Journal Paper

Titanium: the innovators' metal—Historical case studies tracing titanium process and product innovation

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Synopsis

This paper examines innovation in relation to the availability of a new material: the metal titanium. The paper aims to highlight the need for the inclusion of entrepreneurial innovation as a necessary focus area in the development of a titanium metal value chain. Both the Department of Science and Technology (DST) and the Department of Mineral Resources (DMR) have identified the creation of titanium metals production capabilities as a key growth area for South Africa. Using historical literature as a source of data, the activities of selected innovators who used titanium metal as a central component in their success, were investigated. The origin of the process innovation behind the titanium metals industry, and two titanium product innovations: namely, medical implants and sporting goods, were detailed as case studies. It was found that individual innovators were responsible for the creation, and rapid growth, of the titanium industry and titanium product applications. There is a need to link the current research and development into titanium metals production with individuals and organizations capable of commercializing innovative processes and products.

Keywords

titanium, kroll, hunter, sport, medical, defense, innovation, entrepreneur.

Introduction

South Africa has abundant marketable natural resources, and is notably a major exporter of titanium-bearing minerals and a minor producer of processed titanium dioxide—used as pigment. When it comes to high-end titanium products, South Africa has no titanium metals industry and only limited capacity in titanium fabrication[1,2].

Titanium is a modern metal, commercially available only since the 1950s. Titanium has the strength of the best steels at only half the weight, is widely resistant against corrosion, and is biocompatible. Titanium is elastic and tough, hardly expands with increasing temperatures, and can withstand cold without becoming brittle. Importantly, for processing: it can be rolled, forged, and welded. Today titanium is associated with several technological advances in for example, medicine, and the aerospace and chemicals industries[2,3].

The establishment of a local titanium metal industry is a science and technology priority area for South Africa, with sustained efforts by government to support titanium-related research and development. The Department of Mineral Resources launched the Draft Beneficiation Strategy[4] for the minerals industry in South Africa in Midrand on 31 March 2009, which views the development of the titanium value chain (i.e. production of titanium pigment, metal, and downstream fabrication) as a potential key growth area for South Africa. Key points of the strategy aim at the development of a proprietary low-cost titanium metal production process, and the continued development and commercialization of technologies to compete cost-effectively in international titanium markets[4].

Considering that the national strategy for titanium is to markedly change existing technology, and to bring about an industrial revolution in low-cost titanium metal and products at both the national and international scale, it is deemed important to adequately understand the factors involved in the success of such innovations.

An aim of this paper is to introduce and highlight the function of individual innovators, who may be required to fully exploit new opportunities associated with the sudden availability of a new material, and to ultimately trigger significant positive socio-economic developments. The aforementioned aim is to be achieved through the identification

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and study of the entrepreneurs and innovators who, having made use of titanium, established associated markets and rapidly grew new ventures.

The reader should note that there is mention of research and development conducted in South Africa towards the establishment of an innovative low-cost titanium production process, i.e. the industry-sponsored South African Titanium/Peruke process, and DST supported development of CSIR titanium processes. The current strategic focus is therefore on process innovation: however, the delivery of low-cost titanium via an innovative process is also expected to unlock the potential for numerous product innovations, initially projected to be used in architectural and automotive applications. No further distinction is made between the unique requirements for process innovation, as per the first case study, and product innovations as discussed in the final two case studies.

The present article aims to address the following research questions:

- ➤ Does history indicate a relationship between the availability of a new material and technological advancement?
- ➤ Is there evidence to suggest that individual innovators were of primary importance in the establishment of markets for titanium?
- ➤ Can it be reasoned that South African strategy for titanium beneficiation should include efforts to develop and support innovation and entrepreneurship in this field?

Findings are presented in the form of distinct historical case studies, individually broadly outlining the emergence of the titanium metals industry and specific markets. This research is conducted to build a framework for the understanding of process and product innovation in the establishment of a titanium value chain. Such a framework may serve to assist decision-makers, researchers, and innovators in the identification and exploitation of opportunities for South African produced titanium and titanium products.

