State of Titanium in the USA – the First 50 Years

D. EYLON* and S. R. SEAGLE**

*Graduate Materials Engineering, University of Dayton, Dayton, Ohio 45469-0240, USA.
**Consultant, 3376 E. Market St., Warren, Ohio 44484-4630, USA.

ANNOTATION
The state of titanium research, development and industry in 1999 is reviewed in this article. Developments from the last titanium World Conference in 1995 are highlighted. The fifty-year anniversary of commercialization of titanium technology in the USA provides a unique opportunity for a historical perspective. The incorporation of new "information-age" tools into alloy development, processing and production are invigorating the technology. Consolidation, diversification and globalization have been transforming the USA titanium industry in the recent years.

Key words: USA titanium industry, USA titanium market, USA titanium research and development

1. INTRODUCTION

Titanium is the youngest of the major structural metals. In fact, it did not play any role in the tragic military, human, and technological events of World War II. Although the element titanium was, independently, identified by W. Gregor in 1790, and M. Klaproth in 1795, and the Hunter-reduction process was developed in 1910, it was not until 1948, that commercial quantities of sponge and ingot material were produced in the USA [1]. As we have just past the 50-year landmark of titanium industrialization, and the end of the millennium is rapidly approaching, it is appropriate to review the state of the USA titanium industry in respect to its half a century history. According to Schumpeter's wave-concept [2], technologies that conceived around 1950, should have reached maturation in the pace of innovation after 40-years. And indeed, the USA titanium industry, as the result of this maturation, is going through ***consolidation***, ***market-diversification*** and ***globalization***. The evolution, recent developments since the last World Titanium Conference in 1995 [3], and the current-status of titanium science, technology, and industry will be reviewed along the various industrial and application segments. It is interesting to note that some major advancements in the processing of titanium alloys from melting, to shape-casting, powder metallurgy, and primary and secondary processing of ingot material are now taking advantage of ***process modeling***, ***computer-controlled machinery***, ***computer-assisted NDE*** and ***computer-assisted-manufacturing***, for better products, higher yield and lower cost. This is a perfect example of bringing the information revolution into the more traditional world of structural alloy metallurgy. Fifty years of titanium production in the USA are depicted in Figure 1 [4]. It is clear the industry is still expanding with a good outlook into the year 2005. However, this diagram also demonstrates the cyclic nature of the USA titanium market over that period, the result of the strong dependence on military and commercial aviation.

2. PRODUCTION OF TITANIUM

2.1. SPONGE - MAKING

Based on the early research work of Kroll on the Mg-reduction of titanium tetrachloride (TCT), the first commercial quantities (16mt/yr) of titanium metal were produced in 1948 by DuPont using Bureau of Mines technology. By 1949 several companies including National Lead were producing similar quantities [5,6,7]. Reacting to Government incentives in the early 1950's, many major corporations installed commercial plants of either the Na-reduction or Mg-reduction process. In the 1990's, the remaining large commercial-sized Na-reduction plants were closed in the USA (RMI Titanium) and the UK (Deeside Titanium), leaving the Mg-reduction process as the surviving commercial technology. Because of the need for higher purity sponge, a new small Na-reduction process plant (~300mt/yr) was built in Salt Lake City in 1997 by Johnson Matthey Electronics' Alta Group, to service the expanding electronic industry [8]. The fundamental reduction technology remains as developed in the 1940's and 50's. However, the efficiency of the process has been greatly improved through larger batch sizes, recycling of the magnesium and improved process control.

Since 1992, Timet has operated in the USA the largest and only sponge-making plant based on the Toho Titanium technology for vacuum-distillation Mg-reduction. The older Timet's acid-leach Mg-reduction plant, deactivated in 1993, was reactivated temporarily from 1996 to 1999, to supply the expanding market needs and to produce low-Ni sponge, aimed at creep resistant, high temperature, near-α alloys. Oremet Metallurgical (now part of Allegheny Teledyne) operates the other USA Mg-reduction sponge plant. Their technology is based on argon sweep, to remove the volatile salts, instead of the vacuum distillation technique used throughout the rest of the World.

Current metal reduction research is focused in two areas [9]. Small laboratory-scale facilities have demonstrated the reduction of $TiCl_4$ to titanium metal in hydrogen plasma [10]. The current product is titanium powder as opposed to sponge-size particles, which are more easily handled in current commercialized process. Several other processes [9] have been suggested or are in the initial laboratory development stage that involve the reduction of $TiCl_4$ with Mg vapor. The titanium metal accumulates in a melting container that is heated by plasma or induction. The suggested benefit is the elimination of the electrode consolidation and energy savings.

