Advances in Macro, Micro and Nano Additive Manufacturing Processes: A Review

Supravo Paul and Shibendu Shekhar Roy

Abstract--- *With advancement, the emergence of Additive Manufacturing Process for manufacturing purpose has greatly influenced modern industries. Through this paper, the main objective is to find out basic principle and application with further scope of Additive Manufacturing by exploring various fields and materials, that can be used for this technology. This paper also deals about the advantages and several challenges for Additive Manufacturing technology and its effect on sustainable manufacturing. As well as we shall discuss the modern trends of Additive Manufacturing technology gradually extending its field into Micro and Nano scale production.*

Keywords--- *Additive Manufacturing, AM Processes, AM Materials, Applications.*

I. INTRODUCTION

ADDITIVE Manufacturing Processes have emerged as means of rapid prototyping processes in the past 2-3 decades. The advantage of these advanced technology is that they enable cost and resource-efficient small scale production. With advance in technology, Additive Manufacturing has greatly redefined the direct manufacturing processes.

Additive Manufacturing refers to "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional manufacturing" (ASTM standard 2012) [1]. The terms 3D Printing, Rapid Manufacturing, Direct Digital Manufacturing are largely used as a synonym of Additive Manufacturing.Apart from metals like steel, titanium, a range of other manufacturing materials can also be used in Additive Manufacturing such as nylon, glass, wax, photopolymers. The use of these materials depends on the type of Additive Manufacturing process used.

Additive Manufacturing provides the advantage of manufacturing the part level with macro scale complexity, the material level with micro scale complexity and the product level with multi-scale complexity. Apart from that, multi-colour and multi-material parts can also be fabricated with a slight modification through Additive Manufacturing.

In this paper, we will review the principles and applications of various Additive Manufacturing processes available as well as the materials, various challenges, advantages, and opportunities for incorporating these processes in future in different business, marketing and daily-basis aspects. Finally, the adoption of Additive Manufacturing in the field of micro and Nano fabrication process has been discussed along with sustainability effects and further development trends of this technology.

II. GENERAL PRINCIPLES

Additive Manufacturing i.e. 3D Printing is carried out by first 3D modelling of the desired object followed by printing by layers.

A. 3D modelling

3D printable models can be prepared by using Computer-aided-design(CAD) software via a 3D scanner. 3D scanning is a process of collecting digital data on the shape and appearance of a real object, creating a digital model. In order to make the model ready for printing, it is converted into STL file.

B. Printing

The STL file needs to be processed by a software called 'slicer', which converts the model into a series of thin layers and producesa G-code file containing instructions tailored to a specific type of 3D printer. Typical layer thickness is around 100 µm. the particles are around 50 to 100 µm in diameter.

C. Functional Principle

The system starts by applying a thin layer of powder material to the building platform. A powerful laser beam fuses the powder at exact location defined by computer-generated design data. The platform is then lowered and

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Supravo Paul, B.Tech Student, Mechanical Engineering, NIT Durgapur, India, E-mail ID:-sp.20130123@btech.nitdgp.ac.in

Shibendu Shekhar Roy[2]*, Associate Professor, Mechanical Engineering, NIT Durgapur, India, E-mail ID:-ssroy99@yahoo.com*

the next layer is generated by fusing material so as to bond over the previous layer at predefined points.

III. PROCESSES

A. *Macro Additive Manufacturing Processes*

A large number of Macro Additive Manufacturing processes are now available. The main differences between processes are in the way layers are deposited to create parts and in the materials, that are used. Broadly these can be classified as Liquid-based, Solid-based, filament/paste and Powder-based systems.

- *Liquid-based Processes:*

  Stereo Lithography Apparatus (SLA)

  Multi-Jet Modelling (MJM)

  Rapid Freeze Prototyping(RFP)

- *Solid-based Processes:*

  Laminated Object Manufacturing (LOM)

- *Filament/Paste Processes:*

  Fused Deposition Modelling(FDM)

  Robocasting

- *Powder-based Processes:*

  Selective Laser Sintering (SLS)

  Selective Laser Melting (SLM)

  Electron Beam Melting (EBM)

  Laser Metal Deposition (LMD)

  Three-Dimensional Printing (3DP)

According to the manufacturing mode and method, Additive Manufacturing technology can be categorised into the following:

- *Spray Forming*

Spraying equipment is similar to the ink-jet printer, which selectively sprays the liquid moulding material through the nozzle and forms 3-dimensional structure by layers. These liquid materials are usually photosensitive polymer or waxy materials. Photosensitive polymers can be cured rapidly under visible light or ultra-violet light of specific wavelength. In case of a hollow geometry, two materials are needed to be printed: moulding material for parts and manufacture and supporting material for synchronisation manufacture. Supporting material is usually water soluble. The support structure can be removed easily when soaked in water.

