Enhancing the Use of Titanium for Novel Areas Spanning the Domains of Structural, Performance Critical and Innovative Applications in Engineering

Conference Brief

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Stark State College of Technology
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Preface

On April 22, 2008 the Ohio Transportation Consortium presented the conference, “Enhancing the Use of Titanium for Novel Applications Spanning the Domains of Structural, Performance Critical and Innovations in Engineering”, sponsored by Defense Metals Technology Center. Approximately twenty individuals from industry and academia attended the conference which addressed the past, present, and potential future uses of titanium in civil and mechanical structures. The goal was to advance discussion between titanium industry leaders and titanium researchers in regard to the production and use of titanium in place of other more commonly used metals. John Mountford, Director of Marketing for TICO Titanium, Inc. began by introducing the audience to the abundant advantages that titanium has over other metals such as copper, stainless steel, etc. noting that particular interest should be paid to its non-corrosive and shock absorbing characteristics. Dr. Srinivasan, Professor of Mechanical and Materials Engineering at Wright State University, then discussed the difficulties of extracting and processing titanium and addressed where future efforts need to be focused in order to reduce costs. Dr. Srivatsan, Professor of Mechanical Engineering, Division of Materials Science and Engineering, at The University of Akron, examined the many potential alloys and their positive and negative affects on titanium, admitting that certain alloys are more preferable for industrial titanium uses. James McMaster, Consultant on Titanium Application and Business Development for MC Consulting, concluded the conference with his presentation highlighting the many current applications of titanium both in the United States and around the world. He noted that Japan has been utilizing titanium in structures for many years and provided several slides demonstrating titanium’s artistic as well as practical functions. This collaborative approach provided for increased insight into the potential for future research and unique usage of titanium therefore increasing demand and ultimately production of titanium. The following pages provide a brief synopsis of each speaker’s presentation.
Introduction

Titanium has grown both in stature and strength to be recognized as a high performance metal for use in a spectrum of critical and non-critical applications spanning the diverse field of engineering. The newer generation of titanium alloys are recognized as being much stronger and lighter than the most widely chosen and used steels. Three of the most attractive properties of titanium are its high specific strength, outstanding resistance to corrosion in both aggressive aqueous and gaseous environments and superior ballistic properties. Titanium is frequently chosen as one of the primary candidates for aircraft structural parts and components of aircraft engines due to its high strength-to-weight (σ/ρ) ratio, and high stiffness-to-weight (E/ρ) ratio. Despite its superior mechanical properties, the structural use of titanium and the alloy counterparts has, through the years, been limited to performance-critical structures, such as; aircraft wing structures, skin-stiffened panels, armor, structural parts in navy vessels, and in the defense industry.

In an attempt to enhance the selection and use of titanium alloys for non-defense related applications, a study aimed at evaluating, understanding and rationalizing the strength, endurance and performance of structures made from emerging titanium alloys has been recently initiated at The University of Akron. Limited funding was provided by the Defense Metals Technology Center (DMTC) to perform this preliminary study on understanding the structural behavior of the emerging alloys of titanium.

The results of the preliminary study brought to light several important findings. Low cost and performance worthy emerging alloys of titanium have several structural applications that may be of interest to the US Army, U.S. Navy and U.S. Air Force. Recent advances in the extraction, processing, fabrication and joining methods have opened up potentially viable and economically affordable avenues for efficient and effective use of the newer titanium alloys in a spectrum of structural applications. There is a growing need to reduce part weight, cost of production of the structural part or component, and lead time, while concurrently facilitating enhanced performance of structural parts made from the newer generation of titanium alloys. These intrinsic material-related and production-related aspects synergize well with the efforts needed to reduce life cycle cost of the structural component of interest, stemming from sustained use and generous abuse, coupled with concerns arising from a lack of maintenance. To obviate these problems and concerns, the properties of the newer alloys can be tailored to suit an application through a careful control of the following: (i) alloy composition, (ii) processing history to include both primary processing and secondary processing, and (iii) intrinsic microstructural features of need and interest to the specific component.

Two of the new and emerging alloys of titanium are being considered for the purpose of evaluating the most viable structural applications with the objective of validating their overall usefulness in the defense and civil construction industry. A healthy synergy of theoretical analysis and experimental evaluation is being developed to comprehend the structural behavior and/or
response of titanium alloy members under both static loading and fatigue loading conditions.

Further research needs to be extended to study the potential applications of titanium alloys in the civilian non-defense engineering infrastructure sector. Corrosion has proven itself to be a major problem in steel-reinforced concrete and steel bridge girders and deck slabs. It is a well documented fact that the aging transportation infrastructure facilities in the United States are deteriorating at a rate faster than they can be rehabilitated or replaced. As of a recent count, among the nation's 590,000 highway bridges, 152,220 are rated structurally deficient or functionally obsolete and 73,160 bridges are rated as being structurally deficient. A routine replacement of such deficient structures is not feasible from the view point of economics. A few studies have provided estimates for the repair and rehabilitation of these bridges and range in cost from $212 billion to three trillion dollars. In response to this enormous engineering challenge, new materials and techniques are constantly being developed to repair and/or strengthen the existing structures so as to retain them in service and to concurrently prolong their service life. The emerging alloys of titanium are expected to have a tremendous influence in reducing the corrosion-related deterioration of bridges and other related structural elements particularly those members that are exposed to deicing salts and seawater exposure.

Future research will specifically focus on applications of the titanium alloys being developed and put forth for the construction and transportation infrastructure sector. Replacement of steel with titanium alloy hardware for critical elements such as gusset plates, bridge girder bearings, and inserts in precast concrete structural members is a viable solution without a significant increase in overall project cost. The overall suitability of the titanium alloys will be evaluated for applications involving both static and fatigue loading conditions. The synergistic interaction of the titanium alloy with the concrete mixture will be studied so that the appropriate alloys can be embedded within concrete and used as an attractive and viable reinforcement. Large scale tests will be performed using fabricated titanium alloy beams and columns. Finally, design guidelines will be developed for use of titanium alloys for such applications.
Titanium Properties As They Pertain to Its Use in Industry  
Presented by: John A. Mountford, Jr.,  
Director of Marketing,  
TICO Industries, Inc.

Introduction
This section presents an overall view of titanium as a metal, from the most commonly used grade chemistries, physical and mechanical properties, benefits, corrosion resistance (immunities), specifications and available products used for fabrications. Many industrial applications, industries and illustrated product examples are also shown as comparisons between titanium and other competing metals (stainless steel and copper-nickel alloys) to include the physical and mechanical property differences and weight savings.

The high strength / weight ratio of titanium and its corrosion immunity to all waters affords significant potential weight savings and maintenance reduction while providing life cycle cost savings and extreme life of products. Being non-magnetic, having a low elastic modulus and high shock tolerance adds to its attributes for use in defense and shipboard applications as well as for those in a multitude of industrial/commercial enterprises.

Chemistry
The chemical composition of Commercially Pure (CP) Grades 1, 2, 3 & 4 along with Alloy Grades 5 (6Al-4V), 23 (6Al-4V ELI) & 9 (3Al-2.5V) are tabulated in the presentation. A copy of the presentation is included in Appendix A.

Benefits
There are many benefits to using titanium in place of other metals. Titanium is virtually immune to seawater. It has a low density level which equates to a weight savings. Titanium has a high erosion resistance, up to twenty times that of Cu-Ni which leads to a reduction or elimination of maintenance. Titanium’s low corrosion rate makes it environmentally safe. When compared to similar metals, titanium provides a life cycle cost savings.

Mechanical Properties
Tensile strength, yield strengths and elongations of different grades of Titanium presented in the Table and the Chart (see Appendix A for details) compare favorable with stainless steel and Cu-Ni alloys.

Physical Properties
Elastic Modulus, Thermal Expansion Coefficient, Thermal Conductivity, Density and Hardness (RB) comparisons with stainless steel and Cu-Ni alloys in Table and Chart demonstrate that Titanium outperforms stainless steel and Cu-Ni alloys in many respects. Additionally, comparison of ratios of Yield Strength to Density demonstrate favorable performance of Titanium over other metals.
Other details presented (see Appendix A) were melting points and shock resistance.

**Properties & Benefits**

Titanium’s high strength-to-weight ratio results in both a size and weight reduction. Its low elastic modulus creates flexibility while its high shock resistance adds to the system integrity. This could prove advantageous in applications where mechanical or structure movement is high. Titanium is also non-magnetic which may increase its desirability over other magnetic elements such as iron, nickel, etc in certain environments. Titanium has a thermal expansion close to steel (HY 80 = 6.3). It is non-radioactive which results in a short half life and it is also non-toxic making it biocompatible.

**Corrosion Resistance**

Titanium is immune to seawater and all waters including polluted and brackish waters as well as microbiologically induced/influenced corrosion [MIC]. It is fully resistant to crevice corrosion, chlorides and stress corrosion cracking (SCC), pitting & cavitations, sulfides & gases. There is no tidal or splash zone corrosion. Titanium provides over forty years of trouble free seawater service in chemical, oil refining and desalination. It is not affected in the presence of sulfides, is immune to hydrogen embrittlement and is resistant to gases such as SO2, CO2, CO, NH4, H2S, and N2. Titanium’s corrosion resistance and immunity as compared to other metals can be seen in the table below.

**Corrosion Resistance**

<table>
<thead>
<tr>
<th></th>
<th>Cu-Ni</th>
<th>316 SS</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>R / S</td>
<td>R</td>
<td>R / I (&lt; 200°F)</td>
</tr>
<tr>
<td>Crevice</td>
<td>S</td>
<td>S</td>
<td>I</td>
</tr>
<tr>
<td>Pitting</td>
<td>S</td>
<td>S</td>
<td>I</td>
</tr>
<tr>
<td>SCC</td>
<td>S</td>
<td>S &gt; 140°F</td>
<td>I</td>
</tr>
<tr>
<td>Fatigue</td>
<td>S</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Galvanic</td>
<td>S</td>
<td>S</td>
<td>I</td>
</tr>
<tr>
<td>MIC (Microbes)</td>
<td>S</td>
<td>S</td>
<td>I</td>
</tr>
<tr>
<td>Erosion</td>
<td>S</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Weld / HAZ</td>
<td>S</td>
<td>S</td>
<td>R / I</td>
</tr>
</tbody>
</table>

*R = Resistant*, *S = Susceptible*, *I = Immune*

**Erosion Resistance**

Titanium’s tenacious, stable, ceramic-like oxide film provides an instantaneous re-healing characteristic. This provides superior resistance to abrasion, erosion, turbulence, impingement attack, erosion-corrosion, cavitations, and high fluid velocities (sea water: 90-120ft/sec, sand-laden: 15-20+ft/sec).
Specifications

Descriptions of the Specifications used for Titanium products:

- ASTM (American Society for Testing & Materials) “B”
- ASME (American Society of Mechanical Engineers) “SB”
- ANSI (American National Standards Institute) “B xx.xx”
- MSS (Manufacturers Standardization Society) “SP”

Industries and Applications

Many general-use products are currently constructed of titanium including:

- plate, sheet, bar, rings, flanges, seamless and welded tube and pipe, fasteners, fittings, forged and machined block, and machine screws. Titanium applications in specific fields include:
  
  (a) Power generation: condenser tubing; tube sheets (plate); heat exchanger; flue gas de-sul (FGD) liners stacks and ducts; service water piping, inlet water piping, nuclear waste disposal.
  
  (b) Offshore oil and gas: service water piping, fire main systems (piping, fittings, flanges); fire pumps, sprinkler heads, nozzles, valves; coolers – compressor, lube oil, engine; ballast tank systems and valves; heat exchangers – plate/frame and shell/tube.
  
  (c) Mining: mixers, autoclaves (high temperature/ high pressure), valves, shafts, piping, flanges, fittings, fasteners.
  
  (d) Navy and Marine: service water piping; fire main systems – piping, fittings, pumps; desalination units (high pressure); AC chillers and distillation condensers; HVAC ventilation ducting; engine, compressor and radar coolers; bilges and tanks; components – lights, electrical boxes, etc.

Weight Savings

Titanium’s low density level, 56% of steel and 50% of copper or copper-nickel, and nickel alloys, provides for significant weight savings. Thin wall tubing allows for zero corrosion and equates to thermal conductivity equal to that of copper and higher than stainless steels. Pipe allows for a decrease in OD and schedule (wall) sizes adding savings through fittings, flanges, connections, pumps, etc. The following example of an actual case design for Navy LPD 17 demonstrates the weight savings of titanium.

<table>
<thead>
<tr>
<th>Metal</th>
<th>H2O</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>8” Class 200 Cu-Ni</td>
<td>15.3</td>
<td>23.6</td>
</tr>
<tr>
<td>6” Sch 10 Titanium</td>
<td>5.3</td>
<td>13.8</td>
</tr>
<tr>
<td>Weight Savings</td>
<td>10.0</td>
<td>9.8</td>
</tr>
</tbody>
</table>

For every 100 ft = 1,000 + 980 = 1,980 lbs

- 90-10 Cu-Ni 8” Class 200 = 8.625” OD x .148” wall
- Titanium 6” Such 10 = 6.625” OD x .134” wall
Introduction

Titanium is the 9th most common element and the 4th most common structural metal on the earth’s crust. Titanium alloys continue to be vital for many important Defense systems due to their unique combination of excellent mechanical properties, light weight and corrosion resistance. High cost and exceptionally long processing times are major factors currently limiting their pervasive application. Manufacturing methods, which are controlled by the intrinsic metallurgical response of titanium alloys, contribute significantly to these limitations.

Pure titanium exhibits two different forms – the alpha phase which is stable at low temperatures has a hexagonal closed packed (HCP) structure and the beta phase which is stable above the beta transus temperature (~880°C or 1,620°F) has a body centered cubic (BCC) structure. The beta phase is more formable, while the alpha phase has higher creep strength. By alloying titanium with different elements, the temperature ranges over which the two phases are stable, can be modified. Alpha stabilizers, such as oxygen, aluminum and nitrogen, raise the beta transus temperature making the alpha phase more stable, while beta stabilizers, such as molybdenum, vanadium and iron, make the beta phase stable. Titanium alloys are classified as alpha, near-alpha, alpha+beta, near-beta and beta, depending on what phases are present at room temperature. The most common titanium alloy Ti-6Al-4V or T-64, contains both alpha and beta stabilizers, Al and V respectively, and is classified as an alpha+beta alloy.

Processing of titanium

The processing of metallic titanium can be broadly classified into the following stages:

(a) Mineral separation to produce TiO\textsubscript{2} from the ore (rutile or ilmenite): Roughly 95% of the TiO\textsubscript{2} that is produced is used in non-metal applications, such as in the paint, paper and cosmetic industry. About 5% of the TiO\textsubscript{2} is used to extract metallic titanium. This may not be the technology area where extensive cost reduction is possible because the economies of scale have already resulted in fairly inexpensive TiO\textsubscript{2}, and changes in the demand for metallic titanium will initially have little impact on the overall TiO\textsubscript{2} demand.

(b) Extraction of metallic titanium from the TiO\textsubscript{2}. TiO\textsubscript{2} is reduced with coke in a fluidized bed reactor and then treaded with chlorine to create a volatile titanium tetrachloride (TiCl\textsubscript{4}), which is separated by vacuum distillation. Kroll process to produce titanium sponge (liquid/gaseous processing). TiCl\textsubscript{4} is then reduced with liquid magnesium to produce a porous metallic product known as titanium sponge. The MgCl\textsubscript{2} produced can be reduced
back to metallic Mg and re-used. Armstrong process to produce titanium powder: TiCl₄ is reduced with sodium. TiCl₄ vapor is injected into a stream of molten sodium. The sodium flow rate is in excess of the stoichiometric requirements for sodium reduction of TiCl₄. The excess sodium cools the reaction products and carries them to separation stages, where the excess sodium and salt are removed. The reaction product is a continuous stream of powder. The benefits of this are low temperature, continuous, high purity powder that does not need to be refined like the sponge from Kroll process. Byproduct is NaCl.

