Powder Titanium Fabrication Processes, Economics and Market Applications

by

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Purpose: The purpose of this paper is to provide information showing how products can be made successfully from powder titanium, and identify issues associated for use of the material. This information is given to help companies engaged in powder titanium supply, fabrication, and end use better focus their efforts. This paper will

1. Describe the major fabrication technologies, and some properties being achieved.
2. Discuss the economics of selected processes.
3. Present products made from these processes that are a commercial success, and describe potential applications.

Much of this information is based on the experiences obtained by the author while General Manager of Clevite's Titanium Business.

Powder Titanium, Manufacturing Processes and Properties

Powder metal manufacturing methods are used successfully for many materials in high volumes. The success of the powder metal industry in general required the effort of material suppliers, equipment manufactures, powder metal parts producers, and design engineers. A great deal of the infrastructure developed for the powder metal industry is available for use in manufacturing powder metal titanium components. Fabricating titanium products from powder metal methods has had limited success in terms of the number of commercial product applications. Why?

The major manufacturing methods presently developed for powder titanium can be grouped into the following major categories:

- Commercially pure titanium.
- Blended elemental titanium.
- Prealloyed titanium and hot isostatically pressed.
- Prealloyed titanium other.

Titanium powders available to be used are sponge fines, hydride-dehydride powder, and prealloyed powder. Sponge fines used for titanium parts fabrication have been those produced from the sodium reduction process for making sponge. These sponge making processes produce 7-12 percent of their material in a particle size -100 mesh suitable for powder metal parts. The cost of sponge fines is less than half the cost of wrought titanium. The quality of the material for fatigue critical applications is not acceptable for most applications. However, fatigue endurance limits are achieved. Of all titanium powder used in the world for structural parts, titanium sponge fines made from the sodium reduction processes represent the largest commercial success. See table 1.

In an effort to provide higher quality titanium powder, the hydride-dehydride process was developed to produce powder from wrought alloy titanium material. The price of these powders is 3 to 5 times higher than wrought titanium.

Processes were developed to produce prealloyed titanium powder in a spherical shape. The powder produced is of high quality as is the costs which are 4-5 times more expensive than wrought titanium. In addition, the manufacturing methods to use spherical titanium powders is the most expensive of all powder metal fabrication processes.

Powder morphology has a great affect on the economics of a finished part. Morphology determines the type of manufacturing process which can be used, and the properties attainable. In addition, the quality and availability of titanium powder can help or hinder the commercial use of components made with powder titanium.

Titanium based powder can take on one of two powder shapes: irregular or spherical. *The first shape, an irregular or a circular shape,* allows a compact to be formed by:

- Mechanical die pressing.
- Cold isostatic pressing.
- Plasma Spraying.
- Direct powder rolling.
- Hot isostatic pressing (HIP).
- Extrusion.

The first three methods are used on a routine basis for production of parts. The economics of these methods have been accepted by design engineers. The first two methods represent cost reductions versus wrought metallurgy. Plasma spraying offers unique processing capabilities.

A spherical shape titanium powder produced by gas atomization or rotating electrode method can not be fabricated by traditional high volume powder metal methods such as mechanical die pressing, direct powder rolling or cold isostatic pressing. The particles can not be molded with sufficient green strength for handling prior to sintering. Spherical titanium powders can be used by:

- Coatings Plasma Sprayed, and Sintered.
- HIP.
- Powder cloth process.

The irregular shape titanium powder has demonstrated unique metallurgical capabilities by allowing a sintered density greater than 95 percent to occur. In the case of one process, MR-9, 99 percent density is achieved after vacuum sintering. Blending an irregular shaped master alloy with irregular shaped titanium will result in a rapid diffusion of the master alloy into the titanium during vacuum sintering, and result in densities greater than 96 percent. The state of the art is to use minus 100 mesh titanium powder with a master alloy of minus 400 mesh (40) micron size. After blending, parts are pressed to 85 percent green density and vacuum sintered. In the case of commercially pure titanium a 85 percent green density will sinter to 92 percent.

Commercially Pure Titanium Processes

The manufacturing methods used for commercially pure titanium products are the same methods used for blended elemental titanium. The difference is that no master alloys are added. The process for making parts from titanium powder involve cold pressing the powder into a shape (green part) and then vacuum sintering the part. Standard powder metal equipment used for fabrication include mechanical die presses, cold isostatic presses and rolling mills. Low cost sponge fines processed by high throughput powder metal equipment produces parts that are used mainly for the chemical resistant properties of titanium. Fasteners and filters are routinely produced by these methods. Specialty products such as knife handles and watch cases are made from C.P. titanium powder.