This paper has four parts. Firstly, it presents the method used in data gathering and building of case studies. Then a background section sets out to (a) establish the relationship between the availability of a new material and technological progress, (b) provide a brief overview of the metal titanium, and (c) infer the need for innovation and entrepreneurship in the creation of a new industry and markets for titanium. Thirdly, case studies are presented to establish the relationship between the innovator, innovation, and resulting industry/market for titanium. Finally conclusions are made and directions for future research suggested.

Method

For data on the relationship between titanium, innovation, and entrepreneurship, a literature search was conducted peer-=reviewed journal articles using combinations of the keywords Entrep*, Innova*, and Titanium. A study was also made of publications covering the history of the titanium industry, industry-standard market reports, as well as academic publications covering innovation. Case studies were compiled from publicly available secondary data.

From the initial literature search, the origin of the titanium industry and two well-documented and generally accessible titanium markets, namely medical implants and sporting goods, were selected for further analysis. In each of the two selected markets, details of the most prominent innovators and their respective applications of titanium were compiled as case studies. Literature searches were conducted in a reverse time-wise manner, starting with the most modern publications and tracing the history of titanium-based innovation to inception.

Background

Danish archaeologist and museum curator Christian Thomsen in 1816 defined the Stone, Bronze, and Iron Ages in an attempt to organize his museum's artefacts. In so doing he classified the stages of human development by the level of complexity of the materials employed. The fact that this method of classification has stood the test of time hints at an intimate connection between a society's level of advancement and the mastery of materials at its disposal. Thomsen's 'Three Age' system can be said to describe prehistoric variations of periods of technological revolution[5].

Austrian-born Professor of Economics at Harvard University, Joseph Schumpeter (1883-1950) identified cycles of technological advancement within modern history (Table I). These economic cycles were named after the Russian economist Kondratieff, who first proposed such cyclical activity. As with Thomsen's 'Three Age' system, each Kondratieff cycle can generally be associated with materials playing distinctive roles in shaping the respective technological revolution[6]. Similarly, the discovery and utilization of titanium can be seen to contribute to the characteristics of the modern technological age.

Table I

Schumpeter's Kondratieff cycles[6]

Cycle	Description	Material(s)
First Kondratieff (1780s–1840s)	Industrial Revolution: factory production for textiles	Cotton
Second Kondratieff (1840s–1890s)	Age of steam power and railways	Iron/coal
Third Kondratieff (1890s–1940s)	Age of electricity, chemicals and steel	Steel
Fourth Kondratieff (1940s–1990s)	Age of mass production of automobiles, petrochemicals and synthetic materials, Aerospace	Oil, Synthetics, Light Metals
Fifth Kondratieff (late 1990s)	Age of information, communication, and computer networks.	Semiconductors/silicon chips, composites and 'space age' materials

Titanium

As the fourth most abundant metal in the earth's crust, titanium ore is plentiful and widely dispersed over the planet. South Africa is currently the second largest producer of titanium-bearing minerals in the world, contributing 22% of the global output of roughly 6 million tons per annum[1].

Titanium has distinct physical and chemical properties which allow several industrial sectors to benefit from its application. Titanium's high strength to weight ratio is attractive to the aerospace and transport industries, its excellent corrosion resistance makes it an obvious choice in the chemicals, petrochemicals, and maritime industries, and biocompatibility allows for numerous medical applications[2,3,7].

Currently 95% of the titanium bearing minerals mined annually is used in the manufacturing of paints (TiO_2 pigment), paper, and plastics[1], and only 5% is converted to titanium metal[2]. The relatively small size of the titanium metals industry is due primarily to the difficulty and cost of commercial extraction and processing of the metal[2]. Illustrating this struggle to isolate the metal is the fact that, even though titanium was discovered in its mineral form in 1791 by English clergyman William Gregor, it was not until 1910 that the first small amounts of pure titanium metal were produced. Only as late as 1948 was a process finally commercialized, allowing limited-scale batch-wise production of the metal[8].