The typical process of Spray forming is three-dimensional printing. Three-dimensional printing provides the following advantages: fast speed, being able to manufacture complex shaped parts, suitable for heterogeneous material parts and small-batch parts. On the other hand this process has some disadvantages such as poor accuracy and surface roughness of the parts, easy deformation even crack of the parts, and limited production speed due to restriction of injection quantity.

- *Laminated Object Manufacturing Technology*

LOM Technology consists of a computer, raw material store, cutting and feed mechanism, hot viscosity-pressure mechanism, adjustable work table, CNC system and other components. Computer is required for receiving and storing the 3D model of the workpiece. Feed mechanism deposit the raw material on a table gradually. Hot pressure-viscosity mechanism bonds the layers of materials together. According to the cross-section contour extracted by the computer, cutting system cuts the contour of materials above the table one by one.

Compared to other Additive Manufacturing processes, the advantage of the LOM technology is that the laser beam of the cutting system cuts the cross-section contour based on the hierarchical information provided by the computer without scanning the whole system, which reduces production time. Other characteristics of this process are: low material cost, low production cost, large sized parts, non-post-curing process, no requirement for support structure. The parts are able to withstand temperatures upto 200ºC and possess high hardness and good mechanical properties. Also the dimensional accuracy of the parts are precise. Some disadvantages of this process are: non-direct production of plastic parts, the texture appearing on the workpiece surface.

- *Photosensitive Polymer Curing Moulding*

This process utilises some properties of light source to selectively scan liquid photosensitive polymer and cure it fast. The basic principle of the light projection curing moulding is that it direct projects each layer image onto the liquid photosensitive polymer surface and solidifies each layer instantly. A typical process is Stereo Lithography Apparatus (SLA). The dimensional accuracy and the surface quality of this process is the best.

The process used 3D model produced by 3D CAD system to cut into layers of 2D contour surface. Now, according to these data, ultra-violet light controlled by the computer scans the surface of liquid photosensitive polymer resin and produces a thin cured layer. The cured layer surface sinks to a certain height and the second layer is then processed.

The advantages of curing moulding process are high automaticity of moulding process, good dimensional accuracy and surface finish, ability to make complex structure and precise structure with hollow section. Disadvantages of the process are: requirement of flexible support, unstable performance after liquid resin curing, high cost of equipment and maintenance.

- *Materials Extrusion Moulding*

Under certain pressure, filamentous polymer materials, after heating the nozzle become soften and melt. It builds the 3-dimensional structure by means of accumulation. A typical process is Fused Deposition Modelling, where hot melt materials are sprayed through a nozzle. The nozzle controlled by the computer undergoes planar motion of different direction according to the workpiece contour information section. Thermoplastic materials of filaments are heated to the molten state in the nozzle, and then coated on the working table selectively. After the completion of one layer, the table drops down and the next layer is coated above the first one.

Advantages of this process are: simple structure principle, low maintenance cost, formation of complex shaped parts, small warpage deformation of parts, ability to produce colour prototype directly. There are also some disadvantages of the process such as stripes on the moulding surface, requirement of design and production of support structure, long forming time and expensive raw materials.

- *Laser Powder Sintering Moulding*

In this process, the required shape is formed by bonding or fusing the powder material through thermal energy. The heat energy is usually in the form of laser or electron beam and the material needed is usually polymer and metal powder. For the polymer powder, powder itself serves as a natural supporting, so support structure is not required separately. As for the metal powder, it needs support structure of synchronous moulding to make the heavy metal parts to fix on a metal substrate. Typical processes include SLS (Selective Laser Sintering), SLM (Selective Laser Melting), EBM (Electron Beam Melting).

Advantages of this process are: ability to use variety of materials, relatively simple manufacturing process, high precision accuracy. Some shortcomings of this process: rough surface, smell exuded in sintering process, need of complex auxiliary process. Parts manufactured in this process has wide application in aerospace, defence and high-end engineering field.

Some of the most popularly known additive manufacturing processes falling under the above classification are listed below.

- *FDM (Fused Deposition Modelling)*

Material used in this technique is thermoplastic material, a polymer that changes to a liquid upon the application of heat and solidifies to a solid when cooled. Material is injected through an indexing nozzle onto a platform after being subjected to a temperature slightly higher than the melting point temperature of the material inside the head. The nozzles trace the cross-section pattern for each layer and deposit thermoplastic material.After hardening of this layer, next layer is built.

