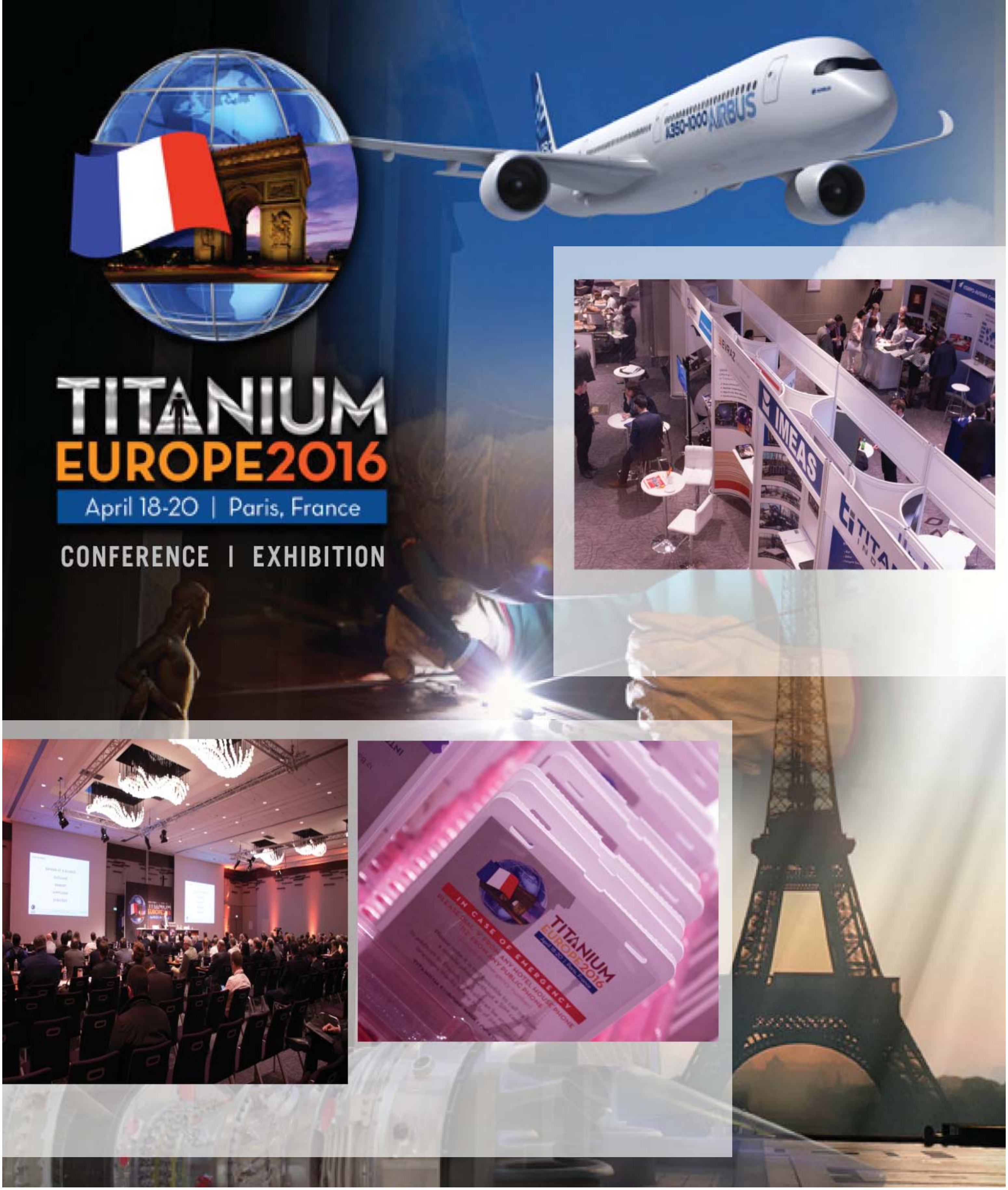
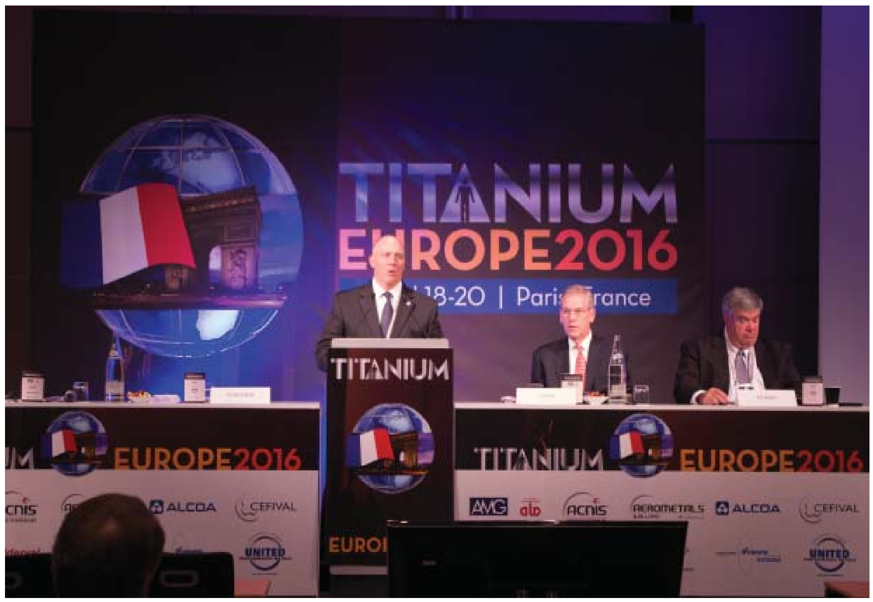


EXECUTIVE SUMMARY REPORT

TITANIUM EUROPE2016
April 18-20 | Paris, France

TITANIUM EUROPE Conference Speakers Forecast Soaring Demand from the Global Aerospace Industry



TITANIUM EUROPE 2016, the conference and exhibition organized by the International Titanium Association (ITA), was held April 18-20 at the Paris Marriott Rive Gauche Hotel and Conference Center. Jennifer Simpson, ITA executive director, said the fourth-annual event served as a platform to provide insights into the European titanium industry.

