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STUDY ON RECENT ADDITIVE MANUFACTURING TECHNIQUES AND THEIR DISTINCTIVE APPLICATIONS

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Abstract : *This article presents a review work on additive manufacturing technologies as reported in various reputed journals and proceedings. Additive Manufacturing (AM), also known as 3D printing, is a transformative approach to industrial production that enables the creation of lighter, stronger parts and systems. The various process involved in AM are discussed in detail in this paper. Moreover, AM eliminates many constraints imposed by conventional manufacturing and this enables various sectors to jump into AM to manufacture required components. The application of AM in various sectors like automobile, medical, constructions, aerospace etc. are discussed in this paper. Sustainability and environmental impact of AM technology are also discussed. COVID-19 has created a lot of uncertainty and disruption in the manufacturing industry. This paper also addresses how additive manufacturing plays a vital role in the current moment of crisis.*

Key Words: Additive manufacturing, 3D printing, applications of AM, AM process.

1.Introduction

Many businesses have adopted AM innovations in recent years and are seeing tangible business benefits as a result of their investment. The technology is improving and has progressed into a variety of different industries[25]. In three-dimensional printers will only print items that are smaller than the printer's casing which limits the size of items that can be made. The technology enables mass customization at low cost. Retailors can design and personalize goods without lengthy delivery time. AM has the ability to amplify the quality of products. Patients all over the world are benefiting from increased quality of treatment thanks to 3-D printed implants and prosthetics. As AM is used in the production of engines and vehicle parts, small-volume manufacturing is expected to expand in the AM industry. As a result of this increase, the AM industry will gain $1.1 billion by 2025. 3-D printing materials are expected to become more affordable as small-scale production grows[25].

2. Literature Review

AM is one of the finest digital technologies since it eliminates the need for tooling and fixtures, lowering costs and waste, and enabling long-term business models[21]. 3-D printers usually have one of two disadvantages : either they have advanced capabilities at a high price or they have simple capabilities at a low price. However, in recent years these are sorted out. Some printers today have higher-end features at a lower cost than in the past.

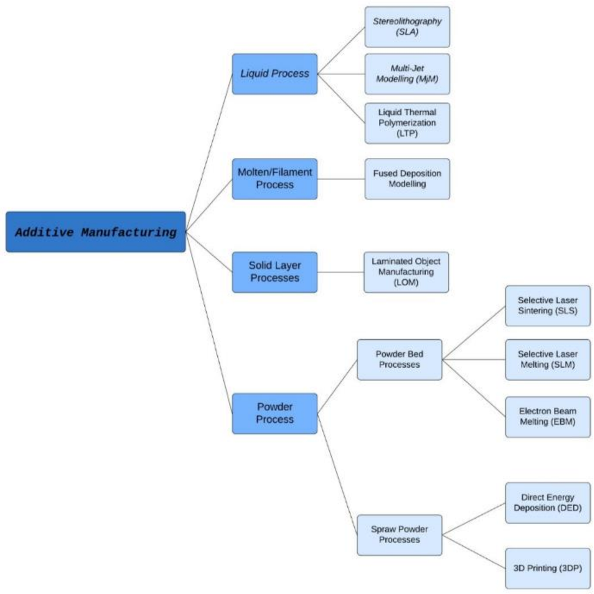

Figure 1: Various additive manufacturing processes

2.1 Fused Deposition Modelling

Fused Deposition Modelling is an additive manufacturing process in which two separate nozzles, one serves as support material and another serves as model material, are used to construct a three-dimensional model designed using the aid of a CAD tool. Parts are generated layer by layer in the FDM process. Each layer is made by depositing semi-liquid material in a temperature-controlled environment on a fixtureless base. This Fused Deposition Modelling process can create parts out of thermoplastics like Polylactic Acid and Acrylonitrile-Butadiene-Styrene. A new hybrid solution was suggested addressing the limitations of size and to fabricate the large components. Process chains, architecture for production, and assembly guidelines were among the outcomes. Due to its various advantages such as low maintenance costs and technology, low material costs, ease of operation, a wide variety of materials available, compact design, low temperature operation, and office friendliness, the Fused Deposition Modelling process is one of the most frequently used additive manufacturing techniques [16].

