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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Acknowledgements

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Contents

Preface p. 4

Introduction p. 5

Titanium Properties As They Pertain to Its Use in Industry p. 7
John A. Mountford, Jr.

A Brief Overview of the Processing of Titanium p. 10
Dr. Raghavan Srinivasan

The Intricacies and Fascination of Processing-Microstructure-Mechanical Property Relationships in Titanium Alloys p. 13
Dr. T.S. Srivatsan
and
Mr. M. Kuruvilla

Applications, Fabrications, and Practical Issues of Titanium Use in Civil Structures p. 18
James A. McMaster

Appendix

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 SO_2, CO_2, CO, NH_4, H_2S, and N_2. Titanium's corrosion resistance and immunity as compared to other metals can be seen in the table below.

Corrosion Resistance

	Cu-Ni	316 SS	Titanium
General	R / S	R	R / I
Crevice	S	S	R / I < 200^0 F
Pitting	S	S	I
SCC	S	S > 140^0 F	I
Fatigue	S	S	R
Galvanic	S	S	I
MIC (Microbes)	S	S	I
Erosion	S	S	R
Weld / HAZ	S	S	R / I

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.

	Metal +	**H2O =**	**Total**
8" Class 200 Cu-Ni	**15.3**	**23.6**	**38.9 lbs/ft**
6" Sch 10 Titanium	**5.3**	**13.8**	**19.1 "**
Weight Savings	**10.0**	**9.8**	**19.8 "**
	65.4%	**41.5%**	**50.9%**
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**

A Brief Overview of the Processing of Titanium

Presented by: Dr. Raghavan Srinivasan
Professor, Department of Mechanical and Materials Engineering
Wright State University

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* (~880ºC 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_2 from the ore (rutile or illmenite): Roughly 95% of the TiO_2 that is produced is used in non-metal applications, such as in the paint, paper and cosmetic industry. About 5% of the TiO_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_2, and changes in the demand for metallic titanium will initially have little impact on the overall TiO_2 demand.

(b) Extraction of metallic titanium from the $TiO_{2:}$ TiO_2 is reduced with coke in a fluidized bed reactor and then treaded with chlorine to create a volatile titanium tetrachloride ($TiCl_4$), which is separated by vacuum distillation. Kroll process to produce titanium sponge (liquid/gaseous processing). $TiCl_4$ is then reduced with liquid magnesium to produce a porous metallic product known as titanium sponge. The $MgCl_2$ produced can be reduced back to metallic Mg and re-used. Armstrong process to produce titanium powder: $TiCl_4$ is reduced with sodium. $TiCl_4$ vapor is injected into a stream of molten sodium. The sodium flow rate is in excess of the stoichiometric requirements for sodium reduction of $TiCl_4$. 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
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Mr. M. Kuruvilla
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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 (TiO_2) is less than that of aluminum oxide (Al_2O_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^{o}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.

<u>A Sample Case</u>: 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 uninterrupted 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

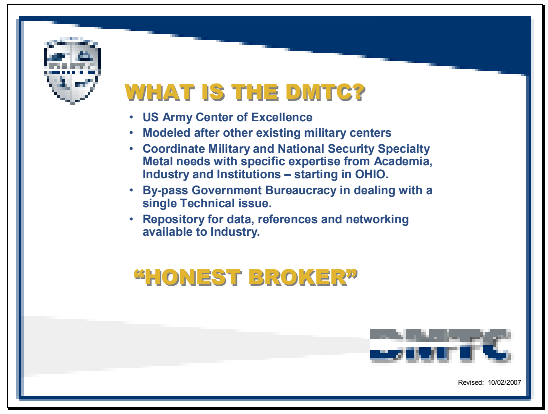
Due to unique welding limitations, consider welding designs that minimize welding, use butt welds where possible, and use similar welding details to the maximum possible extent. Design joints that allow butt welds to be placed away from high stress areas and use that to reduce weight of adjacent components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

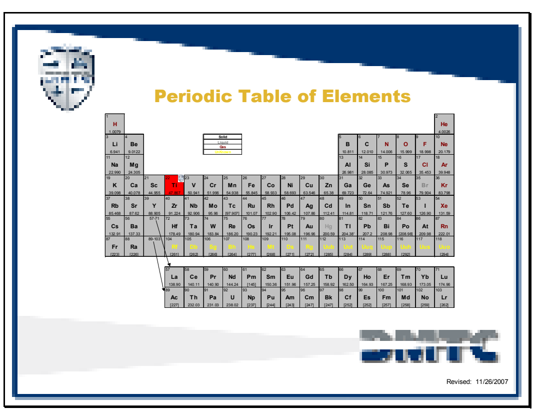
Appendix

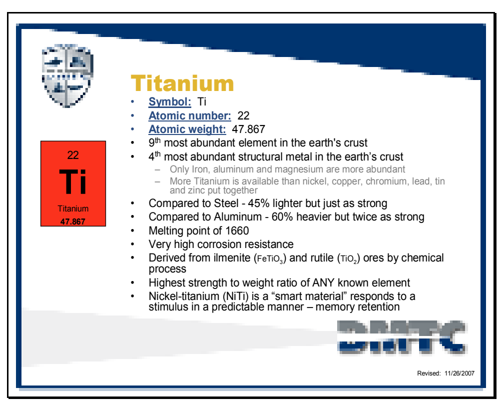

DMTC
STRENGTHENING AMERICA
A 501(c)(3) Entity Incorporated in State of Ohio
Revised 1/07/2008


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.
By-pass Government Bureaucracy in dealing with a single Technical issue.
Repository for data, references and networking available to Industry.
"HONEST BROKER"
DMTC
Revised: 10/02/2007

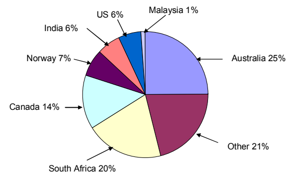

MISSION STATEMENT:
Become the "Go To" knowledge base on specialized metals – initially Titanium.
Create an easily accessed database which captures and provides resources to third parties – generating interest and involvement with Titanium.
Develop an understanding by industrial, academia and technical institutions of titanium and the Army's needs, which in turn creates demand.
GOAL:
By increasing demand, there is more national use and production, and eventually decreased price.
DMTC
Revised: 08/03/2007


Specialty Metals of Specific Interest and Concern to the US Army (ARDEC Picatinny Arsenal)
Titanium
Beryllium
Molybdenum
Cobalt
Vanadium
Manganese
Tantalum
Rhenium
Rare earth metals
DMTC
Revised: 03/27/2008


Periodic Table of Elements
DMTC
Revised: 11/26/2007


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 Iron, aluminum and magnesium are more abundant
More Titanium is available than nickel, copper, chromium, lead, tin and zinc put together
Compared to Steel - 45% lighter but just as strong
Compared to Aluminum - 60% heavier but twice as strong
Melting point of 1660
Very high corrosion resistance
Derived from ilmenite ($FeTiO_3$) and rutile (TiO_2) ores by chemical process
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
22
Ti
Titanium
47.867
DMTC
Revised: 11/26/2007

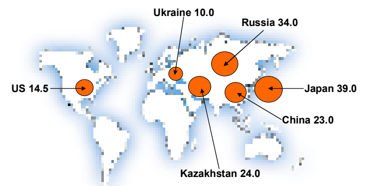
Titanium Minerals Supply By Country



Revised: 11/26/2007

TITANIUM SPONGE BY COUNTRY

2007e Sponge Production ('000 Tons)



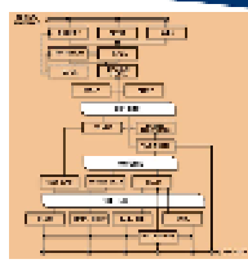
Revised: 11/26/2007

Major US Titanium Companies

Mining Ore	Sponge	Melting	Mill Products	Semi finished products	Final Products	Sales $ millions
	Timet			minor		$1,200
	ATI					1,100 est
	Starting 2010	RTI			minor	505
		Recent & minor	Perryman*			Not available
			Dynamet*			Not available
Mining Ore	Sponge	Melting	Mill Products	Semi finished products	Final Products	

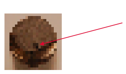
*Primary products made are bar, wire and fasteners. These two companies control the majority of the aerospace fastener market world wide.

Revised: 01/07/2008



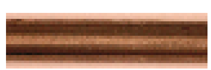
Revised: 01/07/2008

Inclusion Samples



Tungsten-carbide inclusion (end view)

Titanium rod (lateral view)



Tungsten-carbide inclusion (x-ray lateral view)

Revised: 02/20/2008

CENTER OF EXCELLENCE MODEL

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

Revised: 08/03/2007

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
- $150K from State of Ohio Department of Development for 2007/2008
- 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.

