TITANIUM METAL ANNUAL REVIEW *SAMPLE*

T Z M I

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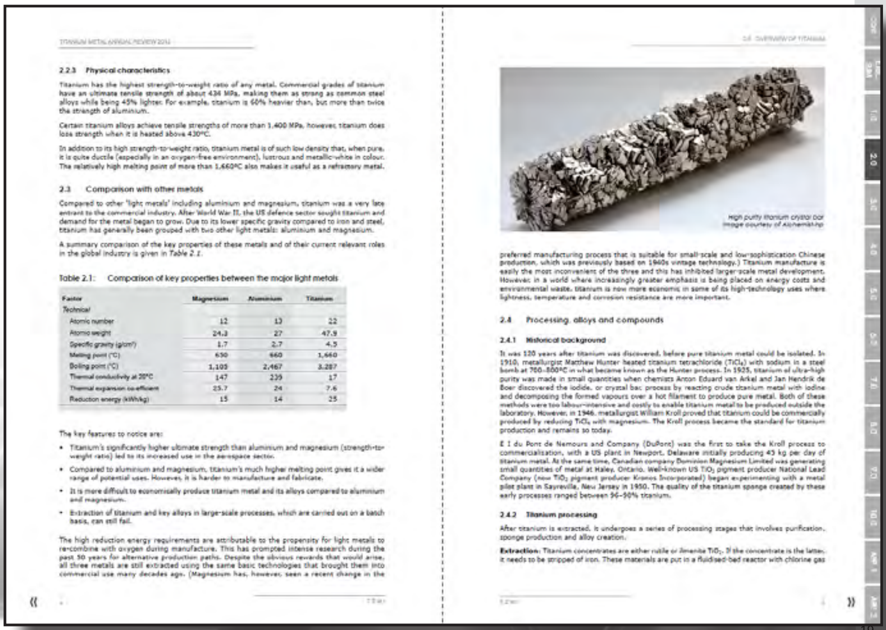
OVERVIEW OF TITANIUM AND THE TITANIUM INDUSTRY

The multi billion dollar titanium metal market is examined from the perspective of the entire value chain.

Common grades of titanium

ASTM Grade	United Numbering System	Nominal composition, wt. %	Description	Crystal structure	Uses
		One half of the oxygen content of ASTM Grade 1	High Purity Titanium	Alpha	Uses include experimentation and research, and applications requiring very low interstitial or other impurities.
1	R50250	Unalloyed; limit 0.18 O, 0.20 Fe, 0.03 N, 0.10C	Commercially Pure (CP)	Alpha	Applications where low iron and interstitial content provide resistance to highly oxidising, mildly reducing environments; resistant to chlorides; maximum formability.
2	R50400	Unalloyed; limit 0.25 O, 0.30 Fe, 0.03 N, 0.10 C	Commercially Pure (CP)	Alpha	Most common CP grade; used in corrosion and oxidation resistance applications requiring higher strength and lower cost than Grade 1.
3	R50550	Unalloyed; limit 0.35 O, 0.30 Fe, 0.05 N, 0.10 C	Commercially Pure (CP)	Alpha.	Applications similar to Grade 2 but requiring higher strength.
	R50700	Unalloyed; limit 0.40 O, 0.5 Fe, 0.05 N, 0.1 C	Commercially Pure (CP)	Alpha	Nearly interchangeable with Grade 3, but slightly higher strength and lower corrosion resistance.
	R56400; R46401 (ELI)	Ti-6Al-4V		Alpha/Beta	Most widely used alloy; high strength and good corrosion resistance.
	R54520; R54521 (ELI)	Ti-5Al-2.5Sn		Alpha	Excellent weldability with moderate strength.
	R52400	Unalloyed, with 0.12 to 0.25 Pd		Alpha	Comparable to Grade 2 in strength, but better crevice corrosion at low pH and high temperature.
	R56320	Ti-3Al-2.5V		Near Alpha, Alpha-Beta	Excellent cold formability; used for seamless tubing.
	R52250	Unalloyed, with 0.12 to 0.25 Pd		Alpha	Comparable to Grade 1 in strength, but better crevice corrosion at low pH and high temperature.
	R53400	Ti-0.3Mo-0.8Ni		Alpha	Stronger than unalloyed grades, less expensive than Grades 7 & 11; crevice corrosion resistance good but less than Pd grades at low pH.
		Ti-0.5Ni-0.05Ru; 0.1 O, 0.2 Fe, 0.03 N		Alpha	Comparable to Grade 1 in strength but better crevice corrosion at low pH and in hot brine; lower cost than Pd containing grades.
		Ti-0.5Ni-0.05Ru; 0.15 O, 0.3 Fe, 0.03 N		Alpha	Comparable to Grade 2 in strength but better crevice corrosion at low pH and in hot brine; lower cost than Pd containing grades.
		Ti-0.5Ni-0.05Ru; 0.25 O, 0.3 Fe, 0.05 N		Alpha	Comparable to Grade 3 in strength but better crevice corrosion at low pH and in hot brine; lower cost than Pd containing grades.
		Ti; 0.04 to 0.08 Pd, 0.25 O, 0.3 Fe	Lean Pd grade	Alpha	Comparable to Grade 2 in strength but with crevice corrosion benefits similar to Grades 7 and 11.
		Ti; 0.04 to 0.08 Pd, 0.18 O, 0.2 Fe	Lean Pd grade	Alpha	Comparable to Grade 1 in strength but with crevice corrosion benefits similar to Grades 7 and 11.
		Ti-3Al-2.5V; 0.04 to 0.08 Pd			Pd containing version of Grade 9 with improved crevice corrosion resistance.
19	R58640	Ti-3Al-8V-6Cr-4Zr-4Mo	Beta C	Beta	Cold drawable and rollable; mainly used for springs
20		Ti-3Al-8V-6Cr-4Zr-4Mo; 0.04 – 0.08 Pd		Beta	Crevice corrosion resistant version of Grade 19.
21	R58210	Ti-15Mo-3Al-2.7Nb-.25Si	TiMetal® 21S, Beta 21S.	Beta	High strength, oxidation and creep resistant; high temperature aerospace applications.
23	R56401	Ti-6Al-4V; extra low interstitials	.	Alpha-Beta.	High ductility and damage tolerance version of Grade 5
24		Ti-6Al-4V; 0.04 – 0.08 Pd		Alpha-Beta	Crevice corrosion resistant version of Grade 5.
25		Ti-6Al-4V; 0.3 – 0.8 Ni, 0.04 – 0.08 Pd		Alpha-Beta	General and crevice corrosion resistant version of Grade 5.
26		Unalloyed, with 0.08 – 0.14 Ru; 0.25 O, 0.3 Fe		Alpha	Comparable to Grade 2 in strength, but better crevice corrosion at low pH and high temperature. Lower cost than Grade 7.
27		Unalloyed, with 0.08 – 0.14 Ru; 0.18 O, 0.2 Fe		Alpha	Comparable to Grade 1 in strength, but better crevice corrosion at low pH and high temperature. Lower cost than Grade 11.
28		Ti-3Al-2.5V; 0.08 – 0.14 Ru		Near Alpha, Alpha-Beta	Improved crevice corrosion version of Grade 9 at lower cost than Grade 9.
29		Ti-6Al-4V; extra low interstitials; 0.08 – 0.14 Ru		Alpha-Beta	Comparable to Grade 23 in mechanical properties, but improved crevice corrosion resistance.
30		Ti, 0.20 – 0.80 Co; 0.04 – 0.08 Pd; 0.03 N, 0.25 O		Alpha	Higher strength version of Grade 16.
31		Ti, 0.20 – 0.80 Co; 0.04 – 0.08 Pd; 0.05 N, 0.35 O		Alpha	Higher strength but lower ductility version of Grade 30
32		Ti-5Al-1Sn-1Zr-1V-0.8Mo			Primarily developed for toughness, weldability & seawater stress corrosion cracking resistance in naval applications, with the popular designation of Ti-5111.
33		Ti, 0.4 Ni, 0.015 Pd, 0.025 Ru, 0.15 Cr; 0.03 N, 0.25 O		Alpha	Improved general and crevice corrosion resistance
34		Ti, 0.4 Ni, 0.015 Pd, 0.025 Ru, 0.15 Cr; 0.05 N, 0.35 O		Alpha	Improved general and crevice corrosion resistance; higher strength and lower ductility than Grade 33.
35		Ti-4.5Al-2Mo-1.6V-0.5Fe-0.3Si			
36	R58450	Ti-45Nb			'Burn Resistant' alloy of moderate strength and very low elastic modulus
37		Ti-1.5Al			Improved oxidation resistance version of Commercially Pure Ti; auto exhaust applications
38		Ti-4Al-2.5V-1.5Fe			Strength and saltwater corrosion resistance comparable to Grade 5; hot and cold workable.

Note: there are no grades 10 and 22



2.2.3 Physical characteristics

Titanium has the highest strength-to-weight ratio of any metal. Commercial grades of titanium have an ultimate tensile strength of about 434 MPa, making them as strong as common steel alloys while being 45% lighter. For example, titanium is 60% heavier than, but more than twice the strength of aluminium.

