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Rheological and Mechanical Properties of Aluminum-ceramic Inks with Nanomaterials Using the Taguchi Method

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ABSTRACT

The use of aluminum ceramic nanoparticles allows for the three-dimensional printing of a wide variety of biomedical goods, such as dental instruments, sutures, blades, and dental tools. Cutting instruments, medicines, bioengineering, and abrasives all use ceramics and other non-metallic materials as heat sources. These are the primary applications of ceramic powder, and they represent a major paradigm change in biological applications generally and dental and skeletal applications in particular. A DIW machine combines ceramic and aluminum to create artificial teeth. The liquid material enables us to construct the teeth in layers. It also determines the necessities of life. Ceramics' resistance to high temperatures and chemicals is an important quality. Ceramics are excellent medical application materials because of their non-corrective nature, low cost, and exceptional thermal, electrical, and optical qualities. Furthermore, they manufacture ultra-thin, light-permeable glass, which enables the detection of internal flaws in materials. the ceramic lenses instead of glass ones. In place of restorative materials made of metal, ceramics are a wonderful choice. Ceramics have a plethora of remarkable properties, including chemical resistance, wear resistance, biocompatibility, and beauty. Despite the numerous benefits of all-ceramic restorations, their limited clinical lifespan and vulnerability to fractures have hindered their widespread use. The recent development of new, harder materials has led to an increasing number of doctors prescribing all-ceramic restorative systems. This is because it consistently delivers first-rate outcomes. One technique that sticks out is the Taguchi method.

Keywords: Biomedical; Aluminium; Dental ceramic; DIW; Nanoparticles.

1. INTRODUCTION

This method simplifies the production of aluminum nanoparticles, which serve as a substitute for other metallic components in the creation of ceramic teeth. It utilizes the DIW machine, which has a number of intriguing potential applications in the field of 3D printing. Additive manufacturing processes enable customized goods, quick and adaptable prototypes, and small-batch production (Hossain *et al.* 2023). These kinds of intricate geometries are difficult to directly fabricate using traditional ceramic techniques and therefore need additional micromachining steps, which increases manufacturing time and expense. Dental amalgam is a useful and inexpensive corrective filling substance, but its popularity is projected to decline due to environmental constraints and cultural concerns (Thompson *et al*. 2007). Due to growing knowledge of the potentially dangerous effects of anthropogenic mercury accumulation in ecosystems, there is a growing push to decrease the discharge of mercury waste (Bindslev, 1992). This has led to an increased focus on mercury waste from dental clinics and restrictions on the handling and disposal of contaminated material in several countries. Additive manufacturing (AM) has the potential to revolutionize the ceramics industry by providing new methods for creating complex ceramic parts without the need for expensive equipment, thereby reducing manufacturing expenses and lead times (Lakhdar *et al*. 2021a). 3D printing, the most current invention in the ceramics sector, has also contributed to the creation of innovative dental and biological applications. Using CAD software and other design tools to construct the teeth and tissues in this research has simplified the process of creating sophisticated medical designs, which was previously challenging (Chen *et al*. 2019a). It offers excellent AM technology performance at a reasonable cost, as well as outstanding fabrication efficiency for ceramic product parts (Cramer *et al*. 2022).

In addition to working in a variety of energy resource applications, it focuses on technology for the production of ceramic materials. 3D printing has emerged as a potential technique for creating ceramic components for both energy and medical purposes (Chen *et al*. 2021). This technique makes complex parts simple to construct using additive manufacturing. In terms of energy and uses, ceramic materials have a higher density than other materials, and this technique makes it simple to create the essential components. Using direct ink writing (DIW) technology, additive manufacturing is another innovative manufacturing technique that reduces waste and can create multi-material items for 3D printing (Rocha *et al*. 2020). Dental restorations composed of resin should be workable in the hand before setting and have enough mechanical strength after setting. Heating, light-curing, and self-curing are just a few of the configuration options available. This study also investigated the mechanical and rheological characteristics of resin dental materials for various applications. Robocasting is one of the best methods for 3D additive manufacturing of bone and human tissues; although this process creates Nano cracks, it does not generate tiny cracks because it uses in-situ processes instead (Feilden *et al*. 2017). Sintering the raw green product after the creation of the 3D model procedure helps to minimize porosity and eliminate air block damage (Diaz *et al.* 2017). Because of their high melting temperatures and resistance to ablation, ultra-high temperature ceramics (UHTCs) are of interest for mechanically and/or thermally demanding situations (Kemp *et al*. 2021).