Blended Elemental Titanium

Blended elemental titanium technology developed from the availability of low cost titanium powder, sponge fines, and the availability of high throughput standard powder metal equipment. Two companies started work on blended elemental titanium technology in the 1960's and pioneered the technology into commercial product applications. These companies are Clevite Industries, and Dynamet Technologies. In addition to these companies The Materials Research Laboratory at Wright Patterson AFB sponsored, funded and evaluated material from these two companies.

Blended elemental titanium is the blending of a irregular shaped titanium powder with a master alloy powder. To make a Ti-6Al-4V alloy, a master alloy consisting of 60 percent aluminium and 40 percent vanadium is blended in proper proportion to yield the desired alloy chemistry. In addition small amount of other materials may be added to adjust the final product chemistry. For example, iron, or copper, may be added as alloy constituents. Powder titanium dioxide may be added to increase the oxygen content of the final material. Recently, Dynamet Technologies achieved metal matrix composites by additions of titanium carbide to the blended elemental process.

The companies that make near net shape components from sponge fines have managed to take a material (sponge fines) whose chemistry is considered inferior to ingot metallurgy and make it a commercial success. This has occurred because of dramatic cost savings in the range of 50-70 percent.

There are three basic processes for achieving full density using irregular shaped titanium powder in a blended elemental process:

1. CHIP Process.
2. MR-9(c) Process.
3. Forged Powder Metal Preforms.

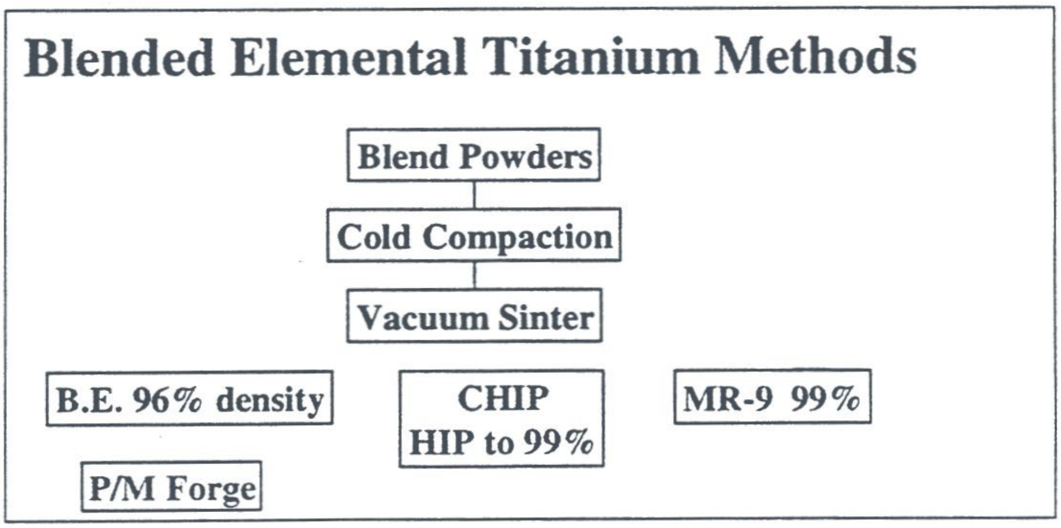


Table 1: Comparison of Major Properties: AMI and Deeside Sponge Fines (Rer. 1)

Property/Element	RMI Typical	Deeside Typical
Particle size -100 mesh	100%	100%
Particle size -200 mesh	23.3%	28%
Apparent Density	0.9gr/cc	1.2gr/cc
Oxygen	.08%	.12%
Nitrogen	.01%	.005%
Chlorine	.14%	.10%
Sodium	.14%	.09%
Iron	.01%	.03%

Sponge fines are the predominant titanium powder form used for blended elemental applications, however electrolytical, Hydride-dehydride titanium powders and other methods are being evaluated.

