Cost-Affordable Titanium: The Component Fabrication Perspective

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Titanium is the material of choice for a wide variety of applications. However, because of its relatively high price—a result of extraction and processing costs—it is used only when it is the only choice. This paper will overview the potential areas that are amenable to cost reduction for titanium products, emphasizing all steps in component fabrication from extraction and processing to the fabrication of final parts.

COST REDUCTION

The major thrust in titanium development has been aimed at achieving cost reduction rather than developing alloys with enhanced properties.[1] The cost of titanium compared to steel and aluminum is shown in Table I. Broadly speaking, cost reduction can come from either a reduction in the cost of production of the metal itself or from creative techniques for the fabrication of final components. Over the past few years there has been much activity in the area of reduced-cost titanium extraction processes. This is a result of new and developing applications such as armor and auto use where a cost reduction could significantly increase use. However, it must be kept in mind that in the big picture the cost of extraction is a small fraction of the total cost of a component fabricated by the cast and wrought (ingot metallurgy) approach (Figure 1).

The possible market penetration resulting from cost reduction is demonstrated in a study of the potential applications for commercially pure (CP) titanium metal powder conducted by T.E. Norgate and G. Wellwood.[2] This work assumed that there could be a 50% reduction in the cost of CP titanium (from \$13.60/lb) and developed the data shown in Table II for various applications. This represents a greater-than-1,100% increase in titanium use, which seems unrealistically high. However, it does demonstrate the great influence that the cost of titanium can have on the magnitude of applications.

Table I. Cost of Titanium—A Comparison*

Item	Material (\$/lb.) Steel	Aluminum	Titanium
Ore	0.02	0.01	0.22 (rutile)
Metal	0.10	1.10	5.44
Ingot	0.15	1.15	9.07
Sheet	0.30–0.60	1.00–5.00	15.00–50.00

*Contract prices. The high cost of titanium compared to aluminum and steel is a result of (a) high extraction costs and (b) high processing costs. The latter relates to the relatively low processing temperatures used for titanium and the conditioning (surface regions contaminated at the processing temperatures, and surface cracks, both of which must be removed) required prior to further fabrication.

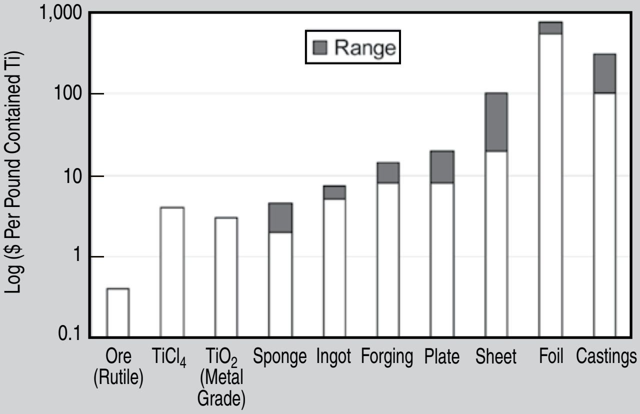

Figure 1. The cost of titanium at various stages of a component fabrication.

Figure 2 shows examples of consumer goods fabricated from titanium.

EXTRACTION

In a review at the International Titanium Association Conference in Scottsdale, Arizona (October 2005), of the various extraction processes under development in various parts of the world, E.H. Kraft noted that there are more than 20 new processes under development, many using the oxide as a precursor.[3] This makes sense as the cost of the contained titanium is less in the oxide than, for example, in the intermediate compound (in Kroll/Hunter

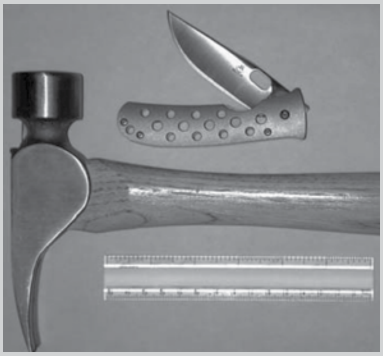

Figure 2. A titanium hammer head and knife handle. (Courtesy Stiletto Tool and Buck Knives, respectively.)