However, their limited usefulness stems from their weak fracture toughness and the challenge of transforming them into intricately formed components. Here, demonstrate the creation of fiber-reinforced UHTC matrix composites (UHTCMCs) using direct ink writing (DIW)-based additive manufacturing methods. Additive manufacturing's (AM) ability to combine various materials with complex and customized designs is rapidly developing (Guo and Zhou, 2021). The combination of additive manufacturing (AM) with porous structure enables new approaches to the creation of multi-scale porous networks as materials research advances. This enhances the 3D-printed product's usability by allowing it to serve multiple purposes. For sturdy and strong clay objects, direct ink writing is a major unsolved problem (M'barki *et al*. 2017). A general dimensionless criterion is provided for printing such items. Used the Al2O3 precursor boehmite to assess the rheological properties that result in thick formations in ceramics produced by direct ink writing. Boehmite suspensions gelling over time makes a rheological lab with flow properties that could meet the needs of printability. Layer by layer, this is used additive manufacturing to integrate the alumina powder fully into the layers (Rueschhoff *et al*. 2016). This is also looked at the temperature and viscosity levels of the process and got excellent results. Upon completion of the additive manufacturing process, the solid load of rheology causes the alumina to become highly viscous. After the layer formed evenly, it was investigated the density and microstructures of the alumina powder in these basic products. Following direct ink writing, investigated pressure-less sintering, an additive manufacturing technique based on extrusion (Lakhdar *et al.* 2021b). Using different amounts of pluronic binder and ceramic powder in boron carbide pastes, its looks like they changed the flow, density, hardness, and how they behaved during processing. Also considered the impact of printing parameters, like orifice diameter and printing speed. As one of the most advanced and precise materials for creating positioning devices, it also summarizes long-term improvements in electrical, thermal, and temporal stability in this process (Hao *et al*. 2019). Careful control of the rheology of direct writing pastes is necessary for high-quality printed ceramics (Walton *et al.* 2020). Researchers developed ceramic pastes to investigate the relationship between the surface chemistry and rheology of complex pastes, which are composed of large powder and a commercial poly acrylic acid-based binder system. This is evaluated the polyacrylic acid's conformation, the ceramic powder's zeta potential, and their effects on rheology in relation to suspension pH demonstrated how to use paste extrusion 3D printing to create piezoelectric ceramic Lead Zirconate Titanate (PZT) additively (Hall *et al*. 2021). In this process investigated a variety of paste compositions with varying water-weight contents to identify an appropriate paste composition for printing. This is assessed the viscosities, yield stresses, and stability of the pastes after aging. Additionally, described and contrasted the material characteristics of ceramics made via paste extrusion with those made using a traditional die-pressing technique. Demonstrated on paste extrusion 3D printing to create piezoelectric ceramic Lead Zirconate Titanate (PZT) additively (Wätjen *et al*. 2014).

This investigated a variety of paste compositions with varying water-weight contents to identify an appropriate paste composition for printing. Also, assessed the viscosities, yield stresses, and stability of the pastes after aging. Additionally, It described and contrasted the material characteristics of ceramics made via paste extrusion with those made using a traditional die-pressing technique. Three-dimensional material patterning is essential for a number of technical applications, such as tissue engineering, composites, microfluidics, and photonics (Lewis, 2006). Without the need for costly tooling, dies, or lithographic masks, direct-write assembly enables the design and quick fabrication of materials in intricate 3D forms. This analysis of recent developments in direct ink writing highlights the drive for finer feature sizes. At room temperature, make titania ceramic ink with a high solid loading (Chen *et al*. 2019b). This is used several test methods to look at the properties of titania ceramics that were sintered at different temperatures. These properties included volumetric shrinkage, porosity, density, microstructures, compressive strength, and elastic modulus. That is used ceramic ink to create three-dimensional titanium ceramic parts. If you add more polyethylene dispersant than necessary to achieve adequate dispersion, the slurry may agglomerate (Mori *et al*. 2012). Tests were conducted to find out how the agglomeration process functioned in a slurry created by adding more polyelectrolytes. The initial concentration of the particles dictated the procedure. The added number of polyelectrolytes strongly influences agglomeration behavior, not the solution's concentration. Ceramic materials have been made using quick prototyping methods due to their many benefits, and there has been a huge increase in research into using biomaterials as raw materials in combination with rapid prototyping in the last several years (Muniz *et al.* 2015). Inkjet printing uses ceramic powder in combination with a binder and a fluid. A printer dispenses the fluid onto the sample. Despite the well-known influence of dispersants, very few research initiatives have focused on their role in the conventional manufacture of alumina-based materials for quick prototyping. This research aims to compare the effects of different fluid and dispersant concentrations by creating alumina pieces using an inkjet model and a 3D printer. It's measured the density, apparent porosity, and size of the specimens.

3D printing is a competitive manufacturing technique that has created new opportunities for the production of complicated ceramic structures and customized products. Ceramic materials widely utilize extrusion-based methods, also known as direct ink writing (DIW) or robocasting (Del and Ginebra, 2021). In these applications, ink rheology affects paste extrudability and printed piece form fidelity. To the best of our knowledge, no one has documented piezoelectric ceramics from aquatic systems (Nan *et al*. 2019). The primary obstacle is the significant hydrolysis processes that the initial powders undergo when they are dispersed in water, which hinders the creation of stable water-based colloidal suspensions. This study talks about how to make stable water-based inks from a powder that has been deagglomerated and treated on the surface using a solid-state reaction. It also talks about the dielectric properties of lead-free, macroporous piezoelectric. Additive manufacturing (AM) advancements, which include transforming design files into fully functioning things straight away, provide smart manufacturing solutions that prioritize the customer and are gradually displacing conventional production processes in numerous industries (An *et al.* 2020). However, the demanding nature of ceramic materials might reduce the advantages of AM for producing ceramic components. To determine if wet granular materials with a high mass fraction are suitable for extrusion 3D printing, Its conduct extrusion experiments and rheological studies (Sweeney *et al*. 2017). Among the many uses for these materials are the creation of thick, durable ceramic, custom components, and the 3D printing of energetic materials with exact geometries. Since 3D-printed colloidal materials have traditionally used inks with a much lower mass fraction, these approaches will not be effective for systems with a higher mass percentage of solids. The behavior of these moist granular materials defies the rules of Newton. High elasticity, non-homogeneous flows, shear thinning, and yield stress all indicate that their behavior is non-Newtonian. Its used a fine powder from the traditional ball milling process to evaluate the additive-free, low-temperature sintering of PZT ceramics. In a ball mill, we mix three millimeters of zirconia balls, an organic surfactant, and isopropyl alcohol. A grain size of 0.5 μm is common for commercial PZT ceramic powder (Zr0.52) (Maiwa *et al*. 2005).