DMTC

Revised: 04/03/2008

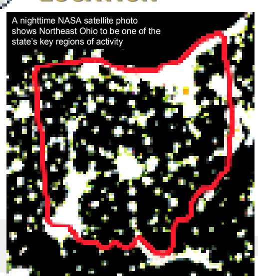
WHY OHIO?

- 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

DMTC

Revised: 08/03/2007

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

DMTC

Revised: 08/03/2007

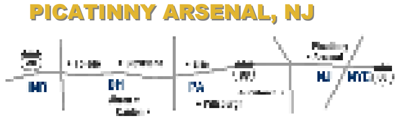
REGIONAL IMPACT

- 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

DMTC

Revised: 10/02/2007

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

DMTC

Revised: 08/03/2007

OUR ARMY PARTNER - PICATINNY ARSENAL, NJ *continued*

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



DMTC

Revised: 08/03/2007

BOARD OF DIRECTORS **Elected July 13th**

Edward F. Colantoni	Retired Picatinny Technical Data Division Chief
George DeMassi	Retired Picatinny Director of the Product Assurance
Julian A. Gravino	President - Edison Industrial System Systems Center, and Head Food Research Institute, Toledo, Ohio
Victor Guadagno	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.

Revised: 08/03/2007

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 Administrative/IS Manager	Computer and IT Expertise

Revised: 11/26/2007

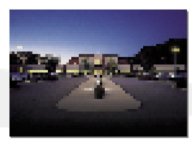
ADVISORY COMMITTEE – IN FORMATION

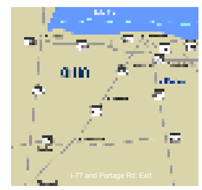
- **Will be comprised of 7 members**
- **Emphasis on national representation and involvement in metals industry, mining, academia and economic development**
- **Will be operational in January**
- **Will act as technical review body for "Project" funding authorization by Board of Directors**

Revised: 11/26/2007

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**





Revised: 08/13/2007

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
- Purveying 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 address client interests
- Target Competition by year-end 2007

Phase II – TBD based on above inputs

Revised: 11/23/2007

ACCOMPLISHMENTS from Inception thru December 2007

- Established and staffed a fully electronic office at Stark State College
- Created and "Identity 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 near-by "sister" Department of Defense Center's of Excellence
- Established the DMTC presence in the Titanium Community in NE Ohio and Western PA
- Effected a position with the International Titanium Association
- Recruited M. Trzcinski as Senior Technical Advisor
- Identified Projects for funding in 2008
- Organized presentation - "Titanium Welding Workshops" – 2 each
  - Ohio Engineering Dean's Council Forum
    - Titanium – Addressing the Army's Needs
  - Ohio Civil Engineering "UTC" Council Conference
    - "Plausibility of using Titanium in Bridge Rehabbing"

Revised: 03/27/2008

DMTC Projects to be funded in 2008

- **Stark State College (SSCT)**
  - Co-Op Program 2007
  - 2 year CAD Trained Engineering Student Semester at Picatinny Arsenal, NJ
    - January 2 Students
    - September 6 Students — Est. Cost/Student **$22,500**
  - *Titanium Machining Course*
    - Start September --- Supplies & Software **$10,000**
  - *Titanium Welding Training*
    - 3rd Frontier Grant Proposal Writing Support (Joint effort with SSCT) **$15,000**
    - 2 Titanium Welding Workshops (Jointly sponsored with SSCT and Edison Welding Institute "EWI") **$12,000**

Revised: 03/27/2008

DMTC Projects to be funded in 2008 (continued)

- *"A study aimed at evaluating, understanding and rationalizing the strength, endurance and performance of structures made from emerging titanium alloys"* **$64,828**
  - The University of Akron College of Engineering, Dr. Anil Patnaik and Dr. T.S. Srivatsan
- *"Development of Continuous Cooling Transformation Curves using the Single Sensor Differential Thermal Analysis Technique"* **$36,690**
  - Joint Experiment between Ohio State University – School of Engineering and American Engineering and Manufacturing (AEM), Lorain Ohio
- "*Identification of Titanium Scrap to meet Army standards and conveyance to a Contract Melt/Fabricator for Conversion into Plate*" **$67,500**
  (A Controlled "Supply Chain" experiment)
  Oversight by DMTC in conjunction with KylCase, Inc. N. Canton, OH
  - Study of Current Dynamics of the Titanium Scrap Market
  - Profiling to Army Specifications
  - Identification of Potential "Contract Melters/Fabricators/Plate Fabricators"
- *"Test to evaluate to Evaluate Final Titanium Welding Wire Properties Produced from Cast Ingot vs. Wrought Billet"* **$73,550**
  Trial Manufacturing Run
  Jointly managed by American Engineering and Manufacturing (AEM), Lorain, Ohio and G&S Titanium, Inc., Wooster, OH

Revised: 03/27/2008

Recent Headlines

Workforce Development Initiative Addressing Shortfall Of Welders

(200,000 by 2010 per American Welding Association)

<u>Strategy:</u>

- Partner with Stark State College of Technology ("SSCT") and
  Edison Welding Institute ("EWI")
- Hold welding workshop to develop "market" generated "Facts" about the need
- Establish SSCT as the Central Training Center
  Third Frontier Grant to put facilities in place and/or
  Other State Funding I.e. Ohio Bi-Partisan Economic Stimulus Package
- Enjoin the Ohio Welding Industry – Lincoln, Hobart and users to emphasize Ohio Manufacturer Equipment and tailor to the "Need"
- SSCT start developing training package in the 2008 Sept semester

<u>Development:</u>

- Have "academia" program designed and scaled so to readily be deployed by SSCT at the other seven Ohio Technical Colleges

<u>Multiplier Concept:</u>

Assume 20 students trained per semester for certification (total of 60) and 20 Associated Degrees
x
Eight Ohio Technical Colleges = **640** / year ready to work

<u>Meeting the DMTC Mission:</u>

- Titanium & other Specialty Welding will be ingrained in the Course work

Revised: 04/15/2008

Titanium Visa Vie the Nations Infrastructure Rehabbing

- Why DMTC Involvement
  - Addresses Mission and Army's Needs
  - Government Affairs expertise and Involvement
  - Ohio's Federal Legislative involvement in Transportation issues
    - Congressman LaTourette / House transportation caucus
- The "Titanium Idea" Drivers
  - Parthenon Story
  - Ongoing Bridge Cost savings by use of Ti – Corrosion Resistant
  - Safety to Public
  - Forward Vision VS Yesterday's Ways
- Questions and Posturing
  - Does Ohio UTC want the be involved and be the National Lead? DMTC can be the conduit.
  - Does Collaboration with Texas (Texas DOT & Texas A&M) have merit?
- Public Forums in Play
  - 1st Transportation Infrastructure convention – DC/March 08
  - 11th Transportation Infrastructure Summit – Irving Texas/June 08
  - Congressional Hearings Contemplated by House
  - 2009 "Transportation Re Appropriations Art" Debate and Structure

Revised: 04/15/2008

2008 Initiatives Scheduled to be sponsored by the DMTC

Objectives:

- Disseminate "needed" information and economic/technical data so to
  Generate industry interest in specialty metals – titanium
- Position the DMTC as A player in the international titanium industry
- Create cohesive environment for the metals industry of ohio and
  Surrounding "like" industrial areas.

Events:

- ❑ Ohio Universities Engineering Dean Council
  Forum / "How can Ohio's academic engineer expertise" address the army's the army's needs for lower cost "armour quality" titanium
- ❑ Ohio Transportation Consortium ("OTC") Coalition Of Civil Engineering Faculties and Ohio Department of Transportation ("ODOT")
  Forum / "Enhancing the use of titanium for novel applications spanning the domain of structure, performance critical and innovations in engineering"
- ❑ Economic Trends And Indicators Relative To The Metals Industry Following The November 08 Election
  Seminar With A National Recognized Keynote Speaker And Panel Discussion By Prominent Authorities In The Ohio Metals Industry, Banking Communities And Economic Development Operatives.

Revised: 04/15/2008

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

Grade	O_2 max	Fe max	H_2 max	C max	N max	Other (each) max	Other (total) max	Ti
1	0.18	0.30	0.015	0.08	0.03	0.10	0.40	Bal.
2	0.25	0.30	0.015	0.08	0.03	0.10	0.40	Bal.
3	0.35	0.30	0.015	0.08	0.05	0.10	0.40	Bal.
4	0.40	0.50	0.015	0.08	0.05	0.10	0.40	Bal.

