A definition of low-cost titanium products was proposed by CTC and refined by delegates as follows: Useful titanium alloy products whose production path involves processing that lowers costs, including reduction processes, electron beam and plasma arc single melt processes, optimized thermo-mechanical processing, and near-net shape fabrication. Some processes allow higher impurity levels (e.g., resulting from melting low-cost scrap) to be tolerated while enabling products to have good properties.

Professor Jim Williams, Dean of Engineering and Honda Chair, The Ohio State University, gave the keynote address and suggested that one or two parts on a high-volume auto or truck could move low-cost titanium technology to a new level and make the technology prosper. He pointed out that in Europe, Volkswagen has placed titanium alloy springs in its cars, and in the United States, some race cars have titanium alloys in valves and springs, and gamma titanium aluminide in turbocharger rotors.

To reduce titanium cost and/or improve quality, a variety of areas should be the object of research programs. These include manufacture of pre-alloyed sponge, development of alternatives to TiO₂ and TiCl₄ as feedstock, and improvement of sources for low-cost titanium powder. In addition, facilities for production of low-cost titanium should be separate from those that make aerospace grades, to prevent cross-contamination problems.

Professor Williams also noted several process developments that increase the likelihood of greater titanium usage: laser additive manufacturing as an alternative to forging; single-melt production of rectangular ingot; and potential breakthroughs in low-cost processes to win titanium from its oxide.

This article reports on the comments of several other speakers at the workshop, focusing on applications for ships and military ground vehicles, and describing low-cost fabrication methods.

**Navy ships**

Michael E. Wells, Project Engineer at Naval Surface Warfare Center, Carderock Division, discussed current applications for titanium on Navy ships and identified data needed to expand applications. Commercial purity (CP) titanium is currently replacing 90:10 CuNi on heat exchangers on the DDG 51 destroyer. CP titanium is also serving on the LPD 17 San Antonio in seawater piping with diameters ranging from 0.5 to 12 inches. The projected savings in life-cycle costs is $17 million per ship.

CP titanium was designed into the ship, and this success underscores the importance of a life-cycle cost justification. Alloy Ti-3Al-2.5V (half 6-4) may replace DH 36 steel for hatches and weather doors on the DDG 51. Designers are looking at Ti-6Al-2Cb-1Ta-0.8Mo (Ti-6-2-1-1) and Ti-5Al-1Sn-1Zr-0.8Mo (Ti-5-1-1-1) as potential hull materials. However, data are needed to ensure that these alloys, as well as half 6-4, have adequate dynamic loading resistance before the life-cycle cost trades will be seriously considered. Moreover, weldment integrity is an important issue, and ways to reduce...
titanium. All enable the low-cost reduction in parts count, weight was reduced from 486 to 350 lb — a 28% reduction.

the cost of welding titanium are needed, such as reducing inert gas cover costs and innovative non-hygroscopic backing tapes.

An NCERT project was recently initiated to identify potential applications for low-cost titanium on aircraft carriers. Candidates for Ti alloy applications include the island, piping, elevator platform, doors, sponsons, armor, deck, and jet blast deflector. Other potential Navy applications include heat exchangers on DDG51 destroyers to replace 90:10 Cu-Ni seawater piping, hatches, and weather doors. For applications that are welded from one side, a non-hygroscopic backing tape is needed to protect the root of the weld.

Dr. William T. Messick, Materials Technology Consultant, Strategic Analysis Inc., cited a calculation showing that 1545 tons could be saved on a CVN class aircraft carrier deck by substituting a titanium alloy for steel. Data are needed to establish the maximum impurity level for dynamic fracture toughness that provides adequate threat resistance.

The Littoral Combatant Ship is in the design stage. It is required to have a 40 to 50-knot top speed, and a >30-year service life. These demanding requirements have led designers to consider aluminum alloys, composites, and titanium alloys.

