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4D Printing: A Revolution towards Sustainable Future

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Abstract: ***The manufacturing process is one of the main fields in Mechanical Engineering. Additive manufacturing has revolutionized this process. Furthermore, the invention of 4D printing is derived from 3D printing by adding a time dimension to the manufactured product. This makes the manufactured product respond to external stimuli and change its shape as time goes by. This process is still in its infant stages but the results shown by it in this stage are astonishing. It proves that this technology will surely drive the future of the manufacturing domain as well as the material sciences. In this paper, we discuss the history of 4D printing, the material required for the process, the difference between 3D printing and 4D printing, current trends with market potential, applications, and the future scope of this technology. Also, the advantages, challenges faced and the potential of this technology is reviewed. As well as its impact on the sustainability of the environment and industries using the process are mentioned.***

Keywords: Additive manufacturing, Stimuli, 4D printing, Smart materials, Sustainability

1. Introduction

1.1 Additive manufacturing(AM)

Additive manufacturing is a transformative approach to the industrial production of stronger and lighter parts or systems. In this actual layer by layer, formation is done to create a part. AM includes many technology subsets like 3-d printing,4-d printing, layer manufacturing, rapid prototyping, etc. It was invented by Chuck Hill in 1984. As technology advances, AM will keep expanding its use in industries as more types of materials are made available to be printed and as the process gets cheaper. In the coming future, AM will be at the forefront of revolutionary manufacturing methods.

While additive manufacturing seems new to many, it has been around for several decades. In the right applications, AM delivers a perfect trifecta of improved performance, complex geometry, and simplified fabrication.

1.2 4D Printing(4DP)

4-D printing is a process through which 3-D printed object transforms into a different structure when external stimuli like temperature, pressure, etc. are applied. The purpose of this technology is to invent self-assembly material aiming at reimagining manufacturing, product assembly, and performance. The idea of 4DP was first introduced by Tibbit. Currently, most research focuses on the shape-changing ability of 4-D printed structures including bending, elongating, twisting, and corrugating. This can help in making toys, robots, lifters, lockers, microtubes, etc. The various research topics in 4D-printing fall into the following categories: Development of equipment, Deformation mechanisms, and Mathematical modeling. The material used for 4DP is called shape memory polymers. This process creates less waste compared to other traditional manufacturing processes. Hence this process can potentially help in lean manufacturing. [4]

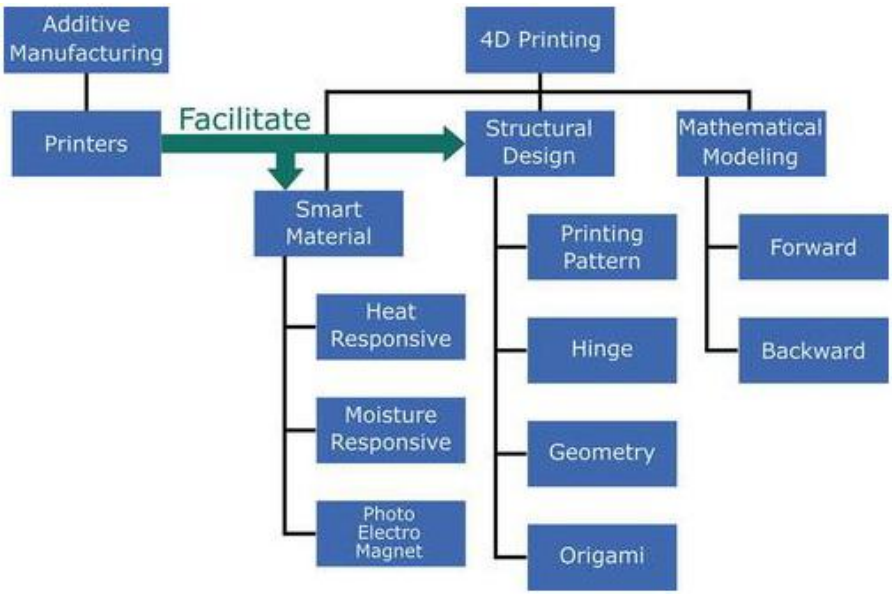


Figure 1: Flowchart of AM and 4DP

1.3 Methods of AM used for 4D printing

Methods used for the production of part by 4DP are:
1) Direct inkjet cure method
   a) Continuous inkjet method
   b) Drop on-demand method
2) Fused deposition modeling method
   a) Material extrusion
   b) Binder jetting
   c) Material jetting
   d) Directed energy deposition
3) Stereolithography method
4) Laser-assisted bioprinting method
5) Selective laser melting method

