DSIAC TECHNICAL INQUIRY (TI) RESPONSE REPORT

European Energetic Additive Manufacturing (AM) Research

Report Number:
DSIAC-BCO-2022-213
Completed May 2020

DSIAC is a Department of Defense Information Analysis Center

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*
18-05-2020

2. REPORT TYPE
Technical Research Report

3. DATES COVERED *(From – To)*

4. TITLE AND SUBTITLE
European Energetic Additive Manufacturing (AM) Research

5a. CONTRACT NUMBER
FA8075-21-D-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Travis J. Kneen

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Defense Systems Information Analysis Center (DSIAC)
SURVICE Engineering Company
4695 Millennium Drive
Belcamp, MD 21017-1505

8. PERFORMING ORGANIZATION REPORT NUMBER
DSIAC-BCO-2022-213

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Technical Information Center (DTIC)
8725 John J. Kingman Road
Fort Belvoir, VA 22060-6218

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution unlimited.

13. supplementary notes
materials and manufacturing processes: materials/processes for survivability and life extension, manufacturing technology for affordability, weapon technologies: ordnances; advanced materials, energetics

14. ABSTRACT
The Defense Systems Information Analysis Center (DSIAC) was tasked with determining the extent of energetics additive manufacturing (AM) research and developing capabilities in Europe. DSIAC searched available resources for any projects or research being performed by universities or defense organizations in Europe that involve the three-dimensional printing of energetic munitions, explosives, propellants, or rocket engines. There were a few organizations and universities that had previously engaged in such research—The Netherlands Organisation, French-German Research Institute of Saint Louis, and Delft University of Technology. The potential lack of research, combined with the potential of AM to help further develop military capabilities and lower costs, most likely spurred the European Defence Agency to organize the Additive Manufacturing Techniques for Energetic Materials project, which should further research efforts in this area in the coming years in Europe. Publicly available energetic AM projects and published research are collected and summarized in this report.

15. SUBJECT TERMS
additive manufacturing, AM, 3-D printing, energetics, propellants, explosives

16. SECURITY CLASSIFICATION OF: U

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	14	Ted Welsh, DSIAC Director

19b. TELEPHONE NUMBER *(include area code)*
443-360-4600

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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A chief service of the DoD IACs is free technical inquiry (TI) research, limited to 4 research hours per inquiry. This TI response report summarizes the research findings of one such inquiry jointly conducted by DSIAC.

ABSTRACT

The Defense Systems Information Analysis Center (DSIAC) was tasked with determining the extent of energetics additive manufacturing (AM) research and development capabilities in Europe. DSIAC searched available resources for any projects or research being performed by universities or defense organizations in Europe that involve the three-dimensional printing of energetic munitions, explosives, propellants, or rocket engines. There were a few organizations and universities that had previously engaged in such research—The Netherlands Organisation, French-German Research Institute of Saint Louis, and Delft University of Technology. The potential lack of research, combined with the potential of AM to help further develop military capabilities and lower costs, most likely spurred the European Defence Agency to organize the Additive Manufacturing Techniques for Energetic Materials project, which should further research efforts in this area in the coming years in Europe. Publicly available energetic AM projects and published research are collected and summarized in this report.

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1.0 TI Request

1.1 INQUIRY

What organizations in Europe are developing energetic additive manufacturing (AM) capabilities?

1.2 DESCRIPTION

The inquirer is looking for ways to improve explosive properties of traditional energetic materials. Three-dimensional (3-D) printing of these materials into novel shapes and forms is one way to do this. The inquirer is also interested in seeing what other countries are doing in this research area, specifically those in Europe.

2.0 TI Response

Additive manufacturing (AM) refers to manufacturing processes that deposit or fuse material together in a layer-by-layer approach until a 3-D part is completely fabricated. With the growing capabilities of AM technologies and feasible material systems in recent years, the ability to create functional parts has become a focus of new experimental research and industrial applications [1]. AM can be used to manufacture custom parts either when traditional manufacturing methods prove difficult or there are potential economic savings. Because of this, AM processes are being employed in energetics applications, with the hope of reinvigorating an aging industry vital to national defense. Energetic materials additive manufacturing (EMAM) solutions utilize techniques and equipment from direct ink writing and the paste-dispensing industry [3].

The European Defence Agency (EDA) identified AM as a major technology to improve Europe's industrial competitiveness, and the defense sector sees the potential of AM technologies to further develop military capabilities. Within the EDA's CapTech Ammunition Technologies, a group of member states agreed to join forces and develop a multinational research project on the use of AM to produce energetic materials (EM) for use as propellants and warheads. This led six participating EDA member states (Finland, France, Germany, Netherlands, Poland, and Sweden) and Norway to sign the Additive Manufacturing Techniques for Energetic Materials (AMTEM) project in December 2018. The AMTEM project team will investigate and assess appropriate materials and related AM production techniques, with a focus on producing new types of warheads and propellants with enhanced performance and faster, cheaper production processes (including short series and rapid prototyping). The launch of AMTEM brought together 15 European organizations involved in EM, including the following: the French-

German Research Institute of Saint-Louis (ISL), Ariane Group, EURENCO, NEXTER Group, Fraunhofer Institute for Chemical Technology (ICT), The Netherland Organisation for Applied Scientific Research (TNO), Norwegian Defence Research Establishment, NAMMO, Chemring Nobel, Polish Military Institute of Armament Technology, Swedish Defence Research Agency, Finish Defence Research Agency, Oy Forcit AB, Raikka OY, and Aalto University [3].

