



iMAST

Institute for Manufacturing and Sustainment Technologies

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DIRECTOR'S CORNER

Ever since we got back from the holidays I've felt like I needed a seat belt on my desk chair! Things are moving fast these days and the iMAST staff is working hard to keep up. Paramount in our prioritized "to do list" is the ongoing effort to identify new projects that, if successful, will have high yields for the Navy. When we look for new projects we concentrate on potential for acquisition or life cycle savings as well as improved availability for the war fighter. Sometimes the payback is near term, like our short article on Cold Spray repair; sometimes its higher risk and mid-term, like a new sintering technology that may reveal opportunities to take better advantage of nano-powders.



Timothy D. Bair

Within this issue you will see a lot of pride in the fact that one of our project's has won recognition for its contribution to the NAVAIR mission through innovative

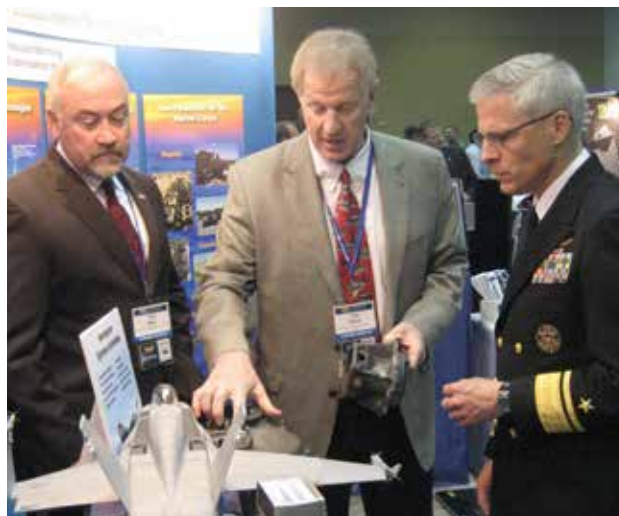
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2013 Defense Manufacturing Achievement Award

Since 1995, the National Center for Advanced Technologies (NCAT), acting as the agent for the associations and societies involved in the Multi-Association Industry Affordability Task Force, has sought to recognize individuals, as well as small working groups/teams in the defense manufacturing community who make outstanding contributions which further the manufacturing science and technology effort within the United States. Through the industry's Defense Manufacturing Excellence Award, these associations and professional societies acknowledge and recognize the contributions of those scientists, designers, engineers, and managers involved in defense-related manufacturing who have sought to conduct research into ways and means to increase the production, affordability, and/or technical

superiority of the nation's defense industrial base effort. During December 2013, at the annual Defense Manufacturing Conference, iMAST was honored as part of a team recognized for the project: **Restoration of Aerospace Parts by Cold Spray**.

Within the Army and Navy aerospace world, conventional repair processes for flight-critical components made from aluminum, titanium or magnesium alloys has always been a challenge. This project addressed several flight-critical aerospace components made



iMAST project leader, Dr. Timothy Eden (center) briefs Rear Admiral Matthew Klunder USN, Chief of Naval Research, on the Cold Spray project award, as it specifically applies to F/A-18 AMAD effort as iMAST Director, Tim Bair (left), looks on.

from of aluminum, titanium or magnesium alloys. Previous efforts to effect repairs using conventional repair processes have been unsuccessful. As a result, costly components are often removed from service and scrapped. This is a very expensive reality that costs the

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DIRECTOR'S CORNER

repair. If you've been reading our newsletters for a year or more you may recall several examples of iMAST's successful approach to innovation in repair and manufacturing technology. The award winning Cold Spray Repair project was instrumental in successfully introducing the NAVAIR depots to the potential of Cold Spray and its use in the repair of previously condemned components worth literally millions of dollars per year. This is a great example of our role in the transition of mature technology in innovative ways. The work being done to characterize FAST (the feature article) and define its sweet spot for innovation in DoD manufacturing is a future success story in the making.

iMAST's plan for the near future is to visit Portsmouth Naval Shipyard as a part of our ongoing Repair Technology (RepTech) program. While there we'll be reviewing ongoing projects, introducing ONR and our SYSCOM reps to new project ideas and asking PNSY how we might be able to help them. This working group meeting takes place twice a year, rotating between State College and a different yard or depot every winter. We're hoping cold and snow are through by early April this year! Enjoy our newsletter and thanks for what you do for our country and its defense!