Titanium industry executives provided outlooks on world supply and demand; the ever-lengthening global supply chain, business trends driving the key commercial aerospace sector; and recent technological advances. The European forum, which attracted 400 attendees, complements the annual North American gathering, which also is sponsored by the ITA. Last year the TITANIUM EUROPE conference was held in Birmingham, England.

Markus Holz, president, AMG's Engineering Systems Division, the chief executive officer of ALD Vacuum Technologies GmbH, a member of the ITA's executive board and co-chair of the education committee, and the 2016 TITANIUM EUROPE conference chair, penned a letter to welcome visitors to the fourth annual TITANIUM EUROPE 2016 conference in Paris. The conference, Holz wrote, "is a platform providing insights into the European titanium industry an excellent opportunity for you to meet with ITA members from all over the world, creating an opportunity for networking, collaboration, sharing of information and the building of relationships internationally."

In particular, Holz, urged attendees to consider the insights that would be contained in keynote address by **Thierry Viguier**, purchasing director of materials for Safran SA, Paris. Safran, Holz explained, is a French multinational designer and manufacturer of aircraft and rocket engines related aerospace components. "Mr. Viguier will share his expertise to address trends in the global aerospace industry, a key market for titanium mill products. Growth in the aerospace industry along with the higher use of carbon fiber composites, which are compatible with titanium, is likely to increase the demand for titanium. As lightweight materials that provide outstanding corrosion resistance and high-temperature properties, titanium mill products have long been the preferred material of choice for aircraft manufacturers in a

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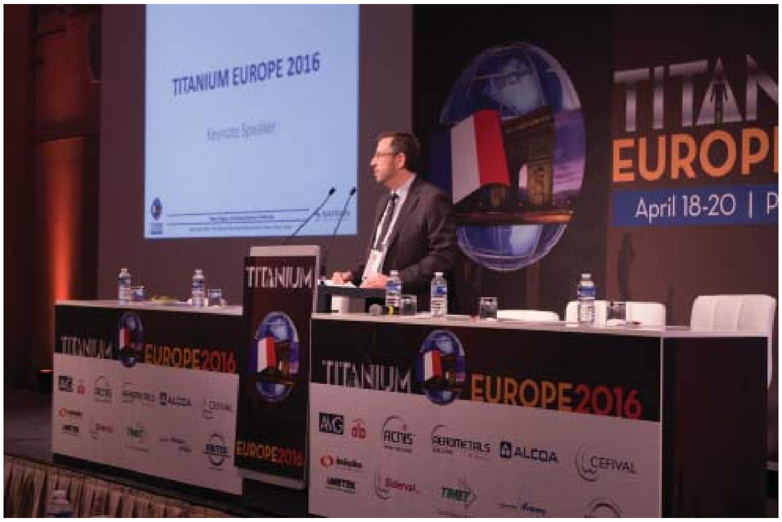


range of applications such as structural components and engine parts."

Viguier's presentation was a call to the international titanium industry to take the necessary steps in order to meet projected demand. He said Safran forecasts that global growth demand for titanium is expected to be 4.5 percent per year, leading up to 2025, which includes an additional need of 85,000 metric tons of bars and billets, driven mainly by the commercial aerospace business. Not surprisingly, he identified production of the titanium-intensive Airbus A350 and Boeing V787 as two aircraft (among many) fueling this growth. Safran projects global melting production capacity needs to ramp up to reach a level of 530,000 metric tons by 2020 in order to keep pace with overall demand for titanium, with 50 percent of that total dedicated for aerospace and defense. By way of comparison, Safran estimates that in 2013 there was 450,000 metric tons of global melting capacity.

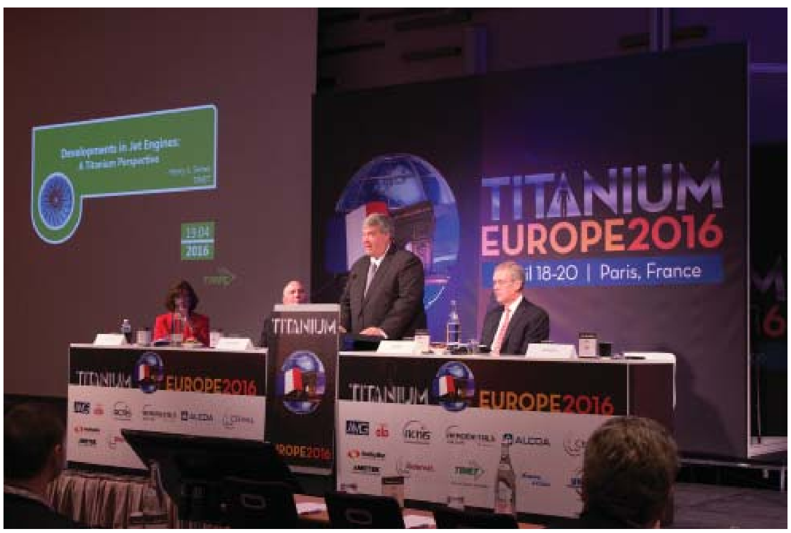
As part of this growth forecast, Viguier said that by the year 2020, current "aeronautical-qualified" sponge capacity will be "just enough" to cover projected demand. As a result, he said "it's necessary that new aeronautical (sponge production) capabilities are developed." Safran forecasts that overall sponge "value chain" production capacity by 2025 will need to be in a range of 560,000 to 620,000 metric tons, of which 53 percent should be aeronautical-qualified sponge. Safran estimated global sponge production capacity in 2015 was 400,000 metric tons, with 65 percent of that total achieving aerospace quality.