CHIP Process

The CHIP process, takes advantage of the fact that interconnected porosity does not exist at densities greater than 95 percent. In the CHIP process a powder metal component that has achieved a green density of at least 83 percent is vacuum sintered at 1260 degrees Celsius (2300 degrees Fahrenheit) for four hours. After sintering, a density greater than 95 percent is achieved. The ability to achieve sintered densities greater than 95 percent allow the use of a hot isostatic press to further consolidate the part to greater than 99 percent. In the case of Clevite's MR-9(c) process hot isostatic pressing is not required. If the parts are not 99 percent dense after sintering and higher density and the associated properties are required, the parts can be batched processed in a HIP cycle without canning. On parts 2-4 pounds in weight and volumes of 500-1000 pieces per HIP cycle, HIP costs per piece range from $4-10 per part. The powder metal fabricator can send his component to a company that specializes in HIP'ing and thereby not have to invest in a HIP unit.

MR-9 Process

Clevite developed and patented a blended elemental powder titanium process MR-9. Based on proprietary processing techniques they achieve sintered densities greater than 99 percent and achieve high mechanical properties and a fatigue endurance limit. The MR-9 process does not use HIP'ing or forging to achieve the high densities. Sponge fines from RMI, Deeside Titanium, and chlorine free titanium powder from Osaka Titanium have been used successfully in the process. Clevite has licensed the MR-9 process to Exotic Metals Inc. a division of Masco Industries, and to a Japanese company.

Great interest has been shown in the automotive industry for the MR-9 process because it allows the use of high volume powder metal manufacturing methods. It is the lowest cost process for making titanium connecting rods in volumes of 100,000 pieces or more.

Forging Powder Metal Preforms

Forging powder metal preforms is emerging as a potential process for making parts. Dynamet Technology has completed process and economic studies with Alcoa Forging Division in Cleveland, Ohio. The powder forging process developed to date for powder titanium includes the following major steps:

- Blending titanium powder with master alloy.
- Cold pressing a part to 85 percent green density.
- Vacuum sintering (96-99 percent density achieved).
- Forging reduction.
- Final finishing(descaling, machining etc.).

A combination of powder metal and forging has resulted in manufacturing cost reductions for certain part geometries. Benefits achieved by the combination of processes are:

1. Improved shape making capability from cold isostatically pressing.
2. Lower material starting cost if sponge fines are used.
3. Reduction in the number of forging dies required too one die.
4. Increased material utilization.
5. Increasing density of the powder metal part to 99 percent.

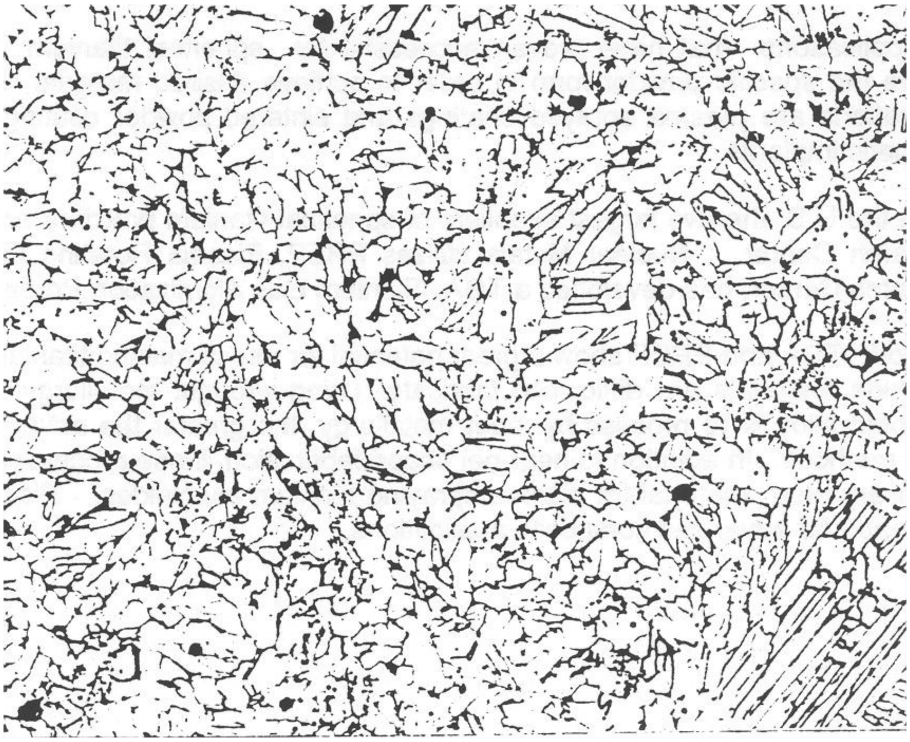
Table 2: Blended Elemental Titanium Properties Using Sponge Fines