Titanium is not being utilized in the full range of potential applications, mostly due its high cost relative to aluminium and steel. Much of titanium's cost is due to the expensive and inefficient processes used in its production. Interestingly, a number of research projects in the pursuit of low-cost titanium production are supported/funded by the US military, with the goal to produce e.g. light, corrosion-resistant ships and armoured vehicles. Should production of low-cost titanium become possible, there is much potential for it to compete with e.g. the stainless steel mass market in most applications[2,3,7]. This potential is also acknowledged in South African efforts to develop cost reduction technologies for titanium processing[4].

Table II

Titanium Time Line[7]

Date	Event
1790	Rev Gregor discovers titanium in mineral form
1887	First preparation of impure titanium (Ti) metal
1910	Small amounts of Ti metal produced for General Electric.
1940s	Kroll develops process to commercially produce Ti metal
1950s	Ti used mostly in military aircraft/defence applications
1970s	Increase in orders for commercial aircraft and Ti market expansion
1980s	Ti increasingly used in medical implants
1990s	Ti increasingly used in sports and consumer goods applications
Present	Ti increasingly used in architecture, automotive, chemicals, etc.

The entrepreneur as Innovator

A key process in economic change, growth, and development is the process of innovation. Innovation can be defined as the exploiting of inventions to enable their trade in a marketplace[6]. Schumpeter[9] is credited with being the first to posit that cycles of economic growth and development did not simply occur, but required the entrepreneur as the prime mover, whose function is to innovate, or to carry out new combinations. Venkaraman[9] proceeds to quote Schumpeter at length, who stated that: '…the function of entrepreneurs is to reform or revolutionize the pattern of production by exploiting an invention or, more generally, an untried technological possibility for producing a new commodity or producing an old one in a new way, by opening up a new source of supply of materials or a new outlet for products, by reorganizing an industry and so on… This kind of activity is primarily responsible for the recurrent 'prosperities' that revolutionize the economic organism and the recurrent 'recessions' that are due to the disequilibrating impact of new products or methods'.

Schumpeter was not alone in identifying the entrepreneur as a central driving force in innovation; Herbig, Golden, and Dunphy[10] stated that 'Entrepreneurs and innovation go together like the proverbial horse and carriage. Entrepreneurs seek opportunities and innovations often provide the instrument for them to succeed.' The entrepreneur 'leveraging business and scientific knowledge… is therefore the linchpin of innovation, and if a society or locale wishes to generate innovation (either low or high technology), it is in a society's best interests to create an environment conducive to the entry and maintenance of entrepreneurs and the associated small new ventures that they produce.'[10]

There have been several instances where government/public enterprise acted as the drivers of innovation, usually in cases of capital-intensive developments. Notably, initial efforts towards the commercialization of titanium were made by the US government[9]. Similarly, the South African Department of Science and Technology, via the Advanced Metals Initiative (AMI), intervenes to progress development of advanced metals capabilities in South Africa. While acknowledging its vital role and importance, government-led innovation falls outside of the scope of the present article, which aims to focus on the contributions of individual innovators.

Case studies

The initial attempt at titanium innovation

In 1910 the General Electric Company (GE) was searching for a material to replace the short-lived graphite filaments used in the incandescent light bulbs of the day. The importance of filament materials in GE's overall success cannot be adequately measured, but according to Friedel and Israel[11] there were up to 22 other inventors active in the field of electric lighting at the time when GE's founder and classical entrepreneur, Thomas Edison, achieved a significant competitive advantage.