World Demand Trends

Dawne S. Hickton, president of the ITA's executive board, chair of the Women in Titanium committee, and the former vice chair, president and chief executive officer of RTI International Metals Inc., served as the moderator for the World Demand Trends panel. Eric Roegner, chief operating officer, Alcoa Investment Castings, Titanium and Engineered Products; president, Alcoa Titanium & Engineered Products; and president, Alcoa Defense, addressed conference delegates with his presentation titled: "Titanium in the Military: Driving Market Growth Through Innovation." Roegner urged the international titanium industry to work outside of the box to advance the use of titanium in military through innovation. He pointed out that European and U.S. defense budgets are responding to threats and regional instability. Titanium content will remain strong in military aero structures such as transports planes, fighter jets and rotor aircraft. He assured the audience that the titanium industry "will thrive when leading with innovation across the value chain," through the development of new materials and advanced manufacturing technologies.

Wade Leach, Jr., senior vice president, commercial, ATI Specialty Materials, discussed "Titanium Demand and Trends in the Airframe Market." Leach showed a bar chart (using Airline Monitor as a source) that projected the active commercial aircraft fleet would double to over 50,000 planes by the year 2034, with a compound annual growth rate (CAGR) of 3.9 percent, compared with the current estimated fleet of 30,000 jets.

Much like keynote speaker Viguier, Leach also identified the A350 and B787 as the commercial aircraft driving next-generation titanium usage, but added the Boeing 737Max, and the Airbus A320Neo and A380 to the mix. He described titanium as a preferred option in a wide range of airframe applications—from small fasteners to landing gear and wing beams.



Henry S. Seiner, vice president, business strategy, Timet (Titanium Metals Corp.), gave a talk on "Developments in Jet Engines: A Titanium Perspective." Seiner pointed out that jet engine size and performance characteristics have evolved in conjunction with changes in the market landscape. In one bar chart, compiling estimates from various sources, including internal estimates by Timet, he indicated that the global titanium forecast for jet engines would reach nearly 20,000 metric tons by the year 2025, compared with the 2016 estimate of 17,000 metric tons.

Seiner also displayed a slide ("Airline Monitor versus OEMs") that compared 20-year outlooks of aircraft production forecasted by Airline Monitor, Boeing and Airbus. Leaving out the category of regional jets, but including the categories of single-aisle, small and medium wide-body, and large wide-body jets, Airline Monitor's total came to 37,682 units, compared with Boeing at 35,560 units and Airbus at 32,600 units.

Dr. Claudio Dalle Donne, vice president, materials and processes, Airbus S.A.S., discussed "Titanium Aerospace Demand and the Integrated Supply Chain." In his talk, **Raphael Duflos**, Airbus vice president, metallic materials procurement, stated that, in the context of growing aircraft demand and of ramp up of new programs, "Airbus titanium supply chain needs to deliver on challenges of both accompanying the ramp up by delivering with excellent industrial performance, and of optimizing total cost of ownership of flying parts. Engineering cost out of the supply chain will be instrumental for that purpose."

Michael G. Metz, president, VSMPO Tirus US, presented information on an "Overview of Russian Market for Titanium Mill Products." Metz displayed a bar chart that showed the forecasted titanium demand for the Russian market would approach 12,000 metric tons by 2021, compared with 10,000 metric tons in 2016. The aviation sector represents the largest share of demand—about 7,000 metric tons for the projected total in 2021.

On the production side, Metz pointed out that Russia has two sponge producers: VSMPO/AVISMA and Solikamsk Magnesium Works (SMW). Avisma holds 44,000 metric tons of sponge production capacity, while SMW's capacity is 2,500 metric tons. As for the five Russian titanium ingot producers, VSMPO leads the pack, holding 67,000 metric tons of the overall 75,500 metric ton production capacity.

Albert Bruneau, executive vice president, Vallourec Heat Exchanger Tubes, offered remarks on global trends in industrial markets. Since mid-2015, virtually all titanium executives and informed observers have lamented that weakness in the global industrial markets has all but offset the strength for titanium demand in the aerospace sector. Application areas include chemical processing, desalination, heat exchangers, automotive and nuclear power. Much of weakness in the industrial sector is tied to the decline in the oil and gas industry.

According to Bruneau, industrial titanium demand, currently estimated at 23,000 metric tons, will rise to nearly 30,000 metric tons by the year 2021. Projected bright spots for titanium industrial demand during this timeframe includes nuclear power projects in China, Russia and the Middle East, and desalination "opportunities" in the Middle East, India and China.

Ren Wei Feng, chief economist, Beijing Antaike Information Development Co., Ltd., tracked "Titanium demand trends in the Asia/Pacific Region." Ren said his group estimates that, by the year 2020, demand for titanium in China and the Pacific Rim will register 122,000 metric tons, compared with an estimated 68,000 metric tons this year.

Ren showed a pie chart that illustrated the breakdown in global titanium sponge capacity. Of the 270,400 metric tons of existing global sponge capacity, China accounted for 88,000 tons of the total. In a separate chart, he indicated that titanium sponge production in China in 2015 totaled 62,035 metric tons. In a separate pie chart, Ren indicated that chemical processing was the largest end-use market sector for titanium in 2015 at nearly 45 percent, compared with the second-largest sector, aerospace, at nearly 16 percent.

World Supply Trends

Robert Baylis, managing director, Roskill Information Services Ltd., moderated the World Industry Supply Trends panel. **Sylvain Gehler**, managing director, Specialty Metals Co., Brussels, Belgium, presented an overview of the world titanium sponge supply and analyzed trends affecting sponge production today. According to Gehler, world titanium sponge production, in recent years, has gradually gone into a large surplus due to an increase of capacity or over production. Gehler estimated that titanium sponge inventories (except for China) have risen to more than 45,000 metric tons in Europe, Asia and the United States.

Gehler also observed that weakening foreign currencies against the U.S. dollar have decreased sponge prices to levels equivalent to six years ago. However, at the same time, demand for titanium from global industrial markets remains in a slump and demand from aerospace sector could slow down if the price of oil remains at low levels. Gehler is the chairman of the board of the UST Kamenogorsk Titanium and Magnesium Plant, a leading integrated producer of titanium sponge and magnesium located in Kazakhstan.