Tim Bair

REPTECH WORKING GROUP MEETING

9–10 April 2014 (Portsmouth Naval Shipyard, NH)



A RepTech working group meeting will take place as noted above. The group will be reviewing a portfolio of 16 ongoing and 3 proposed projects. The group will also take a shipyard tour to talk with Portsmouth Naval Shipyard engineers and trades people in an effort to address some of the challenges they face. If you would like to learn more about iMAST's Repair Technology program, please contact iMAST Director, Tim Bair, at (814) 863-3880, or by email at <tdb14@arl.psu.edu>.

PROFILE



Jogender Singh is a chief scientist within the Materials and Manufacturing Office at ARL Penn State. He holds B.S., M.S. and Ph.D. degrees in materials and metallurgical engineering. His field of specialization includes materials development, coatings, surface-modifications of materials by various techniques including laser, electron beam beam-physical vapor deposition, and synthesis of nano-particles and characterization by various techniques including SEM, X-ray, HRTEM. He is taking leading role in powder processing and sintering of various materials (metals, ceramics, and composites) and net-shaped fabrication of components by Field Assisted Sintering Technology (FAST), cost effectively.

Prior to joining Penn State University, Dr. Singh worked for NASA and GE where he was responsible for the development of new materials and coatings for aerospace applications. His major interest continues to be cost-effective near net-shaped forming of components and solid-state-joining of dissimilar materials.

Dr. Singh is a Fellow of three professional Societies: ASM International (FASM), Institute of Materials (FIM), and the London and American Association for the Advancement of Sciences (FAAAS). Dr. Singh can be reached at (814) 863-9898, or by e-mail at: <jxs46@psu.edu>.

Near Net-Shaped Fabrication of Components by Disruptive Industrial Scale Field Assisted Sintering Technology

by Jogender Singh, Ph.D.

As a member of the Office of Naval Research (ONR) Manufacturing Technology family, iMAST expertise in diverse technology domains brings an expectation from ONR that we will assist in the discovery and development of new or emerging materials and manufacturing trends. One of the emerging technology fields iMAST began looking into three years ago was field-assisted sintering technology, or FAST. iMAST feels FAST will enable broad and significant changes in the materials development arena.

Within the United States, over the course of four years, significant attention has been focused on increasing manufacturing capabilities. An emphasis on efficiency and cost, driven by both industry and the government, however, has often been at the expense of innovation. The Applied Research Laboratory (ARL) at The Pennsylvania State University has been working to identify manufacturing innovations that can support cost cutting demands, especially as demanded by the Department of Defense under fiscal budget constraints. Additive manufacturing, net-shaped fabrication and utilization of powder metal (including nano) are three areas of concentration. This article concentrates on a new net-shaped fabrication technology that encompasses all three thrusts. Industry faces significant challenges in the manufacture of net-shape components having sub-grained microstructures. Typical steps involved in producing net-shaped components using powder include green compaction, sintering at elevated temperatures, and hot pressing to improve density. During conventional sintering and hot pressing processes, there is significant grain growth due to long thermal exposure, thereby destroying the effective functionality of sub-grained materials in the final component. These challenges have been addressed by an emerging manufacturing tool called Field Assisted Sintering Technology



(FAST). FAST is also known as plasma assisted sintering (PAS), pulsed electric current sintering (PECS), and electric pulse assisted consolidation (EPAC). ARL is taking a leading role in the manufacture of near net-shaped components made of metal, ceramic and composite via powder metallurgy using FAST. The principle, benefits, and applications of this technology are illustrated as follows.

