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Additive layered manufacturing: State-of-the-art applications in product innovation

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Abstract

Additive manufacturing technology permits to develop a product with high level of geometrical complex shape and produce it as unique product by implying low cost and quick time production compared with other manufacturing processes. It has proved a faster method across various industrial disciplines to build functional parts from computer-aided design model. Freedom for design in product development is a new reality with additive manufacturing. In this article, a review of additive product development is done in various industries including food, sports, and biomedical. Furthermore, different additive manufacturing techniques which are used in innovative product development are explained with case studies and examples. Also, a conceptual framework has been represented to use additive manufacturing as collaborative tool with theory of inventive problem solving technique in the innovative product development.

Keywords

additive manufacturing, implant, prosthetics, hybrid layered manufacturing, surgery, innovative product, TRIZ

Introduction

In 1986, a new idea has been created to develop a system for layered manufacture of parts by the process of selective solidification of photopolymers (Drstvensek and Brajlih, 2013). Additive laser melting (LM) processes involve adding raw material in layers to fabricate physical component from computer-aided design (CAD) model. A variety of LM technologies are commercially available, which includes stereolithography (SLA) by *3D Systems*, selective laser sintering (SLS) by *DTM Corporation*, fused deposition modeling (FDM) by *Stratasys Corporation*, solid ground curing (SGC) by *IT Cubital*, laminated object manufacturing (LOM) by *Helisis electron beam melting (EBM), digital light processing* (*DLP*) by *Proto Lab*, and so on (Ruan et al., 2014). In 2009, a new nomenclature was made which combines all the layered manufacturing technologies under the umbrella of additive manufacturing (AM).

Today, AM has found a wide range of applications across a various discipline ranging from macro- to micro-level. Binder Jetting is one of the simplest AM processes. An inkjet print head moves across a bed of powder, selectively depositing liquid binding material, and the process is repeated until the complete part has been formed. Polyjet uses a print head to spray layers of photopolymer resin which are cured one by one using ultraviolet light. DLP base AM digitally slices a solid into layers onto the surface of a liquid photopolymer bath. The projected light hardens a layer of liquid polymer as new images are projected onto the liquid, hardening each subsequent layer to produce the finished object (Proto Lab 3D Printing, 2015).

Also the micro-fluidic components can be created using AM with passages ranging from 0.5 to 3.0 mm and wall thickness ranging from 0.032 to 0.5 mm (Rua et al., 2015).

AM has greatly dominated the biomedical industries enabling the manufacturing of implants and prosthetics, also facilitating in bone tissue recreation. Wehmoller et al. (2000) used medical image processing based on computed tomography (CT) or magnetic resonance imaging (MRI) to know the geometry of the patient's prosthesis. Using EBM and direct metal laser

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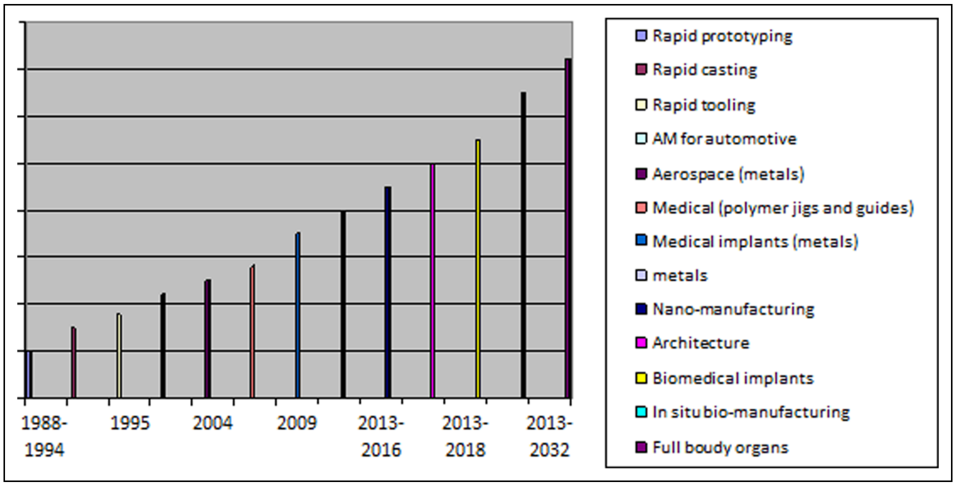

