Chapter 2
Perspective of 4D Printing in Additive Manufacturing

Ajay Sharma and Ajay K. S. Singholi

Abstract The present paper discusses an overview about 4D printing and its applications in different areas. The overview consists of basic discussion on 3D printing or also termed as Additive manufacturing (AM), it operating technique and materials used to make products. 4D printing is based on 3D printing technique and the only difference is that, it uses smart material to print the required product. Information regarding smart materials, their types and method of operation or working is discussed in the paper. Shape shifters, shape memory alloys, shape memory polymers, gels and other active smart materials are some of the significant and most commonly used smart materials which are mentioned in the paper. The paper also includes the various affecting factors and modes by which the response stimulus is generated among the smart materials and accordingly performs the stimulus action. Discussion on stimulus response by effect of heat, water, electric as well as magnetic field, light rays etc. are briefly mentioned in the paper. Lastly, application of 4D printing technology in various fields such as mechanical, medical, commercial, general purpose have been discussed along with scope and suggestions to implement its use further is added in the conclusion.

Keywords Additive manufacturing (AM) · 4D printing · Shape memory polymer (SMP) · Shape memory alloy (SMA) · Shape memory hybrids (SMH) · Shape memory material (SMM) · Response · Stimulus

2.1 Introduction

The term additive manufacturing (AM) is the most efficient technology in order to fabricate three-dimensional (3D) shape structures which are complicated and likely to be hard in fabrication by using conventional manufacturing process [1]. At present, most of the methods used in AM are layer based. Although, these kinds of techniques

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have its own flaws, for example the slow speed and the components manufactured bear anisotropic stiffness (in single direction they are weak in comparison to other directions). Newly, derived by Kirigami and Origami, an exclusive AM based techniques on self-folding models have been developed so as to solve the issues of the traditional approach of layer based manufacturing. The self-folding models; their approach in additive manufacturing is known as 4D printing [2].

The concept of 3D printing permits any consumer to design and generate their own products as per their need, the products created also has almost least possible wastage. Now, with the technique of 4D printing, AM will be significantly impacted by the means of economy and community in the coming decade [3–5].

However, developments are still carried out and researches are progressively being made in additive manufacturing in reference to technologies related to 3D printing and applications, one of the foremost innovative breakthroughs is combining the concept of 3D printing with smart materials to generate such products which can alter their shape with respect to time. Additionally, the products printed via 4D printing technique can self-transform responding to some stimuli with respect to time [6].

2.1.1 Augmented Printing Using 3D Technology

Rapid Prototyping is commonly referred as manufacturing in layers, as it generates a 3D physical model in solid form in consecutive layer by layer manner, by diffusion of printing material which controlled by a computer [7]. There are several types of additive manufacturing of 3D printing process which depends on the handling of the material. In few cases, material in form of liquid is controlled, it might be also in molten form, or in the form of laminates which can be cut out and then joined together to reform the required shape [8, 9].

Augmented Reality (AR) can be defined as collaboration of techniques which permits mixing in real time comprising the input content produced by computer along with live visual display in video form. The concept when is used in combination with 3D printing it is known as Augmented Printing. AR is basically based on virtual reality technique and communicates with the real world as well as virtual world. The simultaneous existence of real environment as well as virtual models enables anyone to observe and visualize complicated concepts, and advance in newer activities which cannot be fulfilled by any other technique [10].

2.1.2 Shape Memory Effect

Shape memory effects form the basic factor in the alteration of 4D of the initial stage modelling specification considering the impression of stimuli and additionally retrieve the path details for the accessibility in the future to the constituted shapes.

Relating to the uniformity of temporary or instant shapes, the shape memory effect might be single way (1-W), double way (2-W), triple way (3-W) or it can be multiple-way [11]. The SMEs comprises of two phases, the initial phase provides the ability to program which forecasts the temporary specifications of the samples that printed on the other hand the next phase is the stage of actuation that signifies the recovery of the shape, printed permanently back through stimulus.

2.1.3 Impact on Different Sectors and Applications

AM technology has been applied in various and varied sectors. The technology is used in China for construction purpose. They were able to build a 10 story building within a day. Additive manufacturing are widely used in medical field in making different products [12]. One of the applications is in creating artificial organs which are similar to real organs. Also AM technique is used in making prosthetic parts for the body [9]. They are cheap and durable and hence save cost. In engineering field especially in mechanical sector, small components of complex machines are built by 3D printing using several materials such as, PLA, Fiber composites etc. [7]. Further electronic devices such as cell phones, speakers, multimedia devices etc. are making their most of the components via 3D printing technique [13].

2.2 3D Printing Technology

Several authors have researched on 3D printing technology and have defined it as per their own prospective. Here are few definitions: 3D printing structures the object or the product in several layers; 3D printing technique creates the output product in several layers accumulated together; the accuracy and the effectiveness of molding regarding the product are comparatively low. Depending on the assimilated innovation comprising the virtual model of the product which is targeted or its 3D modelling, the 3D mould for printing, intelligent mold injection, the "3D printing" technique is presented exclusively and it is assumed to emerge as newer trend in the industries of manufacturing, and additionally they have wider prospects in application [14].

