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ORIGINAL RESEARCH ARTICLE

Advancements in 3D printing materials: A comparative analysis of performance and applications

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ABSTRACT

3D printing has rapidly evolved and matured in recent years, with a key factor being the improvement in printing materials. This paper compares the performance and applications of various 3D printing materials, including plastics, metals, ceramics, and biomaterials. Plastics remain the most widely used material due to their low cost and ease of printing, while metals are gaining popularity due to their superior mechanical properties. However, recent advancements in ceramic and biomaterials have opened up new possibilities for 3D printing in industries such as aerospace, healthcare, and electronics. The comparative analysis provides insights into the strengths and limitations of each material, and how they can be optimized for specific applications. With continuous developments in 3D printing technology and materials, the potential for this technology to revolutionize manufacturing and other industries is promising.

Keywords: additive manufacturing; materials; advancements; printing techniques; material properties

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1. Introduction

Over the years, 3D printing has rapidly emerged as a revolutionary technology with endless possibilities. This technology, also known as additive manufacturing, works by creating a three-dimensional object layer by layer, based on a digital design. The key factor that sets 3D printing apart from traditional manufacturing methods is the wide range of materials that can be used to produce objects with different properties and characteristics. The continuous advancements in 3D printing materials have significantly contributed to the growth and diversification of applications, making it a gamechanging technology across industries[1–7]. One of the most significant benefits of 3D printing materials is their wide range of options. Unlike conventional manufacturing processes, which are often limited to specific materials, 3D printing offers a diverse range of materials that can be used for production. These include plastics, metals, ceramics, composites, and even biological materials[8–12]. Each material comes with its unique set of properties, enabling the production of complex and intricate designs that were previously impossible to create. The development of new materials for 3D printing has also led to significant advancements in the performance of printed objects. Traditional manufacturing methods are limited in their ability to produce complex shapes, but 3D printing can create objects with intricate geometries, precisely tailored to their desired function[13–16]. The field of 3D printing has seen exponential growth and rapid advancements in recent years. One of the key drivers of this development has been the continuous improvement in 3D printing materials. From the early days of 3D printing with simple plastic materials to the current use of advanced materials such as metal alloys and bio-compatible materials, the evolution of 3D printing materials has greatly expanded the range of applications of this technology. The construction diagram has shown in the following **Figure 1.**

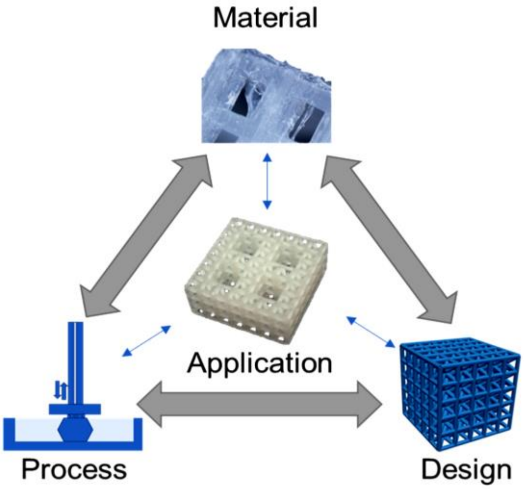

Figure 1. Construction diagram.

The design aspect of the image would also demonstrate how 3D printing allows for the creation of complex and customized designs that were previously impossible with traditional methods. The image could show a detailed and intricate design, such as a complex mesh structure or a layered pattern that has been successfully printed using advanced materials. The materials used in the printing process would also be featured in the image. This could include a variety of materials, such as thermoplastics, metals, ceramics, or biocompatible materials, depending on the focus of the comparative analysis. The image could highlight the different properties and characteristics of each material, such as strength, flexibility, durability, or biocompatibility. The application of 3D printing materials would also be conveyed through the construction image[17–21]. This could include various industries and fields where 3D printing is making significant advancements, such as aerospace, automotive, healthcare, or architecture. The image could show a specific application or use case of 3D printing, such as a customized medical device, a lightweight aircraft part, or a structural component for a building.

