Additive Manufacturing for Maritime Spare Parts Supply: An Overview

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Abstract Additive Manufacturing (AM), also called 3D Printing (3DP) is not a new technology. The technology was invented over 30 years ago. Originally thought of as simply an application for rapid prototyping, it has developed significantly and is now a viable option for many applications including aerospace, automotive, healthcare, construction and consumer products. This paper offers a brief introduction to the history of AM/3DP and an overview of the current state of the art in AM/3DP technologies focusing on their fundamental processes, typical materials, significant benefits, key applications and critical challenges to implementation. Finally a description of the potential benefits to the maritime industry that can be gained by implementation of AM/3DP technologies is presented. The most immediate is the possibility of more efficient logistics, for example the maritime spare parts supply.

Keywords: *Additive Manufacturing, 3D Printing, Maritime Supply Chain, Spare Parts Supply*

Introduction

Additive Manufacturing (AM) is the process of joining materials to make parts directly from a three dimensional (3D) model data, usually layer upon layer, as opposite to subtractive manufacturing methods, such as conventional machining processes. "Additive Manufacturing" is the official industry term, with "3D Printing" (3DP) as a common used synonym. AM/3DP is one of the latest digital manufacturing technologies hyped as the part of what is being called Manufacturing 3.0 and Industry 4.0. This technology, along with the development of intelligent cyber-physical systems, is driving manufacturers towards the goal of zero-inventory in the future [1].

With acceptance of AM/3DP growing at such a rate, what might the implications be for the shipping sector? In theory at least the maritime industry should be among those with the most to gain from this kind of technology – when shipping and naval vessels are travelling across the oceans and something breaks, the ability to immediately repair or manufacture spare items on site has a great appeal. Today modern ships are continually required to order and stock large numbers of spare parts and supplies to make sure that they are not caught short when needs arise out at sea. Manufacturers could make spare part designs available for download so that end-users can get the right spare part through AM/3DP machines on board straight away. That's what many shipping companies are hoping for [2].There is a question arising of how soon this technology might be ready to make a practical contribution to spare parts management on board: some people are insisting that AM/3DP has reached a stage where it could be used on-ship today, while others are sceptical of seeing any significant headway for the technology in maritime in the next decade [3].

In this paper, an overview of AM/3DP technologies is presented covering its brief history, fundamental processes, typical materials, significant benefits, key applications and critical challenges to implementation. Some critical problems in the current maritime industry are identified followed by the potential solution which AM/3DP technologies could offer are discussed. Some initial thinking for the maritime industry to embrace the AM/3DP technologies within their business contexts is provided. The author believes that the integration of AM/3DP into the maritime industry will induce dramatic impacts on shipping and especially revolutionise the future of maritime spare parts supply.

Additive Manufacturing Overview

Introduction to Additive Manufacturing

Additive Manufacturing (AM) technologies refer to a group of technologies that build physical objects from Computer Aided Design (CAD) data. Contrary to conventional subtractive manufacturing technologies, e.g. cutting, lathing, turning, milling and other machining, a part is created by the consecutive addition of liquids, sheet or powdered materials in ultra-thin layers. The geometrical and structural complexity of additively manufactured parts is limited by almost nothing but the used CAD model. Enabling the production of individually shaped parts whose production previously was inconceivable. In the 14 page article “The Third Industrial Revolution” by The Economist [4], AM/3DP is promoted as the production technology of the future, uniting individuality and mass production. AM/3DP is regarded as a nascent technology entailing great disruptive potential, triggering a revolution of product development processes in various industries, and enabling value creation for new business models, new products and new supply chains [4].

In industry, Additive Manufacturing is the accepted term, while ‘3D Printing’ is commonly used to denote those machines used primarily by home users. The terms are often used interchangeably and both refer to “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [5]. There are several synonyms to describe this high-value manufacturing technologies: Additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, freeform fabrication and e-Manufacturing. AM/3DP is used to build physical models, prototypes, patterns, tooling components and production end-user parts in plastics, metals, ceramics, glass and composite materials.