The process of 3D printing involves developing products directly by the means of aligning layer deposition of the material on one another until the final object is created. The alignment of layer is done by any of the several methods based on the type of technology utilized. This technique permits to design and model parts which are complicated and hence overcoming the cost for assembly additionally. The process of 3D printing is deprived of tools which ultimately reduces the overall time consumptions [15].

The technology of 3D printing is the techniques that enables in giving the most effective technique in designing of any product, its manufacturing as well as prototyping. This technique provides fabrication of several products that are cost effective, have high utility, can be altered on maximum scale, and are highly efficient in energy consumption against the wide range of applications [16].

2.2.1 Benefits of Additive Technology Over Conventional Manufacturing

The knowhow might significantly declines the requirement for stocks since the design can be converted in digital form, resulting in delegation in the process of manufacturing. When the manufacturing of products is accomplishing closer to the end target, there will be decline in the cost for logistics and also reduces the influence over environment. Ultimately the time needed for the sales production will also be reduced [17].

Minimizing the cost for tools, as in additive manufacturing, tools are not required. Hence, this provides a supreme deal comprising tractability as in reference to adapting as per the market and declining or even minimizing, the included cost (fabricating tool, its inspection as well as maintenance) when contradicted with conventional manufacturing technique (Fig. 2.1). Depending upon the CAD model generated in 3D, even the complicated design models such as hollow interiors, varying thickness geometry, interior channels as well as non-uniform shape geometries etc. can be easily produced. This is otherwise a time taking and costly process in conventional manufacturing [18].

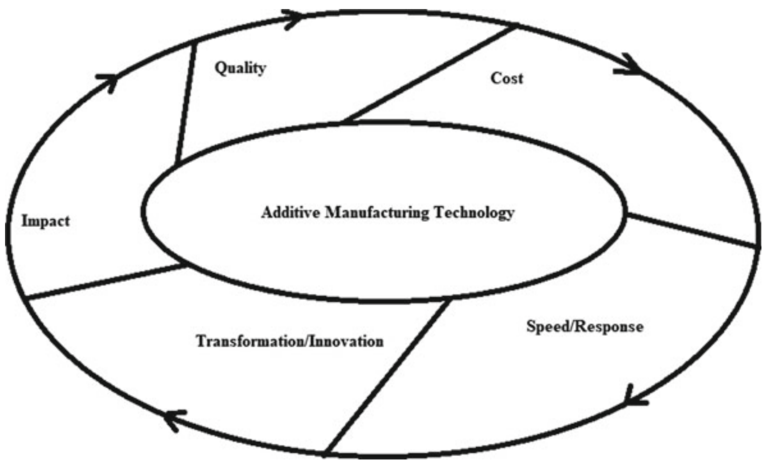

Fig. 2.1 Key advantages of AM over traditional manufacturing [17]

2.3 Shape Memory Materials Used in Printing

Recently the shape memory materials (SMMs), specifically which are polymeric in nature, have begun to grab much attention, as they are subjected to a belief that they add on a new dimensional constraint to the material properties, and exhibits the capability to re-shape the design and model of the object. The most important feature of SMMs is that they can return back to their original shape to the initial condition once any stimulus is applied [19].

Investigations have resulted in emergence of several materials having the capability to "memorize" a non-permanent shape provided, and further "recover" back to the actual shape which is permanent when exposed to external stimuli. This is the "shape memory effect" (SME) which remains the feature of entire SMMs. SME is significantly a wide process, and a broad range of materials such as alloys of metal, polymers, ceramic materials, system of super-molecules in addition with crystalline structure are found to be under SME [20].

2.3.1 Shape Memory Hybrids (SMH) and Shape Memory Composites

In the current scenario, shape memory hybrids (SMH) is growing as an exclusive member among the Shape memory materials. The ideology of SMH is characterized by its easy availability which enables any normal person to design and produce their customized SMM so as to encounter their requirements as per their area of application [21]. Shape memory hybrids use which is made from more than one type of molecules together as one hybrid material. They have the same properties of smart material which is that it can alter its shape with respect to time when an external stimulus is given [22].

Shape memory composites are basically smart materials with polymeric properties or a combination of polymers which can change its shape when exposed under moisture, light or radiation, magnetic field, electric field, temperature variation etc. and further regain its actual shape if the stimulus is stopped with respect to time [23].