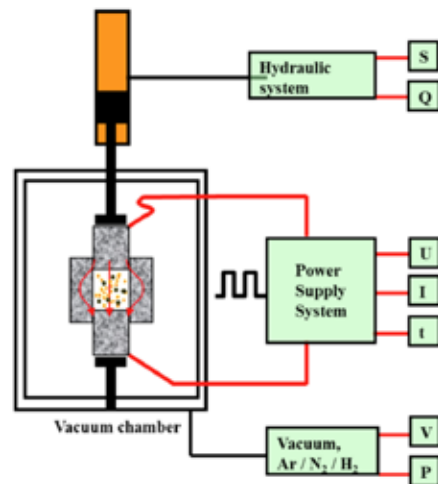


Figure 1. Schematic diagram of a FAST system

FIELD ASSISTED SINTERING TECHNOLOGY

Figure 1 shows a schematic diagram of a field assisted sintering system. The powder material to be sintered is contained in a graphite die. Pressure is applied via an upper and lower punch. The DC current (pulsed or continuous mode) flows through the punches and the die. Electrical current passed through the die provides radiant heating to the powder while current flowing through the powder produces instant Joule heating. Combining the effect of pressure, temperature, and localized heating at the grain boundaries results in a high sintering rate. Sintering can be done in controlled environments including vacuum, backfilled argon or nitrogen gas.

ARL Penn State is the only academic institution in the U.S. that has two FAST units; a small R&D unit with a load capacity of 25 ton (FCT HP D 25) and an industrial prototype unit with a load capacity of 250 ton (FCT HP D 250). The units, manufactured by FCT Systeme GmbH, Rauenstein, Germany enable the engineering of new materials from small samples (up to 80 mm) to large prototype components (up to 300 mm), respectively.

FEATURE ARTICLE

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The system is capable of sintering materials in various environments including nitrogen, argon, and hydrogen (to 1400°C maximum). Three major process variables (pressure, temperature, and high current density) can be applied concurrently during compaction and sintering of material powder in FAST.

APPLICATIONS
Ultrahigh Temperature Ceramic Tiles
Optical Windows and Mirrors
Thermo-electric Materials
Cutting Tool Industry
Thermal Management Electronics
Sensors-MEMS
Net-shaped Forming Components
Bio-medical
Body Armor Protection
Turbine and Nuclear Energy
Dissimilar Materials Joining

Table 1. Selective list of FAST applications

TECHNOLOGICAL BENEFITS

Due to the short processing cycle, there is significant pay off in reduced manufacturing cost of components. The technological benefits of FAST are numerous compared to conventional processing. They are:

- One-step process
- Shorter processing cycles (100–1000 times faster)
- Retention of sub-grained microstructure in components
- Achieves 100% density
- Energy savings of 60–70%

FAST has great potential in a wide range of applications (Table 1, above). It is possible to engineer new materials and to design and develop components with silent features that are not economically feasible using the conventional manufacturing methods. ARL

is working to explore and define the potential applications of FAST. Below are summaries of work areas currently underway.

HYBRID HEAT-SINK COMPONENTS

Thermal management is crucial for optimal performance of micro and macro electronic applications. Heat-sink plates are used to transfer heat generated during the operation of high electronic current density modules. Heat dissipation, thermal stress, and warping, due to large coefficient of thermal expansion (CTE) differences, are critical issues in reliability and packaging of microprocessors, power semiconductors, high power RF devices, laser diodes, LEOs and MEMS. There is no single material that can meet both thermal management and CTE equity cost effectively; thus a novel concept must be considered.

The most common heat-sink plates are made of aluminum, copper or glass fiber-reinforced polymer printed circuit boards (PCBs). Copper is the best known heat-sink plate due to its excellent thermal conductivity but the increased weight and manufacturing cost limits its use. The majority of heat-sink plates are made of Al-alloys because they are light weight and the ease of fabrication of the square fins using the extrusion process. The CTE is equally important in the selection of heat-sink materials and must be compatible with the chip materials. Heat-sink base materials (Cu and Al) are blended with other elements (SiC, W, and Mo) to reduce the CTE mismatch. There is no single material available that offers both excellent heat-transport properties and low CTE simultaneously and be compatible with high-current density module base-plate materials. Copper-tungsten (Cu-W) alloy is an attractive heat sink material in terms of thermal conductivity and CTE compatibility with chip base materials. However, there is a significant challenge in making heat-sink plates made of Cu-W composite materials with fins. Cu-W alloys are very difficult to produce due to a very large difference in melting points (Cu = 1084°C, W = 3387°C). FAST can do it!

