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A Review on 4D Printing Technology

Dr Nitin. Kamble[1], Akshay S Jadhav[2]
[1]HOD Department of production engineering, DYPCOE Akurdi, Pune
[2]Department of production Engineering, DYPCOE Akurdi, Pune

Abstract: 3D Printing has been recognized as a disruptive technology for future advanced manufacturing system. With a great potential to change everything from our daily lives to the global economy, significant advances in 3D printing technology have been made with respect to materials, printers and processes. In this context ,although similar to 3D Printing technology,4D printing technology adds the fourth dimension of time.4D printing allows a printed structure to change its form or function in time and response to stimuli such as pressure , temperature, wind, water and light. recently, rapid advances in printing process and materials development for 3D printing have allowed the printing of smart materials or multi-materials designed to change function or shape. The basic principle of 4D printing with multi material structure is to create precisely controlled localized internal stress with in a printed construct, which upon subsequent stress release can undergo further 3D shape shifting in a predictable manner In this review, we look into the main factors composing 4D printing technology such as smart materials and design. Finally we summarize the current and future applications of 4D printing.
Keywords: 4D Printing; smart materials; stimuli

I. INTRODUCTION

As printing is no more just about ink and paper, printing technology has surpassed its traditional paper and ink process to three dimensional (3D) process and furthermore, four dimensional printing technology (4D). We all are very much familiar with two dimensional printing i.e. printing pages from normal printer at home or office. This thesis is more focused on 3d printing and 4d printing technology.With the history dated back to late 1980's, 3D printing technology has brought revolu-tionary changes in field of manufacturing systems (Industry 3. , 2016). Like any other technological revolution, 3D printing technology is the ultimate product of vision, action and dedication of engineers who are brave enough to transform their vison make it hap-pen. But as the advanced and rapid development in printing technology has taken itself to next level, 3D printing has allowed the printing of smart materials designed to change shape and function, so called 4D printing technology. With a great potential to transform everything from our daily lives, it has become disruptive technology for future advanced manufacturing systems.

A. History

The earlier version of 3D printing technology dates back to late 1980's. During those time it was known as Rapid Prototyping rather than 3D printing. Charles (Chuck) hull invented first Stereolithography apparatus (SLA) machine in 1983 and currently he is cofounder of one of the largest company working in 3D printing sector, 3D Systems Corporation . Though the patent of rapid prototyping was ob-tained by him, In May 1980, Dr Hideo Kodama of Nagoya Municipal Industrial Research Institute of Japan filed the very first patent application for Rapid Prototyping which was unsuccessful. Stereolithography is a technique of creating three-dimensional objects with a computer controlled moving laser beam layer by layer from liquid polymer that hardens with the exposed laser beam. Stereolithography technique was ground breaking development towards prototyping be-cause of fast and more cost effective way. 3D Systems later introduced SLA-1 in 1987 which was first commercial Rapid prototyping system. In 1987, Carl Deckard from University of Texas introduced Selective Laser Sintering (SLS) technology and issued a pa-tent in 1989, later acquired by 3D systems corporation. In 1989, Scot Crump, who is co-founder of Stratasys Inc. introduced a new technique called Fused Deposition Modelling (FDM) which is widely used nowadays for 3D print-ing. [17] Same year, EOS was founded in Germany. EOS pioneered in the field of Direct Metal Laser Sintering (DMLS) and provider of highly productive Additive Manufacturing Systems for plastic materials. (eos, 2016) Within 1990's to 2000, many 3D printing technologies were developed such as Ballistic Particle Manufacturing (BPM), Laminated Object Manufacturing (LOM), Solid Ground Curing (SGC) and Three Dimensional Printing (3DP). Most of technology were focused on research development of industrial manufacturing process.