2.3.2 Smart Materials

Smart materials also referred as functional materials have the capability to change themselves as per the conditions of the environment which is; they have the ability to alter themselves by mean of external stimuli physically and are hence have the fitment in the surrounding. Usually these conversions include transformation of energy (Fig. 2.2). Therefore, smart materials for instance can transform mechanical

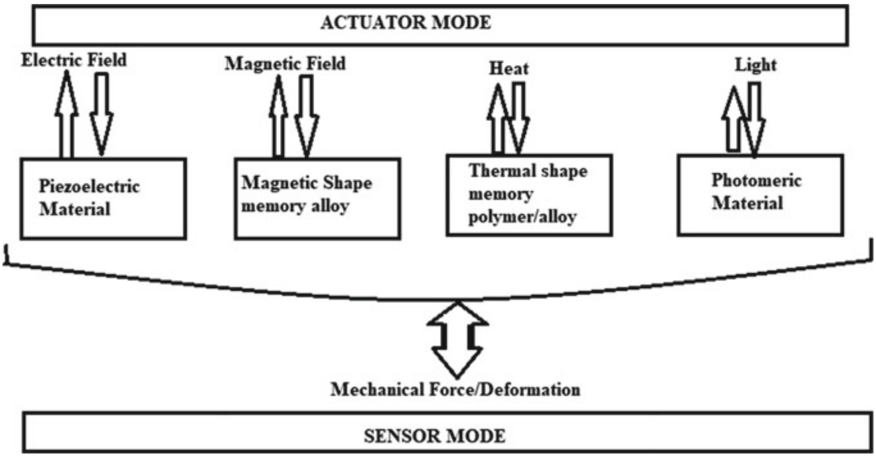

Fig. 2.2 Smart material action overview [7]

energy in form of electrical energy and vice versa. These resemble the smart materials in form of sensors and actuators [24]. Smart materials include all the categories of SMPs, SMAs, SMHs, shape memory active composites and others like gels that exhibit memory effect. One such example of smart material is hydrogel. Hydrogel has the property to undergo deformation and change its shape when water is added to it. The change in the shape is as per the desire of the experiment performed. The change of shape can be one way or two ways [25].

2.3.2.1 Classification of Smart Materials

The 4D printing can be described as additive manufacturing along with dimension of time; this allows any function or shape to change with variation of time when subjected to some external stimulus for instance self-folding movement of a flat 4D printed sheet in such a way that converted in to a closed box when subjected to some stimuli. The other form of folding may be curling, spiral shape or bending at an angle.

Domain of components and various categories tangled in 4D printing [26] are shown and described as follows and shown in Fig. 2.3:

1. Technology of 3D printing: Fused filament fabrication (FFF), Direct ink write (DIW), Digital light processing (DLP), inkjet printing, SLS and SLA.
2. Stimuli for 4D printing: thermal stimuli, photo stimulus, water stimulus, chemical (Chemo) stimulus, and stimulation by magnetic field exposure.
3. 4D printing material system: single active SMP, liquid crystal elastomer, single or composite hydrogel, SMP composites, and other multifunctional materials.
4. 4D printing applications: Active origami, Active actuators, smart packaging, Meta materials, tissue engineering and biomedicine.

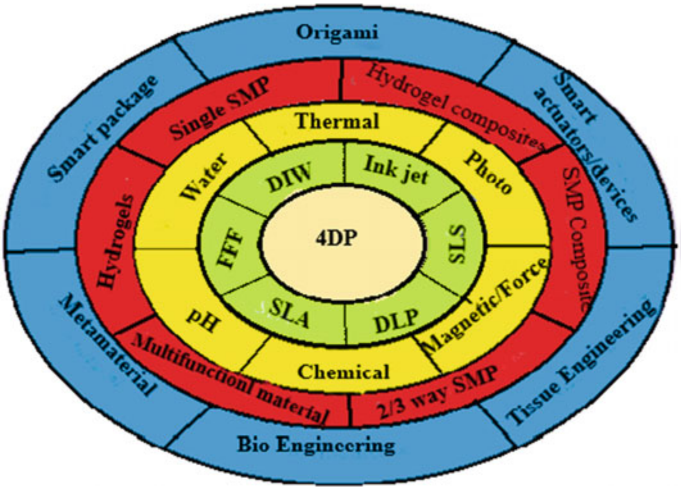

Fig. 2.3 Classification structure of smart materials [27]

Piezoelectric materials are such materials which generate a voltage whenever any stress is incorporated on them. This is a reversible process, hence when a voltage is passed across any sample; it will generate stress inside the sample itself. Appropriately structures made from these materials hence can be used for bending, expansion or contraction when any such voltage is incorporated [28].

Thermo-responsive materials are such materials that can withstand several shapes at different temperatures. They can change their shape form and gain back the original shape on application of heat. In this process, they generate a force actuating in nature. Shape memory alloys, for instance nitinol, which is a mixture of titanium and nickel that bears resistance against corrosion similar to that of stainless steel, makes it a perfect material for biochemical products [29].

Magneto-restrictive materials closely related to piezoelectric, have their response restricted to only magnetic field instead of electric field. These materials are basically utilized in low frequency, sonar transducers that have high power, actuators comprising hydraulics and motor, in addition with SMA Nitinol. Limiting magneto materials are promising materials in order to get active damping vibrations [30].