DARPA-Ti program:
The DARPA Initiative in Titanium Program, now in its second phase, seeks to develop and establish revolutionary industrial production and processing methodologies and capabilities for titanium metal and its alloys. The overall goals of this program are to:
(1) Establish a U.S.-based, high-volume, low-cost, environmentally benign production capability enabling widespread use of titanium and its alloys
(2) Develop and demonstrate unique, previously unattainable titanium alloys, microstructures, and properties that enable new high-performance applications
(3) Develop meltless consolidation techniques that will provide low-cost billet, rod, sheet, and plate products that match the properties of traditional wrought titanium mill product. Currently, efforts are aimed to produce high-quality titanium at target costs of less than $4 per pound. Scale-up of these methods is under way.

(c) Melting and alloying to produce ingots of titanium alloys – required primarily for sponge produced by Kroll process. Vacuum Arc Remelting - VAR (conventional); welded electrodes of sponge + large scrap + master alloys are melted by striking an arc; liquid metal in a much localized melt pool; remelting to make composition uniform. New technologies include Plasma Arc Melting – PAM, Electron Beam Melting – EBM, Induction Skull Melting – ISM. These processes use different energy sources to produce a large amount of liquid metal in a water cooled copper hearth. The entire mass of metal is melted and therefore compositions can be made uniform in a single melt, rather than remelting as in VAR. Greater flexibility in the input material – can use small size scraps

(d) Primary processing or ingot breakdown: to create a fine grained stock for secondary processing. Ingot grain size can be a few millimeters to several centimeters. Primary processing involves a sequence of thermomechanical processes that may last 15 hours or more. Lead time can be large due to limited number of facilities

(e) Secondary processing: Forging, rolling, extrusion, casting etc. to produce finished parts.
Cost reduction opportunities

Opportunities for cost reduction are present at several stages of the titanium processing sequence. However, since much of the titanium alloys is made for the aerospace industry, strict certification requirements of this industry segment make the introduction of new processing technologies, such as alloy composition modification, difficult. These restrictions may not apply to land based applications, such as those of interest to the army, civil structures, or the transportation industry. Also, since the current market is fairly limited, costs tend to be high. The development of a large non-aerospace market for titanium may lead to significant cost reductions that could be achieved by the establishment of new production facilities and the scaling up current facilities. Specific developments that may lead to cost reductions are:

(a) Extraction: Armstrong process instead of Kroll
High purity Ti powder instead of low purity sponge

(b) Ingot Melting: PAM, EBM, or ISM instead of VAR
Single melt processes

(c) Primary Processing
Alloying element additions may reduce the grain size sufficiently to eliminate or substantially reduce the complexity of ingot breakdown
Example: Addition of 0.1 wt% Boron has been shown to decrease grain size in the as cast condition by an order of magnitude to about 200 µm, the same size that is obtained after extensive ingot break down processing of conventional titanium alloys that have no boron.

(d) Secondary Processing
The beta transus temperature dictates a great deal of the current primary and secondary processes. Processing above the beta transus enables high deformation rates and large total strains, but also produces coarse microstructures that degrade the mechanical properties and make subsequent processing difficult. This imposes significant constraints on process paths and also often demands narrow process windows. Relaxing the current barriers set by the poor microstructural response could have an enormous impact on the manufacturing methodologies used to produce mill and finished titanium products.
Minor perturbations in current titanium alloy formulations (addition of 500–1000 ppm boron) have been found to produce dramatic grain refinement in the as-cast condition, which could enable disruptive processing sequences to produce titanium components with significant reductions in cost and time. Promising results have been obtained on lab and pilot scale ingots (3" – 8" diameter) using established manufacturing regimens for conventional titanium alloys. The opportunity therefore exists for a focused effort to establish new manufacturing technologies optimized to take advantage of the unique benefits offered by trace boron modification.
Intricacies and Fascination of Processing-Microstructure-Mechanical Property Relationships in Titanium Alloys

Presented by: Dr. T.S. Srivatsan, FASM, FASME
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Department of Mechanical Engineering
The University of Akron

and

Mr. M. Kuruvilla
Graduate Student, Division of Materials Science and Engineering
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Introduction

Titanium is the ninth most abundant element, comprising in essence 0.6% of the earth’s crust. Further, it is the fourth most abundant structural material after aluminum (8.1%), iron (5.1%) and magnesium (2.1%). Of these four elements, only aluminum has a higher free energy for reduction of its oxide. Nevertheless, production of titanium metal in the United States to include recycling of the scrap is relatively low when compared to magnesium, aluminum and steel.

A few recent studies, encompassing a broad range and comprehensiveness, have documented the existence of a discrepancy in pricing and production volume of the metal and attribute it to the high reactivity of titanium. Titanium has a greater affinity for oxygen, nitrogen, carbon and even hydrogen. Even though the free energy of formation of titanium dioxide \((\text{TiO}_2)\) is less than that of aluminum oxide \((\text{Al}_2\text{O}_3)\), no smelting process similar to the one used for aluminum has been successful. The KROLL process technique and subsequent purification operations that are in use for the majority of titanium alloy production are energy, material and capital intensive. Consequently, the sponge produced sells for $4.00 to $5.00 per pound. A large fraction, in excess of fifty percent, of the titanium produced is used in aerospace applications. Further, since these are the most profitable applications, the requirements of the aerospace industry have dominated and even dictated the evolution, growth and use of titanium production technology. Stringent property requirements to ensure that the alloy meets acceptable performance levels have necessitated the need for a low level of microstructural defects. These requirements have created a need for melt processing either in vacuum or in an inert atmosphere. Double and even triple melting sequences are common. Mill processing, such as conversion of the ingot by hot rolling and forging, can only be carried out in air. Consequently, multiple conditioning steps are required for the purpose of removal of oxides and surface defects. The loss in yield coupled with the cost of secondary processing operations does contribute to over half the cost of both the plate and bar products.

A number of emerging technologies are currently focused on lowering the production cost of titanium. In the years ahead, widely available and low cost titanium could provide the developing countries with an affordable water desalination metal while concurrently aiding the sustainability of the aging population with implantable prostheses. With prevailing environmental guidelines
coupled with legislation paying an increased emphasis on a reduction in carbon emissions, there exists a growing need to reduce weight. The defense sectors, spanning the Air force, Navy and Army, would most certainly benefit from an availability of low cost titanium, as a viable replacement to steel in a wide variety of components. Initially, this could occur on (a) rapid deployment equipment, (b) lightweight tanks and armor, and (c) the heavy duty vehicles, for effective and judicious use in defense-related distribution. If successful and environmentally stable the automotive industry would also benefit from the use of titanium for a spectrum of applications.

Microstructure and Mechanical Properties of Titanium Alloys

The microstructures of titanium metal can be complex. They are the direct result of composition, processing and post processing heat treatment schedule. Essentially the mechanical properties of interest include tensile yield strength, the ultimate tensile strength, ductility, toughness, and cyclic properties to include both low cycle fatigue and high cycle fatigue, and crack propagation during fatigue loading conditions (da/dN) or under environmental constraints (da/dt).

The mechanical properties of the titanium alloys in the finished shape can be affected by one of several factors, or by a combination of factors to include composition. The key factors that must be considered are the following:

(a) Amounts of specific alloying elements and impurity levels
(b) Melting process used to make the primary ingot.
(c) Number of melting steps.
(d) Method of mechanically working the ingots to get mill products
(e) Steps in forging a shape
(f) Casting process and volume of cast article plus the use of densification techniques such as hot isostatic pressing to reducing casting porosity
(g) Powder metallurgy (PM) process to include the method of making powder
(h) Joining process used to fabricate a structure
(i) Post processing heat treatments or the final step employed in working or fabrication
(j) Machining processes and surface treatments

Knowledge of the Basic Properties of Titanium and its Alloys

Pure titanium can be strengthened appreciably by alloying, processing and post processing heat treatments, and the alloys continue to retain low density levels. Consequently, their mechanical properties are attractive, particularly with respect to ratio of strength-to-density. The physical properties of titanium are largely unaffected by processing. However, the kinetics of titanium beta-phase transformation that occurs during heating, cooling and aging strongly influences microstructural development and mechanical properties. Thus the mechanical properties of titanium alloys can be directly related to the processing and post processing heat treatment sequences.

The elastic properties of the alloys of titanium are affected by chemistry and texture, but they are not particularly affected by heat treatment. The modulus of titanium does vary with alloy type (beta versus alpha) from as low as 93 GPa up to
approximately 120.5 GPa. The modulus of titanium alloy is 50% greater than the modulus of aluminum alloys and approximately 60% of the modulus of steels and nickel-base superalloys.

The grain size, grain shape and grain boundary arrangements and orientation or texture in titanium have a very significant influence on mechanical properties. It is the intrinsic ability to manipulate the phases present in the microstructure as a direct result of alloy composition and the size, shape and orientation of the grains by a combination of primary processing and secondary processing operations that is responsible for the variety of properties that can be produced in titanium and its alloys. Transformed beta phase products present in alloys can affect tensile strength, ductility, toughness and cyclic properties. The basic strengthening effects of the alloying elements must be added to these effects.

The Static Properties of Titanium Alloys

The alloys of titanium not only have higher room temperature strength but they have the capability of retaining a much larger fraction of their strength at elevated temperatures. In terms of the principal heat treatments used for titanium, beta annealing of the alpha-beta alloys decreases strength depending on prior grain size, average crystallographic texture, and testing direction. Solution treating and aging can be used to enhance strength at the expense of fracture toughness in alloys containing a sufficient amount of the beta stabilizing element (i.e., 4 weight percent or more). There exists a significant difference among the titanium alloys in fracture toughness values. Transformed microstructures tend to greatly enhance the toughness while only slightly reducing strength. It is well known that toughness depends on thermo-mechanical processing to provide the desired structure. The fracture toughness value can be varied within a nominal alpha-beta titanium alloy by as much as a multiple of two or three. This can be easily accomplished by manipulating alloy chemistry, microstructure and texture. However, a tradeoff with other desired property may be necessary so as to achieve the high fracture toughness.

Within a permissible range of chemistry for a specific titanium alloy and grade, oxygen is an important variable as its effect on toughness is concerned. If high fracture toughness is required, the oxygen content must be kept low, all other things being equal. Reducing the content of nitrogen, as in Ti-6Al-4V ELI, is also good, but the effect is not as strong as it is with oxygen.

The Cyclic Properties of Titanium Alloys

Fatigue is characterized as cyclic degradation of the strength capability of a material. Fatigue damage depends a lot on alloy chemistry, the alloy structure, processing sequences used, surface treatment, the level of applied stress, and even the mode of application of the stress. The fatigue life of unalloyed titanium largely depends on grain size, interstitial content and degree of cold working. A decrease in grain size of unalloyed titanium has been observed to have a beneficial influence on cyclic fatigue endurance limit. The studies have observed
and documented the high cycle fatigue (HCF) limit of unalloyed titanium to depend on interstitial content just as tensile yield strength and ultimate tensile strength. The ratio of the endurance limit during HCF and tensile yield strength at ambient temperature appears to remain relatively constant because tensile yield strength changes with interstitial content while also showing a dependence on temperature.  

For the alloys of titanium in addition to the alpha grain size, degree of aging and oxygen content for the near-alpha and alpha-beta alloys, the fatigue properties are strongly affected by the morphology and arrangement of both the alpha and beta phases. Fatigue of the titanium alloy is far more dependent on microstructure than are the static properties. Most importantly, the key parameters of microstructure affecting fatigue of titanium alloys are the prior beta grain size or colony size of the alpha and beta lamellae and the width of the alpha lamellae in a fully lamellar microstructure.  

With specific reference to high cycle fatigue (HCF) the fatigue endurance limit tends to be relatively flat with temperatures up to 316°C or above. The superior performance of these alloys having a lower primary alpha content can be related to the absence of grain boundary alpha. Also the alloys of titanium have different fatigue crack propagation characteristics just as they have different $K_{IC}$ characteristics. Selected data does indicate that fatigue cracks propagate differently in different alloys and is dictated by a synergism of composition, microstructure and processing history. This can also be attributed to microstructural influences on strength of the alloy.  

**A Sample Case: The Properties of Cast Titanium Alloys**  
The cast titanium alloys are generally the alpha+beta alloys. They are equal, or nearly equal, in strength to the wrought alloys of the same composition. Through the years a number of cast titanium alloys have been studied in the as-cast form. However, much of the existing data in the published literature has been generated from the work-horse alloy Ti-6Al-4V. Consequently, the basis for most cast alloy property data is alloy Ti-6Al-4V. Further, because of the microstructure of the cast titanium alloy parts are quite comparable to that of the wrought (ingot metallurgy processed) material, many properties of the cast plus HIPed parts are at similar levels to those of the wrought alloys. These properties include tensile strength, creep strength, fracture toughness and fatigue crack propagation resistance. The properties of the Ti-6Al-4V alloy castings generally meet the properties of beta-annealed, forged wrought (ingot metallurgy) products, the forged microstructure has superior HCF properties. The forged products typically are processed in the alpha-beta phase field, yielding a refined alpha-beta microstructure that offers good fatigue resistance. By contrast the castings tend to cool slowly from the beta phase field, producing as a result a coarse microstructure. This is aggravated by the additional coarsening that occurs during HIP. Generally a noticeable improvement in cyclic fatigue resistance is gained by HIP of the cast material. This occurs by the closing or reduction of pores that are potential sites for fatigue crack initiation and failure. Also, substantial improvement in resistance to fatigue crack propagation can be
obtained by beta heat treating and over aging of the cast titanium alloy. The actual growth rate of the fatigue crack is influenced both by casting quality and by post cast heat treatment to include HIP.

**Important: Considerations in Processing and the Role of Cost**

Efforts to reduce the cost of titanium and titanium alloy products have continued practically uninterrupt ed since the initiation of the industry into the commercial zone. Sustained progress has been made in improving the efficiency of the conventional processing route, and in the development of technically viable processing alternatives. However, none of these efforts have attempted to provide a pricing that approaches that of the competing materials. In more recent years, there has been a renewed resurgence of interest in developing technically viable processing routes for the production of titanium and titanium alloy products. Much of this effort has been directed at alternatives to the ingots cast from double and triple vacuum arc re-melted Kroll process.
Applications, Fabrications, and Practical Issues of Titanium Use in Civil Structures

Presented by: James A. McMaster
Consultant
MC Consulting

Introduction
Titanium has only been used in engineering applications since about 1950 and initial applications were in strength to weight applications in aircraft and engines, space craft, missiles, etc. Some industrial applications have been in environments that are the most corrosive such as wet chlorine and seawater. Industrial corrosive applications continue to grow as titanium cost relative to other materials continues to drop. In industrial corrosion applications, tubing and sheet for transfer surfaces were some of the first large scale applications. Thin sections took advantage of the important surface characteristic of titanium (corrosion resistance) with minimum material weight. Early large scale applications utilized thin sections and avoided welding.

Titanium Fabrication
Standard metalworking tools used for steel or stainless steel can be used for titanium. Plates can be formed on a brake or rolled to cylinders or cones, bars can be formed or rolled, and hemispheres and other dome shapes can be pressed or spun. Ductility limits some fabrication details. As for fabrication, thermal cutting (oxygen, plasma, and laser) leaves a contaminated edge; however, waterjet cutting and newer processes like electron beam and laser can be readily adapted to titanium. Superplastic forming allows for complex shapes and repetitive details allow for mass productions techniques such as stamping and drawing.

Titanium Applications
Titanium can be used to eliminate corrosion problems for many applications in nearly every industry.
(a) General chemical plant: columns, vessels, towers, heat exchangers, pipe systems, mixers and agitators, pumps, centrifuges, spargers, screens and filters.
(b) Chemical intermediate production: equipment for terephthalic acid for reactor liners, agitators, piping, and heat exchangers.
(c) Chemical transportation: MC 312 Chemical Trailer Tanks, appurtenances, and portable tanks including U. N. containers.
(d) Pulp and paper equipment for bleaching: bleaching towers, retention towers and tubes, drum and diffuser washers, washer vats, mixers, pumps, stock transfer pipe, liquor pipes, scrapers, evaporator tubes, vessels, exchangers and piping for chemical preparation (chlorine dioxide) can be made of titanium.
(e) Chlorine and chlorate manufacturing: anodes and anode components, cell covers, piping, heat exchangers and vessels.
(f) Petroleum refining: heat exchanger tubes, tubesheets, shells and heads, piping, tower internals.