2. Theory

2.1 Approach for 4D printing

Approaches based on mechanisms can be applied to achieve the shape-changing property in a controllable manner. A few of the approaches are mentioned below:
1) Self-assembly of parts: By this approach, the fabrication of elements can be reduced. It can be used in places where fabrication of manual assembly is difficult making it a new and effective way for assembly.
2) Shape memory reaction: Materials tend to change shape when external load or pressure is applied resulting in deformation. But by using a 4D printed body, when the load as external stimuli are applied body deforms, but regains its original shape once the load is removed.[6]

2.2 Material selection based on stimuli

Materials selected for the 4D printer are classified according to the stimuli to which they respond. Classification is as follows:
1) Thermal responsive: Mechanisms that drive this are shape change and shape memory effect. The material used is programmed under specific heat and mechanical treatments and then cooled to be fixed at a temporary shape.
2) Humidity responsive: These materials have a high range of applications since they can expand to 200% of volume when exposed to water or other moisture. Hydrogels are the best materials for these stimuli.
3) Light responsive: This is indirect stimuli in which the area exposed absorbs light and converts it into heat. This was shown by Liu et al by sequentially controlled self-folding structure.
4) Electricity responsive: These materials change shape when an electric current is passed through them.In a humid environment, a voltage drives the head forward due to the absorption of moisture, and the tail follows up when desorption was caused by the absence of voltage.
5) Magnet responsive: Materials responding to magnetic fields fall under this classification. Ferric oxide powder is added to the material solution to obtain this property.[4]

Materials used in 4D printing are:
- Polymeric gel
- Pyroelectric material
- Self-healing materials
- Dielectric elastomer
- Varistors
- Piezoelectric materials
- Electro-rheological fluid

