The Potential Applications for Titanium Metal Powder and Their Life Cycle Impacts

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It has been predicted that new processes being developed for titanium metal production as well as new fabrication techniques will see the cost of fabricated titanium fall by as much as 50%. Potential applications for lower-cost titanium powder are examined in this paper, with cookware being identified as a possible lead product. The potential environmental benefits of using this material in place of competing materials such as stainless steel in chemical process equipment and automotive exhausts are also illustrated, based on a life-cycle approach.

INTRODUCTION

The combined properties of low density and corrosion resistance make titanium a desired material for many applications. However, its relatively high cost of production and fabrication has seen it largely confined to specialized high-value applications such as aerospace. Recent research aimed at reducing these costs has seen the development of more than 20 potential new processes for titanium metal production.[1,2] A number of these new processes, such as the TiRO™ process[2] developed by the Commonwealth Scientific and Industrial Research Organisation's Light Metals Flagship, produce titanium metal in powder form. By utilizing powder metallurgy (P/M) techniques to fabricate items directly from these powders, it is anticipated that the cost of fabricated titanium will be reduced further.

The worldwide production of titanium ingots was approximately 64,000 t in 2004, with the price of fabricated (i.e., mill products) chemically pure titanium being on the order of $13.60/lb. These cost-consumption figures are not too different from those predicted from the data presented by Froes,[3] as shown in Figure 1. Extrapolating the latter data suggests that if the cost of titanium falls by 50% as has been predicted[4–6] as a result of the new production processes and fabrication techniques referred to previously, the annual consumption of titanium will increase 220% to about 205,000 t/y.

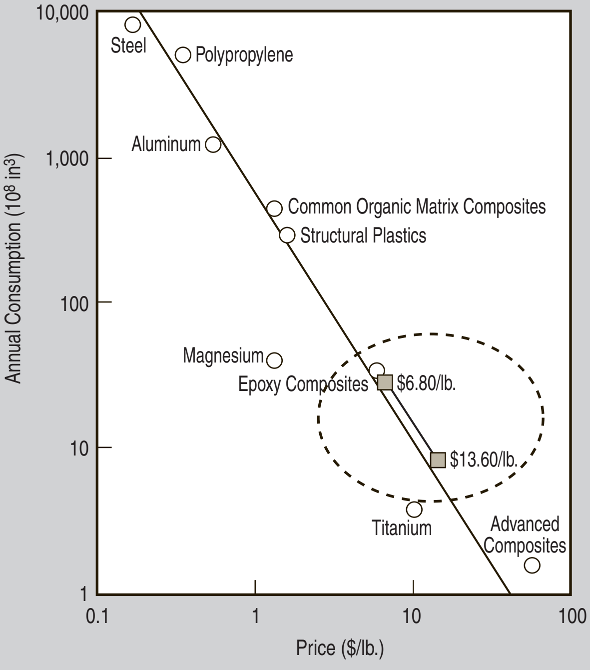

Figure 1. Consumption versus cost for various materials.[3]

Titanium metal is used widely in both its commercially pure (CP) form and in a range of alloys that optimize various properties as required for the intended end use. Highly weldable and formable, CP titanium generally has lower tensile and yield strengths than the alloys. Typically, about 30% of titanium mill products are used in CP form. Assuming a similar ratio applies in the future, this suggests on the order of 40,000 t/y of additional CP titanium could potentially become available, much of it in powder form.

See the sidebar for details on titanium's competitors and powder metallurgy.

APPLICATIONS FOR TITANIUM POWDER

It has been reported[11] that the expansion of aluminum use in the 1930s was helped by the huge increase in its use in manufacturing cookware and kitchenware, particularly teapots and kettles. A similar lead product has not yet been found for titanium, although some attempts have been made (e.g., golf clubs). An analysis was therefore carried out to identify applications that could potentially become a lead product for CP titanium. While new market applications for reduced-cost titanium metal powder can be anticipated, this was beyond the scope of the analysis. Instead, current market applications only were assessed, with a number of criteria used to rank the applications. These criteria were amenability to P/M-based fabrication, volume potential, and high profile. The criterion for the application to be P/M-based did not necessarily mean the product had to be produced directly by P/M (although this would be preferred), but rather that P/M had to be part of the production chain (e.g., the production of titanium sheet by P/M which is then used to manufacture other products by non-P/M methods).