Figure 1. AM application timeline (AM, 2013).

sintering (DMLS) processes, implants are fabricated. These parts are found better functionality and have esthetic look against the currently used methods of reconstruction (Hollister, 2005; Nam et al., 2004). Ma (2014) suggested a new hybrid and adaptive tool-path generation approach which can be used in rapid prototyping (RP) to improve geometrical accuracy and build up time for complex biomedical models. AM improved the ability in the development of innovative scaffold design (Giannitelli et al., 2014). Among the different technology options in RP, three-dimensional (3D) printing can be used to direct printing of porous scaffolds with net shape for bone tissue engineering (Bose et al., 2013).

Nowadays, a variety of materials are used in AM-like polymers ranging from thermo-plastics to photopolymers and metallic powders. The AM application timeline is shown in Figure 1. This article is organized as follows: fundamentals of AM, and role and contribution of AM in various industries across the globe; few case studies are presented in engineering and biomedical applications. Furthermore, the scope of AM in product innovation which is coupled with theory of inventive problem solving technique (TRIZ) is explained.

AM in industries

The analysis of today's industrial scenario shows that many industries are becoming aware of the advantages of AM. A major goal in industries is to manufacture parts with complex shapes and required material properties. Due to this, AM is progressively pushed from RP toward small series production called Direct Manufacturing. The importance of AM is increasing on the characteristics of various industries. This

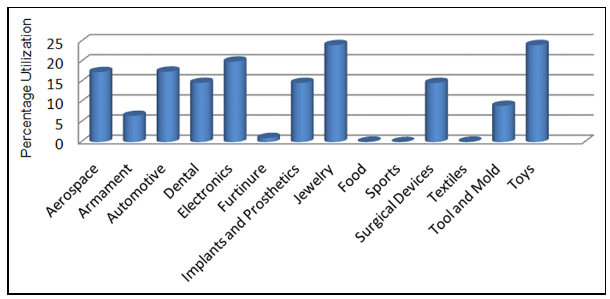

Figure 2. Percentage utilization of additive manufacturing across various industries (Gausemeier, 2011).

encompasses the characteristics of the aerospace, armament, automotive, electronics, furniture, jewelry, specialty food, sports, textiles, tool and mold making, toys/collectibles industry, as well as the implants/prosthetics, dental, and surgical devices/aids (Gausemeier, 2011).

AM has already been used for a number of applications across the various industrial discipline. The percentage utilization of AM in various industries has been elaborated in Figure 2. It has been found that AM has greatly dominated jewelry, toys, aerospace, and electronics industries, whereas it is in initiating phase in food, furniture, and sport industries.

Implants and prosthetics

The high expectations of growing population demands for a better quality of life and the life style of modern society require efficient and affordable health care. This issue is challenging and creates a new problem of increasing the number of implants required and new diseases to be treated e.g. Parkinson's and Alzheimer's (Bartolo et al., 2012). Today, the field of surgery demands devices and instruments that are made with

Table 1. Case studies in engineering and implants and prosthetics.

Process/ category	Technology	Applications	Reference
AM electrochemical and physical process	Electrospinning, stereolithography, laser sintering and melting, EBM	Nano-scale meshes for tissue engineering, scaffolds for tissue engineering. Implants like human vertebra, mandible plate, femoral prototype, acetabular cup, hip implants, and knee implants	Bose et al. (2013)
EBM and DMLS	Load bearing implants with varying mechanical properties to reduce the weight	Hip implantPart of mandible	Ciurana (2013)
Hybrid AM	Ultrasonic AM	Metal parts	Setakia et al. (2014)
RP machine	3D scan data of object	RP models	Gebhardt et al. (2010)
RP machine	RT mold	Graphite and copper electrode for EDM	Zhang et al. (2013)
AM process	FDM	Device for foot orthosis and foot ankle orthosis	Jun (2013)
3D MID	FDM, SLS, SLA	Complex 3D prototype	Hussein et al. (2013)
CLAD	LDMD	New part construction or worn-out part repairing	Mann and Domb (2004) Didier and Simon (2012)
Laser forming	Rapid tooling by SLS and SLM	Dental caps, airborne structures	Custompartnet (ED) (2009)
AM	Low-cost 3D printer machine RepRap	Biocompatible scaffolds	Nam et al. (2004)
Multi-material layered manufacturing	MMVP system	Multi-material objects for biomedical applications	Santos et al. (2006)
SLM process	The Realizer 50 Desktop SLM machine	Dental implants	Ortona et al. (2012)
FDM	Hybrid and adaptive tool-path generation approach to improve build time	Complex biomedical models	Jayanthi et al. (2011)
AM	CT scan files	Total hip replacement guides, acetabular jig	Drstvensek et al. (2008)
Z Printer 450 3D printing	Liquid state, solid state, powder state	Jewel's design and metal art working	Tefler et al. (2012)
SLS	Reverse engineering	Car volume buttons	Mcor Technologies (2013)