PH-sensitive materials are such materials which alter their color due to change in the acidity. This type of materials can be utilized in paints which can alter the color to depict corrosion in any metal component beneath [31].

Electro-chromic materials are able to change their color when any voltage is applied. A basic example of such material is the Liquid crystal display, materials which are photochromic, that alter their color in response to source of light. There are several paints which are thermochromics and photochromic, and they change their color when heat is applied or light is exposed on them [28].

Polymer gels, a typical example is hydrogel, which have cross linked structure of polymers bloated with solvent medium for instance water. The gel is capable of expansion as well as shrinking (~1000 times) by little variation in temperature or pH [32].

2.4 4D Printing

The concept of 4D printing is to print real life products as similar to additive manufacturing but using smart materials such as SMPs or SMAs as printing materials [33]. As discussed earlier, smart materials can respond to specific stimuli when provided such as light source, thermal variation, moisture etc. The concept is simple and aims to print such prototypes that can alter their shapes and size with respect to time as desired by the user. Shape shifting materials are such examples of 4D printing [34].

2.4.1 Classification of 4D Printing Based on Printing Methods

2.4.1.1 SLA (Stereolithography)

The Stereolithography (SLA) principle is based on process of photo-polymerization that allows the transformation of monomers of liquid/ oligomer to a solid polymer, basically by utilizing ultra violet rays, the radiation triggers the photo-initiator in the mixture that activates the reaction of polymerization in those respective areas directly [35]. This high-end technology uses laser techniques in the treatment of layer-above-layer comprising resins of photopolymer. Ultimately, the process of direct digital manufacturing (DDM) is incorporated which generates components directly from the CAD file [17]. Zolfagharian et al. [36] worked on patterns of self-assembling actuators printed by 4D printing method using the method of SLA. The shape memory polymer used in the work can bend itself from a remote distance when exposed to ultra violet lights. The heats from the UV rays were responsible for bending the product as hydrogel inks were used for absorbing the heat.

Chong et al. [37] used cross linked poly lactic acid ink and utilized 4D printing technique in producing flexible electronic circuits by the method of SLA. He used iron oxide as Nano particles in the ink for better stimulus results under UV lights. He created several small 3D components that can be used in soft robotics, electronics etc.

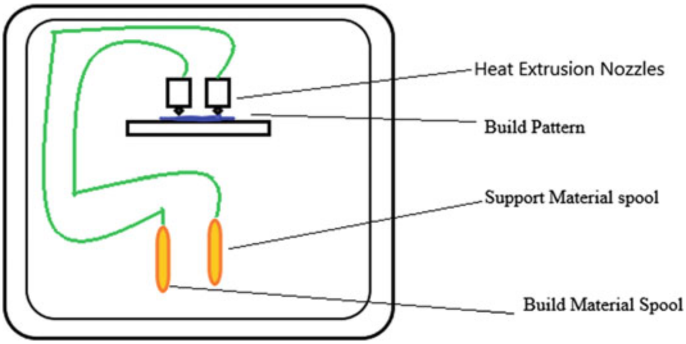

Fig. 2.4 Process of FDM method [43]

2.4.1.2 FDM Printing

In the present days, the maximum printing done in 4D is carried out by Polyjet 3D systems which enables photopolymers through UV rays, hence can transmit a uniform and glossy surface and material properties of several types [38]. Although, the system needs costly investment at beginning and maintenance periodically, in comparison with FDM systems. Particularly the, trays in built and the nozzle of extrusion ought to be replaced for the system of FDM nevertheless the overall expense is less compared to the polyjet system print heads [39].

In the process of FDM printing (Fig. 2.4), the component is generated in layers by melting a thermoplastic material which is diffused on the printer bed through a nozzle with lesser diameter. The component can be made from any CAD model in STL file format. The filament is generally in between 1.75 and 3.0 mm [40].

Kollamaram et al. [41] worked on FDM printing technique on low temperature deposition in 3D printing of thermolabile drugs. Attempts were made to print a low melting and thermolabile drugs by degrading the temperature of FDM process. Two materials such as Kollidon VA64 and Kollidon 12PF were studied in the research. He found that due to heating the drug degrades gradually.

Kür and Eren [42] worked on FDM type 3D printing in creating 3D parts from ABS material to be used for electrical devices and few mechanical devices. The author used multi walled carbon nanotubes for fused deposition so that the final product obtained becomes electronically active.