The volume potential criterion was essentially aimed at excluding applications that consumed only a small overall volume of titanium, despite potential for a significant expansion in numbers. This is illustrated in Figure 2, which shows how the number of product items needs to increase as the mass of titanium in the product decreases for the same nominal titanium consumption of 40,000 t/y. For example, spectacle frames contain around 32 g of titanium; over one billion units would have to be sold compared to the 7–8 million that are currently sold annually worldwide. Although somewhat arbitrary, applications such as medical (e.g., hip) implants were included in the analysis while watches and spectacles were not.

A high profile ranking was taken to mean that the application was well recognized by the general public and created an image or impression that could be readily marketed. While the preference was for high-profile applications, medium- and low-profile applications were also considered. Following are descriptions of the five market applications identified as having the most potential for lower-cost fabricated CP titanium.

Automotive Exhaust Systems

Worldwide, approximately 44 million cars are produced annually. Of the automotive components currently made from CP titanium, most are used in exhaust systems. This application utilizes titanium's unique properties of corrosion resistance and light weight. The main competitors to titanium here are 304 and 400 series stainless steel, with a significant proportion of new motor vehicles now having stainless-steel exhaust systems. It has been reported that most newly registered vehicles in Northern Europe come equipped with stainless-steel exhaust systems. According to Froes et al.,[12] titanium exhaust systems last the lifetime of the car (12–14 years) while stainless-steel systems must be replaced after seven years. This is approaching the required lifespan factor of about 3 outlined earlier for titanium to be price-competitive with 304 stainless steel.

The lightweight advantage of titanium over stainless steel in this application adds further benefit to the use of titanium in place of stainless steel. A typical car exhaust system weighs about 20 kg, and weight reductions on the order of 40–50% have been reported[13,14] when titanium is used in place of steel or stainless steel. This results in a CP titanium exhaust system of about 11 kg, or a 9 kg reduction in car body weight. This weight reduction could be expected to give a reduction in fuel consumption of 0.04 L/100 km,[15] or about 80 L over a typical 200,000 km lifespan.

Based on the above numbers, if CP titanium penetrated only 10% of this

TITANIUM'S COMPETITORS

Assuming that the predicted 50% reduction in cost can be achieved by current technological developments in titanium metal production and fabrication, the projected price of fabricated titanium will be about $6.80/lb. This projected titanium price is compared with the current prices of some other competing fabricated metals in Table A.

In many corrosive applications, titanium is competing with stainless steel. Referring to Table A, and assuming in the first instance that equal volumes of metal are used, the lifespan of titanium would have to exceed that of 316 stainless steel by a factor of about 2 to be more cost-effective, while for 304 stainless steel the factor is about 3. Lifespan factors for titanium of this magnitude or greater are not uncommon in many chemical process applications. Furthermore, in many corrosive applications it is possible to use less volume of titanium compared to stainless steel (e.g., thinner wall thickness with lower or zero corrosion allowance), which would reduce the required lifespan factors further. In lightweighting applications, titanium has an advantage over stainless steel due to its lower density (4.5 g/cm^3 as compared to 8.0 g/cm^3). While the economic value of the reduced weight may be difficult to quantify in some applications, in the case of automobile components it can be quantified in terms of reduced fuel consumption, as discussed later in the paper.

Titanium (in alloy form) exhibits a higher strength-to-density ratio than stainless steel to 550°C, while CP titanium has a lower one.[7] Therefore, it could be anticipated that uses for CP titanium would involve applications utilizing its good corrosion resistance relative to other metals, and lightweighting applications involving low to medium strength (e.g., automotive exhausts and cookware). Lightweighting applications involving high strength (e.g., golf clubs) are better served with titanium alloys. Commercially pure titanium is the most extensively used form of titanium in industrial applications, as corrosion resistance is the principal requirement in all these industries.