(g) Oil and gas production: equipment for offshore, deep well and sour well service including tubulars, riser pipes, downhole equipment and instrumentation, heat exchangers, piping.

(h) Geothermal energy and brine: production tubulars, downhole equipment, heat exchangers, piping for geothermal energy and brine.

(i) Electric power generation: condenser tubing and tubeplates, and waterbox linings for sea water, brackish and polluted water service, ancillary equipment like oil and bearing coolers, breech and stack lining for flue gas desulfurization systems and fans and housings.

(j) Sea Water Distillation and Salt Production: include heat exchangers, evaporators, piping, and brine systems.

(k) Marine hardware: shipboard piping systems (fire water systems), deep diving submersible hulls and structural components, propellers, pressure tanks and bottles, electrical connector housings, camera housings, and trim hardware, high performance sailboat masts, booms, stays, and hardware.

(l) Pollution control equipment: vessels, heat exchangers, FGD systems and stack liners, scrubbers, pipe and fans.

(m) Extractive metallurgy: autoclaves for pressure hydrometallurgy, flash tanks, heat exchangers, slurry mixers, slurry piping, cathodes for copper refining and drums for electrolytic foil production.

(n) Electroplating equipment: trays and racks, clips, heat exchangers and tanks.

(o) Architectural Applications: building sheathing, architectural hardware and building structural systems and components.

(p) Automotive applications: springs, mufflers and exhaust systems.

(q) Leisure and performance and entertainment equipment: golf club heads and shafts, tennis rackets, hockey sticks, climbing equipment, high performance and race car parts, watch cases, eyeglass frames, camera shutters, computer cases, jewelry, and hand tools.

**Why Choose Titanium?**

Titanium is corrosion resistant: immune to atmospheric corrosion even in marine and industrial exposures, immune to salt or polluted brackish waters or spray at normal temperature, and has a wide range of resistance to crevice and under deposit corrosion compared to stainless steels. Its strength in annealed condition is to 65,000 psi for unalloyed grades and to 30,000 psi for common alloys. Titanium’s density is 56% of steel. This light weight and high strength may allow design and configurations not feasible with concrete or steel. It may also be an advantage in erecting large frames and may reduce foundation requirements. Titanium also has no ductile brittle transition at low temperatures therefore it can be used at cryogenic temperatures. Thermal expansion coefficient is compatible with glass and certain composites. Titanium is non-toxic therefore it can also be used in body parts. It’s near zero corrosion rates all but
eliminate metals in run-off (compare to traditional copper roof) which makes it environmentally friendly. Titanium can be finished to provide a wide variety of surface textures and reflectivity through pickling, blasting, polishing, sanding and brushing, and anodizing which allows the creation of a full range of iridescent colors.

Advantages and Disadvantages
Wear and galling can be a problem for moving joints, pins and fasteners. Titanium may cause adjacent metals to corrode galvanically – titanium is very noble (titanium might require a barrier coating to protect less noble metals in galvanic couples). Loss of strength at high temperatures may be a concern (fire protection issue in structural systems). High costs may discourage some from using titanium. Due to complex, energy intensive metal winning and melting processes, the raw material (ingot) cost of titanium is high. Mill production costs are high due to losses in hot working to finished product forms and fabrication costs are high. Price varies widely depending on market conditions which makes it unpredictable for long term projects.

Costs
While cost per pound is high, cost per “board foot”, “unit of strength”, or unit of practical use is a better measure. For example, consider a roofing system:

1 square meter of 0.060” copper weighs 30 pounds
1 square meter of 0.040” copper weighs 20 pounds
1 square meter of 0.040” titanium weighs 10 pounds
1 square meter of 0.020” titanium weighs 5 pounds

Costs can be reduced by using thin sections (e.g. 0.016 to 0.020” for sheathing and roofing) with no corrosion losses. Sheet or tubular forms can be used to take advantage of large surface to unit weight. Welding can be minimized or eliminated in design therefore reducing costs. More sophisticated joint details can be used to simplify welds; welds can be moved away from section changes and other stress raisers; and where welding is required, high productivity processes like EB and laser should be considered. Overall, the long life and low maintenance of titanium may produce the lowest life cycle cost.

ASTM Grades and Specifications
Typical structure applications include: building sheathing, roofing systems, low or zero maintenance structures, weight critical structures or structures with center of gravity limitations, structural members for signature projects, ice shields on bridges and cable supports. Most industrial applications rely on ASTM (American Society for Testing and Materials) specifications. ASTM Specifications are product specifications and each covers several grades or chemical compositions of titanium. ASTM specifications are adopted by ASME for use in the various construction codes. There are many proprietary and
specialized grades, however, the most common grades have a well proven record in even polluted industrial atmospheric conditions, marine exposures, and sea water service; are readily available in a variety of product forms; can be fabricated using equipment similar to that used for stainless steel; are readily weldable; and have a range of properties from which to choose.

**Grade Selection**

When choosing which grade to use, consider availability in required product forms and sizes; adequacy of strength, ductility, and toughness; and fabricability. It is important to understand the various ASTM grades and their characteristics. Unalloyed (Commercially Pure) Titanium (ASTM Grade 2, 2H, or 3) is most widely used in industrial corrosion applications because it is readily available in all product forms, has good strength, sufficient ductility for most forming, is tolerant to service damage, and is easier to fabricate than the higher strength Al-V alloys. Unalloyed or CP Titanium (ASTM Grade 1) is widely used in applications requiring ductility. Grade 1 is the easiest to form and draw of the grades suggested, is readily available in sheet and coil product forms, but not in other product forms, and has very good ductility and will be most tolerant to service damage. Ti 3Al-2.5V, ASTM Grade 9, 90ksi/70 ksi UTS/YS is widely used in aerospace hydraulic tubing, high strength industrial applications like oil production tubulars, and in bicycle frames. It is somewhat easier to fabricate than Grade 23, is available in bulk forms like billet, bar, heavy plate, and extrusions, and also in finished tubular products, and it has slightly better ductility than Grade 23 but will still be tolerant to service damage. Ti 6Al-4V, ASTM Gr. 5 (130 ksi/120ksi UTS/YS) and Ti 6Al-4VELI, ASTM Gr. 23 (120 ksi/110ksi UTS/YS) are also widely used in aerospace and high strength industrial applications. However, they are the most difficult to fabricate of the alloys suggested, are not readily available except in bulk forms like billet, bar, heavy plate, and extrusions, and they have relatively low ductility and will be less tolerant to service damage.

**Welding Considerations**

Due to unique welding limitations, consider welding designs that minimize welding, use butt welds where possible, and use similar welding details to the maximum possible extent. Design joints that allow butt welds to be placed away from high stress areas and use that to reduce weight of adjacent components (fatigue and cyclic loading). Design for inspection of face and root sides.

**Future Applications**

To date, most applications have been in roofing and building cladding, employing thin sheet and generally using techniques similar to other metallic sheathing materials, often driven by architectural appearance issues. Future applications using titanium for corrosion resistance, structural strength, long life, and low maintenance cost where life cycle cost is lower are predicted as titanium becomes more familiar to construction.
WHAT IS THE DMTC?

- US Army Center of Excellence
- Modeled after other existing military centers
- Coordinate Military and National Security Specialty Metal needs with specific expertise from Academia, Industry and Institutions – starting in OHIO.
- Bypass Government Bureaucracy in dealing with a single Technical issue.
- Repository for data, references and networking available to Industry.

“HONEST BROKER”

MISSION STATEMENT:

- Become the “Go To” knowledge base on specialized metals – initially Titanium.
- Create an easily accessed database which captures and provides resources to third parties – generating interest and involvement with Titanium.
- Develop an understanding by industrial, academia and technical institutions of titanium and the Army’s needs, which in turn creates demand.
- By increasing demand, there is more national use and production, and eventually decreased price.

GOAL:

- Titanium
- Beryllium
- Molybdenum
- Cobalt
- Vanadium
- Manganese
- Tantalum
- Rhenium
- Rare earth metals

Specialty Metals of Specific Interest and Concern to the US Army (ARDEC Picatinny Arsenal)

Periodic Table of Elements

Titanium

- Symbol: Ti
- Atomic number: 22
- Atomic weight: 47.867
- 9th most abundant element in the earth’s crust
- 4th most abundant structural metal in the earth’s crust
- Only less abundant structural metals are iron & aluminum
- More Titanium is available than nickel, copper, chromium, lead, tin and rare earth metals
- Compared to Steel - 45% lighter but just as strong
- Compared to Aluminum - 50% heavier but twice as strong
- Melting point of 1660
- High Strength to Weight ratio
- Derived from ilmenite (FeTiO$_3$) and rutile (TiO$_2$) ores by chemical processes
- Highest strength to weight ratio of ANY known element
- Nickel titanium (NiTi) is a “smart material” responds to a stimulus in a predictable manner – memory retention
Titanium Minerals
Supply By Country

- India: 6%
- Other: 21%
- South Africa: 25%
- Canada: 14%
- Norway: 7%
- Australia: 25%
- US: 6%
- Malaysia: 1%

TITANIUM SPONGE BY COUNTRY
2007e Sponge Production ('000 Tons)

- Russia: 34.0
- Kazakhstan: 24.0
- China: 23.0
- Japan: 39.0
- US: 14.5

Major US Titanium Companies

<table>
<thead>
<tr>
<th>Mining</th>
<th>Sponge</th>
<th>Milling</th>
<th>Mill Prod.</th>
<th>Semi- finished</th>
<th>Final</th>
<th>Sales $ millions</th>
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<td>Not available</td>
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</tbody>
</table>

Primary products made are bar, wire and fasteners. These two companies control the majority of the aerospace fastener market worldwide.

Inclusion Samples

- Tungsten-carbide inclusion (end view)
- Tungsten-carbide inclusion (x-ray lateral view)
- Titanium rod (lateral view)

CENTER OF EXCELLENCE MODEL

- The Department of Defense has successfully established and maintained a number of these centers over the years.
  - Electro-Optical Center – Kittanning, PA
  - National Center for Defense Machining and Manufacturing – Lancaster, PA
  - Doyle Center – Pittsburgh, PA
  - Center for Commercialization of Advanced Technology – San Diego, CA
  - Naval Aircraft Carrier Center, – Newport News, VA
**FUNDING**

- Federal
  - $1MM from 2006 Department of Defense Appropriation Act
  - $2MM from 2007 Department of Defense Appropriation Act
  - $3MM Request in 2008
    - “Earmarks as they should be deployed”
    - Responding to a US Government Agency need and desire

- State of Ohio
  - Anticipate participation with academic and industrial partners in relevant 2008 Third Frontier funding.
  - Will be actively soliciting additional funding from the Ohio Department of Development.

**WHY OHIO?**

- Northern Ohio continues to represent the heartland of metals production and manufacturing.
- Convenient location for coordinating with other such geographical industrial bases in western Pennsylvania, Michigan, Indiana and Illinois

**LOCATION**

- Economics transcend artificial political boundaries and reflect regional concentrations of industrial activity that capture strengths and economies of scale. We must move from the artificial and narrow perspectives of city-states to the realities and breadth of regional alliances and opportunities.

  - Dr. Luis M. Proenza
  - President, The University of Akron

**REGIONAL IMPACT**

- Bring forth recognition of a still-viable Metals Industry
- Create common interests and programs which can unite the Industrial, Academia and Institutional interest in “Metals” and their potentials
- Foster job training needed to embrace the requirement for utilization of new Metals in manufacturing process

**OUR ARMY PARTNER - PICATINNY ARSENAL, NJ**

- Dates back to the Revolutionary War
- Has had specific ordinance service in every war since
- Active military base - Combat Garrison
- Commanded by a major general

- It is part of Army Materiel Command (AMC) and houses Armament Research and Development and Engineer Center (ARDEC)
- DMTC takes direction from Prototyping Manufacturing Laboratory (PML) of ARDEC

**Revised:** 04/03/2008

**Revised:** 08/03/2007

**Revised:** 10/02/2007
BOARD OF DIRECTORS

Elected July 13th

Edward F. Colanieri
Retired Picatinny Technical Data Division Chief

George DeMassi
Retired Picatinny Director of the Product Assurance

Julian A. Gravino
President, Edison Industrial Systems Center, and Head Food Research Institute, Toledo, Ohio

Victor Guegagne
Retired Picatinny Civilian Manager

Roy L. Ray
Retired Mayor of Akron
State Senator and Chairman of Finance Committee

The bylaws provide for a board constitution of seven. Consideration is being taken to fill the two open seats by nominees from Ohio.

MANAGEMENT

Charles Clark
Executive Director DMTC
Formerly Director - Government Relations, University of Akron, Extensive experience in corporate management, technology transfer and economic development, Active involvement in Ohio and federal government.

Michael Trzcinski
Senior Technical Advisor
Technology transfer expertise NASA Liaison Experience in titanium industry

Judith Wynn
Computer and IT Expertise

ADVISORY COMMITTEE – IN FORMATION

• Will be comprised of 7 members
• Emphasis on national representation and involvement in metals industry, mining, academic and economic development
• Will be operational in January
• Will act as technical review body for "Project" funding authorization by Board of Directors

LOCATION

• Stark State College of Technology
• Advanced Technology Center
• Includes CAD lab for training
• Includes machine shop for prototyping
• adjoining Tenants
• Rolls Royce – Fuel Cell Program
• Diebold Education Center
• Convenient Location Central Northeast Ohio

ORGANIZATIONAL DEVELOPMENT TACTICS

Phase I – Informational roll-out to the major industrial areas of Ohio
• Creating awareness among academia, industry, economic development agencies, institutional organizations, federal and state labs
• Establishing parameters for database creation on titanium
• Pursuing DMTC’s role as a client’s “honest broker”
• Providing a single information and assistance resource for clients
• Developing projects which create deliverables for the Army but also addresses client interests
• Target Competition by year-end 2007

Phase II – TBD based on above inputs

ACCOMPLISHMENTS from Inception thru December 2007

• Established and staffed a fully electronic office at Stark State College
• Created and "Unity Program" and "Slide Show"
• Started 1st Class Website www.defensemetals.org
• Created Contacts (Currently 1400) and Clients Database
• Made 15 Presentations to establish "Awareness of DMTC" around Ohio including Engineering Deans Council and Edison Center President’s Council
• Established Contact with nearby "honor" Department of Defense Center’s of Excellence
• Established the DMTC presence in the Titanium Community in the Ohio and Western PA
• Efficacy of using Titanium to make a difference in the National Association of Corrosion Engineers
• Identified Projects for funding in 2008
• Established 2nd presentation – "Titanium Welding Workshops" – 2 each
  • Ohio Engineering Deans Council Forum
  • "Titanium – Addressing the Army’s Needs"
• Ohio Civil Engineering "UTC" Council Conference
• "Feasibility of using Titanium in Bridge Revegrowing"
Titanium Visa Via the Nations Infrastructure Rehabbing

- Why DMTC's involvement
  - Student Motivation and Success Stories
  - Support for University, K-12 and Business
  - Collaboration between University/Industry/Transportation
  - Transitions from Graduate School to Transportation Industry

- The "Titanium Idea" Achievements
  - Full RIWa Patient Study
  - 1st Transportation Infrastructure Summit: Oswego June 08
  - Student/Industry/University collaboration and Structure of DMTC (Continued)

Workforce Development Initiative

- Addressing Shortfall Of Welders

DMTC Projects to be funded in 2008 (continued)

- $64,828
- $36,690
- $67,500
- $73,850

DMTC Projects to be funded in 2008

- $22,500
- $10,000
- $15,000
- $12,000

DMTC Projects to be funded in 2008 (continued)