Certain titanium alloys achieve tensile strengths of more than 1,400 MPa, however, titanium does lose strength when it is heated above 430°C.

In addition to its high strength-to-weight ratio, titanium metal is of such low density that, when pure, it is quite ductile (especially in an oxygen-free environment), lustrous and metallic-white in colour. The relatively high melting point of more than 1,660°C also makes it useful as a refractory metal.

2.3 Comparison with other metals

Compared to other 'light metals' including aluminium and magnesium, titanium was a very late entrant to the commercial industry. After World War II, the US defence sector sought titanium and demand for the metal began to grow. Due to its lower specific gravity compared to iron and steel, titanium has generally been grouped with two other light metals: aluminium and magnesium.

A summary comparison of the key properties of these metals and of their current relevant roles in the global industry is given in *Table 2.1*.

Table 2.1: Comparison of key properties between the major light metals

Factor	Magnesium	Aluminium	Titanium
Technical			
Atomic number	12	13	22
Atomic weight	24.3	27	47.9
Specific gravity (g/cm³)	1.7	2.7	4.5
Melting point (°C)	650	660	1,660
Boiling point (°C)	1,103	2,467	3,287
Thermal conductivity at 20°C	147	239	17
Thermal expansion co-efficient	25.7	24	7.6
Reduction energy (kWh/kg)	15	14	25

The key features to notice are:

- Titanium's significantly higher ultimate strength than aluminium and magnesium (strength-to-weight ratio) led to its increased use in the aerospace sector.
- Compared to aluminium and magnesium, titanium's much higher melting point gives it a wider range of potential uses. However, it is harder to manufacture and fabricate.
- It is more difficult to economically produce titanium metal and its alloys compared to aluminium and magnesium.
- Extraction of titanium and key alloys in large-scale processes, which are carried out on a batch basis, can still fail.

The high reduction energy requirements are attributable to the propensity for light metals to re-combine with oxygen during manufacture. This has prompted intense research during the past 50 years for alternative production paths. Despite the obvious rewards that would arise, all three metals are still extracted using the same basic technologies that brought them into commercial use many decades ago. (Magnesium has, however, seen a recent change in the preferred manufacturing process that is suitable for small-scale and low-sophistication Chinese production, which was previously based on 1940s vintage technology.) Titanium manufacture is easily the most inconvenient of the three and this has inhibited larger-scale metal development. However, in a world where increasingly greater emphasis is being placed on energy costs and environmental waste, titanium is now more economic in some of its high-technology uses where lightness, temperature and corrosion resistance are more important.

High purity titanium crystal bar
Image courtesy of Alchemist-hp

2.4 Processing, alloys and compounds

2.4.1 Historical background

It was 120 years after titanium was discovered, before pure titanium metal could be isolated. In 1910, metallurgist Matthew Hunter heated titanium tetrachloride ($TiCl_4$) with sodium in a steel bomb at 700–800°C in what became known as the Hunter process. In 1925, titanium of ultra-high purity was made in small quantities when chemists Anton Eduard van Arkel and Jan Hendrik de Boer discovered the iodide, or crystal bar, process by reacting crude titanium metal with iodine and decomposing the formed vapours over a hot filament to produce pure metal. Both of these methods were too labour-intensive and costly to enable titanium metal to be produced outside the laboratory. However, in 1946, metallurgist William Kroll proved that titanium could be commercially produced by reducing $TiCl_4$ with magnesium. The Kroll process became the standard for titanium production and remains so today.

E I du Pont de Nemours and Company (DuPont) was the first to take the Kroll process to commercialisation, with a US plant in Newport, Delaware initially producing 45 kg per day of titanium metal. At the same time, Canadian company Dominion Magnesium Limited was generating small quantities of metal at Haley, Ontario. Well-known US TiO_2 pigment producer National Lead Company (now TiO_2 pigment producer Kronos Incorporated) began experimenting with a metal pilot plant in Sayreville, New Jersey in 1950. The quality of the titanium sponge created by these early processes ranged between 96–98% titanium.

2.4.2 Titanium processing

After titanium is extracted, it undergoes a series of processing stages that involves purification, sponge production and alloy creation.

Extraction: Titanium concentrates are either rutile or ilmenite TiO_2. If the concentrate is the latter, it needs to be stripped of iron. These materials are put in a fluidised-bed reactor with chlorine gas

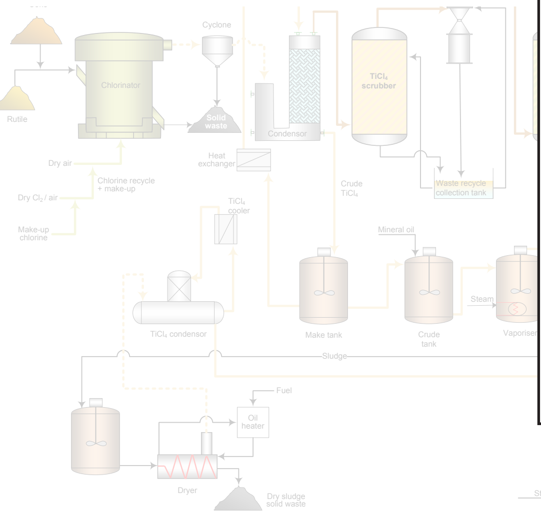
US$110 million titanium feedstock market

US$5.41 billion milled products market

US$2.94 billion titanium sponge market

MANUFACTURE OF TITANIUM PRODUCTS

Titanium metal product manufacture explained with details of various processes.



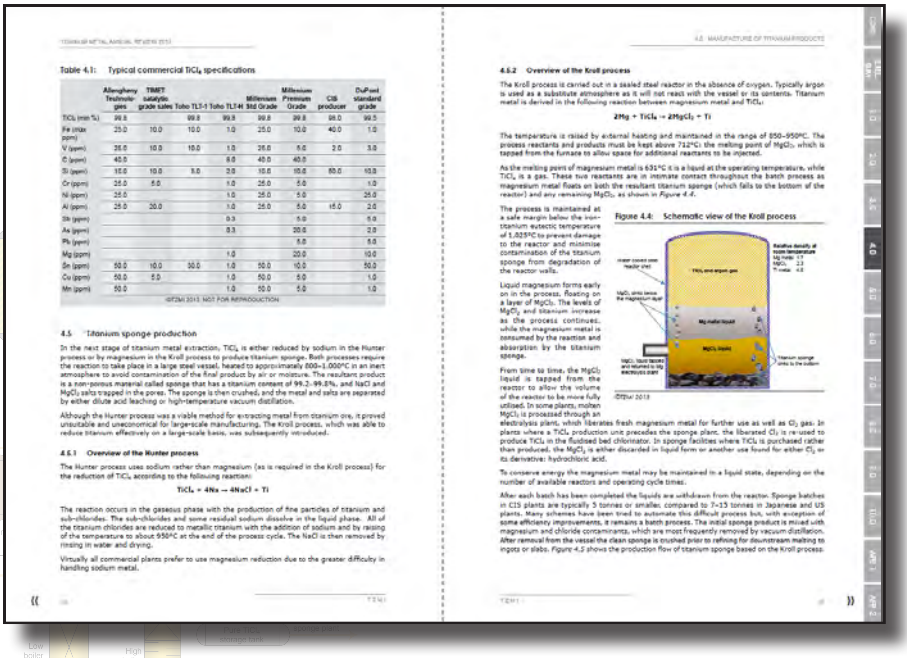


Table 4.1: Typical commercial $TiCl_4$ specifications

	Allegheny Technologies	TIMET catalytic grade sales	Toho TLT-1	Toho TLT-H	Millenium Std Grade	Millenium Premium Grade	CIS producer	DuPont standard grade
$TiCl_4$ (min %)	99.8		99.8	99.8	99.8	99.8	98.0	99.5
Fe (max ppm)	25.0	10.0	10.0	1.0	25.0	10.0	40.0	1.0
V (ppm)	35.0	10.0	10.0	1.0	35.0	5.0	2.0	3.0
C (ppm)	40.0			8.0	40.0	40.0		
Si (ppm)	15.0	10.0	5.0	2.0	15.0	10.0	60.0	10.0
Cr (ppm)	25.0	5.0		1.0	25.0	5.0		1.0
Ni (ppm)	25.0			1.0	25.0	5.0		25.0
Al (ppm)	25.0	20.0		1.0	25.0	5.0	15.0	2.0
Sb (ppm)				0.3		5.0		5.0
As (ppm)				0.3		20.0		2.0
Pb (ppm)						5.0		5.0
Mg (ppm)				1.0		20.0		10.0
Sn (ppm)	50.0	10.0	50.0	1.0	50.0	10.0		50.0
Cu (ppm)	50.0	5.0		1.0	50.0	5.0		1.0
Mn (ppm)	50.0			1.0	50.0	5.0		1.0

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4.5 Titanium sponge production

In the next stage of titanium metal extraction, $TiCl_4$ is either reduced by sodium in the Hunter process or by magnesium in the Kroll process to produce titanium sponge. Both processes require the reaction to take place in a large steel vessel, heated to approximately 800–1,000°C in an inert atmosphere to avoid contamination of the final product by air or moisture. The resultant product is a non-porous material called sponge that has a titanium content of 99.2–99.8%, and NaCl and $MgCl_2$ salts trapped in the pores. The sponge is then crushed, and the metal and salts are separated by either dilute acid leaching or high-temperature vacuum distillation.