Process for Ti-6Al-4V	0.2% YS MPA	UTS MPA	Elongation %	R A %	Density % of Theoretical
CHIP (Ref 2)	827	917	13	26	99+
MR-9 (Ref. 3)	869	972	12	30	99+
P/M Forged (Ref. 4)	931	1028	7.5	14%	99.5
Min.Wrought	827	896	10	25	100

Table 3: TI-6Al-4V Tensile Specimens Using Deeside Titanium Ltd. Sponge Fines

Specimen No.	0.2 % YS MPA	UTS MPA	Elongation%	RA %	Density %
1	840	947	13.8	31.5	99.5
2	843	953	12.8	28.8	99.6
3	845	950	13.5	30.2	99.3
4	843	952	13.6	30.8	99.7
5	842	945	13.9	30.2	99.3
6	839	945	13.8	31.5	99.5
Average	842	948.7	13.6	30.5	99.5

Sample Microstrucure Blended Elemental Ti-6Al-4V Using Deeside Titanium Sponge Fines
Figure 1



Direct Powder Rolling

In the early 1980's Clevite pioneered direct powder rolling of titanium alloy foil. At that time the interest was for monolithic applications. Material could be rolled continuously. Coils could not be sintered in a vacuum furnace and needed to be cut to lengths equal to the length of the furnace. Very successful results were achieved. Cost estimates for rolling titanium alloy foil were five times material costs. In todays cost that would result in $U.S. 77 per kg. ($35 per lb.). Present high alloy titanium fail produced by acid etching (Chemtronics) or rolling and annealing (Texas Instruments) is $ 1,100 - 2,200 per kg. Now there are needs for foil in composite applications.

Use of Spherical Titanium Powder Technology

In an effort to increase the material properties of powder titanium the U.S. government funded major programs to develop high purity powder by funding a titanium gas atomization. TGA, rotating electrode process, REP, and plasma rotating electrode process, PREP. These processes provided high purity powder in a spherical shape. The powder is an order of magnitude, 3 to 5 times, more expensive than the wrought titanium, and 10 times more expensive than sponge fines.

In addition to the premium cost of material, the manufacturing processes needed to fabricate the spherical powder is more expensive than traditional powder metal compaction and processing techniques. A combination of high material costs high fabrication cost require a complicated part geometry to make the process competitive with investment casting or wrought metallurgy. The HIP process offers design engineers unique shape making capability with high material utilization.

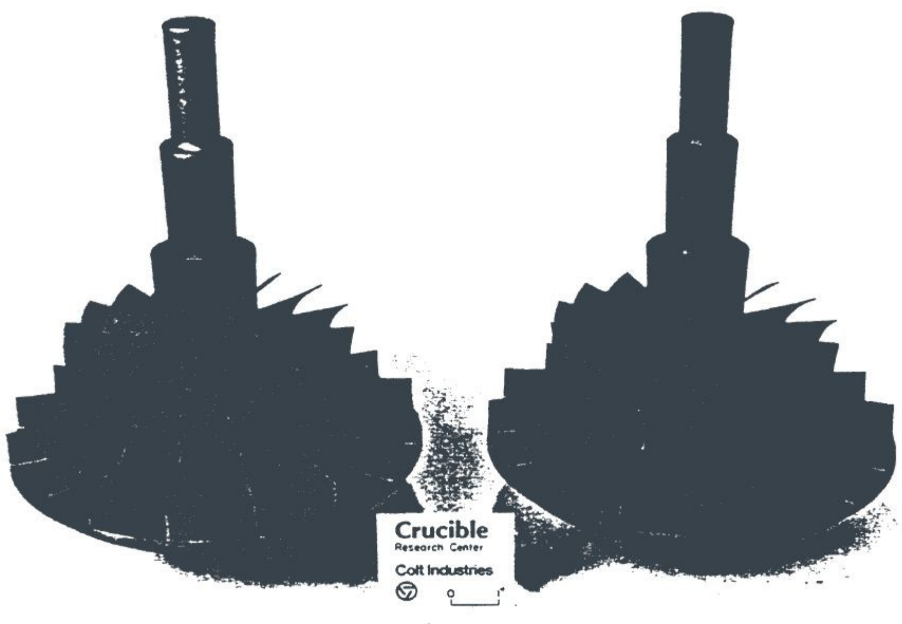
Tooling technology developed for shape making include MBB's electroforming container technology, Crucible Research Center's ceramic mold process, and Kelsey Hayes rapid omni-directional compaction, ROC.