An obstacle to more widespread application of titanium is its need for better adaptation to powder metallurgy (P/M) technologies. Powder metallurgy is a process for forming metal parts by heating (sintering) compacted metal powders at temperatures below their melting points. Powder metallurgy comprises several different technologies for fabricating semi-dense and fully dense components; the various technologies associated with titanium P/M have been described by Froes.[8] The development of titanium P/M has been slower than that of other metals for the following reasons:[9]

- The high reactivity of titanium makes it difficult to obtain unoxidized titanium powder of sufficient purity
- Metallic or non-metallic impurities, which will act as crack-propagation nuclei when the material is put into service, are more difficult to avoid with P/M
- Titanium tends to erode the conventional molds that are used in powder metallurgy

Furthermore, early work on titanium was plagued by the unavailability of suitable powder and a lack of understanding or appreciation of the differences between titanium P/M and conventional P/M (e.g., inadequate protection of the titanium during elevated-temperature processing).[8]

There are a number of titanium P/M technologies currently in various stages of development, the main ones being near-net shapes, powder-injection molding (PIM), laser forming, and cold spraying. Near-net shapes have reached commercial status, PIM and laser forming are at the pilot stage, and cold spraying is still only research-based.[8] More information on powder technology can be found in the powder metallurgy roadmap.[10]

Table A. Comparison of Projected Titanium and Current Fabricated Metal Prices

Metal	Price ($/lb)	$/in^3
Titanium	6.80	1.11
Aluminum	0.84	0.08
Steel	0.33	0.09
316 Stainless Steel	2.31	0.67
304 Stainless Steel	1.35	0.39

market, this would represent a potential demand on the order of 48,000 t/y worldwide. As this application is essentially for a single chemical environment, there is potential for CP titanium to fully replace stainless steel. This potential market volume would be further increased if motorcycles were included as well as automobiles. Approximately 800 t of CP titanium was used largely for motorcycle exhaust systems in Japan in 2003.[14]

Table I. Potential Market Applications for CP Titanium

Market Application	Volume (t/y)	P/M-based[a]	Profile[b]	Ranking Score
Cookware	39,000[c]	D	H	8
Medical Implants	1,000	D	H	7
Architecture, Building, and Construction	343,000[d]	I	H	7
Automotive Exhaust Systems	48,000[d]	I	M	6
Tubing	290,000[d]	I	L	5

[a] D = direct, I = indirect; [b] H = high; M = medium; L = low; [c] 50% replacement of stainless steel (North America and Europe); [d] 0% replacement of stainless steel

Cookware

Stainless steel, anodized aluminum, and aluminum are the dominant materials currently used in cookware. The market shares (by volume) of these materials in the United States in 2003 were 33%, 7%, and 48%, respectively, with the overall cookware market in the United States in that year worth some $1.9 billion. Stainless steel (type 304) is the most popular high-quality (so-called luxury or high-end) cookware material, and it is against this material that CP titanium competes in this application, albeit on a very small scale currently. The substantial overall cookware market share in the United States, held by high-quality stainless steel despite its higher price relative to aluminum, is reflected in the finding that price was only the third most important criteria for consumer cookware purchases. The top criteria are first, quality and second, features, with quality rated more than twice as important as price.[16]

Titanium cookware is reported to be particularly attractive because it:

- Does not leach metal into food as some aluminum and stainless steel cookware products allegedly do
- Is light weight and hence gentle on the wrist
- Provides fast heating response as greater strength permits the use of thinner materials—hence less energy to heat
- Is scratch and dent resistant

There seems to be little doubt that the superior qualities of titanium cookware would see significant expansion of this market if the cost of fabricated titanium fell by half. If titanium was to replace only half of the stainless steel used in cookware applications, the potential market demand for CP titanium in this application is estimated roughly to be 39,000 t/y for North America and Europe combined (by extrapolating United States data on a pro-rata population basis). Rising disposable income and desire for quality of life among Chinese consumers could also be expected to create additional demand for titanium cookware and add to this potential market volume.

Tubing

Unlike the previous applications, there is already an appreciable amount of CP titanium consumed in tubing applications. Approximately 6,200 t of CP titanium is used in steam turbine condenser tubes in power plants, while about 2,100 t is used in heat exchangers[9] (with half of this amount being assumed to be in the form of tubing for the purposes of this study). Desalination is a special application of titanium tubing, having a higher profile than either condenser tubes or heat exchangers. The desalination market for CP titanium tubing has been estimated at 1,100 t/y.[9] Welded titanium tube is available in outside diameters from 12.7 mm to 63.5 mm and wall thicknesses from 0.51 mm to 2.77 mm. Grade 2 CP titanium is generally considered as the workhorse in this application and is approved for pressurized service under the ASME Pressure Vessel and Boiler Code.