Although the Hunter process was a viable method for extracting metal from titanium ore, it proved unsuitable and uneconomical for large-scale manufacturing. The Kroll process, which was able to reduce titanium effectively on a large-scale basis, was subsequently introduced.

4.5.1 Overview of the Hunter process

The Hunter process uses sodium rather than magnesium (as is required in the Kroll process) for the reduction of $TiCl_4$ according to the following reaction:

$$TiCl_4 + 4Na \rightarrow 4NaCl + Ti$$

The reaction occurs in the gaseous phase with the production of fine particles of titanium and sub-chlorides. The sub-chlorides and some residual sodium dissolve in the liquid phase. All of the titanium chlorides are reduced to metallic titanium with the addition of sodium and by raising of the temperature to about 950°C at the end of the process cycle. The NaCl is then removed by rinsing in water and drying.

Virtually all commercial plants prefer to use magnesium reduction due to the greater difficulty in handling sodium metal.

4.5.2 Overview of the Kroll process

The Kroll process is carried out in a sealed steel reactor in the absence of oxygen. Typically argon is used as a substitute atmosphere as it will not react with the vessel or its contents. Titanium metal is derived in the following reaction between magnesium metal and $TiCl_4$:

$$2Mg + TiCl_4 \rightarrow 2MgCl_2 + Ti$$

The temperature is raised by external heating and maintained in the range of 850–950°C. The process reactants and products must be kept above 712°C: the melting point of $MgCl_2$, which is tapped from the furnace to allow space for additional reactants to be injected.

As the melting point of magnesium metal is 651°C it is a liquid at the operating temperature, while $TiCl_4$ is a gas. These two reactants are in intimate contact throughout the batch process as magnesium metal floats on both the resultant titanium sponge (which falls to the bottom of the reactor) and any remaining $MgCl_2$, as shown in *Figure 4.4*.

Figure 4.4: Schematic view of the Kroll process

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The process is maintained at a safe margin below the iron-titanium eutectic temperature of 1,025°C to prevent damage to the reactor and minimise contamination of the titanium sponge from degradation of the reactor walls.

Liquid magnesium forms early on in the process, floating on a layer of $MgCl_2$. The levels of $MgCl_2$ and titanium increase as the process continues, while the magnesium metal is consumed by the reaction and absorption by the titanium sponge.

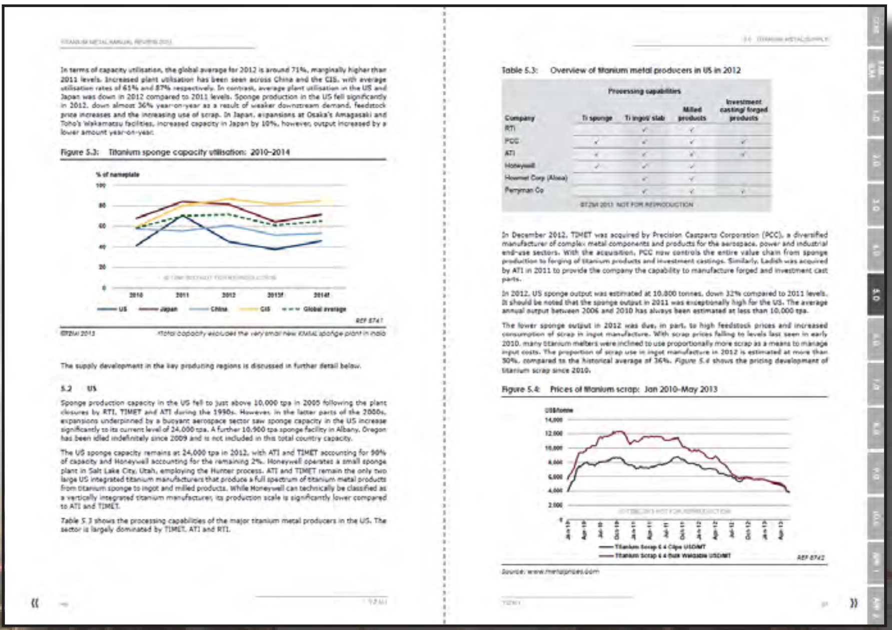
From time to time, the $MgCl_2$ liquid is tapped from the reactor to allow the volume of the reactor to be more fully utilised. In some plants, molten $MgCl_2$ is processed through an electrolysis plant, which liberates fresh magnesium metal for further use as well as Cl_2 gas. In plants where a $TiCl_4$ production unit precedes the sponge plant, the liberated Cl_2 is re-used to produce $TiCl_4$ in the fluidised bed chlorinator. In sponge facilities where $TiCl_4$ is purchased rather than produced, the $MgCl_2$ is either discarded in liquid form or another use found for either Cl_2 or its derivative: hydrochloric acid.

To conserve energy the magnesium metal may be maintained in a liquid state, depending on the number of available reactors and operating cycle times.

After each batch has been completed the liquids are withdrawn from the reactor. Sponge batches in CIS plants are typically 5 tonnes or smaller, compared to 7–15 tonnes in Japanese and US plants. Many schemes have been tried to automate this difficult process but, with exception of some efficiency improvements, it remains a batch process. The initial sponge product is mixed with magnesium and chloride contaminants, which are most frequently removed by vacuum distillation. After removal from the vessel the clean sponge is crushed prior to refining for downstream melting to ingots or slabs. *Figure 4.5* shows the production flow of titanium sponge based on the Kroll process.

TI-METAL SUPPLY

The supply dynamics of the titanium metal industry is covered with in depth analysis of major producers in relevant markets.



In terms of capacity utilisation, the global average for 2012 is around 71%, marginally higher than 2011 levels. Increased plant utilisation has been seen across China and the CIS, with average utilisation rates of 61% and 87% respectively. In contrast, average plant utilisation in the US and Japan was down in 2012 compared to 2011 levels. Sponge production in the US fell significantly in 2012, down almost 36% year-on-year as a result of weaker downstream demand, feedstock price increases and the increasing use of scrap. In Japan, expansions at Osaka's Amagasaki and Toho's Wakamatsu facilities, increased capacity in Japan by 10%, however, output increased by a lower amount year-on-year.

Figure 5.3: Titanium sponge capacity utilisation: 2010–2014

©TZMI 2013 *Total capacity excludes the very small new KMML sponge plant in India

The supply development in the key producing regions is discussed in further detail below.

5.2 US

Sponge production capacity in the US fell to just above 10,000 tpa in 2005 following the plant closures by RTI, TIMET and ATI during the 1990s. However, in the latter parts of the 2000s, expansions underpinned by a buoyant aerospace sector saw sponge capacity in the US increase significantly to its current level of 24,000 tpa. A further 10,900 tpa sponge facility in Albany, Oregon has been idled indefinitely since 2009 and is not included in this total country capacity.

The US sponge capacity remains at 24,000 tpa in 2012, with ATI and TIMET accounting for 98% of capacity and Honeywell accounting for the remaining 2%. Honeywell operates a small sponge plant in Salt Lake City, Utah, employing the Hunter process. ATI and TIMET remain the only two large US integrated titanium manufacturers that produce a full spectrum of titanium metal products from titanium sponge to ingot and milled products. While Honeywell can technically be classified as a vertically integrated titanium manufacturer, its production scale is significantly lower compared to ATI and TIMET.

Table 5.3 shows the processing capabilities of the major titanium metal producers in the US. The sector is largely dominated by TIMET, ATI and RTI.

Table 5.3: Overview of titanium metal producers in US in 2012

	Processing capabilities			
Company	Ti sponge	Ti ingot/ slab	Milled products	Investment casting/ forged products
RTI		✓	✓	
PCC	✓	✓	✓	✓
ATI	✓	✓	✓	✓
Honeywell	✓	✓	✓	
Howmet Corp (Alcoa)		✓	✓	
Perryman Co		✓	✓	✓

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In December 2012, TIMET was acquired by Precision Castparts Corporation (PCC), a diversified manufacturer of complex metal components and products for the aerospace, power and industrial end-use sectors. With the acquisition, PCC now controls the entire value chain from sponge production to forging of titanium products and investment castings. Similarly, Ladish was acquired by ATI in 2011 to provide the company the capability to manufacture forged and investment cast parts.

In 2012, US sponge output was estimated at 10,800 tonnes, down 32% compared to 2011 levels. It should be noted that the sponge output in 2011 was exceptionally high for the US. The average annual output between 2006 and 2010 has always been estimated at less than 10,000 tpa.

The lower sponge output in 2012 was due, in part, to high feedstock prices and increased consumption of scrap in ingot manufacture. With scrap prices falling to levels last seen in early 2010, many titanium melters were inclined to use proportionally more scrap as a means to manage input costs. The proportion of scrap use in ingot manufacture in 2012 is estimated at more than 50%, compared to the historical average of 36%. *Figure 5.4* shows the pricing development of titanium scrap since 2010.