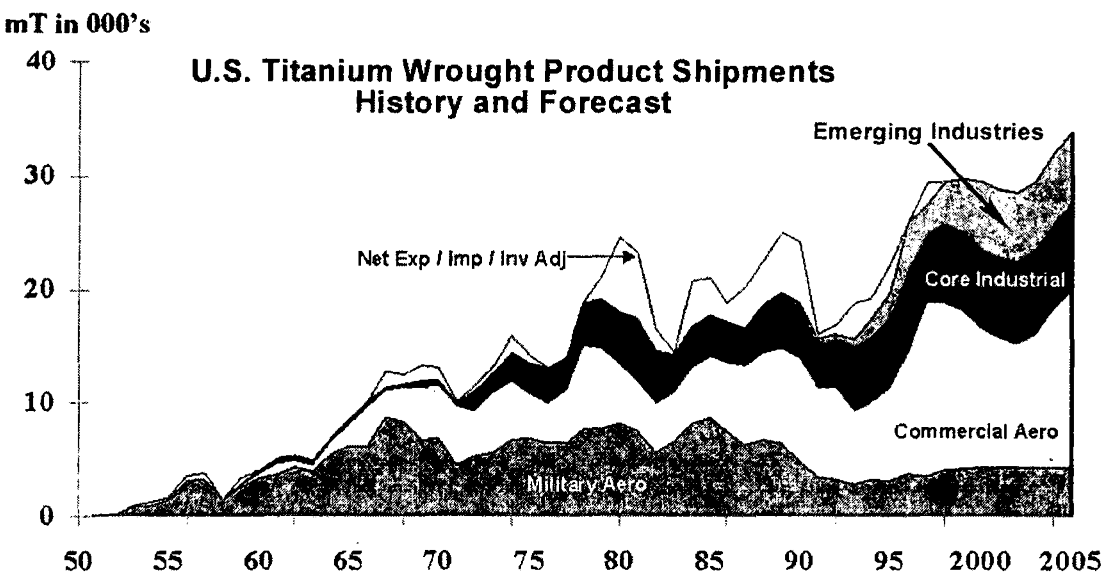


Figure 1: Fifty years of titanium production in the USA by categories, and a prediction up to the year 2005. USA titanium wrought product shipments in mTx1000 vs. the year of production. Courtesy of Timet [4].

2.2. MELTING

In the late 1940's and early 1950's the high reactivity of titanium presented a unique challenge in melting. Both induction and arc melting were initially attempted. Induction melting was abandoned due to the high carbon pickup in the molten from the carbon crucible. Single vacuum arc melting with a carbon electrode arc was also unacceptable because of carbon pickup and inhomogeneity resulting from only one melt [11]. S.A. Herres (at Allegheny Ludlum), in about 1952 [12], promoted the use of the *double melted* consumable-electrode vacuum arc re-melting process (VAR). The initial ingots were very small, by today's standard, about 1.5mt. As the VAR technology developed, larger ingots were produced and eventually *triple melting* was introduced for the demanding high quality rotating components in gas turbine engines.

Vacuum arc re-melt is today still the most common method for melting alloyed titanium and *aerospace* CP grade (unalloyed titanium). However, the electron beam hearth-melting (EBM) process is the main method for producing *industrial* CP grades. Since most industrial applications require strip products, EBM allows direct casting of slabs in one melt, while using high percentage of reverts, all leading to a lower cost strip [13]. Work is now underway to apply process modeling for the control of the size, depth and temperature of the molten pool in the EBM hearth. Improvements in controls, sensors and electronics for automated ingot/slab withdrawal and beam deflection are now applied to new EBM units [14]. The recent advancements in VAR are mostly associated with improving the controls and automation through computer-based system with electromechanical drives instead of the traditional hydraulic systems [15]. Process modeling is now being used by some, to optimize melting parameters for reducing alloy-segregation [13].

The requirements for higher quality alloys for jet engine rotating components have resulted in the application of EB and plasma hearth-melting technologies to reduce the likelihood of hard inclusions [14]. However, not all gas turbine engine manufactures require hearth melting. Improvements in VAR technology in the 1990's have also resulted in extremely low levels of defect rates, particularly in triple melted ingots.

The improved quality, scrap flexibility and shaped ingot products, inherent in hearth melting, has prompted the major titanium producers to install new facilities or purchase existing facilities. This resulted recently in the formation of integrated ingot melting facilities such as Timet North America in Morgantown, PA with EBM and VAR units [14]. This facility has two new 48-inch (1200mm) diameter VAR furnaces, and up to 4900KW EBM furnace capability. Allegheny Teledyne have installed a 5500KW EBM furnace in Richland, WA for melting CP titanium, in addition to the 3000KW plasma (PAM) electrode consolidator in the Oremet facility in Albany, OR that is used for consolidation of scrap into VAR electrodes [16]. RMI Titanium installed in 1999 at its subsidiary Galt Alloys a scrap cleaning line, a plasma electrode consolidator and a 3000KW PAM furnace. With new capacity in both PAM and EB, it appears that both process have advantages depending on each company's product mix and scrap usage.

The need to melt small lots of titanium for casting of golf club heads, created a strong market for Induction Skull-Melting (ISM) units [17], both in the USA and in the Far East. Consarc has recently produced ISM units, up to 50Kg pour-capacity [15]. Some furnaces are equipped with bottom-withdrawal mechanism for the production of small ingots up to 8" (250mm) diameter. Consarc has recently introduced and tested an 85Kg capacity unit.

2.3. CASTING

The titanium casting industry evolved out of the rammed-graphite mold process, followed by the investment-casting process for high-precision aerospace castings and has been using basically the same VAR melting process as in ingot-making [18]. Investment casting constitutes today most of the capacity, with larger shapes available, but permanent metal-mold die-casting has been recently introduced by Howmet. Metal-mold eliminates ceramic inclusions and alpha-case, improves some properties through grain-refinement, but is still limited in size to 300mm parts, and relatively simple shapes [19]. The developments in the titanium casting industry are mostly along the following lines: consolidation and regrouping within the industry; expansion of the non-aerospace market, mostly in the golf club heads area; commercialization of the ISM melting process for small casing lots; beginning of commercialization of titanium-aluminide aerospace cast-parts; introduction of permanent metal-mold die-casting technology for lower cost/high output products; production of larger Ti-6Al-4V fracture-critical investment-cast airframe components (Figure 2). This industry is continuing to expand, as casting is a cost-effective method for shape-making, and the damage-tolerance approach to airframe design is favoring titanium cast-parts that have inherently high fracture toughness and fatigue crack propagation resistance. The only segment experiencing a slowdown are cast-parts for wide-body airframes, suffering from the present Asian economical crisis [20].