- $15,000
- $12,000
- $10,000
- $7,500
- $6,000

Recent Headlines

- Stark State College (SSCT)
- • Public Forums in Play
- • Questions and Posturing
- • "Titanium Idea"
- • Drivers
  - Titanium Welding Training
  - University/Industry/Military/Transportation
  - 2 Year CAD Trained Engineering Student
  - Semester at Picatinny Arsenal, NJ

- Co5Op Program 2007
- - Forward Vision VS Yesterday's Ways
- - Does Ohio UTC want to be involved and be the National Lead?
- - Safety to Public
- - Ongoing Bridge Cost savings by use of Ti –Corrosion Resistant
- - Ohio's Federal Legislative involvement in Transportation issues
- - Parthenon Story
- - Government Affairs expertise and Involvement
- - 2009 "Transportation Re Appropriations Art" Debate and Structure
- - Congressional Hearings Contemplated by House
- - Transportation Infrastructure convention – DC/March 08
- - November 08 Election
- - Economic Trends And Indicators Relative To The Metals Industry Following The Economic Slowdown

DMTC Projects to be funded in 2008

- $4,000
- $5,000
- $6,000
- $7,000

DMTC Projects to be funded in 2008 (continued)

- $12,000
- $12,000
- $10,000
- $7,500
- $6,000

DMTC Projects to be funded in 2008 (continued)

- $7,500
- $6,000
- $5,000
- $4,000
- $3,000

DMTC Projects to be funded in 2008 (continued)

- $10,000
- $15,000
- $12,000
- $9,000

DMTC Projects to be funded in 2008 (continued)

- $15,000
- $12,000
- $10,000
- $7,500
- $6,000

DMTC Projects to be funded in 2008 (continued)

- $15,000
- $15,000
- $10,000
- $10,000
- $6,000

DMTC Projects to be funded in 2008 (continued)

- $10,000
- $10,000
- $7,500
- $5,000
- $4,000
Enhancing the Use of Titanium for Novel Applications Spanning the Domain of Structure, Performance Critical and Innovations in Engineering

Ohio Transportation Consortium
Stark State College of Technology
April 22, 2008

John A. Mountford Jr.
Director of Marketing
Tico Titanium, Inc.
30150 South Wixom Road
Wixom, MI 48393
www.ticotitanium.com

Chemistry – Wgt.%
Commercially Pure [CP] Grades

<table>
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<th>O₂ (max)</th>
<th>Fe (max)</th>
<th>H₂ (max)</th>
<th>C (max)</th>
<th>N (max)</th>
<th>Other (each)</th>
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Chemistry – Wgt. %

**Grade**

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<th>H₂ (max)</th>
<th>C (max)</th>
<th>N (max)</th>
<th>Other (each)</th>
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**TITANIUM**

**Benefits:**
- Immunity to Seawater Corrosion
- Low Density = Weight Savings
- Highly Erosion Resistant [to 20x Cu-Ni]
- Good Mechanical Properties
- Favorable Physical Properties
- Life Cycle Cost Savings [Good Payback]
- Significant Maintenance Reductions
- Environmentally Friendly

**Chemical Composition**

- **Commercially Pure [CP] Grades**
  - Grade 1
    - O₂ max: 0.18
    - Fe max: 0.30
    - H₂ max: 0.015
    - C max: 0.08
    - N max: 0.03
    - Ti max: 0.40
  - Grade 2
    - O₂ max: 0.25
    - Fe max: 0.30
    - H₂ max: 0.015
    - C max: 0.08
    - N max: 0.03
    - Ti max: 0.40
  - Grade 3
    - O₂ max: 0.35
    - Fe max: 0.30
    - H₂ max: 0.015
    - C max: 0.08
    - N max: 0.05
    - Ti max: 0.40
  - Grade 4
    - O₂ max: 0.40
    - Fe max: 0.50
    - H₂ max: 0.015
    - C max: 0.08
    - N max: 0.05
    - Ti max: 0.40

**Mechanical Properties**

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile (min)</td>
<td>35</td>
<td>240</td>
<td>50</td>
<td>345</td>
</tr>
<tr>
<td>Yield (min)</td>
<td>25</td>
<td>170</td>
<td>40</td>
<td>275</td>
</tr>
<tr>
<td>Yield (max)</td>
<td>45</td>
<td>310</td>
<td>65</td>
<td>450</td>
</tr>
<tr>
<td>Elong. (min)</td>
<td>24%</td>
<td>20%</td>
<td>18%</td>
<td>15%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>Titanium Gr 2</th>
<th>90-10 Cu-Ni</th>
<th>70-30 Cu-Ni</th>
<th>316 Stainless</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile (min)</td>
<td>50</td>
<td>345</td>
<td>40</td>
<td>275</td>
</tr>
<tr>
<td>Yield (min)</td>
<td>40</td>
<td>275</td>
<td>15</td>
<td>105</td>
</tr>
<tr>
<td>Yield (max)</td>
<td>65</td>
<td>450</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Elong. (min)</td>
<td>20%</td>
<td>30%</td>
<td>15%</td>
<td>30%</td>
</tr>
</tbody>
</table>
**Mechanical Properties**

- **Yield Strength**
- **Tensile Strength**
- **Elongation**
- **Impact Resistance**

**Yield Strength / Density Ratio**

- Grade 2 Ti: 61
- Grade 5 Ti [6Al-4VAlloy]: 188
- 316 SS: 29
- Alloy 254 Austenitic SS: 38
- Alloy 2205 Duplex SS: 58
- Alloy 400 Ni Base: 20
- Alloy 625 Ni Base: 49
- Alloy 276 Ni Base: 40
- 70-30 Cu-Ni: 13

**Physical Properties**

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>Titanium Gr 2</th>
<th>90/10 Cu-Ni</th>
<th>70-30 Cu-Ni</th>
<th>316 Stainless</th>
</tr>
</thead>
<tbody>
<tr>
<td>El. Modulus (10^6 psi)</td>
<td>16</td>
<td>18</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>Thermal Expansion (Micro in/in °F)</td>
<td>4.8</td>
<td>9.5</td>
<td>9.0</td>
<td>8.9</td>
</tr>
<tr>
<td>Thermal Conductivity (BTUhr·°F/ft²in²)</td>
<td>150</td>
<td>348</td>
<td>204</td>
<td>95</td>
</tr>
<tr>
<td>Density (lbs/in³)</td>
<td>0.163</td>
<td>0.323</td>
<td>0.323</td>
<td>0.286</td>
</tr>
<tr>
<td>(gms/cm³)</td>
<td>4.5</td>
<td>8.9</td>
<td>8.9</td>
<td>7.9</td>
</tr>
<tr>
<td>Hardness (HRB)</td>
<td>85</td>
<td>65</td>
<td>70</td>
<td>95</td>
</tr>
</tbody>
</table>

**Melting Points**

- Aluminum 5086: 565 °C, 1050 °F
- 90-10 Cu-Ni: 1150 °C, 2100 °F
- Steel HY-80: 1480 °C, 2700 °F
- Titanium Gr 2: 1670 °C, 3040 °F
Shock Resistance  $[10^3 \text{ in/sec}]$

### SHOCK RESISTANCE

$S_y / \sqrt{\rho E p/386}$

- $S_y$: Yield Stress [psi] (actual) [used 50,000 psi]
- $\sqrt{\rho E p}$: Square Root
- $E$: Modulus of Elasticity $[14.9 \times 10^6 \text{ psi}]$
- $\rho$: Density $[0.163 \text{ lbs./in.}^3]$
- $386$: Constant $x 1/\text{sec.}^2$

<table>
<thead>
<tr>
<th>Material</th>
<th>$S_y / \sqrt{\rho E p/386}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti Grade 9</td>
<td>0.95</td>
</tr>
<tr>
<td>Ti Grade 2</td>
<td>0.63</td>
</tr>
<tr>
<td>Inconel 625™</td>
<td>0.55</td>
</tr>
<tr>
<td>Monel 400™</td>
<td>0.24</td>
</tr>
<tr>
<td>316 Stainless Steel</td>
<td>0.21</td>
</tr>
<tr>
<td>70-30 Cu-Ni</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### TITANIUM Properties & Benefits

- **Properties**
  - High Strength / Weight - Size & Weight Reduction
  - Low Elastic Modulus - Flexible
  - High Shock Resistance - Survivable/System Integrity
  - Non-Magnetic - No Electronic Interference

- **Benefits**
  - Low Thermal Expansion - Close to Steel ($HV 80 = 6.3$)
  - Non-Radioactive - Short Half Life
  - Non-Toxic - Biocompatible
  - Good Ballistic Properties - Armor [Gr. 2 & 5 (Alloy)]

### Corrosion Resistance

- Immune to: Seawater, Brackish Waters, Polluted Waters
- Immune to: MIC (Microbiologically Induced / Influenced Corrosion)
- Fully Resistant to moist Chlorides
- Fully Resistant to Crevice Corrosion $< 80 \degree C [175 \degree F]$
- SCC
- Pitting
- Cavitation
- No Tidal or Splash Zone corrosion
- Over 40 years trouble free Seawater service in Chemical, Oil Refining & Desalination
Corrosion Resistance

- Not affected in the presence of Sulfides
- No H₂ Embrittlement < 77 °C (170 °F)
- Resistant to Gases:
  - SO₂, CO₂, CO, NH₄, H₂S, N₂

<table>
<thead>
<tr>
<th>Corrosion Resistance</th>
<th>Cu-Ni</th>
<th>316 SS</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>S</td>
<td>R</td>
<td>R / I</td>
</tr>
<tr>
<td>Crevice</td>
<td>S</td>
<td>S</td>
<td>R / I &lt; 200°F</td>
</tr>
<tr>
<td>Pitting</td>
<td>S</td>
<td>S</td>
<td>I</td>
</tr>
<tr>
<td>SCC</td>
<td>S</td>
<td>S &gt; 140°F</td>
<td>I</td>
</tr>
<tr>
<td>Fatigue</td>
<td>S</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Galvanic</td>
<td>S</td>
<td>S</td>
<td>I</td>
</tr>
<tr>
<td>MIC (Microbes)</td>
<td>S</td>
<td>S</td>
<td>I</td>
</tr>
<tr>
<td>Erosion</td>
<td>S</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Weld / HAZ</td>
<td>S</td>
<td>S</td>
<td>R / I</td>
</tr>
</tbody>
</table>

R = Resistant  S = Susceptible  I = Immune

Erosion Resistance

- Tenacious Stable (ceramic-like) Oxide Film
- Instantaneous Re-Healing
- Superior Resistance to:
  - Abrasion
  - Impingement Attack
  - Erosion
  - Erosion – Corrosion
  - Turbulence
  - Cavitation
- High Fluid Velocities:
  - Seawater: 90 - 120 ft/sec
  - Sand-laden: 15 - 20+ ft/sec

SPECIFICATIONS

- ASTM American Society for Testing & Materials “B”
- ASME American Society of Mechanical Engineers “SB”
- ANSI American National Standards Institute “B xx.xx” [a Division of ASME]
- MSS Manufacturers Standardization Society “SP”

- ANSI and MSS Specifications for Titanium are to “Dimensions Only” - (values are for Steel only)

ASTM Specifications

- B 265 Strip / Sheet / Plate
- B 338 Tubes – Condensers / Heat Exchangers
- B 348 Bars / Billets
- B 363 Welding Fittings
- B 367 Castings
- B 381 Forgings
- B 861 Seamless Pipe
- B 862 Welded Pipe
- B 863 Wire

ASME / ANSI Specifications

- B 16.5 Stainless Steel Pipe Flanges, Flanged Fittings
- B 16.9 Steel Butt welding Fittings
- B 16.11 Forged Fittings Socket-Welding & Threaded
- B 16.14 Ferrous Pipe Plugs, Bushings, Locknuts
- B 16.28 Steel Butt weld Short Radius Elbows, Returns
- B 16.48 Steel Line Blanks
- B 36.10 Welded & Seamless Wrought Steel Pipe
- B 36.19 Stainless Steel Pipe
**MSS Specifications**

- **SP – 25** Standard Marking System for Valves, Fittings, Flanges & Unions
- **SP – 43** Stainless Steel Butt Welding Fittings
- **SP – 44** Steel Pipeline Flanges
- **SP – 97** Integrally Reinforced Forged Branch Outlet Fittings – Socket Welding, Threaded, and Butt Welding Ends
- **SP – 119** Factory-Made Wrought Belled End Socket-Welding Fittings

**Products**

**Plate & Sheet**

**Fasteners**

**Machine Screws**

- Flat Head Screws
- Hex Socket Set Screws

**Power Generation**

- **Condenser Tubing** - 1” OD x .025” x L (to 110”)
- **Tube Sheets [Plate]** - 1” Thick x 140” x 160”
- **Heat Exchanger (S & T)** - 1” OD x .035”, .049”
- **Flue Gas De-Sul. (FGD) Liners Stacks & Ducts**
  - Sheet Panels - .063” x 48” x 120”+
- **Service Water Piping** - 2” Sch 10 & Above
- **Inlet Water Piping** - to 32” OD +
- **Nuclear Waste Disposal** - Fuel Rod Racks
**Offshore Oil & Gas**
- Service Water Piping - 2” thru 12” Sch sizes
- Fire Main Systems – Piping, Fittings, Flanges
- Fire Pumps, Sprinkler Heads, Nozzles, Valves
- Coolers – Compressor, Lube Oil, Engine
- Ballast Tank Systems & Valves
- Heat Exchangers - [Plate/Frame & Shell/Tube]

**Chemical Tanks**

**Spray Header & Nozzles**

**Navy & Marine**
- Service Water Piping
- Fire Main Systems – Piping, Fittings, Pumps
- Desalination Units (High Pressure)
- AC Chillers & Distillation Condensers
- HVAC Ventilation Ducting
- Engine, Compressor & Radar Coolers
- Bilges & Tanks
- Components – Lights, Electrical Boxes, etc.

**Chemical Tanks**

**Mining**
- Mixers
- Autoclaves (Hi Temp. / Hi Press.)
- Valves
- Shafts
- Piping, Flanges, Fittings, Fasteners

**Pipe Fabrication**
Flanged Pipe Spool Section

Weight Savings

Factors:
- **Density** - 56% Steel, 50% Cu, Cu-Ni, Ni Alloys
- **Tube** - Thinner walls (no Corrosion Allowance) + brings Heat Transfer to level of Cu-Ni
- **Pipe** - Decrease Sch Sizes (no Erosion)
- **Fittings / Flanges / Connections / Pumps**

Weight Savings [Pipe Comparison]

<table>
<thead>
<tr>
<th>Metal</th>
<th>Metal + $H_2O$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>8” Class 200 Cu-Ni</td>
<td>15.3</td>
<td>23.6</td>
</tr>
<tr>
<td>6” Sch 10 Titanium</td>
<td>5.3</td>
<td>13.8</td>
</tr>
<tr>
<td>Weight Savings</td>
<td>10.0</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td><strong>65.4%</strong></td>
<td><strong>41.5%</strong></td>
</tr>
</tbody>
</table>

For every 100 ft = 1,000 + 980 = 1,980 lbs

90-10 Cu-Ni 8” Class 200 = 8.625” OD x .148” wall
Titanium 6” Sch 10 = 6.625” OD x .134” wall

Ejectors

Emergency Stop Switch

Light
### Fire / Rescue Tools

<table>
<thead>
<tr>
<th>Applications</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>De-salination Units</td>
<td>(S/T &amp; Reverse Osmosis)</td>
</tr>
<tr>
<td>Distillation Unit Condensers</td>
<td>(S/T)</td>
</tr>
<tr>
<td>Distillation Units Heaters</td>
<td></td>
</tr>
<tr>
<td>Lube Oil Coolers</td>
<td></td>
</tr>
<tr>
<td>HVAC Air Ventilation Ducting</td>
<td></td>
</tr>
<tr>
<td>Firemain Systems Piping &amp; Fittings</td>
<td></td>
</tr>
<tr>
<td>Fire Pumps Grades 2 &amp; 5</td>
<td></td>
</tr>
<tr>
<td>Service Water Piping</td>
<td></td>
</tr>
</tbody>
</table>

### Fittings - Tee & Elbow

### Flanges

### Dock Ladder

### Hinges
THE INTRICACIES and FASCINATION OF PROCESSING-MICROSTRUCTURE-MECHANICAL PROPERTY RELATIONSHIPS IN TITANIUM ALLOYS

Dr. T. S. Srivatsan, FASM, FASME
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The University of Akron
Akron, Ohio 44325-3903, USA

OUTLINE
of
VERBAL ELUCIDATION
THE FLOW SEQUENCE

• The Role of Composition
• The Emergence of Microstructure
• Addition and/or presence of Elements
• The Key Alloy Types
• Processing Influences on Microstructure
• Microstructure-Mechanical Property Relationships
• The Highlight(s)

WHY
THE INTEREST-DESIRE and NEED TO SELECT TITANIUM

• TITANIUM HAS FOUND ITS NICHIE IN MANY INDUSTRIES OWWING TO ITS UNIQUE DENSITY, CORROSION RESISTANCE and RELATIVE STRENGTH ADVANTAGES OVER COMPETING METALS SUCH AS ALUMINUM, STEELS and even SUPERALLOYS.

