Global Titanium Mining and Processing

Environmental and Social Impacts



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History of Titanium

- Titanium was first discovered in 1791 by the British clergyman and amateur geologist William Gregor[1]
- In 1795, the German chemist Martin Klaproth named the oxide “titanium” after the Greek Titans, a mythical race of immortal giants with incredible strength and stamina[1]
- 100% pure titanium metal was first isolated in 1910 by chemist Matthew Hunter. Hunter’s difficult isolation process made titanium metal mainly a laboratory curiosity until 1938 when William Kroll developed a method (known as the Kroll method) to produce titanium metal in commercial quantities[1]
- Since the commercial production of titanium dates back only 70 years, it makes titanium a new metal compared with “common metals (e.g., Fe, Al, and Cu)”[2]

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Elemental Properties and Uses

- **The main properties of titanium (Ti) metal include extreme stiffness, lightweight, and high resistance against corrosion**[7]
- **For example, Ti is as strong as steel but 45 percent lighter, and it is twice as strong as aluminum but only 60 percent heavier**[1]
- It is therefore used in various fields such as aerospace, marine and chemical plant materials[7]
- The alloys of titanium with other transition metals also have widespread applications and are good alternatives for iron and aluminum[7]
- It is estimated that Ti6Al4V (6% aluminum, 4% vanadium) alloy is 50% of the global production of titanium metal[8]

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Elemental Properties and Uses (cont.)

- Titanium metal is used for prosthetic devices[9] because it is nonreactive in the human body[1] and bone will grow into properly designed titanium structures[9]
- However, almost **95% of titanium is not used to produce metal, but instead white TiO2 pigment**, for the paint, plastic and paper industries[7]
- TiO2 (in the proper crystalline structure) has the highest refractive index of any other inorganic pigment[10], which means that it has high light-scattering ability.
- As a result, TiO2 imparts whiteness, opacity, and brightness to many products[1]
- TiO2 is the most common white pigment in the world
- Thus, **this makes titanium different than most other metallic elements, in that it is mined primarily to satisfy demands for a chemical product (TiO2 for pigment) rather than for the pure metal itself**[11]

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Substitutability

- **There are no completely satisfactory substitutes for titanium, especially titanium metal.** Titanium metal's combination of corrosion resistance, excellent weight-to-strength ratio, and very high melting point is not found with other metals[11]
- Substitutes for TiO2 pigment, such as zinc oxide and others, generally result in an inferior product and are less environmentally safe[11]
- Although lead has similar whitening properties, titanium dioxide pigment replaced lead as a whitener because of public health issues related to lead toxicity[11]
- **On the other hand, Ti could partially replace stainless steel if its production cost could be reduced**[12]

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Why Geologists are Not Chemists (and vice versa)

- When chemists use the term dihydrogen monoxide, they mean the molecule H2O, which is commonly known as water. When they say titanium dioxide, they mean the molecule TiO2
- But when geologists use the terms rutile, anatase, or brookite, they are generally referring to TiO2, but instead are talking about different crystalline structures (polymorphs) formed by molecules of TiO2. Which polymorph we're talking about matters from an industrial standpoint - e.g. only (pure) rutile has the light refraction properties useful for pigments[11]
- And just to make things a bit more confusing, geologists don't always define terms like rutile that correspond just to one molecule. For example, monazite refers to a crystalline structure consisting of a mixture of molecules - e.g. elements such as Nd or Pr bonded with PO4

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Why Geologists are Not Chemists (and vice versa) (cont.)

- Similarly, while FeTiO3 is the typical “chemical formula” of ilmenite, its chemical composition is (40–65 wt.%) TiO2 and (35–60 wt.%) Fe2O3[13]
- For both rutile and ilmenite, the Ti can be substituted with other elements in the crystalline structure[14]
- And finally, note that terms like “rutile” sometimes are in fact referring to “natural rutile”, which is the form it is dug out of the ground as, along with all its impurities. Clearly this is not white pigment (what we commonly think of as TiO2)