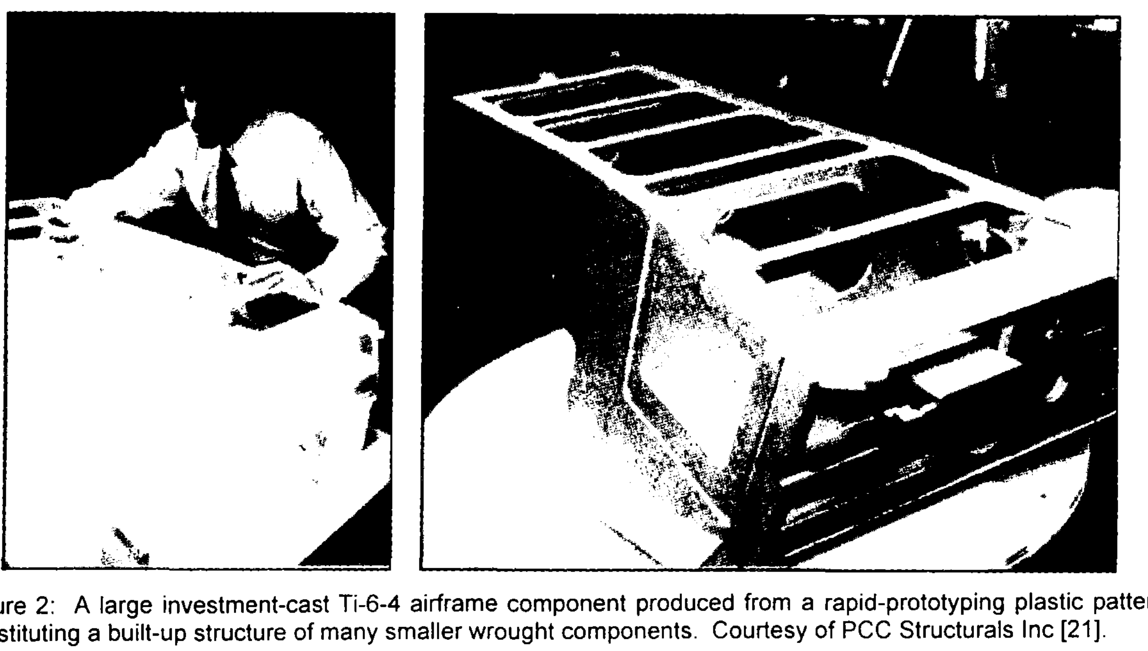


Figure 2: A large investment-cast Ti-6-4 airframe component produced from a rapid-prototyping plastic pattern, substituting a built-up structure of many smaller wrought components. Courtesy of PCC Structurals Inc [21].

The military and commercial airframe industries are now using larger castings for structural members, replacing wrought structures built-up from many smaller forged/machined sections (Figure 2). Some parts are as large as 106-inch (2.7m), which require new larger HIP units up to 64-inch (1.6m) in diameter. The large cast structures result in shorter delivery times, more efficient structures, and improved specific rigidity when hollow sections are used, and potentially lower cost. Such large critical parts present a challenge to NDE techniques. Larger cast TiAl parts, such as jet engine diffusers, have also been recently produced [21].

Process modeling has entered also the titanium casting industry, aiding in the design of certain products, mostly for the gating scheme, and pouring rate. The process modeling assists in predicting porosity and cracking in the more brittle Ti Aluminides. Rapid-prototyping by stereo-lithography is now used for product development, or for making plastic patterns for small series of cast-parts (Figure 2). In some companies, the process modeling and the rapid prototyping activities were integrated into one facility, as they require similar skills and equipment [20]

In 1998, the US titanium casting industry produced about 2.5M golf club heads. The demand slowed down toward the end of the year due to market saturation and inventory build-up. However, the introduction of multi-metal heads, such as Ti with W sole plate, Ti-6-4/Ti-15-3 heads or Ti/stainless-steel heads, is creating a new vitality. This industry is utilizing lower cost CIS produced ingots and new-scrap reverts from the aerospace industry [22].

2.4. PRIMARY AND FINAL PROCESSING

Most of the recent advancements in processing are associated with the application of *process modeling, computer-controlled machinery*, and *computer-assisted non-destructive-evaluation (NDE)* to primary and secondary ingot material processing, for improved quality, yield and cost [23]. Computer-driven rapid prototyping methods are now used in the titanium casting industry for product design and in powder metallurgy for actual component making [24].

2.4.1. *Methods, Procedures, and Equipment*

New hydraulic forging presses are now incorporating sensors and closed-loop computer controls that allow strain-rate profiles, for better die-fill, improved microstructure-control and less forging defects. The process parameters, such as heating time, and strain-rate are taking advantage of an increasing number of available commercial process modeling software. Isothermal forging takes greater advantage form these emerging technologies, since this process lends itself to more control and flexibility [25]. New and old forging hammers are being equipped with control systems that allow imparting only a fraction of the impact energy, as well as time intervals between the hammer blows to allow metadynamic and static recrystallization in addition to dissipation of adiabatic heating. Such processes lead to better microstructural control, including macro and micro-texturing, to less processing defects, nearer net-shape and as a result, to improved properties, yield and cost [26].