THE FACTS and BENEFITS OFFERED BY THE ALLOYS of TITANIUM

• The DENSITY OF TITANIUM is only ABOUT 60 percent THAT OF STEEL and NICKEL BASE SUPERALLOYS.
• THE TENSILE STRENGTH OF THE TITANIUM ALLOY IS QUITE COMPARABLE TO THAT OF LOWER STRENGTH MARTENSITIC STEEL and BETTER THAN THE FERRITIC and even AUSTENITIC STEELS.
• COMMERCIAL ALLOYS OF TITANIUM ARE USEFUL AT TEMPERATURES of 538°C to 595°C DEPENDING ON CHEMICAL COMPOSITION.
• THE COST OF TITANIUM IS FOUR TIMES THE COST OF GOOD STAINLESS STEEL, BUT QUITE COMPARABLE TO THE COST OF SUPERALLOYS.
• EXCEPTIONALLY GOOD CORROSION RESISTANCE, WHICH SURPASSES THE RESISTANCE OF STAINLESS STEELS IN AGGRESSIVE ENVIRONMENTS.
• OUTSTANDING CORROSION RESISTANCE IN THE HUMAN BODY.

GIVEN THE GLORY and POTENTIAL BENEFITS

WHAT THEN ARE PROPERTIES?

• PROPERTIES OF NOTICEABLE and SPECIAL INTEREST ARE THE FOLLOWING:
  1. Tensile Yield Strength
  2. Ultimate Tensile Strength
  3. Ductility
  4. Toughness
  5. Cyclic Properties to include:
     (a) Low Cycle Fatigue (LCF)
     (b) High Cycle Fatigue (HCF)
  6. Crack Propagation in Fatigue (da/dN)
  7. Crack Propagation under environmental constraints (da/dt).

WHY THEN MICROSTRUCTURE?

• THE MICROSTRUCTURES OF TITANIUM CAN BE INDEED COMPLEX.
• THEY ARE A DIRECT RESULT OF COMPOSITION, PROCESSING and POST-PROCESSING HEAT TREATMENT.
• MICROSTRUCTURE MOST CERTAINLY DOES EXERT A PROFOUNDED INFLUENCE ON PROPERTIES and PERFORMANCE and RESULTANT SELECTION OF A TITANIUM ALLOY.
RATIONALE FOR THIS ELUCIDATION

• The MECHANICAL PROPERTIES OF TITANIUM ALLOYS IN THE FINISHED SHAPE CAN BE AFFECTED EITHER BY ONE OF THE SEVERAL FACTORS, OR BY A COMBINATION OF FACTORS, TO INCLUDE COMPOSITION, THAT RESULTED IN A SPECIFIC MICROSTRUCTURE.

EMERGENCE OF THE ALLOYS of TITANIUM

• IN A NUTSHELL, The TITANIUM ALLOYS ARE GROUPED INTO THE FOLLOWING CLASSES:
  1. ALPHA ALLOYS
  2. NEAR-ALPHA ALLOYS
  3. ALPHA-BETA ALLOYS
  4. BETA ALLOYS

• This GROUPING REFLECTS THE CUSTOMARY ROOM TEMPERATURE PRESENCE OF THE
  (a) ALPHA PHASE (Hexagonal Close Packed)
  (b) BETA PHASE (Body Centered Cubic) STRUCTURES IN A PARTICULAR ALLOY.

ROLE OF ALLOYING ADDITIONS

• THE OCCURRENCE OF TRANSFORMATION UPON HEATING and COOLING (FROM THE HIGH TEMPERATURE BETA REGION), AND PHASE COMPOSITIONS CAN BE ALTERED BY THE ADDITION OF ALLOYING ELEMENTS.

• THE VIABLE and AMENABLE ALLOYING ADDITIONS ARE TYPICALLY CLASSIFIED AS:
  (a) ALPHA STABILIZERS.
  (b) BETA STABILIZERS.

THE ELEMENTS and THEIR ROLE

• Aluminum, Oxygen and Nitrogen are the **Alpha Stabilizers**.

• Vanadium, Molybdenum and Iron and Hydrogen are the **Beta Stabilizers**.

A THIRST FOR KNOWLEDGE of The DESIRED “PROPERTIES”

• THE MOST IMPORTANT OF THESE FACTORS INCLUDE THE FOLLOWING:
  1. Amounts of specific alloying elements and impurities.
  2. Melting process used to make the primary ingot.
  3. Number of melting steps.
  4. Method for mechanical working the ingots into mill products
  5. Steps in forging a shape.
  6. Casting process and volume of cast article.
  7. Use of densification techniques, such as hot isostatic pressing, to reduce casting porosity.
  8. Powder metallurgy processed including method of making powder.
  9. Joining process used to fabricate the structure.
 10. Post processing heat treatment or final step employed both in working or fabrication.
 11. Machining process and surface treatment.
PROPERTIES of TITANIUM and its ALLOYS

- Pure Titanium can be strengthened appreciably by a healthy synergism of alloying, processing, and post-processing heat treatment.
- Most notably, even after this the alloys still retain their low density levels.
- The mechanical properties of the Titanium alloys are attractive, particularly with respect to ratio of strength to density.
- The Titanium alloys are remarkably strong in a comparison of strength to density ratio.

<table>
<thead>
<tr>
<th>Model</th>
<th>Density</th>
<th>Tensile Strength</th>
<th>Tensile Strength/density</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP Titanium</td>
<td>4.51</td>
<td>0.163</td>
<td>400</td>
</tr>
<tr>
<td>Ti56Al54V</td>
<td>4.43</td>
<td>0.160</td>
<td>895</td>
</tr>
<tr>
<td>Ti54Al53Mo51V</td>
<td>4.51</td>
<td>0.163</td>
<td>1380</td>
</tr>
<tr>
<td>Ultrahigh strength steel (4340)</td>
<td>7.9</td>
<td>0.29</td>
<td>1980</td>
</tr>
</tbody>
</table>

MICROSTRUCTURE-PROPERTIES-PROCESSING

- Most notably, the physical properties of Titanium are largely unaffected by processing.
- The kinetics of Titanium beta-phase transformations that occurs during heating, cooling, and aging strongly influences microstructure and resultant mechanical properties.
- The mechanical properties of Titanium alloys can also be directly related to the (a) processing, and (b) post-processing heat treatment sequences.

MECHANICAL PROPERTIES OF TITANIUM ALLOYS

- The mechanical properties of Titanium alloys are affected both by chemistry and texture.
- The mechanical properties of Titanium alloys are not appreciably affected by heat treatment.
- The modulus of Titanium can vary with Alloy Type (beta versus alpha) from as low as 93 GPa to 120.5 GPa.
- The modulus of Titanium is 50% greater than the modulus of Aluminium alloys and approximately 60% of the modulus of steels and nickel base alloys.

ELASTIC MODULUS of TITANIUM ALLOYS

- For a given phase, the modulus of a Titanium alloy is a direct function of direction of measurement in the crystal.
- By arranging crystal orientation through grain alignment (referred to as texturing) of the Titanium alloys, certain grain orientations can be achieved that facilitate in the attainment of a higher modulus than is customarily found for an alloy.

THE STRUCTURE OF TITANIUM

- Structure is best defined as the (a) macrostructure (macro-appearance), and (b) microstructure (micro-appearance) of a polished and etched cross-section of a metal visible at high magnifications.
- Two other microstructural features that are not determined visually but are determined by other means, such as, X-ray diffraction are:
  (a) The phase type (alpha, beta)
  (b) The orientation of grains (texture)
THE INTRINSIC ROLE and CONTRIBUTION OF GRAINS

- The grain size, grain shape, and grain boundary arrangements in a titanium alloy have a significant influence on its mechanical properties.
- It is the intrinsic and innate ability to manipulate the phases and grains present as a direct result of alloy composition that is responsible for the variety of properties that can be produced in titanium and its alloys.

MICROSTRUCTURE and PROPERTIES

- In fact, transformed beta-phase products in alloys can affect the following:
  (a) Tensile strength
  (b) Ductility,
  (c) Toughness, and
  (d) Cyclic properties.

THE ROLE OF ALLOYING ELEMENTS OF COMPARABLE SIZE WITH TITANIUM

- Some alloy elements are more or less comparable in atomic size to the atom size of titanium.
- As a direct result, they can easily dissolve as a mixture in titanium, substituting for the titanium atoms.
- Alternatively, they can act to facilitate the formation of an intermetallic compound TiAl.
- They can even form a different mixture of titanium and the element added, which takes on the crystal structure of the added element, but comparably sized.

UNDERSTANDING THE ROLE and SIGNIFICANCE of COMPOSITION

- The alloy elements that dissolve in titanium alloys produce strengthening by interfering with the plastic deformation processes.
- This type of strengthening is referred to or known as solid solution strengthening (SSS).
- For the comparably sized alloy elements that dissolve in titanium the strengthening is referred to as substitutional strengthening.

ALLOYING ELEMENTS and STRENGTHENING: HOW and WHY?

- The alloy elements that dissolve in titanium alloys produce strengthening by interfering with the plastic deformation processes.

ROLE OF ALLOYING ELEMENTS-SECOND PHASE-DEFORMATION

- Those alloying elements that favor the formation of a second phase generally interfere with deformation more effectively than those that tend to dissolve.
- Consequently, the presence of a second-phase favors a greater hardening of the titanium metal matrix than is produced by solid solution strengthening.
THE ESSENCE

THE NORMAL ROLE OF COMPARABLY SIZED ELEMENTS IN STRENGTHENING TITANIUM PROVIDES:
(a) **SOLID SOLUTION STRENGTHENING,**
(b) **ASSISTS IN CONTROLLING MICROSTRUCTURE** THROUGH THEIR EFFECT ON THE AMOUNT OF
   (i) ALPHA PHASE, and
   (ii) BETA PHASE PRESENT.

ROLE OF INTERSTITIAL ELEMENTS

- **THESE ELEMENTS ARE SIGNIFICANTLY SMALLER THAN THE TITANIUM ATOM AND TEND TO EASILY DISSOLVE IN THE TITANIUM PHASE CRYSTAL LATTICE AS SOLID SOLUTIONS.**
- **A FEW INTERSTITIAL ELEMENTS TEND TO FORM ONE OR MORE SECOND-PHASES WITH TITANIUM.**
- **A SIGNIFICANT INFLUENCE ON THE MECHANICAL BEHAVIOR OF TITANIUM IS BROUGHT ABOUT BY THE PRESENCE OF HYDROGEN, OXYGEN, NITROGEN AND CARBON.**
- **THESE ELEMENTS TEND TO EASILY DISSOLVE INTERSTITIALLY IN TITANIUM AND HAVE A POTENT EFFECT ON MECHANICAL PROPERTIES AND/OR RESPONSE.**

THE ROLE OF HYDROGEN

- **THE SOLUBILITY OF THE INTERSTITIAL ELEMENT HYDROGEN IN ALPHA TITANIUM AT 300°C IS APPROXIMATELY 8 percent or 1000 ppm.**
- **HYDROGEN IN SOLUTION HAS LITTLE INFLUENCE ON MECHANICAL PROPERTIES.**
- **THE DAMAGE THAT RESULTS IS CAUSED BY THE PRESENCE OF HYDRIDES, WHICH FORMS AS HYDROGEN DIFFUSES THROUGH THE MATERIAL DURING EXPOSURE TO EITHER GASEOUS OR CATHODIC HYDROGEN.**
- **PRECIPITATION AND PRESENCE OF THE HYDRIDES RESULTS IN AN ADVERSE INFLUENCE ON DUCTILITY.**

HYDROGEN and TITANIUM

- **THE DAMAGE CAUSED BY HYDROGEN IS ESSENTIALLY MANIFESTED AS A LOSS OF DUCTILITY**
  - OCCURRENCE OF EMBRITTLEMENT AND A CONCURRENT REDUCTION IN THE STRESS INTENSITY THRESHOLD FOR CRACK PROPAGATION.
  - A PRACTICAL APPROACH TO CONTROL OR MINIMIZE THE HYDROGEN PROBLEM IS TO MAINTAIN A LOW CONCENTRATION OF THE ELEMENT.

THE PRESENCE and ROLE OF OXYGEN and NITROGEN in Commercially Pure TITANIUM METAL

- **THESE TWO ELEMENTS EXERT A POTENT EFFECT ON STRENGTH.**
- **AS THE AMOUNTS OF THESE ELEMENTS IN TITANIUM INCREASES, THE TOUGHNESS DECREASES UNTIL THE MATERIAL BECOMES BRITTLE.**
- **EMBRITTLEMENT IS FAVORED TO OCCUR AT CONCENTRATION LEVELS WELL BELOW THE SOLUBILITY LIMIT.**
- **DUE TO THE PRESENCE OF OXYGEN AND NITROGEN IN PURE TITANIUM METAL, THE ALPHA PHASE FORMED FROM BETA HAS A DISTINCTIVE “WIDMANSTATTEN” STRUCTURE THAN DOES A TITANIUM ALLOY THAT IS ESSENTIALLY FREE OF THESE TWO ELEMENTS.**

THE MECHANICAL PROPERTIES OF PURE TITANIUM METAL

- **HIGH PURITY (99.9 percent) TITANIUM METAL IS NOT A WIDELY USED COMMERCIAL COMMODITY.**
- **THE CONVENTIONALLY PROCESSED TITANIUM GRADES, WHERE THE TITANIUM CONTENT IS LESS THAN 99.55% BY SPECIFICATION ARE USED AND DO NOT DIFFER MUCH FROM THE MECHANICAL PROPERTY RESPONSE OF HIGH PURITY METAL.**
- **PURE TITANIUM METAL IS A SINGLE PHASE ALLOY.**
THE MICROSTRUCTURE OF COMMERCIAL TITANIUM DEPENDS ON WHETHER OR NOT IT HAS BEEN COLD WORKED AND ON THE SUBSEQUENT ANNEALING USED.

FURTHER, UPON COOLING FROM THE BETA REGION, WHICH BEGINS AT 882°C, THE RESULTANT STRUCTURE DEPENDS ON THE COOLING PROCESS FOLLOWED.

THIS IS BECAUSE THE PROCESS DIRECTLY AFFECTS THE PROGRESSION OF THE BETA TO ALPHA TRANSFORMATION AND FINAL ALPHA GRAIN SIZE.

THE EQUIAXED MICROSTRUCTURE OF TITANIUM AFTER ANNEALING AT 800°C IS AS SHOWN.

HERE THE GRAIN SIZE AND RESULTANT PROPERTIES CAN BE VARIED BY THE CONJONT INFLUENCE OF COLD WORKING AND ANNEALING.

ANNEALING IN THE BETA REGION AT 1000°C FOLLOWED BY RAPID COOLING TO 25°C BY MEANS OF WATER QUENCH PRODUCES THE STRUCTURE SHOWN IN THE MICROGRAPH.

RAPID COOLING DOES NOT TRANSFORM THE BETA-TO-ALPHA TRANSFORMATION.

COOLING SLOWLY RESULTS IN THE MICROSTRUCTURE SHOWN.