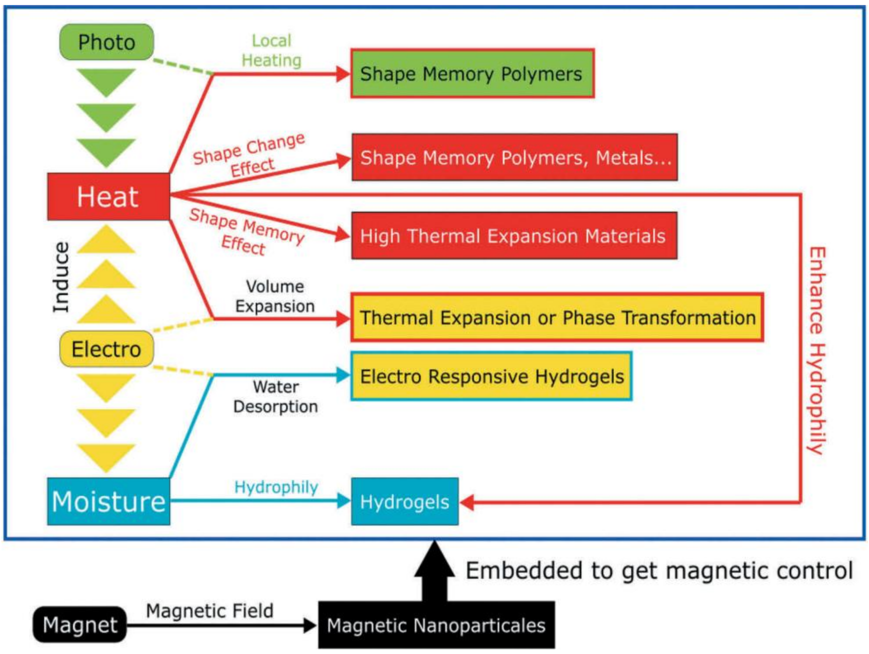


Figure 2: Smart materials responding to different stimuli

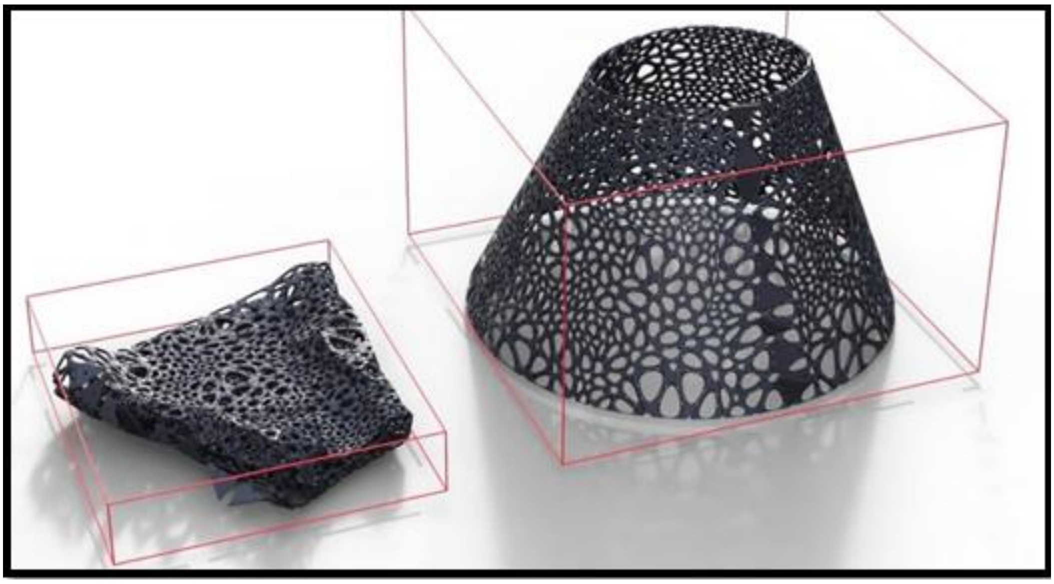
2.3 Difference between 3D printing and 4D printing

The main difference between 3DP and 4DP is that materials used for 4DP are smart materials. Mainly the 3-D printed has a fixed structure but the 4-D printed body can change its shape with time as it responds to the external stimuli of temperature, light, heat, pressure, etc. This additional dimension in 4DP of time is the only main difference between them. Other characteristic differences between 3DP and 4DP are given in the following table:

Characteristics	3-D Printing	4-D Printing
Build Process	The structure formed by layer on layer of 2D material	Extension of 3D printing with the use of smart materials or shape memory programming
Materials	Thermoplastics, ceramics, metals, etc.	Shape memory polymers, shape memory alloys, hydrogel, biomaterials
Shape Flexibility	Creates rigid structure	Characteristics of structure change upon the use of external stimulus
Shape memory programming	No programming is done	Thermomechanical training, using multi-material for differential stresses
Applications	Engineering, dentistry, aerospace, defense, automotive, etc.	Gives a dynamic element to all 3D printing applications.

2.4 Advantages of 4D printing

- Size changing: Through computational folding objects that are larger than the size of the printer can be printed as one part only. Since 4D material can shrink, fold, unfold the objects bigger can be printed by compressing into their secondary structure
- New materials have new properties: This is another advantage of 4-D printing as usage of possible applied materials. This technology can revolutionize the world of material science as we know of today. The multi-material shape memory polymers can "remember" their shape, actively transforming configurations over time in response to external environmental stimuli. For instance, we can make a machine such that it changes shape and releases medicine when the patient gets a fever.



2.5 Current trends in 4D Printing

Being a fairly new concept, this process is still in its research state. Hence this technology is not widely used in industry. Though, the responsiveness of material to adjust according to its environment will be the reason for the growth of this technology in coming years.