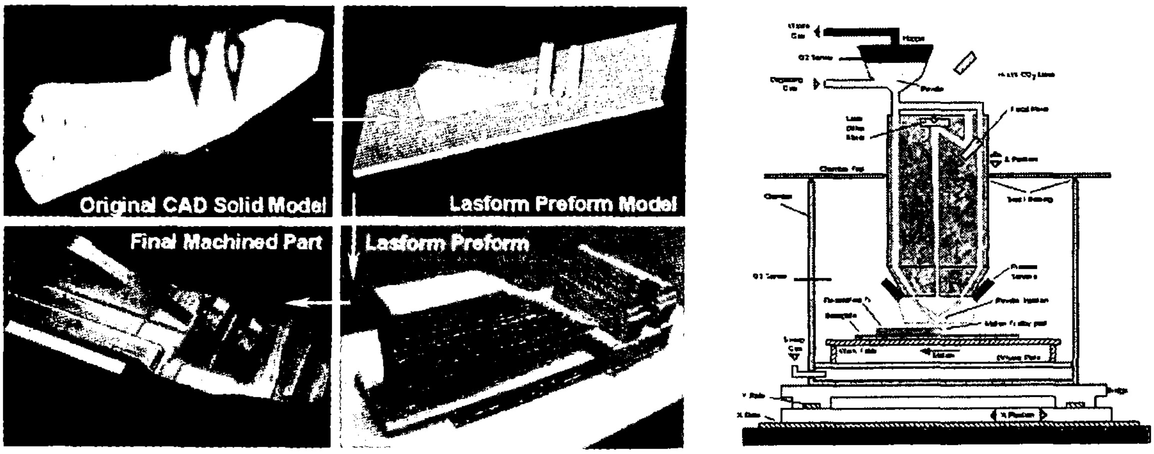
2.4.2. *SPF/DB*

Superplastic forming / diffusion bonding (SPF/DB) technique developed in the 1970's is now finding wider use in both airframe and jet engines. An extensive multi-sheet development took place in Boeing in association with the high-speed civil transport (HSCT) program [27]. The manufacturing of Ti-62222 six sheet structures has been demonstrated. Dedicated SPF/DB alloys, such as SP-700 [28], have improved fatigue strength, and reduced forming and diffusion bonding temperatures by about 100°C. The benefit is added strength with reduced fabrication cost. Pratt & Whitney and Rolls Royce now produce high specific stiffness long fan blades of T-6-4 for military and commercial gas turbine engines using this technology.

2.4.3. *Powder-metallurgy (PM)*

The most notable advancement in titanium PM is the use of laser-forming techniques by direct metal deposition (Figure 3). These are sequential processes of successive layer buildup by solidifying layers of laser melted alloy powder. This is an extension of the stereo-lithography rapid prototyping processes, originally applied only to polymer liquids or powders. Such methods produce high integrity, very complex shapes without the need for a mold or substantial machining. Two methods are available, and basically differ in the laser optics. Optomec uses one, which also build the system. They have a 700W laser system and prefer spherical powders with narrow size distribution for a good flow.

Aeromet operates an MTS system with a 14KW CO_2 laser. It can accommodate a wide range of powders, and has produced 1100mm, 50Kg Ti 6-4 parts at 1 to 5Kg/hr deposition rates. These methods provide 100% dense material with low oxygen pickup. They are still at early commercialization stages, but have the potential of revolutionizing the concept of Ti component making [24].



a b

Figure 3: a) Laser-formed Ti-6-4 component; b) A schematic of a laser-forming unit. Courtesy of AeroMet [24].

Another development is in Gamma TiAl alloys, where Plansee Metalwerke is commercializing the process of producing high quality sheets for SPF application, heat-shields and high temperature honeycomb structures from gas atomized (GA) Crucible powders [29]. More titanium powders are now used for the production of particulate-reinforced Ti-MMC, however, the medical implant field is now the main market for pre-alloyed PREP powders [30]. Titanium Metal Injection Molding (MIM) is still evolving, as it requires smaller powders (10 to 30μm), that are more difficult to make and handle [31].

2.4.4. *Non-Destructive Evaluation (NDE)*

Incorporation of computer control and signal processing with ultrasonic inspection (UI) allows better detection of material defects, or insufficient processing conditions. Detection of an unacceptable material in the very early processing stages leads to great cost savings [26]. Multi-zonal UI of 350mm diameter billets is done today, with flat bottom hole (FBH) resolution of 0.8mm diameter, up to 250mm depth. In a single-zone UI, such resolution is only possible to 75mm depth. After the 1989 Sioux City, Iowa DC-10 titanium compressor failure, pressure was placed on the industry to reduce or eliminate defects. This resulted in the use of hearth melting for rotating components, and pursuing improved sonic inspection techniques. Improved inspection has been accomplished through multi-zonal UI and forging rotating jet engine parts from smaller billet-stock, for better UI reliability.

2.4.5. *Process Modeling*

Process modeling has matured to the point that many organizations now feel comfortable in incorporating it into their alloy production processes. A VAR melting process modeling code was developed by Sandia National Labs through the Specialty Metals Processing Consortium (SMPC), and is proprietary to the consortium members. The process modeling code COMPACT for plasma-arc melting (PAM) and electron-beam melting (EBM) was developed by Innovative Research and was enhanced by CDC Corp., GE and Allvac. It simulates the plasma torch, electron beam, the hearth, and the ingot solidification. A shape-casting code named Procast, is now available from UES. Scientific forming Co. has created the Deform program that simulates close and open-die forging. Some additional codes are created for specialty forming processes such as GFM rotary forging [32].

3. ALLOY - DEVELOPMENT

3.1. CONVENTIONAL ALLOYS

As soon as titanium appeared attractive for military aircraft in the early 1950's, a large effort ensued in alloy development. The popular Ti-6Al-4V (Ti-6-4) alloy was a result of this early research [33] and was immediately designed into existing engines and airframes. The alloy's moderate strength, good fracture-toughness and forgiving nature have resulted in Ti-6-4 being the most popular of all titanium alloys. Today, 56% of the USA production is in Ti-6-4, most of it in a billet, sheet or plate form (Table 1). In fact 82% of current total production is in CP and Ti-6-4, two compositions that were developed and used nearly 50 years ago. Although extensive alloy development has been conducted over the last half-century, only a few additional alloys have been commercialized and mostly for applications requiring unique combination of properties, such as higher elevated temperature strength, higher fracture toughness, improved corrosion resistance or lower elastic modulus. At the moment, there is very limited development of conventional alloys, which is another indication of the maturation stage of the industry. Most producers prefer to invest in improving the production processes for lower alloy cost leading to wider markets.