Applications that have proven successful for spherical titanium powders are applications that require the specific powder form in order to achieve desired material characteristics. Two successful applications are plasma sprayed coatings and sintered powder coatings. Both are used for medical prosthetic implants.

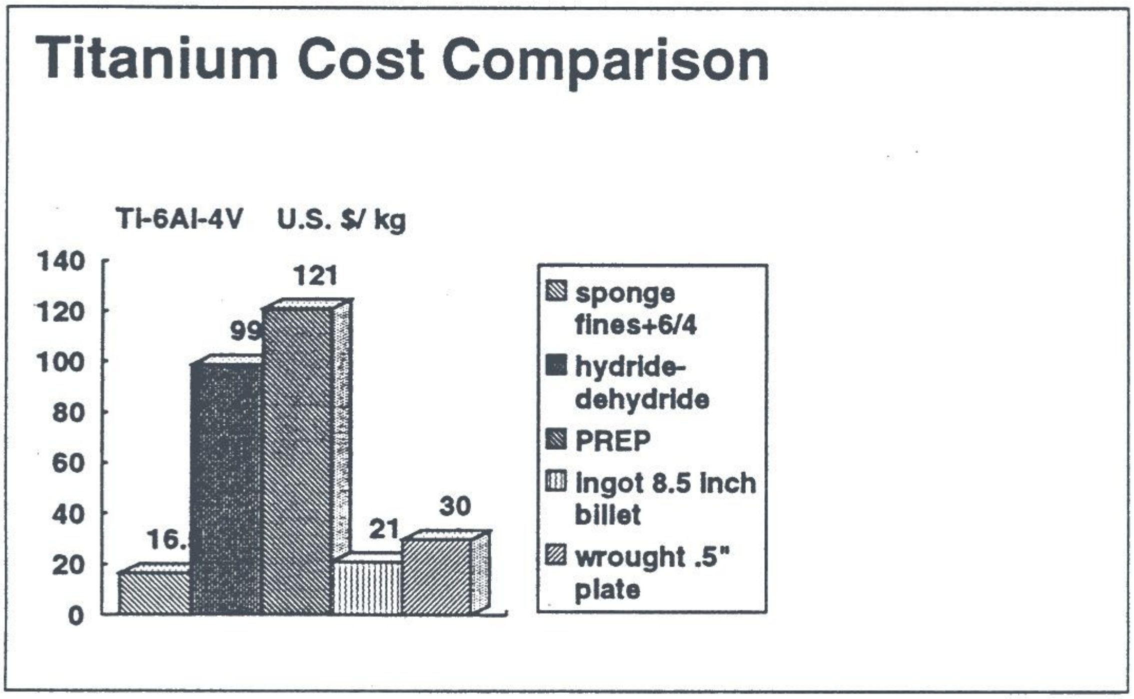
In the U.S. the two largest suppliers of spherical titanium powders are Nuclear Metals and Crucible Research Center. Nuclear Metals utilizes PREP, Plasma Rotating Electrode Process and Crucible Research Center, has developed a TGA, Titanium Gas Atomization Process.

Both TGA and PREP show a great potential for use in making titanium aluminides. Present titanium aluminide materials are difficult to fabricate using wrought metallurgy. The more difficult the titanium aluminide alloy is to process by ingot metallurgy, the greater the advantage for processing by powder metal methods. In addition to near-net shape fabrication, these processes have the ability to provide the necessary feed material for plasma spraying titanium aluminides. Plasma spray processes are being developed for advanced composite applications.

Crucible Materials Corpo Ceramic Mold Process: Alpha 2(T-14Al-21Nb wt%)
Figure 2



Powder Cloth: In addition to the processing methods mentioned PREP titanium aluminide powders are being processed by a powder cloth process. NASA Lewis has fabricated intermetallic matrix composites using titanium aluminide powder dispersed through a binder of PTFE, poly(tetraflouroethylene). Using 3-5 percent weight volume of PTFE allows a web to be formed by fibrillation. The web of PTFE provides a means of rolling the resultant material into thin strips (0.15 - 0.20 mm).