The zirconia and alumina nanoparticles not only produced thick and thin layers of the required materials, but they also produced electron materials, which attracted and improved the strength and high energy storage capacity of materials with high energy storage (Hao *et al*. 2014). These two innovative additive manufacturing techniques created components with higher densities and lower porosities (Popov *et al*. 2021). That is built graphite structures as a platform to test these new technologies. Its compare and contrast both (a) samples created exclusively by BJP and (b) samples created using more traditional uniaxial pressing methods like compaction molding. Together with titania and alumina powders of different sizes, it made green bodies of aluminum titanate (Al_2TiO_5) (Papitha *et al*. 2013). These were then cast using cold isostatic pressing (CIP), pressure slip casting (PSC), or conventional slip casting (CSC). Theses analyzed the powder characteristics, flow patterns, and shape parameters of the precursor-powder combinations. This measured and linked the fractographs and green density. This is investigating the mechanism of ferroelectric deformation based on crystal symmetry using theoretical and experimental approaches (Li *et al*. 2013). This is achieved three unique Al ceramic shapes by combining tetragonal and rhombohedral phases. These shapes are tetragonal, rhombohedral, and morphotropic. Using X-ray diffraction and piezoresponse force microscopy, this characterized the crystal structures and domain patterns. Also, Figure 1. Shows the details of the differences between oxide and non-oxide ceramics. Despite their potential applications, Al_2O_3 composites have not been substantially researched. After being created using different binders and dispersants, the ATZ pieces were examined for rheological and curing properties (Thakur *et al*. 2024). The microstructures produced by debinding and sintering the effective formulations were homogenous and included a well-dispersed mixture of the two phases. In recent decades, resin-based materials have seen an increase in both indirect and direct dental restorative applications (Zhang *et al.* 2021). As a general rule, dental materials based on resin should be moldable or flowable before setting and have enough mechanical strength after setting. Heating, light-curing, and self-curing are some of the setting techniques available. In this study, it can be studied the mechanical and rheological characteristics of resin-based dental materials for various applications. This study makes DIW much better for use in dental implants and other surgical procedures by focusing on accuracy, mechanical stability, biocompatibility, and regulatory compliance. For industrial scalability and mass production, future research should center on in vivo testing. Bioceramic materials are a game-changer in the manufacturing industry, offering modern alternatives to methods that have been used for decades. Bioceramic structures with regulated porosity, bespoke geometries, and straightforward design are now within reach thanks to Direct Ink Writing (DIW), a very promising AM method (Paul and Susila, 2025). Industrial and residential uses both benefit from the effective insulation that porous thermal insulating ceramics provide (Lin *et al*. 2025). This lowers energy use, raises occupant comfort, and helps make manufacturing practices more environmentally friendly. This review delves deep into the topic of 3D-printable porous thermal insulating ceramics. Also covered extensively are the many 3D printing techniques and materials that may be used to create porous ceramics, along with their respective processes, advantages, and disadvantages.

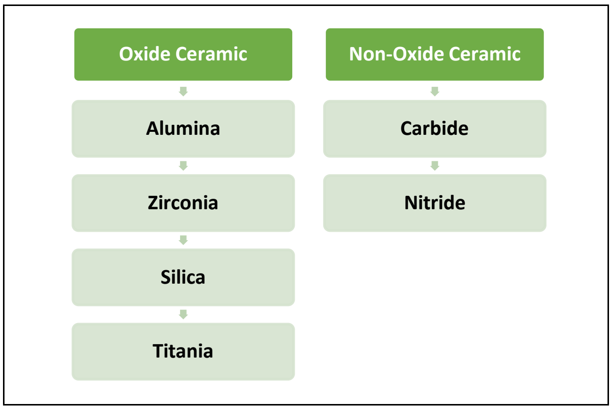

Fig. 1: Flow chart of oxide ceramic vs non-oxide ceramics

2. EXPERIMENTAL SETUP

2.1 Direct Ink Writing

Direct Ink Writing (DIW), also known as Robocasting or Extrusion-Based Printing, is an additive manufacturing technique where a nozzle extrudes ink or paste to create structures layer by layer. DIW machines employ a greater variety of materials, such as ceramics, metals, polymers, hydrogels, and biomaterials, because they print with very viscous materials instead of plastic filament or resin as standard 3D printers do. Advanced manufacturing, biotechnology, electronics, and ceramics often utilize DIW. DIW printing typically uses an extremely viscous paste with certain rheological characteristics, such as ink. This ink must easily pass through the nozzle under pressure while maintaining its form after placement.

A nozzle carefully extrudes the substance. The nozzle travels along predetermined routes under the control of a computer-aided design (CAD) system, producing layers of the required three-dimensional geometry. DIW constructs structures layer by layer, much like FDM or resin-based 3D printing. Once deposited, a layer must retain its structural integrity to support subsequent layers. Also, achieve this by carefully adjusting the ink's characteristics and managing the extrusion speed, as shown in Figure 2. Shows the CIM direct ink writing machine.

The highly specialized process known as CIM (Ceramic Injection Molding) produces precise and complex ceramic components. The Ultra-Precision Ceramic Injection Molding, or CIM UPC, machine is a crucial piece of equipment for this procedure. Depending on the machine's size, its barrel capacity may range from 15 cm^3 to 500 cm^3, its speed range is 10-300 mm/s, and its pressure range is 2000-3000 bar. The machine has to have a surface polish of Ra < 0.2 μm after sintering, a dimensional tolerance of ±0.1% or better, and the ability to remove pieces using robotic arms or conveyors.

Fig. 2: CIM direct ink writing machine

The printed item may need post-processing procedures like drying, curing, or sintering, depending on the material. For instance, hydrogel-based bio-inks may require UV curing, while ceramic DIW prints typically undergo sintering to attain strength. The core of a DIW machine extrudes the ink. This extruder typically operates under mechanical or pneumatic pressure. The application and required resolution will determine the nozzle diameter. Larger nozzles provide quicker, bulkier printing, whereas smaller nozzles are utilized for detailed printing.