2.4.1.3 Inkjet Printing

Free Nano-printing (FNP) was the first technique to incorporate inkjet printing for 4D printing method. The process of FNP gives big opportunity to obtain high specific energy since the loading of material is increased with respect to particular surface area and more specific power since the porous structure is hierarchical simultaneously. In this method (as shown in Fig. 2.5) the droplets of GO comprised of several

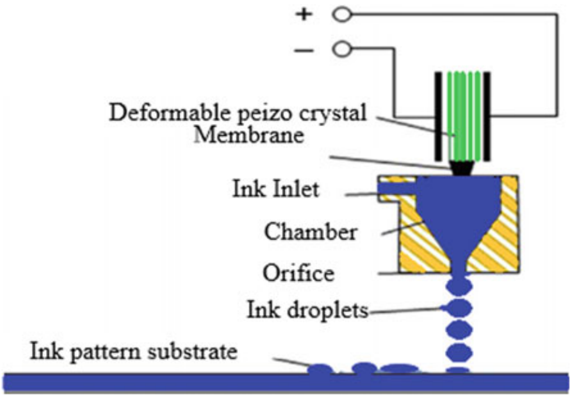

Fig. 2.5 Process of Inkjet printing [46]

concentrations were frosted to solid form rapidly by putting them on a cold substrate that had the temperature of −25 °C [44]. The ink in pure aqueous form used for printing eliminates the requirement for unwanted fillers since only moisture was utilized as the GO dispersant. The resourceful dispersion of inkjet freeze printing along with technique of freeze casting allows a uniform comfortable recognition of complicated 3D shapes and structured aerogels [45].

2.4.1.4 Selective Laser Melting (SLM)

The SLM is a method of additive manufacturing also termed as 3D printing that includes complicated and working components generated by consecutive layers of melting power material with help of a beam of laser [47]. This method is broadly utilized in NiTi (nickel titanium which is a shape memory alloy as material. since the NiTi material has very broad application, they are progressively developed either in form of bulk or porous form material by the means of modern process of manufacturing such as SLM.

The process of SLM includes the technique of 3D printing that is comprised of complicated 3D geometries produced by melting and then solidifying the material in several adjoined layers over one another. The complicated structures and free hand fabrication is provided by SLM which is a great chance to develop and grow further to next level in implementing the NiTi alloys to very complex components (for instance medical sector, devices used in surgery or bone implants, actuators etc.) [48, 49].

Dabiri et al. [50] aimed to research in the fatigue characteristics of several types and grades of steel manufactured through selective laser melting technique. The study included parameters such as surface quality, building orientation, heat treatment, energy density and service condition of the end product. Zheng et al. [51] studied and found that due to heating in the selective laser melting process products made from material alumina ceramics develop cracks. Hence, attempts were made to develop specimen materials from (Al_2O_3) by SLM technique so as to overcome the cracking of ceramics.

2.4.2 *Classification Based on Types of Stimulus Material Used in 4D Printing*

2.4.2.1 Variation of Temperature as Stimuli

Thermoplastics can be induced by the application of heat as stimuli. In fact, heat is utilized or variation in temperature to incorporate shape memory self-healing and self-assembly in response stimuli in thermoplastics [52]. Solicitation of a stimulus like heat then enables reoccurrence to the enduring shape, which is “stored” by the means of covalent bonds. Self-healing materials are capable of restoring degraded functionality, often in the form of structural damage to the bulk material [32].

2.4.2.2 Impact of Water Used for Stimuli

The recovery of shape from deformation comprising shape memory polymers can be agitated by presence of water since the effect of plasticizing in the molecules of water, which elevates the workability of chains of macromolecules. If any smart material is hydrophilic or soluble in water, the recovery of shape might be triggered [53]. The water effect on such smart materials is in the manner to implement expansion or shrinking of the product on addition of water. This feature is characterized by water molecules which actuate the smart material to deform or reform its shape [54]. Hydrogel is one of the moisture or water responsive smart materials.

2.4.2.3 Impact of Magnetic Field in Reshaping and Shaping of SMPs

The working principle of Magnetic Shape Memory Alloy (MSMA) is somewhat similar to the functioning of shape memory alloys as it responds when subjected to magnetic field. The mode of working allows increasing significantly the dynamical bandwidth of the device since instead of a thermo-mechanical it uses a magneto-mechanical energy conversion process [55]. The MSMA material have the characteristics to reshape themselves when they are exposed to any magnetic field. The source can be from electromagnets as well. Ni–Mn–Ga is one such material which belongs to MSMA [56].

2.4.3 Advantages and Applications of 4D Printing

Several sectors and areas such as engineering, medical, aerospace, electronic devices, artificial tissues or organs etc. (more mentioned in Fig. 2.6) can be benefitted with the 4D printing technology. Here are few of them listed below:

1. **In medical field**: the implants produced by the 4D printing method are directly implemented in the body of the patient. This enables in easy operation and makes is more trustworthy and reliable [57].
2. **In aircrafts**: one such instance is the utilization of fiber epoxy resin of carbon which gives reduction in weight by 40% when compared to that of aluminum. The creators of Airbus A380 utilize approximately 25% of their parts of the aircraft completely made out of 4D printing technique, where as Boeing 787 uses almost 50% of the parts from 4D printing [58].
3. **In mechanical field**: A new example using for design and manufacture of turbines blades of wind turbine has been demonstrated using 4D printing process. The blades of wind turbine are made from 4D printing as they are more flexible and can withstand maximum wind load without failure. 4D printed paradigms avoid the bend test coupling BTC of the blades, hence preventing it from getting damaged [59].
4. **In automobile sectors**: In the recent years the technique of 4D printing is utilized in automotive sectors such as making spring suspensions of vehicles specially leaf springs. The smart material enables to get the required curvature among the leaves using 4D printing [60].
5. **In electrical field**: automated assembly or substances which are programmed structurally are flourishing and their usage in the field of electrical field is growing such as in robotics, PV, antenna and measuring instruments etc. The geometries having the ability to alter them reverse have large usability in sector of soft robotics. In the electronics field, the solvent ink is utilized for printing in 3D and a transformed product is assumed to be obtained. Here, the 4D printing