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Abundance

- **Titanium (Ti) is the ninth most abundant element in the earth's crust** and can be found in nearly all rocks and sediments[3]
- It is the fourth most abundant structural metal[4] behind iron, aluminum, and magnesium[5]
- **In fact, more titanium is available than nickel, copper, chromium, lead, tin, and zinc put together**[6]

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Ores and Co-present Materials

- Titanium has been found in more than 140 minerals[15], but **only rutile (TiO2) and ilmenite (FeTiO3) have economic value**[16]
- **Due to the scarcity of natural rutile, ilmenite is now the primary precursor for the extraction of TiO2**[17] **and is the source about 90% of the world's titanium**[11]
- Fe and O are the primary co-present elements with Ti as part of the ilmenite structure
- Some other possible co-present elements include zircon (which is always found in association with Ti-rich minerals)[18], garnet[19], and occasionally uranium[11], arsenic, lead, and tin
- **They must all be removed during processing**[12]

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Why Isn't Titanium Used More Widely?

- **If titanium is has such amazing properties, a wide range of applications, and is highly abundant** — e.g. it is 5 times less abundant than iron and 200 times more than copper, however, its usage is 200 times less than copper and 2000 times less than iron[20] — … **so why isn't isn't it used more?**[12]
- **The number one reason is the cost**
- As such, titanium has been used to date only in industries where its properties are essential no matter the cost. This has limited titanium to applications in technically demanding sectors such as aerospace and biomedical[12]

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Why is Titanium So Expensive?

- While it is true that titanium is extremely dispersed in the Earth's crust[21], despite being abundant, **the primary reason is because of titanium's high affinity for oxygen (not to mention carbon, nitrogen and sulfur as well)**[22]
- **This strong affinity of titanium to oxygen means that it is very energy intensive and costly (not to mention, inefficient[7]) to produce titanium metal with the necessary oxygen content less than 2000 parts per million (ppm) to achieve its excellent metallic mechanical properties**[12], or to produce titanium pigments with the correct crystal structure, without contaminants.
- **As such, titanium is one of the world's scarcest and most expensive structural metals**[23]

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Mining Locations

- **The global titanium resources are concentrated, but the distribution is very uneven**[21]
- The titanium reserves of Australia rank first in the world, followed by China, India, South Africa, and other countries[21]
- **The titanium reserves of the top 13 countries account for about 97% of the world's total reserves**[21]

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Mining Process

- **Ilmenite and rutile are primarily derived from igneous ('hard rock') and sedimentary ('beach sand') mineral deposits**
- Mineralogy is essential for the mineability of titanium deposits[24]
- In sand deposits the Ti minerals are liberated by nature, and the mining can be done on low-grade sands if the Ti mineral is of a sufficiently high-quality[24]
- **In Norway, for example, high quality sands with only 1% rutile are economic and ilmenite sand deposits may be mined at approximately 5% ilmenite**[24]
- In ilmenite hard-rock deposits, however, the ore has to be mined, crushed and the ilmenite separated out by an expensive separation process; therefore ore-grade requirements will be high[24]

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Processing

- The production of titanium metal involves a number of complex steps to get from the raw mineral to a metal product[23]
- **The metal must be not only purified of the inherent contaminants, but also prevented from reacting with external contaminants**[23]

