Solid State Processing of New Low Cost Titanium Powders Enabling Affordable Automotive Components

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Outline

- Introduction
- Potential Applications for Titanium in the Automobile
- Armstrong Process/ITP Powder
- Early Studies Demonstrating Mechanical Properties of Low Cost Powder
  - Vacuum Hot Pressing (VHP)
  - Extrusion
- Development of Economical Solid State Processing of "Low-Cost" Ti Powders
  - Cold Isostatic Pressing Followed by Pneumatic Isostatic Forging (CIP/PIF)
  - Roll Compaction
- Conclusions/Future Work

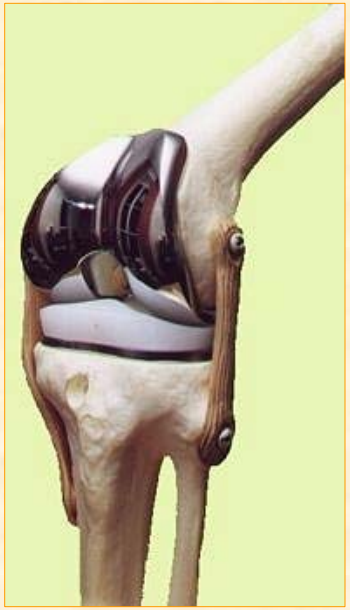
Titanium Plates Hot Pressed from ITP's Low Cost Titanium Powder

Introduction

- Ti Offers Attractive Properties.
  - High Specific Strength.
  - Good Elevated Temperature Properties.
  - Excellent Corrosion Resistance.
  - Allows for Damage Tolerant Design.
- Cost and Availability Rising Concern
  - Lead Times Up to a Year
  - Plate Prices of $40 to $50/Lb
- Cost Limits Application to Specific Markets.
- New Low Cost Titanium Powders Could Initiate a Paradigm Shift in Titanium's Use in Industry, Including Automotive

Land Combat Systems - Pegasus
BAE Systems

Heat Exchangers
http://www.titanmf.com



Biomedical - Knee Replacement

787 Boeing
http://www.boeing.com/commercial/787family/index.html

Titanium in the Automobile

- **Wide Range of Various Titanium Automotive Components Possible**
  - **Outside of Engine: Springs, Body Components, Brake Rotors, Bumper Supports, Muffler, Drive Shafts, Etc.**
  - **Engine: Turbo Charger Compressor Wheels, Turbine Wheel, Intake and Exhaust Valves, Connecting Rods, Piston Crown and Pin, Push Rods, Rocker Arms and Shaft, Camshaft, Valve Spring, Retainer and Rotater**
- **E.G., Recent Study at ORNL Studied Light Weight Materials to Replace Cast Iron in Diesel Engines**
  - **Analyzed Replacing Grey Cast Iron to Ti-6Al-4V in the engine head and blocks**
  - **Increasing the "Power of the Engine by 50% while reducing the weight by 15%" FY2005 Progress Report, DOE-Heavy Vehicle Propulsion Materials**
- **However, Titanium's Cost Prevents Penetration Into the Automotive Market**

Existing Applications of Titanium

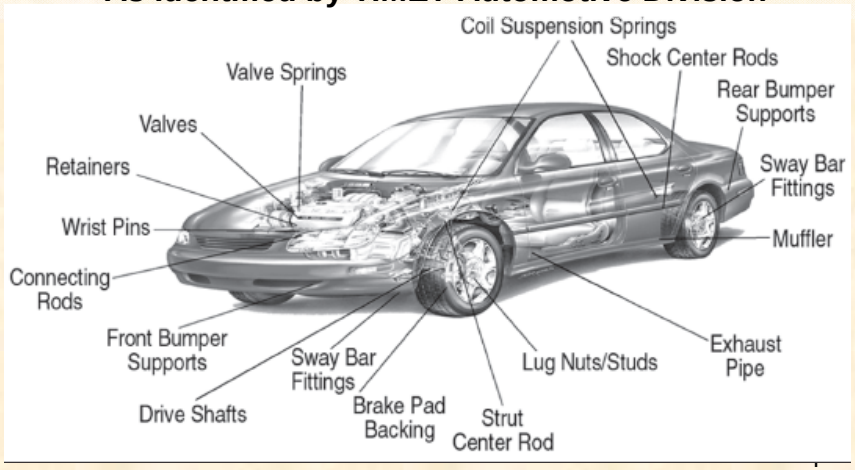
Ti Turbo Charger
http://www.holset.co.uk/files/2_6-recent%20industry%20firsts.php