Figure 5.4: Prices of titanium scrap: Jan 2010–May 2013

Source: www.metalprices.com

MARKETS FOR TITANIUM

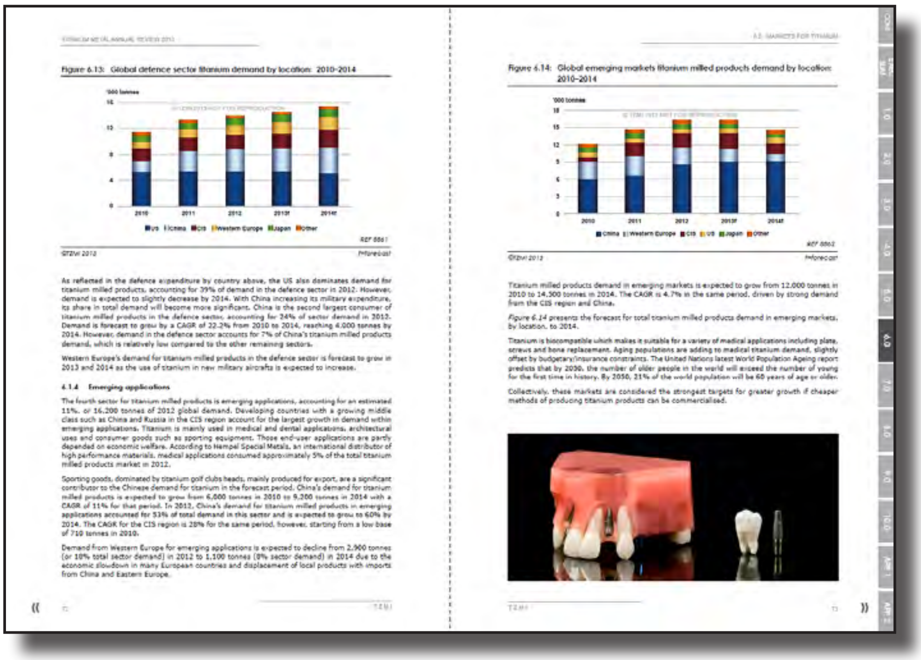

Figure 6.13: Global defence sector titanium demand by location: 2010–2014

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f=forecast

As reflected in the defence expenditure by country above, the US also dominates demand for titanium milled products, accounting for 39% of demand in the defence sector in 2012. However, demand is expected to slightly decrease by 2014. With China increasing its military expenditure, its share in total demand will become more significant. China is the second largest consumer of titanium milled products in the defence sector, accounting for 24% of sector demand in 2012. Demand is forecast to grow by a CAGR of 22.2% from 2010 to 2014, reaching 4,000 tonnes by 2014. However, demand in the defence sector accounts for 7% of China's titanium milled products demand, which is relatively low compared to the other remaining sectors.

Western Europe's demand for titanium milled products in the defence sector is forecast to grow in 2013 and 2014 as the use of titanium in new military aircrafts is expected to increase.

6.1.4 Emerging applications

The fourth sector for titanium milled products is emerging applications, accounting for an estimated 11%, or 16,200 tonnes of 2012 global demand. Developing countries with a growing middle class such as China and Russia in the CIS region account for the largest growth in demand within emerging applications. Titanium is mainly used in medical and dental applications, architectural uses and consumer goods such as sporting equipment. Those end-user applications are partly depended on economic welfare. According to Hempel Special Metals, an international distributor of high performance materials, medical applications consumed approximately 5% of the total titanium milled products market in 2012.

Sporting goods, dominated by titanium golf clubs heads, mainly produced for export, are a significant contributor to the Chinese demand for titanium in the forecast period. China's demand for titanium milled products is expected to grow from 6,000 tonnes in 2010 to 9,200 tonnes in 2014 with a CAGR of 11% for that period. In 2012, China's demand for titanium milled products in emerging applications accounted for 53% of total demand in this sector and is expected to grow to 60% by 2014. The CAGR for the CIS region is 28% for the same period, however, starting from a low base of 710 tonnes in 2010.

Demand from Western Europe for emerging applications is expected to decline from 2,900 tonnes (or 18% total sector demand) in 2012 to 1,100 tonnes (8% sector demand) in 2014 due to the economic slowdown in many European countries and displacement of local products with imports from China and Eastern Europe.

Figure 6.14: Global emerging markets titanium milled products demand by location: 2010–2014

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f=forecast

Titanium milled products demand in emerging markets is expected to grow from 12,000 tonnes in 2010 to 14,300 tonnes in 2014. The CAGR is 4.7% in the same period, driven by strong demand from the CIS region and China.

Figure 6.14 presents the forecast for total titanium milled products demand in emerging markets, by location, to 2014.

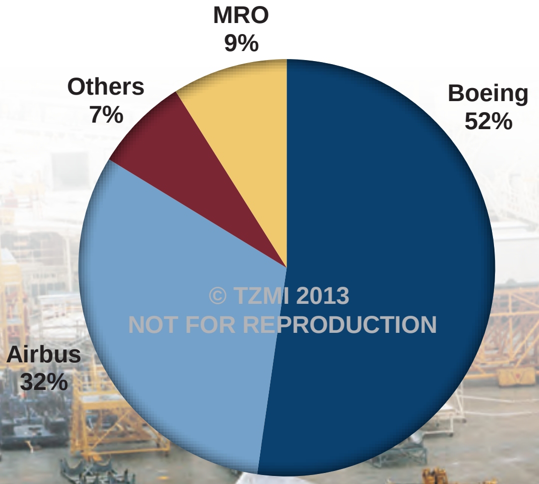
Titanium is biocompatible which makes it suitable for a variety of medical applications including plate, screws and bone replacement. Aging populations are adding to medical titanium demand, slightly offset by budgetary/insurance constraints. The United Nations latest World Population Ageing report predicts that by 2050, the number of older people in the world will exceed the number of young for the first time in history. By 2050, 21% of the world population will be 60 years of age or older.

Collectively, these markets are considered the strongest targets for greater growth if cheaper methods of producing titanium products can be commercialised.

Major end markets for titanium metal

Details of each segment by region and market share

Titanium milled products demand in commercial aerospace in 2012



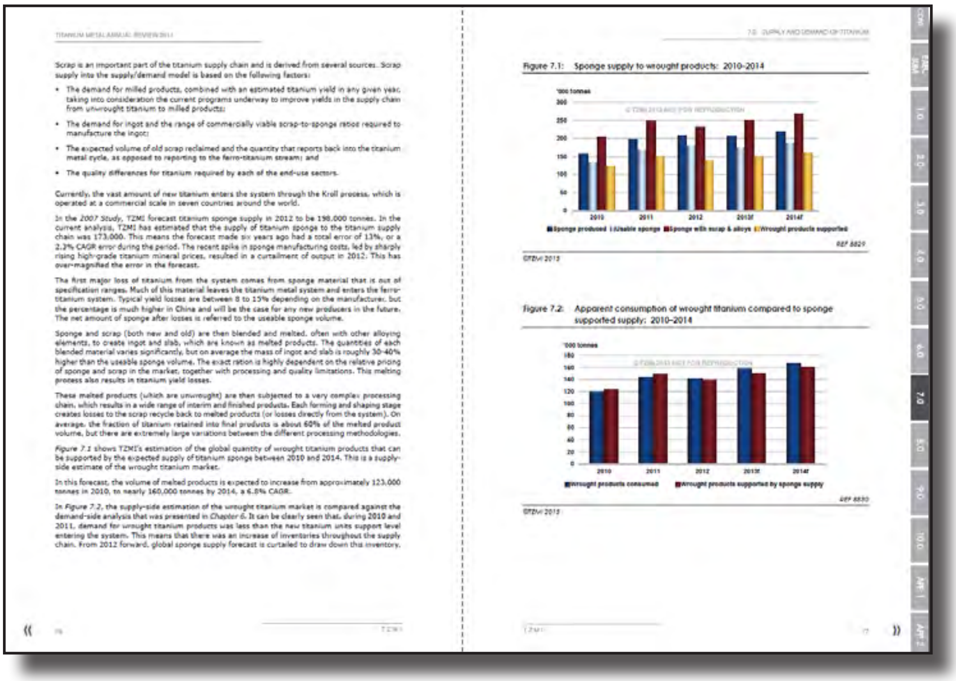
> “Close to 90% of manufactured titanium sponge is used in the manufacture of titanium and titanium alloy products for commercial aerospace, industrial applications, defence and emerging applications.”

SUPPLY AND DEMAND

Demand drivers

Supply dynamics

Regional analysis by segment



Scrap is an important part of the titanium supply chain and is derived from several sources. Scrap supply into the supply/demand model is based on the following factors:

- The demand for milled products, combined with an estimated titanium yield in any given year, taking into consideration the current programs underway to improve yields in the supply chain from unwrought titanium to milled products;
- The demand for ingot and the range of commercially viable scrap-to-sponge ratios required to manufacture the ingot;
- The expected volume of old scrap reclaimed and the quantity that reports back into the titanium metal cycle, as opposed to reporting to the ferro-titanium stream; and
- The quality differences for titanium required by each of the end-use sectors.