Table 1. Titanium Alloy Production and Product-form Shipments in the USA in 1998*

Alloy:	CP Titanium	Near-alpha		Alpha + beta		Beta		Total
	All grades	6242S	Other	6-4	Other	10-2-3	Other	
Market Share:	26%	3%	2%	56%	9%	3%	1%	100%

Product:	Billet	Sheet and Plate	Bar	Casting	Total
Market Share:	44%	40%	14%	2%	100%

*RMI Titanium study

3.2. Ti - ALUMINIDES

The most intensive alloy development activity in the 1990's was in the area on titanium aluminides. This activity resulted in several compositions with reasonable tensile elongation, fracture resistance and high temperature strength. These alloys raise the maximum service temperature of Ti alloys from 550C to 750C, which is so significant for gas turbine engines. That development was also coupled with a substantial fundamental studies on alloying, phase characteristics and evolution, dislocations and mechanical behavior and environmental aspects of ordered metallic alloys, that will assist future evolutions [34,35]

4. APPLICATIONS

The use of titanium has been expanded in recent years to many new areas and applications. However, it is important to note that the traditional USA markets, such as gas turbine engines, airframes and chemical processing equipment, remain the dominant segments (Figure 1).

4.1. AEROSPACE APPLICATIONS

Aerospace is still the most important market for titanium in the USA - about 65% in volume in 1998 (Figure 1), and over 80% of all alloy production (Table 1). Due to the cyclic nature of both military and commercial aerospace (Figure 1), the aerospace market greatly influences the cyclic nature of the titanium industry. The restructuring of the titanium industry in the USA is, in part, an effort to reduce this market instability.

4.1.1. *Military Aerospace*

The US Airforce fighter plane - F-22 is now in production with more titanium than in any recent military airplane. The airframe is 39% by weight, mostly Ti 6-4 (36%) and the rest is Ti 62222S. The requirements for sustained supersonic flight, high maneuverability, and some stealth characteristics, necessitated the extensive use.

The F-22 engine – the F119 by Pratt & Whitney, contains about 40% titanium by weight. It has a unique two-dimensional vectored nozzle system, for increased maneuverability, mostly made out of the burn-proof Alloy-C. In addition, it has a Timetal 834 compressor-ring and an integrally bladed rotor both in the fan and the compressor sections (Figure 4) [36]

4.1.2. *Civil Aerospace*

The new larger wide-body "super jumbo" airplanes, such as Airbus 3xx and Boeing stretch 747-400, are expected to have more titanium applications that any existing plane, including the largest ever made titanium landing gears, which are now being considered both in the USA and in Europe. Timetal 21S is already used for the new Airbus A340-500/600 plugs and nozzles for the engine support structures.

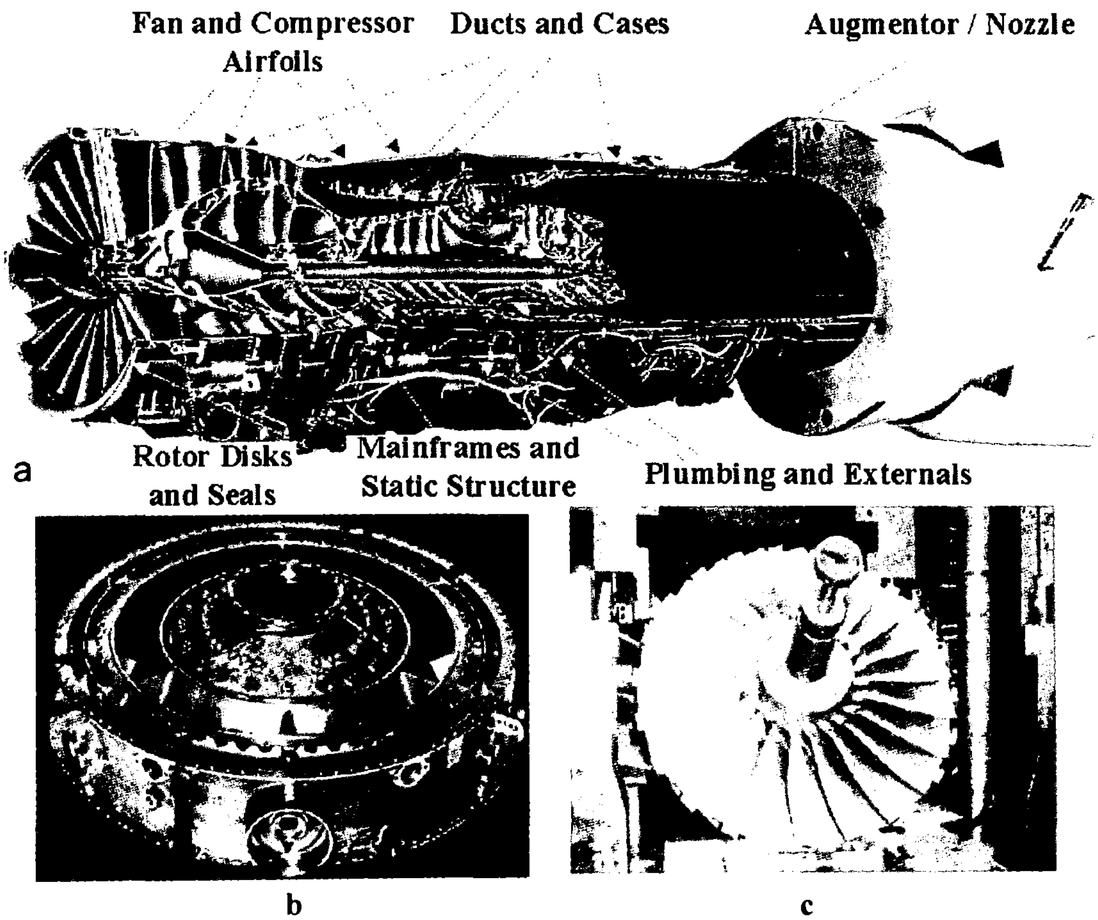


Figure 4: a) Pratt&Whitney F119 engine for the USAF F-22 fighter jet with a large 2-D titanium augmentor for increased maneuverability. Total titanium content in this engine is 40% by weight; b) Cast titanium case ring; c) integrally bladed hollow-airfoil titanium rotor. Courtesy of Pratt & Whitney [36].