This essay aims to provide a comparative analysis of the performance and applications of some of the major innovations in 3D printing materials, namely, bio-compatible materials, metal alloys, and flexible materials. Bio-compatible materials have emerged as a significant innovation in 3D printing, revolutionizing the healthcare industry. These materials are biocompatible and can be used to directly print medical implants, such as dental prosthetics, orthopedic implants, and even human tissues and organs. One of the key bio-compatible materials used in 3D printing is polylactic acid (PLA), a biodegradable and non-toxic plastic derived from renewable resources. PLA has excellent layer adhesion, print resolution, and is easily moldable; making it ideal for creating complex and customized medical implants[22–25]. The key contribution of this article includes:

(1) **Increased Material Options:** One of the key contributions of advancements in 3D printing materials is the exponential increase in material options available. Initially, 3D printing was limited to a few materials such as PLA and ABS. However, with technological advancements, a wide range of materials including metals, ceramics, and composites can now be used in 3D printing.

(2) **Improved Performance:** Another major contribution of advancements in 3D printing materials is the improvement in performance. The newer materials are designed to have better mechanical properties, thermal resistance, and chemical resistance, making them suitable for a wider range of applications. This has opened up new possibilities for using 3D printing in industries such as aerospace, automotive, and healthcare.

(3) **Customization and Complexity:** 3D printing materials have also made it possible to create highly customized and complex designs that were not achievable with traditional manufacturing methods. This is due to the ability of 3D printers to print intricate geometries and structures, which was previously not possible. This has significantly impacted industries like biomedical and fashion, where customized products are in high demand.

2. Existing literatures

Over the past few decades, 3D printing has evolved from a concept to a technology with immense potential in various fields. The ability to create three-dimensional objects from digital models has revolutionized the manufacturing industry and has opened up a whole new world of possibilities. Traditional manufacturing methods have limitations, such as high costs, long lead times, and limited design flexibility. 3D printing materials offer a solution to these issues, as they are versatile, cost-effective, and can produce complex geometries with ease. However, as the demand for 3D printing continues to grow, the need for advancements in 3D printing materials becomes increasingly important. In this essay, we will explore some of the current issues surrounding 3D printing materials and compare the performance and applications of different materials. One of the main concerns with 3D printing materials is their limited range of materials. While traditional manufacturing methods have a vast selection of materials to choose from, 3D printing currently relies on a few materials, such as plastics, metals, and ceramics. This limited range of materials poses a challenge for industries that require specific properties, such as temperature resistance, biocompatibility, or strength[26,27]. The advancements in 3D printing technology have revolutionized the manufacturing industry and opened up new possibilities in various fields. However, the availability of different materials and their varying performance levels pose challenges for designers and manufacturers. In this essay, we will explore the problems associated with advancements in 3D printing materials and compare their performance and applications. One of the primary problems with 3D printing materials is their limited performance capabilities. Traditional manufacturing methods have a wide range of materials to choose from, each with specific properties and strengths. In contrast, 3D printing materials are limited in terms of strength, durability, and flexibility[28]. For example, most materials used in 3D printing, such as plastic and metal alloys, have lower strength and heat resistance compared to their counterparts in traditional manufacturing. This limitation restricts the use of 3D printing in certain applications that require high-performance materials, such as aerospace and medical industries. Moreover, the varying performance levels of 3D printing materials also create challenges for designers and manufacturers. Different materials have different properties and require different printing settings, making it challenging to predict and control the final product's quality. The novelty of this article includes:

(1) **Enhanced Material Properties:** One of the major advancements in 3D printing materials is the development of new materials with enhanced properties. For example, new composites have been developed that are stronger, more flexible, and more durable than traditional materials like plastic or metal. This allows for the production of complex and functional parts that were previously impossible to create with traditional manufacturing methods.

(2) **Improved Print Speed and Resolution:** With the introduction of new materials, 3D printing machines have become faster and capable of printing with higher resolution. This has opened up new possibilities for applications that require intricate details and precision, such as biomedical implants and aerospace components.