Ti Exhaust on Corvette Z06
JOM 11, 2004. p. 32

Toyota Altezza
Toyota Central R & D Labs, Inc.
Froes, F.H. , (http://www.webs1.uidaho.edu/imap/MPRPaper.pdf)

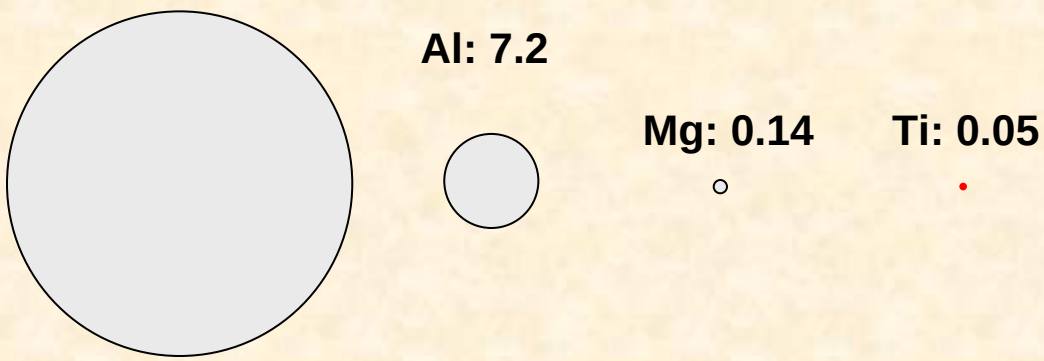
Low Cost Titanium Brake Rotor

Candidate Ti Applications,
As Identified by TIMET Automotive Division



Titanium Production

- 1998 U.S. Production (Million Metric Tons).



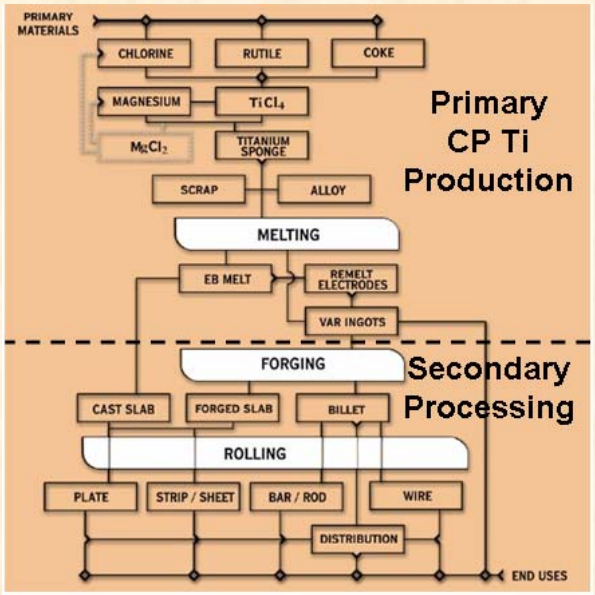
Kraft, J. "Summary of Emerging Titanium Cost Reduction Technologies" (Paper Presented at Low Cost Titanium Workshop, Baltimore, MD, 2003).

Item	Material ($/lb)		
	Steel	Aluminum	Titanium
Ore	0.02	0.10	0.30
Sponge	0.10	0.68	2.00
Ingot	0.15	0.70	4.50
Sheet	0.30-0.60	1.00-5.00	8.00-50.00

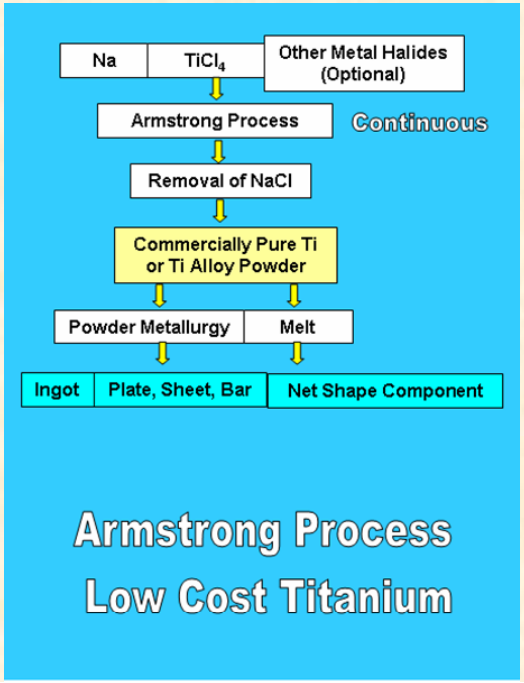
Faller, K. Froes F.H. JOM April 2001. pp.27