The AM/3DP process traditionally begins with the creation of a 3D model through the use of CAD software. The CAD-based 3D model is typically saved as a Stereolithography (.STL) file, which is a triangulated representation of the model. Software then slices the data file into individual layers, which are sent as instructions to the AM/3DP machine. The AM/3DP machine creates the object by adding layers of material, one on top of the other, until the physical object is created. Once the object is created, a variety of finishing activities may be required. Depending on the material used and the complexity of the product, some parts may need secondary processing, which can include sanding, filing, polishing, curing, material fill or painting. Fig. 1 illustrates the overall AM/3DP process [6].

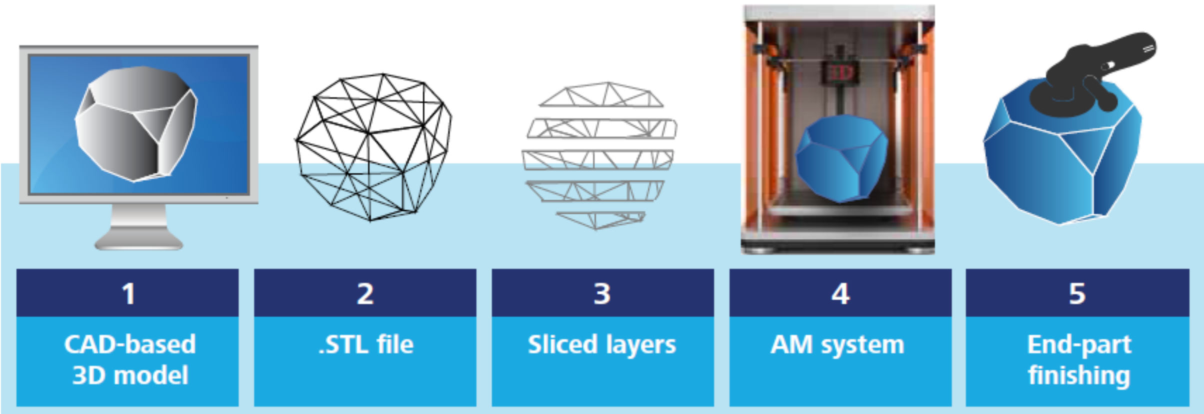

Fig. 1 – Additive Manufacturing Process Flow

History of Additive Manufacturing

AM/3DP has its earliest roots in research activities from the fields of topography and photosculpture during the 19th century. The first successful attempts at AM/3DP derived from technology developed in the 1970s. AM/3DP first approached commercial viability in 1983 when Charles Hull invented stereolithography, enabling a 3D object to be printed from CAD data. In 1986, Hull co-founded 3D Systems, Inc., the first company to commercialise AM/3DP technology with the stereolithography apparatus (SLA). Selective laser sintering (SLS), another popular AM/3DP technology, was first commercialised in the late 1990s. Just like SLA, its applications grew from rapid prototyping to end-part production over the years, driven by lower system costs. Since then, the AM/3DP technologies have evolved to include at least 13 main different sub-technologies grouped into seven distinct process types (see Tables 1 and 2).

AM/3DP processes were largely geared toward rapid prototyping applications in the 1990s. However, since the late 1990s, AM/3DP technologies and processes have increasingly been deployed to large-scale industrial, medical, and consumer end-market applications. Significant developments since the early 2000s include AM/3DP applications in the production of parts for unmanned aircraft, automobiles, consumer products and organ and tissue printing systems. As shown in Fig. 2, AM/3DP technology continues to improve in the speed of processing, the complexity of design and the variety of materials used. Industry adoption of AM/3DP accelerates in the past decade, and AM/3DP has been growing over 30% annually during the past three years, reaching to 35.2% in 2014 [7].