2.2 Aluminum Material

The melting point of nanoparticles may be much lower than that of aluminum, which melts around 660 °C due to size-dependent melting point drop. Aluminum nanoparticles may oxidize or burn at very low temperatures, often between 300 and 500 °C, because of their strong reactivity. Aluminum oxide, also known as aluminum nitride or alumina Al2O3, is the source of aluminum ceramic powder. Both conventional and sophisticated ceramics frequently use these powders for applications that require high hardness, corrosion resistance, electrical insulation, or thermal conductivity. Aluminum powders in this size range are metallic gray and have a relatively limited surface area, in contrast to nanoparticles. There are several applications for aluminum powder, a fine-grain metallic powder, in both industrial and scientific contexts. It often needs an oxidizer to explode since it is stable and non-reactive in air. This method enables the use of aluminum nanoparticles in the creation of objects. Aluminum nanoparticles are crucial due to their small size, which gives them a huge surface area and unique reactivity properties. Figure 3. Shows that the nanoparticles and paste of aluminum and the mixes make it a paste format.

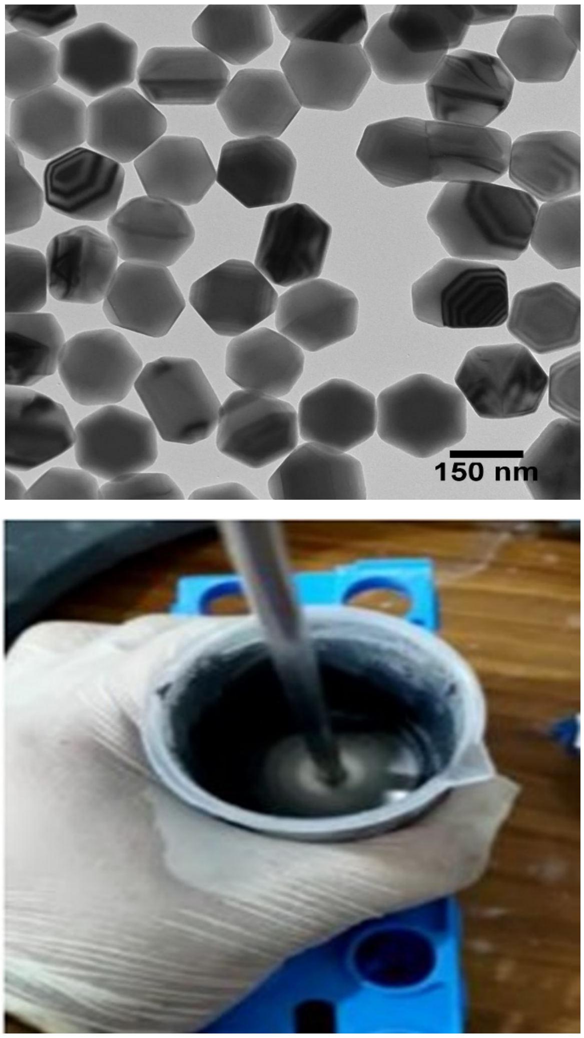

Fig. 3: Aluminum powder paste with nanoparticle images

Thermal coatings, abrasives, electronic substrates, and high-wear components all use powdered aluminum ceramic. 3D printing and powder metallurgy can also utilize these powders to fabricate customized components. Techniques like sintering, hot pressing, or thermal spray can shape these powders into long-lasting coverings or shapes that can withstand hostile conditions.

According to recent studies, aluminum oxide nanoparticles may possess antibacterial properties that might aid in lowering the development of plaque and germs in dental applications. Additionally, Nano-alumina is known to be biocompatible, making it safe for human usage, particularly in oral applications. Furthermore, the high hardness of alumina Nanopowder offers exceptional wear resistance, a crucial feature in dental applications that expose materials to high levels of abrasion. Dental implants use Nano-alumina as a coating due to its strength and biocompatibility. Its excellent wear resistance enables prosthetic devices to endure the mechanical stresses of grinding and chewing.

2.3. 3D Printing and Ink preparation

The ink, a crucial component of DIW, requires precise adjustment for successful 3D printing. That can make ink from metals, ceramics, polymers, or composite materials, but biological applications require ceramic materials. To adjust mechanical properties, drying time, and viscosity, that is do printability experiments. Fine particles reduce the chance of clogging and allow for smooth extrusion. Techniques such as ball milling and ultrasonic agitation ensure the uniform distribution of particles during mixing.

Table 1. Nomenclature and composition of samples

Sample	Al_2O_3 (vol%)	Dispersant (wt%)	5 wt% PVA Solution (vol%)	Glycerol (vol%)	Solid Loading (wt%)	Dispersant/Other Liquids (vol%)
A50D1	50	1	3.50	0.075	42.50	5
A50D2	50	2	7.00	0.160	38.50	5
A52.5D1	52.5	1.5	3.67	0.085	39.50	4.75
A52.5D2	52.5	2.5	7.35	0.180	36.00	4.75
A55D1	55	2	3.85	0.095	37.00	4.52
A55D2	55	3	7.70	0.205	33.00	4.52

The DIW printer connects to a syringe or cartridge that contains the prepared ink. This type of nozzle, with a nozzle diameter of 0.3 mm, facilitates the production of even layers, layer by layer. The printer then uses a computer-generated G-code to trace the required shape. Additionally, the nozzle builds layers vertically while moving along the XY plane. The printed structure may require drying, curing, or sintering (for metals and ceramics) to achieve the desired mechanical strength.

2.4 3D Teeth Process

This method connects the implant to a length of 6 to 8 mm, while the DIW process produces a diameter of 3.5 to 5.00 mm. In order to secure the teeth in the mouth's abutment, also employed UV light to dry them.

