Low Cost Blended Elemental Titanium Powder Metallurgy

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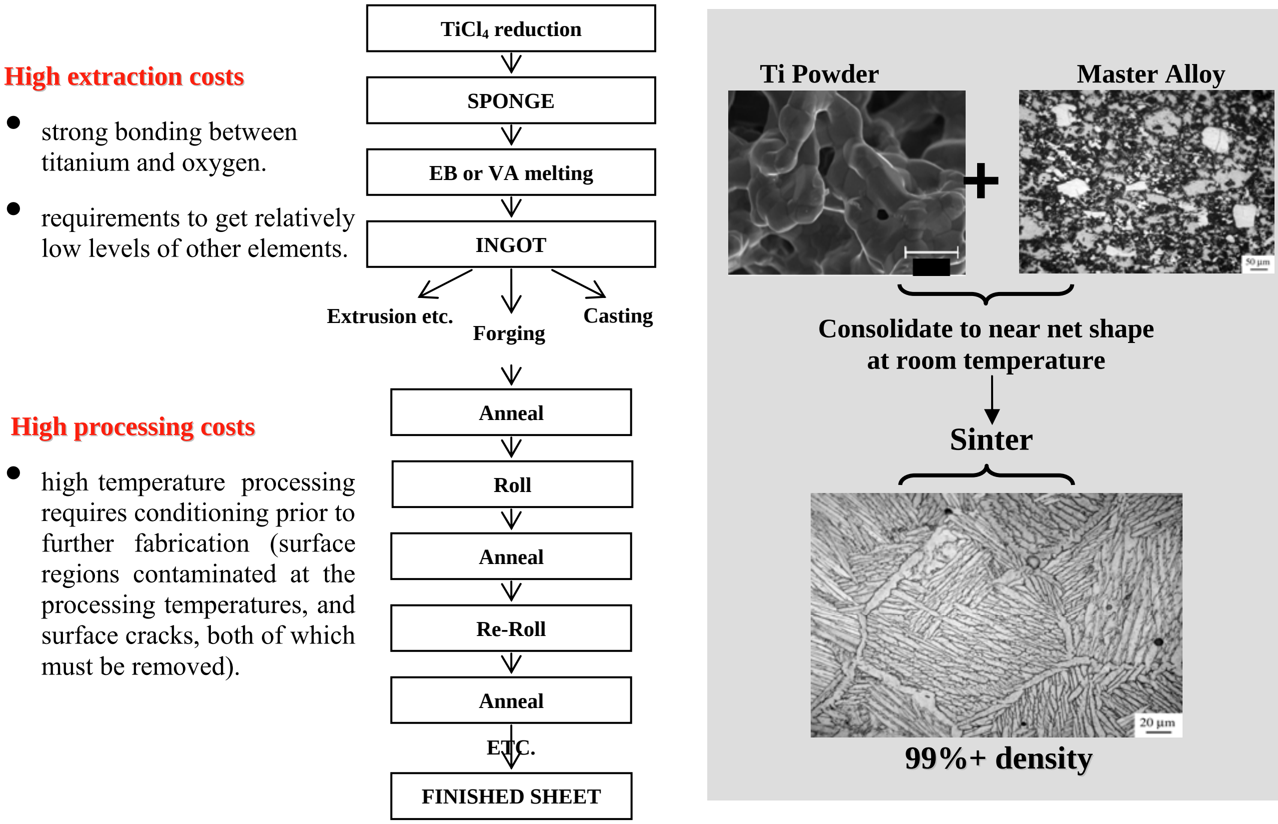
Abstract

Recent substantial increases in price and delivery of components produced by traditional ingot metallurgy (IM) processes caused by shortages in the cyclic titanium market renewed an interest in titanium powder metallurgy (PM) approach to manufacturing. P/M offers cost reduction in manufacturing titanium parts as well as a substantial reduction in lead time. In this paper, titanium PM is reviewed as a substitution of IM processes, and as an approach to manufacturing alloys that are not produced in large quantities. Blended elemental (BE) approaches are potentially the lowest cost processes to produce such alloys. BE processes are based on the use of powder alloying elements or master alloys which are added to commercially pure titanium powder to achieve the required alloy chemistry. Subsequent room temperature consolidation to the required configuration and sintering in vacuum are applied to produce the final, dense components. Room temperature consolidation in BE approach (die pressing, cold iso-static pressing, and direct powder rolling) will be described as viable processes to produce components that have properties meeting the various application requirements. Other advantages of taking the PM approach include ability to produce discontinuously re-enforced, multi-layered titanium components and composite structures not achievable by the conventional IM processes.

Introduction

Titanium alloys are being used in airspace and other high performance applications because they offer excellent strength/weight ratios, good corrosion resistance and good mechanical properties at intermediate temperatures (500-1200°F). However, the cost of titanium components produced by conventional ingot metallurgy is high compare to steel and aluminum and this limits their use in automotive industry and other applications.[1] The elevated cost is associated with high extraction and high processing costs. Powder metallurgy (PM) manufacturing, especially the blended elemental powder metallurgy approach (BEPM) to alloying, is a viable and promising route for cost effective fabrication of titanium components.[2-8] Conventional PM is well developed and mature industry. Global sales in 2006 were >$21 billion, with the North American PM parts business estimated at about $5 billion in 2007 for all metals, however, the titanium powder metallurgy segment is practically non-existent.[9] These sales are in spite of the fact that conventional PM powder, e.g. steels, copper, and other non-ferrous powders, are mainly produced from ingot by an atomization process, making the cost of powder higher than the cost of ingot metal. In the case of titanium, there are several unique, no-melt technologies available for making titanium powder, many of which have been presented at previous ITA conferences and some of which have already been commercialized. Thus the cost of PM titanium and titanium alloy components depends upon titanium powder cost and manufacturing costs and avoids the time associated with casting ingot. Another advantage of powder metallurgy is the ability to produce low cost metal matrix composites (MMC) reinforced by ceramic particles. MMCs have drawn interest for automotive applications due to their improved stiffness, wear resistance, yield strength.



a) Traditional metallurgy b) Powder metallurgy

Figure 1. A schematic comparison of processing steps involved in a) traditional titanium ingot metallurgy vs. b) the powder metallurgy approach.

Blended Elemental Powder Metallurgy (BEPM)

The benefits of P/M processing are well known: fewer steps, no extensive secondary machining, low "buy-to-fly" ratio (scrap rate below 2%), direct alloying, rapid manufacturing cycle, uniform properties in longitudinal and transverse directions (no texture developed), integral processing of composites, laminated or functionally gradient components, more energy efficient, etc. This paper describes our uses of the BEPM approach and associated raw materials and processing steps.

The most cost effective PM processes are based on the use of low cost blended elemental (BE) technology where alloying elements are added to titanium as elemental or master alloy powders. Traditionally this method includes the preparation of powder blends, their consolidation at room temperature, and sintering in vacuum for transformation of initial heterogeneous powder compacts into massive homogeneous alloys. Consolidation at room temperature may be performed by low cost conventional powder metallurgy processes such as die pressing, cold isostatic pressing (CIP), or by direct powder rolling. Table 1 lists the advantages of this BEPM approach. In order to achieve desired mechanical properties, sintered materials should not only exhibit homogeneous chemical composition and microstructure, but also a relative density of greater than 98% of theoretical.[10, 11] However, the relative densities of titanium alloys produced by a blended elemental approach normally do not exceed 95%.[12] In order to increase density, a sintered material can be subjected to hot isostatic pressing (HIP'ing) or other hot deformation process.[13-14] However, this increases the number of production steps which increases part cost and negates the advantages of the PM approach. Our goal is to produce titanium PM alloys, in particular the "work horse" Ti-6Al-4V alloy with a low residual porosity (99% density) using the simple BE method with no subsequent hot deformation step. It has been demonstrated that fully dense "chunky" components with mechanical properties exceeding the ASTM requirements can be produced by die pressing and sintering,[10] CIP and sintering,[7] and flat components by direct powder rolling and sintering process.[14, 16] One objective in this study was to demonstrate the ability to produce low cost titanium alloy parts, re-enforced titanium alloy components for automotive application by applying cost effective room temperature consolidation (die pressing, cold isostatic pressing, and direct powder rolling processes) to achieve near full densities titanium alloys for the various potential applications.

Table 1. Advantages of Blended Elemental powder metallurgy

1	Blended Elemental Powder Metallurgy - is a highly developed method of manufacturing reliable ferrous and nonferrous parts.
2	Made by mixing elemental or alloy powders and compacting the mixture in a die, the resultant shapes are then sintered or heated in a controlled-atmosphere furnace to physically and chemically bond the particles.
3	P/M is the energy and materials conserving process (P/M typically uses more than 97% of the starting raw material).
4	The P/M process is cost effective in producing simple or complex parts at, or very close to, final dimensions in production rates which can range from a few hundred to several thousand parts per hour.
5	P/M parts also may be sized for closer dimensional control and /or coined for both higher density and strength.