(3) **Biocompatible Materials:** The development of biocompatible materials has revolutionized the field of 3D printing in medicine and healthcare. These materials can be safely implanted in the human body without causing any harm, making it possible to create custom-fit implants and prosthetics.

(4) **Sustainable and Recyclable Materials:** In recent years, there has been a push towards using sustainable and eco-friendly materials in 3D printing. This has led to the development of bio-based and recyclable materials that reduce waste and carbon footprint, making 3D printing a more environmentally friendly manufacturing option.

3. Proposed model

3.1. Construction detail

The construction of advancements in 3D printing materials involves the development and improvement of materials used in the 3D printing process. Traditional 3D printing materials such as plastic and metal powders have been widely used, but recent advancements have introduced new materials with improved properties and performance. One key area of advancement in 3D printing materials is in the development of polymers. Traditional polymers used in 3D printing, such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), have limitations in terms of strength, flexibility, and heat resistance. New materials, such as polyether ether ketone (PEEK) and polyetherimide (PEI), have been developed to address these limitations[29–31]. These polymers have better mechanical properties, can withstand higher temperatures, and are more resistant to chemicals, making them suitable for a wider range of applications. Another area of advancement is in the development of metal 3D printing materials. While metal powders have been used in 3D printing for some time, recent advancements have focused on improving the properties of these materials. With the use of new alloys and processes, it is now possible to print parts with higher strength, better surface finish, and improved corrosion.

3.2. Implementation part

Advancements in 3D printing materials have revolutionized the capabilities and applications of additive manufacturing. With the development of new materials and techniques, 3D printing has become more versatile, efficient, and cost-effective. This comparative analysis will provide an overview of the different types of materials used in 3D printing, their properties, and their applications. 1) Plastics: Plastics are the most commonly used materials in 3D printing. They are affordable, lightweight, and have high strength-to-weight ratio. One of the most popular 3D printing plastics is ABS (acrylonitrile-butadiene-styrene), which is widely used in consumer products, automotive parts, and electronics. Other popular plastics used in 3D printing include PLA (polylactic acid), PET (polyethylene terephthalate), and nylon. Advancements in plastic-based 3D printing materials have resulted in increased strength and durability, as well as improved flexibility and resistance to high temperatures. 2) Metals: In recent years, there has been significant development in 3D printing with metal materials. These materials have high strength and durability, making them suitable for applications such as aerospace, medical, and automotive industries. The most commonly used metal materials in 3D printing are stainless steel, titanium, aluminum, and cobalt-chrome alloys. Advancements in metal 3D printing have led to the production of more complex and detailed parts, with precision and accuracy. 3) Ceramics: 3D printing with ceramics has gained popularity in industries such as healthcare, aerospace, and electronics. Ceramics are known for their high strength, heat resistance, and biocompatibility, making them suitable for applications in the medical field. However, the main challenge with 3D printing ceramics is their brittleness. Recent advancements in ceramic-based 3D printing materials have focused on improving the strength and durability of ceramic parts, as well as increasing their design flexibility. 4) Composites: Composites are a combination of two or more material types, such as metal and polymer, resulting in a material with improved properties. In 3D printing, composite materials are used to create parts with enhanced strength, flexibility, and electrical conductivity. Carbon fiber composites, for example, are widely used in aerospace and automotive applications due to their high strength-to-weight ratio and durability. Recent advancements in composite materials have resulted in improved strength and reduced production costs for 3D printed parts.