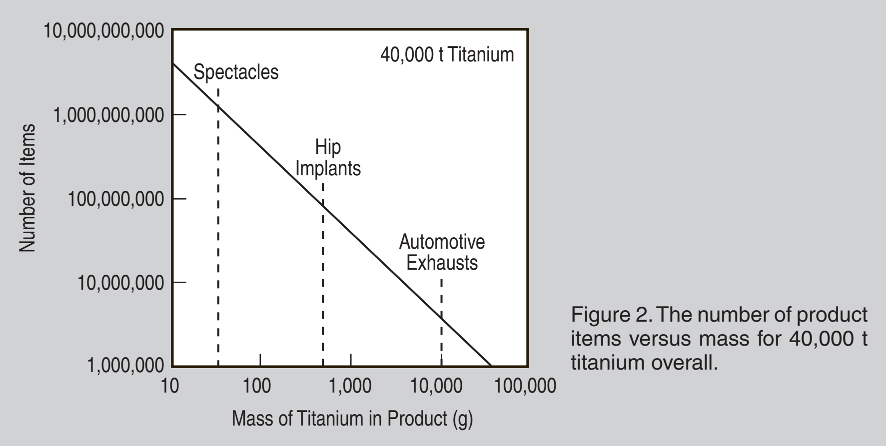

Figure 2. The number of product items versus mass for 40,000 t titanium overall.

As in the previous applications, CP titanium's main competitor here is stainless steel (typically 316 in many chemical applications). Titanium is already competitive with stainless steel due to its corrosion resistance and long life, which allows for a zero corrosion allowance. Hence, thinner-walled titanium tube may be substituted for other materials with thicker walls. For example, the lifespan factor of CP titanium relative to 316 stainless steel in 50–70% nitric acid is about 10, while for wet chlorine gas it is about 25.[15] For this reason, titanium and stainless steel tubing must be compared on a cost-per-unit length basis, not cost-per-unit mass basis.

Given that CP titanium already has a reasonable foothold in this application, it could be anticipated that the potential demand here could expand substantially at the expense of stainless steel if lower-cost titanium became available. However, the potential size of this market is not easy to estimate, as most of the required data regarding markets for stainless steel tubing are not in the public domain. The total amount of stainless steel produced in 2004 was 24,500,000 t[17] with tubing consuming 11.8% of this globally,[18] which corresponds to 2,900,000 t/y.

Unlike automobile exhaust system

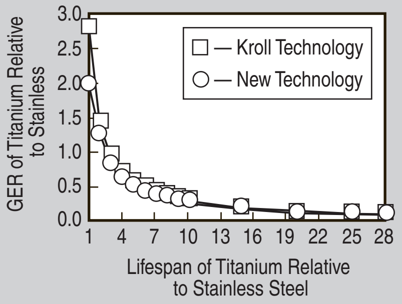

Figure 3. The GER of titanium chemical process equipment relative to stainless steel.

applications, tubing is used in a wide range of chemical environments and CP titanium tubing is unlikely to fully replace stainless steel tubing. If CP titanium was to make a nominal 10% replacement of stainless steel in this application also, the potential market demand would be about 290,000 t/y.

Medical Implants

The market for medical implants is one of the largest healthcare markets and is fast growing. Future growth is driven by technical changes (i.e., active implants and tissue engineering) and the social and economic changes in the developing countries, as well as changes in the age structure of industrialized countries (with the populations of various countries predicted to have 20–35% of over-65-year-old men in 2050[19]). Medical implants come in two groups: pacemakers and defribrillators (devices that regulate heartbeats) and orthopedic implants such as hips and knees. Approximately 850,000 hips and 450,000 knees are implanted per year worldwide.[20] The market for medical implants is one of the largest healthcare markets (on the order of $4–5 billion) with annual growth rates reported at 5–12%. Given that the total mass of a hip implant is on the order of 0.5 kg, and assuming a similar figure for knee implants, the total current annual use of CP titanium in orthopedic applications is likely to be about 650 t. This agrees with reported[9] global use ranging from 600 t/y to 1,000 t/y. At the upper annual growth rate, this consumption could be expected to double in about 6 years. This application on its own is clearly not going to absorb the projected increase in CP titanium production.