POWDER METALLURGY (PM) AS AN ALTERNATIVE METHOD

Powder metallurgy (PM) is an alternative option in fabricating heat-sink components with fins cost effectively. Unfortunately, this

approach has seen very limited effort, requires several processing stages and is HIP'ed for a long time (hours and days) to achieve the 100% theoretical density. To overcome such a long conventional processing cycle, an alternative powder compaction and sintering process has to be considered that will reduce the processing cycle from hours to a few minutes. FAST can do that too!

New electronic developments are being limited by the performance of heat sink material. Significant improvements are needed soon. It is well documented that the thermal conductivity of diamond is 3 to 6 times higher than that of copper, depending upon the purity of diamond. The thermal conductivity of thermally grown pyrolytic (TGP) graphite is 4 times higher (in plane) than copper. Similarly, the thermal conductivities of multiwall carbon nanotubes (MWCNT) and single wall carbon nanotubes (SWCNT) are about 10 times and 20 times higher than copper, respectively. Therefore, blending copper powder with either diamond, MWCNT, or SWCNT will significantly enhance the thermal conductivity of the heat-sink plate. In addition, these additives have very low or negligible CTE, so blending them with copper will also reduce the overall CTE of the copper plates. FAST offers a unique potential to incorporate nano-materials with minimal destruction due to extended exposure to high heat.

FAST ADVANTAGES

FAST is the only process that will allow manufacturing of heat sink plates having the tailored chemistry, encapsulating TGP and fins in a one-step process. The top layer will be composed of composite structure (Cu alloy + diamond or MWCNT) followed by encapsulating TGP in copper and Al alloy. The manufacturing sequence could be envisioned as follows: the base of the die will contain tapered holes for fins that will be filled with Al-alloy powder followed by Cu and a top layer with the blended composite powder (Cu + MWCNT). The proposed design and fabrication concept will be a very cost-effective manufacturing process with significant pay-off about 100 to 200% improvement in performance with 30 to 40% weight savings (Figure 2, next page).