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II. 4D PRINTING TECHNOLOGY

It has been more than 30 years since the first patent was issued for Stereo lithography Apparatus (SLA), invented by Charles (Chuck) Hall in 1980´s. Initially known as Rapid Prototyping technology, with further advancement now called additive manufacturing or 3D printing technology. (Industry 3. , 2014) Nowadays, 3D printing machine is used not just in industry for production but also in school, households and offices. As the price for normal desktop 3D printer has fallen below 1000 euro, affordable price allows unlimited opportunities for individual to print their own customized toys, household appliances and tools.However, there is always something more than can be done with the current ongoing technology. 3D printed materials can be more flexible and useful, the structures of the material can transform in a pre-programmed way in response to any external stimulus. In general, self-changing structure of 3D printed part after post process is called 4D printing process. [14]. The term 4D printing is developed in a collaboration between MIT´s Self-Assembly Lab and Stratasys education and R&D department. In February 2013, Skylar Tibbits, co-di-rector and founder of the Self-Assembly Lab located at MIT´s International Design Cen-ter, unveiled the technology “4D printing” during a talk at TED conference held in Long Beach, California. (TED, 2013) 4D technology is still in the early phase of research and development. This technology has been used only in few labs or prototyping facilities. In current scenario, one can´t just order and buy “4D printer”. As of 2017, MIT´s Self-As-sembly Lab, 3D printing manufacturer Stratasys and 3D software company Autodesk are the key players in the development of 4D printing technology.

III. SMART MATERIALS

Global competition among technological giants and demand for new generation of indus-trial, commercial, medical, automotive and aerospace applications has fueled research and studies focused on advanced materials and smart structures. Researchers are devel-oping ultimate materials which can be applied in multipurpose scientific and technologi-cal applications. Those smart materials or intelligent materials features fibrous polymeric composite materials capable of sensing external command in the form of heat, light, elec-tricity, magnet, water and many other agents. Diverse application and structures of smart materials will certainly revolutionize the current generation. Starting from wooden and stone materials from the Stone Age to copper followed by bronze and Iron Age, human mankind have developed a new age and we can call them Smart Material Age.[6]

Types	Input	Output
Piezoelectric	Mechanical stress	Potential difference
Electrostrictive	Electric field	Deformation
Magnetostrictive	Magnetic field	Deformation
Thermoelectric	Thermal energy	Deformation
Shape memory alloys	Thermal energ	Deformation
Photochromic	Radiation	Color change
Thermochromic	Thermal energy	Color change

Table 1. represents classification of smart materials along with the input force they require and output.

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A. *Piezoelectric Materials*

Those materials capable of generating electric charge in response to applied mechanical stress are piezoelectric materials. Not all the smart materials do exhibit a shape change but they do carry significant properties such as electro and magneto theological fluids. Those fluids can change viscosity upon application of external magnetic or electric field. Naturally occurring crystals like quartz and sucrose, human bone, ceramics, Polyvinyli-dene fluoride (PVDF) are known to have piezoelectric characteristics. Followed by the automotive industry and medical instruments, global demand for these materials have huge application in industrial and manufacturing sector. (Liverpool, 2016). Researchers from University of Warwick in UK have developed new microstereolithog-raphy (MSL) 3D printing technology that can be used to create piezoceramic object. Pie-zoceramics are special type of ceramic materials that can create electrical response and responds to external electrical stimulation by changing shape. These are very useful ma-terials and applicable all around, sensor in airbag systems, fuel injectors in engines, elec-tric cigarette lighter and electronic equipment.

B. *Light Responsive self-Changing Materials*

In order to continue with 4D printing process, it is really important to know about the smart materials and their behavior. The relationship between chemical composition of shape changing polymer and its physical properties such as thermal, mechanical, optical and electrical properties.To measure thermal and optical properties of polymer, processes like UV-Vis spectros-copy, differential scanning calorimetry, and polarizing light microscope are used. Using standard testing bar, stress/strain relationship and hardness measurement can be per-formed. As the main goal is to identify and study about shape changing behavior of ma-terial. Various external sources or energies are applied over the extruded object. Varying thermal energy, magnetic field, electricity, different levels of light intensity and exposing directly towards printed object changes the bending angle, speed, percentage volume con-traction, reversibility and mechanical output. Those measuring data helps to gain knowledge in developing 4D printing process.