Graham P. Walker, vice president, sales and marketing, AMETEK Reading Alloys, shared his thoughts on "Master Alloys—Often Overlooked but Critical Raw Materials." Walker focused his remarks on business trends affecting vanadium and molybdenum. Global vanadium production in 2016 is slated to be 80,000 metric tons, compared with 90,000 metric tons two years ago. Vanadium pricing is driven by steel demand, which accounts for

93 percent of global vanadium consumption, compare with just four percent for titanium. Walker, in one of his charts, indicated that aerospace-grade vanadium production is either off-line or reduced in major producing countries like China and South Africa. Brazil is one exception and is expected to produce 5,500 metric tons compared with 500 metric tons in 2014. However, the chart noted that this Brazilian vanadium production has not yet been aerospace qualified.

Similarly, molybdenum production and consumption also peaked in 2014, in excess of 590 million pounds and 550 million pounds, respectively. This year, Walker estimated that production will fall below 490 million pounds and consumption will dip to around 510 million pounds. (Walker said numbers in the forecast were indexed to 2010 as a base year and represented by percentages compared with the base year. The forecast excluded China and India.) He said between 75 and 80 percent of molybdenum produced goes into steel production, and significant molybdenum mining capacity is closed or on care and maintenance. “Prices need to improve to bring capacity back on line,” he said.

A master alloy is a value-added, semi-finished product, created for use as a raw material by the titanium industry, which typically contains two or more alloying elements to achieve enhance properties, such as enhanced heat and corrosion resistance, for a specific application. Master alloys in the titanium industry are binary, ternary or multi-component alloys used to efficiently and effectively allow the melting of titanium alloys.

Nicholas D. Corby III, titanium product manager, ELG Utica Alloys Inc., discussed “Titanium Scrap Trends—Impacts of a Dynamic Market.” ELG provides certified processing of titanium and super alloy revert turnings and solids, with facilities in North America, Mexico, Europe, South Africa, Singapore and China. Corby underlined the significant reduction in energy consumption and related carbon dioxide emissions (95 percent each) when using scrap to produce titanium ingots, compared with sponge.

Corby said that most of the melting capacity for titanium scrap is concentrated in North American, with new projects in Europe, Japan and China. Scrap has to be sourced globally, but supplied locally, he stated, adding that sophisticated logistic solutions are needed to secure scrap volumes generated in “emerging manufacturing clusters” such as Brazil, North Africa, India and Asia.

Development of Commercial Aerospace and Economic Impact

Henry Seiner, TIMET moderated the Development of Commercial Aerospace and Economic Impact panel, which featured presentations by **Bill Bihlman** and **Charles Armitage**. Bihlman, the president of Aerolytics LLC, addressed “Material Trends in Commercial Aerospace Impacting Titanium.” Bihlman, who began his career as an engineer with Raytheon Aircraft, founded Aerolytics in 2012. He said total annual consumption of raw material for commercial and military aerospace programs is 1.5 billion pounds, about 45 percent of which is aluminum, followed by steel, super alloys, titanium and composites. Most of the metal material comes in the form of billets, primarily for forgings, except for aluminum, which has a large plate market.

“Hard alloys” (titanium, super alloys and specialty steel alloys) make up about one-third of the total raw material demand (about 550 million pounds), with applications in engine components and landing gear. Of aerospace materials, titanium has the largest aerospace market share, with over 40 percent of its total global demand. The titanium alloy mill product market in aerospace is about 150 million pounds, largely billet and predominately the workhorse 6AL-4V grade, Bihlman continued.

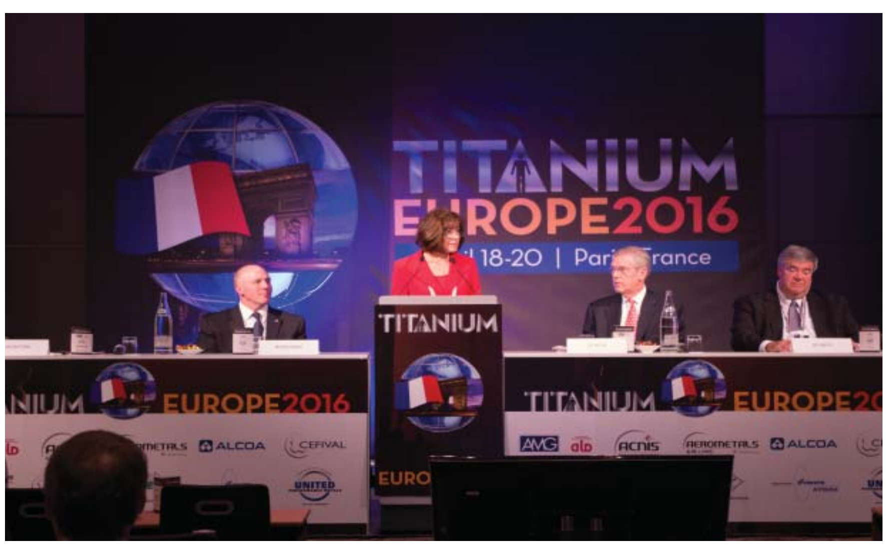
Armitage, the head of the European aerospace and defense equity research for UBS, gave his talk on "Balancing Cash, Risk and Growth to Maximize Value; An Equity Analyst's Perspective." He began by explaining that the concept of value "boils down to three things: cash, growth of that cash; and the riskiness of that cash." He displayed a graphic that showed a triangle of arrows pointing toward cash, growth and risk, with value at the center of the triangle. Too much focus on cash kills growth and reduces risk. Too much on an emphasis of growth means cash declines and risk increases. Too much risk aversion kills growth, but maintains a stable level of cash in the short term.

Building a long-term production forecast in commercial aerospace "should be easy," he said: start with growth demand (how many more flights?), plus replacement demand (knowing how old the current fleet is), which should equal new aircraft demand. However, Armitage cautioned that there is significant level of uncertainty in the aerospace sector, as well as sensitivity to "small changes in the market."

He offered several thoughts for the global aerospace supply chain, in light of the ambitious near-term forecasts for new aircraft issued by Airbus and Boeing. He said the current focus is on managing the "ramp up" of aircraft production as a result of these forecasts and the response of the supply chain to meet the needs of the two aerospace heavyweight original equipment manufacturers. However, Armitage suggest that the supply chain should think about balancing growth, cash and risk. "We're currently seeing the growth, but a downside risk would appear to be increasing. Maybe it's time to start thinking about conserving cash. How will we cope with a downturn?"