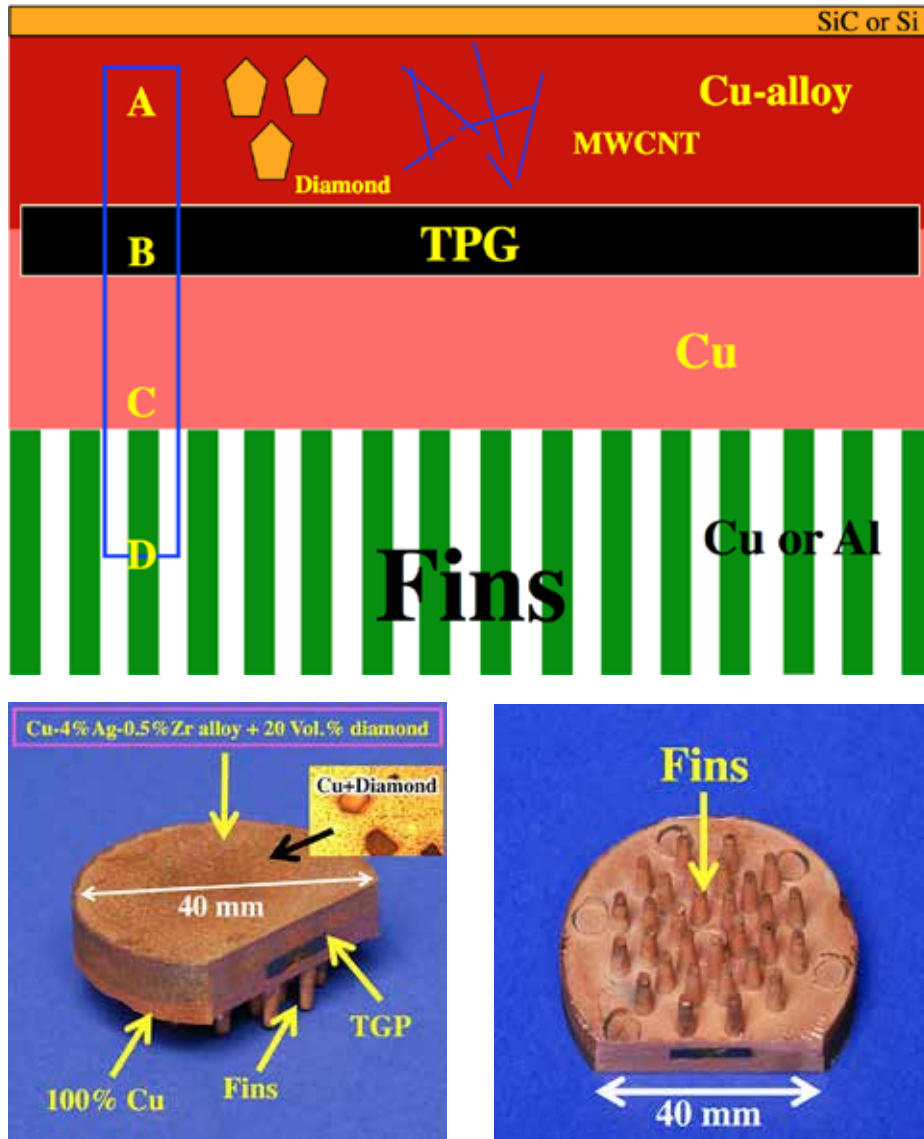


Figure 2. Schematic diagram (top) showing fabrication of lightweight functionally graded composite highly thermal conductive heat-sink plate with fins produced in a one-step process by FAST. Net-shape heat-sink plate (bottom, left and right) consisting of a functional graded structure (top – composite), an encapsulated TPG, and copper with fins fabricated using a one-step FAST process.

Researchers at ARL-Penn State used FAST to demonstrate the proof-of-concept in fabricating a net-shaped heat-sink plate with entrapped TGP and fins as shown in Fig 2. The entire graphite die assembly was placed in the FAST and sintered at about 975°C under 35 MPa pressure for a few minutes, resulting in the sintered product.

NET-SHAPED CEMENTED CARBIDE INSERTS

Ceramic cutting tools are widely employed in machining of nickel and titanium based alloys.

Cemented carbide compositions such as WC-Co are used even more extensively to machine steel, titanium alloys, and other non-ferrous metals. However, in the quest for achieving higher machining speeds and longer tool life, it is apparent that significant improvements in tool toughness, thermochemical durability, and ability to control dissipation of thermal energy during machining are needed. One method for achieving the requisite hardness, toughness, and thermal diffusivity in cemented carbide cutting tools is to design compositional gradients in the tool, resulting

in a harder, more wear resistant outer case with a more fracture resistant (tougher) and higher thermal conductivity core. The concept of compositionally graded or layered structures has been successfully demonstrated at ARL. Recent developments in field-assisted densification of ceramics and ceramic/metal composites have opened opportunities to process nanocrystalline cemented carbide composites without extensive grain growth, and in the absence of a liquid phase sintering. We have successfully produced net-shaped inserts made of WC, and SiC materials for high speed machining of Ti alloys.

NET-SHAPED REFRACTORY MATERIAL COMPONENTS

ARL's research into heat sink technology using FAST lead to a new application in space propulsion technology. For space applications, rocket nozzle are often made of W and Ta based refractory alloyed materials. Rockets are manufactured by hot process followed by wire EDM and machining. During hot press, there is significant grain growth in the alloys that is undesirable for high temperature structural applications. Vacuum plasma spray process has also been explored in making net shaped rocket nozzle using graphite mandrel followed by hot iso-stating pressing (also called HIP'ing). There are many challenges in this manufacturing process including significant porosity at grain boundaries that cannot be removed completely by HIP'ing which will affect the performance of the components. In addition, combined vacuum plasma spray process and HIP'ing requires a long processing cycle, large grain size and is not cost effective with a high rejection rate associated with dimensional changes. These challenges have been address by two ways: (1) development of W and Ta alloys with minimum grain growth during sintering process and (2) make net-shaped rocket nozzle cost effectively using FAST.