THE STRUCTURE IS COMPLETELY ALPHA, BUT THE GRAIN BOUNDARIES ARE LESS IRREGULAR THAN THOSE PRODUCED UPON COOLING RAPIDLY.

THE TITANIUM GRADES HAVE VARYING AMOUNTS OF IMPURITIES: examples: carbon, nitrogen, hydrogen, oxygen.

SOME OF THE MODIFIED GRADES CONTAIN SMALL AMOUNT OF Palladium addition (0.2 Pd), and even Nickel-Molybdenum (Ni-Mo) additions.

SMALL AMOUNTS OF THE INTERSTITIAL IMPURITIES GREATLY AFFECTS THE MECHANICAL PROPERTIES OF PURE TITANIUM METAL.
The Ti-6Al-4V, α+β heat-treated at 1020°C/1h/WC. Optical micrograph shows equiaxed α and transformed β microstructure with prior β boundaries. The volume fraction of α increases with a decrease in cooling rate, and transformed β becomes coarser. The Ti-6Al-4V, α+β heat-treated at 960°C/1h/WC. Optical micrograph shows equiaxed α and transformed β microstructure. The Ti-6Al-4V, α+β heat-treated at 1020°C/1h/FC. Optical micrograph shows martensitic structure with prior β boundaries. The Ti-6Al-4V, α+β heat-treated at 960°C/1h/FC. Optical micrograph shows Widmanstätten α structure with α phase present on prior β grain boundaries.

STRESS VERSUS STRAIN CURVES FOR SEVERAL TITANIUM MATERIALS PLUS STEEL AND ALUMINUM. IMPURITIES PRESENT IN TITANIUM (weight %) [0.04 O, 0.01 N, 0.002 H, 0.04 Fe, 0.010 C]

COMPOSITION-ALLOY-PROPERTIES
- THE TITANIUM GRADE PRODUCES ARE READILY DISTINGUISHED BY THEIR MECHANICAL PROPERTIES.
- FOR A GIVEN LEVEL OF INTERSTIAL CONTENT OR MINOR ALLOY ELEMENT CONTENT, THE PROPERTIES OF COMMERCIAL GRADE TITANIUM METAL ARE PRIMARILY A FUNCTION OF (a) GRAIN SIZE, (b) GRAIN SHAPE, (c) GRAIN ORIENTATION, and (d) AMOUNT OF COLD WORK GIVEN TO THE METAL.
• THE ELEVATED TEMPERATURE BEHAVIOR OF THE TITANIUM GRADES HAVE BEEN THE SUBJECT OF FEW INDEPENDENT INVESTIGATIONS.
• HOWEVER, THESE ALLOYS ARE NOT CUSTOMARILY USED AT HIGH TEMPERATURES.
• OVERALL, THE NEAR ALPHA and ALPHA-BETA ALLOYS ARE THE PREFERRED MATERIALS WHERE GOOD MECHANICAL PROPERTIES ARE DESIRED.

THE ALPHA and NEAR-ALPHA ALLOYS of TITANIUM

• THE ALPHA ALLOYS FIND USE IN GAS TURBINE APPLICATIONS.
• FEW OF THE ALLOYS ARE USEFUL AT TEMPERATURES ABOVE THE NORMAL RANGE FOR THE "WORK HORSE" ALPHA-BETA ALLOY Ti-6Al-4V.
• FEW OF THE ALPHA ALLOYS HAVE BETTER CREEP RESISTANCE THAN THE "WORK HORSE" ALLOY Ti-6Al-4V.
• THE CREEP RESISTANCE IS NOTICEABLY ENHANCED WITH THE PRESENCE OF A FINE AICULAR STRUCTURE.
• THE ALPHA ALLOYS HAVE ALPHA AS THEIR COMMON PHASE AT LOW TEMPERATURE, i.e., BELOW 800°C.

THE ALPHA-BETA ALLOYS

• THE MOST IMPORTANT TITANIUM ALLOY IS THE ALPHA-BETA ALLOY Ti-6Al-4V.
• THIS ALLOY HAS THROUGH THE YEARS FOUND APPLICATION FOR A WIDE VARIETY OF AEROSPACE COMPONENTS AND FRACTURE CRITICAL PARTS.
• IT HAS A STRENGTH-TO-DENSITY RATIO of 25 x 10^6.
• THIS IS NOTICEABLY A LIGHTWEIGHT STRUCTURAL MATERIAL THAT OFFERS STRENGTH-TOUGHNESS COMBINATION THAT IS BETWEEN THOSE OF STEEL and ALUMINUM ALLOYS.

MORE on ALPHA ALLOYS

• THE ALPHA ALLOYS CONTAIN MUCH LESS OF THE BETA PHASE THAN Ti-6Al-4V.
• THUS, THE PROPERTIES OF THE ALPHA ALLOYS ARE BUT READILY AFFECTED OR ALTERED BY HEAT TREATMENT.
• AGE HARDENING TREATMENTS ARE NOT VERY EFFECTIVE BECAUSE THEY DEPEND ON PHASE TRANSFORMATIONS TO EFFECT STRENGTH IMPROVEMENTS.
• OFTEN, AGE HARDENING TREATMENTS ARE DELETERIOUS TO CREEP RESISTANCE.
• THE VIABLE MECHANISMS FOR STRENGTHENING THESE ALLOYS ARE (i) COLD WORKING, (ii) COLD WORK plus ANNEALING, and (iii) SOLUTE ADDITIONS FOR SOLID SOLUTION STRENGTHENING.

THE ALPHA-BETA ALLOYS (Continued)

• ESSENTIALLY, ALPHA IS THE DOMINANT PHASE IN THESE ALLOYS.
• A FEW OF THE ALLOYS THAT POSSESS THIS MICROSTRUCTURE ARE MORE READILY RECEPTIVE TO HEAT TREATMENT THAN Ti-6Al-4V.
• THIS CAPABILITY ARISES FROM THE INCREASED SOLID SOLUTION STRENGTHENING AFFORDED BY BOTH TIN AND ZIRCONIUM
STRUCTURES and STRENGTHENING

- The alpha stabilizing elements aluminum and tin are added to titanium to promote stabilization of the alpha phase over the beta phase while concurrently increasing the strength of titanium by solid solution strengthening.
- The aluminum is balanced by the beta stabilizers so that the resultant product has a mixture of both alpha and beta phases available to control properties.
- The effectiveness of tin as a strengthening element begins to level off at low levels.

MORE ON THE ADDITION OF ELEMENTS

- The addition of beta favoring alloying elements does permit solution heat treatment at lower temperatures.
- These elements tend to solid solution harden the alloy.
- The beta favoring elements can also retard the formation of alpha so that beta is transformed to martensitic or is retained to transform later to alpha.
- Overall, the relative amounts of primary alpha, retained beta and martensitic alpha are a function of alloy chemistry and prior thermal treatment.

SO WHY THEN MICROSTRUCTURAL CONTROL?

- This is effectively effected by using a proper combination of hot work and heat treatment.
- Heat treatment by itself does not suffice to convert the "widmanstatten" structure to an equiaxed form.
- Essentially heat treatment is not used unless a transformed structure is desired.
- Grain refinement cannot be obtained by heat treatment alone.

PROPERTY DEVELOPMENT

- When the alpha-beta titanium alloys are heat treated high in the alpha-beta range and cooled, the resultant structure is equiaxed because of the presence of equiaxed primary alpha in the transformed beta (plate-like) matrix.
- When a 100 percent transformed beta structure is achieved, the structure is called acicular or needle-like.
- Generally the alpha-beta alloys are annealed just below the beta transus to produce a maximum of transformed acicular beta with minimum of equiaxed alpha.

RELATIVE ADVANTAGES OF EQUIAXED AND ACICULAR MICROSTRUCTURES

<table>
<thead>
<tr>
<th>Microstructure</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equiaxed</td>
<td>Higher ductility and formability</td>
</tr>
<tr>
<td></td>
<td>Higher threshold stress for hot work stress corrosion</td>
</tr>
<tr>
<td></td>
<td>Higher strength for equivalent heat treatment</td>
</tr>
<tr>
<td></td>
<td>Better hydrogen tolerance</td>
</tr>
<tr>
<td></td>
<td>Better low-cycle fatigue (fatigue) properties</td>
</tr>
<tr>
<td>Acicular</td>
<td>Superior creep properties</td>
</tr>
<tr>
<td></td>
<td>Higher fracture toughness values</td>
</tr>
</tbody>
</table>

TYPICAL YIELD AND FRACTURE TOUGHNESS OF SEVERAL ALPHA-BETA TITANIUM ALLOYS

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Alpha morphology</th>
<th>Yield Strength</th>
<th>Fracture Toughness (K&lt;sub&gt;IC&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MPa</td>
<td>ksi</td>
</tr>
<tr>
<td>Ti-4Al-2Sn</td>
<td>Equiaxed</td>
<td>910</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Transformed</td>
<td>875</td>
<td>125</td>
</tr>
<tr>
<td>Ti-4Al-6V-2Sn</td>
<td>Equiaxed</td>
<td>1085</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>Transformed</td>
<td>1050</td>
<td>140</td>
</tr>
<tr>
<td>Ti-6Al-4V-5Fe-2Mo</td>
<td>Equiaxed</td>
<td>1155</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>Transformed</td>
<td>1120</td>
<td>160</td>
</tr>
</tbody>
</table>
MICROSTRUCTURE and HARDENABILITY

HARDENABILITY OF THE ALPHA-BETA ALLOYS

- The structure of the titanium alpha-beta alloys of titanium is controlled by:
  (a) How much working is done.
  (b) By how close to, or how much above, the beta transus the alloy is processed
  (c) By section size of the component.
- Most alpha-beta alloys do not have great hardenability.
- The alloy Ti-6Al-4V only has sufficient hardenability to be effectively heat treated to full property levels.
- Essentially, for the alpha-beta alloys having low hardenability, the effective cooling rates for optimum property achievement can be dramatically reduced.

HEAT TREATMENT (AGING) and ALLOY RESPONSE

RELATIONSHIP OF AGING TO STABILITY IN THE ALPHA-BETA ALLOYS

- A least understood concept in the behavior of alpha-beta alloys is the kinetics of aging.
- Titanium alloys do not age in the classical sense, wherein a secondary, strong intermetallic compound forms and strengthens the alloy matrix by dispersion.
- A dispersion of the second phase is certainly produced on aging the alpha-beta alloys.

Typical microstructures of ALPHA, ALPHA-PLUS-BETA and BETA TITANIUM ALLOYS

Typical room-temperature tensile properties and corresponding microstructure for Ti-6Al-4V for different thermal treatments

<table>
<thead>
<tr>
<th>Thermal Treatment</th>
<th>Yield Strength</th>
<th>Ultimate Tensile</th>
<th>Elongation at Fracture, %</th>
<th>Reduction in Area, %</th>
<th>Microstructure</th>
<th>Phase Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>955°C furnace cooled</td>
<td>834 MPa 121 ksi</td>
<td>937 MPa 136 ksi</td>
<td>19% 46%</td>
<td></td>
<td>90% alpha; 10% beta</td>
<td></td>
</tr>
<tr>
<td>961°C furnace cooled</td>
<td>951 MPa 138 ksi</td>
<td>1117 MPa 162 ksi</td>
<td>17% 60%</td>
<td></td>
<td>50% primary alpha; 50% primary alpha + retained beta</td>
<td></td>
</tr>
<tr>
<td>900°C furnace cooled</td>
<td>855 MPa 124 ksi</td>
<td>965 MPa 140 ksi</td>
<td>17% 43%</td>
<td></td>
<td>90% alpha; 10% beta</td>
<td></td>
</tr>
<tr>
<td>923°C water quenched</td>
<td>923 MPa 134 ksi</td>
<td>1117 MPa 162 ksi</td>
<td>15% 54%</td>
<td></td>
<td>60% primary alpha; 40% primary alpha + retained beta</td>
<td></td>
</tr>
<tr>
<td>900°C water quenched</td>
<td>923 MPa 134 ksi</td>
<td>1117 MPa 162 ksi</td>
<td>18% 64%</td>
<td></td>
<td>50% primary alpha; 50% primary alpha + retained beta</td>
<td></td>
</tr>
</tbody>
</table>
THE AGING KINETICS OF THE ALPHA-BETA ALLOYS

- It is essentially the beta phase that is dispersed in the alpha phase or the martensitic alpha phase.
- The effectiveness of strengthening the alpha-beta alloys appears to center on both the number and fineness of the alpha-beta phase boundaries.
- Annealing and rapid cooling, which maximizes alpha-beta boundaries for a fixed primary alpha content, along with aging, can promote additional boundary structure, which tends to enhance the strength of the alloy.

EFFECT OF ORIENTATION (LONGITUDINAL versus TRANSVERSE) on PROPERTIES

- Another governing or influencing factor about strengthening a titanium alloy is the effect of testing direction.
- The texture and mechanical working effects on directionality of the structure can be significant.
- Under normal conditions substantial differences are obtained with the test direction.

THE FASCINATION of the BETA ALLOYS

- An alloy is considered to be a beta alloy if it contains a sufficient beta stabilizing alloying element to retain the beta phase without transformation to martensite upon quenching to room temperature.
- A few titanium alloys do contain more than this minimum amount of beta stabilizing alloy addition.
- The solute lean beta alloys are classified as the beta-rich alpha-beta alloys.

THE AGING KINETICS OF THE ALPHA-BETA ALLOYS

- It is essentially the beta phase that is dispersed in the alpha phase or the martensitic alpha phase.
- The effectiveness of strengthening the alpha-beta alloys appears to center on both the number and fineness of the alpha-beta phase boundaries.
- Annealing and rapid cooling, which maximizes alpha-beta boundaries for a fixed primary alpha content, along with aging, can promote additional boundary structure, which tends to enhance the strength of the alloy.

EFFECT OF AGING ON ROOM-TEMPERATURE TENSILE PROPERTIES OF ALPHA-BETA TITANIUM ALLOY Ti-6Al-4V

<table>
<thead>
<tr>
<th>Thermal Treatment</th>
<th>Tensile Strength, MPa</th>
<th>Yield Strength, MPa</th>
<th>Elongation at Fracture, %</th>
<th>Reduction in Area, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>955 °C (1751 °F)</td>
<td>1017</td>
<td>951</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>1013 °C (1855 °F)</td>
<td>1069</td>
<td>1069</td>
<td>16</td>
<td>17</td>
</tr>
</tbody>
</table>

Effect of Test Direction on Mechanical Properties of Textured Ti-6Al-2Sn-4Zr-6Mo plate

<table>
<thead>
<tr>
<th>Test Direction</th>
<th>Tensile Strength, MPa</th>
<th>Yield Strength, MPa</th>
<th>Elongation at Fracture, %</th>
<th>Reduction in Area, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1027</td>
<td>1017</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>T</td>
<td>1358</td>
<td>1358</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>S</td>
<td>938</td>
<td>938</td>
<td>6.5</td>
<td>26</td>
</tr>
</tbody>
</table>

- There is no truly stable beta alloy primarily because even the most highly alloyed beta will, upon holding at high temperatures, precipitate either as the alpha phase, Ti₃Al or silicides depending on temperature, time and alloy composition.
- All beta alloys do contain trace amounts of aluminum, an alpha stabilizing element, in order to strengthen the alpha that may be present after heat treatment.
INTER-RELATIONSHIP BETWEEN COMPOSITION and PROCESSING

- The composition of the precipitating alpha phase is not constant and largely depends on temperature of heat treatment.
- The higher the temperature in the alpha-beta phase field, the higher will be the aluminum content in the alloy.
- The processing window of the beta alloys is certainly much tighter than that normally used for the alpha alloys and the alpha-beta alloys.

ROLE of PROCESSING of BETA ALLOYS

- The thermomechanical processing (TMP) is critical to the property combinations achieved because this has a strong influence on (a) final microstructure, and (b) resultant mechanical properties.