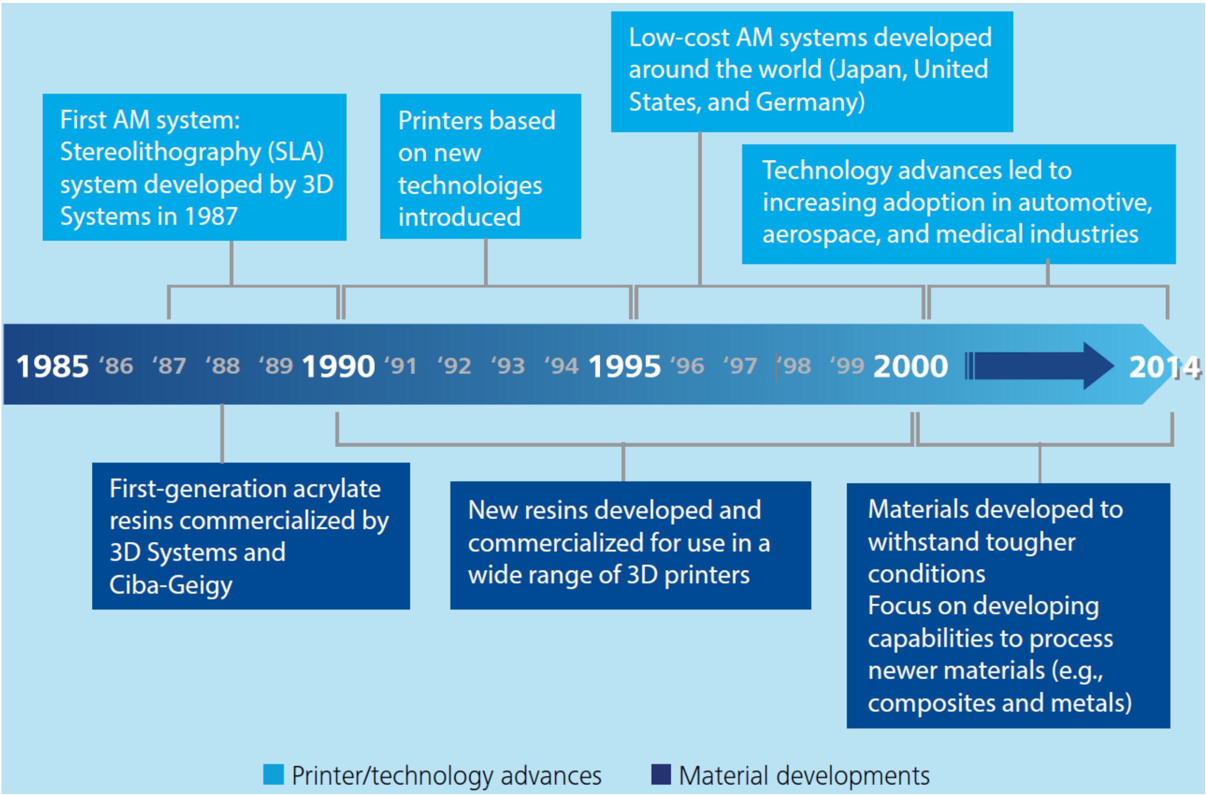

Fig. 2 – Evolution of AM/3DP Technology

Additive Manufacturing Processes and Technologies

AM/3DP is not just a single technology. Instead it encompasses a range of technologies, each at different levels of technological maturity, offering the option of using a variety of materials, with different quality outputs. Among many classifications of AM/3DP, the ASTM proposes seven categories depending on how the layers are created [5]: (1) Vat photopolymerisation; (2) Material jetting;

(3) Material extrusion; (4) Powder bed fusion; (5) Binder jetting; (6) Sheet lamination; and (7) Directed energy deposition. Table 1 below describes the seven AM/3DP process types in details.