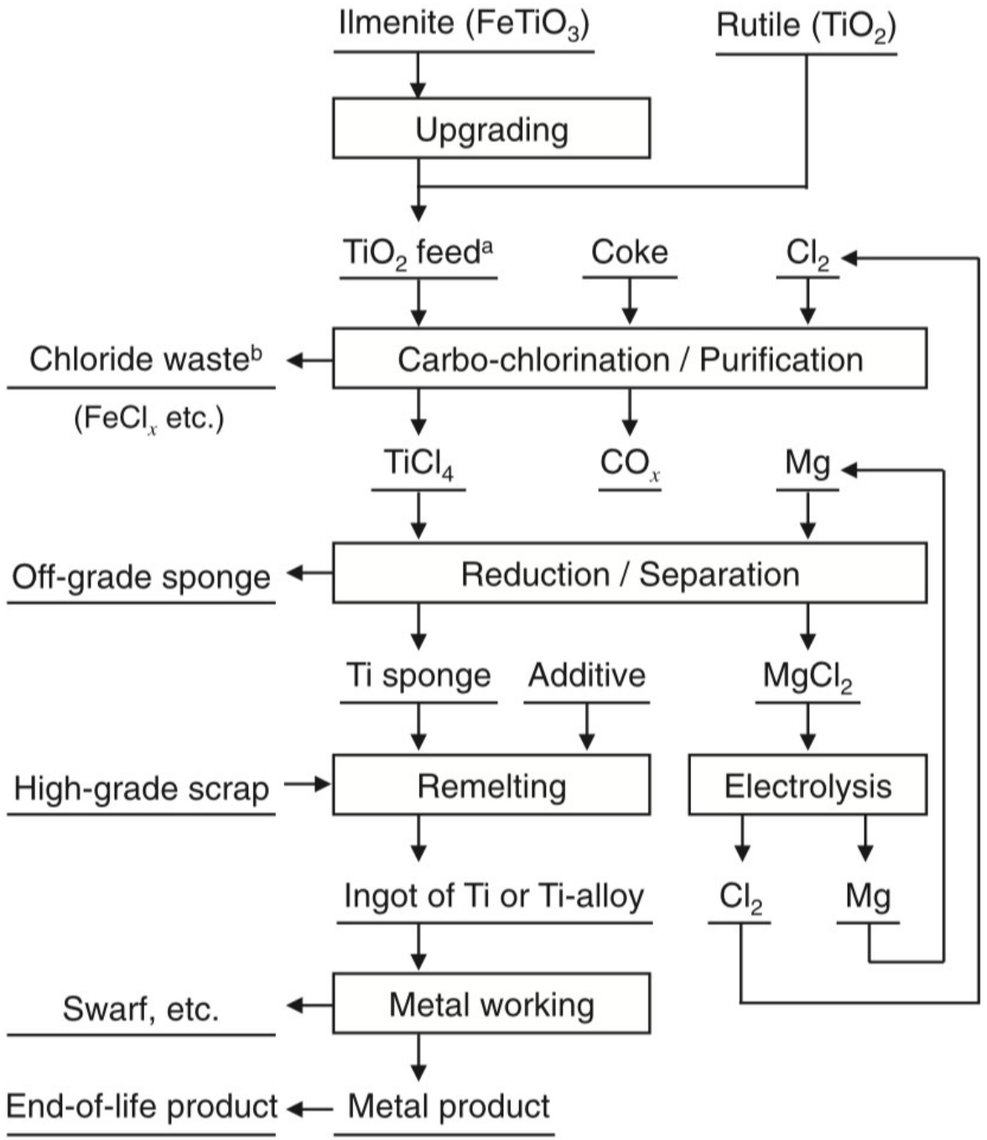


Fig. 1 Typical production process for metallic Ti products based on the Kroll process. [a]: Currently, the purity of this TiO_2 is about 90–95%. Lower grade feed will be used in the future. [b]: Impurities in the TiO_2 feed cause chloride wastes such as $FeCl_x$ and $AlCl_3$ to be produced. The generation of chloride waste results in chlorine loss in the Kroll process.