Currently, the vast amount of new titanium enters the system through the Kroll process, which is operated at a commercial scale in seven countries around the world.

In the *2007 Study*, TZMI forecast titanium sponge supply in 2012 to be 198,000 tonnes. In the current analysis, TZMI has estimated that the supply of titanium sponge to the titanium supply chain was 173,000. This means the forecast made six years ago had a total error of 13%, or a 2.3% CAGR error during the period. The recent spike in sponge manufacturing costs, led by sharply rising high-grade titanium mineral prices, resulted in a curtailment of output in 2012. This has over-magnified the error in the forecast.

The first major loss of titanium from the system comes from sponge material that is out of specification ranges. Much of this material leaves the titanium metal system and enters the ferro-titanium system. Typical yield losses are between 8 to 15% depending on the manufacturer, but the percentage is much higher in China and will be the case for any new producers in the future. The net amount of sponge after losses is referred to the useable sponge volume.

Sponge and scrap (both new and old) are then blended and melted, often with other alloying elements, to create ingot and slab, which are known as melted products. The quantities of each blended material varies significantly, but on average the mass of ingot and slab is roughly 30-40% higher than the useable sponge volume. The exact ration is highly dependent on the relative pricing of sponge and scrap in the market, together with processing and quality limitations. This melting process also results in titanium yield losses.

These melted products (which are unwrought) are then subjected to a very complex processing chain, which results in a wide range of interim and finished products. Each forming and shaping stage creates losses to the scrap recycle back to melted products (or losses directly from the system). On average, the fraction of titanium retained into final products is about 60% of the melted product volume, but there are extremely large variations between the different processing methodologies.

Figure 7.1 shows TZMI's estimation of the global quantity of wrought titanium products that can be supported by the expected supply of titanium sponge between 2010 and 2014. This is a supply-side estimate of the wrought titanium market.

In this forecast, the volume of melted products is expected to increase from approximately 123,000 tonnes in 2010, to nearly 160,000 tonnes by 2014, a 6.8% CAGR.

In *Figure 7.2*, the supply-side estimation of the wrought titanium market is compared against the demand-side analysis that was presented in *Chapter 6*. It can be clearly seen that, during 2010 and 2011, demand for wrought titanium products was less than the new titanium units support level entering the system. This means that there was an increase of inventories throughout the supply chain. From 2012 forward, global sponge supply forecast is curtailed to draw down this inventory.

Figure 7.1: Sponge supply to wrought products: 2010-2014

REF 8829

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Figure 7.2: Apparent consumption of wrought titanium compared to sponge supported supply: 2010–2014

REF 8830

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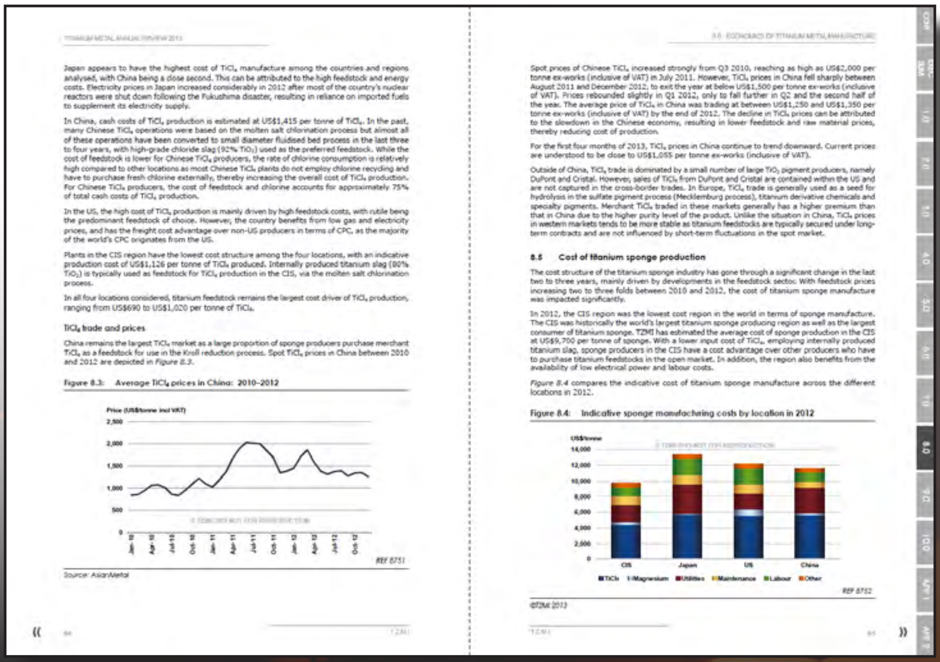
ECONOMICS OF PRODUCTION



Japan appears to have the highest cost of $TiCl_4$ manufacture among the countries and regions analysed, with China being a close second. This can be attributed to the high feedstock and energy costs. Electricity prices in Japan increased considerably in 2012 after most of the country's nuclear reactors were shut down following the Fukushima disaster, resulting in reliance on imported fuels to supplement its electricity supply.

In China, cash costs of $TiCl_4$ production is estimated at US$1,415 per tonne of $TiCl_4$. In the past, many Chinese $TiCl_4$ operations were based on the molten salt chlorination process but almost all of these operations have been converted to small diameter fluidised bed process in the last three to four years, with high-grade chloride slag (92% TiO_2) used as the preferred feedstock. While the cost of feedstock is lower for Chinese $TiCl_4$ producers, the rate of chlorine consumption is relatively high compared to other locations as most Chinese $TiCl_4$ plants do not employ chlorine recycling and have to purchase fresh chlorine externally, thereby increasing the overall cost of $TiCl_4$ production. For Chinese $TiCl_4$ producers, the cost of feedstock and chlorine accounts for approximately 75% of total cash costs of $TiCl_4$ production.

In the US, the high cost of $TiCl_4$ production is mainly driven by high feedstock costs, with rutile being the predominant feedstock of choice. However, the country benefits from low gas and electricity prices, and has the freight cost advantage over non-US producers in terms of CPC, as the majority of the world's CPC originates from the US.

Plants in the CIS region have the lowest cost structure among the four locations, with an indicative production cost of US$1,126 per tonne of $TiCl_4$ produced. Internally produced titanium slag (80% TiO_2) is typically used as feedstock for $TiCl_4$ production in the CIS, via the molten salt chlorination process.

In all four locations considered, titanium feedstock remains the largest cost driver of $TiCl_4$ production, ranging from US$690 to US$1,020 per tonne of $TiCl_4$.

$TiCl_4$ trade and prices

China remains the largest $TiCl_4$ market as a large proportion of sponge producers purchase merchant $TiCl_4$ as a feedstock for use in the Kroll reduction process. Spot $TiCl_4$ prices in China between 2010 and 2012 are depicted in *Figure 8.3*.

Figure 8.3: Average $TiCl_4$ prices in China: 2010–2012

REF 8751

Source: AsianMetal

Spot prices of Chinese $TiCl_4$ increased strongly from Q3 2010, reaching as high as US$2,000 per tonne ex-works (inclusive of VAT) in July 2011. However, $TiCl_4$ prices in China fell sharply between August 2011 and December 2012, to exit the year at below US$1,500 per tonne ex-works (inclusive of VAT). Prices rebounded slightly in Q1 2012, only to fall further in Q2 and the second half of the year. The average price of $TiCl_4$ in China was trading at between US$1,250 and US$1,350 per tonne ex-works (inclusive of VAT) by the end of 2012. The decline in $TiCl_4$ prices can be attributed to the slowdown in the Chinese economy, resulting in lower feedstock and raw material prices, thereby reducing cost of production.

For the first four months of 2013, $TiCl_4$ prices in China continue to trend downward. Current prices are understood to be close to US$1,055 per tonne ex-works (inclusive of VAT).

Outside of China, $TiCl_4$ trade is dominated by a small number of large TiO_2 pigment producers, namely DuPont and Cristal. However, sales of $TiCl_4$ from DuPont and Cristal are contained within the US and are not captured in the cross-border trades. In Europe, $TiCl_4$ trade is generally used as a seed for hydrolysis in the sulfate pigment process (Mecklemburg process), titanium derivative chemicals and specialty pigments. Merchant $TiCl_4$ traded in these markets generally has a higher premium than that in China due to the higher purity level of the product. Unlike the situation in China, $TiCl_4$ prices in western markets tends to be more stable as titanium feedstocks are typically secured under long-term contracts and are not influenced by short-term fluctuations in the spot market.

8.5 Cost of titanium sponge production

The cost structure of the titanium sponge industry has gone through a significant change in the last two to three years, mainly driven by developments in the feedstock sector. With feedstock prices increasing two to three folds between 2010 and 2012, the cost of titanium sponge manufacture was impacted significantly.