SLM: selective laser melting; FDM: fused deposition modeling; AM: additive manufacturing; RT: rapid tooling; CLAD: construction laser additive direct; MID: molded interconnect device; EBM: electron beam melting; DMLS: direct metal laser sintering; RP: rapid prototyping; SLS: selective laser sintering; SLA: stereolithography; LDMD: laser direct metal deposition; MMVP: multi-material virtual prototyping; CT: computed tomography.

maximum precision. For complex surgeries, surgeons are using customized disposable surgical instruments, manufactured by AM methods based on 3D CAD data (CustomPartNet, 2014). A variety of applications can be performed by functional implants which include hip and other joint implants, vascular prosthesis, artificial ligaments, heart valves, cages, spinal fusion and spacer devices, some cochlear implants, artificial hearts, and dental implants (Averyanova et al., 2011; Bartolo et al., 2009; Goswami, 2009).

The challenge in orthopedics is that, for different human body, the implant should fit perfectly and quickly accepted by the body to enhance the patient‘s long-term quality of life. Combination of AM and orthopedic technology produces improved prosthetics and orthotics. AM offers novel applications in engineering as well as in implants and prosthetics, which are presented in Table 1.

Tables 2 and 3 represent the different AM processes used by various researchers in product development and various micro-fabrication processes. Figure 3 represents frequencies of various AM processes used in developing the products.

Current trends in AM

Challenges in the pure manufacturing ecosystem are responsible to create high capability parts for high demand applications. In the coming years, 3D printing technologies will be an alternative to current manufacturing processes. AM facilitates customized production which is location independent (Atos, 2014). Today, not

Table 2. Different AM processes used in product development.

Process used	Material used	Application	References
Laser sintering	CE-certified PA 2200	Biomedical implants	Drstvensek and Tomaz (2013)
Laser cladding	Calcium phosphate bioceramics	Tailored implant	Drstvensek and Tomaz (2013)
3D printer machine	Poly-l-lactic acid	Scaffolds	Ciurana (2013)
Hybrid and adaptive tool-path generation approach	–	Biomedical models	Jin et al. (2013)
AM	–EOS titanium Ti64	Finger implantsSpinal implants	EOS Additive Manufacturing Solutions (2013)
AM	PA 2200	Patient customized cutting and drilling guide	Gausemeier (2011)
AM	Cobalt chrome	Fuel injection swirler	Gausemeier (2011)
SLS	Nimonic 80A	Die inserts	Bi et al. (2010)
SLA	Zn–Al–CuPseudo-alloy	Automobile front fender die	Yucheng et al. (2004)
RP and electroforming	Copper	EDM electrode	Yucheng et al. (2004)
UAM	Shape memory alloy and SiC		Friela and Harrisa (2013)
FDM	–	Ducati engine	Gausemeier (2011)
FDM	Polymer	Gripper	Gausemeier (2011)
Polyjet 3D printing	Plastic reinforced elastomer	Randomly oriented multi-material	Sugavaneswaran and Arumaikkannu (2014)
SLS	Zcorp Z310	Acoustic absorber	Foteini et al. (2010)
SLS	Polyamide	Car volume button	Paulic et al. (2014)
SLM	CoCr and noble materials like gold-based dental metal-ceramic alloys	Dental crown and bridges	Gebhardt et al. (2010) Setakia et al. (2014)
LAAM	Nickel-base alloy Nimonic 80A	Die inserts for liquid forging	Bi et al. (2010)
Hybrid methods	Polymer ink	Pre-ceramic articles	Ortona et al. (2012)
RP	3D scanner	3D objects	Willis et al. (2007)
RP	Based on RT	Molds	Yucheng et al. (2004)
AM	Plaster cast	Devices, a FO and an AFO	Teflar et al. (2012)
EBM	Ti6Al4V	Porous parts	Jayanthi et al. (2011)
SLM	Al_2O_3–ZrO_2 powder	Net-shaped specimens	Hagedorn et al. (2010)
SLS	Semi-crystalline PA12-powder	A 3D MID	Amend et al. (2010)
SLS	Aluminum	Light weight structured components	Buchbinder et al. (2011)
LOM machines	Steel	Keychain design and prototype	Asiabanpour (2008)
FDM	Polymer	2-Light holder for the hand-held drills	Asiabanpour (2008)
FDM	Plastic	3-Luminaire fixture design and development	Asiabanpour (2008)
3D printer	Plastic	Battery terminal cap	Asiabanpour (2008)
DMLS	Titanium alloy Ti6Al4V powder	Lattice support structures	Ahmed et al. (2010)
Indirect selective laser sintering. TIPS was used	Polymer and polymer–ceramic composite particles	High density ceramic parts	Shahzad et al. (2013)
EBM	Atomized Cu powder containing a high density of Cu_2O precipitates	Cu components	Ramirez et al. (2011)
SLM	Pure Ti (Grade 1)Metal powder	Tailored implants	Zhang et al. (2013)