C. *Shape Memory Polymers*

Shape memory alloy or polymers are emerging smart materials that have dual shape ca-pability. Shape memory alloys go transformation under predefined shape from one to another when exposed to appropriate stimulus. Initially founded on thermal induced dual-shape research, this concept has been extended to other activating process such as direct thermal actuation or indirect actuation. The applications can be found in various areas of our everyday life. Heat shrinkable tubes, intelligent medical parts, self-deployable part in spacecraft are few used area with potential in broad other applications.The process in shape memory polymer is not intrinsic, it requires combination of a polymer and programmed afterwards. The structure of polymer is deformed and put it into temporary shape. Whenever required, the polymer gains its final shape when external energy is applied. Most of the shape memory polymers required heat as activating agent

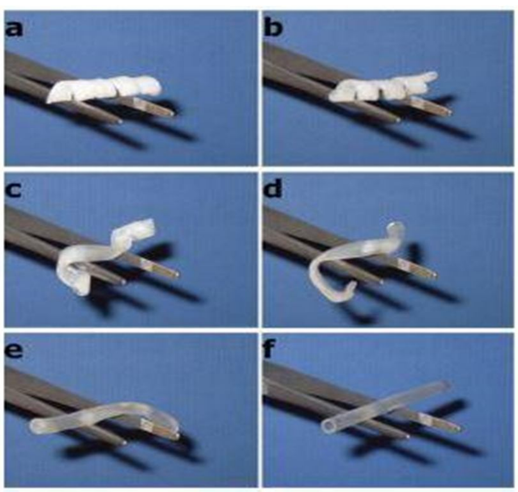

Fig 1 .Shows the time series of shape memory tube. The material used in tube is poly dimethacylate polymer. Initially the shape was programmed to form flat helix, using heat energy ranging from 10 degree to 50 degree centigrade, flat helix transformed into tube shape structure.

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D. Magnetostrictive Materials

Similar to piezoelectric and electrostrictive materials magnetostrictive materials uses magnetic energy. They convert magnetic energy into mechanical energy or other way. Iron, terbium, Naval Ordnance Laboratory (NOL) and dysprosium (D) are most common magnetostrictive materials. Those materials can be used as transducers and actuators where magnetic energy is used to cause shape change. The application include telephone receivers, oscillators, sonar scanning, hearing head, damping systems and positioning equipment. The development of magnetostrictive material alloys with better features will certainly help the 4D printing technology. [16].

IV. 4D PRINTING PROCESS

When Skyalar Tibbits introduced 4D printing technology in 2013, the demonstration of structure folded with only 90 degree transformation and activated when printed specimen was immersed in water. Similar researches were demonstrated with the composite printed materials stretching upon heat activation, light activated materials and electrically acti-vated materials. As the progress is still going on, there still more needed in universality in folding from one shape to another. Further improvement is needed to take control over autonomous transformation rather than human guided energy source A major challenge for 4D printing technology is design structure including both hardware section and software section. In order to design hardware part, special measures needs to be addressed. Since, this requires complex and advanced material programming, precise multi-material printing, designing complex joints for folding, expansion, contraction, curling, twisting process. Software section is even challenging that cooperates with hard-ware design. Sophisticated simulation, material optimization and topology transformation are few of the challenges for software part. Following explanation demonstrates structural transformation regarding its joint angle, folding, curling and bending..

A. Fabrication

As the printer deposits UV curable polymer and cures layer by layer using UV light thereby creating complete 3D structure, printers are capable of printing multiple compo-site materials with various properties such as color pattern, material hardness and trans-parency allowing creation of complex, multiple composite parts in single process. Digital materials can be printed with this process. The properties can be digitally adjusted and altered with the digital material. The combination of digital material with different pro-portion and spatial arrangements plays significant role providing additional flexibility. 4D printed parts are generally composed of rigid plastic and digital material that reacts upon external energy source. In case of hydrophilic UV curable polymer, when exposed to water, the structure absorbs and creates hydrogel with upto 150 percentage of original volume. The shape transformation of the structure is linear in this case, but when the polymer structure is combined with different composite material that reacts differently with water, complex geometric transformation occurs. Transformation can be controlled by adjusting pure expandable polymer with digital composite material as per requirement. [15].