The process included filling the DIW 3D printer, combining the paste type and alumina nanoparticles, and employing CAD software to guarantee exact measurements for the teeth's creation.

2.5 Alumina Characterizations

Aluminum ceramics' mechanical properties enable them to withstand high temperatures on par with room temperatures. The high heat has no effect on the crystallization of the aluminum nanoparticles that fill the gaps. It often pre-mixs ceramic powders (like alumina, zirconia, or PZT) with binders, lubricants, or plasticizers to enhance handling and compaction. After that, we sift the powder to guarantee a uniform distribution of particle sizes. Furthermore, samples are often shaped into cylinders, discs, or rectangular bars. Table 1. Shows the nomenclature and samples of the aluminum Nanoparticles. The size of the die cavity and the powder's compacting ability determine the dimensions. The characteristics of the powder, how efficiently it compacts, and the presence or absence of additives all affect the density of the pressed sample (prior to sintering). Green densities often fall between 50 and 70 percent of the theoretical density.

$$\text{Total liquid volume} = V_{disp}+V_{PVA}+V_{gly}$$

Figure 4. Shows the DIW machine working and the robotic arm helped to take the green product because of damages and any kind of problems that do not occur in the component. Also, the best shear-thinning aims for a greater dispersant concentration (up to 2.5 weight percent), balanced liquid ratios, and glycerol adjustment. Excessive dispersion might stabilize the ink. Additionally, certain pH values (such as pH 8–10) often yield the best results when using alumina dispersants. Should fail to meet this range, it may need to adjust the dispersant concentration.

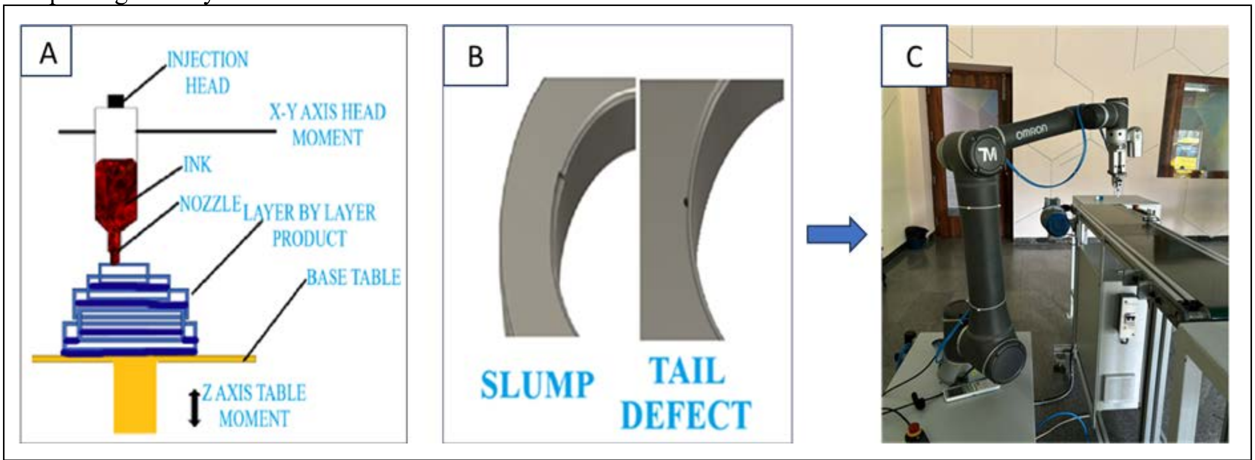

Fig. 4: DIW machine with issues of the samples and possible applications of DIW (a) DIW machine, (b) defect parts, and (c) Robotic arm (objective of our study)

Table 2. Input parameter optimization for DIW machines in additive manufacturing

Stand of Distance	Layer Thickness (mm)	Nozzle Diameter (mm)	Time (Mins)
1	0.1	0.2	75
1	0.2	0.3	60
1	0.3	0.4	62
3	0.1	0.2	38
3	0.2	0.3	30
3	0.3	0.4	42
5	0.1	0.2	80
5	0.2	0.3	85
5	0.3	0.4	90

The incorrect mixing of the powder paste during the initial manufacturing process necessitates the use of robotic arms for the picking and handling of ceramic products, leading to numerous issues throughout the manufacturing process. Aluminum-ceramic is great for improving DIW properties like layer thickness and stand-off distance because it is shear-thin, has high solid loading, keeps its shape, and is thermally stable. This guarantees both the accuracy and structural integrity of the printed pieces. Additionally, we cannot use our hands to pick the green component because doing so would ruin the product. In initially made the foundation, followed by layers that were 1 to 2 mm thick, and then filled the pattern with aluminum nanoparticle paste using the DIW (Direct Ink Writing) additive manufacturing technique. The 3 mm nozzle diameter enables the table to move in the Z direction and the ink hopper to move in the XY direction simultaneously. Furthermore, the output of the DIW machine led to the lowering of the base table also, produced by Omron, intended for precise and cooperative uses in industrial settings and probably used for operations involving the handling, assembling, or dispensing of materials as well as A motorized conveyor in the background likely moves materials or components during an automated procedure. Table 2 provides the optimization parameters in the input parameters and also its values. These values are used in the DIW machine to make the product in the dental, biomedical, and skin tissues are made by this process.

Even if parameters like stand-off distance, layer thickness, and nozzle diameters are input, the result, as shown by the graphical values, suggests which value is ideal Figure 5.