- **Titanium**
  - **9th Most Abundant Element**
  - **4th Most Abundant Structural Metal**
  - **0.6% of Earth's Crust**
- **Cost/Use of Ti Not Reflective of Abundance**
- **Current Synthesis Technology 50 Years Old**
- **Basic Research into Lower Cost Refining and Processing Remains Critical**
- **Integrated Approach Synthesis to Final Product**
- **DTi, "Low-Cost" Ti Powders**
  - **International Titanium Powder**
  - **MER/Dupont**

Conventional Technology Compared to DARPA Funded Armstrong Process



Kroll Process, Titanium Metals Corporation, http://www.timet.com/diagram.html



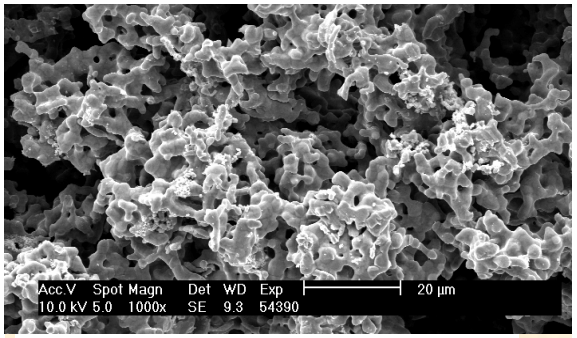
- **Kroll Process**
  - Mg Reduction of $TiCl_4$
  - Batch Process
  - Requires Acid Leaching and Vacuum Arc Remelting
  - Finally Milled into Desired Product
  - PM Approach Not Attractive for Many Applications, Price Above $50/lb

- **Armstrong (ITP) Process**
  - Reduction of $TiCl_4$ in Na Liquid Loop
  - Continuous Process
  - Ability to Produce Prealloyed Powder
  - Cost of Powder $5-8/lb
  - PM Approach Economically Attractive
  - Thousands of Pounds of Powder Have Been Produced

International Titanium Powder (ITP), Armstrong Process Titanium Powder

- New 4 Million Pound Titanium Plant Under Construction in IL
- Chemical Analysis of Powder Has Fallen within Specification
  - Grade 2 for CP Ti (e.g., 0.12 to 0.21 wt. % O)
  - Grade 5 for Ti-6Al-4V
- Energy Consumption for Reduction Process
  - 50 Year Old Conventional Kroll Process = 355 MBtu/ton
  - Armstrong Process = 165 MBtu/ton
  - A 53.4% Reduction in Energy Consumption.
- "Low Cost" Powder Allows for:
  - Economical Solid State / PM Processing
  - Near Net Shape Consolidation
  - Compositing and Layered or Engineered Structures
  - Ability to Use Beneficial Elements Not Possible in Conventional Processing (E.g., Small Additions of Boron Have Greatly Increase Fatigue Lifetime of Titanium Alloys)

