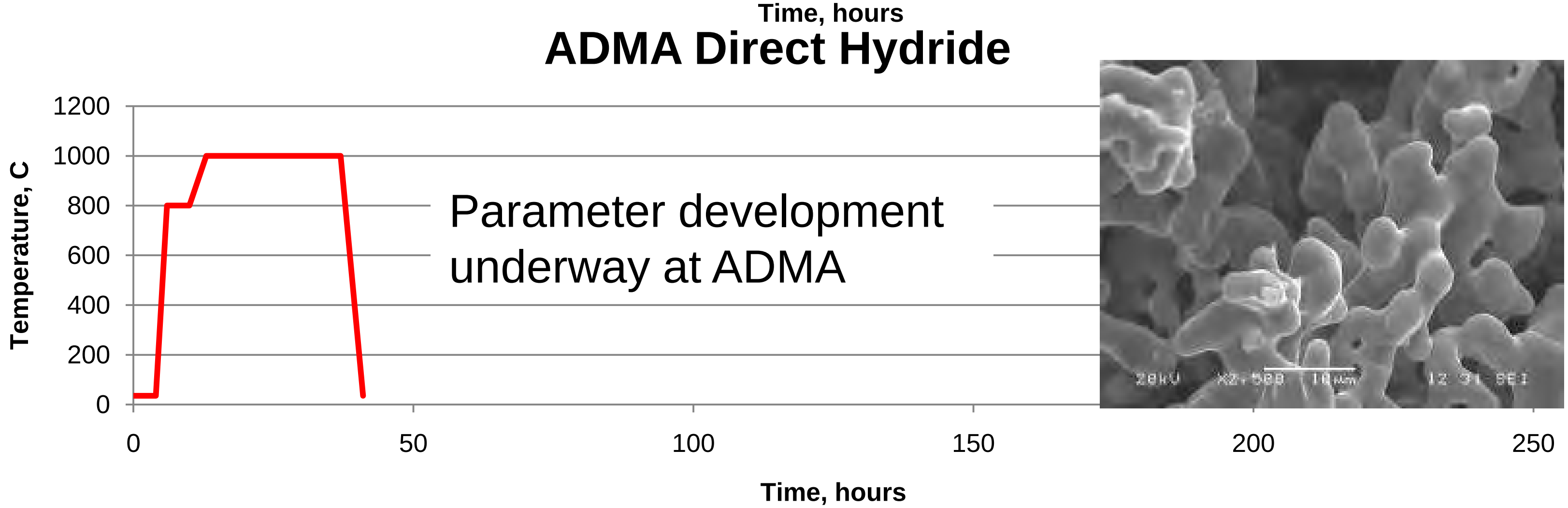
Kroll produced Hydride vs ADMA Approach





Future Work

- Complete fatigue testing with samples machined from blocks large enough for Cummins use
  - Ti 6Al4V in formed and as-sintered conditions
    - RBF and strain controlled fatigue
- Complete fatigue and shear testing on more optimum processed Ti1Al8V5Fe
- Complete engine efficiency analysis and perform analysis of efficiency improvement with titanium
  - Identify additional applications for titanium
- Complete and summarize cost models

Summary

- **A titanium powder developed during a DOE/GIPP project appears to produce a product with mechanical properties sufficient for a propulsion application from a very low-cost press and sinter process**
  - Could replace costly ingot processed forgings
    - Eliminates yield loss associated with ingot forging
    - Greater than 50% cost reduction predicted from yield savings alone
  - Unique properties are developed during sintering of TiH_2
    - High density – critical to fatigue initiation
    - Fine-grain size – import to reduce fatigue crack propagation
- **Cummins Inc. has identified a relevant applications using the Ti6Al4V alloy and provided the requirements to adequately assess the performance of the press/sinter/forged bars produced from TiH_2**
- **Resolve issues associated with chemistry, porosity and microstructure for the Ti6Al4V and Ti1Al8V5Fe alloys**
  - HIPing bars has allowed for downselection of the 2400 ppm O and 3400 ppm Fe for future Ti6Al4V testing with Cummins
    - Microstructure, chemistry and strengths now comply with Cummins materials standard
- **The impact of titanium on engine efficiency is being modeled**
- **Multiple technical cost models are being developed to fully understand the cost of the titanium components made from TiH_2**