3.3. Functional working model

Advancements in 3D printing materials have revolutionized the world of additive manufacturing by making it possible to create highly complex and customized objects with ease and precision. These materials have also expanded the range of applications for 3D printing, making it a viable solution for various industries such as healthcare, automotive, aerospace, and construction. The functional working of advancements in 3D printing materials can be understood by looking at their key characteristics and how they compare to traditional materials. 1) Material properties: 3D printing materials have unique properties that allow them to be printed into complex shapes and structures. The functional block diagram has shown in the following **Figure 2.**

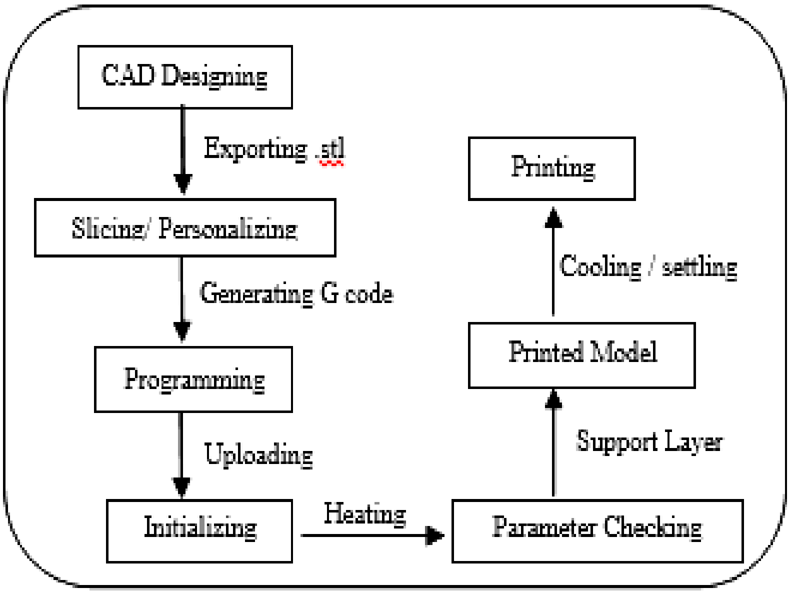

Figure 2. Functional block diagram.

At the beginning of the process, the model is created in CAD (Computer-Aided Design) software. This design stage is crucial as it allows for precise and detailed specifications to be inputted into the software, which will ultimately be used to create the final product. After the design is complete, the model is then sliced into layers. This is an important step in the process as it dictates how the 3D printer will create the final product. The slicing software divides the CAD design into horizontal layers, which are then used as a reference for the printer to build the model layer by layer. The next stage in the process is programming, where the sliced layers are translated into instructions for the 3D printer. This involves specifying parameters such as layer height, infill density, and print speed, which will determine the strength and overall quality of the final product. Once the programming is complete, the 3D printer is initialized and the printing process begins. The printer will follow the instructions set by the programming to extrude hot thermoplastic material layer by layer, building up the final product gradually. Throughout the printing process, the printer's parameters are constantly checked to ensure that the model is being printed accurately and to the desired specifications. This includes monitoring the temperature of the printing material, the speed and movement of the printer's extruder, and the overall progress of the print. Finally, once the printing process is complete, the model is removed from the printer and allowed to cool. The end result is a fully functional 3D printed product that has been created using the most advanced and precise methods available. Overall, this functional working model image highlights the advancements in 3D printing materials and how they are used in a step-by-step process to create high-quality, customized, and functional products. It also showcases the importance of CAD design, slicing, programming (Process parameter auto detected using existing data based on the material), and parameter checking in producing successful 3D printed products.

They are typically lightweight, strong, and have high heat resistance. This makes them ideal for applications such as aerospace and automotive parts, where weight and strength are crucial factors. Material options: With the advancements in 3D printing materials, there is now a wide range of options available, including metals, ceramics, polymers, and composites. Different materials have their own set of properties and can be used for specific applications. For example, metals are ideal for producing functional parts, while polymers are suitable for prototyping and consumer products. Customization: One of the biggest advantages of 3D printing materials is the ability to customize objects according to specific requirements.

3.4. Operating principle

Advancements in 3D printing materials have greatly expanded the capabilities of this technology and have revolutionized many industries. The operating principle of these advancements is based on the use of new and improved materials that possess unique properties and characteristics that make them suitable for 3D printing. Traditionally, 3D printing materials were limited to polymers such as ABS and PLA, which had their own limitations in terms of strength and durability. However, with technological advancements, new materials like metals, ceramics, and composites have been developed, allowing for more complex and functional prints. One of the main principles behind advancements in 3D printing materials is the ability to vary the composition and properties of the materials to meet specific requirements. The operational flow diagram has shown in the following **Figure 3**.