Table 1 – The Seven AM/3DP Process Categories by ASTM F42

Vat photopolymerisation
In vat photopolymerisation, a liquid photopolymer (i.e. plastic) in a vat is selectively cured by light-activated polymerisation. The process is also referred to as light polymerisation. *Related AM/3DP technologies: Stereolithography (SL), digital light processing (DLP)*
Material jetting
In material jetting, a print head selectively deposits material on the build area. These droplets are most often comprised of photopolymers with secondary materials (e.g. wax) used to create support structures during the build process. An ultra violet (UV) light solidifies the photopolymer material to form cured parts. Support material is removed during post-build processing. *Related AM/3DP technologies: Multi-jet modelling (MJM)*
Material extrusion
In material extrusion, thermoplastic material is fed through a heated nozzle and deposited on a build platform. The nozzle melts the material and extrudes it to form each object layer. This process continues until the part is completed. *Related AM/3DP technologies: Fused deposition modelling (FDM)*
Powder bed fusion
In powder bed fusion, particles of material (e.g. plastic, metal) are selectively fused together using a thermal energy source such as a laser. Once a layer is fused, a new one is created by spreading powder over the top of the object and repeating the process. Unfused material is used to support the object being produced, thus reducing the need for support systems. *Related AM/3DP technologies: Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS)*
Binder jetting
In binder jetting, particles of material are selectively joined together using a liquid binding agent (e.g. glue). Inks may also be deposited in order to impart colour. Once a layer is formed, a new one is created by spreading powder over the top of the object and repeating the process. This process is repeated until the object is formed. Unbound material is used to support the object being produced, thus reducing the need for support systems. *Related AM/3DP technologies: Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)*
Sheet lamination
In sheet lamination, thin sheets of material (e.g. plastic or metal) are bonded together using a variety of methods (e.g. glue, ultrasonic welding) in order to form an object. Each new sheet of material is placed over previous layers. A laser or knife is used to cut a border around the desired part and unneeded material is removed. This process is repeated until the part is completed. *Related AM/3DP technologies: Laminated object manufacturing (LOM), ultrasonic consolidation (UC)*
Directed energy deposition
In directed energy deposition, focused thermal energy is used to fuse material (typically metal) as it is being deposited. Directed energy deposition systems may employ either wire-based or powder-based approaches. *Related AM/3DP technologies: Laser metal deposition (LMD)*

The AM/3DP processes can also be classified based on the state of starting material used. The major AM/3DP processes and technologies can be characterised by the typical materials they use and the advantages and limitations they offer. Table 2 gives a summary on the mentioned 13 AM/3DP technologies classified in the seven distinct categories defined by ASTM with their typical materials used, tangible advantages presented and critical limitations experienced.

Table 2 – AM/3DP Technologies, Materials, Advantages and Limitations

Technology	AM/3DP Process	Typical Materials	Advantages	Limitations
Stereolithography (SL)	Vat photopolymerisation	Liquid photopolymer, composites	Complex geometries; detailed parts; smooth finish	Post-curing needed Needs support structures
Digital light processing	Vat photopolymerisation	Liquid photopolymer	Complex shapes and sizes; high precision	Limited thickness Limited materials
Multi-jet modelling (MJM)	Material jetting	Photopolymers and composites	Good accuracy and surface finish; multiple materials; ease removal of support material	Range of wax-like materials is limited Relatively slow build process
Fused deposition modelling (FDM)	Material extrusion	Thermoplastic polymers	Strong parts; complex geometries	Poorer surface finish and slower build times than SLA
Electron beam melting	Powder bed fusion	Metal and metal alloys	Speed; less distortion of parts; less material wastage	Needs finishing; Difficult to clean; Dealing with X-rays
Selective laser sintering (SLS)	Powder bed fusion	Plastics, metal, ceramics, and composites	No support structures; high heat and chemical resistant; high speed	Accuracy limited to powder particle size; Rough surface finish
Selective heat sintering	Powder bed fusion	Thermoplastic powder	Lower cost than SLS; complex geometries; no support structures; quick turnaround	New technology with limited track record
Direct metal laser sintering (DMLS)	Powder bed fusion	Metal and metal alloys	Dense components; intricate geometries	Needs finishing Not suitable for large parts
Powder bed and inkjet head printing	Binder jetting	Ceramics, metals, polymers and composites	Full-colour models; inexpensive; fast to build	Limited accuracy Poor surface finish
Plaster-based 3D printing	Binder jetting	Bonded plaster and composites	Lower price; colour printing; high speed; excess powder reused	Limited choice of materials Fragile parts
Laminated object Manufacturing (LOM)	Sheet lamination	Paper, plastics, ceramics, and composites	Relatively less expensive; no toxic materials; quick to make big parts	Less accurate Nonhomogeneous parts
Ultrasonic consolidation	Sheet lamination	Metal and metal alloys	Quick to make big parts; faster build speed of newer ultrasonic consolidation systems; generally nontoxic materials	Parts with relatively less accuracy and inconsistent quality compared to other AM/3DP processes Need for post-processing
Laser metal deposition	Directed energy deposition	Metals and metal alloys	Multi-material printing capability; ability to build large parts; production flexibility	Relatively higher cost of systems Support structures Need for post-processing