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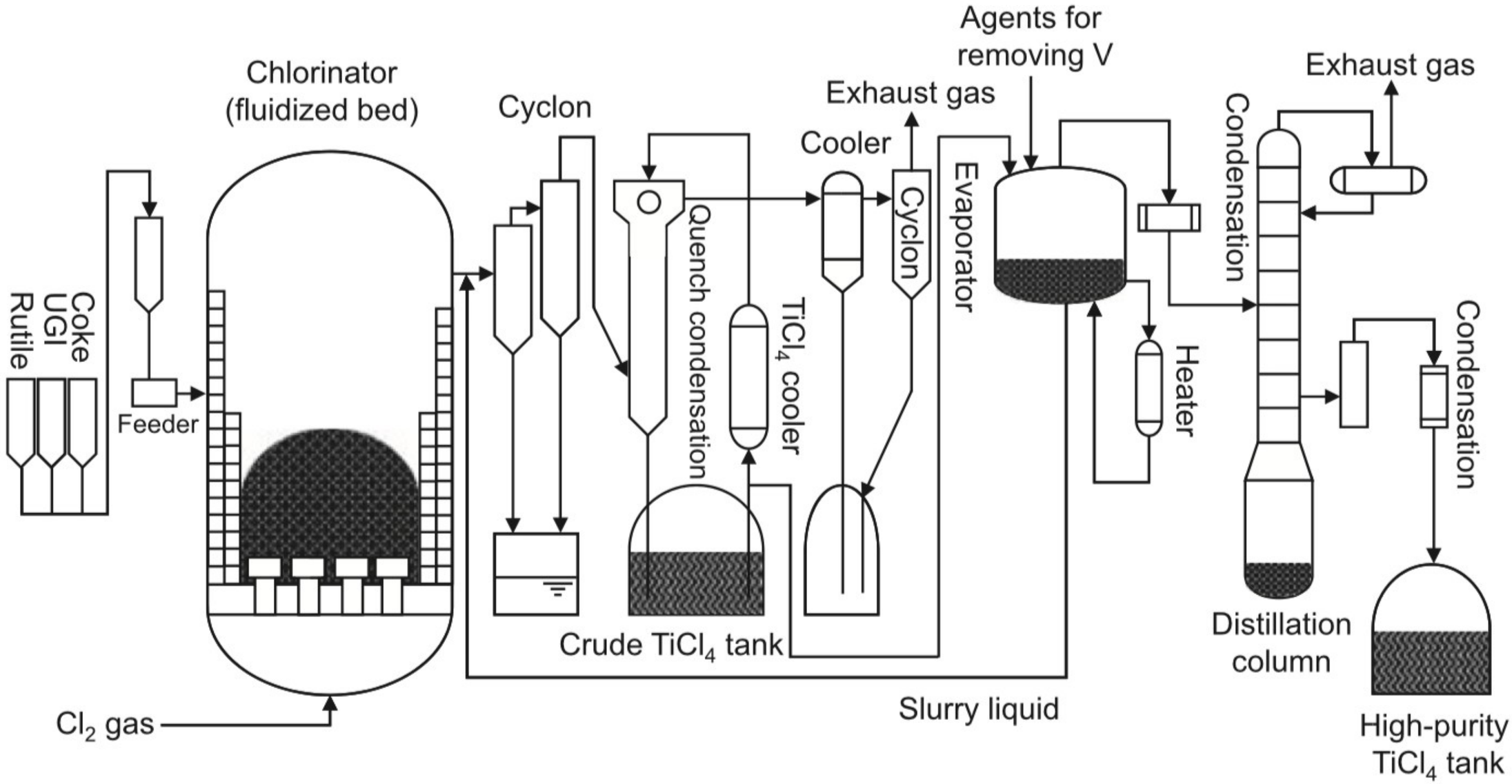


Figure 5.3 Schematic diagram of the carbo–chlorination process with integrated fluidized bed and distillation equipment [10,11].

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Challenges with Titanium Processing

- One of the challenges with the processing titanium, besides its reactivity with oxygen, includes **titanium adhering to the container during processing[12], elements like iron and nickel from the container walls becoming soluble in titanium and contaminating it**[12]
- In addition, **due to the relatively low density of titanium, some alloying elements tend to segregate and multi-step remelting is necessary to achieve full homogenisation of the final alloys at high costs**[26]
- This extensive processing means titanium metal costs are high when compared to e.g. stainless steel[27]
- **Although markets fluctuate, as a result Ti in general is at least 20 times more expensive than carbon steel and approximately 4–5 times more expensive than stainless steel**[31]

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Making Titanium Production Cheaper

- The cost of post-extraction processes (i.e., from ar melting to fabrication) accounts for 62% of the total cost for producing a titanium alloy plate[26]
- This high cost for any type of titanium productio means **significant research efforts have gone into improving the titanium production processes over 60 years**[27]
- Here are at least 10 options for processing titanium, but **over 90% today still uses route 2B, the Kroll Process**[25]