Chemistry - Wgt. %

Grade	O_2 max	Fe max	H_2 max	C max	N_2 max	Al	V	Other (each) max	Other (total) max
2	0.25	0.30	0.015	0.08	0.03			0.10	0.40
9 (3Al - 2.5V)	0.15	0.25	0.015	0.08	0.03	2.5 - 3.5	2.0 - 3.0	0.10	0.40
5 (6Al - 4V)	0.20	0.40	0.015	0.08	0.05	5.5 - 6.5	3.5 - 4.5	0.10	0.40
23 (6Al - 4V ELI)	0.13	0.25	0.0125	0.08	0.03	5.5 - 6.5	3.5 - 4.5	0.10	0.40

ELI = Extra Low Interstitials

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

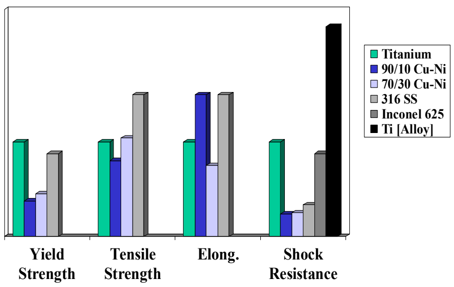
Mechanical Properties

PROPERTY	Grade 1		Grade 2		Grade 3		Grade 4	
	KSI	MPa	KSI	MPa	KSI	MPa	KSI	MPa
Tensile (min)	35	240	50	345	65	450	80	550
Yield (min)	25	170	40	275	55	380	70	483
Yield (max)	45	310	65	450	80	550	95	655
Elong. (min)	24%		20%		18%		15%	

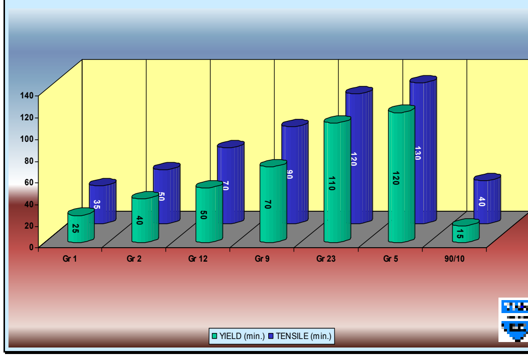
Mechanical Properties

PROPERTY	Titanium Gr 2		90-10 Cu-Ni		70-30 Cu-Ni		316 Stainless	
	KSI	MPa	KSI	MPa	KSI	MPa	KSI	MPa
Tensile (min)	50	345	40	275	52	360	75	515
Yield (min)	40	275	15	105	18	125	35	240
Yield (max)	65	450	--		--		--	
Elong. (min)	20%		30%		15%		30%	

Mechanical Properties



Yield & Tensile Strengths



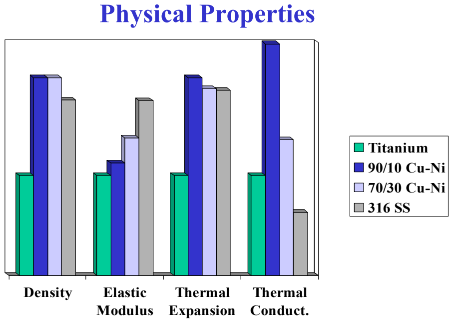
Yield Strength / Density Ratio

- 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

PROPERTY	Titanium Gr 2	90-10 Cu-Ni	70-30 Cu-Ni	316 Stainless
El. Modulus (10^6 psi)	16	18	22	28
Thermal Expansion (Micro in/in ^oF)	4.8	9.5	9.0	8.9
Thermal Conductivity (BTU/hr-ft^2 ^oF/in)	150	348	204	95
Density (lbs/in^3)	0.163	0.323	0.323	0.286
(gms/cm^3)	4.5	8.9	8.9	7.9
Hardness (HRB)	85	65	70	95

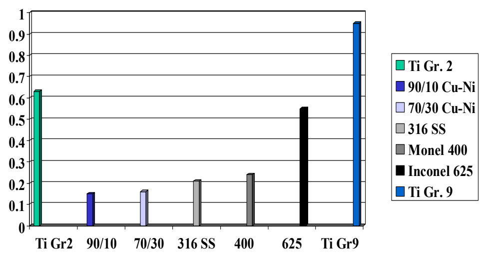
Physical Properties



Melting Points

	^oC	^oF
• Aluminum 5086	565	1050
• 90-10 Cu-Ni	1150	2100
• Steel HY-80	1480	2700
• Titanium Gr 2	1670	3040

Shock Resistance [10^3 in/sec]



SHOCK RESISTANCE

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

S_y	Yield Stress [psi] (actual) [used 50,000 psi]
√	Square Root
E	Modulus of Elasticity [14.9 x 10^6 psi]
ρ	Density @ 0.163 lbs./ in.^{3}
386	Constant x 1/ sec.^{2}

Ti Grade 9 [3Al - 2.5V]	0.95
Ti Grade 2	0.63
Inconel 625 ™	0.55
Monel 400 ™	0.24
316 Stainless Steel	0.21
70-30 Cu-Ni	0.15

TITANIUM

Properties — **Benefits**

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

TITANIUM

Properties — **Benefits**

- Low Thermal Expansion - Close to Steel (HY 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

Corrosion Resistance

- Fully Resistant to:
  Crevice Corrosion < 80 °C [175 °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 H_2 Embrittlement < 77 °C (170 °F)
- Resistant to Gases:

  SO_2 CO_2 CO NH_4 H_2S N_2

Corrosion Resistance

	Cu-Ni	316 SS	Titanium
General	R / S	R	R / I
Crevice	S	S	R / I < 200° F
Pitting	S	S	I
SCC	S	S > 140° F	I
Fatigue	S	S	R
Galvanic	S	S	I
MIC (Microbes)	S	S	I
Erosion	S	S	R
Weld / HAZ	S	S	R / I

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 Buttwelding Fittings
- B 16.11 Forged Fittings Socket-Welding & Threaded
- B 16.14 Ferrous Pipe Plugs, Bushings, Locknuts
- B 16.28 Steel Buttweld Short Radius Elbows, Returns
- B 16.48 Steel Line Blanks
- B 36.10 Welded & Seamless Wrought Steel Pipe
- B 36.19 Stainless Steel Pipe

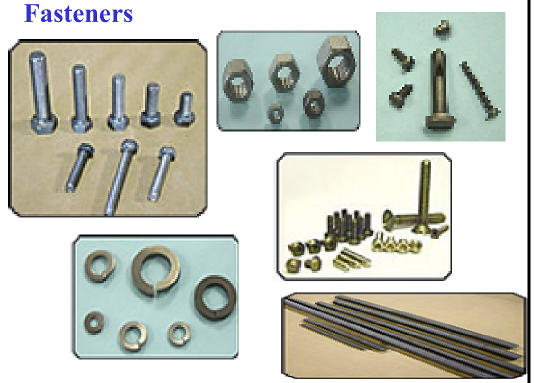
MSS Specifications

- **SP – 25** Standard Marking System for Valves, Fittings, Flanges & Unions
- **SP – 43** Stainless Steel Buttwelding Fittings
- **SP – 44** Steel Pipeline Flanges
- **SP – 97** Integrally Reinforced Forged Branch Outlet Fittings – Socket Welding, Threaded, and Buttwelding 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

Mining

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

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.

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]

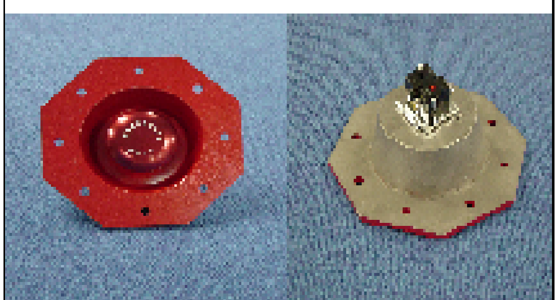
	Metal	+ H_2O	= Total	
8" Class 200 Cu-Ni	15.3	23.6	38.9	lbs/ft
6" Sch 10 Titanium	5.3	13.8	19.1	"
Weight Savings	10.0	9.8	19.8	"
	65.4%	41.5%	50.9%	

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

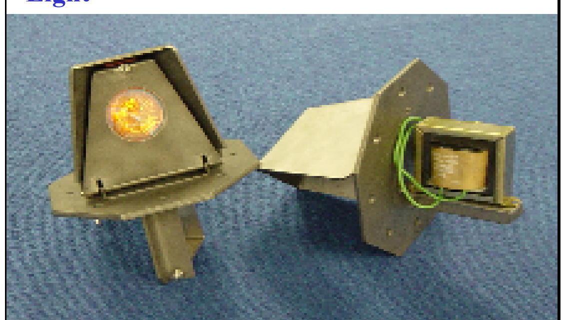
90-10 Cu-Ni	8" Class 200	= 8.625" OD x .148" wall
Titanium	6" Sch 10	= 6.625" OD x .134" wall

