Titanium Technology in the USA – an Overview

D.Eylon†
Graduate Materials Engineering, University of Dayton, Dayton, Ohio 45469, USA
S.R.Seagle
Consultant, 60 Heron Circle Cortland, OH 44410, USA

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The state of Ti research, development and industry is reviewed in this article. The fifty-year anniversary of Ti technology commercialization in the USA provides an opportunity for a historical perspective. Incorporation of "information-age" tools into alloy development, processing, and production invigorates the technology. Consolidation, diversification and globalization have been transforming the Ti industry in the recent years.

1. Introduction

Titanium is the youngest of the major structural metals. It is the only structural metal that did not play any role in events of World War II. Although the element 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 Ti industrialization, it is appropriate to review the state of Ti technology and industry in respect to their half a century history. The evolution, recent developments[2], and the current-status of Ti science, technology, and industry will be reviewed along the various industrial and application segments. Major advancements in the processing of Ti 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, yield and lower cost. Fifty years of Ti production in the USA are depicted in Fig.1.

2. Production of Ti

2.1 Sponge-making

Based on the early work by Kroll on Mg-reduction of Ti tetrachloride (TCT), the first commercial quantities (16 mt/yr) of Ti metal were produced in 1948 by DuPont using Bureau of Mines technology. By 1949 several companies including National Lead were producing similar quantities[3~5]. 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 Ti technology for vacuum-distillation Mg-reduction.

2.2 Melting

In the late 1940′s and early 1950′s the high reactivity of Ti 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[6]. S.A.Herres (at Allegheny Ludlum), in about 1952[7], promoted the use of the double melted consumable-electrode vacuum arc remelting process (VAR). The initial ingots were very small, by today′s standard, about 1.5 mt. As the VAR technology developed, larger ingots were produced and eventually triple melting was introduced for the demanding high quality gas turbine engines rotating components. Vacuum arc remelting is today still the most common method for alloyed Ti and aerospace CP grade (unalloyed Ti). However, the electron beam hearth-melting (EBM) process introduced in the 1980′s is the main method for producing industrial CP grades[8]. Since most industrial applications require strip products, EBM allows lower cost strip by direct casting of slabs in one melt, while using high percentage of reverts[9]. 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[10]. Recent advancements in

† To whom correspondence should be addressed
E-mail: deylon@engr.udayton.edu

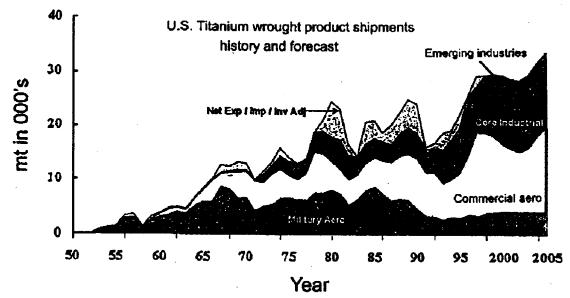


Fig.1 Fifty years of Ti production in the USA by categories, and a prediction up to the year 2005. USA Ti wrought product shipments in mTx1000 *vs* the year of production. Courtesy of Timet

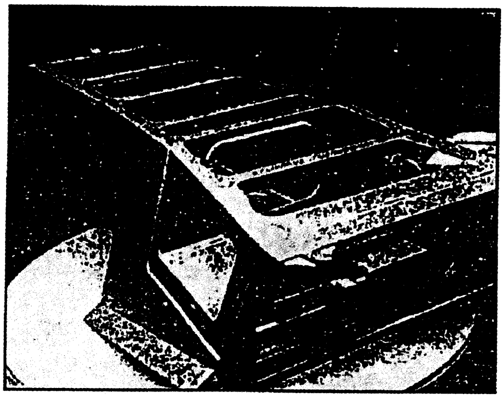


Fig.2 A large investment-cast Ti-6-4 airframe component produced from a rapid-prototyping plastic pattern, substituting a built-up structure of many smaller wrought components. Courtesy of PCC Structurals Inc.