A Case Study: Manufacturing Economics for Blended Elemental Titanium

Since blended elemental titanium has been proven to be highly cost effective, two cost models will be discussed. One model will deal with using a cold isostatic pressing method to make a missile housing. A second example will summarize the manufacturing economics of making a titanium connecting rod in high volumes using a mechanical die press.

In this paper cost information will be provided based on the following exchange rates:

U.S.	U.K.	Germany	Japan	Italy
1.00	0.51	1.49	130	1120

Source : Wall Street Journal, November 9, 1990. Rates as of late N. Y. Trading November 8,1990

Case One: Ti-6Al-6V-2Sn Housing Blank, See Figure 3

Material Property Requirements for Application:

- 862 MPA - Yield Strength Minimum at a .1% offset
- 3.0% - Elongation minimum
- 13 % - Reduction of area, average value
- 6ft/lb. - Minimum V-notch charpy impact at-40 degrees Fahrenheit

Quantity: 10,000 pieces per year

Part Weight: 967 grams

Cost Rates for CIP Housing

Variable	U.S. $	U.K.	Germany	Japan (000)	Italy (000)
Tooling Cost	10,000	5100	14,900	1300	11,200
Titanium - cost per kg	13.22	6.74	19.7	1.72	14.81
Master Alloy - cost per kg	26.43	13.58	39.38	3.44	29.6
Direct Labor Rate cost/hour	12	6.12	17.88	1.56	13.44
Furnace Rebuild - Cost /600 furnace cycles	50,000		74,500	6,500	56,000
Chemical Analysis / lot	150	76.5	223.5	19.5	168
Certified Mechanical Tesing per lot	600	306	894	78	672
Quality Assurance/lot	750	382.5	1117	97.5	840
Capital & Overhead Costs					
Vacuum Furnace	180,000	91,800	268,200	23,400	201,600
CIP	150,000	76,500	223,500	19,500	168,000
Other	50,000	25,500	74,500	6,500	56,000
Depreciation -10%	38,000	19,380	56,620	4,940	42,500
Supervision	25,000	12,750	37,250	3,250	28,000
Maintenance	5,000	2,550	7,450	650	5,600
Rent	10,000	5,100	14,900	1300	11,200
Other	8,000	4,080	11,920	1040	8,960
Total Over Head Costs	86,000	43,860	128,140	11,180	96,320

Manufacturing Rates for CIP Housing

Process	Rate
Blend Size	158.9kg
Labor Hours per Blend	8 hours
CIP Pressing Rate	2 cycles/hour
Pieces per CIP Cycle	4
Sinter Load	180 parts
Inspect/Machine	20 parts/Hour
Scrap Rate	5-10%

A computer model using a Lotus 123 language was developed with the information mentioned above for a missile housing. This part was very successful at replacing a 2,043 gram forging. A 52 percent material savings was achieved. The following summarizes the major cost categories of the model:

Cost Category	U.S.$	U.K.	Germany	Japan	Italy
Material	16.88	8.61	25.17	2,194	18,906
Labor	2.28	1.16	3.40	296	2,544
Testing	4.59	2.34	6.84	597	5,141
Over Head	9.46	4.82	14.1	1230	10,595
Total Cost/Part	33.21	16.93	49.51	4,317	37,196
Selling Price	75	38.25	111.75	9,750	84,000

Note: The properties for the product mentioned above were achieved without hot isostatically pressing. Using the CHIP process for the above product would add approximately $5, (2.5 U.K. Sterling), (7.5 German D.M.), (650 Japan Yen), (5,600 Italy Lire).

This product is routinely produced. A material savings of over 52 percent was achieved and a tremendous cost reduction. The near-net shape part allowed for a reduction in final machining costs. This part is a good example of using low cost sponge fines with standard powder metal fabrication methods.

Cost Summary For Titanium Connecting Rod

In the past five years Clevite received a lot of attention for it's MR-9 process from major automobile manufactures. The automotive industry has evaluated alternative methods for achieving increased fuel economy and reduced noise, shock and vibration in four-cylinder engines. A known means of accomplishing this goal is through lightweight, high-temperature/high-strength engine components. Full dense blended elemental material was supplied for testing and evaluation. Connecting rods were fabricated using both the CIP and mechanical die press technology. The fatigue endurance limit of sponge fines for the application matched the existing iron based connecting rods and provided for a minimum of a 35 percent weight savings.