Edison made the discovery that a bamboo filament that had been carbonized could last up to 1200 hours, and could therefore be commercialized. As the original filament was patented in the 1880s, by 1910 GE realized that to maintain competitive advantage, they needed to lead, or keep up with, research into metallic filaments[8,11].

Of primary importance to metallic filament construction was the metal's melting point, and since titanium had yet to be extracted in commercially viable metallic form, its properties were unknown. GE was hoping that titanium metal would withstand the operating conditions required in a long-life filament. Titanium was found to melt at 1668°C by metallurgist Matthew Albert Hunter, who extracted the first samples. The process used by Hunter, using sodium metal to reduce titanium tetrachloride to titanium metal[7,8], still bears his name.

Rather than joining the Third Kondratieff as a critical part of Thomas Edison's light bulb, titanium was abandoned for the metal tungsten, which has a much higher melting point (3422°C). It took almost a further three decades before titanium found its primary innovator. GE can, however, be mentioned as a prominent part of the Third Kondratieff, that of electricity, chemicals, and steel, and has grown to be the 10th largest company in the world (in terms of market capitalization) with a published net income in 2007 of 22.2 Billion US dollars[12].

Case Study 1—William Kroll, titanium process innovator

In her book *Black Sand: The History of Titanium*, Kathleen Housley[8] provides numerous facts from history of the development of titanium metal. The book dedicates a number of chapters to discuss the work of William Kroll (1889–1973), a Luxembourg metallurgist who is today known as the father of the metallurgical processes for the production of zirconium and titanium. Kroll was already a seasoned metallurgist when he set up his private laboratory in 1923 in the city of Luxembourg at the age of 34. His first production of titanium via the Hunter process was in September 1930. In 1932 he travelled to America where he attempted to interest the likes of GE and Bell Telephone in the metal, without success. Steel was widely used, since it was in sufficient supply and produced commercially at costs that did not warrant interest in the new metal, titanium.

Kroll returned to his laboratory and started work on developing a new production method to replace the Hunter process, which was deemed explosive and not entirely suitable for commercialization. In 1938 Kroll manufactured titanium via a process using magnesium to reduce titanium tetrachloride[13]; the patented process still bears his name. In the same year Kroll made another visit to the USA in an attempt to interest companies in the metal, but again failed in attracting support from industry to commercialize his process[8].

In 1940, in order to escape the invasion of Luxembourg by the advancing German army, Kroll fled to America. Aged 50 and armed with only patents to his name and his personal belongings, Kroll started over in the USA. Due to World War II, the US congress tasked the US Bureau of Mines to secure and stockpile strategic and critical materials. Among these materials were titanium and zirconium, both of which could be produced via Kroll's patented process. Kroll was approached and offered employment by the Bureau of Mines, which he took up in January 1945. Within two years the Bureau had produced two tons of titanium via the Kroll process[8]. The Kroll process is widely known to be costly and inefficient; however, to date no other process has been able to supplant it, and nearly all international production of titanium metal still occurs via the Kroll process[2,3].

Since becoming commercially available, the largest industrial application for titanium alloy remains the aerospace sector[2,3]. To survive in these harsh environments, the materials from which aerospace components are made must have high strength and be capable of surviving high temperatures in an oxidizing environment with severe acoustic loads. However, the materials should have low density and, for most applications, must be reusable[14]. Titanium is therefore ideally suited for aerospace applications. It can be argued that, were it not for Dr Kroll's push to develop and commercialize a viable process for titanium production, the aerospace age might have lacked a component critical to its rapid development.

Case Study 2—Per-Ingvar Brånemark,titanium product innovator

Titanium is well documented as being biologically inert, primarily due to its resistance to corrosion; however, factors such as being non-allergenic and non-toxic also enable the 'fit and forget' attitude to titanium implants[15,16]. Being non-magnetic, titanium also interferes less with a form of medical scanning called magnetic resonance imaging (MRI), where even the low ferromagnetic properties of surgical steel could lead to distorted images[17].