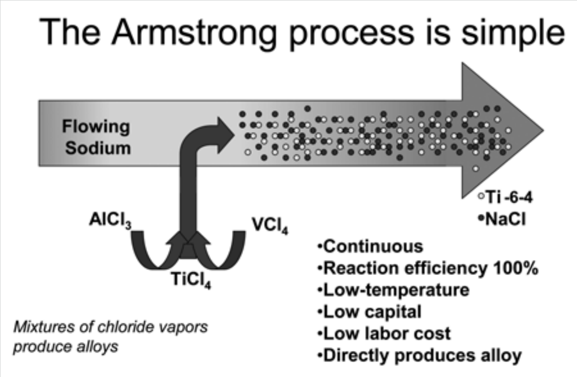

Figure 3. A schematic of the Armstrong/International Titanium Powder Process indicating the production of Ti-6Al-4V alloy powder.

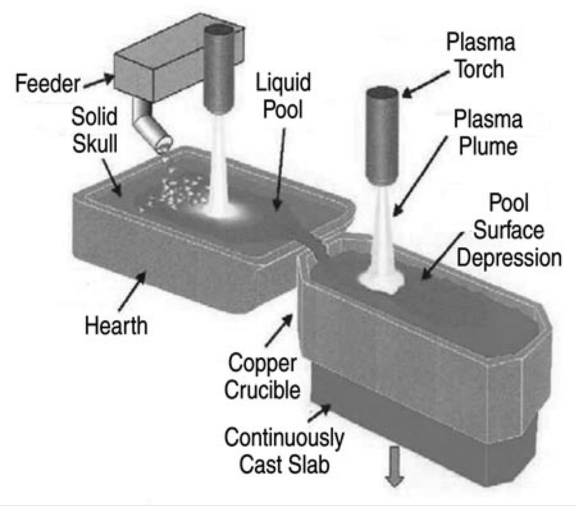

Figure 4. A schematic of slab casting by the plasma arc melting process.[8]

reduction) tetrachloride (Table III). He noted that the costs of providing adequate purity and morphology of oxides must also be considered, as should the potential of halide recycling. Kraft also pointed out that a number of the new processes could result in products that eliminate some of the current ingot metallurgy processing steps (Figure 1), hence giving a greater cost reduction than from lower extraction costs per se. Examples are the production of sheet and chunky shapes directly from powder.

The approaches mentioned by Kraft are shown in Table IV, and include four processes being funded by the Defense Advanced Research Projects Agency (DARPA). Among these processes the Fray–Farthing–Chen (FFC) approach has been quoted as capable of producing sponge for as little as \$1 per pound[4] compared to Kroll sponge at \$3.50 per pound. Another analysis of this method,[5] however, suggests a cost similar to the Kroll approach. Timet has experienced difficulties in scale-up of this process, but more promising results have been obtained by Norsk Ti.

The extraction process closest to commercialization is the Armstrong/International Titanium Powder (ITP) process (Figure 3), which is scheduled for scale-up to 4 million pounds per year by late 2007. Perhaps the process with the greatest potential is MER Corporation's process, projected to produce titanium for a cost of \$1.30 per pound. Whether any of these processes will mature to the point where it supercedes the Kroll/Hunter approach remains to be seen.

PRIMARY FABRICATION

In the melting arena, plasma arc melting (PAM) and electron beam melting

Table II. Potential Worldwide Market For Commercially Pure Titanium*[2]

Application	Volume (t/y)
Cookware	39,000
Medical Implants	1,000
Architecture, Building and Construction	343,000
Automotive Exhaust Systems	48,000
Tubing	290,000

*Assuming a cost reduction in titanium extraction and fabrication of 50%; emphasis on the powder metallurgy approach.

