2010 DOE Hydrogen Program and Vehicle Technologies Program AMR Oral Presentations and Posters

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 – $475 K
- Cost Share – 75%

Funding FY10: $300 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

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

- Strain-controlled fatigue data from press/sintered and press/sintered/forged Ti6Al4V fabricated from TiH_2 powder
  - Now added press/sinter/HIP
- 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 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
      - 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
      - More vessels are readily available
      - US production under development

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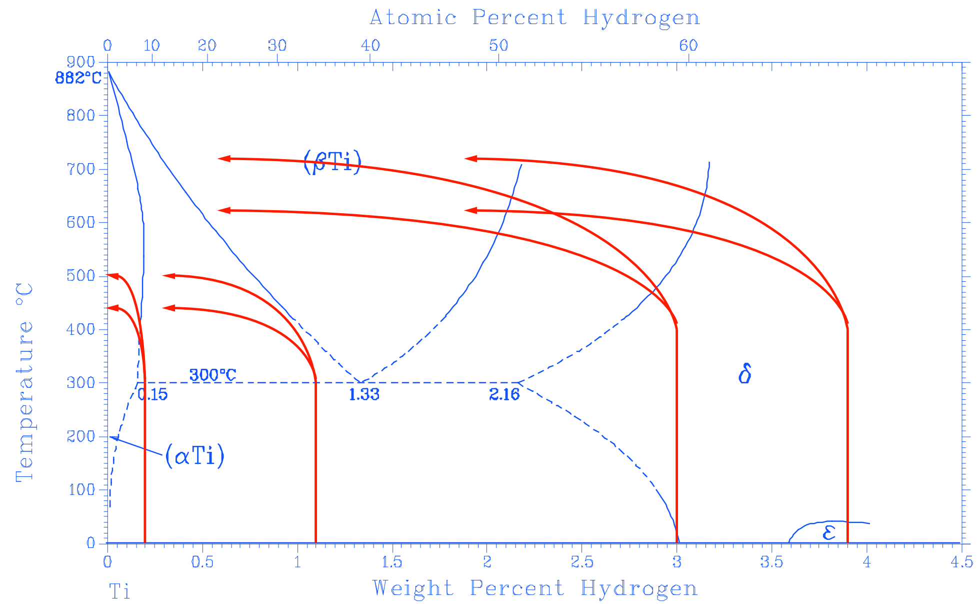
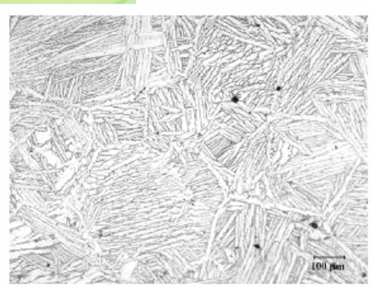
Technical Progress

- Fabrication of high bars by rod rolling was completed
  - Heat treatment studies and tensile test characterization was completed
    - RBF samples to be fabricated
- Ti6Al4V
  - Encountered an issue with oxygen content of starting powder
    - New vessels used for powder production produce lower oxygen content powder – good
    - New task added to the work to understand the effect of oxygen
      - Encounter a delay due a sintering change at ADMA that resulted in low density
- Identified a source for modeling of titanium impact on efficiency
  - Will be letting a contract to Dr. PK Mallick University of Michigan at Dearborn