STRUCTURE-PROPERTY (MECHANICAL) RELATIONSHIP

- In the fully annealed condition, the alpha-beta alloy (Ti-6Al-4V) derives its annealed strength from several sources.
- The principal source is a combination of substitutional and interstitial alloying of the elements in solid solution in both the alpha and beta phases.
- Oxygen, nitrogen, hydrogen and carbon are the interstitial elements which generally increase strength while degrading ductility.

THE ROLE OF ALUMINUM IN STRENGTHENING TITANIUM

- Aluminum is the most important substitutional solid solution strengthenener.
- Its effect on strength of the titanium alloy is essentially linear.

OTHER SOURCES CONTRIBUTING TO STRENGTH

- Other less important sources of strengthening are the following:
  1. Interstitial solid solution strengthening.
  2. Grain size strengthening.
  4. Ordering in the alpha phase.
  5. Age hardening.
The "WORK-HORSE" ALLOY
Processing-Microstructure-Properties

- At room temperature the Ti-6Al-4V alloy is about 90 percent alpha and thus the alpha phase dominates the physical and mechanical properties of the alloy.

- The overall effects of processing history and heat treatment on microstructure are complex and involved.

- Microstructure depends on the conjoint influence of processing history and concomitant heat treatment.

THE "ESSENCE"

- The microstructure that combines the highest static strength and ductility is not necessarily the microstructure that provides
  (a) an optimum fracture toughness,
  (b) good fatigue resistance or resistance to crack growth.

HEAT TREATMENT and MICROSTRUCTURE

- The beta phase present in the work-horse alloy Ti-6Al-4V can be manipulated both in amount and composition by heat treatment.

- The transformation of beta to a alpha-beta reaction at low temperatures leads to an increase in strength.

- The key is to quench from a high temperature in the alpha plus beta field and then age at a lower temperature.

INCORRECT PROCESSING

- When an alloy such as the Ti-6Al-4V is processed improperly after heating into the beta field, the alpha phase can form preferentially along the prior beta grains.

- Extensive hot working is required to break up such structures.

THE ALPHA and NEAR ALPHA ALLOYS

- The Ti-8Al-1Mo-1V alloy is a classical example of a near alpha category.

- This particular alloy has the highest modulus and lowest density of any commercial alloy.

- The Ti-6Al-2Sn-4Zr-2Mo-0.08Si alloy is one of the most creep resistant titanium alloys.

- This particular alloy offers an outstanding combination of tensile strength, creep strength, toughness and high temperature stability for long term or extended term applicability at temperatures up to 420°C

THE "KEY" ALLOY TYPES
THE BETA ALLOYS

- There is no single beta alloy having the same broad applicability as Ti-6Al-4V.
- Specific beta alloys are chosen and used because their properties suit a particular application.
- The beta alloys are chosen and used for workability, corrosion resistance, coupled with intrinsic ability to heat treat large section sizes than the alpha-beta alloys.
- Most noticeably the beta and beta-rich alpha-beta alloys offer an opportunity to tailor the combinations of strength and toughness properties for a specific application.

OVERALL, MODERATE STRENGTH with high toughness or high strength with moderate toughness can be easily achieved for the beta alloys.

This is generally not possible with the other types of titanium alloys because they cannot be heat treated over a wide range of temperatures.

UNDERSTANDING THE STATIC PROPERTIES OF TITANIUM ALLOYS

In terms of the principal heat treatments used for titanium, annealing of the alpha-beta alloys does tend to decrease strength by 35-100 MPa depending on:
1. Prior grain size
2. Crystallographic texture
3. Testing direction.

Room-temperature tensile properties for selected titanium alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Nominal composition</th>
<th>Condition</th>
<th>Room temp TS (MPa)</th>
<th>Room temp YS (MPa)</th>
<th>760 TS (MPa)</th>
<th>760 YS (MPa)</th>
<th>870 TS (MPa)</th>
<th>870 YS (MPa)</th>
<th>930 TS (MPa)</th>
<th>930 YS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1210 Ti6Al4V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1280 Ti6Al4V</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1350 Ti6Al4V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

TENSILE and CREEP-RUPTURE PROPERTIES

Overall, the titanium alloys not only have higher room temperature strength but also retain much larger fractions of the strength at elevated temperatures.

In terms of the principal heat treatments used for titanium, annealing of the alpha-beta alloys does tend to decrease strength by 35-100 MPa depending on:
- Prior grain size
- Crystallographic texture
- Testing direction.

Percent of room-temperature strength retained at elevated temperature for several titanium alloys

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100</td>
<td>86</td>
<td>73</td>
<td>67</td>
<td>61</td>
<td>57</td>
<td>53</td>
<td>50</td>
<td>47</td>
<td>44</td>
</tr>
<tr>
<td>2200</td>
<td>85</td>
<td>72</td>
<td>66</td>
<td>60</td>
<td>56</td>
<td>53</td>
<td>50</td>
<td>47</td>
<td>44</td>
</tr>
<tr>
<td>2300</td>
<td>84</td>
<td>71</td>
<td>65</td>
<td>60</td>
<td>56</td>
<td>53</td>
<td>50</td>
<td>47</td>
<td>44</td>
</tr>
<tr>
<td>2400</td>
<td>83</td>
<td>70</td>
<td>64</td>
<td>59</td>
<td>55</td>
<td>52</td>
<td>50</td>
<td>47</td>
<td>44</td>
</tr>
<tr>
<td>2500</td>
<td>82</td>
<td>69</td>
<td>63</td>
<td>60</td>
<td>56</td>
<td>53</td>
<td>50</td>
<td>47</td>
<td>44</td>
</tr>
</tbody>
</table>

Note: The results are for a single 1.0 in. diameter mill test bar, room temp TS, and strength.
HEAT TREATMENT and STRENGTH of TITANIUM ALLOYS

- A COMBINATION of SOLUTION HEAT TREATMENT AND AGING CAN BE USED TO ENHANCE STRENGTH AT THE EXPENSE OF FRACTURE TOUGHNESS IN ALLOYS CONTAINING SUFFICIENT amount of the BETA STABILIZING ELEMENTS.

FRACTURE TOUGHNESS of TITANIUM ALLOYS

- BASIC ALLOY CHEMISTRY AFFECTS THE RELATIONSHIP BETWEEN STRENGTH and TOUGHNESS.
- THE TRANSFORMED MICROSTRUCTURES TEND TO GREATLY ENHANCE TOUGHNESS WHILE SLIGHTLY REDUCING STRENGTH.
- TOUGHNESS IS LARGELY DEPENDENT ON THERMO-MECHANICAL PROCESSING (TMP) TO PRODUCE THE DESIRED STRUCTURE.

TOUGHNESS VERSUS YIELD STRENGTH OF A SOLUTE-LEAN BETA TITANIUM ALLOY, Ti-5Al-2Sn-4Zr-2Mo-2Cr, PROCESSED TO TWO DIFFERENT STRUCTURES

MICROSTRUCTURE and TOUGHNESS

- FRACTURE TOUGHNESS CAN BE VARIED WITHIN A NOMINAL ALPHA-BETA ALLOY BY AS MUCH AS A MULTIPLE OF TWO or THREE.
- THIS IS EASILY ACCOMPLISHED BY MANIPULATING ALLOY (a) CHEMISTRY, (b) MICROSTRUCTURE, and (c) TEXTURE.
- THE MICROSTRUCTURAL OBJECTIVES IN BETA TITANIUM ALLOYS RANGE FROM (a) FULLY TRANSFORMED, AGED BETA STRUCTURES, to (b) CONTROLLED AMOUNTS OF ELONGATED PRIMARY ALPHA IN AN AGED BETA MATRIX.
CHEMISTRY-IMPURITY CONTENT-TOUGHNESS

- Within the permissible range of chemistry for a specific titanium alloy and grade, oxygen is an important variable insofar as its effect on toughness is concerned.
- If high fracture toughness is desired, then the oxygen content has to be kept low, all other things being equal.
- Reducing nitrogen is also beneficial, but the effect is not as strong as in the case of oxygen.

UNDERSTANDING THE MARVELS and MYSTERIES BEHIND FATIGUE DEFORMATION: Specifically CYCLIC FATIGUE

THE CYCLIC BEHAVIOR OF TITANIUM ALLOYS

- Fatigue can be succintly rationalized as cyclic degradation of strength capability of a material.
- Fatigue damage depends on the independent or mutually interactive influences of the following:
  1. Alloy Chemistry
  2. Alloy Structure
  3. Surface Treatment
  4. Stress Levels, and
  5. Mode of Application of Stress.

CLASSIFYING THE FATIGUE BEHAVIOR

- Bearing in mind that failure cycles in the range less than $3 \times 10^4$ cycles are classified as the domain of low cycle fatigue.
- Failure at and above $10^6$ cycles are classified as high cycle fatigue (HCF).
- For titanium alloys the fatigue cycles can be induced by
  1. Mechanical means.
  2. Thermal means.
  3. Combined mechanical and thermal means (thermo-mechanical treatment).

“FATIGUE” that is SOLELY THERMALLY-INDUCED IS KNOWN AS “THERMAL FATIGUE”.
MICROSTRUCTURE-COMPOSITION-PROPERTIES-FATIGUE RESISTANCE

- WITH SPECIFIC REFERENCE TO THE UNALLOYED TITANIUM METAL, FATIGUE LIFE DEPENDS ON
  (i) GRAIN SIZE.
  (ii) INTERSTITIAL CONTENT.
  (iii) DEGREE OF COLD WORKING.

- A DECREASE IN GRAIN SIZE IN AN UNALLOYED TITANIUM FROM 110 to 6 microns IMPROVES the 10^7 CYCLE FATIGUE ENDURANCE LIMIT BY AS MUCH AS thirty PERCENT.

- THE HIGH CYCLE FATIGUE LIMIT OF UNALLOYED TITANIUM DEPENDS ON INTERSTITIAL CONTENT JUST AS TENSILE YIELD STRENGTH and ULTIMATE TENSILE STRENGTH.

MORE ON FATIGUE OF THE ALLOYS OF TITANIUM

- IN ADDITION TO THE ALPHA GRAIN SIZE, DEGREE OF AGING and OXYGEN CONTENT FOR THE NEAR ALPHA and ALPHA-BETA ALLOYS, FATIGUE PROPERTIES ARE MOST CERTAINLY AFFECTED BY THE MORPHOLOGY AND ARRANGEMENT OF BOTH THE ALPHA AND BETA PHASES.

- THE TITANIUM FATIGUE PROPERTIES ARE EVEN MORE DEPENDENT ON STRUCTURE THAN ARE THE STATIC PROPERTIES.

MICROSTRUCTURE & FATIGUE LIFE

- ESSENTIALLY, THE IMPORTANT PARAMETERS OF MICROSTRUCTURE AFFECTS ON FATIGUE LIFE OF THE TITANIUM ALLOYS ARE
  (a) THE PRIOR BETA GRAIN SIZE
  or
  (b) COLONY SIZE OF THE ALPHA and BETA LAMELLAE IN A FULLY LAMELLAR MICROSTRUCTURE.
MICROSTRUCTURAL PARAMETERS

- The important parameters of microstructure affecting fatigue of titanium alloys are the prior beta grain size or colony size of the alpha and beta lamellae in a fully lamellar microstructure.

- Overall, the finer the lamellae in the transformed beta phase, the stronger the alloy in fatigue.

CRACK INITIATION IN FATIGUE

- The time to the first crack, at a fixed strain, varies with microstructure of the alpha-beta alloy.

- The time to crack initiation is optimized with a structure that has high amounts of transformed beta.

- Overall, the crack propagation resistance of the beta-processed alloy still exceeds the alpha-processed material.

SOME MORE ON FATIGUE RESPONSE and/or CHARACTERISTICS

- The low cycle fatigue behavior of the titanium alloys is difficult to quantify due to the wide range of variables and to a limited amount of published data in the open literature.

- In general data available in the open published literature is on stress-controlled fatigue and not strain-controlled fatigue.

- The microstructure of a forging is quite different from the microstructure of a bar stock.

HIGH CYCLE FATIGUE BEHAVIOR OF ALLOYS OF TITANIUM

- Depending on the alloy the fatigue endurance limit tends to be relatively flat with temperatures up to 300°C and above.

- Normally, there will result a range of data scatter that can be found in a given alloy of titanium at a given stress intensity and temperature.

MICROSTRUCTURE & HIGH CYCLE FATIGUE OF TITANIUM ALLOYS

- Microstructures of the alloys having lower primary alpha content revealed superior high cycle fatigue resistance.

- This superiority is ascribed to the absence of grain boundary alpha.
HIGH-CYCLE (5X10^7 cycles) FATIGUE STRENGTH TO-FAILURE OF SEVERAL TITANIUM ALLOYS COMPARED WITH SOME STEELS ONCE USED IN THE COMPRESSOR SECTIONS OF GAS TURBINES.

CURVES DEPICTING STRESS VERSUS CYCLES TO FAILURE FOR COARSE-GRAINED Ti-6Al-2Sn-4Zr-2Mo ALLOY WITH AND WITHOUT THERMO-MECHANICAL PROCESSING (TMP) TO PRODUCE LOCAL GRAIN REFINEMENT AT THE SURFACE.

CURVES DEPICTING STRESS VERSUS CYCLES TO FAILURE FOR Ti-6Al-2Sn-4Zr-2Mo ALLOY WITH AND WITHOUT THERMO-MECHANICAL PROCESSING TO PRODUCE LOCAL GRAIN REFINEMENT AT THE SURFACE.

TYPICAL DUCTILE FRACTURE IN A Ti ALLOY SHOWING FINE EQUIAXED DIMENTES.

TYPICAL TRANSCRYSTALLINE CLEAVAGE FRACTURE IN TITANIUM ALUMINIDE.

TYPICAL FATIGUE FRACTURE SHOWING STRIATIONS.
TYPICAL INTER-CRYSTALLINE FRACTURE IN A Ti ALLOY

SURFACE TREATMENT and CYCLIC FATIGUE

- Titanium alloy fatigue capability can be significantly affected or altered not only by microstructure, but also by the surface condition.
- Fatigue data reported in the published literature is on material having favorable residual stresses induced by processes such as turning and milling.
- Fully stress relieved and even the chemically milled surfaces have inferior high cycle fatigue resistance when compared to the stress component.

INTRINSIC INFLUENCE of SURFACE TREATMENT

- Essentially mechanical surface treatments such as shot peening, polishing, surface rolling have been successfully used to improve the endurance limit of titanium alloys by altering the:
  1. Extent and severity of surface roughness,
  2. Degree of cold working or strain hardening.
  3. Dislocation density
  4. Residual stresses

EFFECTS OF SURFACE CONDITION ON LOW-CYCLE FATIGUE LIFE OF Ti-6Al-4V at 21°C (70°F)

THE ROLE OF SURFACE and FATIGUE RESPONSE

- Essentially the surface roughness determines and/or dictates if fatigue strength is controlled by crack nucleation or by crack propagation.
- Overall, great care must be taken in the preparation of titanium surfaces so as to not introduce any defects in the form of scratches, notches, burns.
- Ordinary machining may be beneficial to fatigue strength as does surface modification by shot peening to induce favorable residual stresses.

FATIGUE CRACK PROPAGATION

- The alloys of titanium have different FCP characteristics just as they have different Stress (S)-Fatigue Life (N) Characteristics.
- Selected data taken from the open literature does indicate that the cracks propagate easily and rapidly in alloys having high strength.
- Relative alloys of the beta phase in alpha-beta alloys can result in intrinsically different fatigue crack propagation characteristics.
IN A NUTSHELL

- Intrinsic variation in microstructure produces parallels between fracture toughness and fatigue crack propagation resistance.
- Both $K_I$ and FCP are favorably influenced by a transformation microstructure and also by the application of thermal cycles of recrystallization-anneal.
- Overall, the beta annealed microstructures in near alpha and the alpha-beta alloys have the least fatigue crack growth rates.
- The mill annealed microstructures yield the highest growth rates.

ROLE OF PRODUCT FORM ON CRACK PROPAGATION

- Results from bar stock tend to differ from those of sheet stock and even forgings.
- This is a serious issue or cause for concern since destruction of forgings, with specific reference to the aerospace industry, is not to be taken lightly.