B. Joint and Folding Angle Strands

For any bending or folding structure, joint plays important role as controlling of joints adjusts the desired shape of structure.

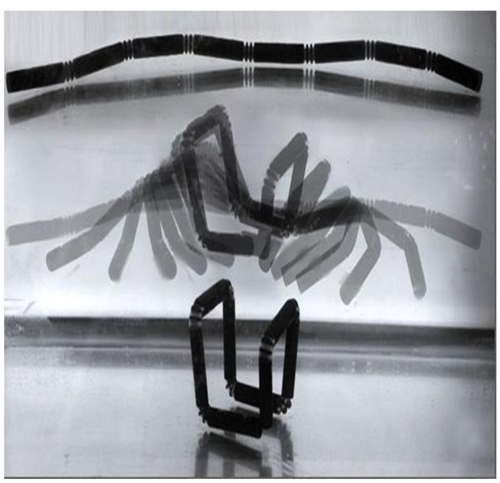

Fig 2 Self-Folding Strand

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Printing 4D joint includes multiple layers of material. Composition of rigid polymer, ex-panding material and digital material depicts the folding direction and pattern. Those ma-terials are placed above or below of each other depending upon the type of transformation If the expanding composite is placed above rigid polymer, the surface will fold down-wards and if placed below, the surface will fold upwards. This folding happens due to downward or upward force applied to rigid material. With the digital polymer composite, the control of folding the joints becomes much desirable. The time duration of folding depends upon the expandable material or digital material. If higher expanding composite is used, there will be more folding force increasing folding time. Similarly, less expanding composite will generate less folding force thereby decreasing folding time. The angle of folding can be controlled by printing rigid discs at each vertex. The distance between rigid disc and diameter of disc defines angular variation. Those discs bumps each other when expanding material is activated and stops folding at certain angle. The angle of folding is determined by the distance of rigid disc and its diameter. When the discs are placed fur-ther away from each another, angle of folding will increase and when discs are place close to each other, folding angle decreases. Also the increasing diameter of discs decreases the folding angle and vice versa. ([14])

C. Custom Angle Surfaces

In his research, Skyler Tibbits demonstrated custom angle transformation creating trun-cated octahedron shape. Similar mechanism as folding strand described previously, series of flat two dimensional structures were generated with edge joints. The position and spac-ing of materials at each joint specifies the desired fold angle hence positioned accord-ingly. In such case, folding accuracy can be monitored with the help of code producing custom angle joints and accommodation of date from calibration test. After the digital model was sent to be printed, physical model was immersed in water. The transformation process occurred within certain time with the final desired model having edges aligned perfectly aligned with neighboring edges. With this technique, a two dimensional poly-hedral shape was folded and self-transformed into precise three dimensional structure..[2]

Fig 3 Self-Folding Truncated Octahedron ([14])

The advantage of this process includes efficiencies of printing flat shape with quick print-ing time and minimal resources used. If the final model were to be printed directly, it would have taken longer time consuming more support materials. On the long run, this technology can be effective for logistics operation where flat surface material can be cre-ated, shipped and self-transformed into three dimensional structure when required.[13]

D. Curved Surface Folding

Curved surface folding mechanism is based upon a technique called curved-crease ori-gami, where two dimensional flat sheets are folded along curved creases forming double curved surface with mountain and valley shaped linear pattern. (Figuring, 2016) This mechanism can be further explained with the example of concentric circles made of ex-panding polymers separated by rigid or less expanding polymer. The position of expand-ing polymer above or below rigid polymer in each circle with the ring being neutral, cre-ates mountain and valley folds. When the design print is placed in water, after certain time period, the structure transforms itself from two dimensional crease to doubly curved structure. [13]