4.2. MILITARY APPLICATIONS

Titanium has been accepted into the latest versions of light and heavy US Army tanks. The Bradley Infantry Fighting Vehicle – M2 (known as the Bradley) now incorporates Ti-6Al-4V hatch and top armor appliques, for added protection without sacrificing weight. The main battle tank M1A2 (Abrams) is now in the process of incorporating Ti-6Al-4V Gunner Primary Sight-Cover, and Turret Blow-off Panels. Both parts weigh hundreds of pounds. In addition, a titanium prototype light weight 155mm howitzer has been developed and being prepared for production by the Army, and high strength beta alloys are now being considered for body armor pouches to enhance the Kevlar fiber protection capability.

4.3. GENEAL APPLICATIONS

Titanium is now becoming more favorable in various hydrometallurgy ore-leaching processes for metals such as gold or Ni. There is an increase in its use for the process of leaching Ni from Ni laterite-type ores. Such use is becoming a substantial volume application for the autoclave liners, where titanium cladded steel is replacing the traditional brick lining [13].
There is a substantial increase in the use of titanium for sport, watches, eyeglass frames and architecture. In the Guggenheim Museum in Bilbao, Spain, 32,000m^{2}of 0.4mm thick CP-Ti Grade-1 with standard pickle-finish were used. The many kinds of durable surface finishes available make it an attractive architectural material [13].

4.4. ENERGY APPLICATIONS

Oil drilling, oil production, offshore drilling and production are recent emerging markets for titanium with a very large volume potential. Offshore exploration and pumping present a challenging market opportunity. The tubing needed are very massive, as they act also as *risers* that anchor the drilling and production platforms to the ocean bottom. As a result, they have to withstand high stresses and fatigue loading in seawater, for periods as long as the life of the oilfield, yet they constitute a very high volume market, especially production risers [37].

Titanium taper stress-joints are another challenge for offshore oil activity. They are attached at the bottom or the top of the production riser line, taking the bending motion from the risers. Here, the relatively low elastic modulus, yet high tensile and fatigue strength unaffected by seawater, make titanium an excellent candidate [38].

Another important market are the geothermal brine wells, such as in Salton Sea in Southern California where Ti 6-4-Ru (ASTM Grade 29) is used [37,38]. Recently, corrosion-resistant alloys use Ru in place of Pd for lower-cost.

5. STATE - OF - THE - BUSINESS

5.1. CONSOLIDATION, DIVERSIFICATION, AND GLOBALIZATION

Titanium producers for the first 40 years were primarily joint ventures, with the ownership residing with large companies. This was the result of using available facilities and sharing the inherent risk in the marketing of a new metal. As the industry grew, the cyclic nature of profit and loss also was more easily absorbed by these partnerships. The 1990's were a period of change for the management of the titanium companies. In the early part of the decade, the major titanium companies became public-owned companies. As public companies, management looked for ways to minimize the cyclic nature of the business. With the return to profitability in the mid-90's, the resources were available to implement new investment strategies. The resulting acquisitions and mergers took the form of globalization, diversification and consolidation. Three companies, RTI International Metals, Timet and Allegheny Teledyne now supply 90% of the titanium mill product business in the USA. Each has taken a different approach to the metals market. The diagram in Figure 5 shows the current organization of the USA titanium industry reflecting the recent acquisitions.

Timet (Figure 5) has created a large vertically integrated company through consolidation of several titanium businesses in both the USA and throughout the World. Their primary product is titanium and the company produces sponge but due to the current strong demand for titanium, it is not entirely self-sufficient. The melting facilities of Timet include both VAR and EBM furnaces.

Allegheny Teledyne (Figure 5) has acquired and consolidated the former Oremet and Allvac facilities resulting in a diversified special metal facility that produces stainless, zirconium and nickel base alloys as well as titanium. The use of the same mill equipment for all metals is expected to result in improved efficiencies. This company is also self sufficient in sponge with VAR and both EBM and PAM hearth units.

RTI International Metals (Figure 5) has taken a different approach. They have diversified into finished products of several metals including titanium, stainless steel and nickel base alloys. The diversification has resulted in facilities throughout the World. RTI chose to close their sponge plant in the early 90's and rely on USA and foreign purchases. However, they did strengthen their raw material base by installing a large, sophisticated scrap handling facility at their Galt Alloys subsidiary. RTI has both VAR and plasma hearth melting.

The growth of the USA titanium industry during the 1990's (Figure 1), resulted in a significant expansion of melting and finishing facilities. The expansion was done by the different producers to strengthen market positions, allow for new growth and increase market diversity. The USA titanium industry, as a whole, is not self sufficient in sponge and will continue to import from the large production capacities available in Japan and the CIS.

5.2. PROFITABILITY

Since the last titanium conference, all the titanium companies have enjoyed substantial profits from the expanding markets. These profits were used to accommodate the industry changes discussed above. This year (1999) is a pivotal year because of reduced demand. The titanium unit of RTI Industries completed a long strike in late April. Timet is reporting small losses while RTI is reporting profits but reduced from 1998. The titanium business of Allegheny Teledyne is only a small portion of the parent company, but the company as a whole is performing at a reduced level of profits. The current, softer market will be a good test of the effectiveness of the diversification, consolidation and globalization efforts of the USA titanium industry.