The Defense Advanced Research Projects Agency has a program to scale up and further develop three leading reduction technologies to make low-cost titanium: the Fray-Farthing-Chen or FCC process, the MER (Materials & Electrochemical Research Corporation) process, and the Stanford Research Institute or SRI process. All enable the low-cost reduction of titanium from feedstock to form titanium or titanium alloy powder. If any become successful, the production cost of titanium could be dramatically reduced, and it could be applied on Navy ships such as fast combatants and aircraft carriers.

Military ground vehicles
James Dorsch, Principal Engineer of United Defense, presented several noteworthy examples of current and potential applications in military vehicles.

- **Bradley Fighting Vehicle**: Low-cost titanium is currently serving as add-on roof armor for the A3 Bradley Fighting Vehicle. In addition, the Bradley A2 commander’s hatch is now titanium. Bradley prime contractor United Defense made a limited production run of M8 Armored Gun Systems, and included titanium bolt-on armor and a hatch forging to keep weight low while providing ballistic protection.

- **Crusader howitzer**: The Crusader self-propelled 155-mm howitzer, which will not go into production, included conventional Ti-10-2-3 trunion blocks and a welded gun cradle assembly to reduce both weight and parts count.

- **Future Combat System – Wheeled vehicle (FCS-W)**: This state-of-the-art combat vehicle resulted from collaborative work involving United Defense, the Tank-Automotive Research Development & Engineering Center (TARDEC), the University of Delaware Center for Composites Manufacturing, RMI Titanium, Armaments Research Development & Engineering Center (ARDEC, Picatinny), Army Research Lab, CTC and others. FCS-W has a Ti-6Al-4V lower hull that has been welded to demonstrate that large, high-oxygen titanium structures could be successfully fabricated. The technologies are expected to find their way into future combat systems.

Dr. William A. Herman, Manager of Material Engineering & Survivability for General Dynamics Land Systems (GDLS), presented MGV titanium work on several platforms and noted that the acquisition cost premium should be included in the prime contract for a weapons system platform.

- **Stryker**: Under TARDEC sponsorship, CTC worked closely with GDLS and PCC Structurals to redesign the gun pod for the Stryker mobile gun system to exploit low-cost titanium. This team demonstrated that two titanium castings could replace the welded steel pod, which is comprised of 40 subcomponents. In addition to the significant reduction in parts count, weight was reduced from 486 to 350 lb — a 28% reduction. James Barrett and Bret Clayton of PCC Structurals noted that near-net-shape casting technology has enabled manufacturing costs to be reduced by 42 to 60% in MGVs, with a 77% decrease in weld lineage and an 80% reduction in parts count.

- **M1 Abrams tank**: Dr. Herman noted that titanium parts on the M1 Abrams include turret blowoff panels, the gunner’s primary sight structure, and the demonstration use of titanium for the commander’s hatch. For the Marines Expeditionary Fighting Vehicle (formerly the AAV), he listed several titanium applications, including the forged Ti-6-4 hydropneumatic suspension units.
 • **M777 howitzer**: Stephen Luckowski, Materials Engineer of U.S. Army TACOM-ARDEC, and Christopher Hatch, Product and Process Manager, JLW-155mm Program Office, presented numerous examples in which near-net-shape Ti-6-4 castings reduced parts count and welding costs on the M777 towed lightweight 155-mm howitzer. The M777 is a titanium-intensive weapons system in the low rate initial production stage that is providing an excellent opportunity to advance low-cost titanium components and technologies. The 9000-lb M777 will replace the 16,000-lb M198 steel-intensive howitzer.

Mr. Luckowski also described an interesting application of titanium in small arms, including the receiver for the M240 machine gun and the base plate for the 120-mm mortar. Titanium reduced the weight of the M240 from 27 to 20 lb, and the mortar base plate from 135 to 70 lb.

### Low-cost processing

A variety of approaches have been developed in an effort to reduce the cost of manufacturing titanium parts.

- **Flow forming**: Dynamic Machine Works recently fabricated the world’s largest flow-formed titanium tube under an NCEMT project.