Ejectors

Emergency Stop Switch

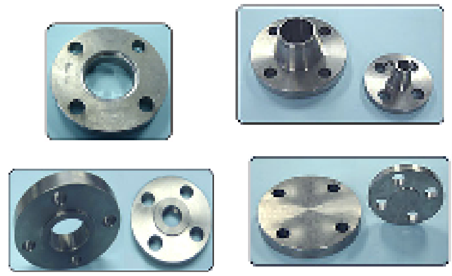


Light

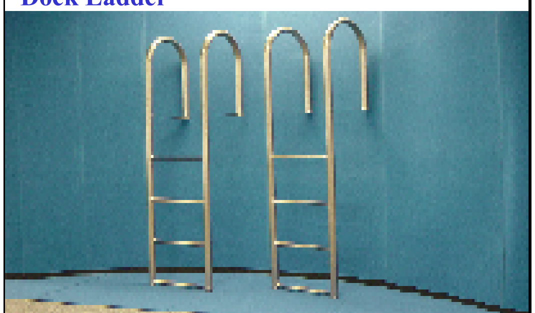


Fittings - Tee & Elbow

Flanges



Dock Ladder



Hinges

Fire / Rescue Tools

APPLICATIONS

SHIPBOARD	OFFSHORE
Ship Service Turbine Generator	Fire Sprinkler Heads, Deluge
Distillation Unit Condensers (S/T) CG 47, DDG 51	Nozzles and Deluge Valves
Distillation Units Heaters CG 47, DDG 51	
Lube Oil Coolers CG 47, DDG 51, CVN	Lube Oil Coolers
Phalanx & LPAC/HPAC Coolers CG 47, DDG 51, CVN	
Aegis Radar Electronics Cooler (S/T) & (P/F)	Compressor Cooler
De-Salination Units (S/T & Reverse Osmosis)	Ballast Systems and Valves
Firemain Systems - Piping & Fittings LHA 2, LPD-17	Firemain Systems
Fire Pumps Grades 2 & 5 CG 47, DDG 51	
Service Water Piping	Service Water Piping
Air Conditioning Condenser (S/T)	Central Exchanger (P/F)
HVAC - Air Ventilation Ducting	Discharge Cooler
Distillation unit - Brine Heater and Brine Pre-Heater (P/F) and (S/T)	Direct Low Pressure Crude Oil Service Cooler (S/T)

(S/T) = Shell & Tube (Heat Exchanger)
(P/F) = Plate & Frame (Heat Exchanger)

APPLICATIONS cont'd.

SHIPBOARD		OFFSHORE
Engine Jacket Coolers	CG 47, DDG 51, CVN	Engine Jacket Cooler
TAO oilers (P/F)		
Low Pressure Air Compressor Cooler		Quench Water Cooler (S/T)
Exhaust Uptakes Liners (Gr. 9)	DDG 51 approx. 9 yrs.	Propane Condenser
Light Boxes		Gas Dehydrator Cooler (S/T)
Oil Waste Systems *		Natural Gas Cooler (S/T)
Magazine Sprinkler Systems *		Glycol Cooler (S/T)
Deck Drainage Systems Urinal Drain Piping	LHA 2	Flash Gas Compressor
Bilges *		Intercooler (S/T)
Countermeasure Washdown Piping *		Interstage Oil Cooler (S/T)
Seawater Compensated Fuel Oil Systems *		
Missile Deluge Systems *		
Stanchions *		

* = Applications for Consideration On Board Ship

(S/T) = Shell & Tube (H. E.)
(P/F) = Plate & Frame (H. E.)

SHIPBOARD APPLICATIONS [POTENTIAL & IN DESIGN]

Magazine Sprinkler Systems
Oil Waste Systems
Bilges
Seawater Compensated Fuel Oil Systems
Stanchions / Safety Lines
Structurals: Pump Foundations
Hose Reel Foundations
LCAC Systems
Valves
Sprinkler Heads & Nozzles
Chillers & Coolers
Ladders
Ballast Tank Systems
Countermeasure Washdown Piping
Missile Deluge Systems

CURRENT APPLICATIONS OUT IN THE FIELD, APPROVED & UNDER EVALUATION

Recessed Boxes	Installed & In Service
Recessed Electrical Box	Installed & In Service
Emergency Stop Switch [Cover]	Mandatory for DDX & Approved all DDG's Retrofit on several DDG's
Light Fixture [Cover]	Installed & In Service
Fire / Rescue Tool (Halligan)	Navsea purchases
Valves	
Ball	Submarines, other Vessels, Chemicals
Globe	Tested with new Designs under Test
Gate	Tested with new Designs under Test
Butterfly	Testing @ Carderock
Hinges	
Door	Fabricated
Cabinet	Fabricated
Piano	Fabricated
for Composites	Potential
for Hatches	Potential
Hatches & Doors	in use by the Army / in test by Navy
Ventilation Ducts	Installed - Puget Sound home port
Ventilator Screens	Potential
Wire Mesh Screens (for Stealth)	Hanger Doors & Boat Deck Potentials
Bulkhead Penetration Sleeves	Potential

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

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1

OUTLINE of VERBAL ELUCIDATION

2

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)**

3

WHY THE INTEREST-DESIRE and NEED TO SELECT TITANIUM

- **TITANIUM HAS FOUND ITS NICHE IN MANY INDUSTRIES OWING TO ITS UNIQUE DENSITY, CORROSION RESISTANCE and RELATIVE STRENGTH ADVANTAGES OVER COMPETING METALS SUCH AS ALUMINUM, STEELS and even SUPERALLOYS.**

4

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 538ºC to 595ºC 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.**

5

GIVEN THE GLORY and POTENTIAL BENEFITS

6

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 PROFOUND INFLUENCE ON PROPERTIES and PERFORMANCE and RESULTANT SELECTION OF A TITANIUM ALLOY .**

7

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).**

8

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.

9

MOST VIABLE FACTORS GOVERNING MECHANICAL PROPERTIES of TITANIUM ALLOYS

- 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.

10

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.

11

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.

12

THE ELEMENTS and THEIR ROLE

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

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

13

A THIRST FOR KNOWLEDGE of The DESIRED "PROPERTIES"

14

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 (WEIGHT) RATIO.

15

COMPARISON OF TYPICAL STRENGTH-TO-DENSITY VALUES FOR SEVERAL TITANIUM ALLOYS AND 4340 ALLOY STEEL AT 20°C (68°F)

Metal	Density		Tensile Strength		Tensile Strength/density	
	g/cm^3	lb/in^3	MPa	ksi	MPa÷ g/cm^3	ksi÷ lb/in^3
CP Titanium	4.51	0.163	400	58	89	356
Ti-6Al-4V	4.43	0.160	895	130	202	813
Ti-4Al-3Mo-1V	4.51	0.163	1380	200	306	1227
Ultrahigh-strength steel (4340)	7.9	0.29	1980	287	251	990

16

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

17

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 MODLUS 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 ALUMINUM ALLOYS and APPROXIMATELY 60% of THE MODULUS OF STEELS and NICKEL BASE ALLOYS.

18

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.

19

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 VISIBILE 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)

20

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.

21

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.

22

UNDERSTANDING THE ROLE and SIGNIFICANCE of COMPOSITION

23

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 Ti_3Al.
- 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.

24

ALLOYING ELEMENTS and STRENGTHENING: HOW and WHY?

- THE ALLOY ELEMENTS THAT DISSLOLVE 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.**

25

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.

26

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.

27

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.

28

THE ROLE OF HYDROGEN

- THE SOLUBILITY OF THE INTERSTITIAL ELEMENT HYDROGEN IN ALPHA TITANIUM at 300ºC 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.

29

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.

30

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.

31

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.

32

PROCESSING and MICROSTRUCTURE

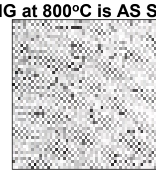
- THE MICROSTRUCTURE OF COMMERCIALLY PURE TITANIUM DEPENDS ON WHETHER OR NOT IT HAS BEEN COLD WORKED and ON THE SUBSEQUENT ANNEALING USED.
- FURTHER, UPON COOLING FROM THE BETA REGION, WHICH BEGINS at 882ºC, THE RESULTANT STRUCTURE DEPENDS ON THE COOLING PROCESS FOLLOWED.
- THIS IS BECAUSE THE PROCESS DIRECTLY AFFECTS THE PROGRESSION OF THE BETA to ALPHA TRANSFORMATION AND FINAL ALPHA GRAIN SIZE.