The most important aspect of titanium's application in medicine was, however, discovered by chance. Working at Lund University in the 1950s, Dr. Per-Ingvar Brånemark used an ocular piece inserted into a rabbit's ear to visually study bone healing. It was found that after completion of the study that the costly instrument, constructed out of titanium, could not be extracted. Titanium was found to integrate and be structurally accepted by bone, leading Dr Brånemark to call the discovery 'osseointegration'. This property is virtually unique to titanium[18].

The use of titanium at the time of the discovery was coincidental, in Dr. Brånemark's own words: 'By coincidence, an orthopaedic surgeon, Hans Emneus, in Lund, was studying different metals used for hip joint prostheses. At that time I happened to meet him and he indicated a new metal, titanium, from Russia used in nuclear industry, that might be optimal. I managed to get a sample from Russia via Avesta Jernverk, Director Gauffin, and from there on it has been pure titanium. Initially we tried tantalum, which was too soft.'[19]

Dr Brånemark sought to take his discovery to the market and approached relevant technology companies to assist in the commercializing of titanium implants. In 1978 Swedish chemicals and defence company Bofors agreed to partner with Dr Brånemark to develop his implants. Bofors Nobelpharma (later Nobel Biocare) was founded in 1981. In 2008 Nobel Biocare achieved turnover of 619 million EUR and gross profit of 374 million EUR[20].

Considering that NobelBiocare was officially started in 1981, but the innovation that the company is built on had been under development since the early 1960s[16], it took around 20 years for Dr Brånemark to commercialize his discovery. Dr Brånemark's mentioned that a primary reason for this was that osseointegration was looked upon with mistrust, which prevented penetration of the idea[16]. Without Dr Brånemark's persistence the market for medical titanium implants might still have been dominated by less efficient materials.

Dr Brånemark's innovation led to the establishment of vibrant new markets, Sweden is today known as having one of the leading clusters of biomaterials companies in the world, where Rickne[21] reported establishment of 25 new companies in the field in the period 1978–1993.

Titanium is also utilized by some of the leading US biomaterials companies, such as world-leading spinal implants company AcroMed of Ohio, which was founded in 1983 by spine surgeon A. Steffee and businessman E. Wagner. Acromed's time from invention to innovation took around two years; however, it can be argued that osseointegration was already well researched at that stage[16]. Competing with the Swedish cluster, in the period 1978–1998 the US state of Massachusetts saw the founding of 30 biomaterials companies, followed by Ohio with 18 companies in the same period[16].

Case Study 3—Ely Callaway, titanium product innovator

Titanium is 40% less dense (mass per unit volume) than steel, yet it possesses a higher strength-to-modulus ratio than steel. The combination of titanium's weight advantage and its improved impact resistance and spring-back following loading has brought forth innovations such as titanium bedsprings, tennis racquets, and fishing rods[22]. One of the largest and fastest growing consumer markets for the metal, however, came from its use in golf clubs.

Ely Callaway, retired president of multinational textiles firm Burlington, founded Callaway Vineyard and Winery in southern California, which he sold in 1981 for $14 million. Aged 60, Callaway went on to establish The Callaway Golf Company in 1983[23]. In 1994, Callaway Golf went to market with a golf club incorporating titanium in its construction. With the 'Great Big Bertha' titanium driver, Ely Callaway promised 'a driver that is not only easier to hit for distance without swinging harder, but significantly more forgiving of off-center shots'[23].

Optimal golf club head design requires the use of a metal/alloy having the best combination of high modulus of elasticity and high strength-to-density ratio; Dahl, Novotny, and Martin[24] asserted that such attributes allows for a larger 'sweet spot' (centre of percussion) without adding unacceptable weight. The combination of an enlarged center of percussion and increased energy transfer enables the golfer to drive the ball a greater distance and straighter, without swinging harder.