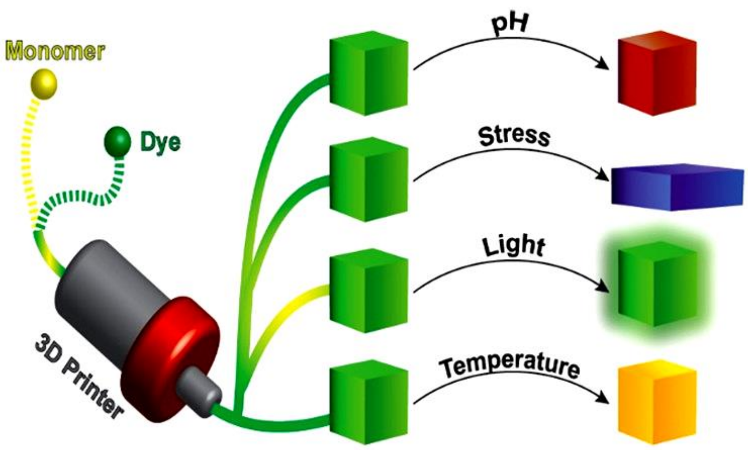

Figure 3. Operational flow diagram.

Monomer, also known as building blocks, is the basic units of a material. These can be customized and combined with different chemical structures to create a wide range of properties. In the 3D printing process, monomers are the starting material that is used to build the final product. Dye plays a crucial role in the color and aesthetics of the 3D printed material. It provides the ability to add color and visual appeal to the final product. Dyes can also be added to provide functionality, such as UV protection or conductivity. The 3D printer is the technology that enables the printing process to occur. It works by melting the monomer and dye mixture and depositing it in precise layers according to the desired design. The printer can also control the environmental factors such as temperature and light to ensure optimal conditions for the printing process. Environmental factors such as pH, stress, light, and temperature play important roles in the performance of 3D printed materials. The pH level can affect the chemical reactions and polymerization of the monomer, while stress can determine the strength and durability of the final product. Light can be used to initiate or accelerate the polymerization process, while temperature can affect the melting and solidification of the material. Furthermore, advancements in 3D printing materials have allowed for the creation of highly specialized materials for specific applications. By adjusting the composition of the monomer and dye mixture, and controlling various environmental factors during the printing process, 3D printing materials can possess unique properties such as flexibility, strength, and chemical resistance. This has opened up new opportunities for applications in fields such as medicine, engineering, and aerospace. In conclusion, the operating principle of advancements in 3D printing materials combines the use of monomer, dye, 3D printer technology, and environmental factors to create high-performance and specialized materials for various applications. With continued advancements and innovations, the potential for 3D printing materials is continuously expanding, making it a promising technology for the future.

For instance, metal filaments can be reinforced with metal particles to increase their strength and conductivity, while polymer materials can be blended with additives to enhance their durability. Another principle is the use of different printing techniques to accommodate the properties of the materials. For example, some materials require high temperatures to melt and solidify, while others may need to be cured under UV light. 3D printing machines have been developed with multiple print heads and temperature controls to accommodate a range of materials and their printing requirements.

4. Results

3D printing, also known as additive manufacturing, has revolutionized the way to design, prototype, and manufacture products. One of the key factors driving this revolution is the advancements in 3D printing materials. The proposed model has been compared with the existing FDM (Fused Deposition Modeling), EBM (Electron Beam Melting), CFF (Continuous Filament Fabrication) and DED (Direct Energy Deposition).

4.1. Durability

With the continuous development and improvement of new materials, 3D printing has expanded its use cases and has become an integral part of various industries such as healthcare, aerospace, automotive, and consumer products. To understand the performance analysis of advancements in 3D printing materials, it is important to first look at the traditional materials used in manufacturing. These include metals, plastics, and ceramics, which have been used for decades in various manufacturing processes. However, these materials have limitations in terms of design flexibility, customization, and production speed. This is where 3D printing materials have a major advantage. **Figure 4** shows the comparison of various 3D printing processes with the proposed method. In this, based on the input material the proposed method automatically selected the process parameter and these results in sustainable durability.