Experimental

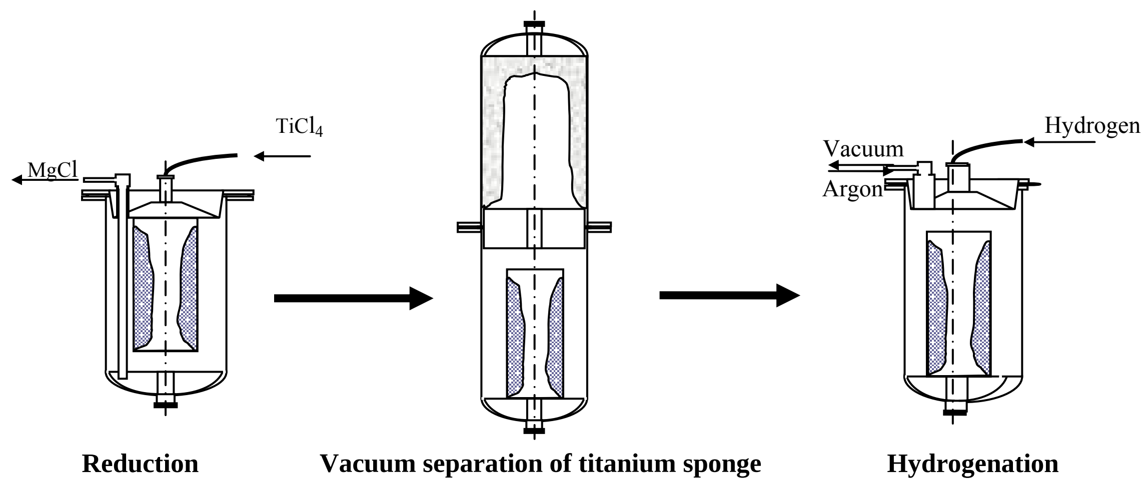
Raw Materials: Titanium Powders and Master Alloy

The applications and properties of BEPM Ti-6Al-4V are well developed for sodium and magnesium-reduced titanium sponge fines,[12, 16-17] calcium hydride reduced titanium powders,[10, 18-19] hydride/de-hydride titanium powders,[11] powders produced from turnings[20-22] and others. Recently, ADMA Products, Inc. in association with Ukrainian scientists and scientists from Pacific North West National Lab (PNNL) became involved in development and production low cost hydrogenated titanium (TiH_2) powder.[23] Application of this TiH_2 powder allow manufacturing near full density P/M Ti-6Al-4V alloy meeting property requirement specifications of ingot metallurgy alloys.[24-26] Low-cost hydrogenated titanium powder production system was built and is shown in Figure 2. This system consists of furnace and vessel for reduction, vacuum separation and titanium sponge hydrogenation, a vacuum system, a system for $TiCl_4$ storage and supply, a system for $MgCl_2$ extraction from the reduction reactor, an argon storage and supply system, cooling systems, a process control and monitoring system, a load-lifting mechanism a ventilation system, a system of gas treatment and effluents neutralization, an auxiliary equipment. The system was designed and built for research activities aimed for developing a combined technology of hydrogenated titanium sponge production in accordance with the US Patent No. 6, 638, 336 and being used for studying three process stages: 1) Titanium tetrachloride reduction with magnesium; 2) Vacuum separation of reaction products; and 3) Titanium sponge hydrogenation.

Results of this project improved the efficiency of the new process and obtained the following advantages as compared to the existing Kroll process:

- The duration of the process of titanium sponge vacuum separation is reduced by 30 %, which provides economy of the electric power for the production by 1000-1400 kWh.
- Hydrogenation of partially separated titanium sponge with the subsequent hydride extraction from the vessel, in comparison with the production of titanium sponge, actually excludes the stage of crushing and grinding associated with expenses for the equipment and labor.

Expenses for the process of hydrogenation will take 10-12 % of cost of the raw material being used for hydrogenation. Expenses for leaching, crushing and classification of titanium hydride will be in the range of 5-7 % of raw material for hydrogenation costs. Thus, the shop cost of titanium hydride will be below the shop cost of titanium sponge by 5-10 %. The cost of titanium hydride powder will be substantially lower than that of hydride produced from titanium sponge by conventional technologies, and that of titanium powders produced by other methods. The hydrogenated titanium sponge was ground to -100 mesh powder TiH_2 powder at ADMA Products, Inc. Chemistry of the sponge used for this study is listed in Table 2. The influence of compacting pressure on sintered density is shown in Figure 3. As compared with other titanium powder, it can be seen that compacting pressure is not a critical parameter to achieve the near full density for TiH_2 powder. This unique feature allows manufacture of more complex shape components by die press molding because the variable cross-section of the component will densify during the same movement of the punch. This phenomenon is attributed to compaction mechanism of low strength and brittle hydrogenated titanium particles. Based on this result, we conclude that this powder can be widely used for production of complex shaped titanium components.



Cost-effectiveness	Processing
Hydride-Dehydride process TiH_2 is lower cost than Ti powder Lower cost starting materials (low grade Ti sponge can be used)	Low adherence of titanium hydride provides easy operating on die compaction

Figure 2. Integrated low-cost hydrogenated titanium powder production.

Table 2. Chemistry of hydrogenated titanium sponge

Material	Fraction of total mass of specified impurities, %					
	Fe	N	C	O	H	Ti
Sponge (-12+2 mm)	0.080	0.030	0.010	0.090	3.50	Bal
ASTM B348 Grade 2	0.300	0.030	0.080	0.250	0.015	Bal

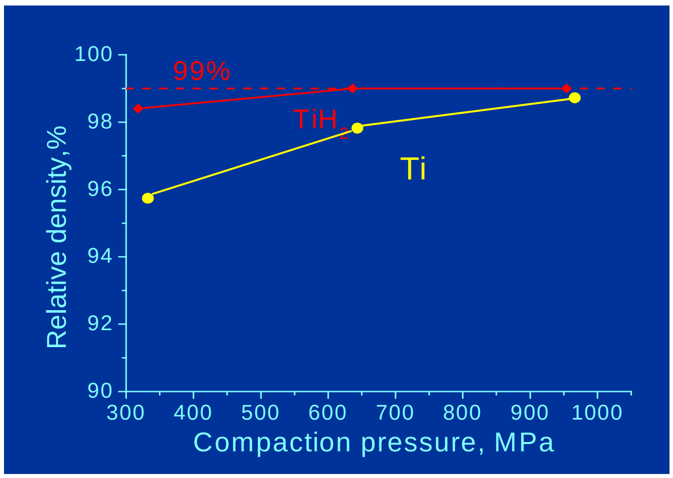


Figure 3: Influence of compaction pressure on relative density.

Die Pressing

Low cost TiH_2 (-100 mesh) was used in this study. Chemical composition of this powder is shown in Table 3. Blended elemental approach with 60%Al + 40%V master alloy was used to achieve the Ti-6Al-4V composition.

Table 3. Chemical composition of titanium powder

Ti Powder	%, weight								
	Fe	Si	Ni	C	Cl	N	O	H	Ti
Hydrogenated magnesium reduced	0.018	0.01	0.014	0.061	0.12	0.015	0.21	3.90	bal

C.P. titanium and Ti-6Al-4V washers made by die-pressing followed by vacuum sintering are shown in Figure 4, and Table 4 lists their chemistries. Both alloys met the corresponding ASTM specifications. Microstructures of P/M Ti-6Al-4V alloy are shown in Figure 5 and tensile properties are listed in Table 5.

Figure 4: C.P titanium and Ti-6Al-4V washer components produced by die pressing + sintering.

Table 4. Chemical composition of washers produced by die-pressing + sintering

Material	Composition, %							
	N	C	H	Fe	O	Al	V	Ti
CP Ti washers	0.015	0.016	0.0014	0.14	0.206	-	-	Bal.
ASTM B 348 Grade 2	0.030	0.080	0.015	0.20	0.250	-	-	Bal.
Ti-6Al-4V washers	0.019	0.014	0.0014	0.05	0.263	6.32	4.23	Bal.
ASTM B 817-98, Type I	0.040	0.10	0.015	0.40 max	0.30	5.50 - 6.75	3.50 - 4.50	Bal

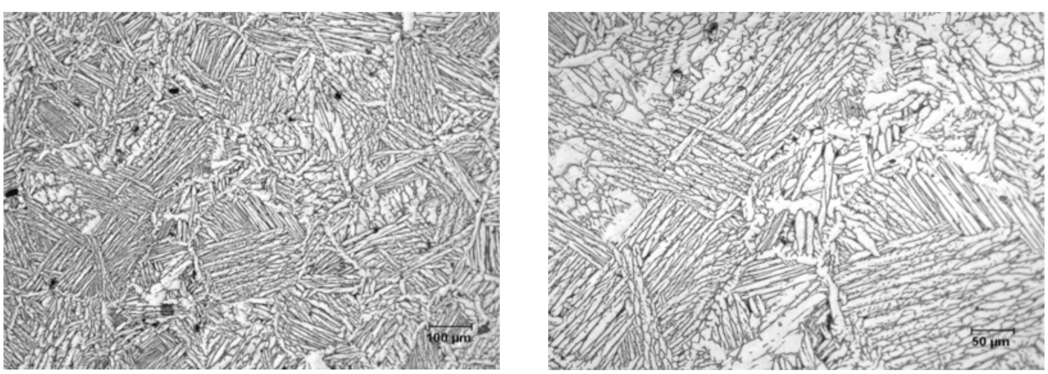


Figure 5: Microstructure of Blended elemental P/M Ti-6Al-4V alloy produced from hydrogenated Ti powder by die-pressing + sintering.

Table 5. Tensile properties of BE P/M Ti-6Al-4V alloy produced from hydrogenated Ti powder by die-pressing + sintering.

Material	Ultimate Strength, (KSI)	Yield Strength, (0.2%) (KSI)	Elongation %	RA, %
BE P/M Ti-6Al-4V	144,900	133,900	10.0	27.0
ASTM B347-97	130,000	120,000	10.0	25.0

Cold Isostatic Pressing (CIP)

CIP room temperature consolidation is cost effective method to produce complex shape and large components. Figure 6 shows titanium alloy tube and large pre-forms and bars, respectively, which were produced by CIP + Sinter process (CIP/Sinter). Figure 7 illustrates the plates produced by high temperature rolling the CIP/Sinter process and the resulting refined microstructure that resulted from rolling.

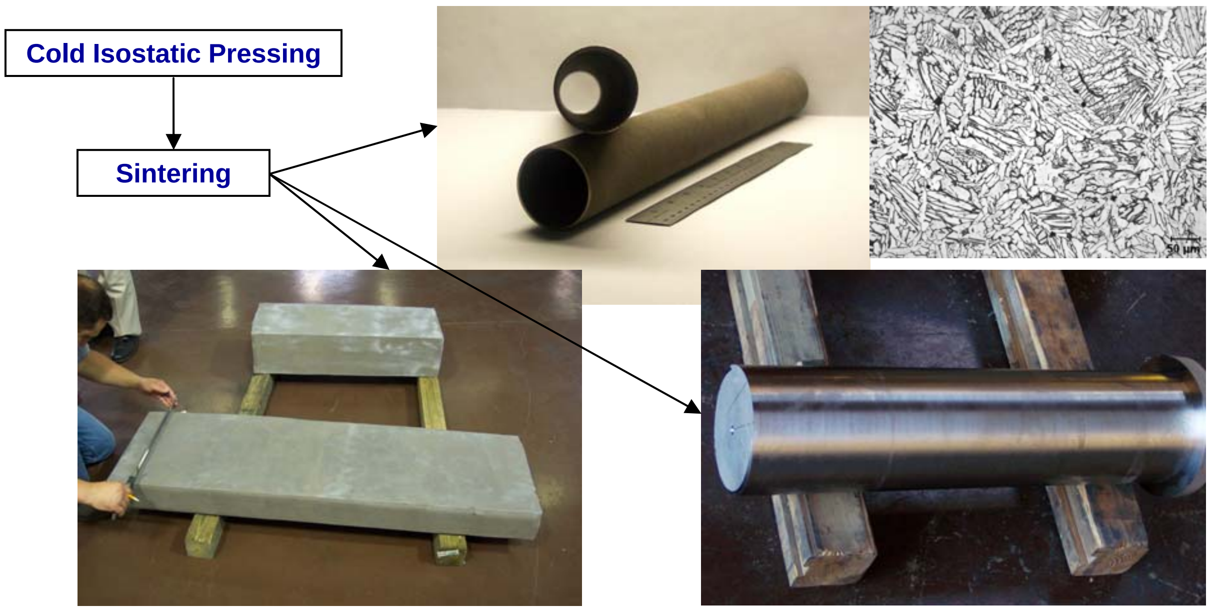


Figure 6: Titanium alloy tube and large pre-form slabs for hot rolling and bars for extrusion produced by CIP + sinter process.