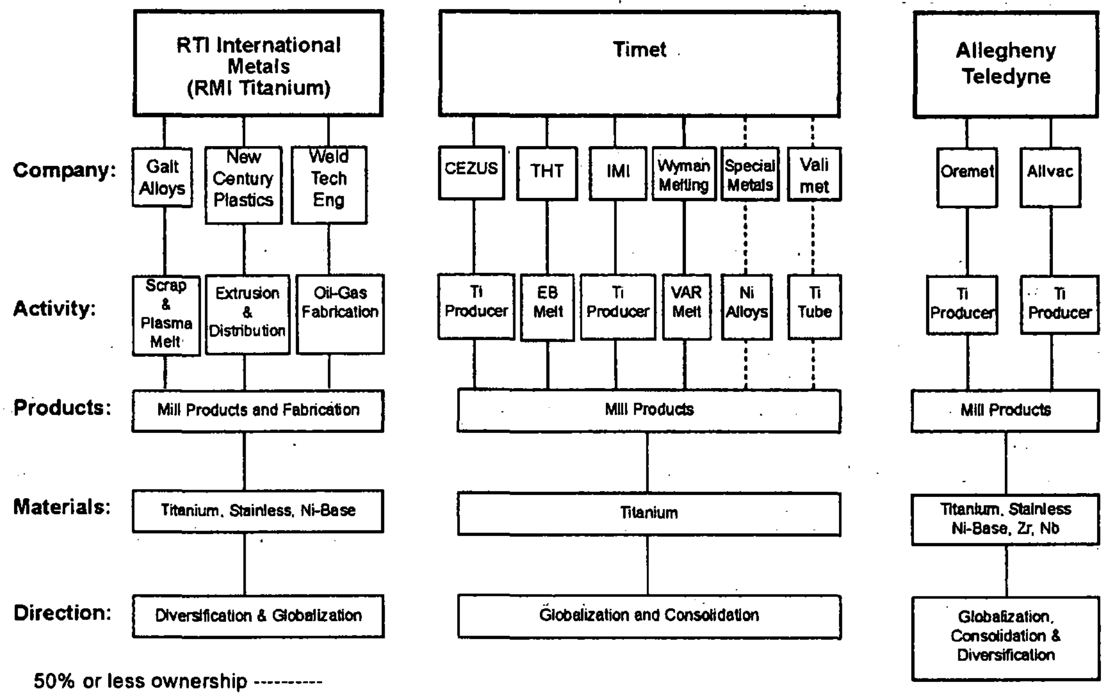


Figure 5: The structure of the titanium industry in May 1999. The three companies produce 90% of the USA Ti.

5.3. OUTLOOK

The Kroll sponge technology has matured, with no obvious replacement on the immediate horizon. Significantly lower sponge prices will be required to move titanium applications to substantially higher levels and this will not occur in the near future.

The relatively new hearth technology will result in the future in a single-step alloy melting processes. The new capacity in hearth furnaces will likely fragment the producers. Those with electron-beam furnaces will emphasis commercially pure titanium, while the plasma hearth producers will specialize in alloys. This could be a sign of industry maturation as producers re-align to specialize in specific alloys and products.

Titanium will continue to penetrate new non-aerospace markets in an evolutionary manner. Because of the metal's energy efficiency in transportation, market growth may be dependent on energy cost. Large markets, such as the automotive, appear only in the distant future unless there is a decrease in titanium cost or a substantial increase in fuel cost. However, we should keep in mind that aluminum penetrated the automotive market only 70 years after its commercialization in the 1890's.

First TiAl applications are expected to enter into gas turbine engines, initially, in a limited scale. Introduction of larger commercial airframes will no doubt result in some new applications for relatively new alloys, and for larger castings. This industry segment is waiting for the end of the Asian economic crisis

The information-age revolution will continue to impact and improve the field of alloy processing, with better process modeling codes, improved computerized process-control, computer-aided manufacturing, and better computer-driven NDE techniques. These are already influenced by developments that are now undergoing in the technologies of other structural metals such as steels, aluminum and nickel-base alloys.

More regrouping and consolidation will continue inside this industry, such as the very recent announcement of the intended purchase of Wyman-Gordon by PCC. This may lead to more diversification and globalization of the titanium industry, both in the USA and in the industrial world.

6. ACKNOWLEGMENTS

The authors wish to acknowledge the many people and organizations that helped them in gathering all the information needed for this review paper:

J.A. Hall (*Allegheny Teledyne*); J. R. Wood (*Allegheny Teledyne*); P. Allen (*Timet*); C. Entrekin (*Timet*); J. Fanning (*Timet*); S. Fox (*Timet*); M. Metz (*Timet*); V. Eudaly (Timet); J. Odle (*RMI Titanium*); R. *Schutz (RMI Titanium*); K.O. Yu (*RMI Titanium*); S.L. Semiatin (*AFRL*); D. Dimiduk (*AFRL*); J. Thorn (*Ruger Titanium*); J. Barrett (*PCC Structurals Inc*); N.E. Paton (*Howmet Research Corp.*); R. Boyer (*Boeing*); D. Yoel (*Consarc*); D. Furrer (*Ladish*); W. Miller (*Optomec*); J. Nicholson (*Starmet*); F. Arcella (*AeroMet*).

7. REFERENCES

1 H.B. BOMBERGER, F.H. FROES, and P.H. MORTON: "Titanium - A Historical Perspective", *Titanium Technology, Present Status and Future Trends*, ed. by F. H. Froes, D. Eylon and H. B. Bomberger, TDA Publication, 1985, p.3-17.

2 J. SCHUMPETER: "Catch the Wave", *The Economist*, 20 February 1999.

3 R.R. BOYER: "R&D and Applications Developments in the Titanium Industry in the USA", *Titanium '95*, ed. by P.A. Blenkinsop, W.J. Evans, and H.M. Flower, The Institute of Metals, Cambridge, UK, 1995, p.41-50.

4 J.L. MARTIN: "The Future of Titanium: Evolution or Revolution", *1998 Proceedings of the Fourteenth Annual Conference & Exhibition*, ITA, Monte Carlo, 1998.

5 "Titanium: Past, Present, and Future", *National Materials Advisory Board Report NMAB-392*, Jan 1983.

6 J.L. HENRY, W.W. STEPHENS, D.D. BLUE, and J.M. MAYSILLES: "Bureau of Mines Development of Titanium Production Technology", *Bulletin 690*, United States Department of Interior, 1987.