The competitors to CP titanium in this application[21] are 316 stainless steel, Co-28Cr-6Mo and Ti-6Al-4V alloys, CP tantalum, and alumina. While CP titanium is chemically and biologically more compatible with human fluids and tissues, its strength is less than half that of the Ti-6Al-4V alloy. For this reason, it is not used for prostheses that must bear heavy loads, such as leg implants. However, it has been reported that researchers have developed a process that increases the strength of CP titanium by 70% (using a two-step process combining equal channel angular pressing and cold rolling or cold extrusion), thereby making it suitable for prosthetic replacements.[22] This would create additional demand for CP titanium in this application as it is cheaper than the alloy. Furthermore, the small percentages of aluminum and vanadium (particularly the latter) in the alloy are potentially toxic and it could be expected that there would be a preference for CP titanium provided it is strong enough. Although 316L stainless steel has been widely used for many implants, it is now generally restricted to temporary implants due to problems with pitting and fretting corrosion. Tantalum also has excellent corrosion properties and biocompatibility, but its mechanical properties have limited its service. Thus, the main competitors to CP titanium are Ti-6Al-4V and Co-28Cr-6Mo alloys.

While CP titanium is chemically and biologically more compatible with human fluids and tissues, its strength is less than half that of the Ti-6Al-4V alloy.

Medical implants are largely produced by casting, rolling, and forging techniques. It has been reported[23] that while P/M is well-suited to the manufacture of medical implants, more trials are needed before powder-injection molded biomaterials gain acceptance as implants.

Architecture, Building, and Construction

Titanium is used in architecture, building, and construction (ABC) because of its low density and weight, attractive appearance, good corrosion resistance, and minimal maintenance needs. Titanium's corrosion resistance and other physical properties combine to allow reduced wall thickness, lowering its installed unit cost. Furthermore, its light weight means that it requires less massive structural support.

The current market demand for titanium in this application tends to be intermittent, although it is becoming more commonplace. It is used for railings, ventilators, domes, roofing, eaves and gables, interior and exterior decorative panels (cladding), wall curtains, and window frames. In Japan, titanium has been used in hundreds of buildings, mainly near the sea, because of the corrosive environment. There are a number of public buildings around the world with titanium cladding. Perhaps the most well-known of these is the Guggenheim Museum in Bilbao, Spain which has 35,000 m^2 of 0.38 mm titanium tile sheets weighing some 60 t. The French Titanium Association reports global use of titanium in this application currently to be 500 t/y.

Grade 1 and Grade 2 CP titanium are the two most commonly used grades for external cladding on buildings, with quality criteria of 0.18–0.25% oxygen and 0.03% nitrogen. However, it is probable that lower grades of titanium (e.g., Grade 4) can be used for internal architecture in buildings, in which case the oxygen and nitrogen quality criteria are 0.4% and 0.05%, respectively.

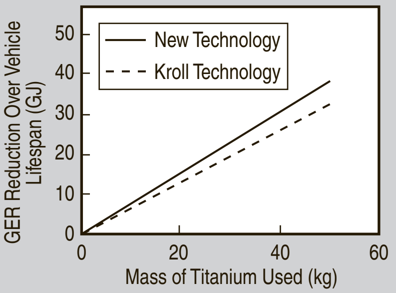

Figure 4. The GER reductions over vehicle lifespan.

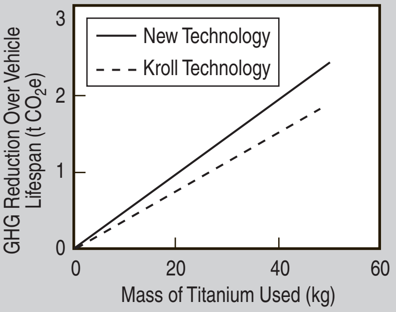

Figure 5. The greenhouse gas (GHG) reductions over vehicle lifespan.

Titanium, once again, largely competes with stainless steel in this application. It cannot compete with aluminum (e.g., window frames) due to the latter's low cost (see Table I). The types of stainless steel most commonly used in architecture are 430, 304, and 316. Type 430 is used in indoor, rural, or urban locations with little potential for corrosion. Type 304 is used in indoor, rural, or moderately polluted urban areas, while Type 316 is used in marine, coastal, industrial, and some urban locations. It has been reported[24] that the ABC industry globally consumes 14% of the world production of stainless steel, which corresponds to about 3,430,000 t/y. If CP titanium can achieve a 10% replacement of stainless steel in this application, similar to that assumed for automotive exhausts and tubing, the potential market volume is 343,000 t/y.

The potential market volumes for reduced-cost CP titanium powder in the five applications identified are given in Table I, along with the other two criteria (P/M suitability and profile) used to assess each application. Apart from medical implants, all applications have the capability of absorbing the projected increase in CP titanium production. The various applications were ranked by applying the following numerical weighting factors to these criteria, and the result is shown in Table I: volume >100,000 t/y = 3, 1,000–100,000 t/y = 2, <1,000 t/y = 1; P/M applicability D = 3, I = 1; profile H = 3, M = 2, L = 1.