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Fig 4 Curved-Crease Origami ([14]

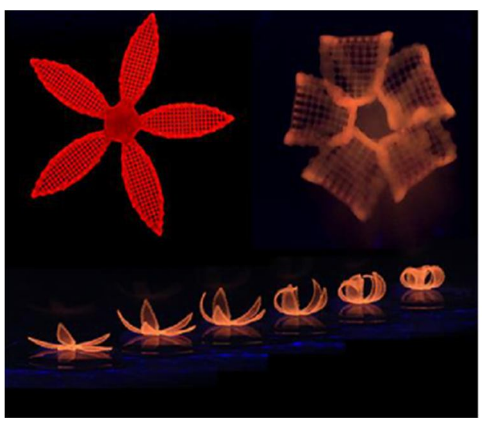
E. Surface Curling

Rather than joints, edger or curve crease folding, similar mechanism can be applied to perform surface curling. With the gradient of material deposition, continuous surface can be achieved. Instead of using expanding material only in the joints or folding section, larger expanding polymer can be used with thin surface in order to have even expansion force. The curling effect is much more visible with increasing length and breadth of sur-face. Placing expanding material over the top of rigid material gives curved surface with smaller radius towards the rigid surface, similarly placing expanding material below the rigid material results reverse effect. Since there are not any joints and discs for folding process, the quantity of the material distribution and positioning is extremely important for maximum precision. [2].

V. 4D PRINTING EXAMPLE: ORCHID TRANSFORMATION WHEN IMMERSED IN WA-TER

A team of scientists at Wyss Institute at Harvard University and the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) has developed their micro-scale three dimensional printing technology to create transformable structure. This method was inspired by natural structures like plants, which reacts and changes their be-havior over time according to external environmental stimuli such as water, heat and moisture. In order to process the technology, the team developed 4D printed hydrogel composite structure that changes its shape upon immersion in water as shown in Figure Newly developed hydrogel composite consists of cellulose fibrils derived from wood and their microstructure are similar to the plants that enables shape changes. In general, when the three dimensional composite structure is immersed in water, it swells into cer-tain pattern as programmed. (WYSS Institute, 2016).

Hydrogel cellulose fibril has anisotropic nature which means upon exposed to water, it undergoes different swelling behavior which can be predicted and controlled. To achieve transformable shapes, hydrogel composite needs to be programmed with precise and swelling behavior.



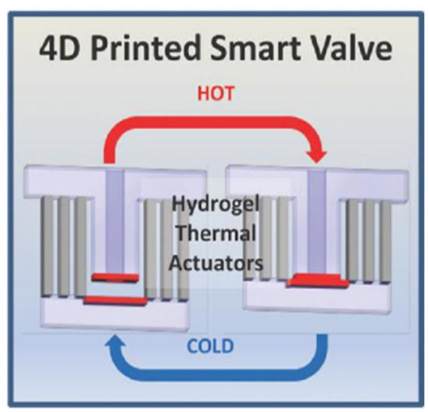


Fig 5 Transformation of 4D printed orchid and Smart Valve (WYSS Institute, 2016) (Shannon E. Bakarich, 2015)

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The composite material is liquid state matter that flows through print head and solidifies rapidly once it is printed. Different hydrogel components can be used to achieve different stimuli-responsive characteristics. Conductive fillers, cellulose fillers can be replaced with other anisotropic fillers. This advancement in 4D printing field enables shape changes from the available materials with potential application, establishing new platform for self-assembling structure. Similar printing technology has been unveiled by researchers at University of Wollon-gong, Australia. A 4D printed temperature responsive valve shown in figure 20 was de-signed by combining active hydrogels and three dimensional printing. The hydrogels[07] are made up of alginate and poly (N-isopropyl acrylamide), which are thermally sensitive and expand in volume when heated. This mechanically robust valve expands upon exposure to hot water, subsequently blocking the water flow and closes itself upon flow of cold water.