To demonstrate the cost effectiveness of the process for high volume applications, the writer developed an economic model using Lotus 123. The cost model included a dedicated facility over a ten year period. Based on this cost model the MR-9 process proved to be the most competitive titanium technology for achieving significant weight reduction. The information below summarizes the price attainable given the current price of sponge fines, quality of titanium powder available, and the current state of the art for powder metal titanium fabrication. **See Figure 4**

Quantity:	1 million pieces per year
Part Weight:	340 grams
Pressing Rate:	4 parts per minute using a 500 ton press.
Price of Sponge Fines:	U.S. $ 11.56/ kg (U.K. 5.90/kg) (Germany 17.22/kg) (Japan1503/kg) (Italy 12.947/kg)

The selling price required to justify a dedicated facility for making titanium connecting rods is :

- US $ 7.5 - 8.0 per part
- U.K. 3.83 - 4.08
- Germany 11.18 - 11.92
- Japan 975 - 1,040
- Italy 8,400 - 8,960

The major cost items affecting the high volume production of titanium connecting rods are the price of sponge fines, and the vacuum furnace capacity. A vacuum furnace represents a considerable investment and is a batch process with complete degassing and sintering cycle of at least 12 hours. Existing sponges fines meet the fatigue requirements and offer the lowest cost material and an optimum fatigue endurance limit for the cost. Chlorine free titanium powder at the same price of sponge fines would dramatically increase the performance of the finished part and allow for less material to be used. Ford Motor Company has evaluated the use of titanium in the main part of the connecting rod and use of steel in the cap end. This approach minimizes the use of an expensive material.

Product Applications For Powder Titanium

Commercially Pure Products: C.P. titanium products are made by mechanical die pressing, cold isostatic pressing and powder rolling. Products produced currently include chemical resistant fasteners, filters, knife handles, watch cases, and coatings for medical applications.

Blended Elemental Titanium Products: The major applications for blended elemental titanium exist in non-man-rated weapon systems. Missile housings are produced to densities of 96 - 99 percent, depending on the application. Components are produced for the Sidewinder, Seeker and Stinger Missiles.

Prealloyed Titanium Products: Titanium powder made by the PREP, TGA and hydride-dehydride process are used in coating applications for medical prosthetic implants. Coatings are applied by plasma spray and vacuum sintering.

Major Applications under development: Major applications for powder titanium under development include automotive engine components, MMC missile fins, and plasma sprayed coatings for composites. In addition powder titanium capabilities developed for the TGA and PREP process are being used to provide titanium aluminide powder for advanced applications.

Summary

The use of powder titanium for structural parts has evolved due to the availability of low cost sponge fines and standard powder metal fabrication techniques. In addition design engineers were educated to the capabilities of the various technologies. High purity powder titanium in spherical forms is used successfully in coating applications.

Major factors limiting a broader use of the available technologies are educating design engineers to the materials and capabilities, and the cost and availability of titanium powder. Lowering the cost of sponge fines or the availability of improved powder at prices equal to wrought titanium will make these technologies more competitive.