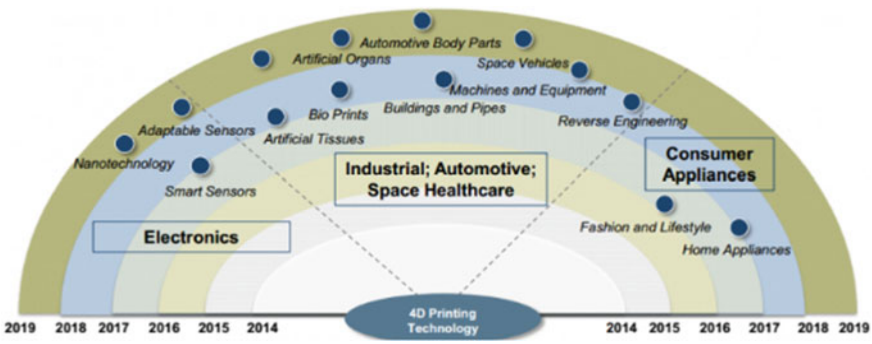

Fig. 2.6 Application of 4D printing technology: a forecast (www.machinedesign.com)

has excellent application since it has negligence of droplet spreading and can print non uniform as well as varying thickness products [61].

2.4.4 Scope of 4D Printing and Application and Advantage in General

1. Environment responsive home appliances and product with improved comfort and features [54].
2. Shoes which can transform themselves according to the use required [9].
3. Buildings that could assemble and disassemble themselves [9].
4. Printing bio components that can be implanted to human body [62].
5. In aeroplane wings that responsive to the flow of air for better lift [58].
6. Alternative to Smart valves and sensors used in pipe showing response to pressure flow [28].

2.5 Conclusion and Future Scope

As 3D printing continues to grow in its applications and evolve high quality materials at large scales, it is sure that this new concept of 4D printing would provide many ingenious ways in creating highly functional and complex surfaces. In intelligent material structure 4D printing has vast scope of involvement as environment sensitive house and structures are in their development phase. However, research and development of 4D printing with different aspects will definitely have impact on traditional additive manufacturing applications. Several types of 4D printing techniques including use of various smart materials and type of response stimulus has been discussed in the paper. We can say that still 4D printing is in its nascent phase and need to be work more to explore its full strength. In the near future, with 4D printing technology we will be able to provide substitute to intelligent material structures integrated with drivers and sensors assembled using traditional methods. The majority of use of this technology is in medical field such as making artificial tissues, organs, implants etc. However, in technical sector, especially in mechanical field, the concept of 4D printing is utilized mostly in the automotive industries. In machine industries it still remains a big challenge to implement products made based on 4D concept of printing and using them in workshops or industries.

References

1. Qiu, C.: Helical Kirigami-enabled centimeter-scale worm robot with shape-memory-alloy linear actuators. J. Mech. Robot. **7**, 1–10 (2015)
2. Kwok, T., Wang, C.C.L., Deng, D., Zhang, Y., Chen, Y.: 4D printing for freeform surfaces: design optimization of origami and Kirigami structures, no. 213 (2017)
3. Jiang, R., Kleer, R., Jiang, R., Kleer, R., Piller, F.T.: Predicting the future of additive manufacturing: a delphi study on economic and societal implications of 3D printing for 2030 Technological Forecasting & Social Change Predicting the future of additive manufacturing: a Delphi