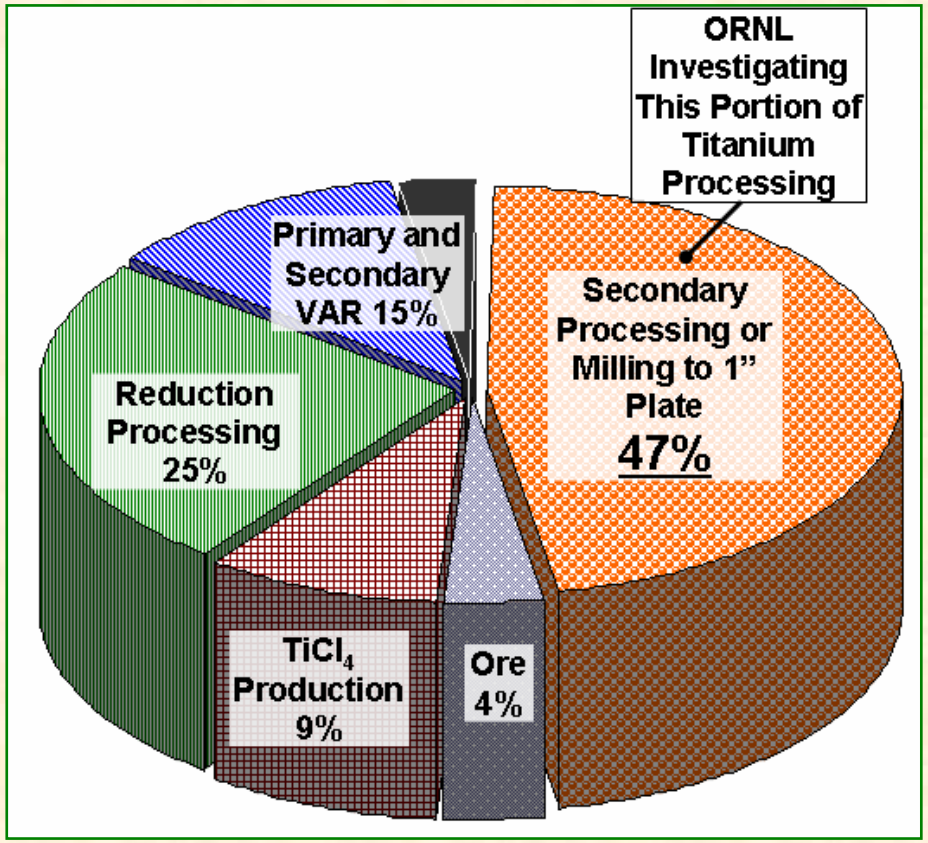
Morphology



International Titanium Powder 4 Million Pound Per Year Plant to be Finished in 2008

Processing – Cost Break Down of Fabricating 1” Ti Plate

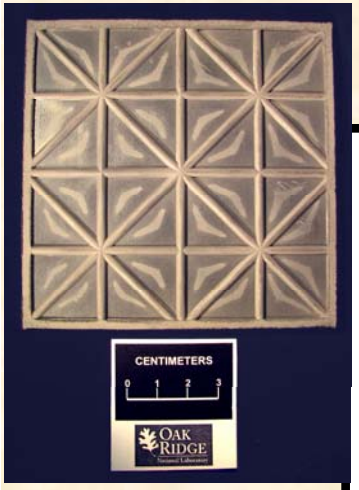
- ITP “Low Cost” Ti Powders Developed in DTi Program Address 25% of 1” Plate Fabrication Costs
- The Secondary Processing or Processing into Finished Product (62% VAR and Milling) Needs to Be Addressed
- Conventional Milling Operations, Scrap Generated: 40 to 60%
- PM Approach with ITP Powder Ability to Reduce Scrap to Less Than 10%



Cost Break Down to Produce 1” Thick Titanium Plate Using Kroll – VAR Melted Titanium

Hartman, A.D. et al. JOM September 1998. pp. 16-19

Development of Multiple PM Processes for Economical Product



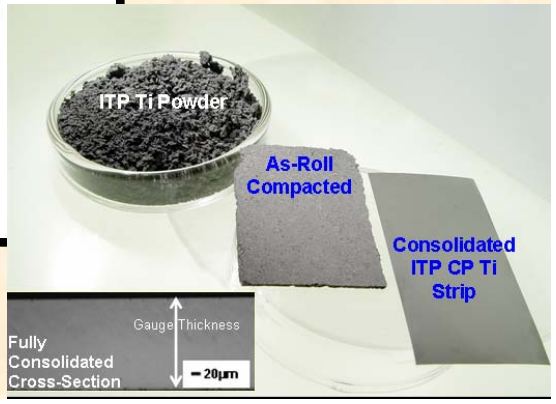
Near Net Shapes
Hot Pressed, Forged, Press+Sinter