Titanium Powder

The Titanium Powder panel, moderated by **Dr. Christian Lehnert** of ALD Vacuum Technologies GmbH, featured four speakers, beginning with a presentation by **Dr. Thomas Ebel**, head of the Materials Design and Characterization department, Institute of Materials Research division, Metallic Biomaterials, Helmholtz-Zentrum Geesthacht, titled "From Powder to Demanding Components—Titanium and Powder Metallurgy." Ebel reviewed the state of the art regarding the use of titanium powders, comparing additive manufacturing/3D printing and metal injection molding. Manufacturers can create parts with mechanical properties matching standards of wrought material, if properly processed. Optimization of powder metal parts is possible via alloy modification and, in certain applications, offers a great potential for "low-cost titanium," according to Ebel.



Ebel did note areas of needed additional research, such as the development of robust alloys; grain refinement for optimized mechanical properties; strengthening by addition of hard particles in metal matrix composites; and a greater scientific understanding of the role of interstitial and other alloying elements. In particular, he cited the need to boost mechanical properties, especially low-fatigue resistance due to residual porosity or embrittlement by impurity uptake during processing. He also saw a need for improved surface treatment of powder metal parts.

“Titanium Powder Markets—Chances and Risks,” a presentation by Christoph Genter, managing partner, AMCG Unternehmensberatung GmbH, described powder metallurgy—a substitute for conventional titanium mill products and processes—as a disruptive technology, with “chances and risks” for the complete titanium metal value chain. AMCG is a management consulting company focused on market intelligence and business development for the customer industries special metals, chemicals and engineering.

Chris van Dam, general manager, Airborne Metals, covered the industrial aspects of titanium powder metallurgy and additive manufacturing, and considered potential applications of the technology for aerospace components. Two years ago van Dam established Airborne Metals as a distributor of aerospace grade raw materials and semi-finished products working with mills holding relevant system certifications.

Neill McDonald, director, MetaFensch Institut de Métallurgie du Val de Fensch, in his talk on “Pilot-Scale Research in Titanium Powder Production,” discussed the importance of pilot-scale production trials as a way to “bridge the gap from idea to industrialization.” McDonald said tailor-designed titanium powders, especially for additive manufacturing, are in increasing demand due to new applications and stringent final product specifications in various industrial sectors. The development of materials and processes is complex and time consuming. Pilot- and semi-industrial scale research on titanium powder is an often underestimated step in this process and beneficial in order to reduce risk, in particular related to investments, and to optimize processes and productivity both before and after industrialization.

Multiple questions remain regarding the optimization of titanium powder production, in particular for additive manufacturing applications, quality and yield, productivity and cost reduction, alloy development and the use of recycled materials. Research and development programs at MetaFensch will include investments in a 100 mm-diameter, crucible-free atomizer coupled with a plasma arc melter/cold-hearth refiner will allow the study of these questions and accelerate the deployment of new industrial titanium powder processes. MetaFensch is a publicly funded research center, founded in France in 2014, and dedicated to accompanying innovative metallurgical projects through to industrialization. In order to carry out this mission, a platform has been created in Lorraine (near the Belgian, German and Luxembourgish borders), which houses pilot-scale melting, casting and powder manufacturing equipment.

Industrial Markets

Robert Henson, manager, business development, VSMPO-Tirus US, moderator for the Industrial Markets panel, introduced Stuart Bond, group corrosion business development manager, Exova Group plc, who presented his paper on “Lab Testing to Qualify Titanium Grade 12

(UNS R53400) for Potential Ballot for Inclusion in NACE MR0175." Bond began by pointing out that "sour service" applications in upstream oil and gas require materials demonstrated to be resistant to the relevant cracking mechanisms, which can manifest in such service. Titanium Grade 12 has been covered for application in sour service without limitation but with restrictions on both the material properties and manufacturing parameters. This historic information is no longer aligned with modern processing and therefore the titanium industry desires to produce data to permit a change to the document to accommodate current manufacturing parameters.

In 2015, the Industrial Sub Group of the ITA, part of the ITA's Applications Committee, launched a first step in a project to remove restrictions on the use of Grade 12 titanium on the NACE MRO 175 (also known as ISO 15156, the international designation of the standard) specifications—a standard for the petroleum and natural gas industries regarding the use and performance of industrial materials in a corrosive, hydrogen-sulfide work environment. The hope is that removing certain restrictions will open up significant business opportunities for the titanium alloy.

Henson, chair of the ITA's Industrial Sub Group, interviewed last year, said the key development to move the project forward involves working with the Corrosion Centre of Exova Group Plc, West Midlands, U.K., which will conduct testing on titanium Grade 12 and present the findings to Houston-based NACE. Titanium Grade 12, an alloy that includes nickel and molybdenum, is very resistant to hydrogen sulfide industrial environments and represents a perfect application for this material, according to Henson. However, he pointed out that titanium Grade 12 currently is "not in harmony" with the MRO 175 specification, originally written in the 1980s, in areas such as basic mill practices, plate hardness and heat-treating techniques.

Rand Dannenberg, Ph.D., a materials scientist and optical physicist working in the CTO's Office of nanoPrecision Products Inc., discussed "A New High-Throughput Ultra-High Precision Process for the Manufacture of Fiber-Optical Components." Dannenberg said nanoPrecision Products, Inc. has developed a breakthrough ultra-high precision, high-throughput titanium stamping process that will disrupt the single-mode fiber-optic ferrule interconnect marketplace. He said the market is anticipated to be on the order of 500 million parts per year by 2020, and our product will consume 1,600 metric tons per year of titanium Grade 2.

The name of the product is the FerroIder®. Dannenberg said nanoPrecision's cost-and-performance competitive advantage "stems from our stamping technique that retains the traditional high production throughput of stamping, yet enables us to achieve geometrical form tolerances on the stamped parts on the order of 100 nanometers."