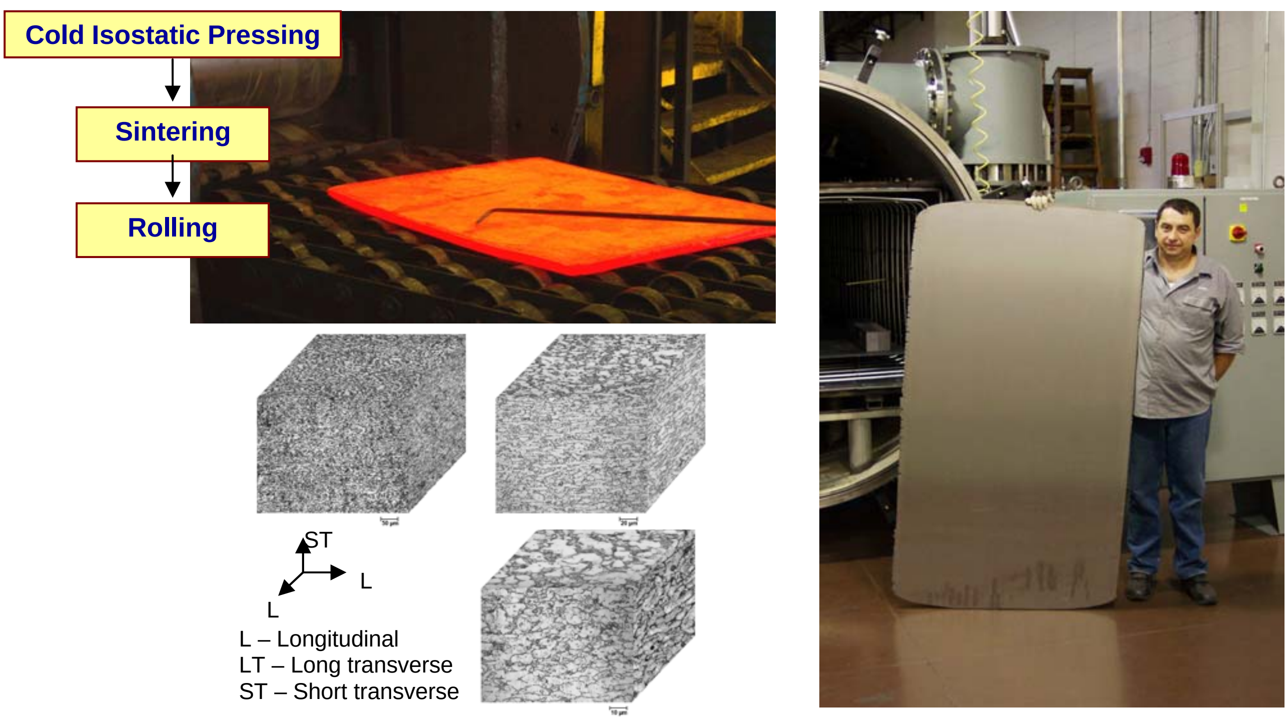


Figure 7: P/M Ti-6Al-4V 0.50 in. thick plate produced by CIP + sintering + hot rolling.

Direct Powder Rolling (DPR)

DPR is most cost effective approach to produce flat products like foil, sheets and plates. The scrap rate is very low – less than 2% while for conventional rolling process buy to fly ration is rather high. A recently commissioned direct powder rolling mill used in this study is shown in Figure 8, along with 0.28”thick plate and 26”wide titanium strip produced in this mill.

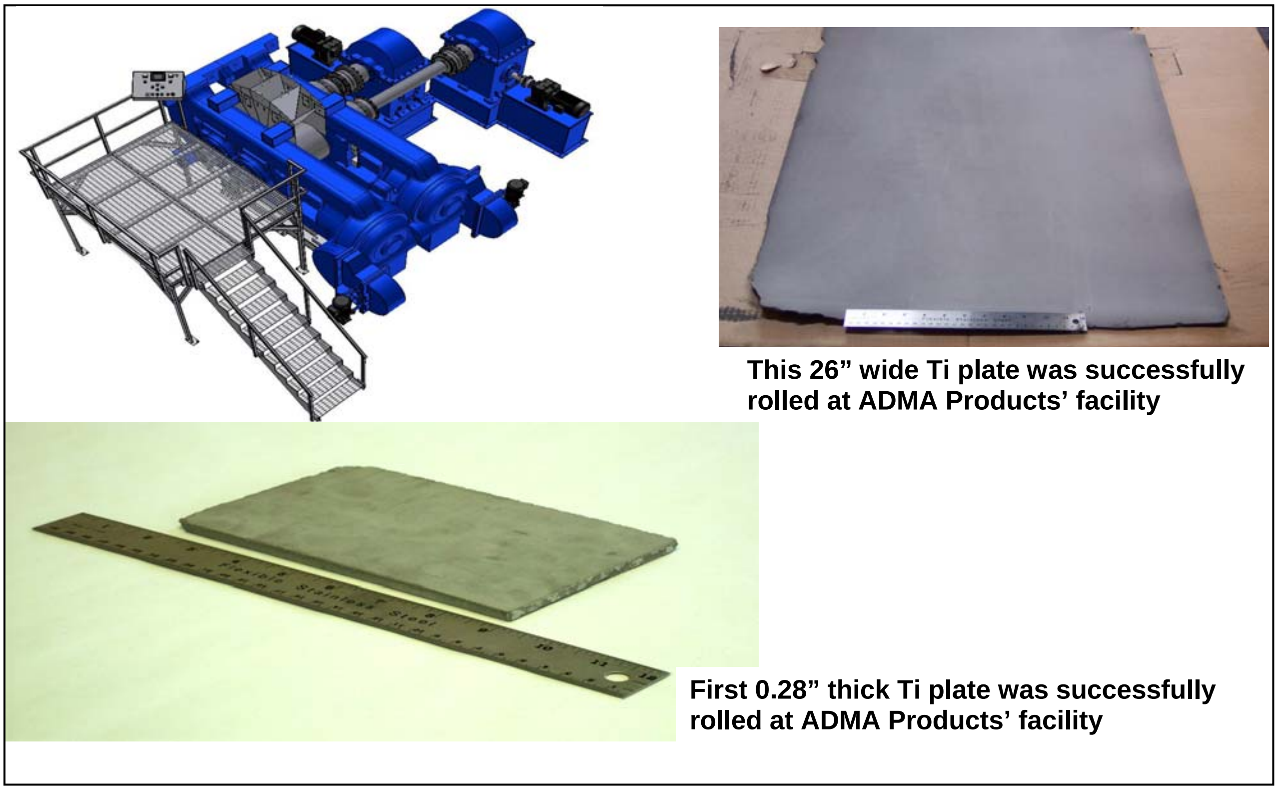


Figure 8: Direct powder rolling mill and 0.28”thick plate and 26”wide titanium strip rolled at ADMA Products, Inc.

Blended Elemental Reinforced Titanium Alloys, Multi Layers Titanium Sheets

Another advantage of the BEPM approach is an ability to produce complex materials, difficult or impossible to make via ingot metallurgy. Discontinuously reinforced titanium metal-matrix-composites (Ti MMC) have drawn interest for many applications due to their improved stiffness, wear resistance, yield strength, creep resistance, and work hardening. In order to fabricate the composite samples, the mixtures of Ti, Cr, and C powders with particle sizes less than 70 μm were prepared first by ball milling for 4 hours and then by blending with BE Ti-6Al-4V powder.[19] Pre-mixed blends were consolidated at room temperature by die-pressing, cold isostatic pressing, or direct powder rolling, and sintered in vacuum under identical conditions. Estimated volume fraction of TiC particles was varied between 0% and 20%.

The microstructures of BE Ti-6Al-4V composite materials manufactured from hydrogenated magnesium reduced titanium powder by simplest room temperature consolidation and sintering approach are presented in Figure 9. Homogeneous lamellar α+β microstructure with average grain size of 100-120 μm and fine TiVCrC (5-20 μm) reinforcements uniformly distributed was observed in all three room temperature consolidation techniques performed in this study, i.e. die pressing, CIP, and direct powder rolling.