SLM: selective laser melting; FDM: fused deposition modeling; AM: additive manufacturing; MID: molded interconnect device; EBM: electron beam melting; DMLS: direct metal laser sintering; RP: rapid prototyping; SLS: selective laser sintering; SLA: stereolithography; UAM: ultrasonic additive manufacturing; LAAM: laser-aided additive manufacturing; TIPS: thermally induced phase separation; 3D: three-dimensional.

only the requirement of sophisticated devices and structures with novel properties is increasing but also trend of decreasing component sizes, material usage, and energy consumption of product. This further leads to the development of nano-AM (Lin et al., 2011).

Protolab is one of the world's fastest sources for custom prototypes and low-volume production parts (Proto Lab Services, 2015). In Protolab, AM fineline offered three distinct AM technologies SL, SLS and DMLS under common umbrella (Proto Lab Fineline, 2015).

Table 3. Micro-fabrication processes (Vaezi et al., 2013).

Process	Material	Application
MSL	IH polymer	Micro-machines and micro-sensors, micro-fluidic systems, optical waveguides, 3D photonic band gap structures, fluid chips for protein synthesis, and bio-analysis
Vector-by vector MSL	Polymer	Special micro-clamping tool
SL	Glass photomask	Mask pattern
Refrigerated MSL	Sol–gel transformable resin	Mask patterns via drawing
SL process	Liquid crystal material (LCD)	Array of light valves
The LCD-based MSL systems	Alumina	Alumina base component
LCD-based MSL system	Liquid crystal material	Direct mask photocuring
DMD-based MSL digital micro-mirror device	Cellular material	High quality 3D micro-parts
MSL	Mode locked titanium (Ti)–sapphire	3D micro-parts
MLS	Ceramics and metals	Micro-components
SLM 50	Super alloys, aluminum (Al), stainless steel, tool steel, cobalt (Co) chromium, and titanium	Micro-parts
3DP	Micro-zirconia ceramic	Investment casting of micro-components
Micro-3DP process	Stainless steel and Al/zinc alloy	Metal micro-parts
FDM	PCL, PLLA, PLGA, PCL/PLLA, gelatin, and alginate hydrogels	Polymeric scaffolds
Multi nozzle bioplotter	Biopolymer solutions	3D tissue scaffolds
RPBOD	Chitosan-HA	Scaffolds
Direct-write assembly	Inks including colloidal suspensions and gels, nanoparticle-filled inks, polymer melts, fugitive organic inks, hydrogels, sol–gel, and polyelectrolyte inks	Scaffolds
Micro-LOM process known as CAM-LEM process	Sheet of green ceramic	Micro-sensors, miniature diagnostic devices, lab-on-a-chip, micro-reactors and heat exchangers, and micro-fuel cell components
LCVD process	Jets of gas	Various micro-parts from variety of ceramics and metals
LCVD	Carbon, silicon carbide, boron, boron nitride, and molybdenum (Mo) onto various substrates including graphite, grafoil, zirconia, alumina, tungsten, and silicon	Ceramic micro-parts
LCVD	Al_2O_3	3D photonic micro-parts
LCVD	Ethylene gas	3D micro-coils