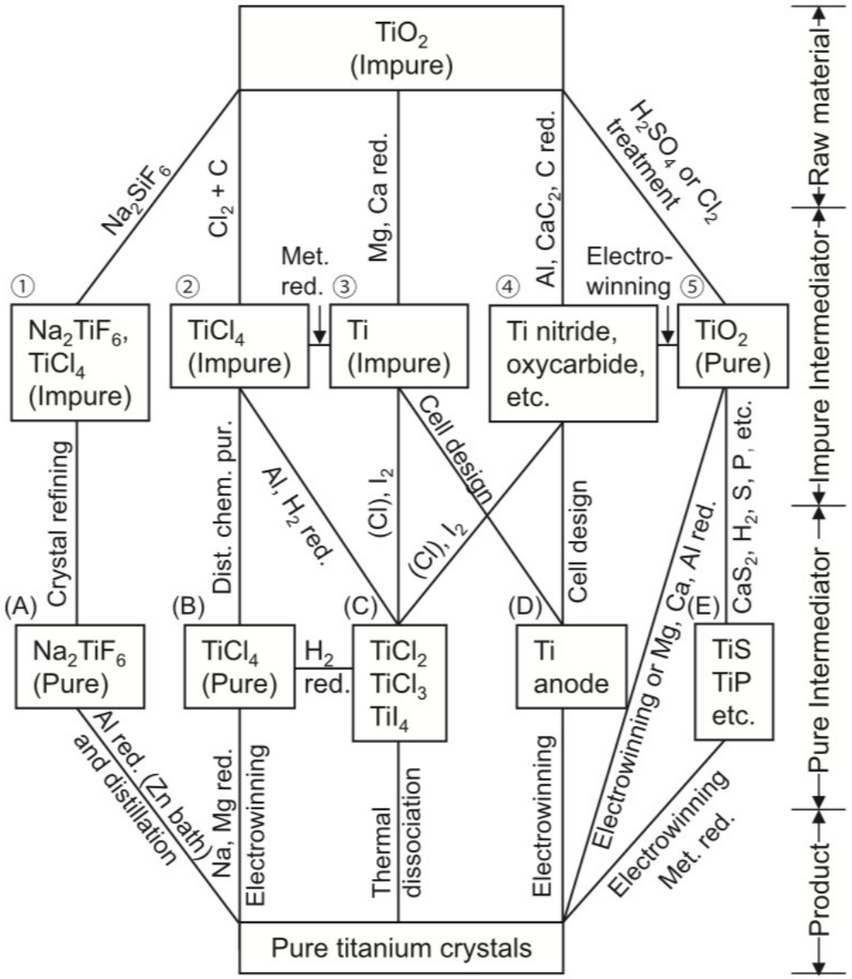


Figure 8.1 Possible titanium smelting pathway. Modified chart obtained from the original figures produced by Henrie,1968, and Hayes et al., 1984 [1–4].

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Machining

- Important alloys, such as Ti6Al4V, are extensively used
- Nevertheless, **titanium alloys present several problems in machining processes[28] due to its low thermal conductivity, low elastic modulus, and high chemical reactivity[4]**
- Lubricants and cutting fluids have traditionally been used to solve this problem. **However, this option is unsustainable as such lubricants represent a risk to the environment and to the health of the operator due to their different chemical components[28]**

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Waste

- **The unfortunate and unavoidable high cost of Ti is exacerbated in almost every step of manufacturing from mineral to products**[31]
- Normally, **about 10-20% of the produced sponge becomes off-grade as the feed** for the following remelting process[25]
- During aerospace component manufacture, **the majority of the forging is machined away with examples where 80-95% of a titanium alloy is disposed of as a low-value waste product**[29]
- There are two main methods for recycling this part of waste titanium: remelting recovery method and the molten salt electrolysis method[21]
- **Direct remelting recovery is the most economical and effective widely used method to recover waste. However, the O content of Ti waste is much higher than that of sponge titanium and needs to be deoxidized first**[21]

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Environmental Impacts

- **The major environmental issues of concern from titanium oxide mining are pollution of ground-water resources, mineral transport with heavy vehicles, dredging operations in fragile coastal areas and deforestation**[30]
- Titanium deposits and related waste products are usually sulfide-poor and generally generate near-neutral pH drainage after interacting with rain, surface water, or groundwater[11]
- **Therefore, acid mine drainage, which is a common potential problem for many types of ore deposits, is not a significant concern at titanium mines**[11]