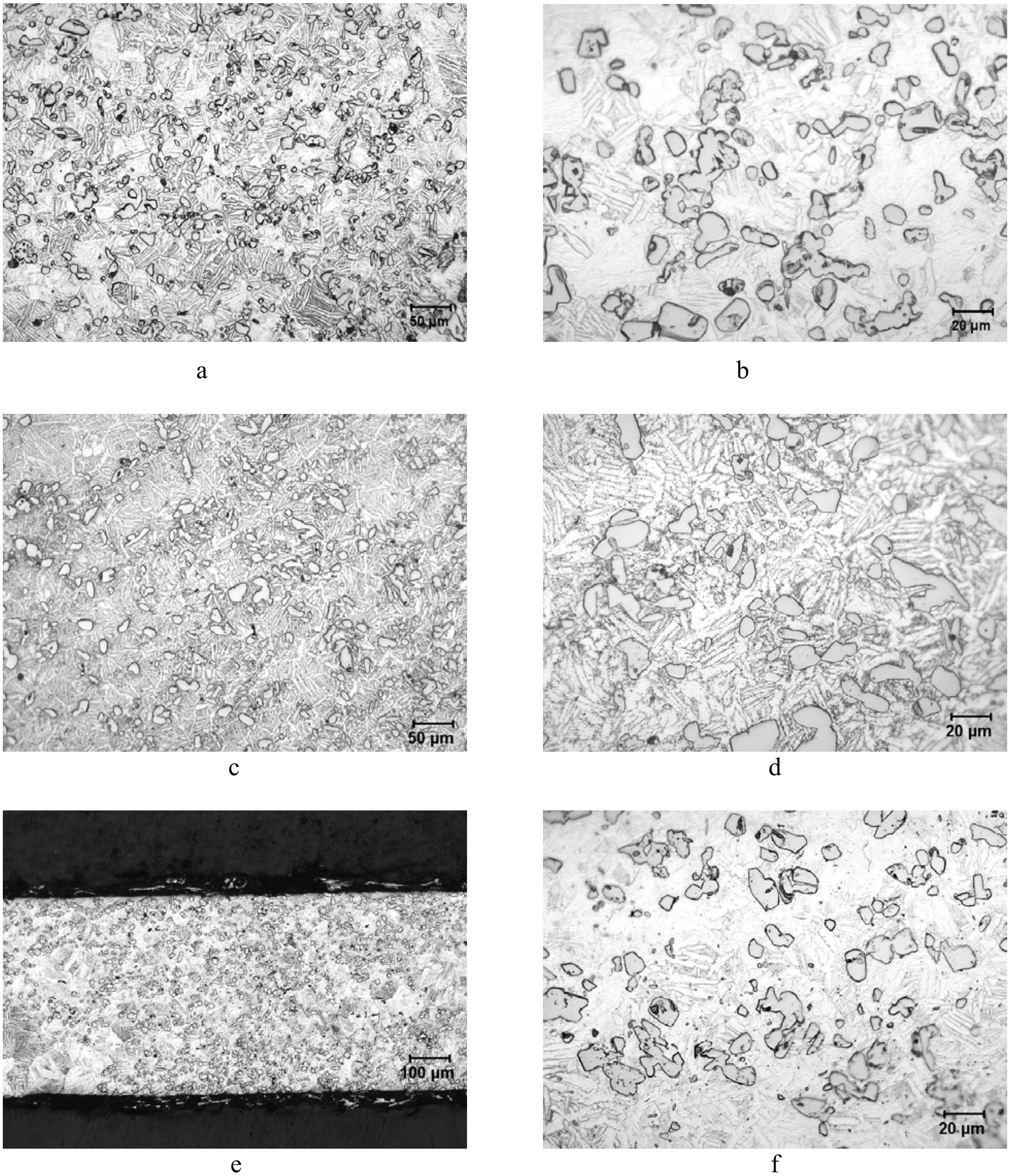


Figure 9. Microstructure of MMC from hydrogenated titanium powder die pressing + sintering (a, b); cold isostatic pressing (c, d); and direct powder rolling + sintering (e, f). Density is 4.30 gcm^{-3}.

The relatively small grain size is caused by the pinning effect of particulates. EDS analysis and X-ray diffraction analysis (Figure 10) on the polished surfaces confirmed that the TiVCrC particles were formed in both types of based material. Metallographic observation together with X-ray analysis confirmed that carbon diffuses into Ti-Al-V matrix and forms the carbide particles during sintering. Chromium content in precipitates does not exceed 2.0 % (wt.) which is consistent with previously reported results.[27] The densities of sintered material were close to full theoretical density for all methods of room temperature consolidations (die pressing, CIP'ing or direct powder rolling).

Room temperature tensile properties of Ti-MMC studied are shown in Table 6. Blended elemental Ti-6Al-4V reinforced with 10% and 20% particulates exhibit high strength, but the ductility is still below the ASTM requirements. Reinforcement with the particulates increased the modulus from 17 Msi for non-reinforced Ti-6Al-4V alloy to 19 Msi for 10% reinforcement and to 20 Msi for 20% reinforcement.

Intensity (imp/sec)

	Cr	V	Al	Ti
Particle 1	300	6500	120-180	75000
Particle 2	1500	7500	200-250	73000
Matrix: white	10500	14000	350-400	78000
Matrix: gray	9000	15000	430-450	78000

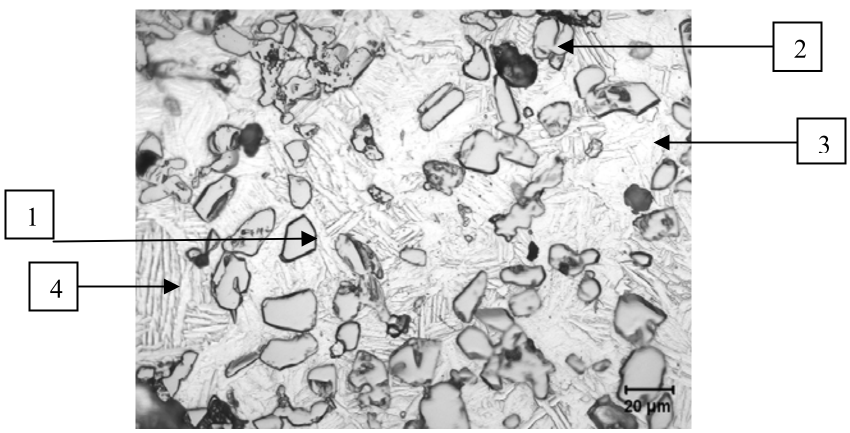


Figure 10. X-ray diffraction analysis of MMC from hydrogenated titanium powder via die pressing + sintering.

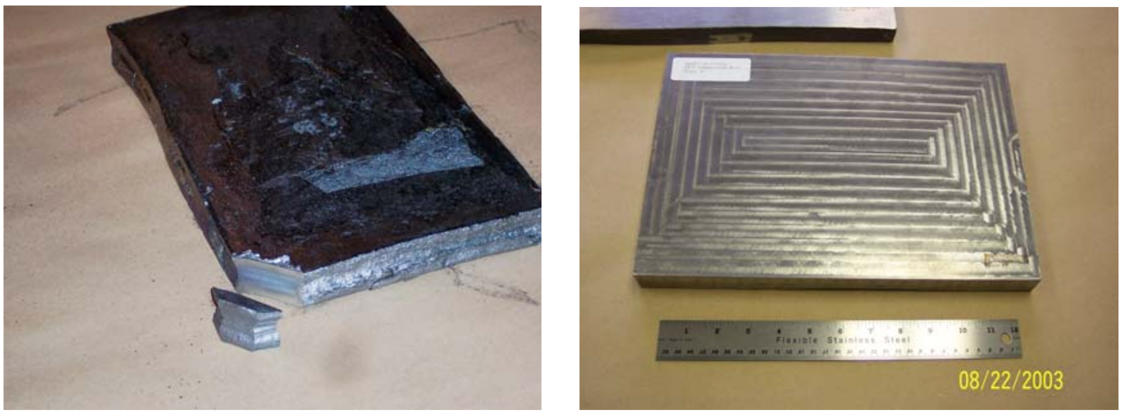
Table 6. Room temperature tensile tests ASTM E8-04 MMC from sodium reduced titanium powder.

Composition	Sample	Tensile Strength, psi	Yield Point, psi	Yield Strength (0.2%), psi	Elongation, %	Modulus, Msi
Ti-6Al-4V +10% Ti,V,Cr,C	1	150.30	-	143.50	3.0	17.70
	2	151.40	-	137.90	3.0	17.70
	3	150.40	-	142.40	3.0	17.90
	4	150.10	-	143.00	2.0	18.10
	5	148.50	-	141.10	2.0	17.50
Ti-6Al-4V +20% Ti,V,Cr,C	1	115.00	115.00	-	2.0	18.30
	2	119,20	119.20	-	1.0	19.00
	3	124.50	124.50	-	2.0	20.10
	4	122.30	122.30	-	2.0	19.50
	5	121.50	121.50	-	2.0	19.60

Multi Layered Titanium Composites

Ti-6Al-4V/TiAl/Ti-6Al-4V plate produced from Blended Elemental Ti-48Al-2Cr-2Nb powder and Blended Elemental Ti-6Al-4V powder.

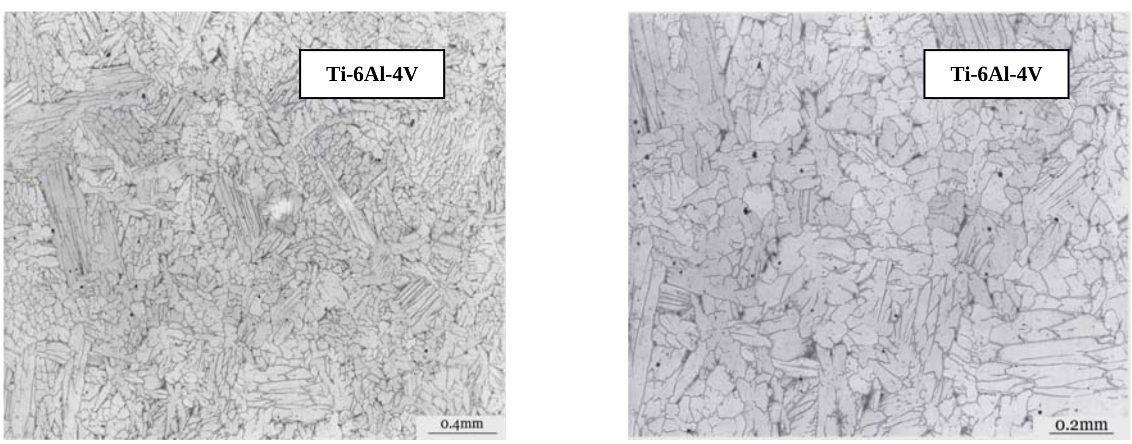
Composite Ti-6Al-4V/TiAl/Ti-6Al-4V plates were produced from BE Ti-48Al-2Cr-2Nb powder and BE Ti-6Al-4V powder by loose vacuum sintering and hot pressing. The samples for microstructure analysis were cut, as shown in Figure 11. The cross-section faces and the surfaces of the sample were used to evaluate their microstructures.



a) b)

Figure 11. Blended Elemental Ti-6Al-4V/TiAl/Ti-6Al-4V plates after a) sintering and hot pressing and b) machining.

The microstructures of the composite sample taken from the Ti-6Al-4V section seen in Figure 12a, and b show the Ti phase with an α+β microstructure, which is essentially uniform throughout the sample.



a) b)

Figure 12. Microstructure of Ti-6Al-4V section of composite Blended Elemental Ti-6Al-4V/TiAl/Ti-6Al-4V plate.

The cross-sectional microstructure of the composite plate shown in Figure 13 shows the presence of the reaction zone between the matrix of Ti-6Al-4V and TiAl. The differences in grain size of the two phases and that in the interaction zone can be seen. The grain morphologies within the reaction zone and within the Ti phase section are similar. However, the former region contains larger sized grains. The width of the reaction zone is approximately 1.4 mm.