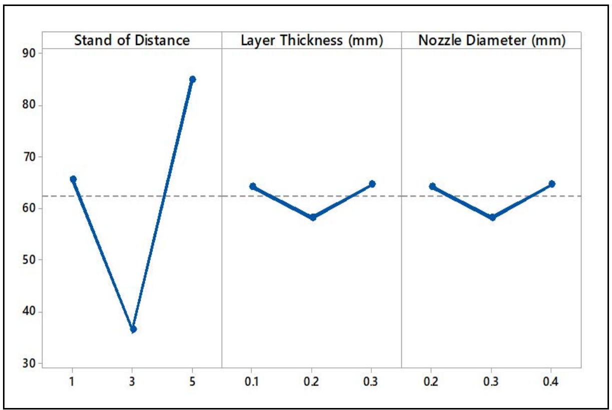

Fig. 5: Stand of distance, layer thickness, and nozzle diameters

Table 3. displays the parameters that the Taguchi technique uses to produce its result. Referring to the computer language, this will supply these values as input values. The parameters of this type are defined by the rank and delta values, which also determine the output values. Table 4. also, shows the input values of the Taguchi method of the DIW machine specifications this gives the factor information of the input parameter.

The dimension of the aluminum nanoparticles used in the previous tables ranges from 2 to 50 nm, and the component determines the layer thickness. In this procedure, it refers to the distance between the base table and the nozzle as the stand-off distance, which can vary from 0.1 to 0.5 mm. Hence, its construct the layer sequentially, guaranteeing that it is 0.3 mm thick. It might take a long time. Using computer-aided design (CAD) software, which takes input parameters and converts them into G-codes, is one of the easiest methods to build dentistry and biomedical-oriented production. Technological advancements have made dental inlays and outlays, implants, teeth, and surgical tools feasible.

2.6 Mechanical Properties of Aluminum Ceramic Nano Particles

Due to improved wrapping and inter-particle adhesion, nanoparticles often increase strength and wear resistance. Mixing these nanomaterials with others may enhance heat stability or fracture toughness. Alumina ceramic powders find extensive usage in high-wear fields such as advanced coatings, dental work, and cutting tools. Table 5. details the mechanical properties of the aluminum nanoparticles used in this method.

Previously, using 3D printers for additive manufacturing was a significant challenge. This procedure uses the Direct Ink Writing machine to produce dentistry-related commodities.

Table 3. The mean values of the input parameters

Level	Stand of Distance	Layer Thickness (mm)	Nozzle Diameter (mm)
1	45.00	58.33	58.33
2	70.00	66.67	66.67
3	85.00	75.00	75.00
Delta	40.00	16.67	16.67
Rank	1	2.5	2.5

Table 4. Factor information of input parameters

Factor	Type	Levels	Values
Stand of Distance	Fixed	3	1, 3, 5
Layer Thickness (mm)	Fixed	3	0.1, 0.2, 0.3

Also, to get more people to use ceramics, it's important to make ceramic materials that can stand up to a lot of different harmful substances while still having good mechanical properties. The response surface technique optimizes parameters in the experimental "sample-corrosive media" domain. Variables affecting corrosion resistance include ambient temperature, the kind of hostile media utilized, and the purity and microstructure of the ceramic material. Alumina ceramics were exposed to water in accordance with the Box-Behnken design. The regression functions were set up, and then optimization was done in the test area to find the values that would give sintered ceramics the best corrosion resistance. The 200-400 GPa range of alumina ceramic particles demonstrates their extreme stiffness and resistance to deformation caused by elastic forces. Ceramics are renowned for their rigidity due to their strong ionic and covalent bonds, far higher than metals such as steel (~200 GPa) or aluminum (~70 GPa). As a result, they are ideal for applications requiring stiffness. Porosity reduces Young's modulus because the material's spaces make it more difficult for stress to escape. Dental restorations such as implants, braces, and crowns, both biocompatible and structurally significant, make this point quite clear. Modulus reductions of 30% or more are common for 10% porosity increases.

Table 5. Mechanical properties of aluminum ceramic powder

Properties	Value Range	Descriptions
Density	3.5–4.5 g/cm³	Depends on the specific ceramic composition and porosity.
Hardness	1200–2000 HV (Vickers Hardness)	The high hardness makes it resistant to wear and abrasion.
Young's Modulus	200–400 GPa	Indicates stiffness and ability to resist deformation under stress.
Compressive Strength	200–800 MPa	Reflects the ability to withstand compressive loads without fracturing.
Flexural Strength	100–300 MPa	Indicates resistance to bending before failure.
Thermal Conductivity	15–30 W/m·K	Moderate thermal conductivity varies with porosity and particle size.
Coefficient of Thermal Expansion (CTE)	$6–8 \times 10^{-6}$/°C	The low expansion makes it suitable for high-temperature applications.
Fracture Toughness	2–5 MPa·$m^{0.5}$	Moderate resistance to crack propagation compared to pure ceramics.
Wear Resistance	Excellent	High durability due to hardness and low friction.
Porosity	5–15%	It affects mechanical strength and thermal properties and varies based on processing.
Specific Surface Area	10–30 m²/g	Reflects particle fineness, impacting sintering and bonding characteristics.

Fig. 6: Aluminum nano ceramic powder

3. RESULT AND DISCUSSION

Usually black, gray, or white and ranging in size from 20 to 100 nm, aluminum ceramic Nano powders are one of the best materials for human health because of their exceptional thermal, mechanical, and electrical properties. For this process, however, this wewill use particles at a scale of 18 to 20 nm. The plates for the DIW machine undergo one of the most straightforward processes, melting at 6600^0 C. Aluminum Nanopowder has a density of 2.7 g/cm³ and a lower melting point due to its increased surface area and smaller size. Figure 6. Shows that the aluminum Nanopowder. Their behaviour implies that they flow readily yet retain their structure once laid down. This procedure is required for accurate layer thickness control because it ensures incessant and smooth extrusion with little spreading. Monitoring the rheology also lets you precisely change the stand-off distance, which is the space between the nozzle and the substrate. This makes the deposition uniform.