Based upon the information illustrated in both Tables 1 and 2, most AM/3DP technologies can be further differentiated into two main groups: laser-based and nozzle-based technologies. Laser-based processes, e.g. Selective Laser Sintering (SLS), employ the principle of layer-wise solidification by applying energy via laser. Individual, thin layers of metal, plastic or sand powder are bonded with previous layers by laser sintering, laser melting or laser light solidification. In nozzle-based processes, e.g. Fused Deposition Modelling (FDM), wire-shaped thermoplastics are partly melted and extruded in the nozzle. The nozzle moves to produce the profile of the part. Due to the thermal fusion, the material bonds with the layer beneath and solidifies.

AM/3DP technologies use a range of materials. Alternatively most AM/3DP processes can be categorised into main four groups based upon the material types: (1). Liquid material-based; (2) Powder material-based; (3) Molten material-based and (4) Solid material-based. A classification of these materials into broad categories reveals that materials such as polymers and metals are widely used in AM/3DP systems. To a less extent, ceramics and composites also support AM/3DP processes. Use of varied materials in one AM/3DP process at the same time is an area of focus for research and development in the future.

Benefits of Additive Manufacturing

AM/3DP and conventional manufacturing face different trade-offs, with each process likely to play a role in the deployment of manufacturing capabilities. AM/3DP has the huge potential to vastly accelerate innovation, compress supply chains, minimise materials and energy usage and reduce waste. All these key benefits of AM/3DP technologies are discussed below in more details:

Lower energy consumption: AM/3DP saves energy by eliminating production steps, using substantially less material, enabling reuse of by-products and producing lighter products [8].

Less waste: Building objects up layer by layer, instead of conventional machining processes that cut away material can reduce material needs and costs by up to 90% [9]. AM/3DP can also reduce the "cradle-to-gate" environmental footprints of component manufacturing through avoidance of the tools, dies, fixturing and materials scrap associated with conventional manufacturing processes. Additionally, AM/3DP reduces waste by lowering human error in production [10].

Reduced lead time/time to market: Items can be fabricated as soon as the 3D digital description of the part has been created, eliminating the need for expensive and time-consuming part tooling and prototype fabrication.

Innovation: AM/3DP equips designers with high degree of design freedom without thinking of how their design will be realised at the manufacturing stage. AM/3DP enables designs with novel geometries that would be difficult or impossible to achieve using conventional manufacturing processes, which can improve a component's engineering performance. Novel geometries enabled by AM/3DP technologies can also lead to performance and environmental benefits in a component's product application [11].

Part simplicity/consolidation: The ability to design products with fewer, more complex parts rather than a large number of simpler parts – is the most important of these benefits. Reducing the number of parts in an assembly immediately cuts the overhead associated with documentation and production planning and control. Also, fewer parts mean less time and labour is required for assembling the product, again contributing to a reduction in overall manufacturing costs. The "footprint" of the assembly line may also become smaller, further cutting costs [12].