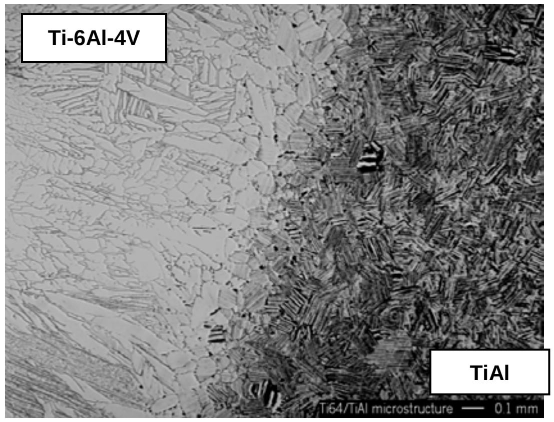


Figure 13. Microstructure of Blended Elemental Ti-6Al-4V/TiAl/Ti-6Al-4V composite plate.

Summary

1. The cost-effective Blended Elemental PM technology has been developed for the titanium alloys. Nearly dense Ti-6Al-4V alloys were synthesized with press-and-sinter approach using hydrogenated magnesium reduced titanium powder.
2. The sintered BE Ti-6Al-4V alloys exhibited good mechanical properties due to high density, chemical homogeneity and relatively fine microstructure.
3. BE powder metallurgy approach is very attractive for creating new high performance titanium based materials which could not be manufactured via conventional ingot metallurgy. Titanium MMCs reinforced with titanium carbide particles were fabricated by simplest BEPM room temperature consolidation and sintering approach.
4. It was demonstrated that room temperature consolidation by Die pressing, Cold isostatic pressing and Direct powder rolling followed by sintering process allow to produce the low cost flat products (foils, sheets, and plates) and “chunky” components with properties equal or exceeding those for cast titanium components and meeting the corresponding military and ASTM specifications
5. Blended elemental Ti-6Al-4V reinforced with 10% and 20% particulates exhibit high strength, but the ductility is still below the ASTM requirements. Heat treatment optimization is required for improvement of mechanical property combination. Reinforcement with the particulates increased the modulus from 17 Msi for non-reinforced Ti-6Al-4V alloy to 19 Msi for 10% reinforcement and to 20 Msi for 20% reinforcement.
6. The composite Blended Elemental Ti-6Al-4V/TiAl/Ti-6Al-4V plates were produced using the cost-effective P/M approach. The microstructure of Ti-6Al-4V section displays the homogeneous Ti phase with an $\alpha+\beta$ microstructure. TiAl phase with a lamellar microstructure are essential uniform throughout the samples. Porous areas in Ti-6Al-4V phase regions are almost extinct, and porous areas in TiAl phase section and the interaction zone were observed.

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26. O. M. Ivasishin, D. G. Savvakin, V. S. Moxson, V. Duz, A. N. Petrunko, F. H. Froes, C. A. Lavender, "Synthesis of Powder Metallurgy Titanium Using Hydrogenated Titanium,” presented at AEROMAT 2006, Seattle, WA.
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Low Cost Blended Elemental Titanium Powder Metallurgy

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TITANIUM 2007
October 7-9, Orlando, FL

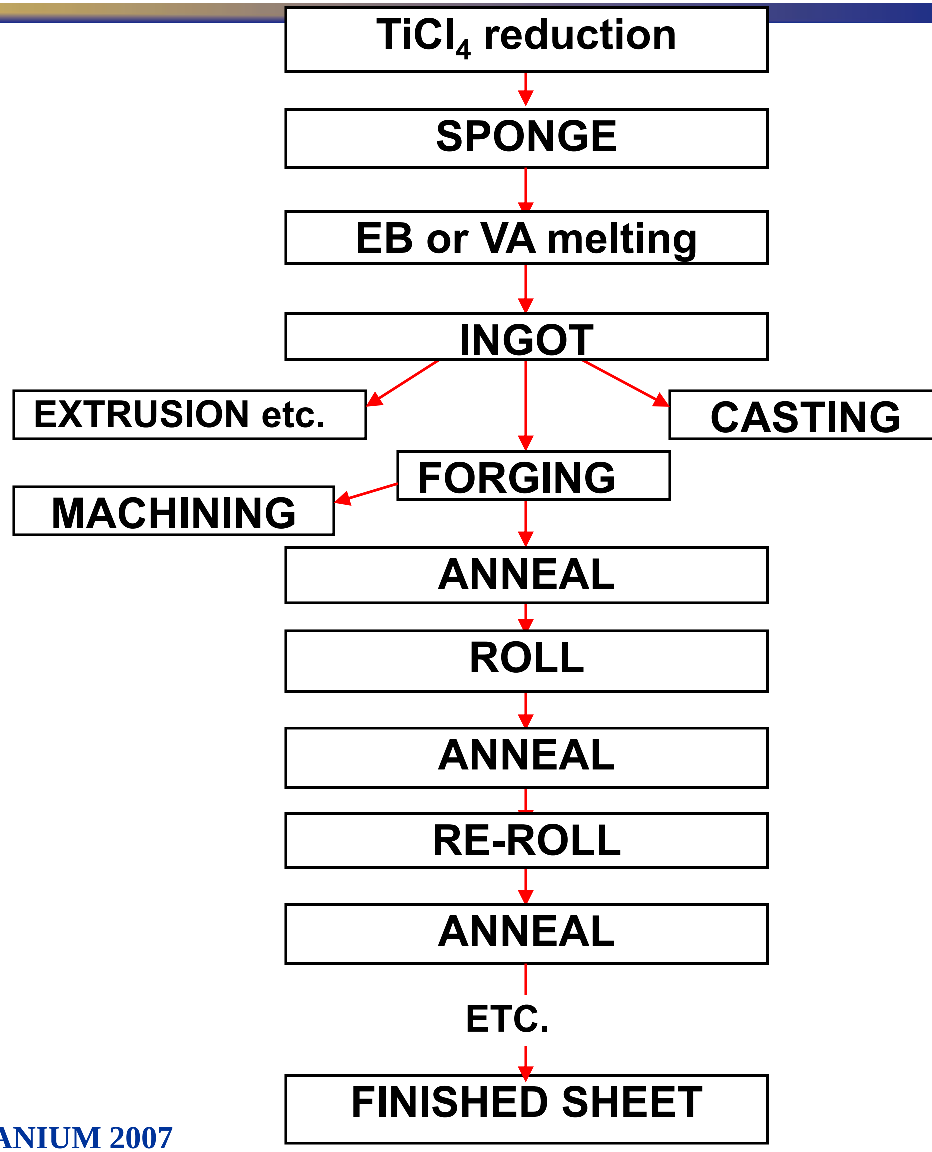
What Factors into Making Titanium Costs High?

High extracting costs

- strong bonding between titanium and oxygen;
- requirements to get relatively low levels of other elements;

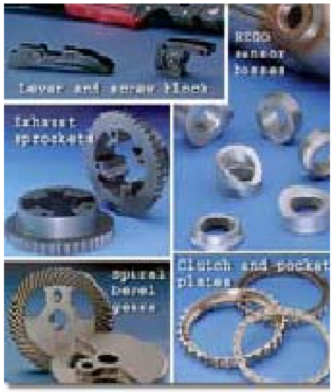
High processing costs

- high temperature processing requires conditioning prior to further fabrication (surface regions contaminated at the processing temperatures, and surface cracks, both of which must be removed);



U.S. 2006 Powder Metallurgy (P/M) Industry Sales

Conventional P/M vs. **Titanium P/M**



INGOT → ATOMIZATION → POWDER → FORGING → P/M PARTS

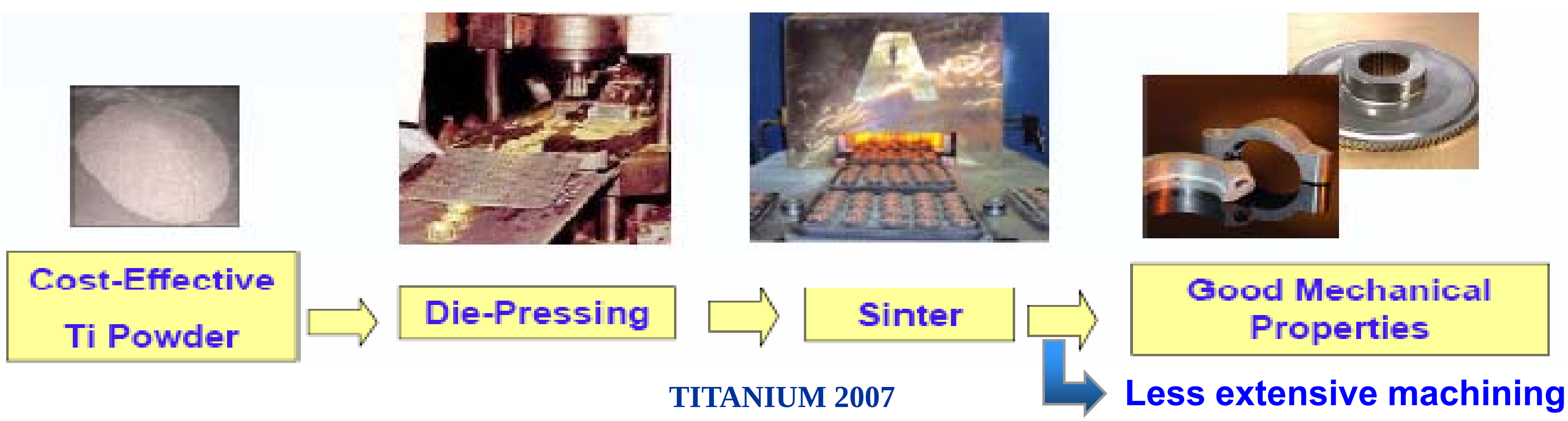
$5,000,000,000

Ti SPONGE → POWDER → P/M PARTS

$10,000,000

Benefits of P/M Processing

- Fewer steps
- No extensive secondary machining
- Low buy-to-use ratio: scrap rate ≤2%
- Direct alloying
- Rapid manufacturing cycle
- Uniform properties in longitudinal and transverse directions
- No texture developed
- Integral processing of composites, laminates or gradients
- More energy efficient



ADMA Processing Step Options for P/M Ti Alloy Part Production

Base TiH_2 powder (--150 µm) **+** Alloying elements added as

Base Ti powder master alloy powders (MAP)