Bertrand Flipo, senior project leader, TWI Ltd., presented information on "Linear Friction Welding for Increased Industrial Titanium Productivity." Flipo provided recent developments from his group in the joining of Titanium alloys using the linear friction welding (LFW) process. He said such components are machined from solid blocks of titanium alloys, resulting in poor scrap ratios. According to Flipo, the use of near net shape parts produced by LFW can significantly reduce production costs for a wide range of components.

He said the build-up of near net shape parts by LFW also provides the opportunity for selection of appropriate dissimilar alloys in different parts of the part structure. “This approach allows the production of tailored components, resulting in both functional and economic benefits.” He described LFW as a high-integrity, quick, automated, repeatable forging process, adding that the manufacturing technology is well suited for the production of aerospace engine “blisks” (bladed disks).

“Titanium Alloy Bars for Renewal of Civil Infrastructure,” a paper by **Christopher Higgins, Ph.D., P.E.**, School of Civil and Construction Engineering
Oregon State University, offered a solution for aging, deteriorating, civil transportation infrastructure. Higgins, who teaches graduate and undergraduate courses, and conducts research in structural, bridge, and earthquake engineering, was the 2015 recipient of the prestigious ITA Titanium Applications Development Award.

Higgins explained that due to limited resources, strengthening, rehabilitation, and renewal of existing infrastructure have become necessary alternatives to replacement. Carbon-fiber reinforced polymers (CFRP) have become the material of choice for rehabilitation projects but have many drawbacks that can be overcome using titanium alloy bars. He said current research is focused on demonstrating the potential of using titanium alloy bars to strengthen aging and deficient reinforced concrete bridges. “The addition of titanium alloy bars will allow the bridges to carry heavier truck loads and resist large earthquakes. Ti-6-4 bars with special surface deformations were developed for this application. The surface deformation pattern permits epoxy bonding to the underlying concrete.”

As reported last year in a story published by the ITA, the Oregon Department of Transportation (ODOT), Salem, OR, selected a repair concept by Higgins—a titanium “staple” to reinforce fractures in the reinforced concrete—which was deployed by ODOT on the Mosier Bridge, an “overcrossing” of Interstate 84, which is a major east/west corridor for the state. Higgins designed the idea of the staple and the requirement of a surface treatment that would allow titanium alloy bars to be used to strengthen concrete bridges. Perryman Co. manufactured the titanium staples and developed the methods to produce the surface treatment. Oregon State tested alternatives and selected the final pattern. Perryman handled the entire production of the staples. Perryman engineers then went on site to collaborate with repair contractors for the installation of the staples.

Medical Applications

Frank L. Perryman, president and chief executive officer, Perryman Co., served as the moderator of the Medical Applications panel. **François Ory** discussed “Titanium Alloys in Metals and Processing for the Orthopaedic Global Markets. Forecreu is president and owner of Forecreu, a business group that specializes in extruded and drawn hollow bars in special steel and titanium alloys used for the manufacturing of cutting tools, orthopaedic and trauma instrument or implants. Ory showed a pie chart with Forecreu estimating the global orthopaedic market in 2014 was $37.4 billion. In a separate bar chart, Forecreu forecasted that, considering a compound annual growth rate of 6.2 percent, this market would climb to a value of $53.7 billion by 2020.

Lars Ryberg, area sales director, Arcam AB of Sweden, in his paper “Additive Manufacturing of Implants—The Path to Production,” shared experiences on how the implant manufacturers who have implemented 3D/additive manufacturing technology in their operations, have obtaining CE certification and FDA clearance for their EBM-manufactured orthopedic and spinal implants.

Seung Eon Kim, principal researcher, Korea Institute of Materials Science, shared highlights of his work on "A Study on Microstructure and Mechanical Properties of a New Beta Titanium Alloy." Kim said that a new beta titanium alloy, Ti-39Nb-6Zr (TNZ40), has been studied for biomedical implant applications. He described the alloy as demonstrating a low elastic modulus, good mechanical properties and biocompatibilities, and reduced implant fracture in dental applications.

"Microstructure and mechanical properties are very sensitive to processing and heat treatment condition of beta titanium alloys," he said. "In this study, we have investigated the effect of heat treatment on microstructure and mechanical properties after swaging of TNZ40 alloy. Swaging process was conducted up to 75-percent reduction before heat treatment. After swaging, direct aging was only employed with temperature range from 350˚C to 450˚C.

Kim said the elastic modulus was dramatically decreased below 45GPa after 10 minutes aging and it was steeply increased again with aging time at all aging temperatures. Tensile strength showed similar behavior to elastic modulus in all aging conditions. He said that the fatigue property of this alloy will be also discussed as a candidate alloy for dental implants or orthopedic implant applications, such as hip replacements.

Titanium Aluminides

Henrik Franz, head of research and development, vacuum metallurgy, for ALD Vacuum Technologies GmbH, served as moderator for the Titanium Aluminides panel. **Dr. Volker Güther**, AMG Titanium Alloys and Coatings, GfE Metalle und Materialien GmbH, provided information on "Alloy Development and Production of Titanium/Aluminide TNM Forging Stocks for Low-Pressure Turbine Blades." Güther said that a beta-stabilized titanium aluminide (TiAl) exhibiting improved wrought processing capability has been developed. Based on this alloy (TNM), he said that an entire production line for low-pressure turbine (LPT) blades for the PW1000G aircraft engine has been established in Germany consisting of: vacuum arc remelting (VAR) TNM ingot production; VAR skull melting/induction skull melting with subsequent centrifugal casting; hot isostatic pressing (HIP); isothermal forging; thermal treatments; and machining to final blade.

Güther explained that alloy development was based on thermodynanamic modeling. "The adjustment of the final composition has been made after the evaluation of the thermomechanical properties of different alloy variations. Due to the defined fracture of beta phase in the microstructure, the TNM alloy shows outstanding wrought processing capability. Furthermore, tensile strength, fatigue strength and creep resistance exceed the figures of conventional TiAl alloys."