33

PROCESSING and MICROSTRUCTURE

- THE EQUIAXED MICROSTRUCTURE OF TITANIUM AFTER ANNEALING at 800ºC is AS SHOWN.

Annealed 1 h at 800ºC (1472ºF), water quenched, 0.2% yield strength: 124 MPa (18 ksi), tensile strength: 248 MPa (36 ksi), elongation: 80%; 100X.



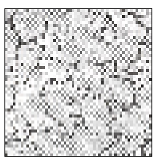
- HERE THE GRAIN SIZE and RESULTANT PROPERTIES CAN BE VARIED BY THE CONJOINT INFLUENCE of COLD WORKING and ANNEALING.

34

MORE ON PROCESS-MICROSTRUCTURE RELATIONSHIP

- ANNEALING IN THE BETA REGION at 1000ºC FOLLOWED BY RAPID COOLING to 25ºC BY MEANS OF WATER QUENCH PRODUCES THE STRUCTURE SHOWN IN THE MICROGRAPH.

Annealed 1 h at 1000ºC (1832ºF), water quenched, 0.2% yield strength: 228 MPa (33 ksi), tensile strength: 290 MPa (42 ksi), elongation: 60%; 100X.



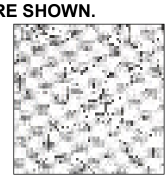
- RAPID COOLING DOES NOT TRANSFORM THE BETA-TO-ALPHA TRANSFORMATION.

35

PROCESS INFLUENCE ON MICROSTRUCTURE.

- COOLING **SLOWLY** RESULTS IN THE MICROSTRUCTURE SHOWN.

Annealed 1 h at 1000ºC (1832ºF), furnace cooled, 0.2% yield strength: 165 MPa (24 ksi), tensile strength: 262 MPa (38 ksi), elongation: 60%; 100X.



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

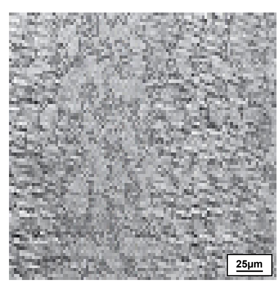
36

A QUICK OVERVIEW ON PROPERTIES of TITANIUM ALLOYS

- THE TITANIUM GRADES HAVE VARYING AMOUNTS of IMPURITIES:
  <u>examples</u>: 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.

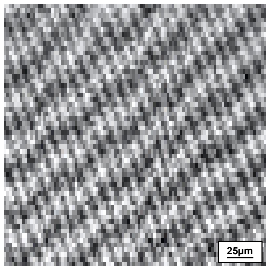
37

Ti-6Al-4V, α+β heat-treated at 960ºC/1h/AC.
Optical micrograph shows equiaxed α and transformed β microstructure.

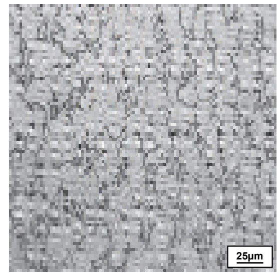


38

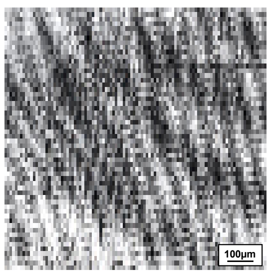
Ti-6Al-4V, α+β heat-treated at 960ºC/1h/WC.
Optical micrograph shows equiaxed α and transformed β microstructure.



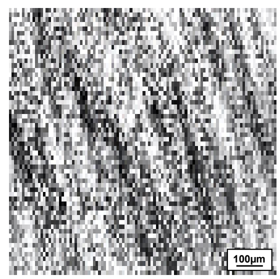
Ti-6Al-4V, α+β heat-treated at 960ºC/1h/FC.
Optical micrograph shows equiaxed α and transformed β microstructure.
The volume fraction of α increases with a decrease in cooling rate, and transformed β becomes coarser.



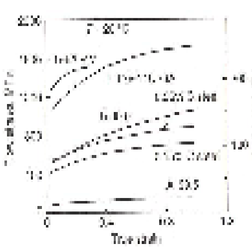
The Ti-6Al-4V, β heat-treated at 1020ºC/1h/WC.
Optical micrograph shows martensitic structure with prior β boundaries.



Ti-6Al-4V, β heat-treated at 1020ºC/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_2, 0.01 N_2, 0.002 H_2, 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.

45

THE ALPHA and NEAR-ALPHA ALLOYS of TITANIUM

46

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 ACICULAR STRUCTURE.
- THE ALPHA ALLOYS HAVE ALPHA AS THEIR COMMON PHASE AT LOW TEMPERATURE, i.e., BELOW 800º C.

47

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.

48

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.

49

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

50

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.

51

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 MARTENSITE 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.

52

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.

53

PROPERTY DEVELOPMENT

- WHEN THE ALPHA-BETA TITANIUN 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.

54

RELATIVE ADVANTAGES OF EQUIAXED AND ACICULAR MICROSTRUCTURES

Microstructure	Advantage
Equiaxed	Higher ductility and formability Higher threshold stress for hot-salt stress corrosion Higher strength (for equivalent heat treatment) Better hydrogen tolerance Better low-cycle fatigue (initiation) properties
Acicular	Superior creep properties Higher fracture toughness values

55

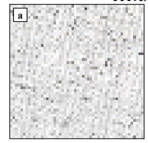
TYPICAL YIELD AND FRACTURE TOUGHNESS OF SEVERAL ALPHA-BETA TITANIUM ALLOYS

Alloy	Alpha morphology	Yield Strength		Fracture Toughness (K_{Ic})	
		MPa	ksi	MPa√m	ksi√in
Ti-6Al-4V	Equiaxed	910	130	44-66	40-60
	Transformed	875	125	88-110	80-100
Ti-6Al-6V-2Sn	Equiaxed	1085	155	33-55	30-50
	Transformed	980	140	55-77	50-70
Ti-6Al-2Sn-4Zr-6Mo	Equiaxed	1155	165	22-23	20-30
	Transformed	1120	160	33-55	30-50

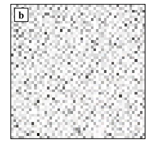
56

MICROSTRUCTURE
and
HARDENABILITY

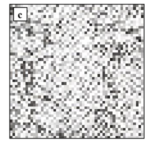
Typical microstructures of ALPHA, ALPHA-PLUS-BETA and BETA TITANIUM ALLOYS



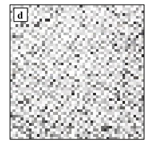
a — Equiaxed alpha in unalloyed Ti after 1h at 699°C (1290°F)



b — Equiaxed alpha + beta



c — Acicular alpha + beta in Ti-6Al-4V



d — Equiaxed beta in Ti-13V-11Cr-3Al

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.

TYPICAL ROOM-TEMPERATURE TENSILE PROPERTIES AND CORRESPONDING MICROSTRUCTURE FOR Ti-6Al-4V FOR DIFFERENT THERMAL TREATMENTS

Thermal Treatment	Yield Strength		Tensile Strength		Elongation at Fracture, %	Reduction in area, %	Microstructure at 25°C (77°F), ~ vol % phases
	MPa	ksi	MPa	ksi			
955 °C (1751 °F) furnace cooled	834	121	937	136	19	46	90 % alpha; 10% beta
955 °C (1751 °F) water quenched	951	138	1117	162	17	60	50 % primary alpha; 50% alpha primary + alpha double + retained beta
900 °C (1652 °F) furnace cooled	855	124	965	140	17	43	90 % alpha; 10% beta
900 °C (1652 °F) water quenched	923	134	1117	162	15	54	60 % primary alpha; 40% alpha primary + alpha double + retained beta

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.

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.

63

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

Thermal Treatment	Yield Strength		Tensile Strength		Elongation at Fracture,%	Reduction in area, %
	MPa	ksi	MPa	ksi		
955 °C (1751 °F) water quenched + age 1	951	138	1117	162	17	60
955 °C (1751 °F) water quenched + age 2	1069	155	1186	172	17	56
900 °C (1652 °F) water quenched + age 1	924	134	1117	162	15	54
900 °C (1652 °F) water quenched + age 2	1013	147	1117	162	15	48

64

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.