In 2012, the CIS region was the lowest cost region in the world in terms of sponge manufacture. The CIS was historically the world's largest titanium sponge producing region as well as the largest consumer of titanium sponge. TZMI has estimated the average cost of sponge production in the CIS at US$9,700 per tonne of sponge. With a lower input cost of $TiCl_4$, employing internally produced titanium slag, sponge producers in the CIS have a cost advantage over other producers who have to purchase titanium feedstocks in the open market. In addition, the region also benefits from the availability of low electrical power and labour costs.

Figure 8.4 compares the indicative cost of titanium sponge manufacture across the different locations in 2012.

Figure 8.4: Indicative sponge manufacturing costs by location in 2012

REF 8752

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Manufacturing costs

Cost inputs by region and segment

EMERGING TECHNOLOGIES

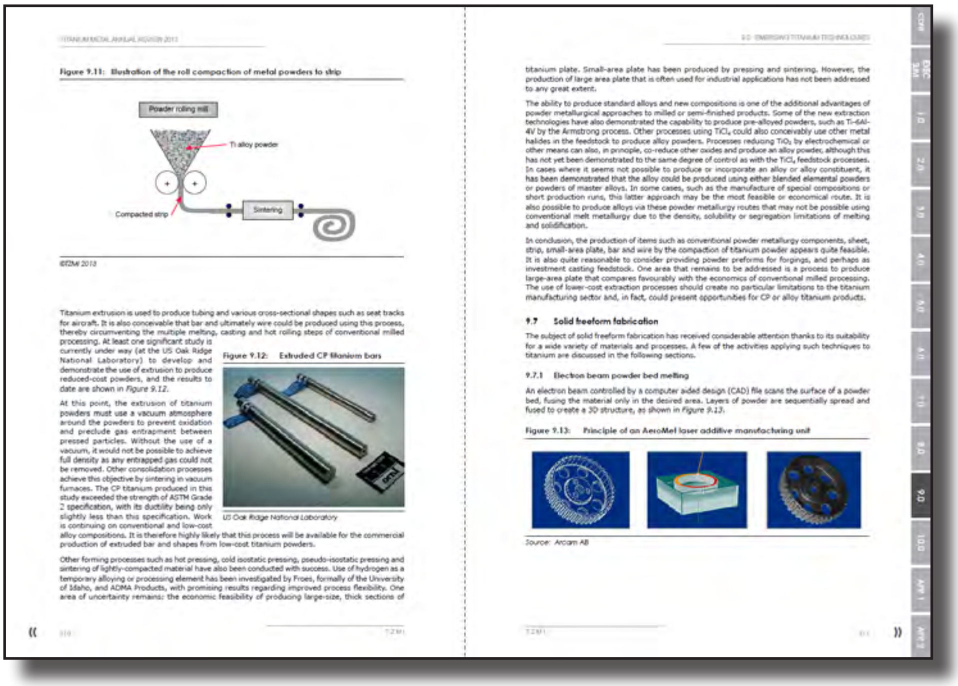

Figure 9.11: Illustration of the roll compaction of metal powders to strip

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Titanium extrusion is used to produce tubing and various cross-sectional shapes such as seat tracks for aircraft. It is also conceivable that bar and ultimately wire could be produced using this process, thereby circumventing the multiple melting, casting and hot rolling steps of conventional milled processing. At least one significant study is currently under way (at the US Oak Ridge National Laboratory) to develop and demonstrate the use of extrusion to produce reduced-cost powders, and the results to date are shown in *Figure 9.12*.

Figure 9.12: Extruded CP titanium bars

US Oak Ridge National Laboratory

At this point, the extrusion of titanium powders must use a vacuum atmosphere around the powders to prevent oxidation and preclude gas entrapment between pressed particles. Without the use of a vacuum, it would not be possible to achieve full density as any entrapped gas could not be removed. Other consolidation processes achieve this objective by sintering in vacuum furnaces. The CP titanium produced in this study exceeded the strength of ASTM Grade 2 specification, with its ductility being only slightly less than this specification. Work is continuing on conventional and low-cost alloy compositions. It is therefore highly likely that this process will be available for the commercial production of extruded bar and shapes from low-cost titanium powders.

Other forming processes such as hot pressing, cold isostatic pressing, pseudo-isostatic pressing and sintering of lightly-compacted material have also been conducted with success. Use of hydrogen as a temporary alloying or processing element has been investigated by Froes, formally of the University of Idaho, and ADMA Products, with promising results regarding improved process flexibility. One area of uncertainty remains: the economic feasibility of producing large-size, thick sections of titanium plate. Small-area plate has been produced by pressing and sintering. However, the production of large area plate that is often used for industrial applications has not been addressed to any great extent.

The ability to produce standard alloys and new compositions is one of the additional advantages of powder metallurgical approaches to milled or semi-finished products. Some of the new extraction technologies have also demonstrated the capability to produce pre-alloyed powders, such as Ti-6Al-4V by the Armstrong process. Other processes using $TiCl_4$ could also conceivably use other metal halides in the feedstock to produce alloy powders. Processes reducing TiO_2 by electrochemical or other means can also, in principle, co-reduce other oxides and produce an alloy powder, although this has not yet been demonstrated to the same degree of control as with the $TiCl_4$ feedstock processes. In cases where it seems not possible to produce or incorporate an alloy or alloy constituent, it has been demonstrated that the alloy could be produced using either blended elemental powders or powders of master alloys. In some cases, such as the manufacture of special compositions or short production runs, this latter approach may be the most feasible or economical route. It is also possible to produce alloys via these powder metallurgy routes that may not be possible using conventional melt metallurgy due to the density, solubility or segregation limitations of melting and solidification.

In conclusion, the production of items such as conventional powder metallurgy components, sheet, strip, small-area plate, bar and wire by the compaction of titanium powder appears quite feasible. It is also quite reasonable to consider providing powder preforms for forgings, and perhaps as investment casting feedstock. One area that remains to be addressed is a process to produce large-area plate that compares favourably with the economics of conventional milled processing. The use of lower-cost extraction processes should create no particular limitations to the titanium manufacturing sector and, in fact, could present opportunities for CP or alloy titanium products.

9.7 Solid freeform fabrication

The subject of solid freeform fabrication has received considerable attention thanks to its suitability for a wide variety of materials and processes. A few of the activities applying such techniques to titanium are discussed in the following sections.

9.7.1 Electron beam powder bed melting

An electron beam controlled by a computer aided design (CAD) file scans the surface of a powder bed, fusing the material only in the desired area. Layers of powder are sequentially spread and fused to create a 3D structure, as shown in *Figure 9.13*.

Figure 9.13: Principle of an AeroMet laser additive manufacturing unit

Source: Arcam AB

New technology

Updates on developments

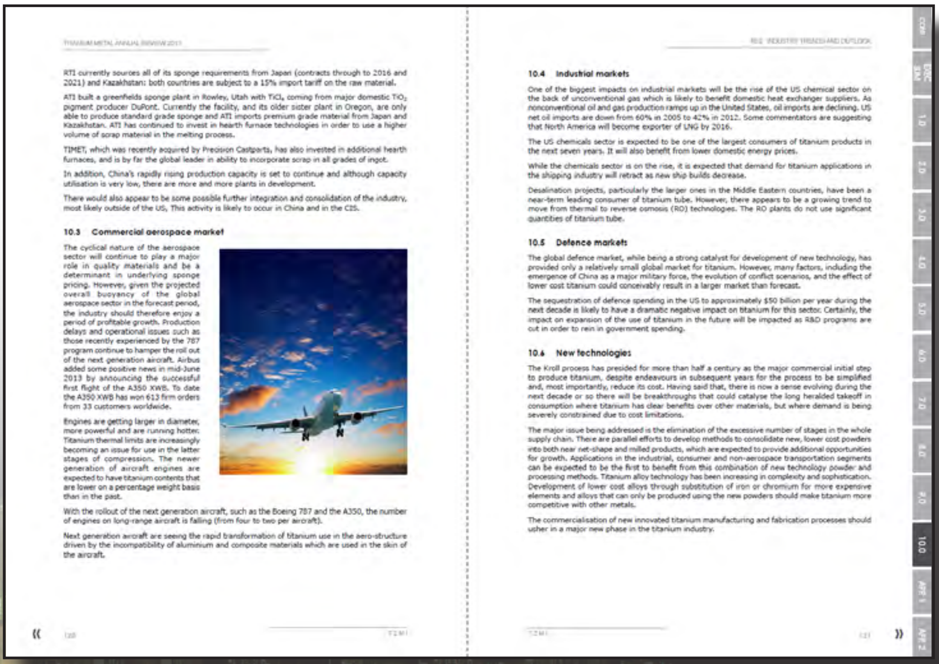
New processes

INDUSTRY TRENDS AND OUTLOOK

Outlook for titanium metal markets

Strategic issues for the industry

Key challenges in the future



RTI currently sources all of its sponge requirements from Japan (contracts through to 2016 and 2021) and Kazakhstan: both countries are subject to a 15% import tariff on the raw material.