THE HIGHLIGHTS THAT WARRANT CONSIDERATION and COMFORT

- For well over a decade and approaching the titanium industry has experimented with the development of alloys and processes specifically designed to reduce the overall cost of titanium.
- During the early stages the lower cost was achieved through direct modification to arc melting practices and to subsequent fabrication steps.
- Resurgence of the titanium industry towards the end of last decade hampered the urgency to reduce cost to produce titanium.
HIGHLIGHTS (Continued)

• QUESTION OF WHETHER LOWER COST TITANIUM ARE USED WILL BE DETERMINED BY PRODUCER CAPACITY TO MAKE SPONGE and THE EXTENT TO WHICH PRODUCERS AND USERS ARE WILLING TO DEVOTE RESOURCES TO GENERATE DESIGN DATA.

• APPLICATIONS FOR LESS DEMANDING AND LESS LIFE-THREATENING SITUATIONS SPANNING THE AUTOMOTIVE SECTOR and DEFENSE SECTOR HAVE A FAIRLY GOOD CHANCE FOR RESURRECTING ABUNDANCE OF INTEREST IN ENGINEERING LOWER COST TITANIUM ALLOYS.

NEAR NET SHAPE CAN CUT THE COST OF TITANIUM PRODUCTS.

• EXPANDED USE OF TITANIUM SCRAO IS ESSENTIAL and LIKELY.

• RELAXATION and CONSOLIDATION OF SPECIFICATIONS CAN HELP IN ENABLING PRODUCERS TO REDUCE COSTS.

Structural and Building Applications of Titanium

Developed by
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MC Consulting
Huletts Landing, New York

Titanium Structural Applications Forum
Stark State College, Canton, Ohio
April 22, 2008

Objectives

• Provide an overview of titanium and titanium alloys most suitable for building and structural applications

• Provide an overview of the characteristics of titanium that may be useful for S&B

• Review industrial corrosion structural applications

• Review specific cases in building and structural applications

Titanium Characteristics

• Titanium is an element

• No. 22 on the Periodic Chart

• It is the ninth most abundant element and the fourth most abundant metallic element

• Titanium metal is a dull gray in color

• Titanium is a reactive metal that gains its corrosion resistance from a thin protective oxide film

• TiO₂ as a pigment is one of the brightest and whitest materials known

Titanium Physical Properties

• Density 4.51 (0.163 lbs/cu.in)

• Elastic Modulus, E 14.9 x 10⁵ psi

• Modulus of Rigidity, G 6.0 x 10⁴ psi

• Poisson’s Ratio 0.32

• Therm. Expan Coef. 4.6 to 5.2

• Melting Point 3100°F

Near Net Shape Can Cut the Cost of Titanium Products.

Expanded Use of Titanium Scrao Is Essential and Likely.

Relaxation and Consolidation of Specifications Can Help in Enabling Producers to Reduce Costs.
Titanium Applications

- Earliest Titanium Surface Condensers used thin wall titanium tubing installed by rolling only

Titanium Applications

- Plate heat exchangers use thin sheet formed to create flow passages. Installation does not require welding.

Titanium Applications

- Dimensionally stable titanium anodes replaced mercury in electrolytic cells for chlorine production

Industrial Corrosion Applications

- Pulp Washers: Welded in two halves, field assembled, unalloyed Grade 2 titanium valves, 0.078" and 0.125" Gr. 26 flanges for crevice corrosion resistance

Industrial Corrosion Applications

- Integrally Stiffened Titanium Grade 2 Brine Reservoir for Chlorine Production, 6.078" and 6.125", Gr. 26 flanges for crevice corrosion resistance
Industrial Corrosion Applications

- Repetitive Production Reduced Cost Significantly

  Extensive use of forming (drawing and forming) saved significantly on welding cost while reducing stresses at welds and stiffness changes.

Nonmagnetic Characteristic Application

- Titanium Crane Hook

  Used in aluminum smelter for nonmagnetic characteristics.

Structural & Corrosion Applications

- NASA Space Shuttle Manipulator Arm
- Training Tank (Johnson Space Center)

Transportation Applications

- 4400 Gallon Nitric Acid Tank Trailer

  First all-titanium MC-2312 cargo tank trailer in USA
  - Corrosion resistance and weight reduction

Other Marine Titanium Applications

- Helicopter Transportable Hyperbaric Diver Rescue System – Ti 6Al-4VELI

Marine Structural Applications

- Current Alvin Frame

  Grade 2 unalloyed titanium fabricated standard plate and pipe.
Marine Structural Applications

Shinkai 6500 Frame

Alloy thought to be similar to Grade 2, fabricated of rectangular and round tubular products, simple welded joints.

Other Marine Titanium Applications

Spars & Mast for 12 Meter America’s Cup Sailboat

Why Choose Titanium?

Thermal expansion coefficient compatible with glass and certain composites

<table>
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<th>Material</th>
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<th>in/in/°F</th>
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<tr>
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<tr>
<td>Aluminum</td>
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</table>

Titanium Production

Availability of Ti Materials

- Product forms like plate, sheet, coil, strip, billet, bar, wire, pipe, tube, castings covered by ASTM Standards.
- Shapes produced only by extrusion due to quantities usually required. Could be hot rolled.
- Ingots up to 30,000 pounds allow very large components.
- Several companies have added significant capacity in the past 5 years.
- Explosion clad plate products.

Cost Issues

- Cost per pound is high. Cost per “board foot”, “unit of strength”, or unit of practical use is a better measure (example roofing system).
- 1 square meter of 0.060” copper weighs 30 pounds.
- 1 square meter of 0.040” copper weighs 20 pounds.
- 1 square meter of 0.040” titanium weighs 10 pounds.
- 1 square meter of 0.020” titanium weighs 5 pounds.
- Use thin sections, e.g., 0.016 to 0.020” for sheathing and roofing (no corrosion losses).
- Take advantage of large surface to unit weight, e.g., sheet or tubular forms.
**Cost Issues**

- High welding cost – minimize or eliminate welding in design
- Use more sophisticated joint details to simplify welds
- Move welds away from section changes and other stress raisers
- Where welding is required, consider high productivity processes like EB and laser welding

**Titanium Application Guidelines**

- Minimize section thickness
- Minimize welding
- Use repetitive details to allow mass production of components

**Why Choose Titanium?**

- Long life and low maintenance may produce Lowest life cycle cost

**Typical Structural Applications**

- Building sheathing
- Roofing systems
- Low or zero maintenance structures
- Weight critical structures or structures with center of gravity limitations
- Structural members for signature projects
- Ice shields on bridges
- Cable supports

**ASTM Grades and Specifications**

- B265-07 Titanium and Titanium Alloy Strip, Sheet, and Plate
- B338-06a Seamless and Welded Titanium and Titanium Alloy Tubes for Condensers and Heat Exchangers
- B348-06a Titanium and Titanium Alloy Bars and Billets
- B363-06a Seamless and Welded Unalloyed Titanium and Titanium Alloy Welding Fittings
- B367-06a Titanium and Titanium Alloy Castings
- B381-06a Titanium and Titanium Alloy Forgings
- B861-06a Titanium and Titanium Alloy Seamless Pipe
- B862-06c Titanium and Titanium Alloy Welded Pipe
- B863-06a Titanium and Titanium Alloy Wire

**Specification and Grade Selection**

**Which Grade?**

There are many proprietary and specialized grades. However, the most common grades have a well proven record in even polluted industrial atmospheric conditions, marine exposures, and seawater service, are readily available in a variety of product forms, can be fabricated using equipment similar to that used for stainless steel, are readily weldable, and have a range of properties from which to choose.
### Specification and Grade Selection

**Which Grade?**
- Available in required product forms and sizes?
- Adequate strength
- Adequate ductility & toughness
- Fabricable – formable, machinable
- Welding – readily weldable by GTAW?
- Cost – overall, including

### Grade Selection

**Common ASTM Grades**
- Grade 1 Unalloyed Titanium (35 ksi UTS/20 ksi YS)
- Grade 2 Unalloyed Titanium (50 ksi UTS/40 ksi YS)
- Grade 2H Unalloyed Titanium (58 ksi UTS/40 ksi YS)
- Grade 3 Unalloyed Titanium (65 ksi UTS/55 ksi YS)
- Grade 9 Ti 3AI-2.5V (90 ksi UTS/70 ksi YS)
- Grade 23 Ti 6AI-4V ELI (120 ksi UTS/110 ksi YS)
- Grade 5 Ti 6AI-4V (130 ksi UTS/120 ksi YS)

### Grade Selection

**Which Grade?**

Unalloyed (or Commercially Pure) Titanium (ASTM Grade 2, 2H, or 3) are most widely used in industrial corrosion applications
- Readily available in all product forms
- Good strength – 50, 58, 65 ksi UTS
- Sufficient ductility for most forming
- Tolerant to service damage
- Easier to fabricate than the higher strength Al-V alloys

### Grade Selection

**Which Grade?**

Unalloyed or CP Titanium (ASTM Grade 1) is widely used in applications requiring ductility
- Grade 1 is the easiest to form and draw of the grades suggested
- Grade 1 is readily available in sheet and coil product forms, but not in other product forms
- These grades have very good ductility and will be most tolerant to service damage

### Grade Selection

**Which Grade?**

Ti 3AI-2.5V, ASTM Grade 9, 90ksi/70 ksi UTS/YS is also widely used in aerospace hydraulic tubing, high strength industrial applications like oil production tubulars, and in bicycle frames

However:
- It is somewhat easier to fabricate than Grade 23
- It is available in bulk forms like billet, bar, heavy plate, and extrusions, but also in finished tubular products
- It has slightly better ductility than Grade 23, but will still be tolerant to service damage

### Grade Selection

**Which Grade?**

Ti 6AI-4V, ASTM Gr. 5 (130 ksi/120ksi UTS/YS) and Ti 6AI-4VELI, ASTM Gr. 23 (120 ksi/110ksi UTS/YS) are widely used in aerospace and high strength industrial applications

However:
- It is the most difficult to fabricate of the alloys suggested
- It is not readily available except in bulk forms like billet, bar, heavy plate, and extrusions
- It has relatively low ductility and will be less tolerant to service damage
Grade Selection

- Which Grade to Choose?
- Available in required product forms and sizes?
- Adequate strength
- Adequate ductility
- Adequate Toughness
- Fabricability – formable, machinable
- Welding – readily weldable
- Cost – overall, including

Welding Processes

- GTAW (gas tungsten arc welding) is most common process, can be used manually or automatically
- Keyhole TIG and Buried Arc TIG are high current GTAW suitable for butt welding plate up to 0.75”
- PAW (plasma arc welding) can be used like GTAW, but is generally used in automated seaming equipment only GMAW (gas metal arc welding) in limited use
- EB and LAW (electron beam and laser welding) are better suited for specialized and repetitive production cases
- RW (resistance welding) readily applicable to sheet structures with welding cost similar to other metals

Welding

Manual GTAW Applied to Titanium Pipe

Welding Design Considerations

- Minimize welding
- Use butt welds where possible
- Use similar welding details to the maximum possible extent
- Design joints that allow butt welds to be placed away from high stress areas and use that to reduce weight of adjacent components (fatigue and cyclic loading)
- Design for inspection of face and root sides

Welding Design

Why do welds fail?

- Welds are too often located at hard points and joints
- These are the points of highest real stress
- Move welds away from hard points and joints

Why do welds fail?

- Fillet and partial penetration welds include a sharp notch at the root
- Difficult to shield with inert gas – gas not pressurized or flowing to displace air
- Cannot be inspected visually
- Butt welds that avoid overlapping other welds are better – keep it simple!
Welding Design

- Design welds to allow for inspection of both surfaces if possible
- Avoid partial penetration welds in areas subject to fatigue
- Repairs are very difficult when the joint cannot be cleaned

Tubular vs. Open Sections

Open sections allow easy inspection of all surfaces
- Can be fabricated from sheet or plate by bending (alloys have limited bend radius)
- Extrusion is possible for open sections up to 5 – 6” diameter

- Tubulars are likely more efficient in truss type structures
- Tubulars readily available in a range of sizes likely to be required
- Minimal concern for internal corrosion
- Hidden interior surfaces difficult to inspect in service

Structural and Building Applications

Flame Holder for Nagama Winter Olympics - Color anodizing produces a full spectrum of colors

Color anodizing of titanium produces a full spectrum of colors based on refraction in transparent oxide film

Les Labyrinthes de l’Eternite Exhibit - d’Electricite de France - Paris

5,000 square feet of anodized titanium for light box exhibit

Titanium accent table with locally anodized color patches, lighted at night
**Structural and Building Applications**

**Titanium Water Fountain**
- 30 inch diameter

**Etched and anodized titanium vessel**
- 5 inch diameter

**Titanium Wall Hanging**
- Etched and anodized titanium and niobium 21”

**Denver Art Museum, Denver, Colorado**
- Titanium Cladding
- Architect David Childs

**Cerritos Millennium Library**

**Guggenheim Museum, Bilbao, Spain**
- Clad in polished titanium Grade 1 sheet
- Architect Frank Gehry
Structural and Building Applications

- **Guggenheim Museum, Bilbao, Spain**
  32,000 sq.m. of Grade 1 titanium sheet, manufactured to the architect's specification with a deliberately introduced ripple and soft textured finish.

- **National Scottish Science Center**
  Clad in polished titanium Grade 1 sheet.

- **Sun Plaza, Jakarta, Indonesia**
  36,000 sq. ft. undulating wall panels & canopy titanium Grade 1 sheet.

- **Vinos Herederos del Marques de Riscal winery in the Rioja region of Spain**

- **Okinawa Prefecture Building, Okinawa 21997**
  5,000 sq. m. 0.4 & 0.8 mm roll dull, seam welded.

- **Tokyo and Nara Museum Annex - 1998**
  6,300 sq. m. Alumina Blasted standing seam roof, titanium Grade 1 sheet.
Structural and Building Applications

Uchinada Town Office/Ishikawa Prefecture, Japan - 1998
1,700 sq. m Roll dull & green color development 0.4 mm stepped roofing, titanium Gr. 1 sheet

City Harvest Church, Singapore
18,000 sq. ft. flat seam panels, titanium Gr. 1 sheet

Issey Mikaya showroom, New York
8,000 sq. ft. titanium Gr. 1 sheet, annealed and pickled

DFS Watch Store Hong Kong
400 sq. ft. cladding on display cases, titanium Gr. 1 sheet

Sheathing for ice protection for Trans Tokyo Bridge is made of titanium bonded to steel.
Structural and Building Applications

Yumeshima-maishima Pontoon Bridge - 2000
Titanium clad steel 2 mm on 5 mm

Structural and Building Applications

Shin-kanon Undersea Tunnel Trolley Wire Frame
Life cycle cost and importance of maintaining availability of the system easily justified the cost

Structural and Building Applications

Abu Dhabi Airport Structural System
Ti 6Al-4V Electron Beam Welded Structural System

Abu Dhabi Airport Structural System
Curved triangular shaped beams were 80 meters in length

Abu Dhabi Airport Structural System
Ti 6Al-4V Electron Beam Welded Structural System

Building would have required 1250 tons of titanium Ti 6Al-4V
Structural and Building Applications

Abu Dhabi Airport Structural System
Use curved, electron beam welded structural shapes

Abu Dhabi Airport Structural System proposed to use field welded joints

Project was ultimately cancelled because the Sheik promoting it died, the size of the airport terminal needed to double, and titanium priced itself out of the picture.

To date, most applications have been in roofing and building cladding, employing thin sheet and generally using techniques similar to other metallic sheathing materials, often driven by architectural appearance issues.

Future applications using titanium for corrosion resistance, structural strength, long life, and low maintenance cost where life cycle cost is lower are predicted as titanium becomes more familiar to construction.

Titanium for Structural and Building Applications

Images courtesy of:
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Timet, Dallas, Texas
Nippon Steel, Tokyo, Japan
Titanium Information Group, UK

titaniumart.com - Fine Art and Functional Works in Titanium and Other Earth Elements Artist Bernie Wire