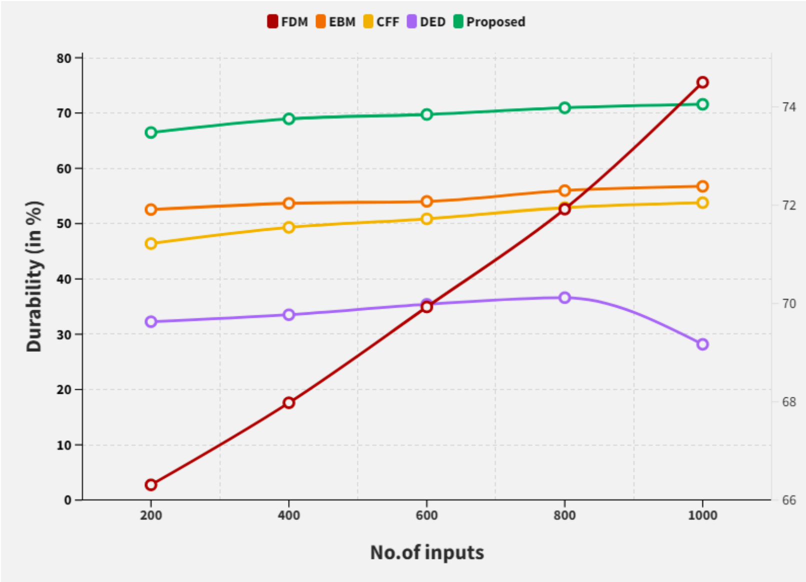

Figure 4. Comparison of different process with Durability.

One of the major advancements in 3D printing materials is the development of new polymers and composites specifically designed for 3D printing. These materials have improved mechanical properties, are lightweight, and have excellent wear and tear resistance. This has opened up new possibilities for applications such as lightweight components in the automotive and aerospace industries.

4.2. Printability

3D printing has revolutionized the way products are manufactured, offering a faster, more cost-effective and customizable alternative to traditional manufacturing methods. As the technology advances, so do the materials used in the process. This has led to improved performance and a wider range of applications for 3D printing. One key aspect of performance optimization in 3D printing materials is the selection of the right material for the desired application. Different materials have different properties and characteristics that make them suitable for specific purposes. **Figure 5** shows the comparison of various additive manufacturing processes printability and this is to proposed method better than other methods. A number of samples are needed to print with optimized process parameters in the additive manufacturing process with programming that may better results and the proposed method depicted suitable.

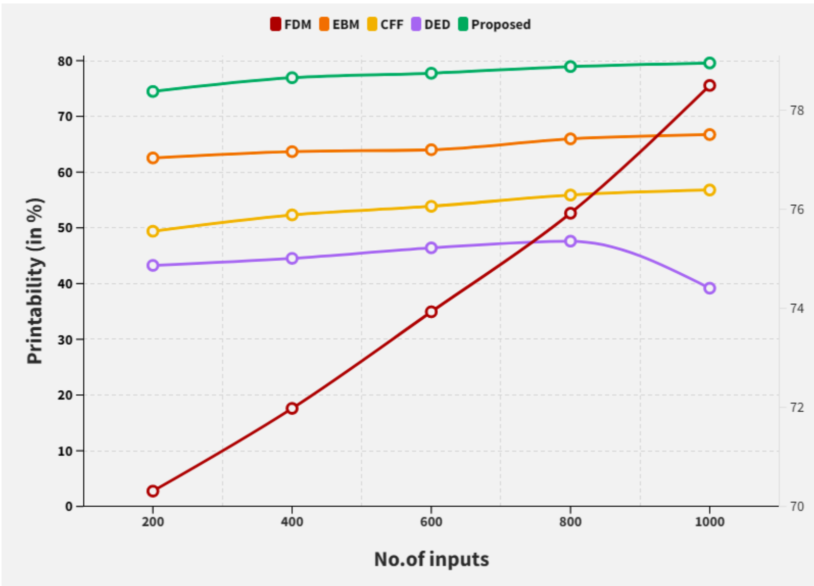

Figure 5. Comparison of different process with Printability.