2.2 Directed Energy Deposition

The Directed energy deposition process is used to create net form prototypes or components starting from wires or powder in a layer-by-layer manner. This method permits the fabrication of functionally graded and complex formed parts that can be used in various engineering applications. Due to very high cooling/heating rates, and bulk temperature increment, large temperature gradients, the thermal history of a component that is deposited has a significant impact on features that are at the microstructural level (such as grain size and morphology) in a Directed energy deposition method. In this type of AM, a melt pool is formed on the last deposited layer or substrate's surface by using a relatively high powered laser. Each layer is constructed path by path by using a defined pathing of the tool which is set by the user. After this, the operation is repeated layer by layer with the help of a 3D CAD file, constructing the component [30]

2.3 Selective Laser Melting

Metal selective laser melting in AM, is rapidly becoming industrialized. The powdery particles are fused together on a layer-by-layer basis by directing the energy beam. It can either be a laser or it can be an electron beam. Based on the powder fusion process types, laser powder bed fusion processes are called by various names, the most general ones are selective laser melting and laser sintering. Selective laser melting process monitoring ultimately aims to provide real-time assurance of quality and, eventually, closed-loop feedback control of the AM machines [36].

2.4 Selective Electron Beam Melting

In SEBM, components are developed in a layer-by-layer manner by selectively melting the powder inside a powder bed using a powerful beam of electrons, which starts with CAD data. Unlike selective laser melting (SLM), which can be used on metals, polymers, and ceramics, the electron beam's application field is limited to metallic components due to the need for electric conductivity. The electron beam, on the other hand, operates in a vacuum, can travel at extremely high speeds and has a large beam capacity. Using electrons as an energy source has its own set of advantages and drawbacks. Electromagnetic lenses can focus and transfer an electron beam inertia-free. As a result, the electron beam will achieve speeds of up to 10^5 m/s and is able to jump almost instantaneously from one point to another. As a result, innovative heating and melting techniques can be realized using an electron beam. On the other hand, a vacuum condition is needed, and there is a risk of the powder being electrostatically charged, resulting in instabilities [34].

3. Applications

3.1 Automobile

One of the primary objectives of car manufacturers is to reduce vehicle weight. Since the weight of a car accounts for 75% of its fuel consumption, lowering its weight often reduces emissions [6]. Many of the lightweight polymers and metals used in the automobile industry can be used in AM to create components. Several AM processes have materials that can withstand temperatures well above the average engine compartment temperature of 105°C. High-temperature applications are possible with SLS nylon and some photo-cured polymers. One of the most significant advantages of additive manufacturing is the ability to post-process all printed parts to create a watertight and moisture-resistant barrier[13]. BMW uses an HP Multi Jet Fusion metal 3D printer to manufacture 100 window guide rails in less than 24 hours for the i8 Roadster. In addition, BMW is launching a new engine that will replace the S55 engine. This engine is made up of many components, including a cylinder head printed using a PBF metal AM printer. APWorks uses metal additive manufacturing to create lightweight structures out of Scalmalloy, which is a solid, corrosion-resistant, lightweight, and ductile high-performance alloy[4]. Bugatti developed a completely functioning titanium brake caliper that was entirely 3D printed. Using selective laser melting, inkjet technology and selective laser sintering tyres, hubcaps and suspension springs can be made from polymers and aluminum alloys [13]. Additive manufacturing has been brought to Formula 1 by McLaren Racing and Stratasys [9].