- *SLA (Stereo Lithography Apparatus)*

This is a very high end technology utilizing laser technology to cure layer-upon-layer of photopolymer resin (polymer that changes properties when exposed to light). Specialized material may be needed to add support to some model features. In this process, a CAD model is sliced into layers, each of which is then scanned in UV light to cure the resin selectively for each cross-section. After a layer is built, the platform descends by one layer thickness alloying the resin-filled blade to form the next layer.

- *MJM (Multi Jet Modelling)*

Multi Jet Modelling incorporates hundreds of small jets to apply a layer of thermo-polymer material, layer-by-layer. Each jet dispenses UV curable polymer. The MJM head shuttles back and forth to build each layer, followed by UV lamp flashing to cure the deposited polymer. After completion of one layer, the platform is descended by one layer thickness and the next layer is processed.

- *SLS (Selective Laser Sintering)*

Selective Laser Sintering (SLS) works by the principle of high-power laser applied to fuse small particles of plastic, metal, ceramic or glass. Unlike SLA technology, support material is not needed as the build is supported by unsintered material. A roller is used to lay a layer of powder material on the working table. Then laser beam controlled by the computer scans the powder according to section contour information. The powder particles at the junction melt and bond with each other. The working table drops the height of a cross-section layer, and the next layer is formed.

- *EBM (Electron Beam Melting)*

Electron Beam Melting builds parts by melting metal powder layer by layer with an electron beam in a high vacuum chamber. The fabricated parts are fully dense, free of voids and extremely strong.

- *LOM (Laminated Object Manufacturing)*

Laminated Object Manufacture involve cutting a cross-section in the sheet and attaching the cross-section to the part being build. A sheet of material is spread across a movable substrate, and a laser cuts it along the contour of the parts geometry determined by the CAD model. The layers bond with each other when a hot roller compresses the sheet and activates heat-sensitive adhesive. Materials used in this process can be layers of adhesive-coated paper, plastic or laminated metal.

All available 3D printer in this chart by their types

Type	Technologies	Materials
Filament/Paste	Fused deposition modeling (FDM)	Thermoplastics (e.g. PLA, ABS), eutectic metals, edible materials
Powder-Based	Powder bed and inkjet head 3d printing, Plaster-based 3D printing (PP)	Plaster
	Electron beam melting (EBM)	Titanium alloys
	Selective laser sintering (SLS)	Thermoplastics, metal powders, ceramic powders
	Direct metal laser sintering (DMLS)	Metal alloy
Solid-Based	Laminated object manufacturing (LOM)	Paper, metal foil, plastic film
Liquid-Based	Stereo lithography (SLA)	Photopolymer
	Digital Light Processing (DLP)	liquid resin

B. *Micro Additive Manufacturing Processes*

After making its name in macro manufacturing processes, Additive Manufacturing makes its way into the micro additive processes with a potential to make 3D products with micro-scale dimensions and Nano-scale accuracy. With the addition of new laser based production processes for micro scale additive manufacturing, a Nano scale accuracy can be obtained with ultra-short Femto and Pico second laser pulses, that opens a manufacturing process window, where temperature effects have no longer a decisive influence on the final result. Micro additive processes can also apply micro size features to a larger scale structure produced by another process.

Among attainable alternatives, Additive Manufacturing processes that are based on layer-by-layer manufacturing are identified as an effective method for attaining 3D microproducts. 3D Micro Additive Manufacturing can be classified into following main groups: (1) scalable Additive Manufacturing technologies, which can be implemented on both macro and micro scale; (2) 3D direct writing technologies, which have been merely developed for micro scale and (3) Hybrid processes.

1. *Scalable Additive Manufacturing Processes*

Fabrication of 3D microparts/structures is also within the reach of some specific Additive Manufacturing technologies via implementation of some essential modifications and improvements to obtain proper conditions for micro fabrication. Scalable Additive Manufacturing technologies including Stereo Lithography (SLA), Selective Laser Sintering (SLS), 3D Printing (3DP), Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM) etc. can be regarded as a promising approach for micromanufacturing and can be employed efficiently to fabricate complex 3D micro components/assemblies. However, this class of Micro Additive Manufacturing systems suffer by some difficulties for micro scale manufacturing since Additive Manufacturing technologies have been primarily developed for normal size fabrication.