- **Rotary piercing**: Mitchell Dziekonski, President of Titanium Engineers Inc., described a joint effort with Timken Steel to use Timken’s rotary piercing process to make affordable seamless titanium tube. A billet is spun over a mandrel with rotary rollers that elongate the billet over a mandrel. Each tube can be produced in 90 seconds or less. Several alloys have been successfully shaped into tubes by this technique: Size range capability is 2 to 11.5-inch outside diameter, with lengths up to 28 feet.

- **Reaction sintering**: Dr. K.S. Ravi Chandran, Professor of Metallurgical Engineering, University of Utah, discussed titanium matrix composites containing titanium boreide whiskers (TiBw). These are formed by an in-situ reaction sintering process. Composites reinforced with varying volume fractions of TiB have been made with a maximum Vickers hardness of 1800 kg/mm². Dr. Chandran is also making fully dense graded armor plates by titanium powder metallurgy that are under evaluation by the Army Research Laboratory.

He also described a TiB-coating technology for surface hardening titanium to increase surface performance in contact and wear applications. He highlighted the possible applications of TiB-reinforced or coated titanium in the biomedical, bearing, and firearms fields.

- **Powder metallurgy**: Dr. Vladimir Moxson, who has extensive experience with titanium powder technology from the former Soviet Union, is President of ADMA Products Inc., a successful P/M titanium company in the United States. Dr. Moxson and Professor F.H. (Sam) Kroes of the University of Idaho, who was not able to attend the workshop, prepared a joint presentation. Dr. Moxson noted that angular Ti powder is easier to press and mold than spherical powder. He described fasteners made by the blended elemental P/M approach.

- **CHIP powder metallurgy process**: Dynamet has a proprietary process that involves blended titanium and alloy powders, cold isostatic pressing, sintering to 95% theoretical density, and hot isostatic pressing (CHIP) without encapsulation. Stanley and Susan Abkowitz of Dynamet presented the advantages of this titanium powder metallurgy process. Stanley Abkowitz, of this father-daughter team, has been involved in titanium technology since it became viable in the mid 1950s, and is the inventor of mainstay alloy Ti-6Al-4V. The CHIP process produces near-net-shape parts with properties equivalent to those of wrought Ti-6-4, but at significantly lower cost. It has been successful for several alloys, including Ti-6-4, Ti-6Al-6V-2Sn, and titanium matrix composites. Some 45,000 Sidewinder missile dome housings, 2000 seeker housings, and 50,000 Stinger missile warheads have been made by this process.

Dynamet also makes the CermeTi family of titanium composites reinforced by TiC or TiB₂/TiB. Typical CermeTi grades have Young’s modulus values in the 19 to 20 Msi range. CermeTi B5 has cutting-edge retention superior to that of Rockwell C 63 steel. It is clear that titanium powder metallurgy parts will be made in greater volume if novel powder production processes advance to the production scale.

Titanium has been successful in making porous P/M plates for oxygen generators on spacecraft. Novel, low-density titanium-matrix composites have been made by infiltrating a titanium skeleton.

### Panel discussion

A panel of experts discussed relevant titanium production topics and answered a variety of questions. The panel included Dr. Stephen P. Fox, Timet; Dr. Kuang-O (Oscar) Yu, RMI Titanium Company; John Hebda, Wah Chang Titanium; Dr. Vladimir Moxson, ADMA Products; Dr. William T. Messick, Strategic Analysis Inc.; Stanley Abkowitz, Dynamet Technology Inc.; and chairman Dr. Joseph R. Pickens, CTC.

In closing remarks, Dr. Pickens encouraged delegates to interact after the workshop to identify and pursue applications for low-cost titanium. He noted that cost-effective scale up of the novel reduction processes could cause rapid demand for Ti P/M products. Dr. Pickens emphasized that expanded use of low-cost titanium requires close cooperation among titanium producers, designers, users from the commercial sector and prime contractors, government program offices, and the R&D community.

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