BODY ARMOR CERAMIC TILES

SiC and B4C materials are commonly used for body armor protection applications. SiC ceramic tiles are produced by pressure-less sintering whereas B4C ceramic tiles are produced by hot press process. In general, sintering of B4C materials is challenging. The production of ceramic tiles is inherently a time-consuming process. FAST, however,

FEATURE ARTICLE

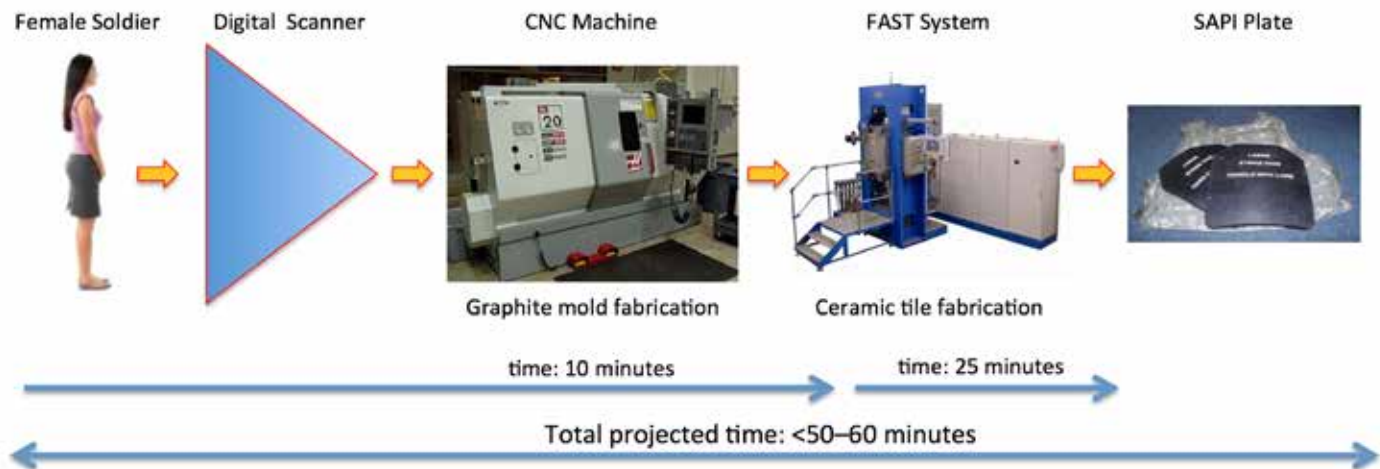


Figure 3. Custom Specified Manufacturing of Light Weight High Performance Ceramic Tiles for Female Soldiers By FAST

provides a degree of flexibility that will enhance production of ceramic tiles within a more cost-effective process, as compared to the current state-of-the-art. Further, the flexibility FAST provides can be used to adapt it for unique manufacturing processes not cost-effective under current manufacturing practices. This provides an opportunity to inject a manufacturing capability that supports unique requirements our soldiers, sailors, airmen and Marines deserve. Figure 3 provides a specific “unique requirement” example. It is important to note that the process has demonstrated that the ballistic performance of B4C ceramic tiles produced by FAST are

comparable with ceramic tiles produced by the hot press method.

LIGHT WEIGHT, THERMALLY-MANAGED OPTICS FOR HIGH-POWERED LASERS

Silicon Carbide (SiC) and Boron Carbide (B4C) are the only two candidate materials that offer excellent physical and mechanical properties. Additional benefits include hardness, resistance to contamination, light weight, stability to ionizing radiation, and favorable elastic modulus. Comparatively, Boron Carbide provides excellent material for space-based mirrors, when compared to Silicon Carbide. Boron Carbide's high elastic

modulus (460 GPa) and low density (2.52 g/cc) provide a modulus to density ratio (specific modulus) that exceeds beryllium, silicon carbide and other ceramic materials. Boron carbide is capable of being finished to better than 19 Å, and can provide a bi-directional reflectance distribution function (BRDF) suitable for kinetic energy weapons targeting.