<u>Ti alloy compositions</u>

- C.P. Ti
- Ti-6Al-4V
- Ti-3Al-2.5V
- Ti-6-6-2
- Ti-6-2-4-2
- Alpha and Gamma TiAl
- Other Ti alloys

<u>Metal Matrix Composites</u>

<u>Multilayered Structures</u>

Blending

Room temperature consolidation
- Direct powder rolling
- Cold-isostatic pressing
- Die-pressing

Vacuum sintering

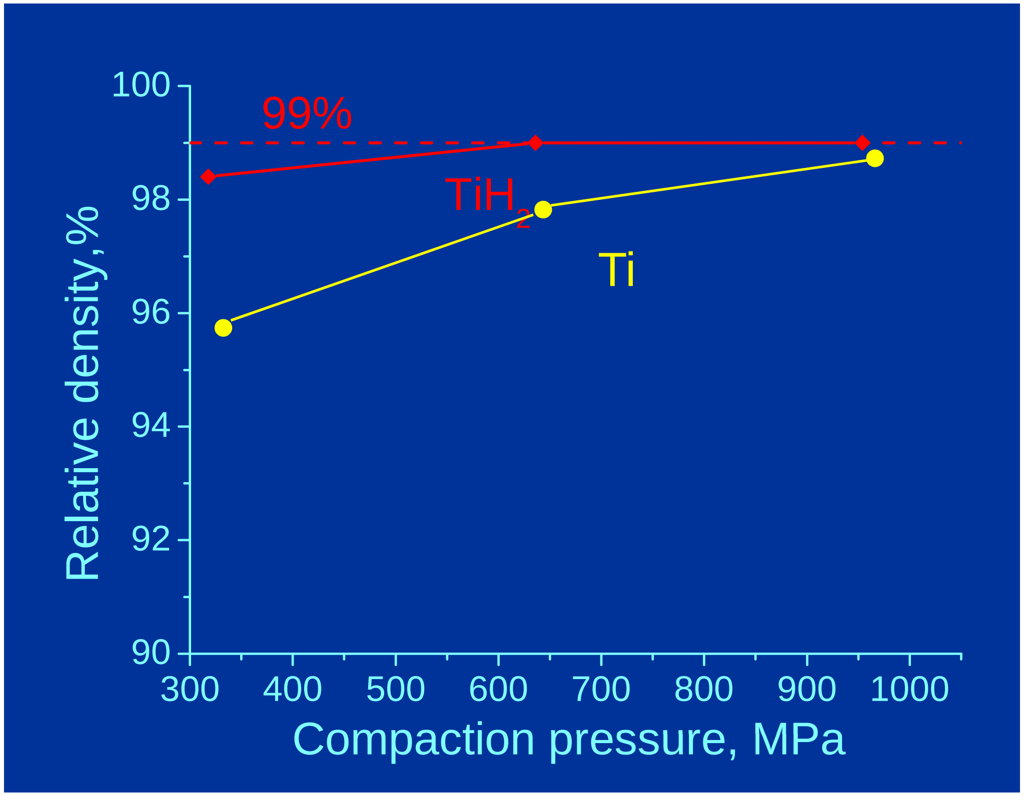
Post processing
- Rolling
- Forging

Types of Titanium Powders Evaluated

- Sodium Reduced Titanium Sponge Fines
- Magnesium Reduced Titanium Sponge Fines
- Calcium-Hydride Reduced Titanium Powder
- ITP Armstrong Titanium Powder
- H/DH Titanium Powder from Magnesium Reduced Sponge
- H/DH Extra Low Chlorine Titanium Powder
- H/DH Powder Produced from Scrap (Turnings)
- Swarf
- Plasma Rotated Electrode Processed Ti powders
- Atomized Titanium Powders
- Innovative Magnesium Reduction Process
- DuPont Titanium Powder

✓ Low Cost TiH_2 Powder -ADMA U.S. Patent No. 6,638,336 B1

Influence of Compaction Pressure



Density: To attain sufficient sintered density compaction pressure value is not critical parameter for titanium hydride powder contrary to titanium powder. This unique feature of the titanium hydride approach is attributed to compaction mechanism of low strength and brittle hydride particles.

MIL-DTL-46077F
Chemical Composition of Ti-6Al-4V for Armor Plates

									Other[2]	
Class	Al	V	C	O	N	H	Fe	Ti	Each	Total
1	5.50-6.50	3.50-4.50	0.04 max	0.14 max	0.02 max	0.0125 max	0.25 max	Rem[1]	0.10 max	0.40 max
2	5.50-6.75	3.50-4.50	0.08 max	0.20 max	0.05 max	0.0150 max	0.30 max	Rem[1]	0.10 max	0.40 max
3	5.50-6.75	3.50-4.50	0.08 max	0.30 max	0.05 max	0.0150 max	0.30 max	Rem[1]	0.10 max	0.40 max
4			0.08 max	0.30 max	0.05 max	0.0150 max		Rem[1]		

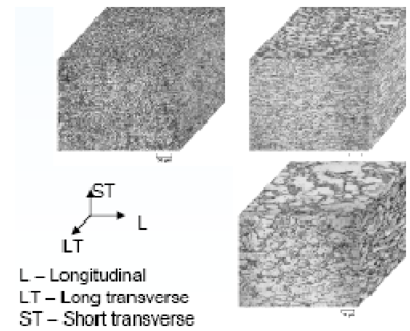
Chemical Composition of P/M Ti-6Al-4V

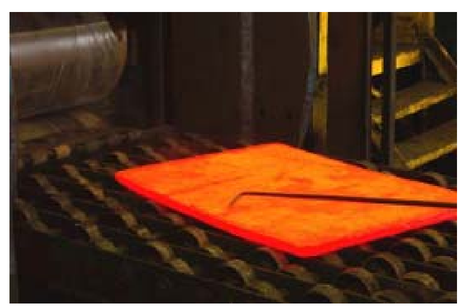
									Other[2]	
Class	Al	V	C	O	N	H	Fe	Ti	Each	Total
RMI	6.0*	4.0*	0.0153	0.10	0.0041	0.011	0.0036	Rem[1]	Cl 0.20 Na 0.13	0.40 max
Armstrong Powder (ITP)	6.0*	4.0*	0.0052	0.15	0.0086	0.005	0.001	Rem[1]	Cl 0.0027 Mg 0.019 Na 0.055	0.40 max
DuPont Powder	6.0*	4.0*	0.021	0.123	0.11	0.018	0.006	Rem[1]	Cl 0.023 Na 0.11	0.40 max
Hydrogenated Powder	6.0*	4.0*	0.006	0.150	0.024	3.10	0.06	Rem[1]	Cl 0.11	0.40 max

ADMA Processing Steps for P/M Ti Alloy Part Producing

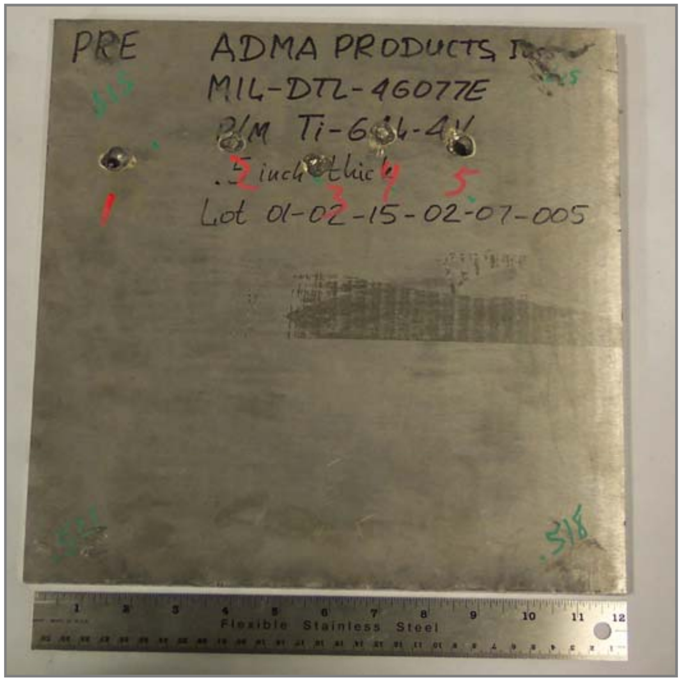
Billet size and weight: 12"x 8"x 30"–410 lbs

16"x 5"x 55"–560 lbs





Successful Initial Ballistics on P/M Ti-6Al-4V 0.50 inch plate



FRONT

BACK

Successful V_{50} ballistic test of 0.50 inch Ti-rolled P/M 6Al-4V plates against 0.30 caliber AP M2 according to MIL-DTL-46077E.

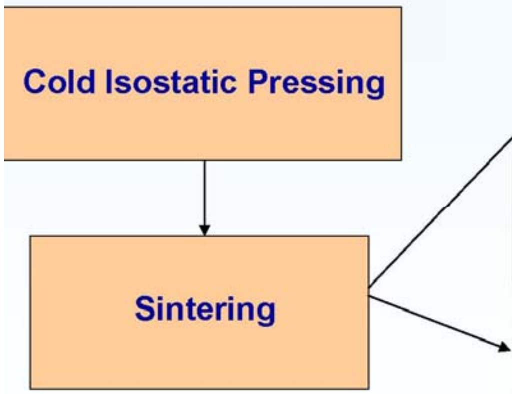
High Oxygen Content Degrades Ballistic Performance of Ti-6Al-4V