2. *3D Direct Writing Technologies*

The second group of 3D Micro Additive Manufacturing processes is 3D direct Writing technologies. These technologies have been developed basically for 2D writings, but some methods such as Laser Chemical Vapor Deposition (LCVD), Focused Ion Beam (FIB), Laser Induced Forward Transfer (LIFT), Matrix-assisted pulsed-laser direct write (MAPLE) etc. can be utilized to produce high resolution 3D micro-structures. However, DW technologies need more improvements to become more compatible with 3D micro-fabrication, since most of these methods have been developed normally for 2D purposes.

Some of the key 3D Direct Writing Processes are listed below.

- *Laser Chemical Vapor Deposition (LCVD)*

LCVD is a 3D Direct Writing process that employs laser beam to convert gaseous reactants into thin solid layers in a selective manner. Laser beam is focused to a spot via optical microscope lens and gaseous reactant comprising the materials is fed into a build chamber. The substrate is heated selectively by scanning the laser beam over it at an approximate speed of 0.5-5 mm/s to dissociate the reactant gas. Consequently, a thin layer of material is set down onto the substrate. In this way, the desired micro component can be formed layer by layer. Fabrication of multi-material and gradient 3D micro-structures can be done by feeding different gases into the build chamber at different times or using a blend of gases with desired concentrations.

A lot of factors such as laser beam diameter, energy density and wavelength, as well as substrate thermal properties influence the resolution of this process. Also, the deposition rate depends upon the process parameters such as the scanning speed, gas pressure and laser power density. Increase in gas pressure of the precursor materials and laser power density results in linear increase in deposition rate.

- *Focused Ion Beam Direct Writing (FIBDW)*

This process is similar to LCVD with the exception that instead of laser beam, focused ion beam is used in this case. A FIB generated from a liquid gallium scans the substrate in the presence of gaseous precursors and as deposits solid materials onto the substrate.

As compared with LCVD, FIBDW has lower deposition rate but also offers higher resolution. Energy of the ion beam is usually 10 to 50 keV. Since organometallic mixtures are utilized in this process, layers deposited are not pure due to the presence of ions and organic impurity.

FIBDW is a slow process, so it is usually employed for repair work and low volume production. Particularly, this process can be used for the fabrication of 3D microstructures which are utilized for hermetic encapsulation in micro-sensors.

- *Laser Induced Forward Transfer (LIFT)*

LIFT is a 3D direct writing method suitable for precision printing of various structural and functional materials, e.g. DNA for sensor applications or nanoparticle inks for electrical applications. The LIFT process in its variations has gained a lot of interest during the last few years. The main advantage of LIFT is the unparalleled flexibility in processing materials that can be processed with a high accuracy.

The ejection process is quite complex. Using ps laser pulses and thin (about 200 nm) metal donor layers at low fluences, the release of a single droplet with radius 3 µm is observed. At high fluences, a jet like ejection process is observed. To understand the physics completely numerous numerical investigations have been carried out to model the different steps of the LIFT process.

As a numerical approach towards LIFT investigating the thermal and hydrodynamic behavior under pulsed laser irradiation showed the formation of small gold droplets in a equilibrium of inertial forces and surface tension.

Shugaev investigated the phenomenon of transfer occurring at different phase states of different materials gold, chromium and zinc under similar irradiation conditions for femtosecond LIFT and different metallic films. This computationally efficient stress analysis approach is used to investigate the dynamics of heating, melting and formation of stress waves to determine the phase state during transfer.

Another emerging application of the LIFT process is the direct writing of organic substances for additive manufacturing in the fields of tissue engineering, regenerative medicine and biosensor fabrication. For successful deposition of cells understanding of the formation of mechanical stress is important to minimize the cell damage during LIFT process. For characterization of mechanical properties such as stress, acceleration, maximum shear strain component, Wang used the Smooth Particle Hydrodynamics (SPH) method.

Currently, LIFT process is not only based on Femtosecond and Picosecond laser pulses, but also on Nanosecond laser pulses. For Nanosecond pulses droplet sizes are in the order of 500-700 nm, whereas LIFT processes based on Femtosecond laser pulses are able to achieve droplet size of 300 nm.

3. *Hybrid Processes*

Hybrid processes can be classified as the third group of Micro Additive Manufacturing technology. Some typical processes are Shape Deposition Modelling (SDM) and EFAB. EFAB process uses electro-chemical deposition and subtractive planarization process to build 3D microstructures layer-by-layer. SDM process utilizes additive and subtractive processes sequentially to produce 3D microstructures. Among hybrid processes, EFAB has shown great applicability for 3D micromanufacturing.

Some of the key Hybrid processes are listed below.