study on economic and societal implications of 3D printing for 2030. Technol. Forecast. Soc. Chang. (2017)
4. Jackiewicz, J.: Manufacturing of instructional aids for students at low cost by means of 3D printing. Mater. Manuf. Processes **32**(10), 1116–1130 (2017). https://doi.org/10.1080/10426914.2016.1257135
5. Sun, M.G., Rojdamrongratana, D., Rosenblatt, M.I., Aakalu, V.K., Yu, C.Q.: 3D printing for low cost, rapid prototyping of eyelid crutches. Orbit (2018). https://doi.org/10.1080/01676830.2018.1445760
6. Chung, S., Song, S.E., Cho, Y.T.: Effective software solutions for 4D printing: a review and proposal. Int. J. Precis. Eng. Manuf. Green Tech. **4**(3), 359–371 (2017)
7. Ahn, S., Montero, M., Wright, P.K.: Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyp. J. (2012)
8. Le Duigou, A., Castro, M., Bevan, R., Martin, N.: 3D printing of wood fibre biocomposites: from mechanical to actuation functionality. JMADE **96**, 106–114 (2016)
9. Mpofu, T.P., Mawere, C., Mukosera, M.: The impact and application of 3D printing technology, June 2014 (2016)
10. Lara-prieto, V., Bravo-quirino, E., Rivera-campa, M.Á., Enrique, J.: An innovative self-learning approach to 3D printing using multimedia and augmented reality on mobile devices. Procedia Procedia Comput. Sci. **75**(81), 59–65 (2015)
11. Pei, E., Hsiang, G.: Technological considerations for 4D printing: an overview. Prog. Addit. Manuf. (2018)
12. Birbara, N.S., Otton, J.M., Pather, N.: 3D modelling and printing technology to produce patient-specific 3D models. Hear. Lung Circ. **28**(2), 302–313 (2019)
13. Tahalyani, J., Khanale, M., Kandasubramanian, B.: Dielectric polymeric compositions for improved electrical properties of flexible electronics. Elsevier Inc. (2018)
14. Yang, W., Jian, R.: Research on intelligent manufacturing of 3d printing/copying of polymer. Adv. Ind. Eng. Polym. Res. (2019)
15. Jasveer, S., Jianbin, X.: Comparison of different types of 3D printing technologies. Int. J. Sci. Res. Publ. (IJSRP) **8**(4), 1–9 (2018)
16. Bailey, C., Stoyanov, S., Tilford, T., Tourloukis, G.: 3D-Printing And Electronic Packaging (2014)
17. Attaran, M.: The rise of 3-D printing: the advantages of additive manufacturing over traditional manufacturing. Bus. Horiz. (2017)
18. Jiménez, M., Romero, L., Dom, I.A., Dom, M.: Additive manufacturing technologies: an overview about 3D printing methods and future prospects, vol. 2019 (2019)
19. Lv, P., Wang, C.C.: CR (2017)
20. Uto, K., Deforest, C.A., Kim, D.: 5.2—Soft Shape-Memory Materials. Elsevier Inc. (2016)
21. Wang, C.C., Huang, W.M., Ding, Z., Zhao, Y., Purnawali, H.: Cooling- /water-responsive shape memory hybrids. Compos. Sci. Technol. **72**(10), 1178–1182 (2012)
22. Yao, Y., et al.: Fabrication and characterization of auxetic shape memory composite foams. Compos. Part B **152**(May), 1–7 (2018)
23. Zhao, J., Li, J., Li, Y., You, J.: Thermoplastic shape memory composites with enhanced recovery stress and recovery ratio based on double roles of PVAc-g-GO. Compos. Commun. **13**, 52–56 (2019)
24. Drossel, W., Meinel, F., Bucht, A., Kunze, H., Giebichenstein, B.: The field of smart materials Smart materials for smart production—a cross-disciplinary Costing models for capacity optimization in Industry 4. 0: trade-off between used capacity and operational efficiency. Procedia Manuf. **21**, 197–204 (2018)
25. Wu, D., Xie, X., Kadi, A.A., Zhang, Y.: SC. Chinese Chem. Lett. (2018)
26. Khare, V., Sonkaria, S., Lee, G., Ahn, S., Chu, W.: From 3D to 4D printing—design, material and fabrication for multi-functional multi-materials (2017)
27. Kuang, X., et al.; Advances in 4D printing: materials and applications (2018)
28. Kamila, S.: Introduction, classification and applications of smart materials : an overview, Feb 2015