Lightweighting: The unique AM/3DP process allows the creation of scaffolding-like structures, mimicking materials found in nature. These complex structures can reduce weight without compromising strength or increasing surface area. With the elimination of tooling and the ability to create complex shapes, AM/3DP enables the design of parts that can often be made to the same functional specifications as conventional parts, but with less material [13].

Agility to manufacturing operations: Additive techniques enable rapid response to markets and create new production options outside of factories, such as mobile units that can be placed near the source of local materials. Spare parts can be produced on demand, reducing or eliminating the need for stockpiles and complex supply chains [8].

The advantages that AM/3DP can bring are manifold. As one of advanced manufacturing technologies, AM/3DP can deliver a new concept of 'Better (improved performance and quality), Quicker (reduced lead time/time to market) and Cheaper (decreased production cost)' plus extra value-added features such as sustainability and customisation for manufacturing operations. Table 3 summarises the often mentioned major benefits as discussed above.

Table 3 – Additive Manufacturing Benefits

Lower costs	Better design	Customisation	Sustainability	New business models
• No tooling • Less transportation • Lower warehousing • Less working capital required • Easy to change design and complexity	• Complexity for free • Added features (cooling, isolation, etc.) • Hybrid materials • Lighter, stronger and less assembly by integrated design	• Ergonomics • Interfaces with other products • Body contours (internal and external) • Aesthetics • Use specific variations	• Less waste • Light-weight • Less energy consumption • Efficient supply chains • Life cycle analysis	• Prototyping •Shorten lead time/time to market • Small series • Supply chains (on demand and at location) • Services • Co-creation

Applications of Additive Manufacturing

The development of AM/3DP techniques has progressed greatly in recent years, yielding broader and broader industry applications. Compared with conventional subtractive manufacturing, AM/3DP is particularly suitable for producing low volumes of products, especially for parts with complex geometries. While prototyping still remains the most popular AM/3DP application, the sectors utilising AM/3DP techniques have also been expanding the scope of applications, leading to more innovative and more consolidated manufacturing methods. Improvements and progress in material and processes allowed a constant development not only along the whole AM/3DP value chain, but also along products development process chains [14].

The released Wohlers Report 2015 published the results of a questionnaire concerning the sectorial distribution of AM/3DP systems [7]. The questionnaire was circulated to 40 manufacturers of industrial AM/3DP systems and about 90 service providers. Although the results were quite diversified, the most common sector of application is related to Industrial/business machines (17.5%), while consumer products/electronics reach 16.6% and motor vehicles and aerospace respectively 16.1% and 14.8% of the total. Medical & dental are the fifth sector with a share of 13.1% (as illustrated in Fig. 3 below). Aerospace, automotive, medical, dental, consumer products, electronics and industrial/business machines have been successfully integrated AM/3DP with conventional subtractive techniques. This allows them to benefit from substantial reductions in manufacturing costs and enables the development of innovative and lighter new products for customers.

Recently, other sectors also started to benefit from AM/3DP related advantages. For example, the oil & gas industry is using it as a rapid prototyping tool. Potential applications include major process equipment innovation for improved reaction vessels, heat exchanger, machines and valve part design.