Table III. Cost of Titanium Precursors

Precursor	Cost (\$/lb)	Cost of Contained Ti (\$/lb)
TiO_2*	1.75	2.94
$TiCl_4$	1.00	4.00
Ti Sponge	5.44	5.44

* Metal grade

Table IV. Titanium Extraction Processes[3]

Techniques	Comments
FFC*	Oxide, electrolytic molten $CaCl_2$
MER*	Oxide, electrolytic
SRI*	Fluidized bed H_2 reduction of $TiCl_4$
BHP (Billiton, Australia)	Oxide electrolytic, pre-pilot plant
Idaho Ti	Plasma quench, chloride
Ginatta, Italy	Electrolytic, chloride
OS (Ono, Japan)	Electrolytic/calciothermic oxide
MIR, Germany	Iodide reduction
CSIR, South Africa	Electrolysis of oxide
Okabe-I, Tokyo, Japan	Oxide, reduction by Ca
Okabe-II, Tokyo, Japan	Oxide, Ca vapor reduction
Vartech, Idaho	Oxide, Ca vapor reduction
Northwest Inst. for Non-Ferrous Metals	Innovative hydride-dehydride
CSIRO, Australia	Chloride, fluidized bed, Na
Armstrong/ITP*	Chloride, continuous reduction with Na
DMR	Aluminothermic rutile feedstock
MIT	Oxide, electrolysis
QIT/Rio Tinto	Slag, electrolysis
Tresis	Argon plasma, chloride
Dynamet Technology	Low-cost feedstock

* DARPA funded.

Figure 5. A 33 cm × 86 cm × 127 cm slab cast in the furnace shown in Figure 4.[8]

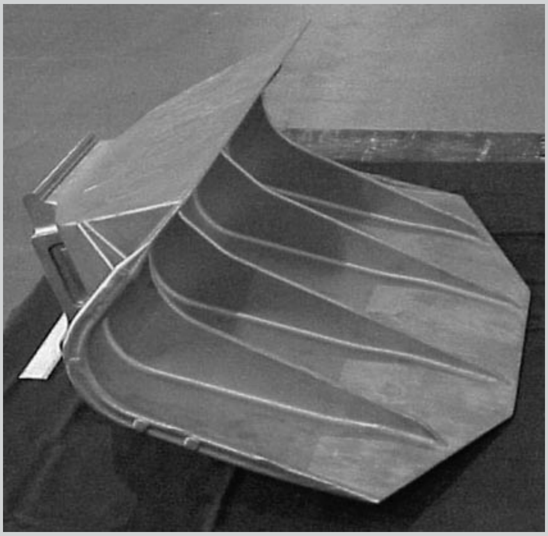

Figure 6. An investment cast Ti-6Al-4V M777 component.[12]

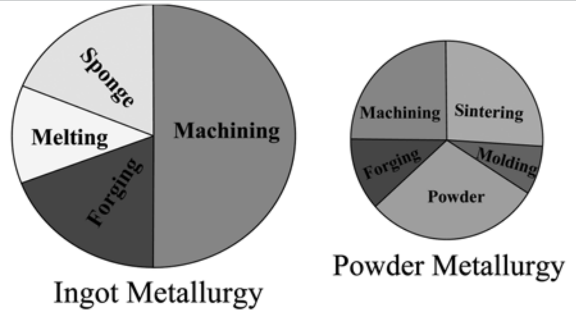

Figure 7. A comparison of the price of conventional ingot metallurgy product ("chunky" forging) with a powder metallurgy near net shape, not to scale.

(EBM) are cold hearth melting processes that provide the advantage of flexibility using various forms of low-cost input materials, leading to reduced costs.[6,7] Specifically, PAM and EBM offer the potential to make single-melt near-net shaped (NNS) slabs and ingots and currently the U.S. Army, Navy, and Air Force all have active programs in this area. Figures 4 and 5 show a schematic of the PAM slab casting process and an as-cast slab.[8]

These techniques also increase the time for which metal is molten, hence increasing the chance of homogeneity and removal of defects such as the type I species (oxygen-nitrogen stabilized). This latter effect is particularly important for rotating quality stock produced from alloys such as Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo-Si, and Ti-17.