Matthias De Sousa, Ph.D., Silimelt research and development manager, presented a talk that pondered the question: "Can TiAl Oversized Powder Coming from EIGA Process be Managed?" De Sousa said that, due to its low ductility and poor-machinability, "TiAl-parts are quite hard to manufacture using classical shaping techniques. Powder metallurgy, like Metallic Injection Molding (MIM), or additive manufacturing techniques, supports the development of structural TiAl-parts manufacturing, even if it is highly related to the powder quality and cost."

De Sousa said that, because of its high reactivity, TiAl powders are usually produced thanks to free-crucible gas atomization like electrode induction gas atomization (EIGA) or rotating electrode process (REP). “These two methods produce a quite large size distribution (from 5 up to 300 µm), in particular for the REP technique. Powders with particles size above 100 µm are called ‘oversized’ powder, because their low-value market compared to powders with particles size below 100 µm.”

A study led by the companies Silimelt and ALD Vacuum Technologies devised a two-step process for TiAl powder production. The first step consists in producing TiAl powder using EIGA process, developed by ALD Vacuum Technologies. The EIGA-produced powder contains around 55 percent of particles sized below 100 µm and only 22 percent sized below 50 µm. The second step deals with the plasma fragmentation of oversized TiAl powders (greater than100 µm), in order to convert coarse powders into finer ones. A parametric study of this new plasma process has been led in order to define a range of optimized operating conditions for enhancing the production of fine particles. Starting from particles size above 100 µm, up to 50 percent of the raw material can be converted into particles sized below 100 µm, after in-flight plasma treatment. Dr. Wilfried Smarsly, representative, advanced materials, MTU Aero Engines GmbH, reviewed the “Status of Titanium Aluminides for Aero Engine Applications.” Smarsly noted that advances in gas-turbine development typically are driven by the need to reduce fuel consumption, emissions and costs. He said that, from material aspect, these requirements enhanced the development of highly creep- and oxidation-resistant materials of greater temperature potential than titanium alloys and of lower density than nickel super alloys.

“Advanced TiAl alloys are complex multi-phase alloys, which can be processed by ingot or powder metallurgy as well as precision casting methods or even forging,” he said. “Each process leads to specific microstructures that can be altered and optimized by thermo-mechanical processing and/or subsequent heat treatments.”

The blades can be forged using isothermal forging equipment. Subsequent, two-step heat treatments were conducted to adjust balanced mechanical properties; a sufficiently high plastic fracture strain at room temperature and good creep properties at elevated temperatures.

Manufacturing Technologies

Dr. Romain Vert, Ph.D., technical sales and research and development manager, Europe, TEKNA Group, delivered a presentation on “High Quality Ti-Based Powder Production and Recycling by Induction Plasma Technology” for the Manufacturing Technologies speaker panel, which was moderated by **Dietmar Fischer**, consultant, Titanium Consultancy and Training. Vert said that the performances of metal powder-based additive manufacturing (AM) technologies like electron-beam melting (EBM) and selective laser melting (SLM) greatly depend on powder characteristics such as flowability, packing density and purity. Particles exhibiting a perfectly spherical morphology largely contribute at optimizing both the flowability and the packing density of a powder.

However, Vert pointed out that not all the powder manufacturing processes succeed at optimizing these critical characteristics for the AM needs since satellites, pores and/or particles of irregular morphologies are regularly observed in commercial powders. Furthermore, powder flow, packing density and purity can be altered to different extent by the AM process and this is known to limit the recyclability of the powders.

The inductively-coupled plasma (ICP) proprietary technology developed by Tekna over the last 25 years has the capability to produce and/or recycle high quality titanium based materials, according to Vert. "The 'speroidization' process can produce pure titanium or titanium alloys such as Ti64, Ti6242 or TiAl for example," Vert said. "Tekna has developed a proprietary classification process specifically for removing ultrafine particles within a powder, allowing thereby the reuse of powders in AM processes that would otherwise be out of specification in terms of powder purity and flowability."

"Advanced Technologies for Hard Metals Forming" was the title of the paper by **Guillaume Sana**, research and development process manager, ACB. Sana said that titanium alloys and hard metals, such as nickel- or cobalt-based alloys, are very attractive regarding their mechanical and chemical properties (corrosion, oxidation) for aircraft parts application, either for structural or engine parts. But, he said, the main issue is the low formability of these alloys in ambient conditions, which makes it difficult to produce complex-shape parts. In ambient conditions, the bending ratio or spring-back effect sets the limit of part design and manufacturing processes. Customers have stringent requirements concerning processes and parts repeatability. For those main reasons, Sana said other processes must be considered.

Sana said that, for several decades, ACB (France) and its sister company Cyril Bath (USA), have developed several processes in order to solve this customer demand and to develop and promote the use of hard metals in the aerospace industry especially titanium alloys (Ti-6Al-4, Ti-6242, Beta-21S). Both companies, as suppliers of hydraulic presses and parts, can focus on supplier and customer point of view simultaneously. He said that advanced technologies can now be applied to part manufacturing with following objectives: parts without spring-back; process repeatability and homogeneous part quality; residual stress-free parts; and components with an improved buy-to-fly ratio. During his presentation, Sana reviewed manufacturing technologies such as superplastic forming, hot and cold stretch forming, elastoforming, and linear and rotary friction welding.

Dmytro Kovalchuk, director, JSC NVO Chervona Hvilya, discussed "New Electron Beam Equipment for Additive Manufacturing of Titanium." Kovalchuk said additive manufacturing (AM) is receiving considerable attention as a technology for near-net-shape production of titanium parts. Electron beam AM appears to be most attractive for titanium, thanks to the high-power of an electron beam and production of parts in a vacuum, according to Kovalchuk. "But in spite of impressive progress in implementation of additive manufacturing into titanium industry during last few years, there are still numerous technological problems caused by the imperfection of existing methods and equipment including residual porosity, non-uniform mechanical properties in different directions, residual stresses as well. In addition currently applied equipment and feedstock materials are quite expensive."