3.2 Aerospace

In the aerospace industry, additive manufacturing is used to create lightweight parts with geometric and material complexities that are needed for safe travel under extreme conditions. Complex aerospace components are manufactured using Electron Beam Technology [29]. The structural performance of an unmanned aerial vehicle (UAV) can be improved in two ways: by using lightweight structures and high-strength-to-weight materials. Honeycomb structures, inspired by nature, are widely used in the form of sandwich panels by aircraft designers to reduce weight. Extra UAV and aircraft spare parts are commonly kept on hand for repairs and emergencies. Despite this, the cost of holding parts in stock may be very high. They become obsolete and unusable after a certain period of time. Additive manufacturing could potentially overcome this supply chain problem by printing them on-site, which would solve the supply chain problem [26].

Inconel 718 is a Ni-Cr-based superalloy used in applications of high temperature such as aerospace and aviation due to its superior strength and thermal properties under extreme mechanical conditions and temperature. Inconel's 718 Hybrid fabrication prototype parts can be additively manufactured using these two technologies: Directed-energy Deposition (DED) and Selective Laser Melting (SLM). This combination could allow the production of larger parts with geometrically complex structures that would be impossible to accomplish using other technologies. In the space industry, a hybrid approach is a game changer because it allows for close matching of part specifications and material characteristics to optimize component efficiency, despite the challenges [1].

3.3 Defense

Additive manufacturing technology is increasingly used in military and defense technologies. Deployable AM units are developed which can print basic plastic medical components and more complex AM units that can print temporary or permanent tailor-made prosthetics to aid in disaster relief missions. It is used in military bases to support individual soldier's needs like body armors, kit, special tools and to print or repair unmanned vehicles (ground, sea, air). There is no need for much inventory since the required kit or object is 3D printed on the spot [33].

3.4 Food

Ingredients such as salt, sugar, and fat can be placed between layers in specific locations that influence mouthfeel perception. Low-calorie and low-sugar foods can be printed by distributing them evenly between the layers. Chocolate was one of the first food that was suitable for 3D printing due to its inherent melting and freezing properties. Chocolate melts during the heat extrusion process and quickly solidifies afterward. AM technology enables the production of foods with the desired consistency and soft texture, as well as enhanced nutritional value and hence it is very useful for people with dysphagia (swallowing difficulties)[5]. Chewing and swallowing problems affect 15 percent to 25 percent of elderly people over the age of 50 and up to 60 percent of nursing home patients. 3D printing of food could help the elderly people [28]. The price of 3D printers after 2014 was considerably reduced. After 2018 it was bought with much lower costs [23].

The US army has interest in 3D food printing because meals can be personalized depending on a soldier's nutritional and energy requirements, and this technology could extend the shelf life of food material[28].

The appearance of printed food samples can be affected by parameters such as flow rate, printing speed, and nozzle diameter [5]. Conditions like mechanical force, design and suitable feeding ingredients are to be optimized. Each food requires different pressure. The room temperature can also affect the flow rate. Even with the right nozzle size and adequate velocity, some ingredients may not be stable [31].

3.5 Construction

AM allows for freeform, artistic, and innovative designs while lowering construction costs in terms of ecological, manpower, time, energy, and capital [18]. By minimizing on-site worker exposure to harsh conditions and automating certain construction tasks, AM can benefit the construction industry [24]. The printed rebars had about 20% lower yield stress and tensile strength than conventionally manufactured ones in experimental tests, but they had a larger elongation at break and roughly equal bonding capacity.

Big Area Additive Manufacturing (BAAM), a 3D-printing technique similar to FDM has been designed to manufacture large polymer components measuring up to $6\times2.4\times1.8\ m^3$ at Oak Ridge National Laboratory[18]. WinSun, a Chinese firm printed an office building in 17 days in segments and assembled it on-site in just two days. For a single-story home, both printing and assembly costs, with labor savings of 50 to 80 percent and construction waste savings of 30 to 60 percent as compared to traditional construction techniques [24].