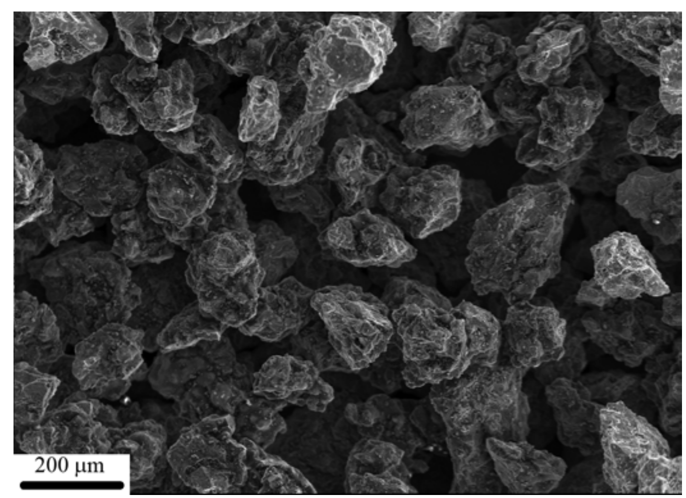
Low Cost Titanium Hydride Processing

- 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 approximately 70 bars for RBF and tension testing to determine interstitial content
- Average bulk density greater than 98%
  - Core density is lower – new sintering paramters at ADMA focused on extrusion that did not require full density
    - Sintering will be adjusted

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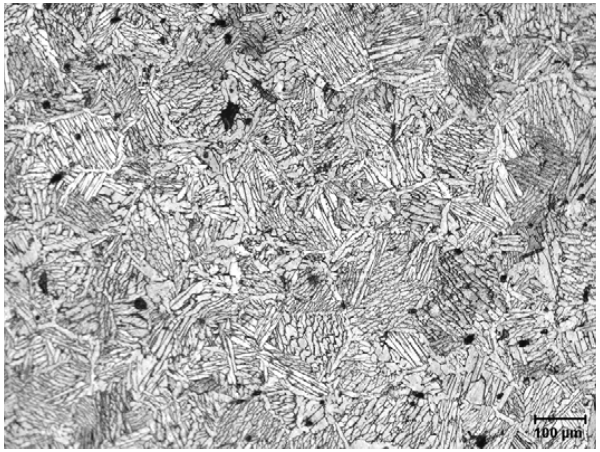
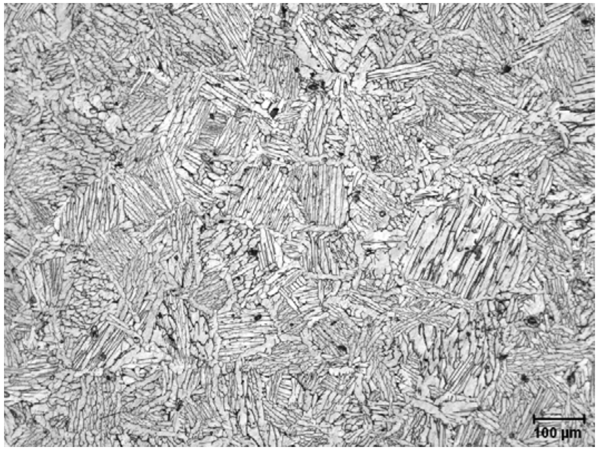
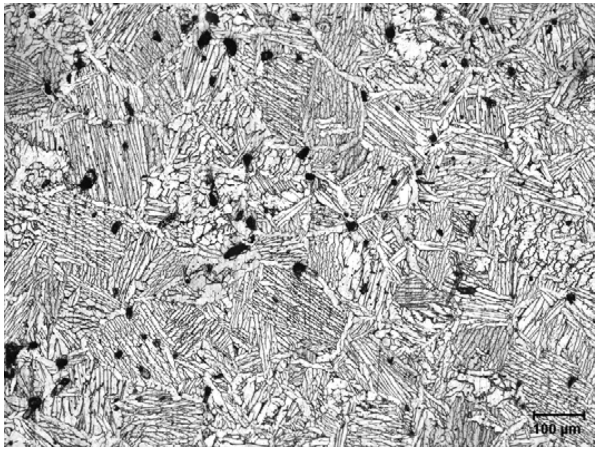
Microstructure of Sintered T6Al4V with varying Oxygen and Iron content