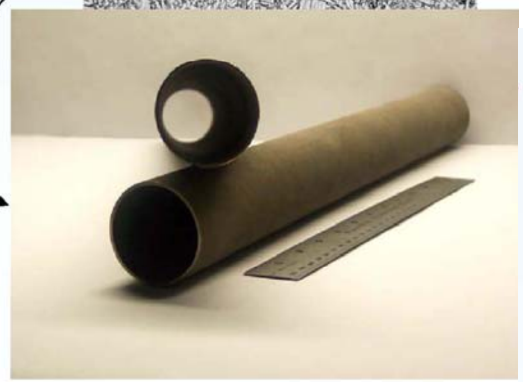
Grade 3 – 4 plate fails

MIL-DTL-46077F

0.75 in thick vs. 20 mm FSP

Cold Isostatic Press + Sinter

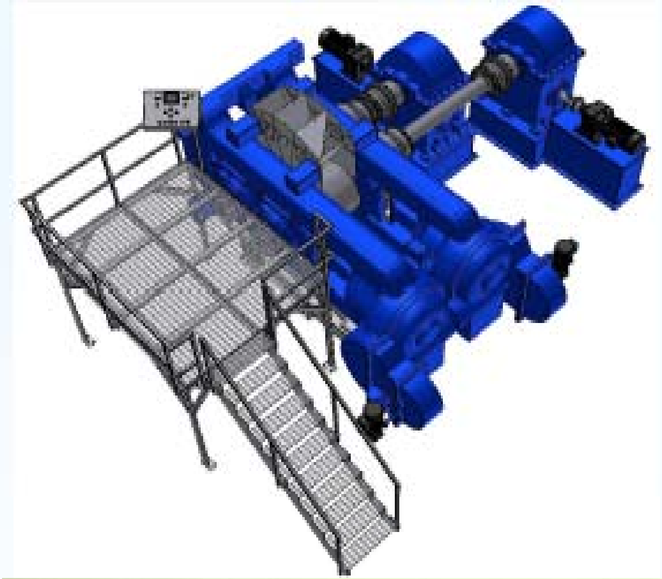




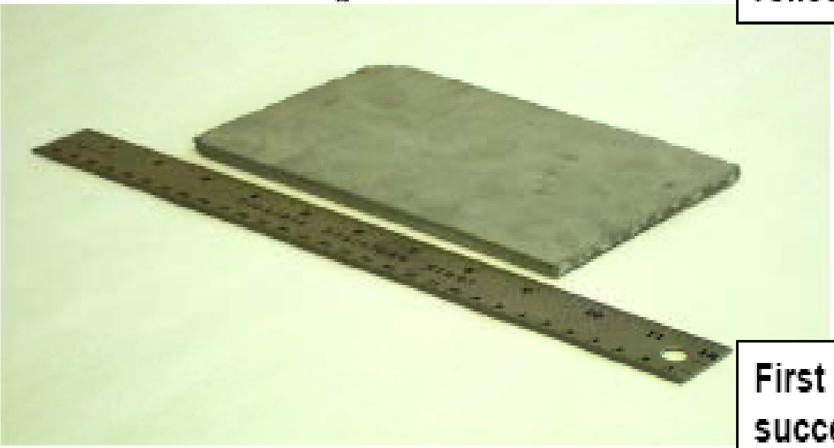
Tube Sleeve / Flange

Ti-6Al-4V Extrusion Billets

33"x 26"wide Direct Powder Rolling Mill- Initial Plate Product



26" wide Ti plate was successfully rolled at ADMA facility



First 0.28" thick Ti plate was successfully rolled at ADMA facility

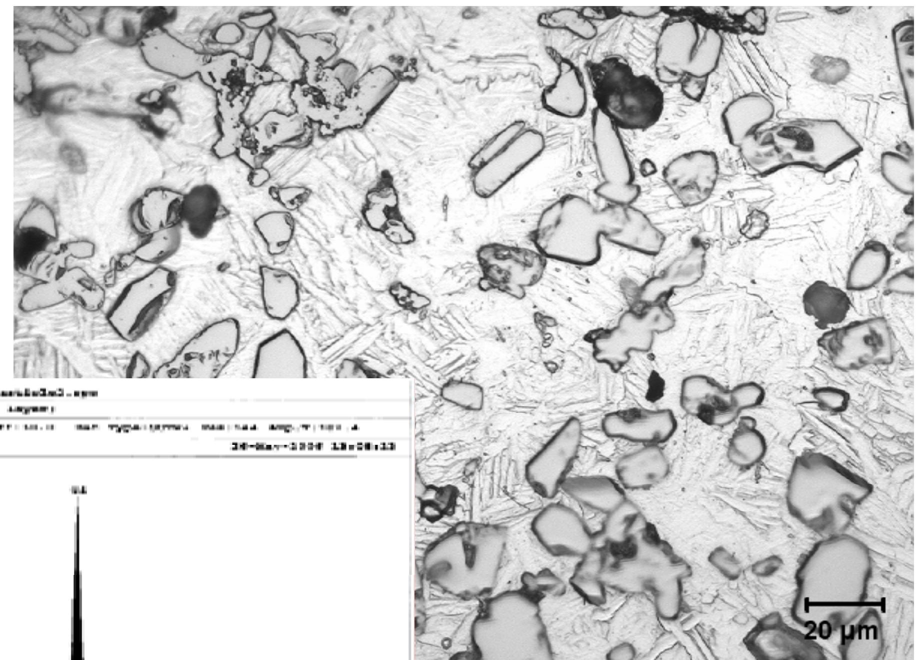
Discontinuously Reinforced BE P/M Titanium Metal Matrix Composites (MMC)

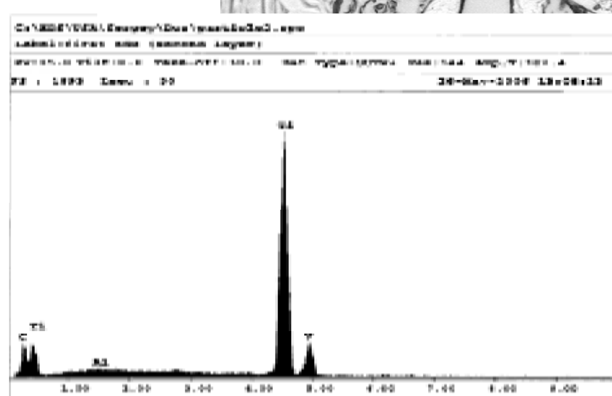
Ti powder
or
Ti + master alloy

\+ Ti, Al, Zr, W, Cr, C, etc. → Ti MMC

Example:

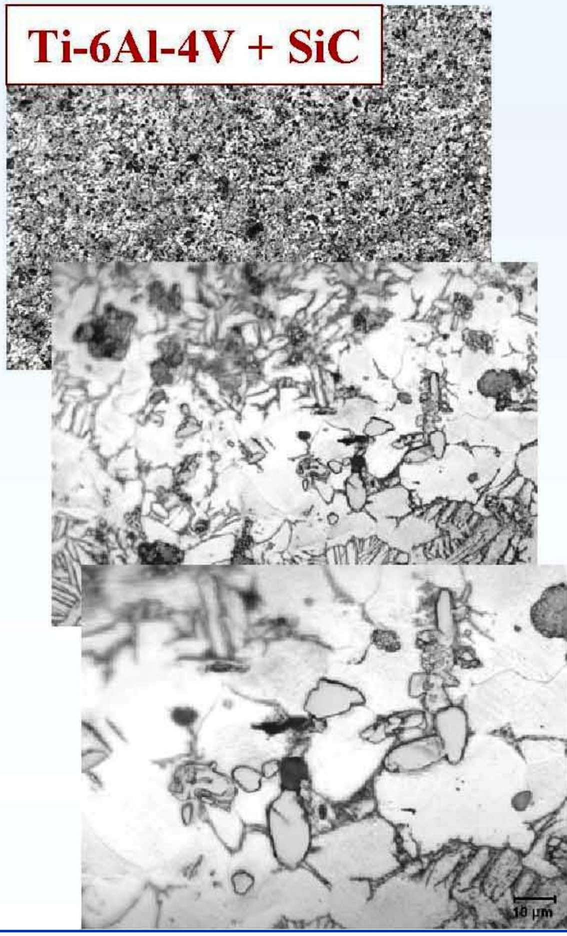
Instead of incorporating TiC ceramic particles into the matrix, TiC reinforcement particles were synthesized from a mixture of Ti, Cr, C co-attrited powders.