7 E.R. POULSON and J.A. HALL: "Extractive Metallurgy of Titanium: A Review of the State of the Art and Evolving Production Techniques", *JOM*, June 1983, p.60-65.

8 J.M. GAMBOJI: "Titanium", *Engineering and Mining Journal*, March 1997, p.56.

9 "Final Report from Titanium Industry Workshop" ASME CRTD Vol. 46, Welches, OR, July 1997.

10 A. Donaldson: "Low Cost Titanium by Plasma Quench Process", Ibid., p.195.

11 Sharon Steel Record, September 1953.

12 "Titanium: Part Product, Part Cause", author unknown, circa 1965.

13 S. FOX, Timet, private communication, April 23, 1999.

14 C. ENTREKIN, Timet North American Operations, private communication, April 23, 1999.

15 D. YOEL, Consarc, private communication, April 20, 1999.

16 J.A. HALL, Allegheny Teledyne, private communication, April 29, 1999.

17 D.J. CHRONISTER, S.W. SCOTT, D.R. STICKLE, D. EYLON, and F.H. FROES: "Induction Skull Melting of Titanium and Other Reactive Alloys," *Journal of Metals*, Vol. 38, No. 9 (1986), p.51-54.

18 D. EYLON, J.R. NEWMAN, AND J.K. THORNE: "Titanium and Titanium Alloy Castings," A chapter in *Metals Handbook, Tenth Edition, Volume 2, Properties and Selection: Nonferrous Alloys, Special-Purpose Materials,* ASM International, Materials Park, OH, 1990, p. 634-646.

19 R.R. BOYER, J.C. WILLIAMS, and N.E. PATON: "Evolving Aerospace Applications for Ti Alloys". *Proceedings of this Conference*, June, 1999.

20 N.E. PATON, Howmet Research Corp. private communication, April 27, 1999.

21 J. BARRETT, PCC Structurals Inc., private communication, April 30, 1999.

22 J.K. THORNE, Ruger Titanium, private communication, April 23, 1999.

23 S.L. SEMIATIN, E.B. SHELL, I.R. ROCCA, I. WEISS, and V. SEETHARAMAN: "Design of Thermomechanical Processes for the Breakdown of α/β Titanium Alloys with Transformed Beta Microstructure", *Proceedings of this Conference*, June, 1999.

24 F.G. ARCELLA, AeroMet, and W.D. MILLER, Optomec Design Company, private communications, April, 1999.

25 D. FURRER: "Forging Aerospace Components", Advanced Materials and Processes 3/99, 1999, p.33-37.

26 D. FURRER, Ladish Co., private communication, April 28, 1999.

27 W.D. BREWER, R.K. BIRD, and T.A. WALLACE: "Titanium Alloys and Processing for High Speed Aircraft", *Thermomechanical Processing and Metallurgy of Titanium Alloys*, ed. by D. Eylon, S. Fujishiro, G. Lütjering, I. Weiss and T. Chandra, published by Elsevier, *Materials Science and Engineering A*, Vol. A243, (1998), p.299-304.

28 A. OGAWA, M. NIIKURA, C. OUCHI, K. MINAKAWA, and M. YAMADA: "Developments and Applications of Titanium Alloy SP-700 with High Formability", *Journal of Testing and Evaluation*, March 1996, p.100-108.

29 H. CLEMENS, W. GLATZ, P. SCHRETTER, C.F. YOLTON, P.E. JONES, and D. EYLON: "Sheet Rolling of Ti-48Al-2Cr-2Nb Prealloyed Powder Compacts", *Gamma Titanium Aluminides*, ed. by Y-W Kim, R. Wagner and M. Yamaguchi, TMS Publications, Warrendale, PA, 1995, p.555-562.

30 D. EYLON, F.H. FROES, and S. ABKOWITZ: "Titanium Powder Metallurgy Alloys and Composites", a chapter in ASM handbook, vol. 7 on *Powder Metals technology and Applications*, ASM International Publication, Materials Park, OH, (1999), p.876-882.

31 J. NICHOLSON, Starmet, private communication, April 30, 1999.

32 K.O. YU, RMI Titanium Co., private communication, May 7, 1999.

33 S. ABKOWITZ: "The Emergence of the Titanium Industry and the Development of the Ti-6Al-4V Alloy", *JOM Monograph Series*, Vol. 1, TMS, 1999.

34 D.M. DIMIDUK: "Gamma Titanium Aluminide Alloys - an Assessment within the Aerospace Structural Materials". *Metallurgy Technology and Applications of Titanium Alloys*, ed. by D. Eylon, G. Lütjering and L. Zhou, published by Elsevier, *Materials Science and Engineering A*, Vol. A263, 1999, p.281-288.

35 D.M. DIMIDUK, P.A. McQUAY, and Y-W KIM: "Gamma Alloy Technology 1999" *Proceedings of this Conference*, June, 1999.

36 B.A. COWLES: "Application and Life Prediction of Titanium Alloys in Aircraft Gas Turbine Engines", *Fatigue Behavior of Titanium Alloys*, ed. By R.R. Boyer, D. Eylon and G. Lütjering, published by TMS, Warrendale, PA, 1999, p.277-290.

37 R.W. SCHUTZ, and H.B. WATKINS: "Offshore Titanium Risers: an Overview of Alloy Selection, Design, Fabrication, and Application Status". *Proceedings of the Titanium Risers and Flowlines Seminar*, Trondheim, Norway, February 17, 1999, SINTEF.

38 R.W. SCHUTZ, and H.B. WATKINS: "Recent Developments in Titanium Alloy Application in the Energy Industry". *Thermomechanical Processing and Metallurgy of Titanium Alloys*, ed. by D. Eylon, S. Fujishiro, G. Lütjering, I. Weiss and T. Chandra, published by Elsevier, *Materials Science and Engineering A*, Vol. A243, 1998, p.305-315.