Plate
Forged, PIF, Hot Roll, HIP

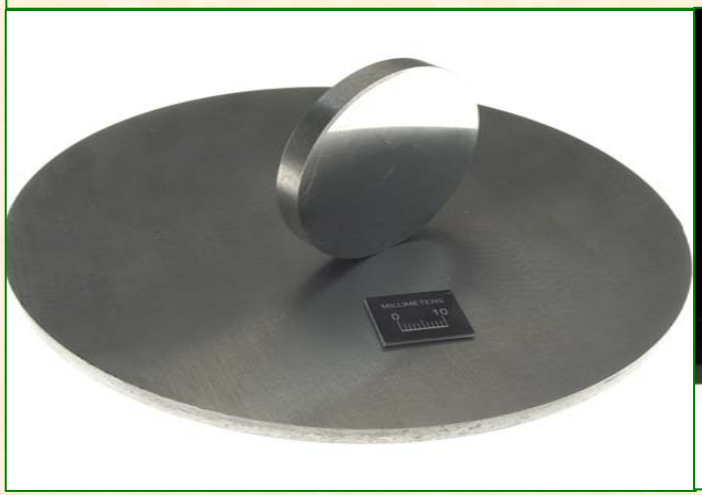
Bars and Rod
Extrusion

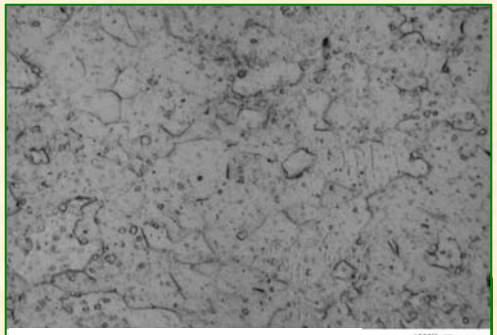
Powder

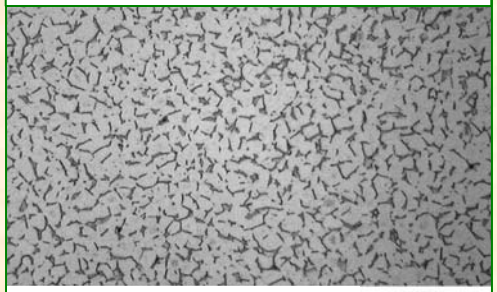
Sheet
Roll Compacted



Vacuum Hot Pressing (VHP) of ITP CP Ti and Ti-6Al-4V – Plate and Near Net Shape Production







As VHP microstructures

- Armstrong Ti and Ti-6Al-4V powder were vacuum hot pressed.
- Interstitial Levels of ITP CP Ti, VHP Produced Plate within Specification
- Mechanical testing, microstructures, and chemical analysis comparable to conventional wrought properties.
- Rivard, J.D.K. et al. JOM 57, 11, 2005. pp. 56-60

Sample	YS [MPa]	UTS [MPa]	Ductility [%]
ITP VHP CP Ti 900°C/30min	**517**	**617**	**20.7**
CP Ti Grade 2	*345*	*448*	*20.0*
ITP VHP Ti-6Al-4V 950°C/60min	**963**	**994**	**13.8**
Ti-6Al-4V Grade 5	*828*	*897*	*10.0*

Ti Processing – Extrusion

- Mechanical testing and microscopy

ORNL, 1250 ton - extrusion press

Extruded CP Ti Tensile Bars

Sample*	YS [MPa]	UTS [MPa]	Ductility [%]
Extruded Ti	**407**	**552**	**17.0**
Ti Grade 2	*345*	*448*	*20.0*

** Insufficient Ti-6Al-4V powder was available at the time of initial extrusion demonstration. Recent Increase in ITP Ti-6Al-4V powder production will enable ORNL to produce Ti-6Al-4V extrusions and test bars in the near future.*