The use of lighter weight titanium is also said to have opened up the market for female golfers, who were reported to have problems with the heavier stainless steel clubs[23]. Froes[25] noted that by 1999, in the driver and woods segment of the market 40% of the clubs produced were made of titanium, 59% of stainless steel, and 1% other materials; and amongst producers in this segment, Callaway had achieved market leadership (42%) followed by Taylor Made (35%).

Table III

US Titanium-metal woods sales[25]

Year	Clubs sold (millions)
1994	~500 clubs
1995	0.19
1996	1.16
1997	1.72

The reason for titanium drivers not completely dominating the market was price; titanium drivers were sold for prices upward of $500 in the USA and in the range of $600-$1800 in Japan, which was comparable to an entire set of standard golf clubs[25].

The popularity and cost of the drivers were such that in 1998 an organized gang of robbers started to target golf stores, specifically stealing Callaway Great Big Berthas and Biggest Big Bertha drivers. In two months the gang had broken into 25 golf stores and stolen an estimated 1 500 Callaway drivers and other woods[26].

In 2000, the US Golf Association (USGA) which oversees golfing competition in the United States, banned one of the Callaway club designs, the ERC club, based on their evaluation that its titanium head provided unfair advantage[27].

In an interview with Englade[23], Ely Callaway said: 'We went from the smallest golf company in the country in 1983 to the largest in 1995… It all was done on product. We make products that are the most rewarding in the world, products that are demonstrably superior to and pleasingly different from our competitors'. In 1997, Ely Callaway was inducted into Babson College's Academy of Distinguished Entrepreneurs[28]. Callaway Golf declared a $1.117 billion turnover and a gross profit of $486.8 million in 2008[29].

In what has been dubbed the Starbucks Effect[30], it has been observed that a trendy product can benefit the related market segment. The 1990s subsequently saw rapid growth in the overall use of titanium in the field of sport and recreation[31]. Beech *et al.* reported on the trend favouring titanium sporting equipment, observing that:

- ➤ The Mongoose Pro RX 10.7 bicycle's titanium frame weighed only three pounds, the high resilience imparted by the titanium frame was said to absorb shock better than other materials in use at the time
- ➤ Merlin VI SL titanium skis from K2 were both lightweight and claimed to produce less 'chatter' at speed than standard fibreglass and wooden skis, due to resiliency and durability of titanium
- ➤ Wilson's titanium line of golf balls reportedly increased ball sales by 50%. Wilson claimed that the titanium core offered a larger sweet spot, decreasing hooks and slices by three to four yards
- ➤ In October 1997 sporting company Head brought to market the titanium/graphite Ti.S2, which became the top-selling tennis racket worldwide.

Conclusions

This article investigated individual innovators and their use of a new material, specifically titanium, to establish new industries and markets.

History points to a relationship between availability of a new material and increased potential for technological and economic development. This relationship also proves to be accurate for the history of the development and commercialization of titanium metal and subsequent technological advances. Theory of innovation makes note of the entrepreneur, seen to be a driving force behind innovation. Entrepreneurs can be observed to e.g. innovatively use new materials, thereby causing technological change and economic growth.

The requirement for an innovator to unlock the potential of a new material has been shown in the histories of some of the leading figures in titanium production and applications: William Kroll, Per-Ingvar Brånemark, and Ely Callaway. From the case studies presented, it can be argued that without these individuals the required process and product innovations may not have occurred, and that the aerospace, medical implant, and sporting goods markets may not have undergone the revitalization and rapid growth set off by the introduction of titanium.

It is reasonable to expect that similar efforts will be required in the commercialization of the titanium technologies developed in South Africa's drive to beneficiate its titanium resources and create a titanium value chain.

The study is limited by the inclusion of only three successful and popularly published instances of innovation in titanium, and therefore cannot be considered conclusive. An investigation into the workings and potential integration of South African structures and systems for the development and support of entrepreneurship and innovation in advanced metals is perceived to be a valuable direction for further research.

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