Currently, SiC mirrors are produced at elevated temperatures by a chemical vapor deposition (CVD) process. In general, the CVD process produces columnar structure with intergranular porosity. The presence of porosity in the mirror is removed by HIP'ing. The combination of CVD and HIP'ing contribute to significant high cost, coupled with a long processing time. Using FAST, ARL successfully produced SiC discs with a theoretical density >98.7%. After fine polishing, the surface of the SiC discs exhibited properties similar to highly reflective optics (See Figure 4). Interaction with high energy laser beam is currently being characterized.

SUMMARY

FAST is considered a disruptive manufacturing technology. It is capable of manufacturing metal, ceramic and composite components with tailored properties using a powder metallurgy approach. In many instances it is a one-step manufacturing process that saves time and money when compared to current mainstream manufacturing methods. The technology is viable and ready to be transitioned to industry in the production of net-shaped components.

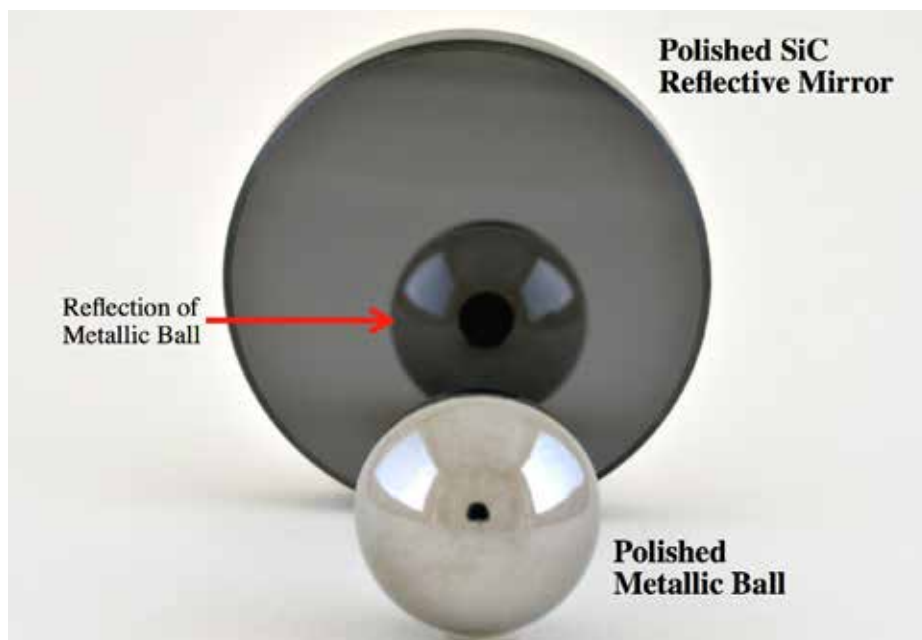


Figure 4. Photograph showing highly reflective surface of SiC disc produced from powder with theoretical density >98.7% using FAST cost effectively



iMAST Director, Tim Bair, discusses current activities with Ms. Elaina Broitman, acting director of OSD Manufacturing and Industrial Base Policy (MIBP).

Defense Manufacturing Conference 2013

As the year 2013 closed out, iMAST participated in the annual Defense Manufacturing Conference (DMC) event which was held in Kissimmee, Florida. This year's focus addressed "How Can Manufacturing Innovation Improve Affordability?" With the growing interdependency of the defense industrial base, and associated national science and technology base with the commercial sector, DMC 2013 attempted to broaden attendees awareness of the growing importance of these relationships at a time of political, economic and budgetary uncertainty and national strategy, based upon more complex international, asymmetric and transitioning wartime scenarios. iMAST's Jeff Banks was invited to present a brief on "Total Ownership Cost Reduction for Ohio Replacement Class Submarines". Dr. Tim Eden presented "Implementation of Portable Cold Spray for NAVAIR Aerospace Components". Rounding out invited iMAST presenters, Dr. Mark Traband addressed "Using the iFAB Architecture to Execute Rapid Development". Dr. Traband was followed by Dr. Rich Martukanitz who discussed ARL Penn State's Center for Innovative Metal Processing through Direct Digital Deposition (CIMP-3D).