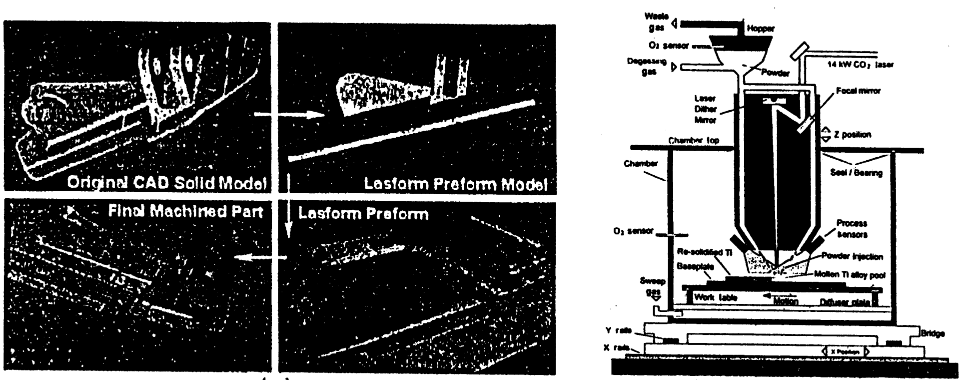
VAR are mostly associated with improving the controls and automation through computer-based system with electromechanical drives instead of hydraulic systems[11]. Process modeling is now being used to optimize melting parameters for reducing alloy segregation[9]. The requirements for higher quality alloys for jet engine rotating components have resulted in the application of EB and plasma hearth-melting technologies to reduce the likelihood of hard inclusions[10]. However, not all gas turbine engine manufacturers require hearth melting. Improvements in VAR technology in the 1990's have also resulted in extremely low levels of defects, particularly in triple melted ingots. The improved quality, scrap flexibility and shaped ingot products, inherent in hearth melting, has prompted the major Ti 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[10]. This facility has two new 48-inch (1200 mm) diameter VAR furnaces, and up to 4900 kW EBM furnace capability. Allegheny Teledyne has installed a 5500 kW EBM furnace in Richland, WA for melting CP Ti, in addition to the 3000 kW plasma (PAM) electrode consolidator in the Oremet facility in Albany, that is used for consolidation of scrap into VAR electrodes[12]. RMI Ti installed in 1999 at its subsidiary Galt alloys a scrap cleaning line, a plasma electrode consolidator and a 3000 kW PAM furnace.

2.3 Casting

Titanium casting industry evolved out of the rammed-graphite mold process, followed by the investment-casting process for high-precision aerospace parts, using the same VAR melting process as in ingot-making[13]. Investment casting constitutes today most of the capacity, with larger shapes available. Permanent metal-mold die-casting has been recently introduced by Howmet[14]. Metal-mold eliminates ceramic inclusions and alpha-case, improves some properties through grain-refinement, but is still limited to 300 mm parts, and relatively simple shapes[15]. There is the beginning of commercialization of Ti-aluminide aerospace cast-parts; introduction of permanent metal-mold die-casting technology for lower cost/high output products; and production of larger Ti-6Al-4V fracture-critical investment-cast airframe components (Fig.2). 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 (Fig.2). Some parts are as large as 2700 mm, which require new larger HIP units up to 1600 mm 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[16]. Process modeling has also entered the Ti 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 (Fig.2). In some companies, process modeling and rapid prototyping were integrated in one facility, as they require similar skills and equipment.

2.4 Primary and final processing

Most recent advancements 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



(a) (b)

Fig.3 (a) Laser-formed Ti-6-4 component, (b) A schematic of a laser-forming unit. Courtesy of Aeromet

cost[17]. Rapid prototyping methods are now used in the Ti casting industry for product design and in powder metallurgy for actual component making[18].