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Heavy Metals, Tailings, and Radioactivity

- Although titanium may not be an environmental concern, other metals found in trace sulfides may be deleterious to the environment. Some metals, such as cobalt, nickel, and zinc, will remain in solution even at neutral pH[11]
- Nickel values have been reported from waters draining waste piles at the Lac Tio Mine [in Canada] at times exceeding U.S. and Canadian water-quality guidelines[11]
- Studies suggest that ecosystem health concerns from high nickel concentrations in mine drainage waters may increase as mine wastes weather[11]
- Mine tailings from Tellnes [in Norway] are almost inert and are nontoxic to marine life. Disposal of tailings underwater can lead to increased water turbidity, however, and, depending on the sedimentation rate, to the smothering of organisms living in bottom sediment[11]

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Heavy Metals, Tailings, and Radioactivity (cont.)

- **Independent studies of a titanium mine in Madagascar found elevated levels of uranium, and lead — 52 and almost 40 times higher than WHO safe drinking water guidelines respectively — in some parts of the waterways and lakes adjacent to the mine where approximately 15,000 local people fish and collect their drinking water**[32]

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Human Health Impacts of Titanium Itself

- Per the USGS, "**The EPA and the World Health Organization (WHO) have not established drinking water guidelines for titanium nor has the EPA established soil screening levels for industrial or residential land use for remediation purposes**. In fact, TiO2 replaced lead carbonate and lead oxide in paints in the United States because of its low toxicity to humans"[11]
- All studies on human health impacts of titanium found related to TiO2 pigment, not the metal. According to the USGS "Human health risks from titanium and titanium mining are minimal, [...] however **an exception to this is some industrial inhalation exposures to high amounts of dust during processing**"[11]
- A study in China **noted abnormalities in pulmonary function and pleural disease among people associated with titanium manufacturing**[44]

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Land Use Change and Water

- **In Madagascar, a titanium mine's planned clearance amounts to 80% of the Southeastern littoral forest.** The unique habitat and biodiversity has been significantly degraded with the decline in forest cover becoming one of the most acute threats to the ecosystem[33]. A small section was "conserved" for the purpose of "ecotourism" but with restricted access to local communities[34]. **In addition, those who rely on fishing have either seen their fishing stock reduced or denied access to fishing sites due to dam construction by the company**[33]
- Water is used for producing saleable Ti products, both in the mining stage as well as the processing stage.[14]
- In Vietnam, near a titanium mine, one resident stated that the **wells in the village had run dry, forcing residents to spend a hefty sum of money to dig new wells**[35]

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Energy

- **While it's understood that titanium is very energy intensive due to its processing requirements, there aren't any high-quality, global LCA studies calculating energy usage for titanium mining and processing**[14]
- In China, 2018 study results indicated that the electrolysis of magnesium chloride and the smelting of titanium slag accounted for 39.6% and 22.4% of the total impact of Kroll process, respectively. **The accumulative energy consumption of the titanium sponge production in China was 423 GJ/t**. Electric power accounted for 66% of the accumulative energy consumption[36]
- For more details on the data that would be useful for calculations of the impact of titanium mining and processing, see *Perks, Cameron (2022) - Using corporate sustainability reporting to assess the environmental footprint of titanium and zirconium mining*

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Artisanal Small-scale Mining (ASM)

- **There doesn't appear to be any significant amounts of ASM associated with titanium mining**, presumably because of the complicated process to even prepare the ore for processing

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Displacement

- On one hand, the local communities are convinced that they are the real owners of the land having been the first occupiers of it and no one has the right to dispossess them of their land (and the resources on it). Governments on the other hand use the doctrine of eminent domain to forcefully acquire private land for public use[37]
- Complicating the matter are land ownership titles. In Madagascar, just 10% of the Malagasy population hold official title to their land, with most holding customary land rights that are afforded a lower legal status despite having been held for generations[38]

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Displacement (cont.)