65

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

Test Direction (a)	Tensile Strength		Yield Strength		Elongation %	Reduction in area %	Ealstic Modulus		K_{Ic}		K_{Ic} Specimen Orientation (b)
	MPa	ksi	MPa	ksi			GPa	10^6 psi	MPa√m	ksi√in	
L	1027	149	952	138	11.5	18.0	107	16	75	68	L-T
T	1358	197	1200	174	11.3	13.5	134	19	91	83	L-T
S	938	136	924	134	6.5	26.0	104	15	49	45	S-T

(a) High basal pole intensities reported in the transverse direction, 90° from normal, and also intensity nodes in positions. L, longitudinal; T, transverse; S, short transverse direction. (b) 45° from the longitudinal (rolling) direction and about 40° from the plate normal.

66

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.

67

ON THE RELATIONSHIP BETWEEN STRUCTURE and STRENGTHENING OF BETA ALLOYS

- 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, Ti_3Al 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.

68

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.

69

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.

70

STRUCTURE-PROPERTY (MECHANICAL) RELATIONSHIP

71

RELATIONSHIP BETWEEN STRUCTURE and PROPERTIES

- 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.

72

THE ROLE OF ALUMINUM IN STRENGTNENING TITANIUM

- ALUMINUM IS THE MOST IMPORTANT SUBSTITUTIONAL SOLID SOLUTION STRENGTHENER.
- ITS EFFECT ON STRENGTH OF THE TITANIUM ALLOY IS ESSENTIALLY LINEAR

73

OTHER SOURCES CONTRIBUTING TO STRENGTH

- **OTHER LESS IMPORTANT SOURCES OF STRENGTHENING ARE the FOLLOWING:**
  1. **INTERSTITIAL SOLID SOLUTION STRENGTHENING.**
  2. **GRAIN SIZE STRENGTHENING.**
  3. **SECOND-PHASE STRENGTHENING.**
  4. **ORDERING IN THE ALPHA PHASE.**
  5. **AGE HARDENING.**
  6. **EFFECTS of CRYSTALLOGRAPHIC TEXTURE**

74

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.

75

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.

76

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.

77

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.

78

THE "KEY" ALLOY TYPES

79

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 425^{o}C

80

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 OPPORTUNUTY TO TAILOR THE COMBINATIONS OF STRENGTH AND TOUGNESS PROPERTIES FOR A SPECIFIC APPLICATION.

81

- **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.**

82

UNDERSTANDING THE STATIC PROPERTIES OF TITANIUM ALLOYS

83

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 TITANUM, 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.

84

Room-temperature tensile properties for selected titanium alloys

Alloy name	Nominal composition	Condition	Ultimate strength		Yield strength		Elongation %
			MPa	ksi	MPa	ksi	
5-2.5	Ti-5Al-2.5Sn	Annealed (0.25-4h/ 700-870°C, or 1300-1600°F)	830-900	120-130	790-830	115-120	13-18
3-2.5	Ti-3Al-2.5V	Annealed (1-3h/ 650-760°C, or 1200-1400°F)	650	95	620	90	22
6-2-1-1	Ti-6Al-2Nb-1Tb-1Mo	Annealed (0.25-2h /700-930°C, or 1300-1700°F)	860	125	760	110	14
8-1-1	Ti-8Al-1Mo-1V	Annealed (8h /790oC, or 1450oF)	1000	145	930	135	12
Corona 5	Ti-4.5Al-5Mo-1.5Cr	α-β annealed after β processing	970-1100	140-160	930-1030	135-150	12-15
Ti-17	Ti-5Al-2Sn-2Zr-4Mo-4Cr	α-β or β processed plus aged	1140	165	1070	155	8
6-4	Ti-6Al-4V	Annealed (2h/700-870°C, or1300-1600°F) Aged	970 1170	140 170	900 1100	130 160	17 12
6-6-2	Ti-6Al-6V-2Sn	Annealed (3h/700-820°C, or1300-1500°F) Aged	1070 1280	155 185	1000 1210	145 175	14 10
6-2-4-2	Ti-6Al-2Sn-4Zr-2Mo	Annealed (4h /700-840°C, or1300-1550°F)	1000	145	93	135	15
6-2-4-6	Ti-6Al-2Sn-4Zr-6Mo	Annealed (2h /820-870°C, or1500-1600°F) Aged	1030 1210	150 175	970 1140	140 165	11 8
6-22-22	Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si	α-β processed plus aged	1120	162	1010	147	14

85

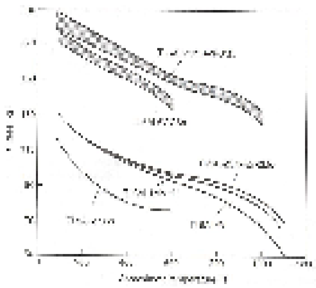
PERCENT OF ROOM-TEMPERATURE STRENGTH RETAINED AT ELEVATED TEMPERATURE FOR SEVERAL TITANIUM ALLOY

Temperature		Room–temperature strength retained, %													
		Unalloyed Ti		Ti-6Al-4V		Ti-6Al-6V-2Sn		Ti-6Al-2Sn-4Zr-6Mo		Ti-6Al-2Sn-4Zr-2Mo		Ti-100		IMI-834	
°C	°F	TS	YS	TS	YS	TS	YS	TS	YS	TS	YS	TS	YS	TS	YS
93	200	80	75	90	87	91	89	90	89	93	90	93	92	...	...
204	400	57	45	78	70	81	74	80	80	83	76	81	85	85	78
316	600	45	31	71	62	76	69	74	75	77	70	76	79	...	...
427	800	36	25	66	58	70	63	69	71	72	65	75	76	...	...
482	900	33	22	60	53	...	...	66	69	69	62	72	74	...	...
538	1000	30	20	51	44	...	...	61	66	66	60	69	69	...	...
593	1100	...	...	...	...	...	...	...	...	...	...	66	63	63	61

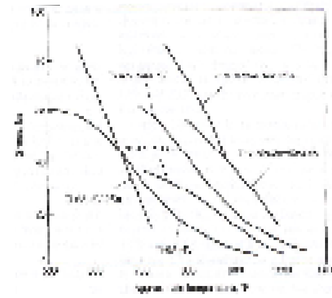
Short time tensile test with less than 1 h at temperature prior to test. TS, tensile strength; YS, yield strength.

86

A COMPARISON OF ULTIMATE TENSILE STRENGTHS OF SELECTED TITANIUM ALLOYS AS A FUNCTION OF TEMPERATURE



COMPARISON OF TYPICAL 150 HOURS, 0.1% CREEP STRENGTH FOR SELECTED TITANIUM ALLOYS



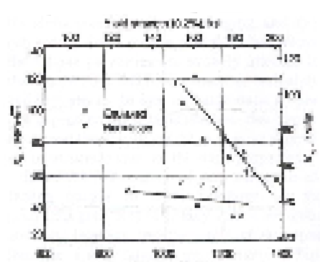
HEAT TREATMENT and STRENGTH of TITANIUM ALLOYS

- 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-4Mo-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 MULTILPLE 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.

93

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

94

THE CYCLIC BEHAVIOR OF TITANIUM ALLOYS

95

UNDERSTANDING FATIGUE BEHAVIOR OF UNALLOYED TITANIUM

- 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.

96

CLASSIFYING THE FATIGUE BEHAVIOR

- BEARING IN MIND THAT FAILURE CYCLES IN THE RANGE LESS THAN 5×10^4 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).

97

"FATIGUE" that is SOLELY THERMALLY-INDUCED IS KNOWN AS "THERMAL FATIGUE".

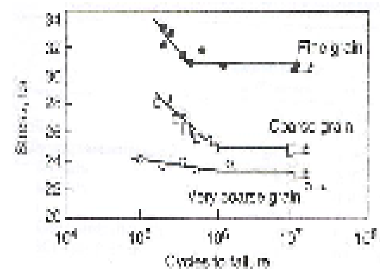
98

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.

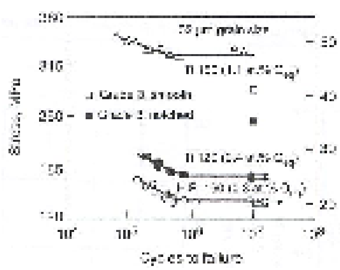
99

CURVES DEPICTING STRESS VERSUS CYCLES-TO-FAILURE FOR PURE TITANIUM AS AFFECTED BY GRAIN SIZE



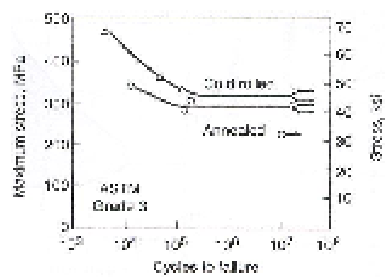
100

CURVES DEPICTING STRESS VERSUS CYCLES TO FAILURE FOR PURE TITANIUM AS AFFECTED BY OXYGEN CONTENT



101

CURVES DEPICTING STRESS VERSUS CYCLES TO FAILURE FOR PURE TITANIUM AS AFFECTED BY COLD WORK



102

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.