Following are the few key trends in the current 4-D printing market:

- The advancements in this field are resulting in development in the medical and defense sectors.
- In medical, doctors use 4-D printed self-transforming components to minimize the surgeries of a patient.
- In the military, soldiers can use camouflage that can change according to the environment around them.
- Also increase in performance of tanks and trucks according to the environment is being explored.
- Industry 5.0 will encourage 4-D printing since it will help in concentrating on the design process rather than the manufacturing process.
- Industry 5.0 will push the boundaries of the physics of the design process. For example, in the production of next-generation aircraft, there is a hindrance in manufacturing capabilities in industry 4.0, whereas it will be easier to manufacture in industry 5.0 since the process will be more automated and people are more to be focused on the design of the aircraft.

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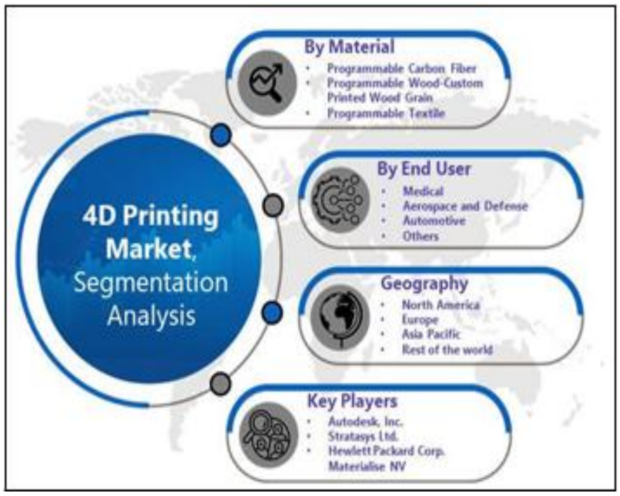
- According to the Organisation for Economic Co-operation and Development (OECD), healthcare expenditure for the united states, as a percent of GDP, is higher than any other country since 4D scanners can be used in the healthcare system for making 4D models of body parts which can be of help as prosthetics.
- Region wise North America has the largest market share in the 4-D printing technology.
- Hence the increase in demand for Industry 4.0, and the emergence of Industry 5.0 will be the major driving force for 4D printing.



2.6 Impact of 4D Printing on the sustainable future

- This technology has made companies take a stand on reducing their carbon footprint which has been a valuable step towards green manufacturing. Also, the program was started in 2016 by name SUSTAINOVATE sustainability program.
- Some of the benefits of sustainability of AM and 4DP are:
  a) Efficient product design: Main advantage is products designed to use less material to manufacture. For example, advanced design tools have many capabilities like lattice structure can create more strength by using less material. And also, by AM many parts can be manufactured as one using the printer.
  b) Efficient manufacturing process: In traditional manufacturing, subtraction is done i.e block of material is cut after the forging process is done. Hence scrap material increases some of which can be reused some of which cannot. But to reuse it needs to be reprocessed which increases cost. In AM, no molds are involved hence no waste material is left. There has been a great success in using the surplus material again for the process. For instance, HP high reusability PA 12 has an 80% reuse rate on surplus powder.
  c) Efficient supply chain: Traditionally three modes of supply chain exist namely air, water, ground. But with AM there exist another mode by the name of cloud. This cloud is replacing physical storage with a virtual warehouse. Due to the ability to print on demand, the unnecessary production of parts and their storage is avoided hence reducing the obsolescence cost. Also, this helps in lesser use of carbon-heavy transportation since printing on demand is possible. The integration of digital and physical logistics can be revolutionary in the future of the supply chain.
  d) Process optimization: Because of the rapid iteration of ideas and no prototyping limitations, companies can produce at a faster rate and respond to human needs more quickly, with efficient use of materials, processes, and people.
  e) Earth-friendly manufacturing: With industry 4.0 innovations we can create better, efficient, and environmentally friendly work processes for future generations. Some fortune 100 companies are already taking charge of converting their supply chain from traditional to additive to create better products, reduce the carbon impact, and reduce waste.