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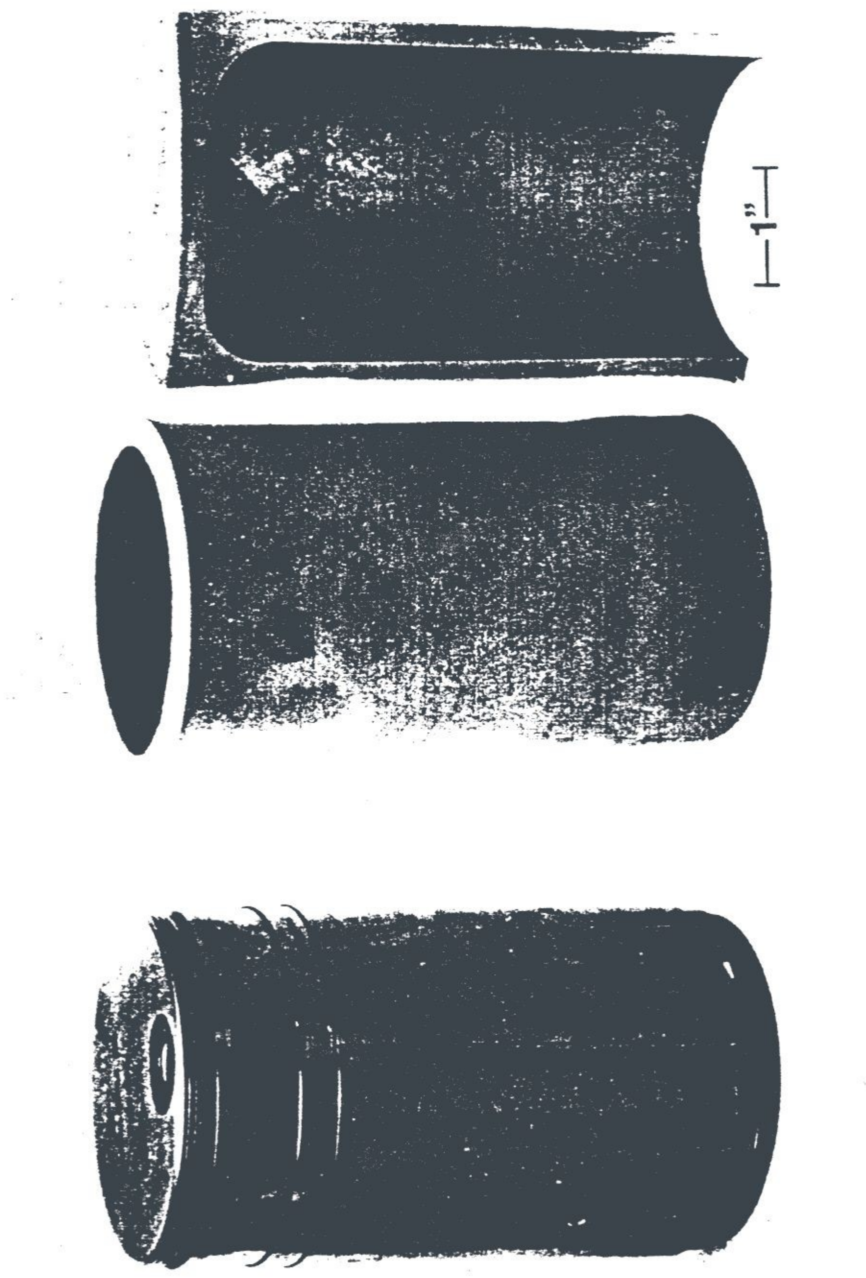

Fig. 3 – P/M Ti-6Al-6V-2Sn housing blank

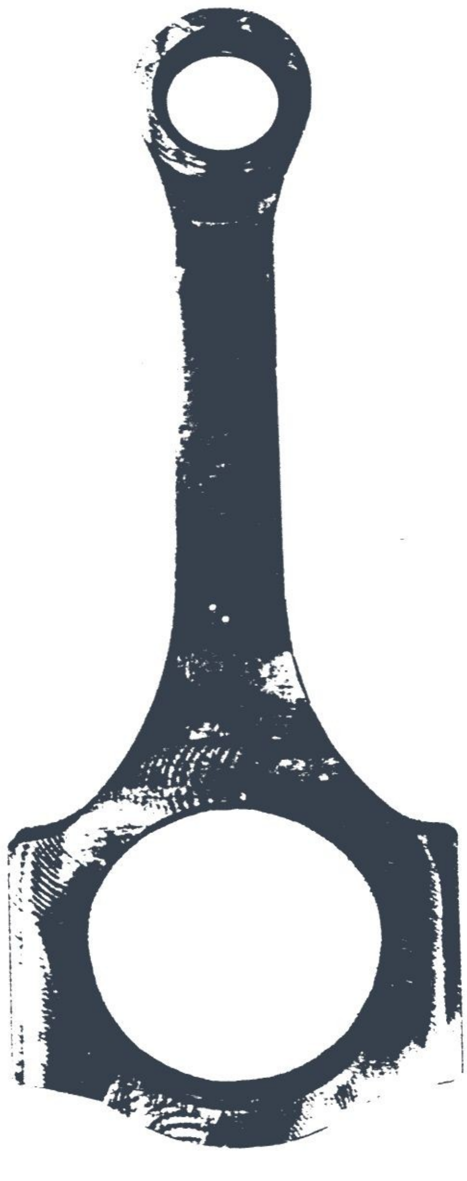

Fig. 4 - P/M Ti-6Al-4V connecting rod