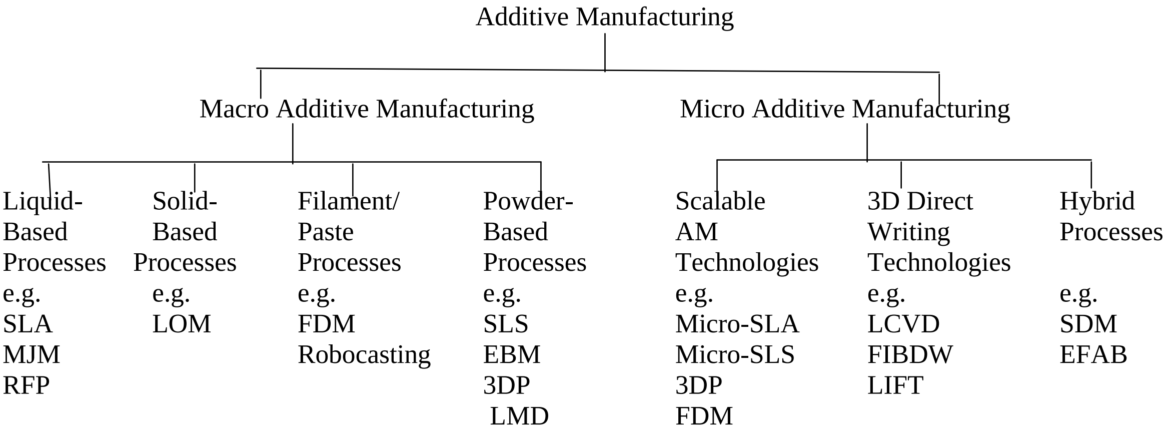
- *Electrochemical Fabrication Process (EFAB)*

EFAB is a hybrid process for volume manufacturing of micro devices with features as small as 20 µm. This process is based on electrodeposition and planarization of at least two metals: one structural material and one sacrificial material.

Three-step process is used to generate each layer in EFAB. The three- step process involves structural material electrodeposition, sacrificial material electrodeposition and planarization respectively.

This process has a wide range of applications in micro-industries, including probes for semiconductor testing, microfluidic devices. Minimally invasive medical instruments and implants, high accuracy probes for testing memory chips and microprocessors, inertial sensing devices etc.

Now, with reference to the large scale Additive Manufacturing Technologies discussed before, along with the modern micro-scale technologies, briefly the whole field of Additive Manufacturing can be shown with the help of the following flow chart.



IV. MATERIALS

The materials that can be used for Additive Manufacturing will play a significant role in determining where and how the process can be used and also the effectiveness of the process. The materials mostly used for Additive Manufacturing are as follows.

1. *Metals*

Industrial machines have the ability to use metals, this is not really an option for the home printers because of the cost. The main metals which can be used for Additive Manufacturing are:

- Stainless Steel
- Steel
- Gold
- Titanium
- Silver

In addition to pure metals, compounds can also be used. In case of metal compounds, they are generally not melted wholly at the time of sintering process, but the particles are merged. This provides waterproofing qualities not otherwise available.

2. *Thermoplastics*

Thermoplastics or Polymers are the cheapest material available for Additive Manufacturing and are the typical content for commercial 3D printers used for home purpose. The main thermoplastics used in Additive Manufacturing are:

- Acrylonitrile butadiene styrene (ABS)
- Polylactic acid (PLA)
- Polyvinyl alcohol (PVA)
- Polycarbonate

ABS is the type of polymer which is the most widespread. PLA, is however recently gaining popularity because of its flexibility, being available in both rigid and soft finishes. PVA is used as a material to create supports within Additive Manufacturing Process and is entirely dissolvable. These supports can be removed when the final design is accomplished. Polycarbonate requires a very high temperature nozzle but can be favourable for future use. The Additive Manufacturing process allows the combination of plastics with carbon fibre. This provides strength to the product without adding weight to the design.

3. *Unusual Materials*

Apart from metals and thermoplastics, there are, however, possibilities for other materials to be used in Additive Manufacturing, although they may not be used as widespread.

- *Medical and Bio-chemical Materials*

Additive Manufacturing can be used in medical field too. Bio-ink can be created from stem cells, which are then printed and layered like other materials, forming new tissue. Exciting results have been found with this technology, with bladders, blood vessels and kidney parts all being successfully printed.

By printing a compound of a material made from calcium phosphate, silicon and zinc, and combining this with bone cells, new bone growth was stimulated. Later the printed material was dissolved, leaving just the new bone.

- *Glass*

Ground down into powder, so it can be layered thinly as requires, glass can be used for Additive Manufacturing. An adhesive bond is required as the cross-section of the design is created and it requires baking before use.