As-extruded Ti

As-extruded Ti-6Al-4V

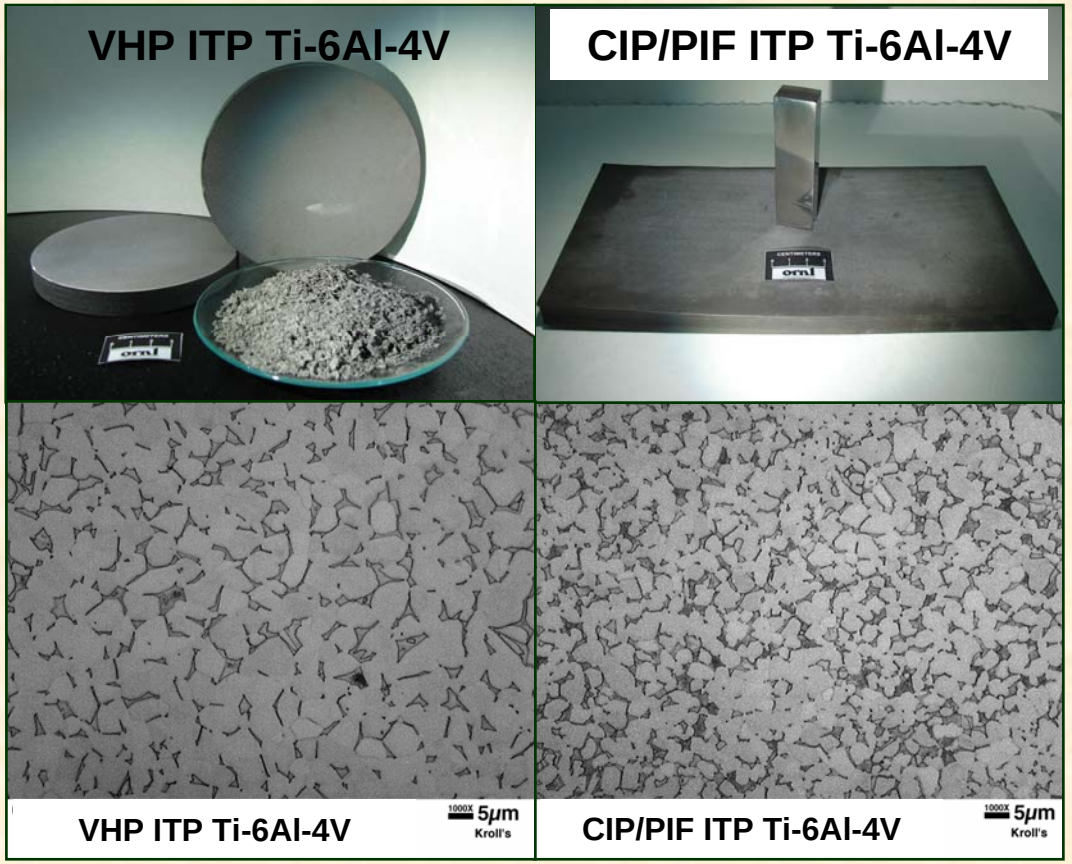
Development of Cold Isostatic Pressing / Pneumatic Isostatic Forging (CIP/PIF) Process

CIP/PIF Near Net Shape Stainless Steel Components

CIP/PIF Tubes

- Necessity for Cost Effective Method of Producing Plate and Near Net Shape Components
- PIF AMETEK Patented Process – Rapid Gas Pressurization (1 to 2 Minutes)
- Very Preliminary CIP/PIF Work Performed with AMETEK Shows Promising

Description	VHP	CIP/PIF
% of Theoretical Density	99.4%	99.6%
Oxygen Pickup (wt. %)	0.02	0.04
Microstructure	Equiaxed	Equiaxed
Hardness (VHN)	343 +/- 31.9	346 +/- 27.3



Roll Compaction of Armstrong (ITP) Derived Ti Powders

Roll Compacted Rolls of Nickel Sheet Commercially Produced at AMETEK with over 50 years experience

- **Collaborative Effort Between ORNL and AMETEK to Develop Roll Compaction Manufacturing Technology for Low Cost Titanium Powders**
- **Both Commercially Pure Ti and Ti-Al-V Alloys Have Been Roll Compacted**
- **ITP Powder Has Resulted in:**
  - **Green Densities of 60 to 70%**
  - **Sheet Widths of 15" (or Greater)**
  - **Coils of 28' in length have been produced with no binders required.**
  - **Initial Studies Performed on Thin Sheet (0.02"), But Projections Indicate Thicknesses at 0.1" or Higher Are Possible with Large Roll Diameters**
- **Solid State Sheet Processing After Roll Compaction: Sinter, Cold Roll, And Anneal Lead to Fully Consolidated Sheet (>99%)**
- **Initial Trial Resulted in High Strength/Low Ductility Due to High Oxygen**
- **However, Further Development Has Led to Acceptable Oxygen Levels: 200ppm Pickup or Less During Roll Compaction, and Less Than 800ppm Pickup After Full Consolidation – Mechanical Testing Ongoing**