SLM: selective laser melting; FDM: fused deposition modeling; RT: rapid tooling; RP: rapid prototyping; LCVD: laser chemical vapor deposition; RPBOD: RP robot dispensing; PLLA: poly(l-lactic acid); PLGA: poly(lactic-co-glycolic acid); LCD: liquid crystal display; FO: foot orthosis; AFO: ankle foot orthosis; IH: integrated hardened; 3D: three-dimensional; PCL: Polycaprolactone, MSL: Micro sterolithography, MLS: Micro laser sintering.

Injection molding is the best suited and cheapest method for mass production. However, the development of molds for this process is critical and expensive. At Protolab, automated software identifies moldability issues and recommends solutions in an interactive quote which quickly turn printed prototype into production-ready part (Lior and Sella, 2013; Proto Lab 3D printing, 2015).

Emerging 3D printing business could use the ubiquitous postal network to connect their customers for the fast delivery of 3D printed goods (RARC-WP-14). The various industries and researchers are involved in the development of AM across the globe. Still, AM especially faces the problem in multi-material processing which expands the potential of AM into areas of multi-functionality and self-servicing. It needs to increase build speed, decrease the time to create each layer, and support high-volume production (AM, 2013). Also, there is a restriction on choice of material in AM. However, 3D printing using FDM technique is commercially most successful. The selective laser melting (SLM) and SLS are still developing and finding difficulties in processing of materials.

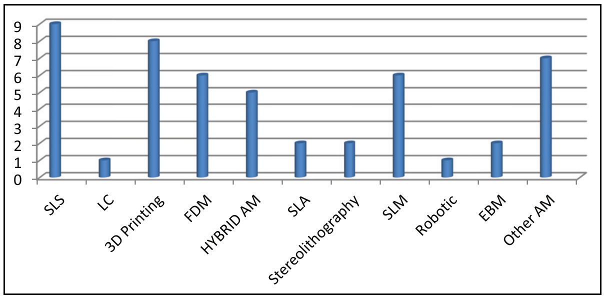

Figure 3. Frequency of different AM processes used by various researchers.

Since development is a continuous process, recently selective deposition lamination (SDL) or paper 3D printing was invented in 2003. It uses ordinary, affordable, and ubiquitous office paper as build material with a blade for cutting, and 3D printer selectively deposits adhesives only where it is needed. It supports industry-standard file format for 3D product designs, STL, as well as OBJ and VRML (for color 3D printing) and includes a control software called Slice IT. The control software reads the digital data and slices the computer model into printable layers equivalent in thickness to the paper (Mcor Technologies, 2013).

Product innovation with layered manufacturing (a collaborative approach using TRIZ)

Creativity and innovation have become strategic issues for the organization to remain competitive in the market (Nakagawa, 2007). TRIZ, the theory of inventive problem solving, provides a realistic and systematic way to solve the problem which helps the user to solve the innovative problem (Kang, 2004; Nakagawa, 2007). Development of contradiction matrix is one of the major contributions of Altshuller in solving the innovative problem, which is popularly known as "Classical TRIZ" matrix. The matrix comprises the 39 engineering conflicting parameters which are to be used for solving a problem either by improving or by worsening and 40 innovative principles to offer the solution of the problem (Generich, 1996; Schwiezer, 2003). Although TRIZ offered a systematic approach for problem solving, the specific solution offered to the problem is not realistic and often this issue remains as a debate for different researchers. Most of the researchers left the use of contradiction matrix because of this issue.