- *Chocolate*

To revolutionise baking and cooking industry, a new entry to the Additive Manufacturing field is Chocolate. With the increasingly competitive market, Additive Manufacturing can be utilised to create even more complex shapes and designs.

The use of materials and the field of application for Additive Manufacturing is recently getting really expanded. There are numerous industries that could benefit from incorporating AdditiveManufacturing Process.

4. Designing 3D parts for Additive Manufacturing

To obtain 3D design data for printing, use of CAD software is necessary. This type of production depends mostly on the quality of the CAD design and also the precision of the printer. There are many types of CAD software available, some are free others require you to buy the software or have a subscription. Deciding what type of CAD software is good for you will depend on the requirements of what you are designing. However, for beginners, that simply want to learn CAD and create basic shapes and features, any of the free CAD software packages will do.

While designing a part to be printed some points need to be kept in mind

- The part needs to be a solid, that is, not just a surface; it needs to have a real volume.
- Creating very small, or delicate features may not be printed properly, this depends greatly on the type of 3D printer that is going to be used.
- Parts with overhanging features will need supports to be printed properly. This should be taken into account since after the model needs to be cleaned by removing the supports. This may not be an issue unless the part is very delicate, since it might break.
- Be sure to calibrate the 3D printer before using it, it is essential to ensure that the part sticks properly to the build plate. If it does not, at some point the part may come loose and ruin the entire print job.

Some thought should be given to the orientation of the part, since some printers are more precise on the X and Y axes, then the Z axis.

V. DESIGN OPPORTUNITIES FOR ADDITIVE MANUFACTURING

A. Design Freedoms with macro scale complexity

1. Material and color

Additive Manufacturing can process a wide variety of materials. Commercial machines can process polymers, metals and ceramic materials. Sheet lamination processes are compatible with paper, wood, cork, foam and rubber. Investment casting molds and cores have been printed in sand and large structures have been printed in clay and concrete. Various Additive Manufacturing processes have been used to print edible items such as chocolates, sugar, frosting, cheese etc. Along with variety of materials, some Additive Manufacturing processes can print the product in full color. This can be done by adding color to the raw materials (by ink-jet printing on paper or powder), by using different color feedstock for different parts of the model. Sometimes color can be used as a communication tool in Additive Manufacturing to highlight features such as tumors in medical models and to map analytical data onto objects thus making the information easier to understand.

2. Freeform geometry for art and aesthetics

The ability of Additive Manufacturing to create unique, intriguing and complex geometric forms has led to its adoption by artists and industrial designers. Additive Manufacturing is used in jewelry industry for direct production and to produce patterns for investment casting. It is also used to explore new forms of clothing, shoes and other accessories in fashion industry.

3. Internal freeform geometry

Additive Manufacturing provides the advantage of creating complex internal features to increase functionality and improve performance. For example, integrated air ducts and wiring for industrial robots, 3D flexures for integrated actuators and universal grippers, optimized fluid channels and such other complex geometries can be manufactured with the help of Additive Manufacturing.

B. Design freedoms at the micro scale material level

Additive Manufacturing allows designers to modify and combine materials, micro-structures to create new properties, forms and functionality. Since Additive Manufacturing simultaneously creates the material and geometry of an object, it can be used to make custom alloys and composite materials. This is important for achieving some quality mechanical properties such as increasing mechanical strength, modify the thermal expansion coefficient. Similarly, it is possible to control the porosity, micro-structure and material properties of metal, polymers and ceramic parts through the choice of materials, process parameters and build orientation. Finally, post-processing of finished parts can control and improve mechanical properties. For example, heat treatment influences grain structure and increases mechanical strength of metal parts.

Additive Manufacturing can process 3-dimentional lattices and trusses with specific mechanical, thermal, optical and biological properties. In biomedical engineering, lattices can be optimized for cell attachment, growth, transport of nutrients, metabolic waste, biocompatibility and biomedical properties.

VI. ADVANTAGES AND CHALLENGES OF ADDITIVE MANUFACTURING

Manufacturing is the process of converting material input into goods and services. The efficiency of this conversion process is the key determinant of the environmental impact associated with the manufacturing technique employed. Additive Manufacturing has been identified as having the potential to provide a number of manufacturing advantages. Studies are on process investigating and analysing the degree to which these potential advantages are being realised. Undoubtedly there are some challenges for this productive technology. Through optimisation and further research, the Additive Manufacturing is expected to become a key manufacturing technology for the sustainable society in the future.