103

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.

104

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.

105

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.

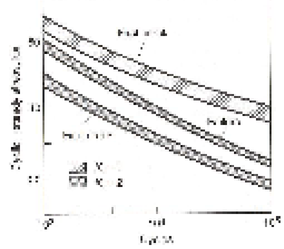
106

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.

107

LOW-CYCLE FATIGUE PROPERTIES OF ALPHA-BETA TITANIUM ALLOY Ti-6Al-4V SHOWING EFFECTS OF NOTCH ACUITY AND TIME TO FIRST CRACK



108

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 300ºC 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.

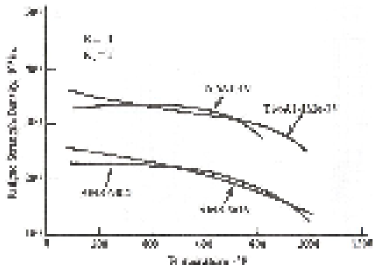
109

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.

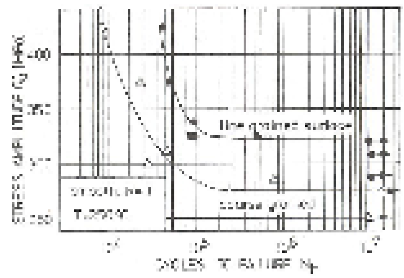
110

HIGH-CYCLE (5X10^7 cycles) FATIGUE STRENGTH-TO-DENSITY OF SEVERAL TITANIUM ALLOYS COMPARED WITH SOME STEELS ONCE USED IN THE COMPRESSOR SECTIONS OF GAS TURBINES



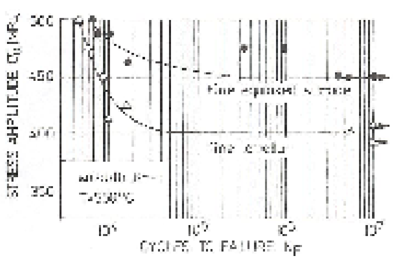
111

CURVES DEPICTING STRESS VERSUS CYCLES-TO-FAILURE FOR COARSE-GRAINED Ti-8Al ALPHA ALLOY WITH AND WITHOUT THERMO-MECHANICAL PROCESSING (TMP) TO PRODUCE LOCAL GRAIN REFINEMENT AT THE SURFACE



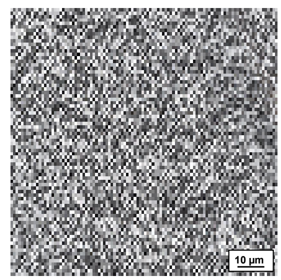
112

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



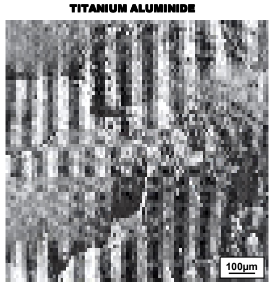
113

TYPICAL DUCTILE FRACTURE IN A TI ALLOY SHOWING FINE EQUIAXED DIMPLES



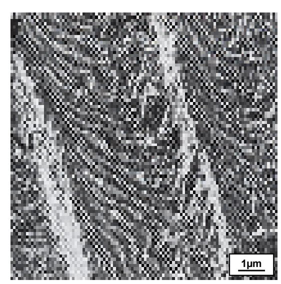
114

TYPICAL TRANSCRYSTALLINE CLEAVAGE FRACTURE IN TITANIUM ALUMINIDE



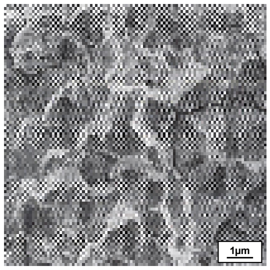
115

TYPICAL FATIGUE FRACTURE SHOWING STRIATIONS



116

TYPICAL INTER-CRYSTALLINE FRACTURE IN A TI ALLOY



117

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.

118

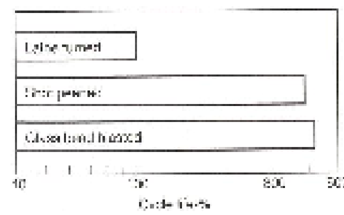
INTRINSIC INFLUENCE of SURFACE TREATMENT

- 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

119

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



120

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.

121

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.

122

IN A NUTSHELL

- INTRINSIC VARIATION IN MICROSTRUCTURE PRODUCES PARALLELS BETWEEN FRACTURE TOUGHNESS AND FATIGUE CRACK PROPAGATION RESISTANCE.
- BOTH K_{IC} 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.

123

Fatigue crack propagation data for mill-annealed alpha-beta alloy Ti-6Al-4V showing data scatter.
Data are for six heats of mill-annealed Ti-6Al-4V.
[T-L, transverse-longitudinal].

124

Effect of heat treatment on fatigue crack growth rate in Ti-6Al-4V alloy.
[L-T, Longitudinal-transverse]

125

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.

126

THE HIGHLIGHTS THAT WARRANT CONSIDERATION and COMFORT

127

- **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,**

128

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- THREATINBG SITUATIONS SPANNING THE AUTOMOTIVE SECTOR and DEFENSE SECTOR HAVE A FAIRLY GOOD CHANCE FOR RESURRECTING ABUNDANCE OF INTEREST IN ENGINEERING LOWER COST TITANIUM ALLOYS.

129

- **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.**

130

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

1

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

2

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
- TiO_2 as a pigment is one of the brightest and whitest materials known

3

Titanium Physical Properties

Density	4.51 (0.163 lbs/cu.in) 56% of steel 160% of aluminum
Elastic Modulus, E	14.9 x 10^6 psi for the unalloyed grades
Modulus of Rigidity, G	6.0 x 10^6 psi
Poisson's Ratio	0.32
Therm. Expan Coef.	4.6 to 5.2 a little lower than steel
Melting Point	3100°F

4

Titanium Applications

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

Titanium Applications

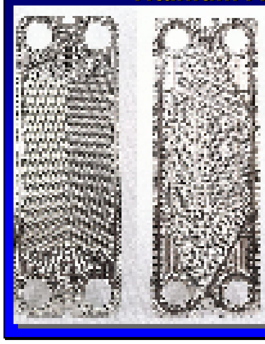
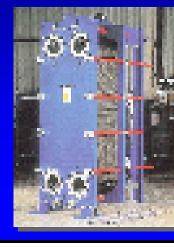
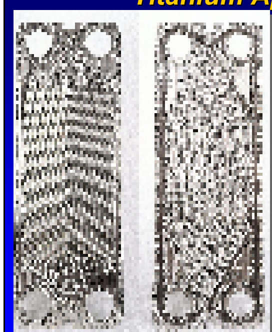


Plate heat exchangers use thin sheet with mechanical assembly

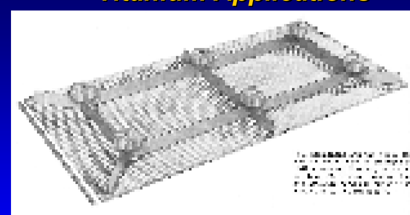


Titanium Applications



- 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, rings 20 feet in diameter, weights in excess of 50,0000 pounds. Machine is subjected to severe corrosion and low cycle fatigue loading of the order of 5 x 10^5 cycles

Industrial Corrosion Applications

Integrally Stiffened Titanium Grade 2
Brine Reservoir for Chlorine Production,
0.078" and 0.125", 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-312 cargo tank trailer in USA

Corrosion resistance and weight reduction

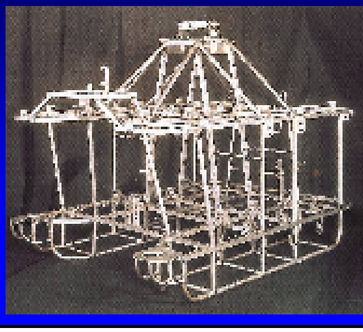
Other Marine Titanium Applications

Helicopter Transportable Hyperbaric Diver Rescue System – Ti 6Al-4VELI (SWRI-TiFab Photo)

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

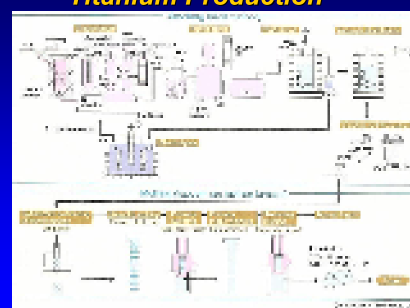
Why Choose Titanium?