Difficulties in handling the contradictions

Technical and physical contradictions are the two sides of TRIZ. The formulation of technical contradiction

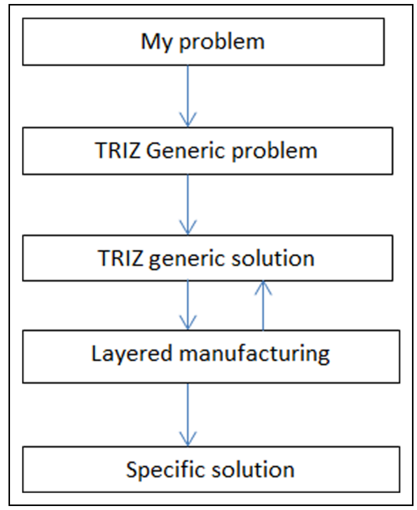

Figure 4. Collaborative approach (RP + TRIZ).

results in better understanding of the problem and finding the exact solution at a faster rate. If there is no technical and physical contradiction, then it is not an inventive (or TRIZ) problem (Campel, 2012). For solving an innovative problem, multiple pairs of physical and technical contradictions are needed, and then parameters are found in the 39 characteristics at the intersecting area of contradiction matrix. Contradiction matrix recommends one to four principles. Selecting the proper inventive principle and applying it to the engineering system for developing new concept are complex processes. Specific solutions to the problem are one or more which moves far away from the specific problem (Mann and Domb, 2004).

Modern organizations need both creativity and innovations together to achieve this goal most efficiently; the authors suggested the use of a collaborative approach (a conceptual framework) of TRIZ with AM. This approach provides realistic and systematic way to solve the innovative problems. Proposed collaborative tool of using AM technologies with TRIZ emphasizes upon minimizing the gap between TRIZ-specific problem and its specific solution (Figure 4).

Mirzadeh and Hasanpour (2013) carried out a case study of an innovative design on medical glasses. In this study, the customer's requirements of new product were gathered, and then the engineering parameters from TRIZ related to those requirements were explored. The engineering parameter includes weight of the stationary object, area of a stationary object, tension/pressure, and shape. These selected engineering parameters are again prioritized and finally tension/pressure was chosen. Using TRIZ contradiction matrix and examining two above parameters, four inventive principles—extraction, changing the color, homogeneity, and composite materials—were selected. Using RP and brainstorming, the inventive principle extraction was chosen as close relationship with customer's requirement. Finally, the prototype is produced by RP machine.

Conclusion

The AM industries have attained a tremendous growth today world-wide since its 26 years of history started in 1987 with first commercialization of SLA. AM is still capable of new technological innovation. Today, a variety of AM techniques are available to serve the various industries like food, sports, textiles, aeronautical, and the most prominent application offered in biomedical industries where customized implants, prosthetics, and customer-specific biomedical devices can be manufactured additively. Furthermore, the collaborative tool (AM and TRIZ) proposed can carve new revolution to explore AM in product innovations and generation of new product concept. In surgical procedure, digitally designing and manufacturing implants before operation will reduce operating time, improve accuracy, and provide improved fitting. By understanding the fundamentals of AM, processes can be used for affordable health care. Both nano- and micro-technologies can be applied for enhancing efficacy and precision. Hybrid layered manufacturing is a cheaper and faster method. The multi-material virtual prototyping is capable to process CAD model and CT/MRI data to represent complex objects for biomedical and dental applications.

The range of application of AM was also extended to produce functional technical parts, medical parts, rapid tooling, micro-fabrication, and so on although prototype remains the main application. Today, the greater challenge is to turn AM into production technology. The most significant issue probably related to the material used in AM. Recent AM materials have better mechanical, thermal, and dimensional properties which made it suitable to produce hard material, ceramic, and composite parts. AM is mostly used in jewelry and ornaments, whereas it is less utilized in specialty food, sports, and textile industries. Higher turnover has been recorded for AM in electronics and household items. The highest preferred AM technologies are SLS, 3D printing, and FDM wherein EBM has found less applicability. AM techniques are clean as they do not consume water, tooling, and chemicals and are material efficient. The future scope of AM is as follows:

1. Focus on production speed and market growth;
2. Development of new material for AM processing, such as biomaterials and nano-particulate and nano-fiber material;
3. In process monitoring and control methodology;
4. In product innovation and new concept generation.

Declaration of Conflicting Interests

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