Given these challenges, Kovalchuk outlined a technology known as the "Electron Beam Pencil," which is based on the concept of direct deposition of feedstock in the form of wire or powder using special low-voltage gas-discharge electron beam guns. An electron beam in the shape of hollow inverted cone is used for creation of molten pool on the substrate and for melting of feedstock material. Feedstock in the form of wire or powder is supplied in the center of molten pool through a guide in the hollow conical electron beam, and low-voltage gas discharge electron beam gun and feedstock guide form together a common functional assembly. He said this method can enable AM of small and large-scale production of parts with high efficiency. Pilot electron beam installation based on this method is currently under review.

Melting Technologies

Pierre-Francois Louvigne, a titanium consultant and ITA affiliate member, served as moderator for the Melting Technologies panel. **Alexander Alexandrov**, lead research engineer of the Central Scientific Research Laboratory (CSRL), JSC (Chepetsky Mechanical Plant), outlined information on the "Production of Industrial Ingots of the Intermetallic VTI-4 Alloy Using Vacuum-Arc and Skull Melts." Alexandrov explained that the VTI-4 is an ortho-alloy on the basis of the Ti2NbAl compound. The composition of VTI-4 alloy involves six alloying elements: aluminum, niobium, zirconium, molybdenum, vanadium and silicon. The alloy is well suited for the production of blades and disks of aircraft engine's high-pressure compressor, with a working temperature at a long-term usage up to 700 °C. Alexandrov said that, despite the known advantages of such alloys, any ortho-alloy has limited usage because of the complexity in its metallurgical production.

Alexandrov said that the JSC Chepetsky Mechanical Plant is mastering now the production of industrial ingots of the intermetallic VTI-4 alloy through its cooperation with VIAM (Moscow), the developer of this alloy. In his talk he discussed the manufacturing of two triple remelted ingots of VTI-4 alloy: the first, with the estimated weight of 490 kg (1,080 pounds), via vacuum-arc melting; the second, with the estimated weight of 630 kg (1,382 pounds), through carrying out one remelting in the vacuum-arc skull furnace. The following materials were used for smelting of VTI-4 alloy's ingots: titanium sponge, aluminum, silicon, zirconium and master alloys aluminum-molybdenum-vanadium-titanium, vanadium-aluminum, niobium-titanium.

Briquettes were pressed on a vertical hydraulic press and then welded into consumable electrodes in the electron-beam unit. Smelting of ingots was carried out with use of vacuum-arc and vacuum-arc skull furnaces. The final third vacuum-arc remelting was carried out in a mold with a diameter of 360 mm (14 inches).

Bernd Friedrich, head of institute, RWTH Aachen, IME—Institute of Process Metallurgy and Metal Recycling, discussed "Ceramic Crucible Melting of Titanium Alloys and Intermetallics in VIM (vacuum induction melting)." Friedrich began by acknowledging that the recycling of titanium/aluminum alloys has become more important in recent years due to requirements set forth by the aerospace and medical business sectors. He said that a common way to melt titanium through VIM is to employ vacuum induction skull melting. A water-cooled copper crucible results in strong cooling of the molten material and the formation of a solid metal "skull" protecting the copper crucible from the liquid melt. However, due to the enormous amount of cooling water used, this process is very expensive. As a result, the use of ceramic crucibles is considered to be more cost efficient.

Friedrich said that the challenge when melting titanium-based alloys in a VIM using ceramic crucibles is to avoid any oxygen pickup. As the oxygen affinity of titanium is extremely high, most of the common crucible materials such as Al2O3 or MgO cannot be used. CaO, which is thermodynamically stable enough, is hard to handle as it is very hygroscopic and tends to react with air moisture. He said his group has examined various methods for melting different titanium alloys in ceramic crucibles. The research is focused on melting intermetallic TiAl alloy (GE 48-2-2) in yttria-coated Al2O3-crucibles as well as melting Ti-6Al-4V, Ti-6Al-2Sn-4Zr-6Mo and Ti-6Al-2Sn-4Zr-2Mo in a CaZrO3 crucible. “The results of our research show that it is possible to use these crucible materials with a reasonable oxygen pickup.”

Mohamed Bouzidi, vice president, strategic business unit aerospace, Aubert et Duval, discussed the business mission of UKAD, a joint venture between UKTMP of Kazakhstan and Aubert et Duval of France. UKAD was created in 2008 and launched its industrial ramp-up in 2012. Today UKAD is a supplier of bars and billets in the European market. UKAD receives ingots from UKTMP, produced in VAR furnaces, which are shipped and transformed in France. Bouzidi said plasma (and VAR) furnaces will be installed in UKAD’s facility in France and is expected to be in operation by 2018. The goals is to create a closed-loop revert recycling process for customers.

Benoit Noel, south Europe sales director and service and distribution operations director for Timet, examined the role of French companies involved in the titanium supply chain serving the aerospace market, and his observations on the changes in titanium demand in recent years. Noel has been working in the aerospace industry for the past 20 years, involved in metal forming and melting.

Titanium Workshop

Frauke Hogue, a member of the ITA’s education committee, conducted the “Metallography of Titanium and Its Alloys” workshop at the Paris conference, which provided an overview and understanding the microstructures of titanium alloys. Hogue reviewed a brief history of titanium and alloy development, along with an overview of the general properties of the major titanium alloy groups and their applications; and information on the basic metallurgy of titanium including the terminology used to describe microstructures.

Hogue received her education in metallography and testing of materials in Berlin, Germany. In 1967 she moved to the Los Angeles area and worked for Voi-Shan, a manufacturer of aerospace fasteners. Frauke later became an independent consultant in metallography, and since 1985 she has been teaching intensive courses at ASM International and at companies throughout the United States and abroad. Frauke developed “Practical Interpretation of Microstructures” in 1998, which consists of a collection of about 300 mounts and a notebook of annotated images of various materials and conditions. This was followed by “Metallography for Fasteners” and “Metallography for Failure Analysis.”

Next Conference in the USA

The ITA will host TITANIUM 2016, the 32nd annual international conference and exhibition, *Sept. 25-28, at the J. W. Marriott Desert Ridge Golf Resort in Scottsdale, AZ, USA.*

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