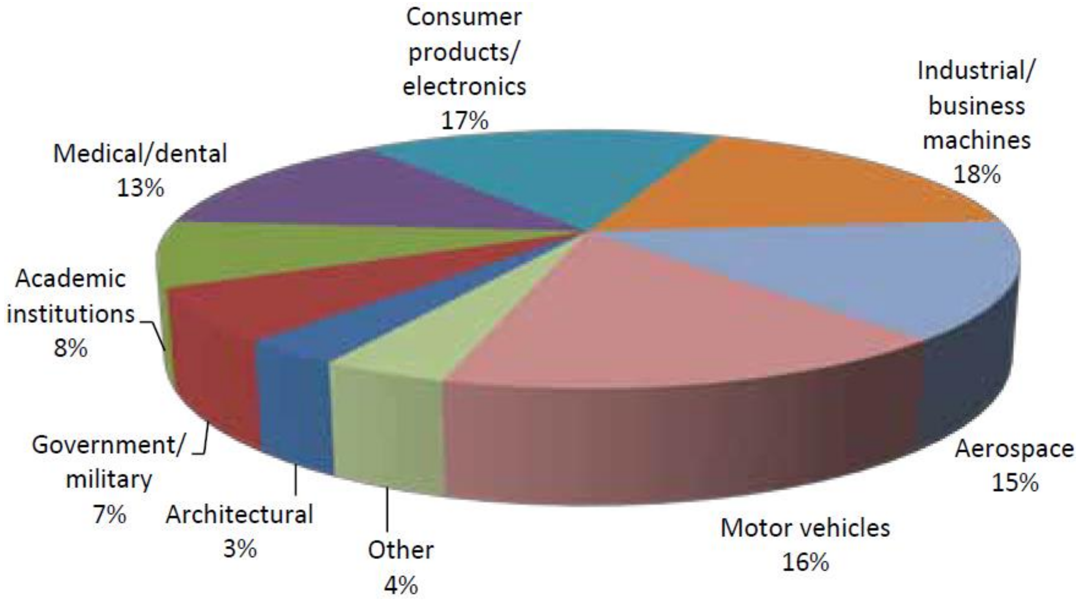

Fig. 3 – Industries served by AM/3DP manufacturers and service providers

Challenges of Additive Manufacturing

To achieve a wider range of applications for AM/3DP, research and development efforts will need to overcome some critical technical challenges including the following key areas:

Materials and size restrictions: Materials play a key role in all AM/3DP processes. Compared to other conventional manufacturing techniques, the range of used materials in AM/3DP is quite limited. It is good to see that the metal branch of AM/3DP is growing much quicker than the rest of the industry. Currently major AM/3DP machines have limited build volumes so they cannot make very large objects economically. And the major AM/3DP machines cannot use multiple materials at the same time.

Process modelling and control: Process stability, capability and productivity, feedback control systems and metrics are needed to improve the precision and reliability of the process and to increase throughput while maintaining consistent quality [15].

Finish and tolerances: The surface finishes of products manufactured by AM/3DP require further refinement, e.g. post-processing is needed for optimal surface finish. With improved geometric accuracy, finishes may impart corrosion and wear resistance or unique sets of desired properties. Some potential applications would require micron-scale accuracy in printing [16].

Standardisation, qualification, certification and validation: Manufacturers, standards organizations and others maintain high standards for critical structural materials and processes, such as those used in safety critical areas such as aerospace and biomedical applications. Providing a high level of confidence in the structural integrity of components built with AM/3DP may require extensive testing, demonstration, validation and certification before its bulk applications [16].

Intellectual property (IP) issues: AM/3DP triggers new challenges from a legal perspective. When existing objects or designs are redesigned for manufacturing through AM/3DP, this may constitute a breach of third party IP rights on the original objects or designs. New or modernised legislative frameworks/regulations for IP copyright, patent protection and ethical considerations (e.g. guns, bioprinting of human cells, etc.) are required to provide legal certainty to AM/3DP business ecosystems.

Education and training: Due to the fact that operating AM/3DP machines is still not very automated, it requires special knowledge, skills and manual operations. Promoting AM/3DP education and training at all levels through "Best Practice" cases demonstration and technology transfer with industrial focus and regional support.

Additive Manufacturing for Maritime Spare Parts Supply

The maritime industry is under a big transformation due to the current economic environment such as shipment demand decrease, surplus capacity, profit lessening, intensive competition and labour cost increase, etc. In addition the maritime industry has had a long suffering from components/parts breaks when shipping and naval vessels are travelling across the oceans. The ability to immediately repair or manufacture spare parts on site has a definite appeal. If the ships don't have required spare parts or any way of making the broken parts on board to fix the damage, on the one hand the shipments will be delayed and money and resources will be lost. On the other hand the ships will be dead in the water which leads to the high risk for seafarers' life safety due to the long time at sea without any aids. This scenario reveals the big issue of operation performance and cost control which is one of the critical problems existing in the current maritime industry.