29. Briseño, S., et al.: Materialia NiTi shape memory alloy helixes through the hydriding—dehydring method. Materialia **5**, 13–15 (2019)
30. Rastogi, P., Kandasubramanian, B.: Breakthrough in the printing tactics for stimuli-responsive materials: 4D printing. Chem. Eng. J. (2019)
31. Nadgorny, M., Xiao, Z., Chen, C., Connal, L.A.: Three-dimensional printing of pH-responsive and functional polymers on an affordable desktop printer (2016)
32. Bekas, D.G., Tsirka, K., Baltzis, D., Paipetis, A.S.: Self-healing materials: a review of advances in materials, evaluation, characterization and monitoring techniques. Compos. Part B **87**, 92–119 (2016)
33. Mao, Y., et al.: 3D printed reversible shape changing components with stimuli responsive materials. Nat. Publ. Gr. 1–13 (2016)
34. Gladman, A.S., Matsumoto, E.A., Nuzzo, R.G., Mahadevan, L., Lewis, J.A.: Biomimetic 4D printing, vol. 15, Apr 2016
35. Mauricio, A., Rodriguez-hernandez, J.: Polymers for additive manufacturing and 4D-printing: materials, methodologies, and biomedical applications. Prog. Polym. Sci. (2019)
36. Zolfagharian, A., Kaynak, A., Khoo, S.Y., Kouzani, A.: Pattern-driven 4D printing sensors and actuators A: physical pattern-driven 4D printing. Sens. Actuat. A. Phys. **274**, 231–243 (2018)
37. Chong, S., Pan, G., Chin, J., Show, P.L.: Integration of 3D printing and Industry 4.0 into engineering teaching
38. Kollamaram, G., Croker, D.M., Walker, G.M., Goyanes, A., Basit, A.W., Gaisford, S.: Low temperature fused deposition modeling (FDM) 3D printing of thermolabile drugs. ScienceDirect **7**(5), 41–43 (2016)
39. Ly, S.T., Kim, J.Y.: 4D printing—fused deposition modeling printing with thermal-responsive shape memory polymers. Int. J. Precis. Eng. Manuf. Green Tech. **4**(3), 267–272 (2017)
40. Singh, R., Kumar, R., Farina, I., Colangelo, F., Feo, L., Fraternali, F.: Multi-material additive manufacturing of sustainable innovative materials and structures, pp. 1–14 (20190
41. Kollamaram, G., Croker, D.M., Walker, G.M., Goyanes, A., Basit, A.W., Gaisford, S.: Low temperature fused deposition modeling (FDM) 3D printing of thermolabile drugs. Int. J. Pharm. (2016)
42. Kür, H., Eren, O.: FDM 3D printing of MWCNT reinforced ABS nano-composite parts with enhanced mechanical and electrical properties, 37, July 2018, pp. 339–347 (2019)
43. Stratasys.com: FDM and PolyJet 3D printing a global leader in applied additive technology solutions FDM and PolyJet 3D printing (2017)
44. Khoo, Z.X., et al.: 3D printing of smart materials: a review on recent progresses in 4D printing, July 2015
45. Zhang, F., Wei, M., Viswanathan, V.V., Swart, B., Shao, Y.: Nano Energy 3D printing technologies for electrochemical energy storage. Nano Energy **40**(May), 418–431 (2017)
46. Killard, A.J.: 4—Screen printing and other scalable point of care (POC) biosensor processing technologies. Elsevier Ltd. (2017)
47. Van Humbeeck, J.: additive manufacturing of shape memory alloys. Shape Mem. Superelasticity **4**(2), 309–312 (2018)
48. Dadbakhsh, S., Vrancken, B., Kruth, J., Luyten, J., Van Humbeeck, J.: Materials science & engineering a texture and anisotropy in selective laser melting of NiTi alloy. Mater. Sci. Eng. A **650**, 225–232 (2016)
49. Petrovskaya, T.S., Toropkov, N.E., Mironov, E.G., Azarmi, F.: 3D printed biocompatible polylactide-hydroxyapatite based material for bone implants. Mater. Manuf. Processes **33**(16), 1899–1904 (2018). https://doi.org/10.1080/10426914.2018.1476764
50. Afkhami, S., Dabiri, M., Alavi, S.H., Björk, T., Salminen, A.: Fatigue characteristics of steels manufactured by selective laser melting. Int. J. Fatigue **122**, Dec 2018, 72–83 (2019)
51. Zheng, Y., Zhang, K., Liu, T.T., Liao, W.H., Zhang, C.D., Shao, H.: Cracks of alumina ceramics by selective laser melting. Ceram. Int. **45**(1), 175–184 (2019)
52. Lee, C., Boydston, A.J., Nelson, A.: SC. Prog. Polym. Sci. (2019)
53. Hu, J., Meng, H., Li, G., Ibekwe, S.I.: A review of stimuli-responsive polymers for smart textile applications, May 2012

54. Huang, W.M., Yang, B., Zhao, Y., Ding, Z.: Thermo-moisture responsive polyurethane shape-memory polymer and composites: a review, pp. 3367–3381 (2010)
55. Hubert, A., Calchand, N., Le Gorrec, Y., Gauthier, J.: Magnetic shape memory alloys as smart materials for micro-positioning devices. HAL Id: hal-00720674, Aug 2012
56. A.I. Pristupag, Magnetic-field-sensitive polymer composite materials, vol. 409 (2014)
57. Javaid, M., Haleem, A.: SC. Clin. Epidemiol. Glob. Heal. (2018)
58. Ntouanoglou, K., Stavropoulos, P., Mourtzis, D.: 4D printing prospects for the aerospace industry: a critical review Mourtzis review 4D Printing Prospects for the Aerospace a critical Costing models for capacity optimization in Industry 4. 0: Trade-off between used capacity and operational efficiency. Procedia Manuf. **18**, 120–129 (2018)
59. Momeni, F., Sabzpoushan, S., Valizadeh, R.: Plant leaf-mimetic smart wind turbine blades by 4D printing. Renew. Energy **130**, 329–351 (2019)
60. S. Van Hoa; Development of composite springs using 4D printing method. Compos. Struct. (2018)
61. Mohanta, K.: 4D printing—will it be a game-changer?, pp. 3–5 (2018)
62. Zarek, M., Mansour, N., Shapira, S., Cohn, D.: 4D printing of shape memory-based personalized endoluminal medical devices, vol. 201600628, pp. 1–6 (2016)