3.6 Sports

Nike was the first to use AM technologies on sports. Nike was able to prototype 30 different versions of plate for its Zoom Superfly Fly knit and reduced the sampling time from weeks to days. Adidas was able to minimize weight and improve durability without sacrificing stability by using AM to build a running shoe midsole. To provide the ultimate personalized experience, Adidas plans to produce customized shoes immediately and in-store by digital measurements of the foot with foot scanning technologies. New Balance collaborates with athletes to build a 3D model of a running shoe by generating mechanical data [17]. A rifle support for biathlon is created using AM. A steady shooting motion is needed in biathlon, so the geometry of an athlete's body was obtained through 3D scanning, and a rife support was designed to fit the athlete's body. After that, topology optimization was combined with a FE review to minimize component weight while also ensuring structural protection and stiffness. The printed rifle support was found to be capable of withstanding a load of 13.92 KN or 14,294 times its weight (99.4 g). This result represents a 40% improvement over the original design, indicating that the proposed topology optimization design is successful. Since the printed rifle support is less than 100 g, it can be used in biathlon [19].

3.7 Fashion

One of the main limitations in printing clothes is the commercially available materials. The filament material needs to be flexible and absorbent. However, the present filaments are not matchable with the above properties. Textiles printed with the above filaments cannot be machine washed. The advantages of AM in textile are that by printing the exact size of the clothing, there is no wastage and hence it can be environmentally good. 3D garment printing is beneficial to mass customization and there is almost no design limitation. Human error occurring in conventional methods can be avoided by this technique [37].

3.8 Medical

Additive manufacturing is a digital manufacturing technique that is increasingly revolutionizing the medical industry by printing unique body parts with intrinsic shapes and providing personalized solutions to each patient. Dental implants, heart valves, and joint replacements have all been developed using AM technology. This is a technology that creates a physical model directly from CAD models by layering materials on top of each other, resulting in a robust mechanical model. As compared to ceramic and polymeric materials, metallic biomaterials often used to replace and support skeleton parts have high fracture durability, tensile properties, and fatigue strength [2].

3.8.1 Surgery

A color model fabricated by 3D printing is very useful in distinct visualization of tumors and other anomalies. Using a CT or MRI scanner, a 2D digital image can be obtained. The imaging technologies are used to model internal human body structures such as bones, soft tissues, and so on. This data must be extremely precise, which necessitates the use of a spiral scanning technique that allows for a full volume scan of the body component. This is exported in DICOM format. By superimposing many of these 2D images, a 3D model of the scanned body part or organ is formed. The threshold technique is applied based on the tissue density. We only have pixels with a value equal to or greater than the threshold value at the end of the image segmentation step. The virtual model should have high pixel density with good segmentation to generate a 3D physical model. The created 3D model is imported into a suitable 3D modelling software for displaying and evaluating the model's various parameters. The design engineers, in conjunction with the surgeons/doctors, determine how the model should be changed to suit the patient's needs. The 3D model can be directly exported as a STL file and fed into an additive manufacturing machine for part fabrication. The post-processing of the file is carried out to remove errors [15].

3.8.2 Biomaterials

AM technology has been used to regenerate tissue structures that can be used as regenerative implants. Biofabrication is the name given to this region. Biofabrication refers to the automated generation of biologically functional products. It is being explored as an approach for several tissue constructs like cartilage, bone, skin, etc. It is still a challenge to match the generated bioprinted tissue with the properties of the native tissue patient-specific implants. Some companies in this area are active in the market, and the implants are already used in clinics. AM has also been used for prosthetics and orthotics [32]. 3D Printing can become more common in the field of drug or protein delivery in the near future. Many diseases need the regulated delivery of drug protein-loaded biomaterials. The developed 3D printed model of the liver allows for accurate tumor position identification and preparation, as well as experience with laparoscopy or hepatic resections [11].