1. *Advantages of Additive Manufacturing*

- Small batches of customised products are economically attractive relative to the traditional mass production techniques.
- Direct production from 3D CAD models for which no tools and moulds are required, hence no switch over cost.
- Designs in the form of digital files facilitate modification and customisation of components.
- Material savings as the process enables reuse of material (i.e. powder, resin).
- Complex structures such as free-form enclosed structures and channels can be produced.
- Final part has low porosity.

2. *Challenges of Additive Manufacturing*

- Cost and speed of production.
- Development and standardisation of new materials.
- Validation of the mechanical and thermal properties of the existing materials and Additive Manufacturing technologies.
- Additive Manufacturing technology lacks the presence of an effective design software for printing and prototyping tissues and scaffolds.
- Automation of Additive Manufacturing systems and process planning to improve manufacturing efficiency.
- Deficits of designer and engineers skilled in Additive Manufacturing.

VII. MAJOR APPLICATIONS OF ADDITIVE MANUFACTURING

- *Biomedical Engineering*

Recently scientists and engineers have succeeded in implementing 3D printing technology to create body parts and parts of organs. The process is very much similar to creating a plastic or metal part only difference being the raw material used, in this case which is biological cells created in a lab.

Another application of Additive Manufacturing in the biomedical field is creating limbs and other body parts made of metal or other materials to replace lost or damaged limbs. Prosthetic limbs are used in many occasions due to injuries sustained during war, by disease or accident. Available prosthetic limbs are very expensive and generally not customized for the patient’s needs. Additive Manufacturing is being used to design and produce custom prosthetic limbs to meet the patient’s precise requirements. By scanning the patient’s body and existing bone structure, designers and engineers have been able to re-create the lost part of that limb.

- *Aerospace and Automobile*

Aerospace and automobile manufacturers have been using Additive Manufacturing as a prototyping tool for some considerable time now. However, in recently years, with further advancement in Additive Manufacturing technology, they have been able to create functional parts used for testing. This process of design and prototyping has allowed these companies to advance their designs faster than before due to the large decrease in the design cycle. This helps in reducing the time period required to obtain 3D part from design data.

The future of Additive Manufacturing in these industries lies in creating working parts directly from CAD design using a 3D printer in the final product. Additive Manufacturing process is already underway for future cars and aircraft. Creating a product layer by layer allows the designer to create the part with precision to accomplish the task at hand. Extremely complex geometry can be easily created using Additive Manufacturing, at the same time allowing the parts to be lighter, yet stronger than their machined counterparts.

- *Construction and Architecture*

Architects and city planners have been using Additive Manufacturing to create the layout or shape of a building for many years. Now efforts are being made to apply this concept to create entire buildings. There are already prototype printers that use concrete and other specialized materials to create a structure similar to a small house. Applying Additive Manufacturing can reduce the huge number of cranes and workers required for each construction. The idea is tousethe 3D design model created on CAD software, to create a layer by layer pattern of the building. Most of the innovation in this field depends on the selection of appropriate materials.

- *Product Prototyping*

The creation of a new product involves many iterations and modifications of the same design. Additive Manufacturing has revolutionized the industry by allowing the designers to create their design in very short time period along with its prototype instead of waiting months for the actual part to arrive.

VIII. ADDITIVE MANUFACTURING AND SUSTAINABILITY

Sustainable manufacturing can be defined as the manufacturing processes that minimize negative environmental impacts, conserve energy, natural resources and are economically sound. When assessing sustainability of any manufacturing process, the entire life cycle must be considered to analyze the sustainability impact. The actual manufacturing process is the combination of environmental impacts associated with the product life cycle.

Life cycle analyses have shown that the adoption of Additive Manufacturing could have significant savings in the production and use phases of a product. The savings in the production phase conducts reduced material inputs and handling, along with shorter supply chains. In the use phase, lightweight components enable energy consumption to be reduced. However, further studies are required to compare AM products with traditionally manufactured products in terms of pollution, and other potential environmental impacts over their lifetime.

More recently the sustainable benefits of Additive Manufacturing have been widely hypothesized both by industry and academia. But to promote the widespread implementation of the technology, we need scientific data through established measurement methods. There has been reported work on performance evaluation for Additive Manufacturing processes. Appropriate benchmark parts have been designed for performance evaluation of these processes, and provide helpful decision support data. Several benchmark studies have been carried out to determine the levels of dimensional accuracy and surface quality achievable with current Additive Manufacturing processes. Besides the process and the material, there may be other factors, such as the building style and specific process parameters which may affect the accuracy and finish of the desired part. Considering sustainability, measurement science methods need to be developed and standardized for Additive Manufacturing.