This direct ink writing method requires a three-dimensional CAD model of the teeth. The DIW machine can produce ceramic teeth after converting the model into G-codes. The remarkable biocompatibility, mechanical, and thermal qualities of alumina (Al_2O_3) Nano ceramic powder make it a popular choice for dental applications. Crowns, bridges, and implants are dental restorations that depend on alumina. Ceramic restorations made of alumina, including dental bridges and crowns, may have their aesthetic value enhanced by porcelain overlays. Figure 7. shows a computer-aided design (CAD) for ceramic teeth, and the DIW machine fabricates them for dentistry and other biomedical applications.

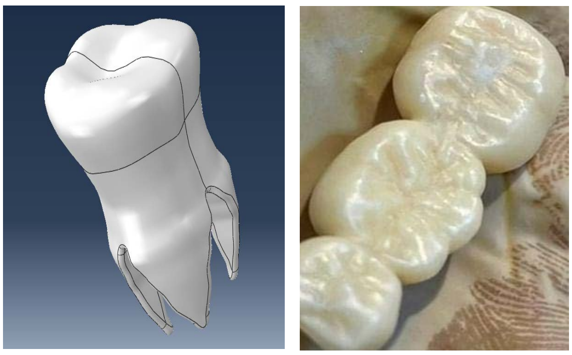

Fig. 7: The CAD model and ceramic teeth

After building the CAD model, a direct ink writing machine prepares the aluminum ceramic teeth for insertion into the human replacement teeth. This process takes 45 minutes to generate and ensure a suitable surface finish. Although these teeth work similarly to regular teeth, maintaining our existing teeth is necessary for reimplantation.

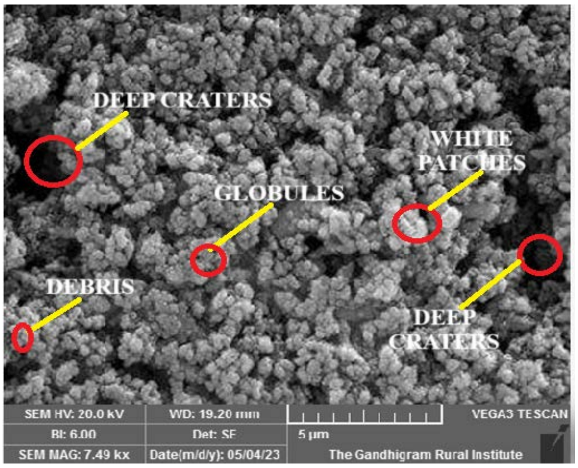

Fig. 8: SEM image of aluminum nano ceramic powder

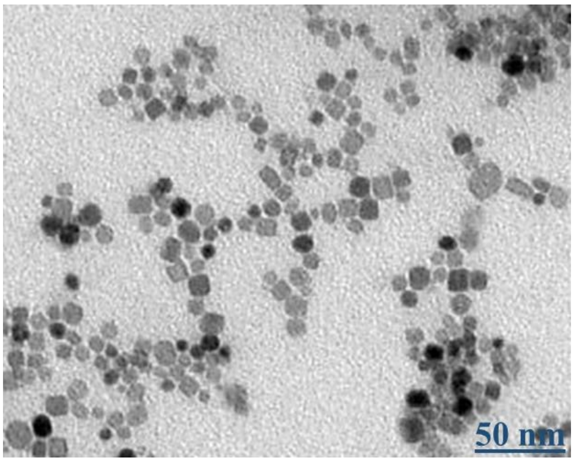

Fig. 9: TEM image of aluminum ceramic powder

The alumina (Al_2O_3) is probably in powdered form due to the shape of the particles and the greater voltage employed to gain better electron penetration and a complete image of the surface. By detecting low-energy electrons produced from the surface, this mode not only collects secondary electrons to provide high-resolution surface images but also shows surface topography. Unlike crystalline alumina powders, which tend to have smooth surfaces, they have fractured and uneven surfaces. The particles' size distribution is often shown by the 100 µm scale bar, covering a size spectrum up to the given scale. Aluminum nanoparticles are very reactive due to their high surface-to-volume ratio. Aluminum nanoparticles and oxygen might spontaneously combine to create a strong exothermic reaction and a large amount of energy release. In contrast to nanoparticles, aluminum powders of this size range usually have a small surface area and a metallic grayish hue. Numerous other coatings, composites, pyrotechnics, and 3D printing also utilize this powder. Fig 8. Displays a scanning electron micrograph (SEM) of aluminum ceramic powder; the picture clearly reveals surface imperfections and the microstructures on the material.

This TEM picture shows the shape and microstructure of the aluminum Nano ceramic particles. Nanoceramics result from various physical and chemical processes, although the resulting particles are often spherical or irregular in shape. These particles are in the nanometre range, as shown by the 50 nm scale bar in the bottom-left corner. Aluminum Nano ceramics get their superior mechanical, thermal, and electrical qualities at this nanoscale level. Figure 9. displays a TEM picture of alumina ceramic powder.