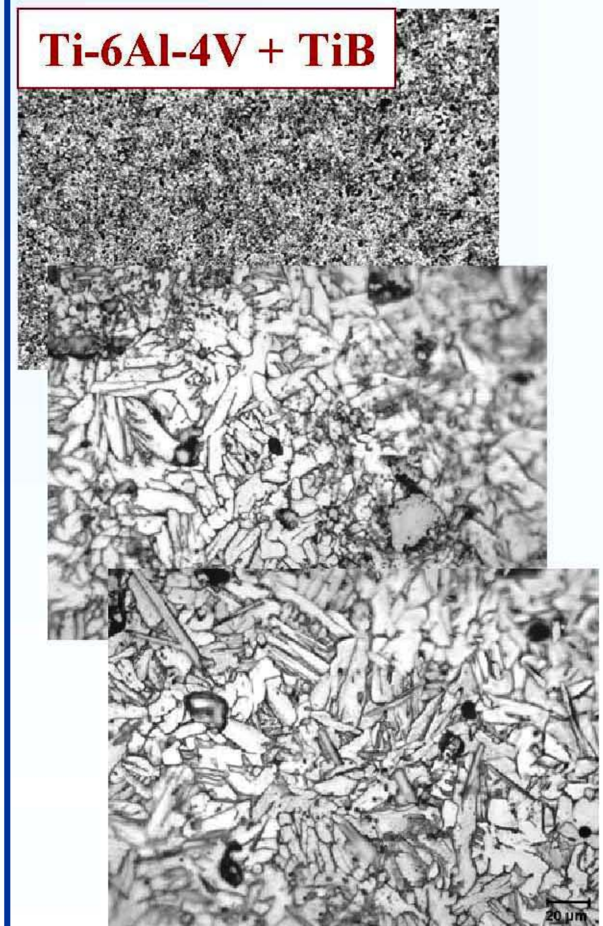


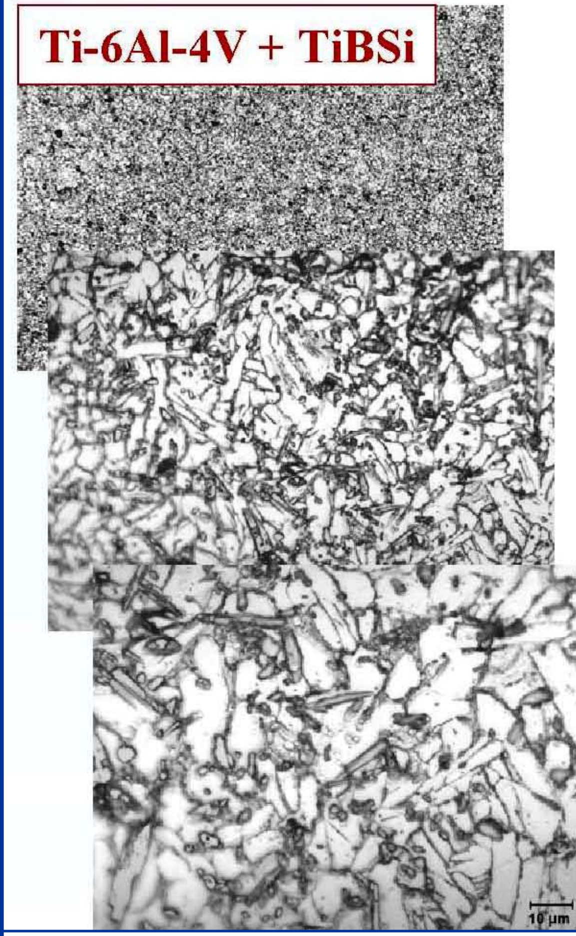


Blended Elemental P/M Titanium Discontinuous MMCs

US Patent Application No. 11/890644







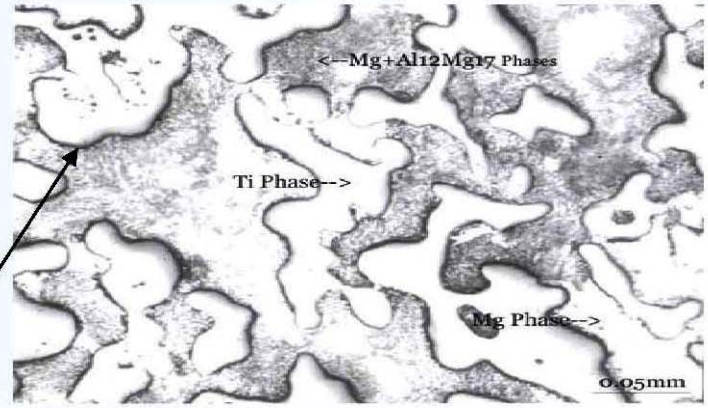
Ti or Titanium Alloy Advanced Modulus (with Titanium/Magnesium Eutectics)

ADMATAL-21™
US Patent 6,599,466 B1

Loose Sintering

↓

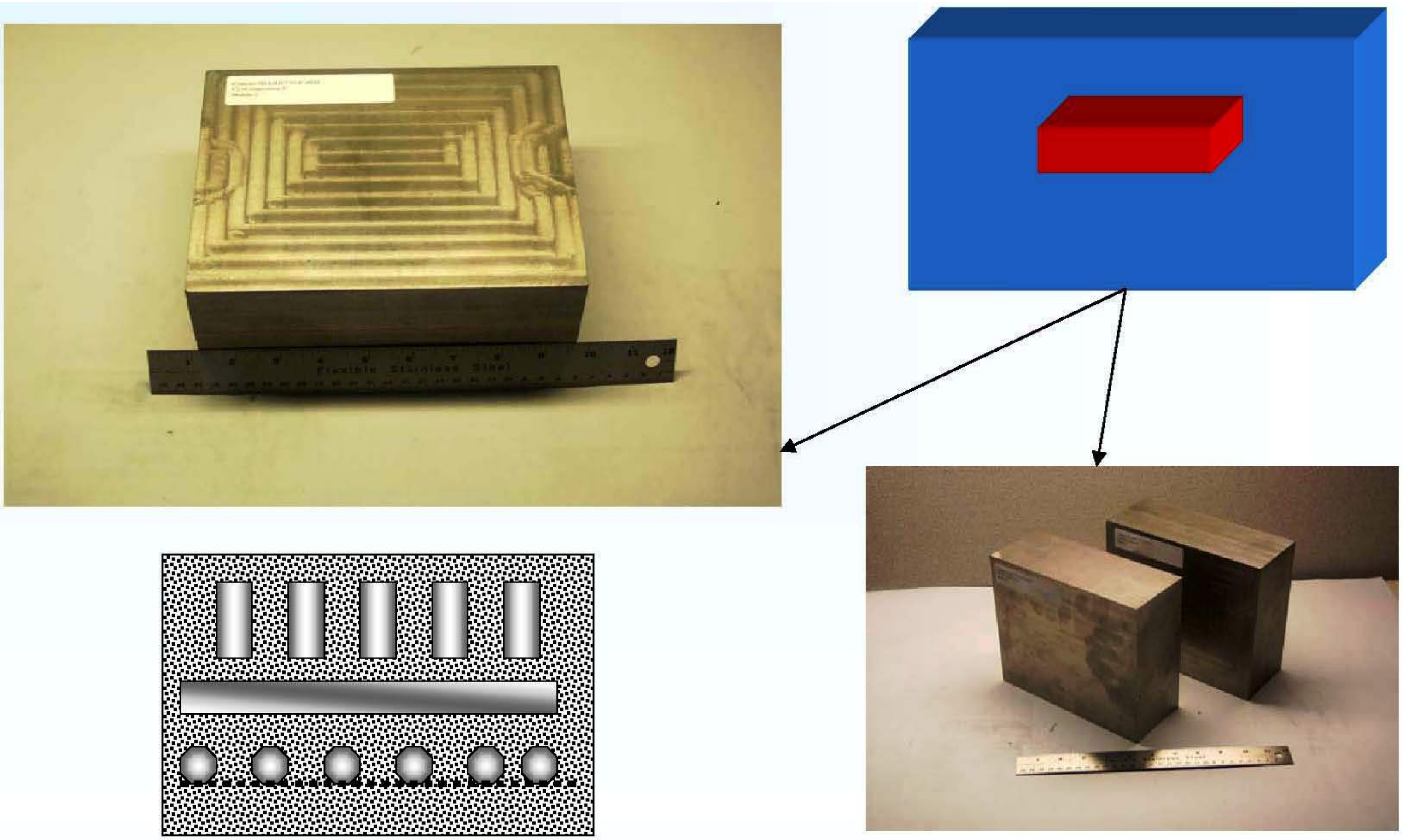
Infiltration with Mg Eutectic or other light alloys



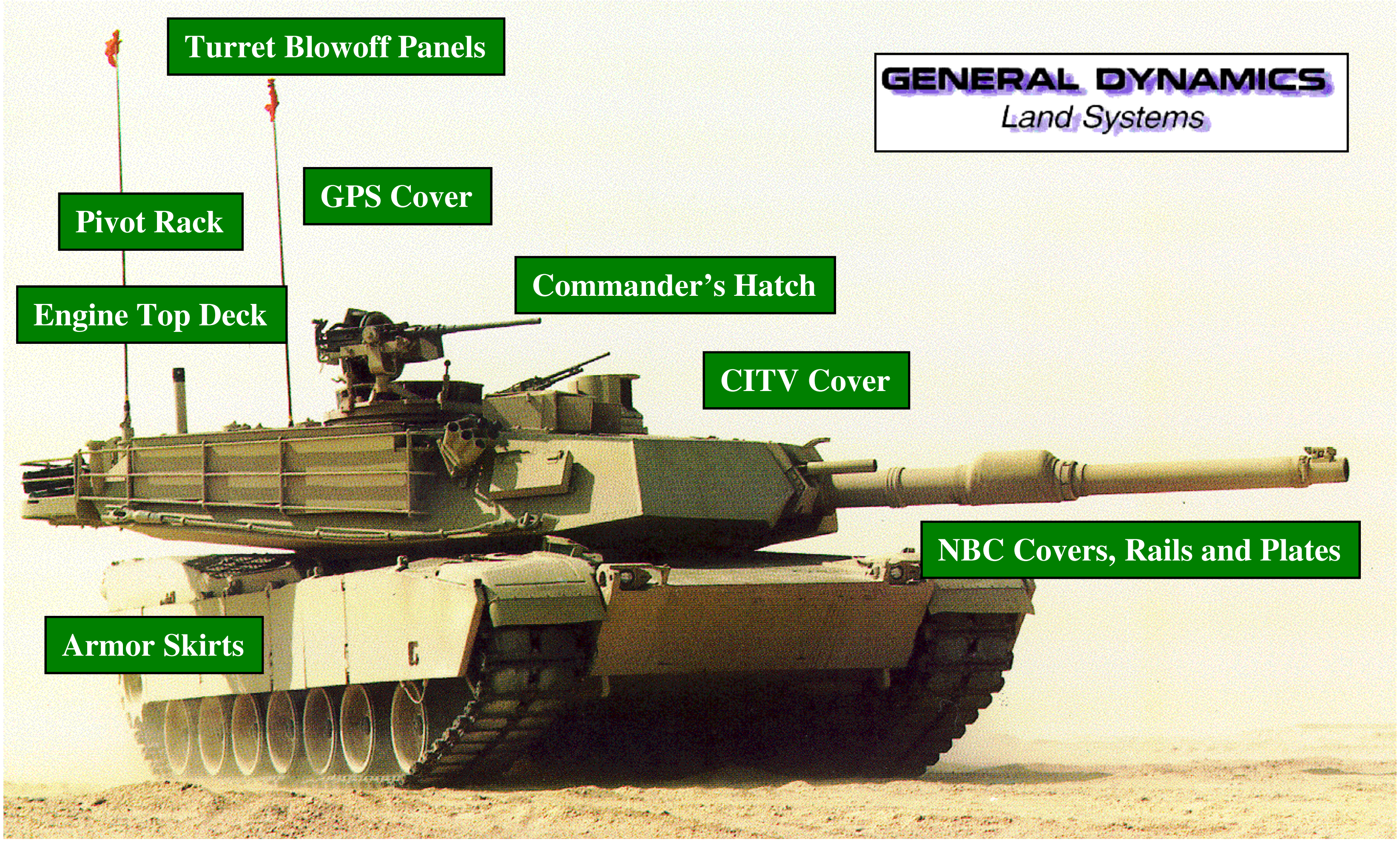
Ti-6Al-4V infiltrated with 90%Mg - 10%Al

Titanium or Titanium Alloy w/Advanced Modulus to encapsulate ceramic tiles

US Patent 6,635,357 B2



Abrams Titanium Integration



Ongoing P/M Activities

- ✓Welding studies
- ✓Bradley vehicle Commander's Hatch
- ✓FCS skirt armor
- ✓Various commercial applications:
  - extrusion preforms
  - direct powder rolled plate
  - forging preforms

Summary

- ✓ P/M reduces cost by alloying and pre-forming at RT
- ✓ P/M manufacturing reduces processing steps
- ✓ P/M manufacturing can reduce time to delivery
- ✓ Low oxygen powders are becoming commercially available.
- ✓ Capabilities for larger Titanium P/M parts:
  - Plate
  - Extrusion pre-forms
  - Encapsulated materials

PM Ti advancements are linked to powder availability. Fortunately, this situation is improving!