ATI built a greenfields sponge plant in Rowley, Utah with $TiCl_4$ coming from major domestic TiO_2 pigment producer DuPont. Currently the facility, and its older sister plant in Oregon, are only able to produce standard grade sponge and ATI imports premium grade material from Japan and Kazakhstan. ATI has continued to invest in hearth furnace technologies in order to use a higher volume of scrap material in the melting process.

TIMET, which was recently acquired by Precision Castparts, has also invested in additional hearth furnaces, and is by far the global leader in ability to incorporate scrap in all grades of ingot.

In addition, China's rapidly rising production capacity is set to continue and although capacity utilisation is very low, there are more and more plants in development.

There would also appear to be some possible further integration and consolidation of the industry, most likely outside of the US, This activity is likely to occur in China and in the CIS.

10.3 Commercial aerospace market

The cyclical nature of the aerospace sector will continue to play a major role in quality materials and be a determinant in underlying sponge pricing. However, given the projected overall buoyancy of the global aerospace sector in the forecast period, the industry should therefore enjoy a period of profitable growth. Production delays and operational issues such as those recently experienced by the 787 program continue to hamper the roll out of the next generation aircraft. Airbus added some positive news in mid-June 2013 by announcing the successful first flight of the A350 XWB. To date the A350 XWB has won 613 firm orders from 33 customers worldwide.

Engines are getting larger in diameter, more powerful and are running hotter. Titanium thermal limits are increasingly becoming an issue for use in the latter stages of compression. The newer generation of aircraft engines are expected to have titanium contents that are lower on a percentage weight basis than in the past.

With the rollout of the next generation aircraft, such as the Boeing 787 and the A350, the number of engines on long-range aircraft is falling (from four to two per aircraft).

Next generation aircraft are seeing the rapid transformation of titanium use in the aero-structure driven by the incompatibility of aluminium and composite materials which are used in the skin of the aircraft.

10.4 Industrial markets

One of the biggest impacts on industrial markets will be the rise of the US chemical sector on the back of unconventional gas which is likely to benefit domestic heat exchanger suppliers. As nonconventional oil and gas production ramps up in the United States, oil imports are declining. US net oil imports are down from 60% in 2005 to 42% in 2012. Some commentators are suggesting that North America will become exporter of LNG by 2016.

The US chemicals sector is expected to be one of the largest consumers of titanium products in the next seven years. It will also benefit from lower domestic energy prices.

While the chemicals sector is on the rise, it is expected that demand for titanium applications in the shipping industry will retract as new ship builds decrease.

Desalination projects, particularly the larger ones in the Middle Eastern countries, have been a near-term leading consumer of titanium tube. However, there appears to be a growing trend to move from thermal to reverse osmosis (RO) technologies. The RO plants do not use significant quantities of titanium tube.

10.5 Defence markets

The global defence market, while being a strong catalyst for development of new technology, has provided only a relatively small global market for titanium. However, many factors, including the emergence of China as a major military force, the evolution of conflict scenarios, and the effect of lower cost titanium could conceivably result in a larger market than forecast.

The sequestration of defence spending in the US to approximately $50 billion per year during the next decade is likely to have a dramatic negative impact on titanium for this sector. Certainly, the impact on expansion of the use of titanium in the future will be impacted as R&D programs are cut in order to rein in government spending.

10.6 New technologies

The Kroll process has presided for more than half a century as the major commercial initial step to produce titanium, despite endeavours in subsequent years for the process to be simplified and, most importantly, reduce its cost. Having said that, there is now a sense evolving during the next decade or so there will be breakthroughs that could catalyse the long heralded takeoff in consumption where titanium has clear benefits over other materials, but where demand is being severely constrained due to cost limitations.

The major issue being addressed is the elimination of the excessive number of stages in the whole supply chain. There are parallel efforts to develop methods to consolidate new, lower cost powders into both near net-shape and milled products, which are expected to provide additional opportunities for growth. Applications in the industrial, consumer and non-aerospace transportation segments can be expected to be the first to benefit from this combination of new technology powder and processing methods. Titanium alloy technology has been increasing in complexity and sophistication. Development of lower cost alloys through substitution of iron or chromium for more expensive elements and alloys that can only be produced using the new powders should make titanium more competitive with other metals.

The commercialisation of new innovated titanium manufacturing and fabrication processes should usher in a major new phase in the titanium industry.

APPENDIX 1 *Producer profiles*

TITANIUM METAL ANNUAL REVIEW 2013

Carpenter Technology Corporation

Ownership Publicly listed on the New York Stock Exchange

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Stephen Peskosky – Vice President – F
Russell E Reber Jr – Vice President – Q
John L Rice – Vice President – Human
David L Strobel – Senior Vice Preside
Tony R Thene – Senior Vice President
Sunil Y Widge – Senior Vice President
Andrew T Ziolkowski – Senior Vice Pr
Alloy Operations and Latrobe Operati

Background
Carpenter Technology Corporation (C
James Carpenter as the Carpenter S
entity in 1937.

In 1928, Carpenter announced the w
steel, Type 416 which is still used toda
nickel free machining stainless steel in
new products improved tool life and pr
became synonymous with stainless st

The company is now a leader in dev
distribution of cast / wrought and powd
alloys. Its specialty materials are
aerospace and defence industries as
medical markets.

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APPENDIX 1

Carpenter Technology Corporation

Operations

Carpenter's subsidiaries and activities are organised under two business groups:

- Special Alloy Operations and
- Performance Engineered Products.

The Special Alloy Operations produce cast-wrought stainless steels, high-temperature alloys, high-strength steels (nickel-, iron- and cobalt-based), alloy steels, magnetic and controlled expansion alloys, tool and die steels, and special-purpose alloys including solid stainless reinforcing bar.

Performance Engineered Products include:

- Dynamet Incorporated, the company's titanium business unit,
- Carpenter Powder, which manufactures spherical gas-atomised power alloys, and
- Amega West Services, which manufactures and rents downhole drilling tools and components. The company was acquired in January 2011.

Recent developments

In February 2012, Carpenter acquired Latrobe Speciality Metals, a manufacturer and distributor of high-performance, remelted materials for aerospace, defence, energy and other industrial applications. Operations are located in North America, Europe and Asia.

In November 2012, Carpenter and Sandvik Materials Technology announced that they will dissolve their joint ventures Powdernet AB and Carpenter Powder Products AB, both located in Sweden. Instead the two companies agreed that the growth of their respective powder metal businesses would be better served by a supply agreement by which Carpenter will supply Sandvik.

In April 2013, Carpenter entered a supply agreement that will provide Rolls-Royce with advanced technology materials used in the manufacture of jet engines components. The five-year agreement runs until 2017 and is valued at approximately US$75 million.

Carpenter reported first quarter 2013 net income of US$33 million from net sales of US$582 million. Revenues increased in the aerospace and defense markets by 20% to US$215 million, and in the energy market by 24% to US$71 million year on year. Other markets such as transportation, and industrial and consumer applications remained flat. Revenues in medical applications declined by 26% to US$25 million from Q1 2012 to Q1 2013.

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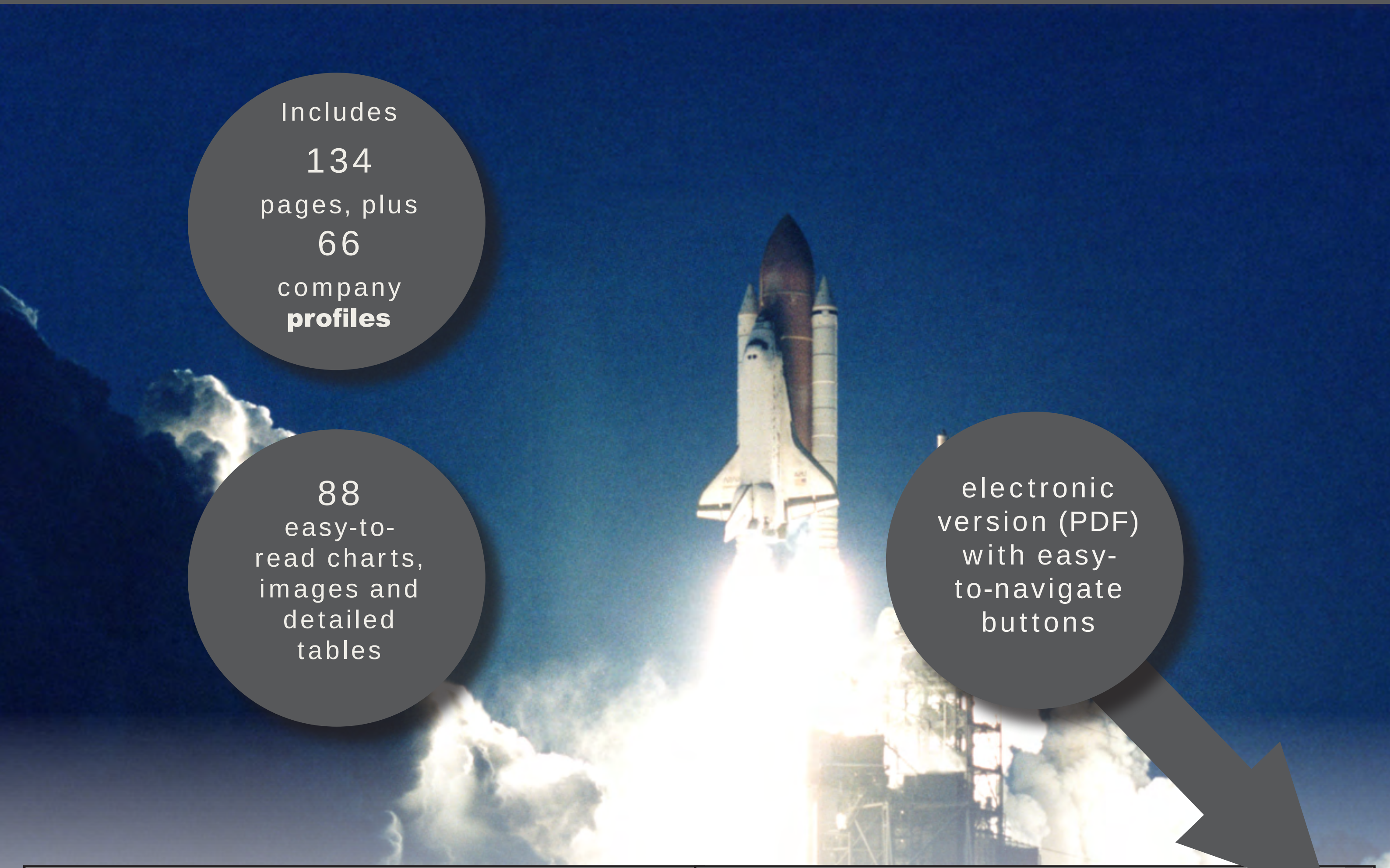
SAMPLE PAGES