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 from these emerging technologies, since this process lends itself to more control and flexibility[19]. New and old forging hammers are being equipped with control systems that allow imparting only a fraction of the impact energy, as well as programmed time intervals between the hammer blows to allow metadynamic and static recrystallization in addition to dissipation of adiabatic heating. These lead to better microstructural control, including macro and micro-texturing, less processing defects, nearer net-shape and to improved properties, yield and cost[20].

2.4.2 Powder-metallurgy (PM) The most notable advancement in Ti PM is the use of laser-forming techniques by direct metal deposition for fully dense low oxygen pickup material (Fig.3). Layers are successively buildup by solidifying layers of laser-melted alloy powder. It 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 produces a 700 W laser system and for spherical powders with narrow size distribution for a good flow. Aeromet operates a 14 kW CO_2 laser MTS system for a wide range of powders, producing 1100 mm, 50 kg Ti 6-4 parts at 1 to 5 kg/h deposition rates. These methods are still at early commercialization[18]. Another development is in γ 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[21]. More Ti 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[22]. Titanium metal injection molding (MIM) is still evolving, as it requires more difficult to make and handle fine powders (10~30 μm)[23].

2.4.3 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 Laboratory 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 available from UES. Scientific forming created DEFORM program simulating close and open-die forging. Additional codes are created for specialty forming processes such as GFM rotary forging[24].

3. Alloy Development

As soon as Ti 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[25] and was immediately designed into existing engines and airframes.

Table 1 Titanium alloy production and product form shipments in the USA in 1998 (RMI study)

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%

The moderate strength, good fracture-toughness and forgiving nature have resulted in Ti-6-4 being the most popular of all Ti 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 indicates of the industry maturation.

4. Applications

4.1 Aerospace applications

Aerospace is still the most important market for Ti in the USA-about 65% in volume in 1998 (Fig.1), and over 80% of all alloy production (Table 1). Due to the cyclic nature of both military and commercial aerospace (Fig.1), the aerospace market greatly influences the cyclic nature of the Ti industry. The restructuring of the Ti 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 Ti 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% Ti 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 section[26].

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 Ti applications that any existing plane, including the largest ever made Ti 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.

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 Ti prototype light weight 155 mm 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 General applications

Titanium is now becoming more favorable in various hydrometallurgy ore-leaching processes for metals such as Au 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 Ti cladded steel is replacing the traditional brick lining[9]. There is a substantial increase in the use of Ti for sport, watches, eyeglass frames and architecture. In the Guggenheim Museum in Bilbao, Spain, 32,000 m^2 of 0.4 mm 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[9].

4.4 Energy applications

Oil drilling, oil production, offshore drilling and production, are recent emerging markets 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[27]. 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 Ti an excellent candidate[28]. Another important market is the geothermal brine wells, such as in Salton sea in Southern California where Ti 6-4-Ru (ASTM Grade 29) is used[27,28]. Recently, corrosion-resistant alloys use Ru in place of Pd for lower-cost.

5. Industry Consolidation, Diversification, and Globalization

Three companies, RTI International Metals, Timet and Allegheny Teledyne now supply 90% of the Ti mill product business in the USA. Each has taken a different approach to the metals market. Timet has created a large vertically integrated company through consolidation of several USA and World Ti businesses. Their primary product is Ti and the company produces sponge. Their melting facilities include both VAR and EBM furnaces. Allegheny Teledyne has acquired and consolidated the former Oremet and Allvac facilities resulting in a diversified special metal facility that produces stainless, Zr and Ni-base alloys as well as Ti. 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 has taken a different approach of diversification into finished products of several metals including Ti, stainless steel and Ni-base alloys with 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 Ti industry during the 1990′s (Fig.1), resulted in a significant expansion of melting and finishing facilities.

The expansion was done by the different producers to strengthen market positions, allowing for new growth and increasing market diversity. The USA Ti industry, when operating in a strong market, is not self sufficient in sponge and will continue to import from the large production capacities available in Japan and the CIS.

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