MGen Robert Walsh USMC, Director, Expeditionary Warfare Division, N95, OPNAV congratulates iMAST Director Tim Bair on progress of lightweight shipboard watertight door effort undergoing trials aboard various naval warships.

Surface Navy Association Symposium 2014

The Surface Navy Association kicked off the year with its annual symposium in Crystal City, Virginia. This year's theme "Surface Warfare... Warfighting First". The symposium brings together military, government and industry to highlight our Surface Navy Warriors . . . past, present and future. An assortment of senior guest speakers from government, industry and the naval services provided an opportunity for iMAST to share its Navy ManTech activities within an appropriate venue. A focus of the iMAST exhibit was the lightweight shipboard watertight door, which is currently under evaluation aboard the USS Porter (DDG-78), USS Monterey (CG-61) and the USS Wasp (LHD-1).

Other Navy ManTech activities, to include repair technology efforts, caught the attention of the "fixers" in the crowd.

iMAST Web Site Updated

The web site for the Institute for Manufacturing and Sustainment Technologies has been recently updated. To view, please visit <http://www.arl.psu.edu/centers_imast.php> or Google "Penn State iMAST". Within the web site all iMAST newsletters and annual reports are archived. If you have recommendations for additional material to be incorporated into this site, please contact the iMAST administrator, Greg Johnson, at (814) 865-8207 or by email at <gjj1@arl.psu.edu>.



Cover Story

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Department of Defense (and ultimately the U.S. taxpayer) millions of dollars replacing those parts. Many of these parts have long lead times. In some cases, there are no replacement parts in inventory. Working in concert, the Navy (Office of Navy Research, NAVAIR, FRC East and FRC Southwest) and the Army (Army Research Laboratory, AMRDEC) along with OEMs (Sikorsky and Moog) developed processes for aerospace application

that included: test protocols, validation and acceptance requirements, process procedures, and inspection requirements. As a result of these efforts the Cold Spray process has been implemented within Army, Navy and commercial aerospace facilities. Specific aerospace components being repair with the process include F/A-18 airframe mounted accessory drive (AMAD) gearbox, as well as the UH-60 magnesium gear box sump. Additional candidate components are

currently being evaluated. Team members include: Navy—**Timothy Eden**, iMAST ARL Penn State*; **Greg Woods**, ONR; **Frederick Lancaster**, NAVAIR; **Luc Doan** and **Conrad Macy**, FRC-SW; **Robert Kestler**, FRC-East; Army—**Victor Champagne***, Army Research Laboratory; **Michael Kane** and **Fernando Merritt**, AMRDEC; OEMs: **William Harris**, Sikorsky and **Bob Bierk**, Moog Inc.]

* Co-project leader



“Today we’ve moved to a process where affordability has been brought to the table as a requirement on the front end. We’re effectively, in the requirements-definition process, making all the trades up front to ensure the program that follows is affordable and executable.”
—Sean Stackley, Assistant Secretary of the Navy for Research, Development and Acquisition

CALENDAR of EVENTS

2014

7–9 Apr	Navy League Sea-Air-Space Expo	** National Harbor, MD
14–17 Apr	Air Worthiness & Sustainment Conference	Baltimore, MD
20–22 May	American Helicopter Society Forum 70	Montreal, Canada
28–30 May	Johnstown Showcase for Commerce	** Johnstown, PA
18–19 Jun	NCMS Cold Spray Action Team Meeting	Worcester, MA
24–26 Jun	Mega Rust	San Diego, CA
9–10 Sep	Fleet Maintenance & Modernization Symposium	** Virginia Beach, VA
23–25 Sep	Modern Day Marine Symposium	** Quantico, VA
13–15 Oct	AUSA Expo	** Washington D.C.
TBA	DoD 2014 Maintenance Conference	TBA
1–4 Dec	Defense Manufacturing Conference	** San Antonio, TX

** Visit iMAST booth