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company
profiles

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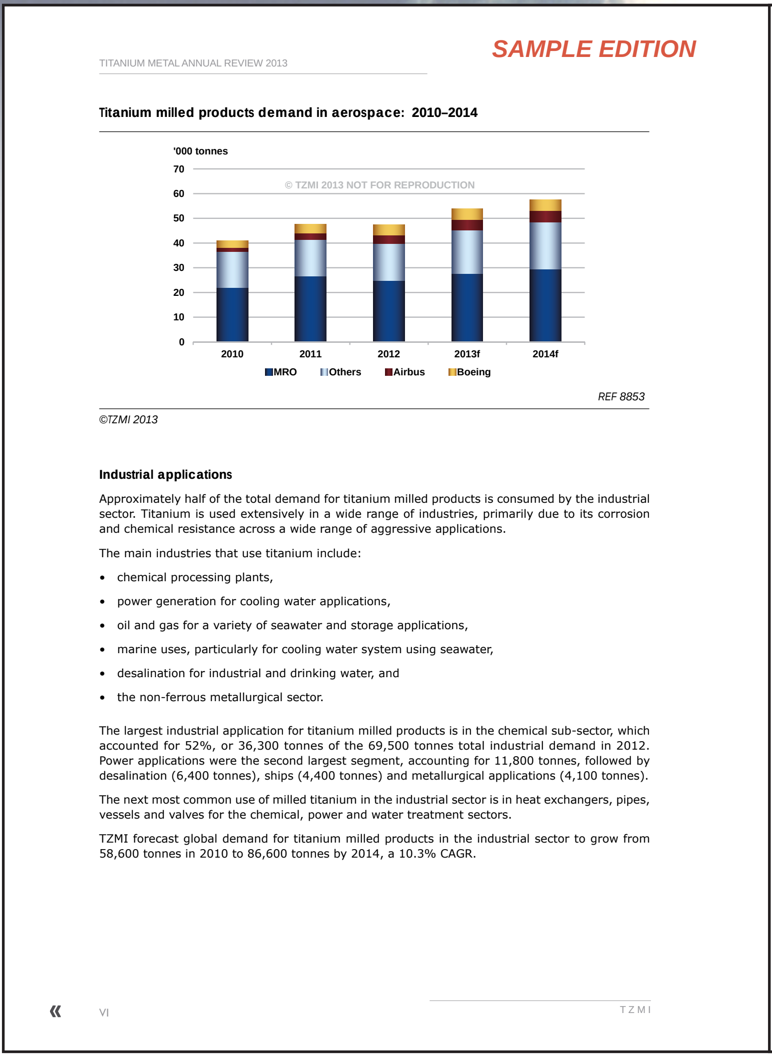

TITANIUM METAL ANNUAL REVIEW 2013

SAMPLE EDITION

Titanium milled products demand in aerospace: 2010–2014

REF 8853

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Industrial applications

Approximately half of the total demand for titanium milled products is consumed by the industrial sector. Titanium is used extensively in a wide range of industries, primarily due to its corrosion and chemical resistance across a wide range of aggressive applications.

The main industries that use titanium include:

- chemical processing plants,
- power generation for cooling water applications,
- oil and gas for a variety of seawater and storage applications,
- marine uses, particularly for cooling water system using seawater,
- desalination for industrial and drinking water, and
- the non-ferrous metallurgical sector.

The largest industrial application for titanium milled products is in the chemical sub-sector, which accounted for 52%, or 36,300 tonnes of the 69,500 tonnes total industrial demand in 2012. Power applications were the second largest segment, accounting for 11,800 tonnes, followed by desalination (6,400 tonnes), ships (4,400 tonnes) and metallurgical applications (4,100 tonnes).

The next most common use of milled titanium in the industrial sector is in heat exchangers, pipes, vessels and valves for the chemical, power and water treatment sectors.

TZMI forecast global demand for titanium milled products in the industrial sector to grow from 58,600 tonnes in 2010 to 86,600 tonnes by 2014, a 10.3% CAGR.

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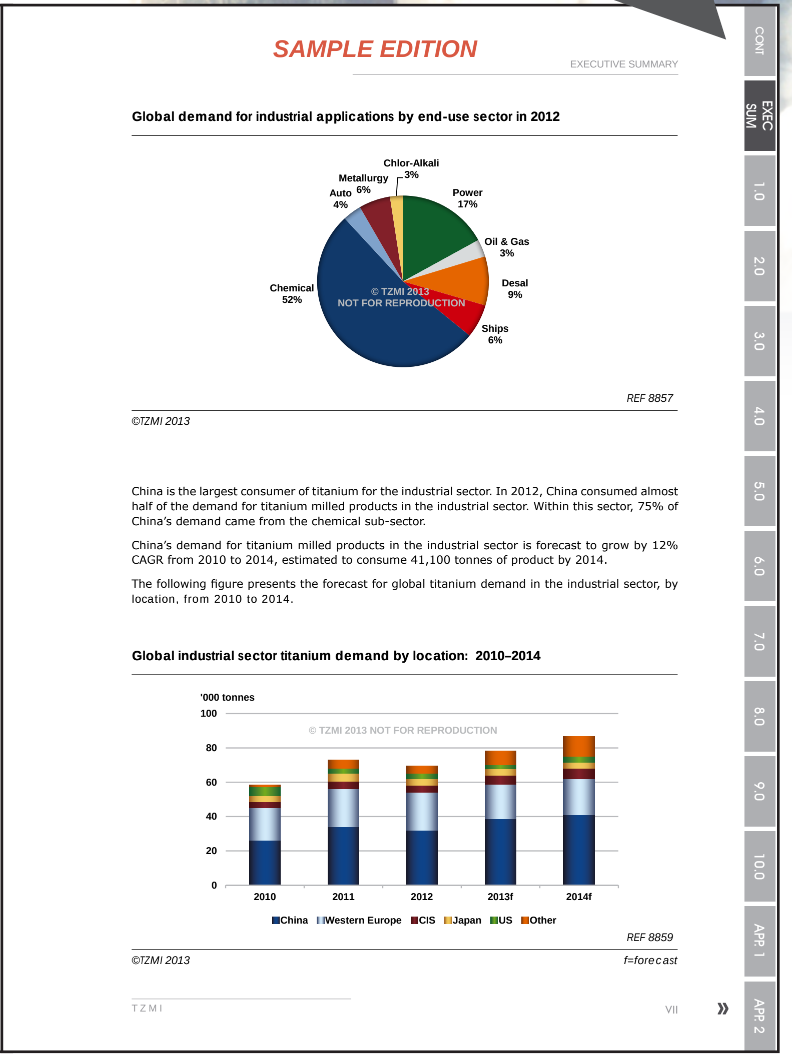

SAMPLE EDITION

EXECUTIVE SUMMARY

Global demand for industrial applications by end-use sector in 2012

REF 8857

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China is the largest consumer of titanium for the industrial sector. In 2012, China consumed almost half of the demand for titanium milled products in the industrial sector. Within this sector, 75% of China's demand came from the chemical sub-sector.

China's demand for titanium milled products in the industrial sector is forecast to grow by 12% CAGR from 2010 to 2014, estimated to consume 41,100 tonnes of product by 2014.

The following figure presents the forecast for global titanium demand in the industrial sector, by location, from 2010 to 2014.

Global industrial sector titanium demand by location: 2010–2014

REF 8859

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TZMI VII »