VI. APPLICATION AREA AND FUTURE DEVELOPMENT

4D printing technology has the potential to change the current business environment. Fu-ture advancement of this mechanism depends and remains focused on variety of capabil-ities. For example, current process that allows 4D printed structure to expand when ex-posed to water and when structure is allowed to dry, it tends to unfold and regain its original shape. However, when similar process is repeated again and again, the material degrades over time and process is not infinitely repeatable. To control directionality and reversibility process, further research and development need to be conducted. This devel-opment points towards changing future of education and science. With the study of exist-ing self-changing structures and models, new experiment with new material properties and functional behaviors can be tested.

The self-changing ability of material leads to range of applications in various industries. It is essential for any business to reduce manufacturing cost and increase profit to stay in fierce competitive environment. The concept of 4D printing technology along with 3D printing provides platform for new business ideas that can adapt and compete current market trend by lowering capital requirement, time efficient, less space for holding in-ventory and increasing efficiency of the business. 4D printing promotes maintaining sus-tainable environment as the self-transforming capability of 4D printed item allows after use disposition, changing back to original shape.

A. Medical Research

University of Michigan developed a 3D printed stint that gets absorbed into the body over time. For the patient with weak cartilage in walls of bronchial tubes, the stint was used to open airways for two or three years, which is enough time for bronchial cartilage to form back to the shape. This biomedical splint which was printed using 3D printing technology changes shape and conform over time as the body moves or grows. There has been suc-cessful implants of those 4D printed structure, which needs to be biocompatible with pa-tient’s immune system and able to adapt the external surrounding tissues within the body.

B. Aeronautics and Robotics

MIT Research Scientist Skylar Tibbits and Emerging Technology and Concept team from Airbus collaborated together to develop special air inlet component. This collaboration with Airbus developed new air inlet which adjusts automatically to control air flow which is used to cool the engine. As the current air ventilation inlets are static and air flow varies with speed of an airplane. (Group A. , 2016) A team of researchers at MIT and Harvard University developed origami robots, which is reconfigurable robots capable of folding themselves into arbitrary shapes and crawling away. The prototype robot was made up of printable parts entirely. (Hardesty, 2014)

C. Military Applications

Programmable matter will have a vast application areas in military sector. US army and Navy are developing three dimensional printed spare parts in the field and developing programmable elements that forms into full building with all the necessary components such as electricity, plumbing and other technical structures. . In 2013, US Army Research Office granted $855,000 to researchers at three universities, Harvard's School of Engineering and Applied Science, The University of Illinois and The University of Pittsburgh Swanson School of Engineering.

D. Furniture and House Appliances

People are much more familiar with IKEA furniture which comes in parts and packed. It takes lots of time and effort for normal customer to assemble and make ready. However, one could imagine the relief when those flat packaged furniture self assembles and the furniture is ready to use without any hassle.

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E. Fashion

The idea of clothes and trainers adjusting their shape and function in response to external environment and comforting the user, sounds fascinating. Fitting perfectly upon pressure being applied or gears becoming water proof itself when raining. Massachusetts based design studio Nervous System have developed 4D printed wearable which is composed of thousands of unique interlocking component and the dress responds to the wearer's body.[5]

VII. CONCLUSION

The actual technology resides upon existing contributions over the years. 3D printing technology has been around the field for more than 30 years. From Charles (Chuck) hull's first Stereolithography apparatus (SLA) machine in 1983 to Skylar Tibbits from the MIT self-assembly lab proves the consistent research and contribution on material processing technology over the years. (There has been vast developments in existing 3D printing process with multi-material printing capabili-ties. With the introduction of 4D printing, the technology will take over wide range of application such as home appliances and consumer goods that can adapt to heat and mois-ture for added comfort and functionality. Pre-programmed self-deforming materials in health care sector including biocompatible implants inside human body such as cardiac tubes will certainly bring revolution in medical research. The introduction of many new companies and competition, quality of the printing has improved surprisingly and price becoming cheaper. The result of priorities and personal choice are forcing developers to work much harder as there are lots of room for improvement. In coming years, it is most likely that those printers will become increasingly available with very low price