The subsequent sections aim to summarize the research and work in EMAM that is being done by European nations and organizations.

2.1 THE NETHERLANDS ORGANISATION (TNO)

TNO was founded by law in 1932 to enable business and government to apply knowledge and create innovations that boost the competitive strength of industry and the well-being of society in a sustainable way [4]. One of TNO's Energetics Materials group's focus area is processing energetic materials by pressing, mixing/casting, extrusion, resonant acoustic mixing, and 3-D printing. The group also has multiple different energetic testing facilities, including ballistics analysis, insensitive munition, chemical analysis, thermal analysis, and mechanical analysis centers [5]. The Energetic Materials, Additive Manufacturing, and Material Solutions groups of TNO have worked closely together to develop new types of energetic materials that can be processed in standard 3-D printers, aiming at better performance and flexibility in manufacturing energetic products. In a 2017 paper presented at the 30th Ballistics International Symposium, TNO describes its research efforts since 2013, specifically on using stereolithography to produce gun propellants. This included the results of material development and characterization, as well as performance test results that included test firings with a 30-mm gun [6]. A photocurable energetic resin developed for photopolymerization AM is detailed in a January 2020 paper by Straathof et al. [7]. They describe the resin's composition as containing, by weight, 50% cyclotrimethylenetrinitramine, 25% acrylate binder, and 25% energetic plasticizer. The material is characterized in terms of compatibility, printability, mechanical properties, and ballistic performance by multiple print trials and, once again, firing a 30-mm gun setup with 3-D-printed propellants. Currently, TNO is researching propellants with variable characteristics, which could allow customization of missile paths and speeds and developed new print heads that measure temperature and pressure for safety monitoring during a print [8].

2.2 FRENCH-GERMAN RESEARCH INSTITUTE OF SAINT-LOUIS (ISL)

ISL is a binational institute operated jointly by the Federal Republic of Germany and the French Republic based on a Convention signed in 1958 [9]. Its mission is to develop technical innovations in the defense and security fields. The Institute's activities focus on controlling the effects of projected energy while increasing precision and improving the protection of military and security operational staff at the best cost-performance ratio. One of their four main research topics is "Energetic and Advanced Protective Materials," which is broken into four subsections: (1) physics and chemistry of energetic nanomaterials; (2) advanced materials and mechanical testing; (3) propellants, energetic materials, and shock physics; and (4) detonics [10].

M. Chiroli et al. presented work describing an approach that consists of deposing a viscous energetic paste, containing a solvent, with an adapted machine to develop colayered propellant grains to adjust the gas pressure released during a ballistic cycle. They investigate the layer formation and adhesion between the layers. The ISL group prepared seven different inert materials, of which only two were soluble in acetone—ethylene vinyl acetate LEVAPREN 700 HV (Bayer AG) and cellulose acetate (Sigma Aldrich). The EM considered in their study is an in-house formulation consisting of 54 wt% of nitrocellulose mechanically mixed with other energetic materials. This solid propellant is achievable in different viscosities, depending on the weight percentages dissolved in acetone. The inert and energetic syringes were printed using a fused deposition modeling (FDM), extrusion-based desktop printer (Printrbot Simple Metal). They were able to find inert materials that closely matched the viscosity of the EM so the testing and configuring of the AM setup could be done more safely. They plan to optimize the printing of the inert mixture and identify the best printable inert material and then develop an EM paste within the same range of dynamic viscosity. Only then would a simple shape of solid propellant be printed and evaluated [11].

2.3 DELFT UNIVERSITY OF TECHNOLOGY (TU DELFT)

TU Delft is the oldest and largest technical university in the Netherlands. Much of their current AM research involves wire and arc manufacturing of metal alloys or functionally graded materials [12], though Professor Antoine van der Heijden is leading a project on the rheological behavior of 3-D-printed energetic materials. The aim of the project is to understand and numerically model AM of heterogeneous, two-phase flows consisting of solid particles (energetic material) dispersed in a liquid medium. Working in close collaboration with TNO (where van der Heijden is a senior research scientist), this will be achieved by carrying out experiments using AM techniques complemented with modifying or developing numerical models with which the experimental results can be described and understood [13]. In a master's thesis, Bart Rijnders explores the possibilities of utilizing AM to 3-D-print multimaterial, continuous gradients that can be used to produce optimized geometries and compositions of energetic propellants. Computer simulations of the printer paths were performed before printing multimaterial, continuous gradient using TNO's multimaterial 3-D printer. It was concluded that energetic materials behave much differently than typical AM plastics, but that multimaterial, continuous gradient objects are viable using AM [14]. TU Delft, in conjunction with TNO, sent out a Ph.D. proposal in 2017 that would expand upon the research into 3-D-printed propellants and gain detailed knowledge and tools to optimize the propellant composition and mechanical properties for performance and safety. The project would develop computational models to study and predict the response and damage development in heterogeneous propellant materials, with a special focus on the dynamic loading conditions during launching of rockets or missiles [15].