When characterizing for sustainability, all aspects of the entire Additive Manufacturing process from raw material preparation to pre-processing, actual fabrication and post-processing to the final part must be carefully examined and appropriate measurement methods should be followed to account for sustainability. Comparisons to established processes are needed to be performed to understand the sustainability aspects. For example, powder metallurgy products are considered sustainable since it can use recycled material. A way to theoretically model sustainability for Additive Manufacturing needs investigation.

While Additive Manufacturing has yet to dramatically transform industrial systems, there are early signs of how the characteristics of this advanced production process will lead to advances in industrial sustainability. Additive Manufacturing is particularly suited for industries in which mass customization, light weighting of parts, and shortening of the supply chain are economically valuable.

IX. DEVELOPMENT TRENDS

Additive Manufacturing is a sign of third industrial revolution. It plays a catalytic role in industrial development, making design, development and production of Additive Manufacturing technology equipment step onto a higher position. The current development of Additive Manufacturing technology has shown the following characteristics: (1) growing industrial scale, (2) application of new materials and new devices, (3) new products and new standards emerging in the market. In future, Additive Manufacturing technology will mainly focus on three aspects: materials, design and application. The future trends of the technology are as follows.

- Developing new materials, such as tissue engineering materials, functional gradient materials and non-homogeneous materials has important significance in the development of Additive Manufacturing technology. Currently, the generality of the materials used is poor and the performance is not satisfactory, thus hindering the growth of Additive Manufacturing molding technology. Consequently, it is of importance to develop environment-friendly new material of excellent performance, low cost, small deformation and high strength to promote standardization of Additive Manufacturing technology.

- Higher popularization of Additive Manufacturing technology equipment. The concerned equipment should develop towards the intellectualized direction to make its operation easier with high production rate, high accuracy and reliability.
- The accuracy and performance of the parts will be improved with the development of Additive Manufacturing technology and composite materials will also develop from microstructure to macroscopic organization structure.

In the recent years, the most significant advances in Additive Manufacturing technology is direct manufacturing of metal structures, especially in the field of aerospace, where the breakthrough progress has been made. Although progress has been made in Additive Manufacturing technology, technology upgrade and cost reduction need further attention in order to promote its wider application and greater business value.

X. CONCLUSION

Over the approaching centuries, many see a once-in-a-generation opportunity in advanced manufacturing technologies. Specially, Additive Manufacturing has garnered widespread interest as a key component of the future of manufacturing. Though thus far mostly the focus of Additive Manufacturing technology has been on prototyping and tooling, a diverse set of industries including aerospace and defense, automotive, medical devices, consumer products, and retail have already felt this technology’s impact. These early applications, and the promise of many more to come, have fueled business leader’s excitement about applying Additive Manufacturing technologies to achieve new levels of innovation, performance and growth.

Additive Manufacturing has the potential to reduce the capital required to reach the minimum efficient scale for production, thus lowering the barriers to entry to manufacturing for a given location. On the other hand, the flexibility of Additive Manufacturing facilitates an increase in the variety of products that a unit of capital can produce, reducing the costs associated with production changeovers and customization and the overall amount of capital required. These impacts current companies with choices on how to deploy Additive Manufacturing across their businesses.

At this exploratory stage of research into the implications of Additive Manufacturing, deep-dive single case studies and comparative case studies of different sectors, organizations, products and components are required along with models of Additive Manufacturing based systems. Such studies can provide richer insights into the effects of Additive Manufacturing including the means through which opportunities are exploited.

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Supravo Paul[1] is pursuing his B.Tech degree in Mechanical Engineering from National Institute of Technology, Durgapur. He is currently in 4th year of his course. His area of interest is Additive Manufacturing and Automation related topics. E-mail ID:-sp.20130123@btech.nitdgp.ac.in

Shibendu Shekhar Roy[2] received his B.E and M.Tech degrees in Mechanical Engineering from R.E. College, Durgapur in 1999 and 2001, respectively. He obtained his Ph.D from IIT, Kharagpur, India, in 2011. Currently, He is an Associate Professor in the Department of Mechanical Engineering, National Institute of Technology, Durgapur, India. He has published a great deal of research papers at national and international journals, conference proceedings, book chapters and filed number of patents in product development. He has written a book on “Modelling and analysis of six-legged robots”, which has been published by Lap Lambert Academic Publishing GmbH & Co. KG, Germany. His current research interests include application of computational intelligent tools like Fuzzy logic, Genetic algorithm, Neural networks etc. for modelling of different manufacturing process and additive manufacturing, robotic systems.(E-mail ID:-ssroy99@yahoo.com)