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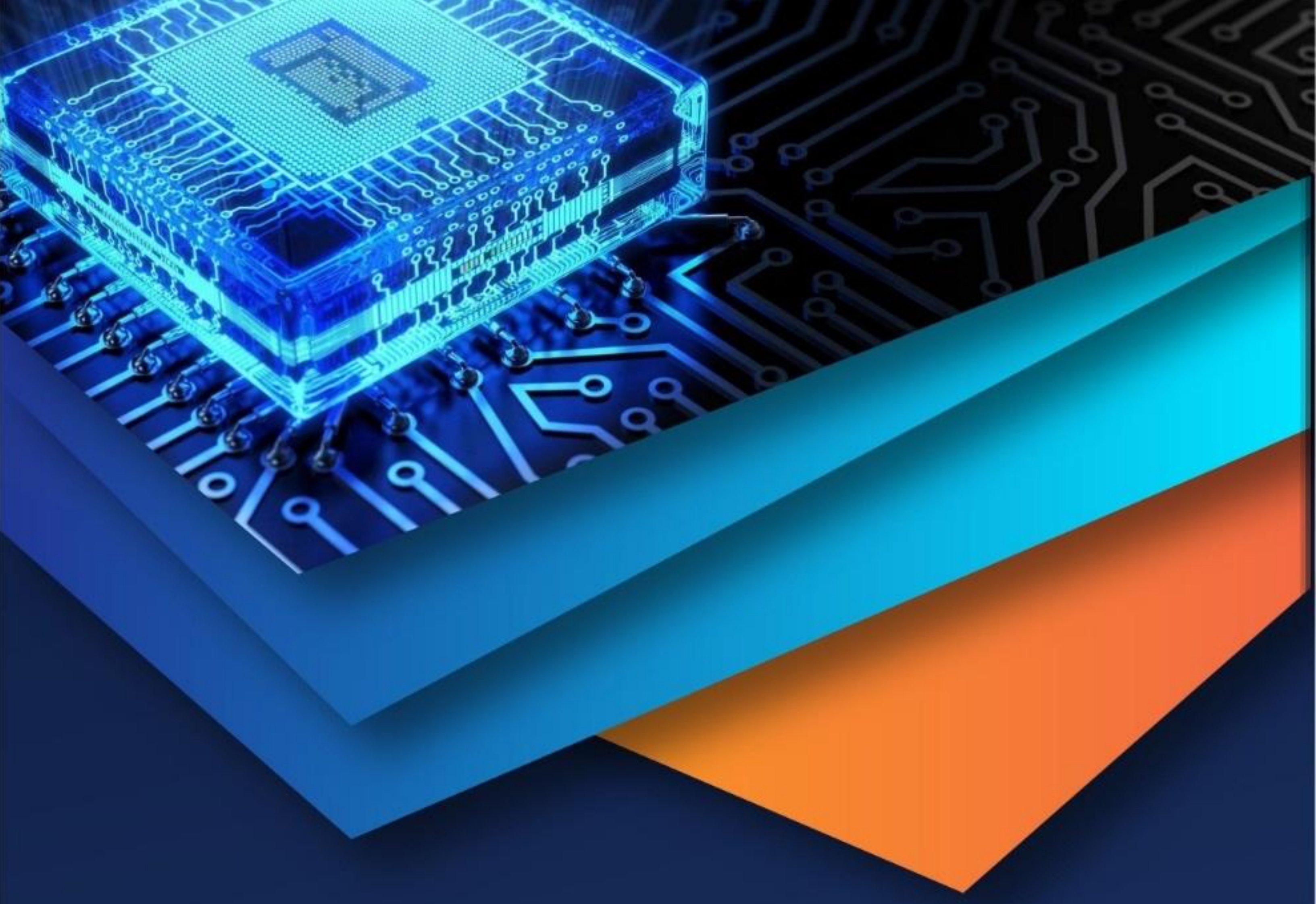

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