2.4 FRAUNHOFER INSTITUTE FOR CHEMICAL TECHNOLOGY (ICT)

ICT has core competences in chemical processes, energy systems, explosive technology, drive systems, polymer technology, and composite materials in Germany. ICT's Energetic Materials Department is concerned with the development, manufacture, and application of propellants and explosives for defense and security applications. Research areas include the synthesis of explosives, propellants for rockets and guns, chemical process technology and flow chemistry, and particle technology, among others [16]. Research published in August 2019 describes an improved synthesis of the energetic ionic liquid 4-amino-1-butyl-1,2,4-triazolium nitrate (C4 N), which could be used as an energetic additive to improve the rheological properties of glycidyl azide polymer (GAP)-based energetic thermoplastic elastomers (ETPEs). The researchers conclude that with its good thermal and long-term stability, C4 N may find application as a processing additive in GAP-based ETPE compositions to enable AM via the FDM process without decreasing the glass transition temperature [17]. A joint ICT publication with the Russian Academy of Sciences summarizes the progress in AM with energetic materials. The present review discusses various methods of AM based on their governing principles, robustness, sample throughput, feasible compositions, and available geometries. For chemical composition, nanothermites are among the most promising systems due to their high-ignition fidelity and energetic performance. Applications of reactive microstructures are highlighted, including initiators, thrusters, gun propellants, caseless ammunition, joining, and biocidal agents [18].

2.5 UNIVERSITY OF APPLIED SERVICES WIENER NEUSTADT

FOTEC Forschungs- und Technologietransfer GmbH was founded by the University of Applied Sciences Wiener Neustadt (Austria) in 1998 and supports the initiation and implementation of national and international research and development projects [19]. In 2017, FOTEC Forschungs- und Technologietransfer GmbH and University of Applied Sciences Wiener Neustadt teamed up with the University of Poitiers (France) and Lithoz GmbH (Austria) to present test results of the monopropellant decomposition of monolithic ceramic catalysts produced by AM and using ceramic precursors. The performance results of the AM monoliths were compared to traditionally manufactured catalysts as well as different washcoat layers, both with respect to the decomposition of highly concentrated hydrogen peroxide [20].

2.6 AALTO UNIVERSITY

Aalto University is a Finnish research university whose Department of Mechanical Engineering's research has focused on mechanics and energy technology [21]. Research was presented at the 2019 AIAA Propulsion and Energy Forum on using 3-D-printed polylactic acid (PLA) in hybrid rockets [22].

2.7 BRITISH MINISTRY OF DEFENCE – DEFENCE SCIENCE AND TECHNOLOGY LABORATORY (DSTL)

DSTL, an executive agency sponsored by the British Ministry of Defence (MOD), has begun to develop 3-D-printed explosives. The project focuses on AM's ability to produce intricate and complex designs to create new explosive effects and reduce transportation and storage costs. This effort is part of the MOD's Future Energetics Project, which has invested nearly £10 million in training experts, developing technology, and equipment since 2015. Currently, the DSTL is focusing on material extrusion and 3-D-printer capabilities in the hopes of developing individual shapes for warzone missions and production of explosive charges on demand at forward-operating bases [23].

2.8 AUSTRALIAN DEFENCE SCIENCE AND TECHNOLOGY GROUP

The Australian government has awarded $2.6 million to research institutions to develop methods to 3-D-print energetic materials through the Cooperative Research Centre Program [23, 24]. The project will partner the Defence Science and Technology Group, Australia's leading authority of energetics materials, with DefendTex Pty Ltd. (a Victorian-based defense research company), the Royal Melbourne Institute of Technology, Finders University, and Cranfield University in the United Kingdom. It is anticipated that using AM to produce explosives, propellants, and pyrotechnics can transform performance while also supplying significant logistical and cost benefits in the manufacturing supply chain [24].

3.0 Conclusions

While there are universities and research organizations exploring AM as a method to produce or advance energetic munitions, propellants, or rockets, the European community is less advanced than the Americans in their energetic AM research efforts based on publicly available publications. It seems likely that this lack of published research is a reason for the funding of the EDA's AMTEM project, and the amount of EMAM-related work being done at ISL could be why France is the lead nation [25].

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