Modern ship companies are continually required to order and stock large numbers of spare parts and supplies to make sure that they are not caught short when needs arise out at sea. Taking the transportation into consideration, the delivery of single spare part at sea multiplies the complexity and cost since most spare parts are neither that large nor too expansive. In many cases, this will result in significant delay and great cost, as the item must be flown in. Therefore, manufacture and repair near the point of use hold the huge potential to reduce cost, improve asset availability and increase operation effectiveness.

While spare parts for cars and planes are already being 3D printed, is it also possible to make parts of ships while on board? Introducing AM/3DP to the maritime industry brings much potential to shift the current paradigm from storing a large numbers of spare parts either on boards or offshores to making the spare parts on demand either on board or at the nearest onshore (e.g. the hyper-connected ports). It is expected that the smart use of AM/3DP in the maritime industry will lead to the fewer-inventory or even digital inventory of spare parts in the future. AM/3DP will open up significant possibilities and provide such a unique capability to address this critical problem existing in the current maritime industry. Therefore applying AM/3DP to the maritime industry will be expected to bring a new dimension of the supply chain of maritime spare parts.

AM/3DP will provide applications that reduce costs, improve logistic responsiveness, facilitate seabasing and help enable shipping logistics integration. In order to derive the greatest value from AM/3DP as the technology matures, the maritime industry must become involved in the guidance of this development. The maritime industry is unlike the other services. Their requirements are often unique. The benefits of AM/3DP promise to be even greater for the maritime industry if development is properly managed.

In order to take advantage of this disruptive leap in technology, the maritime industry must first conduct a detailed study of the current state of the industry particularly as it applies to the maritime industry. Once that study is complete, a mechanism must be established to continue to monitor industry development and assess its impact on the maritime industry. This is important because the rapid progress of the AM/3DP industry will certainly take unpredictable turns as it moves forward, and the maritime industry must be cognizant of these changes in order to take the maximum advantage of them.

Following that initial study or in concert with it if possible, a Concept of Operations (ConOps) may be developed to define the ways in which AM/3DP will be used. Also, a rigorous Business Case Analysis (BCA) must be conducted to demonstrate the overall value of the effort. Since it will be impossible to do everything at once, that ConOps should be prioritised based upon (1) the most immediate needs of the maritime industry and (2) the Technology Readiness Level (TRL) of any specific AM/3DP capability deemed useful. Because of the rapid progress of the AM/3DP technology, it should be understood that the ConOps and BCA will be living documents subject to frequent updates and additions.

Recent developments in the technology and accompanying price reductions on AM/3DP and raw materials have brought AM/3DP to the tipping point of becoming a mainstream means of producing products for both consumer and business applications. Once AM/3DP reaches the stage when the final 3D printed product is as strong and/or as reliable as the original product, the mass adoption of AM/3DP will revolutionise the supply chain in the maritime industry and shift the whole global transport paradigms as well.

Conclusions

AM/3DP have demonstrated multiple advantages over conventional manufacturing techniques including reduced material waste, lower energy intensity, reduced time to market, just-in-time production, and construction of structures not possible with conventional manufacturing processes. However current AM/3DP technologies also have experienced several challenges such as intellectual property/privacy issues, limited choice of materials, materials and process manufacturing qualification and certification standards and scalability limitations.

It is noted that AM/3DP offers the unique capability of creating parts/products on demand, in the locations where the parts are needed. Integrating this unique feature within maritime spare parts supply will lead to the fewer-inventory or even digital inventory of spare parts in the future. This will dramatically reduce cost (the need for unnecessary stock inventory), improve asset availability (as much locally as possible) and increase operational effectiveness.

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