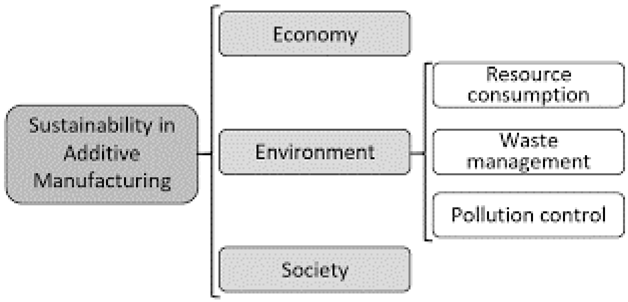


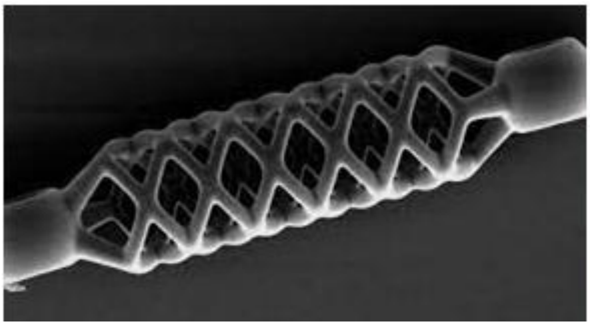
Figure 3: Tree diagram of sustainability

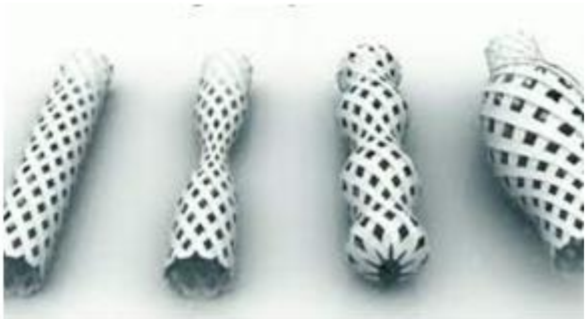
2.7 Potential Applications of 4D printing

- Self-repair piping system: Another potential real-life application can be its use in a piping system. This can be used so that pipes can change their diameter according to the flow rate. Also, the wear and tear can be repaired by the pipe on its own if self-repair material is used. This can help in pipe leakage problems and every time digging is done to repair it.
- Medical industry: Researchers are currently trying to print protein using 4DP. This protein will be a self-folding protein. Other applications also include the design of stents such that programmed stents would travel to the required destination in the body and then open up. The drug capsules are being printed using smart material so that they will dissolve or release medicine into the body. Self-shrinking/tightening staples are being researched using 4DP. This process can have a big break for biomedical applications.[1]
- Fashion industry: One of the main applications under research in this industry is that the clothes printed can shape according to weather or the activity being performed by the person. For instance, using shoes that change shape when a person starts running to provide comfort. Self-repairing clothes can be created which will save money and avoid the tear of clothes for people working in small spaces or while working with sharp objects.[2]
- Automotive industry: Not many applications have been reported in this industry but research is being done. Currently, BMW and MIT are working on "inflatable interiors". In this technology system is created such that

inflate and deflate stretchy material using a process called 'liquid printed pneumatic'. This is done to protect people inside the car during an accident.

- Aerospace industry: 4D printed material can react to change in atmospheric pressure and climate. Hence it has huge scope in this industry. This can be used to replace hinges and hydraulic actuators so that they can reduce the weight of the overall body. This technology has a huge opportunity in space structures since it can adapt to the surrounding and self-repair the body of the satellite [5]





After all, there is still much work to be done to meet today's environmental and global challenges, but the promise and potential exist. If more engineers get together to learn and understand the new technology and bring them into business in a meaningful way, we have an opportunity to create a big change in efficiency across the manufacturing economy.

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3. Conclusion

Advances in this technology will help many industries as research progresses. Mainly by this process, we can save material and eventually saving money.The environment will benefit as there will be a reduction in waste and the requirement of less material will help increase the availability of raw material.Pollution will reduce since no carbon is emitted by this method.