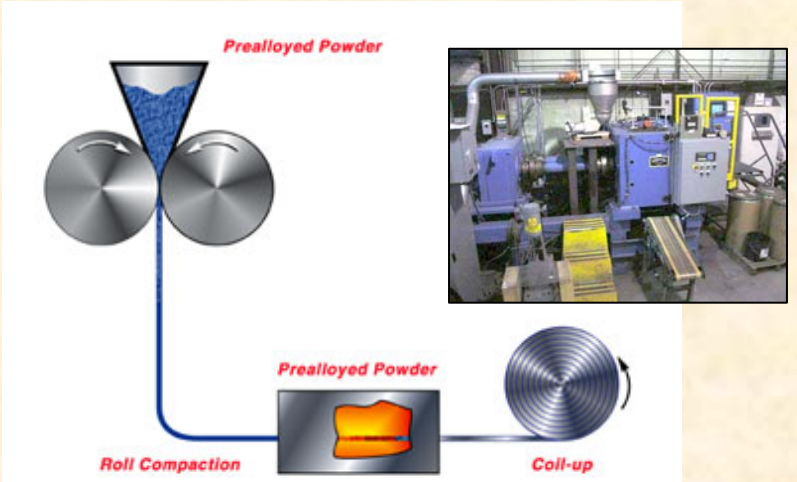
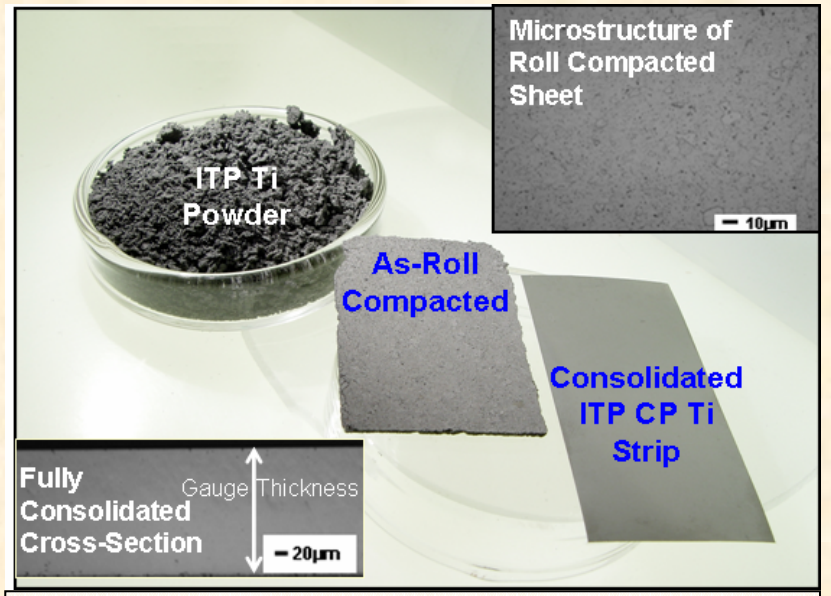


Diagram of Roll Compaction Sheet Production with AMETEK Roll Compaction Mill



Roll Compacted Titanium Sheet

Conclusions

- Low Cost Titanium Powders Are Now Produced That Could Cause a Paradigm Shift in the Use of Titanium for Automotive Applications.
- Further Development in Powder Metallurgy or Solid State Consolidation of the New Titanium Powders Is Required to Realize the Most Economical Components and Penetrate the Automotive Industry.
- Vacuum Hot Pressed Plates and Extruded Bar of the Low Cost Titanium Have Been Produced with Tensile Properties that Meet ASTM Specifications.
- Oak Ridge National Laboratory Is Currently Collaborating with Industry to Develop Economical Processes to Produce Plate, Sheet, Bar/Wire, and Net Shape Components.

Future Work

- Further Development of Existing Work Shown Today
  - •Comprehensive Mechanical Properties (Fatigue)
  - •Other Low Cost Powders as Available
- Development of Other Solid State Technologies (e.g., Upset Forging, Press+Sinter)
- Current Program to Produce and Join Plates for Military Application
- Further Collaboration with Industrial Partners to Allow for the Penetration of Titanium Into New Markets Is Invited

Current Titanium Plate Production and Joining for 200lb Life Size Military Component