3.8.3 Dentistry

Implants can be made to replace teeth in case of deformed jaw bones, dentures and false teeth. Some patients suffer from fracture of the chin or the jaw, and cancer may spread to the jaw. For these cases, 3D printed metallic implants can be created to replace those. This is done through a powder metallurgy-based AM process known as Selective Laser Melting. The implant is a bioinert one that remains inert created by using powdered titanium. Metallic dentures have been created using a process known as Direct Metal Laser Sintering. An alloy comprising cobalt, chromium and molybdenum was used to create the dentures [22]. The tools used by dentists can also be designed and developed by AM methods. Now the dentist can scan the patient's mouth and send the scanned file directly to the 3D printer lab, resulting in a 3D printed model that perfectly matches the patient's mouth. Hence, AM has a great potential in the dental field [14].

3.8.4 Covid

The coronavirus has been declared as a global pandemic by the World Health Organization, and millions of people have already died as a result of it. With the complete shutdown of major manufacturing countries, the increased number of positive COVID-19 cases has resulted in a greater demand for personal protective equipment (PPE), and these demands could not be met by the conventional manufacturing systems[3]. The materials used for the development of surgical masks are polypropylene, polystyrene, polycarbonate, polyethylene, polylactic acid (PLA) and polyester, and these masks are easily printed by extrusion based additive manufacturing methods. The low cost of the FDM-based printers offers tremendous opportunities for the developing countries which are currently under lockdown. The face shields and medical gloves can be printed on a mass-scale by additive manufacturing with fewer costs. Further, syringes, test tubes and swabs can also be 3D printed and mostly it uses polymers [7].

In China, WinSun, a 3D printing company, built additively manufactured houses to isolate the positive case citizens with electricity and water supply. A 3D Printable Door Opener can be fitted to entryways in clinics and organizations to protect polluted surfaces and enable people to open doors without using their hands [3]. While India only has about 3% of Asia and Oceania's AM installed base, companies like GE, Wipro, and Intech are pushing 3D printing technologies in the country. The current market is small, but it has the potential to expand significantly in the future. AM is helping in creating specific design drones that are used by police and authorities to monitor people in lockdown and to public broadcast. It is also helpful distributing medical and food supplies, spraying disinfectants, etc [10].

4. Defects

In metal-based additive manufacturing processes, solidification defects such as porosity and hot cracking are normal. Their presence has a significant impact on the mechanical and physical properties of additive processed products, limiting their application potential. Porosity, a solidification flaw, can serve as a cracking initiator. Its formation is influenced by both initial powder conditions and process parameters, which may contain or result in trapped gas bubbles, solidification shrinkage, or fusion failure [20]. Industrial X-ray Computed Tomography, which can scan for dimensional errors relative to the nominal model and also for internal defects, is currently a powerful tool for qualifying a medical device [12].

5. Sustainability and environmental Impacts

The usage of AM could possibly save thousands of tonnes of aluminium, titanium, and nickel alloys, as well as 92.1 to 215 million metric tonnes of greenhouse gas emissions during production [35]. AM has the potential to cut overall primary energy use by 2.54–9.30 EJ and reduce CO2 emissions by 130.5–525.5 Mt by 2025, according to a comprehensive study from a global sustainability perspective [8]. Selective Laser Melting (SLM) has a 45 percent nitrogen consumption effect on the climate. Even though these post-treatment processes are an essential part of the AM process chain, their environmental effects are often ignored or underestimated as compared to other manufacturing processes [27].

6. Conclusion

Additive manufacturing is quickly transitioning from rapid prototyping to rapid manufacturing. In the last decade, significant progress has been made in terms of speed, precision and material properties, as a result, these technologies are now capable of fabricating end-user parts with high density and excellent mechanical properties. Nearly all products can be made by additive manufacturing ranging from small products to a house. However, with the present techniques there are some issues with high cost of procedure in certain fields. Hence some of these issues restrict usage of additive manufacturing in those sectors. Further research is to be done in this field to reduce the overall cost of AM process and to overcome the current restrictions.

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