As Received Powder



Target 1



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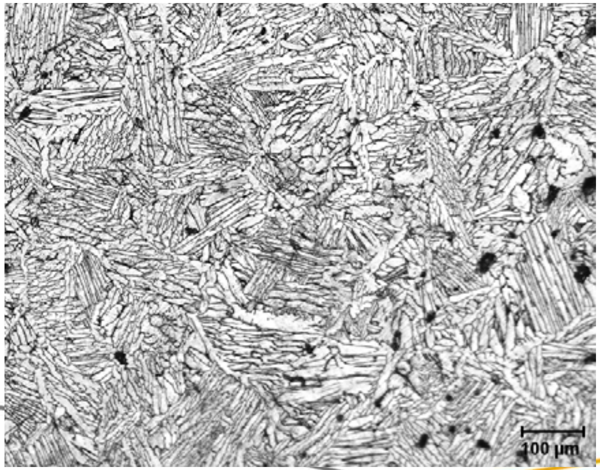

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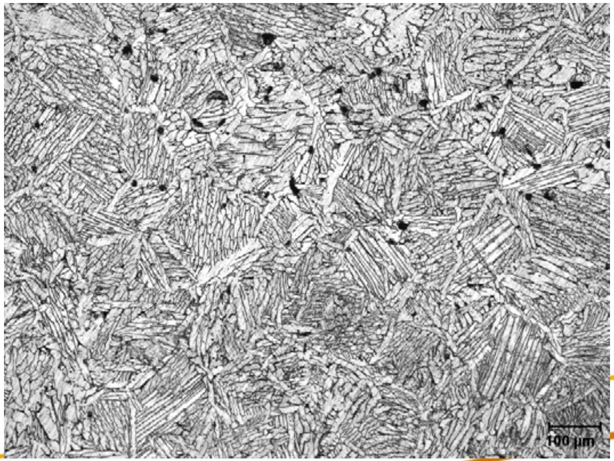


Target 4

Preliminary Tensile Test Results

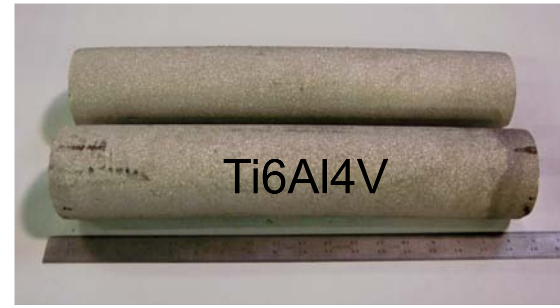
									Strength, ksi	
Composition	C	O	N	H	Fe	Al	V	Oxygen equivalent	0.2% Offset	UTS
As-Received	0.001	0.192	0.022	0.0006	0.083	6.25	4.3	0.26976	96	117
Target 1	0.009	0.289	0.021	0.0006	0.130	6.18	4.4	0.37503	98	120
Target 2	0.009	0.176	0.022	0.0006	0.320	6.04	4.3	0.3028	96	117
Target 3	0.010	0.227	0.024	0.0004	0.200	6.3	4.3	0.33552	99	121
Target 4	0.010	0.249	0.023	0.0004	0.340	6.27	4.4	0.38275	100	124

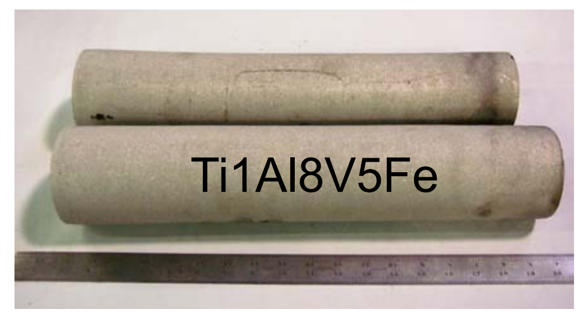
- Preliminary data
  - 0.2% offset strengths are lower than the desired 115,000 psi
    - Does not correlate with O-equivalent
  - Results will be analyzed to predict new composition that meets 115,000 psi.
- As received implies only alloyed for Al and V
- Further analysis revealed less than 94% dense cores
  - HIPing will be performed and then re-test and RBF