For example, materials like ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid) are commonly used for prototyping and functional parts due to their high strength and heat resistance. Another factor that contributes to performance optimization is the design of the material itself. With the advancements in technology, materials can now be designed with specific properties to meet the requirements of different applications. For instance, materials can be engineered to have higher flexibility for soft and flexible parts, or high stiffness for structural components.

4.3. Chemical resistance

The field of 3D printing has advanced significantly in recent years, with new materials being developed and utilized for a wide range of applications. In this comparative analysis, we will examine the performance and applications of three major advancements in 3D printing materials: Thermoplastic Polyurethane (TPU), Carbon Fiber (CF), and Metal Powders. Thermoplastic Polyurethane (TPU) is a highly versatile material that has gained popularity in 3D printing due to its elasticity, durability, and resistance to a variety of chemicals. TPU can be easily printed with FDM (Fused Deposition Modeling) printers, making it accessible to a broad range of users. TPU has been used for a wide variety of applications, including flexible and wearable electronics, shoe soles, and medical devices. **Figure 6** shows the comparison of various materials printed with different additive manufacturing process and the results depict, in term of resistance that the process parameters can effectively intake by the proposed programming method.

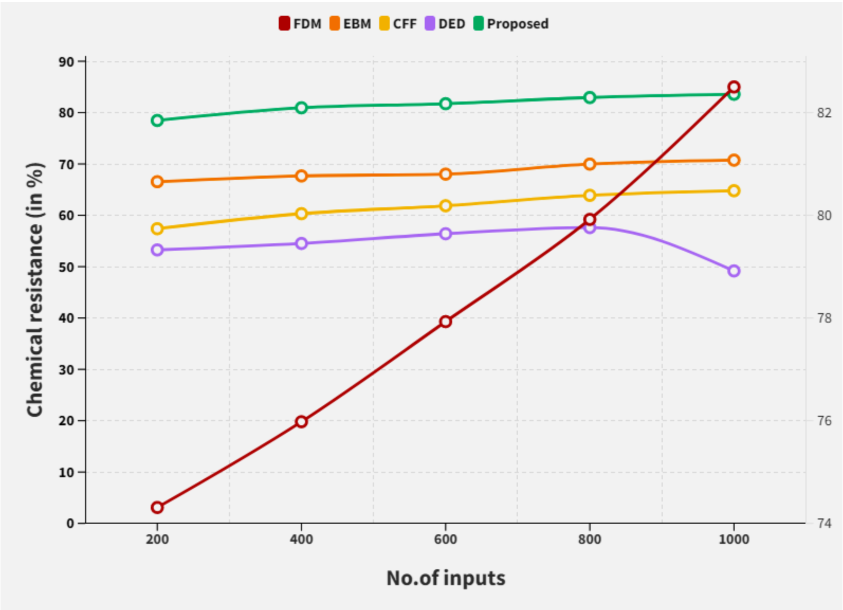

Figure 6. Comparison of different process with chemical resistance.

Carbon Fiber (CF) is another material that has seen significant advancements in 3D printing applications. CF offers a unique combination of strength, stiffness, and lightweight properties, making it ideal for applications in industries such as aerospace and automotive. Recent advancements in CF 3D printing have resulted in improved printing speeds and reduced costs, making it a more viable option for commercial use.

4.4. Heat resistance

3D printing technology has seen significant advancements in recent years, particularly in terms of the materials used in the printing process. These advancements have not only improved the quality and efficiency of 3D printing, but also expanded its range of applications. In this analysis, we will compare the performance of traditional 3D printing materials with the newer, more advanced materials. One major improvement in 3D printing materials is their increased strength and durability. Traditional materials such as

ABS and PLA have limitations in terms of strength and can be brittle. With the introduction of stronger and more flexible materials such as nylon, polycarbonate, and carbon fiber reinforced composites, 3D printed parts are now able to withstand higher stresses and have more versatile applications. **Figure 7** shows the comparison of various materials processing in different additive manufacturing process in term of heat resistance. The proposed method is better compare to existing process.