Various combinations of weighting factors were used by the authors, with all essentially indicating cookware as the most likely candidate to become the lead product for CP titanium powder.

ENVIRONMENTAL IMPACTS

Recent concerns regarding the global environment and the sustainable utilization of natural resources has meant that products produced from these resources are now being assessed over their production life cycles to quantify their environmental impacts. One of the methodologies developed for this purpose is life cycle assessment (LCA). Life cycle assessment results for titanium metal production by the traditional Kroll process and two of the new processes[15] suggest that life-cycle-based energy consumption (i.e., gross energy consumption [GER]) for titanium metal production could be reduced by up to 30% with the new technologies. If, as expected, energy reductions also result from the new fabrication techniques, a projected 30% reduction in GER for fabricated titanium does not seem unreasonable, as the production and fabrication stages make the greatest contribution to the GER. These LCA results may be used to illustrate the life-cycle benefits of titanium compared to stainless steel in certain applications such as chemical process equipment and automotive exhausts.

> **When titanium is used for automotive exhausts, it provides a lightweighting benefit as well as a lifespan benefit, and this translates to a reduction in fuel consumption over the life of the vehicle.**

Figure 3 shows the GER of chemical process equipment made from CP titanium relative to that made from stainless steel as a function of the relative lifespan of the two metals. It should be noted that the values plotted in this figure are ratios on both axes. The assumptions made in making this comparison are: stainless steel is replaced by titanium on an equivalent volume basis (thinner wall design was not considered); GER for stainless steel production is 75 MJ/kg;[25] GER for titanium production (Kroll) is 361 MJ/kg;[15] primary energy required for equipment fabrication is assumed to be similar for both metals and is not included.

The GER for the titanium equipment becomes less than that for the equivalent stainless-steel equipment once the lifespan of the former exceeds that of the latter by a factor of about three. For a lifespan factor of ten the GER reduction ratio is about 0.28, while for a factor of 25 it is about 0.11. In the latter case the GER of the titanium equipment is only 11% of that of the equivalent stainless steel equipment. Examples of lifespan factors of this magnitude were given earlier.

When titanium is used for automotive exhausts, it provides a lightweighting benefit as well as a lifespan benefit, and this translates to a reduction in fuel consumption over the life of the vehicle. However, when considered on a life-cycle basis, this reduction in energy consumption during vehicle use must be offset by the additional amount of energy required for production of titanium compared to the stainless steel it replaces. While a complete cradle-to-grave LCA taking into account all raw material and energy inputs over the life cycle of the vehicle is strictly required in order to compare the two scenarios, some simplified calculations can indicate potential benefits. The assumptions made in performing these calculations are:

- Stainless steel is replaced by titanium on an equivalent volume basis
- The lifespan of a motor vehicle is 200,000 km
- The reduction in fuel consumption from lightweighting is 0.46 L/100 km for a 100 kg reduction in body weight[15]
- The gasoline calorific value is 34.2 MJ/L and the carbon dioxide emission factor is 66 kg CO$_2$/GJ
- Greenhouse gas emissions for stainless steel production are 6.8 kg CO$_2$e/kg[25]
- Greenhouse gas emissions for titanium production (Kroll) are 35.7 kg CO$_2$e/kg[15]
- Titanium exhausts last the lifespan of the vehicle, while stainless steel

ones last only half this time.

The results of these simplified calculations for the replacement of a stainless steel exhaust system with a titanium one are shown in Figures 4 and 5 in terms of GER and greenhouse gas emissions, respectively, as a function of the amount of titanium used. Both traditional Kroll technology and new technology for titanium production are shown in these figures. As outlined earlier, 11 kg of titanium is used in place of 40 kg of stainless steel over the lifespan of the vehicle, and Figures 4 and 5 indicate this would give reductions of about 7 GJ and 0.4 t CO_2e over the lifespan of the vehicle based on titanium produced by the Kroll process. These amounts could increase to 8 GJ and 0.5 t CO_2e with new technology. Even if only half of the new vehicles produced annually worldwide converted to titanium exhaust systems, this would amount to an annual reduction of at least 1.5 Mt CO_2e based on an average lifespan of 12 years.[26]

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