Semi-finished bar stock

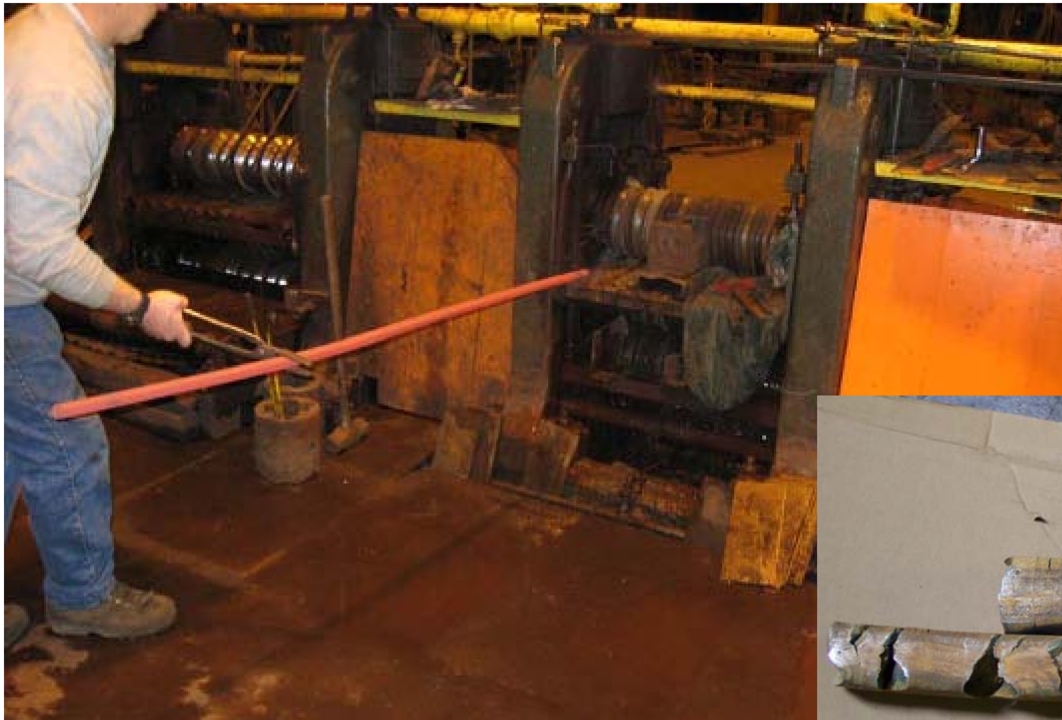
- There has been some effort in beta alloy development from other emerging low cost titanium powders however all have used CIP/sinter and extrusion or vacuum hot pressing and extrusion
  - For the automotive industry round bar is a more useful semi-finished product and is most cost-effectively produced by rod-rolling
- Selected 2 beta alloys and Ti6Al4V to be consolidated by CIP/Sinter and rod rolling
  - Ti6Al4V – to be used to compare consolidation process with extrusion
  - T5Al5V5Mo3Cr – not a low cost alloy but under development and will provide process baseline for beta alloys
  - Ti1Al8V5Fe – a low cost alloy developed in 1950's and dropped due to Fe segregation that occurs during melt
- Powder
  - Ti64 made by ITP powder; Hunter Fines and TiH_2
  - Ti5553 and Ti185 made by TiH_2
- Rod Rolling Trials completed
  - Ti6Al4V and Ti1Al8V5FeBillets sintered to greater than 97% dense
  - *Ti5553 sintered to 92% - resulted in excessive cracking*
  - 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

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Ti1Al8V5Fe; Ti6Al4V Rods

- Ti1Al8V5Fe High strength fastener alloy
  - Good candidate for springs – 1400MPa; low shear modulus
  - High oxygen tolerance
- Ti6Al4V – "workhorse" alloy