Thermal expansion coefficient compatible with glass and certain composites

Thermal Expansion of Common Building Materials

	mm/mm/°C	in/in/°F
Marble	5.5	4.5
Granite	8.5	4.7
Titanium	8.6	4.8
Plate Glass	9.0	5.0
Carbon Steel	13.0	7.3
Concrete	14.5	8.0
Stainless Steel (316)	16.0	8.9
Copper	16.5	9.3
Aluminum	22.2	12.3

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

40

Titanium Application Guidelines

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

41

Why Choose Titanium?

- Long life and low maintenance may produce

Lowest life cycle cost

42

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

43

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

45

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 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

46

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**

47

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 3AL-2.5V (90 ksi UTS/70 ksi YS)
- Grade 23 Ti 6Al-4V ELI (120 ksi UTS/110 ksi YS)
- Grade 5 Ti 6Al-4V (130 ksi UTS/120 ksi YS)

48

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

49

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

50

Grade Selection

Ti 3Al-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

51

Grade Selection

Which Grade?

Ti 6Al-4V, ASTM Gr. 5 (130 ksi/120ksi UTS/YS) and Ti 6Al-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

52

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

Welding

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

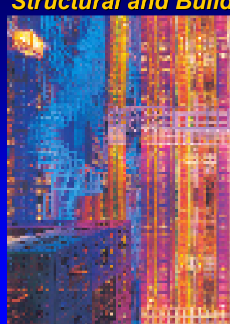
Structural and Building Applications

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

Structural and Building Applications

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

Structural and Building Applications



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

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

Structural and Building Applications

Titanium accent table with locally anodized color patches, lighted at night

Structural and Building Applications

Titanium Water Fountain

30 inch diameter

Structural and Building Applications

Etched and anodized titanium vessel

5 inch diameter

Structural and Building Applications

Titanium Wall Hanging

Etched and anodized titanium and niobium 21"

Structural and Building Applications

Denver Art Museum, Denver, Colorado **Titanium Cladding**

Architect David Liebskind

Structural and Building Applications

Cerritos Millennium Library

Structural and Building Applications

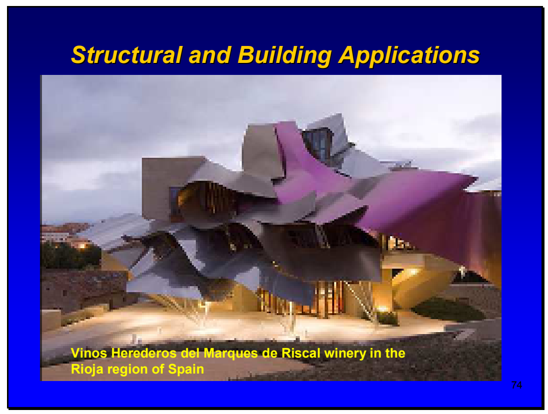
Guggenheim Museum, Bilbao, Spain

Clad in polished titanium Grade 1 sheet Architect Frank Geary

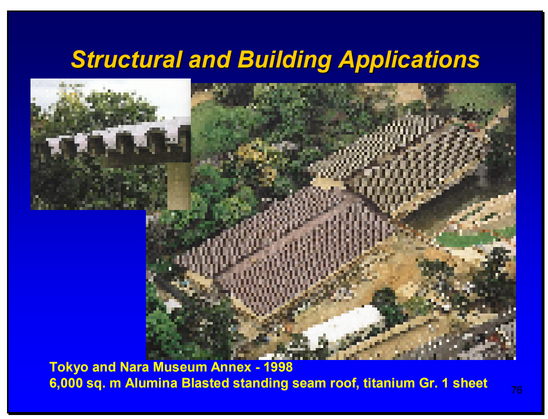

Structural and Building Applications
Guggenheim Museum, Bilbao, Spain
32,000 sq.m. of Grade 1 titanium sheet, manufactured to the architects specification with a deliberately introduced ripple and soft textured finish
71


Structural and Building Applications
National Scottish Science Center
Clad in polished titanium Grade 1 sheet
72


Structural and Building Applications
Sun Plaza, Jakarta, Indonesia
36,000 sq. ft. undulating waqll panels & canopy titanium Gr. 1 sheet
73


Structural and Building Applications
Vinos Herederos del Marques de Riscal winery in the Rioja region of Spain
74

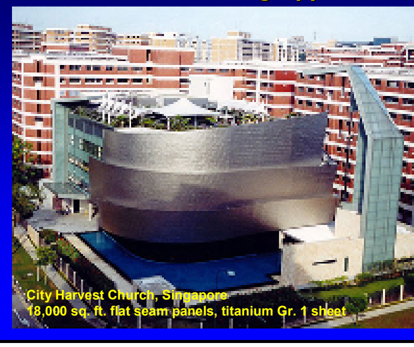

Structural and Building Applications
Okinawa Prefecture Building, Okinawa - 1997
5,000 sq. m. 0.4 & 0.8 mm roll dull, seam welded
75


Structural and Building Applications
Tokyo and Nara Museum Annex - 1998
6,000 sq. m Alumina Blasted standing seam roof, titanium Gr. 1 sheet
76

Structural and Building Applications

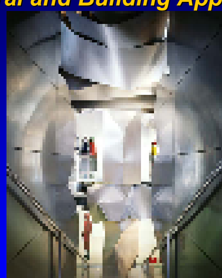
Uchinada Town Office/Ishikawa Prefecture, Japan - 1998
1,700 sq. m Roll dull & green color development 0.4 mm stepped roofing, titanium Gr. 1 sheet

Structural and Building Applications



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

Structural and Building Applications

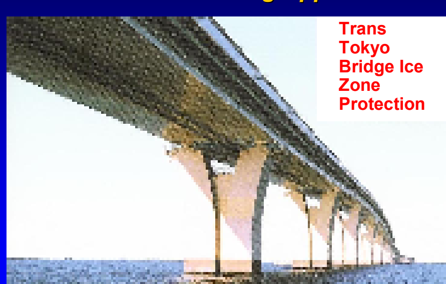


Issey Mikaya showroom, New York
8,000 sq. ft. titanium Gr. 1 sheet, annealed and pickled

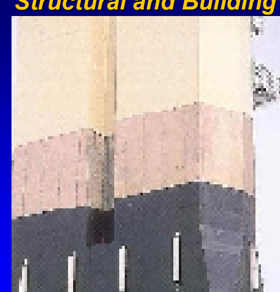
Structural and Building Applications

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

Structural and Building Applications



Structural and Building Applications

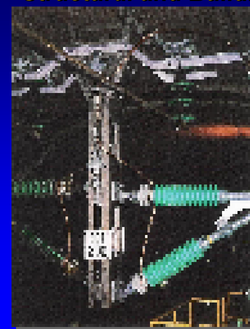


Sheathing for ice protection for Trans Tokyo Bridge is made of titanium bonded to steel

Structural and Building Applications

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

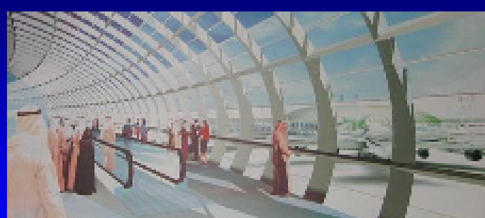
Structural and Building Applications



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

Structural and Building Applications

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

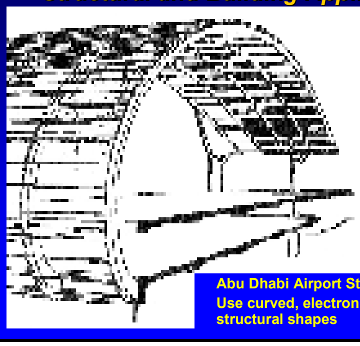
Structural and Building Applications

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

Structural and Building Applications

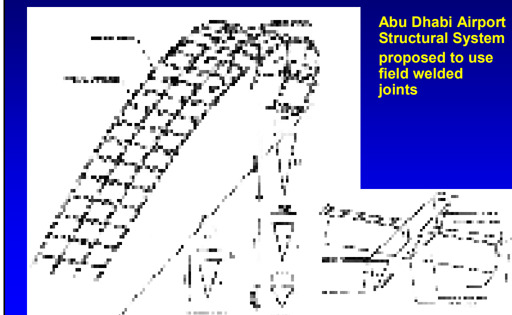
Abu Dhabi Airport Structural System
Building would have required 1250 tons of titanium Ti 6Al-4V

Structural and Building Applications



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

Structural and Building Applications



Abu Dhabi Airport Structural System proposed to use field welded joints

Structural and Building Applications

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.

Structural and Building 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

Structural and Building Applications

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:

Architectural Titanium LLC,
Lawrence, Kansas

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