- The actions of the mining companies matter, too
- A study used satellite imagery and elevation data to show that the Madagascar Rio Tinto QMM mining operation had advanced 117 meters onto the bed of the estuary, in violation of the agreement that required a 50-meter buffer zone between any mining activities and the estuary[32]
- **After numerous denials by Rio Tinto that they had breached the buffer zone at all, Rio Tinto admitted that the QMM mine had advanced 90 meters into the buffer zone, or 40 meters onto the bed of the estuary. They called it "an unintended occurrence"**[32]

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Displacement: An Example from Kenya

- In 2007, over 3000 residents were displaced from their ancestral land in Kwale, Kenya, to make way for titanium mining[37]
- The Kenyan government offered a compensational package to the local Kwale community as a way of mitigating the impact of the displacement[37]
- However, these measures did not succeed in assuaging the disaffection of the displaced farmers[37]
- As a result, since the inception of the mining project in 2001-2 the local community has been in conflict with the government and with the extractive company over the mining project[37]

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"We love our land because unlike the developed countries that have industries, our land is our only factory. We do not look for employment because our farms are our employers. We depend on our land for rearing of animals and growing food, the produce of which we use to raise our children. Our land is our source of livelihood. Land belongs to the whole family and as such, we do not sell it as this will not only impoverish the seller, but it will also impoverish the generations to come. One therefore holds land in trust not only for himself and for his immediate family, but also for his clan and for future generations as well; and even for the dead."[37]

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“With our farms we could never go to bed hungry. But now our stomachs are grumbling like posho mill machines. We educated our children with proceeds from the farm but now that we have been deprived of these, some of us can no longer take our children to school – most of our children have dropped out of school and are in [the resort town of] Diani trying their luck in the tourist trade.”[37]

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“Now that they have chased us away from land, why can’t we have shares in this industry so that we can get dividends as happens in other companies where people have bought shares? Why do they have to cart away the raw materials for processing in foreign lands and hence robbing us of gainful employment? This processing industry should have been established here, don’t you think so?”[37]

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Recycling Rates and Sources

- At present, **many of these end-uses of titanium are non-circular and largely non-recyclable** (e.g. 90% of titanium minerals are used in pigment)[14]
- In addition, **the recycling of post-consumer Ti metal products is not currently important because Ti is mainly used for long-life products**. Although the demand is increasing, it takes time for them to go to scrap[12]
- **The nominal recycling rate, defined as the ratio of the statistical volume of Ti product scrap to the production volume of primary metal (Ti sponge), is quite low, less than 1%**[12]
- **The recycling rate of titanium, including cascade recycling, is estimated to be very high (above 90 pct)**[2]
- **Currently, less than 20% of titanium secondary resources can be recycled at the same level of quality**[21]

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Recycling challenges

- Direct remelting generally needs to be supplemented with other refining processes such as Electron Beam Melting (EBM), Plasma Arc Melting (PAM), and/or Vacuum Arc Remelting (VAR) in order to obtain a non-cacading recycled material[21]
- Each of these approaches has their own challenges and costs, not to mention energy consumption needs[21]
- For more detailed technical information on titanium recycling and recovery methods, see *Feng, E., Gao, D., Wang, Y., Yu, F., Wang, C., Wen, J., Gao, Y., Huang, G., & Xu, S. (2023). Sustainable recovery of titanium from secondary resources: A review. Journal of Environmental Management, 339, 117818. https://doi.org/10.1016/j.jenvman.2023.117818*

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Summary

- Titanium is a unique metallic element in that 95% of its extraction is to create a compound (the pigment TiO2), rather than metal itself
- Due to titanium's high affinity for oxygen and other elements, it is extremely complicated to process (and even machine) titanium into the metal with the properties it is known for (strong, lightweight, non-corrosive)
- The result is that while titanium is the 9th most abundant element in the earth's crust, it is not widely used due to its high cost of production. The process is also generates a lot of waste, and consumes a lot of energy
- The mining impacts of titanium are less related to pollution and more related to land-use changes and energy consumption
- Displacement of people for the establishment of titanium mines is common, and there are many documented protests around the world against titanium mining
- While recycling of Ti metal could be a better alternative to mining (unfortunately there aren't high-quality LCA studies available), some re-processing inevitably has to be done to produce high-quality titanium metal

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Thank you

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