Ti6Al4V and Ti1Al8V5Fe bars rolled from CIP/Sinter billets

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

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Tensile Properties

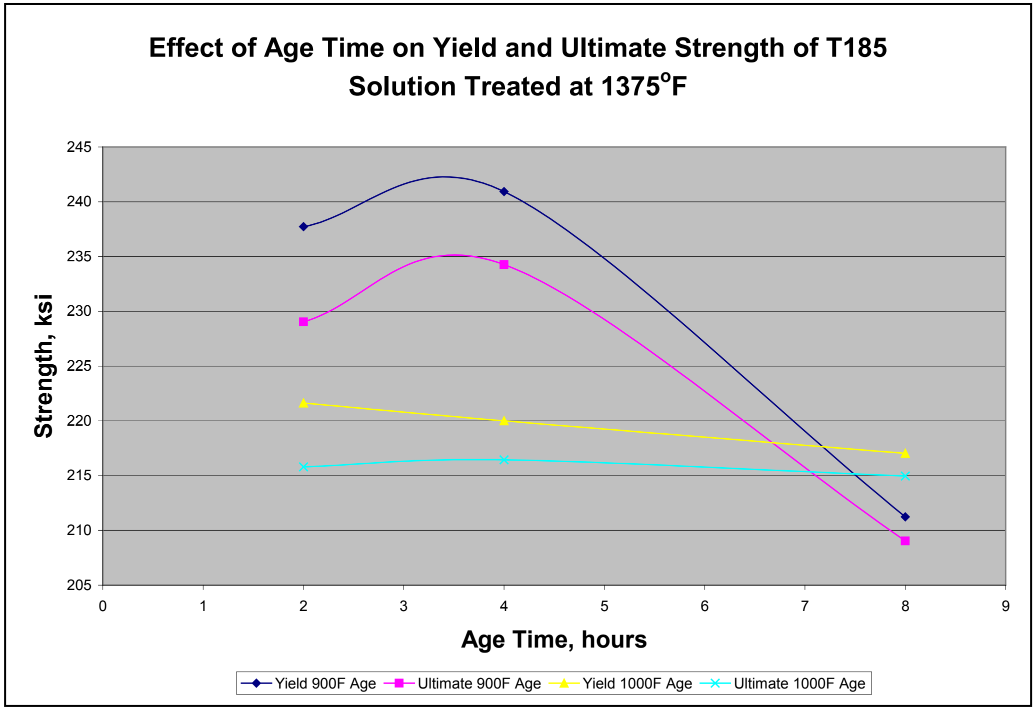
- Billet and As-Rolled Properties
  - Improvement in strength and ductility with rolling
  - TiH_2 starting powder

Condition/Alloy	Ultimate Tensile Strength	Yield Strength	Elongation
	(ksi)	(ksi)	(%)
As-Sintered billet/Ti185	124	104	0.4
As-Sintered billet/Ti64	110	101	4.4
As-Rolled Ti185	210	205	1.2
As-Rolled Ti64	165	150	16.6

Tensile Properties of 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 8% 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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Future Work

- HIP tensile and RBF bars for interstitial determination
- Fabricate test bars and machine fatigue samples from down-selected interstitial content
  - ADMA will blend/press/sinter and PNNL will forge
- Perform strain controlled fatigue tests
- Complete engine efficiency analysis and perform analysis of efficiency improvement with titanium
  - Identify additional applications

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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
- **Encountered lower than expected interstitial content in powder**
  - Performing interstitial study based on Fe and O
  - Found low tensile strength in initial tests
    - ADMA made a small adjustment in sintering
    - HIP will be used to complete study
    - A test matrix of sintering time will be completed to assure 98+% density
- **Cummins Inc. has identified a relevant application using the Ti6Al4V alloy and provided the requirements to adequately assess the performance of the press/sinter/forged bars produced from TiH_2**
- **The impact of titanium on engine efficiency will be modeled**

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