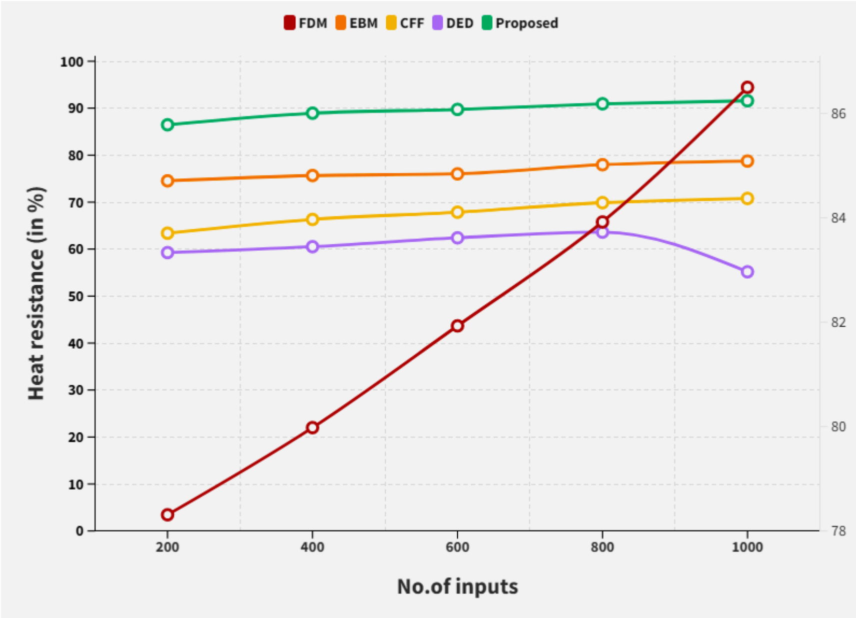

Figure 7. Comparison of Heat resistance.

This is especially beneficial for industrial use, where parts must endure constant wear and tear. Another key improvement is the wider variety of materials available for 3D printing. In addition to plastics and polymers, materials such as metals, ceramics, and even biological materials like food and human tissue can now be printed. This has opened up a whole new world of possibilities, from creating complex and intricate metal components to printing prosthetics and custom implants for medical use.

5. Conclusion

One of the main findings is the improved performance of materials in terms of strength, flexibility, and durability. These advancements have made it possible to produce 3D printed parts for various industrial applications, including aerospace, automotive, and healthcare industries. The use of high-performance polymers and composites has also expanded the potential of 3D printing technology in creating complex and functional structures. Furthermore, the comparative analysis highlights the importance of material selection in achieving desired results in the 3D printing process. Each material has its unique properties and characteristics that make it suitable for specific applications. Therefore, understanding the performance and capabilities of different materials is crucial in selecting the right material for a particular 3D printing project. Additionally, the analysis also sheds light on the limitations and challenges associated with 3D printing materials. Some materials may have superior properties in certain aspects but may lack in others, making it crucial to consider the trade-offs before selecting a material. Moreover, the cost of materials and equipment required for processing also needs to be taken into account. In conclusion, the comparative analysis of advancements in 3D printing materials highlights the rapid progress in material science and its impact on the field of 3D printing. The availability of various high-performance materials has expanded the applications of 3D printing, making it a viable and efficient manufacturing process for complex and customized parts. However, further research and development are needed to overcome the existing limitations and optimize the capabilities of 3D printing materials.

Author contributions

Conceptualization, RS; methodology, RS; validation, RS, and MAR; formal analysis, RS, DH and NR; investigation, RS and ZKA; resources, RS and MAM; data duration, RS; writing—original draft preparation, RS and NR; writing—review and editing, RS, AJR and GKG; supervision, RS, HMAT, APK and NR. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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