NEAR-NET SHAPE PROCESSES

Castings

Castings are a cost-effective method of producing complex near-net shapes. Castings offer cost reduction by minimizing machining, reducing part count, and avoiding part distortion from fabrications such as machining and welding. Traditionally, the investment casting technique has been used for aerospace (mainly gas turbine engine) parts and rammed graphite castings for large chemical processing industry components. One recent excellent demonstration of titanium castings use is in M777 Lightweight Howitzer applications where fabricated titanium parts have been converted into unitized investment castings to reduce cost and distortions.[9–12] One good example of a cast component developed and implemented is shown in Figure 6.[12] This part reduced cost because 60 fabricated parts integrated into a single part.[11]

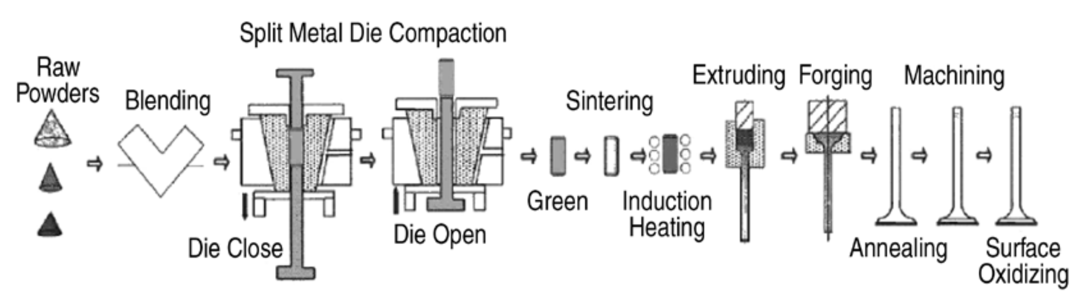

Figure 8. The processing steps for the blended elemental Ti-MMC engine valve production.[15]

Figure 9. Titanium MIM knife handles.

Figure 10. Titanium MIM parts.

Recently, low-cost metal mold titanium castings have been developed that exhibit finer grain sizes and much lower alpha case (oxygen-enriched surface regions). Already, variable blades for the F119 gas turbine engine (the power system for the advanced tactical fighter, F22) and automobile valves for Formula I racing cars have been made using this approach. At 1,500 shots per die the process is well beyond the break-even point to be profitable.

Powder Metallurgy

Powder metallurgy (P/M) approaches to production of near-net shapes have been explored in various parts of the world. Both blended elemental (BE) and prealloyed (PA) methods[4,13] have been investigated as techniques for production of cost-effective shapes (Figure 7). High-integrity P/M components have been produced via PA in the United States from both conventional alloys and the intermetallic TiAl, but with virtually zero commercial applications. Creative advances in the use of BE components in Japan have included the Toyota *Altezza* valves.[14] In the United States, hydrogenated Ti-6Al-4V leads to higher and more consistent densities. This can be achieved at lower cost by innovative direct production of hydrogenated powder.[4,13] This approach is also amenable to the incorporation of reinforcing particles into the titanium matrix (Figure 8).[15]

Another P/M NNS approach that is receiving increased attention is metal injection molding (MIM).[16] This process, developed from plastic injection molding, is capable of producing very complex parts generally less than 500 g in weight in large numbers (Figures 9 and 10).

Thus, while there is no widespread established titanium P/M industry as yet in the United States (or worldwide), this approach does offer the potential for cost-effective titanium compacts.

OTHER PROCESSES

Beyond casting and P/M products, other recent advances in the NNS arena include laser forming and, further into the future, possibly semi-solid processing and cold spraying. Minor perturbations to existing titanium alloy formulations—adding as little as 500 to 1,000 parts per million boron—have been shown to alter the intrinsic processing response of titanium alloys leading to a radical shift in the manufacturing process paths including dramatic reduction or elimination of ingot breakdown enabled by an order-of-magnitude decrease in the as-cast grain size, and relaxing constraints in secondary manufacturing processes resulting in lower cost titanium.

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