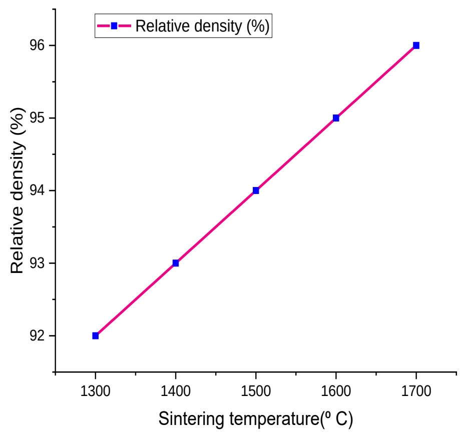

Fig. 10: Relative density vs. sintering temperature

This image illustrates the positive linear relationship between relative density and pressure; as relative density rises, so does pressure. The blue squares on the picture represent relative density data points at various pressures, either from experiments or calculations. Subjecting a material (such as powder) to pressure likely increases its relative density (in percentage form), indicating its compactness or densification. As pressure increases, the relative density goes from a lower value (about 0%) at low pressures to a near-complete densification (~100%). Figure 10. Shows that the relative density and sintering temperature

To make aluminum ceramics, sintering is a necessary process that requires very low temperatures (below a melting point) to fuse powdered ingredients into a dense, solid structure. Careful control of the sintering temperature of aluminum ceramics, often falling between 1400^0C and 1600°C, is necessary to achieve the desired mechanical and physical properties. Higher sintering temperatures are required for high-purity aluminum oxide due to the reduced number of impurities that act as sintering aids. Controlled environments may also influence grain density and growth.

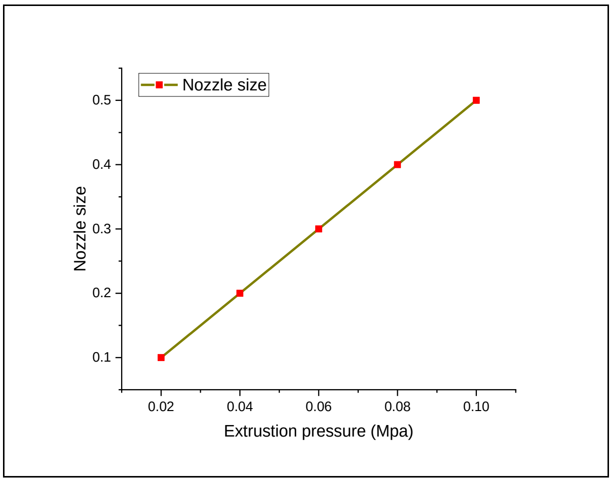

Fig. 11: Nozzle size vs. extrusion pressure

With values increasing from 0.1 to 0.5 for layer height and from 0.2 to 1.0 for nozzle size, the graph in the figure shows the relationship between the two variables. Red squares show the correlation between layer height and specific nozzle size measurements. A straight correlation exists between the two variables (layer height and nozzle size), as seen by the yellow line that joins the data points. Figure 11. illustrates how two factors determine the values.

Fig. 12: Nozzle of the DIW machine

The creation's material influences the nozzle diameter; this 3D DIW machine requires a 0.3mm nozzle and Figure 12 to achieve a visually appealing surface quality. It shows the 0.3mm diameter nozzle. That use a pressure of 0.02 to 0.10 MPa to feed the green ceramic paste into the machine. The hopper's connection to the nozzle generates a high nozzle pressure during this process, pushing and injecting the ceramic paste downwards. The CAD model generated the required shape, and each layer moved the table downward by 0.1 mm, thereby building the model upwards.

Hardened steel or another sturdy substance appears to be the composition of the dark-finished nozzle. These materials often form nozzles to withstand wear, especially when printing abrasive materials. The bottom portion, threaded, signifies its intended attachment to the extruder assembly of a 3D printer. Moreover, the pointed tip enables precise filament extrusion. The exact size of the nozzle's aperture (0.3 mm) determines its high-resolution capabilities.

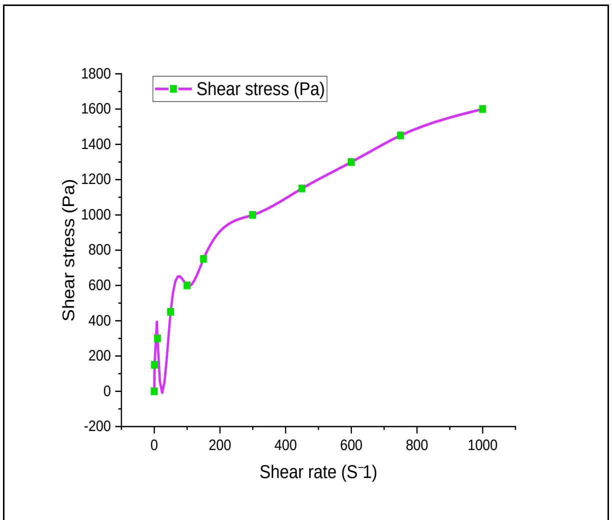

Fig. 13: Shear rate vs. shear stress

The nozzle links to the hopper, which moves in an XY orientation due to the tooth's form and design and contributes to the shape and thickness of the aluminum nanomaterials used in biomedical applications.

The y-axis displays a material's resistance to shear force in Pascals (Pa). It illustrates the maximum force per unit area the material can withstand before failing at a specific shear rate. The material's deformation rate under shear is measured via the x-axis and is represented in reciprocal seconds (s^{-1}). If the shear stress increases dramatically just before the operation starts, the material isn't responding linearly at low shear rates. The minimal tension needed to start a flow is known as yield stress, and this indicates it. The curve becomes more linear at higher shear rates, indicating a plastic or shear-thinning property in which the material flows more quickly as the shear rate increases.

The process begins with a shear stress of 0 Pa and continues until it reaches 1600 Pa. Similarly, the shear rate starts at zero (S-1) and ends at one thousand (S-1). Both the shear tension and the shear rate increase continuously. These materials often display viscous or viscoplastic behaviors as the quantity of shear stress fluctuates randomly with the shear rate. Nanoscale ceramics affect rheological properties due to their enhanced dispersion and interaction with the matrix. Composition, particle size, and spreading media are among the variables that impact the shear rate and shear stress of dental nanoceramic materials made of aluminum.

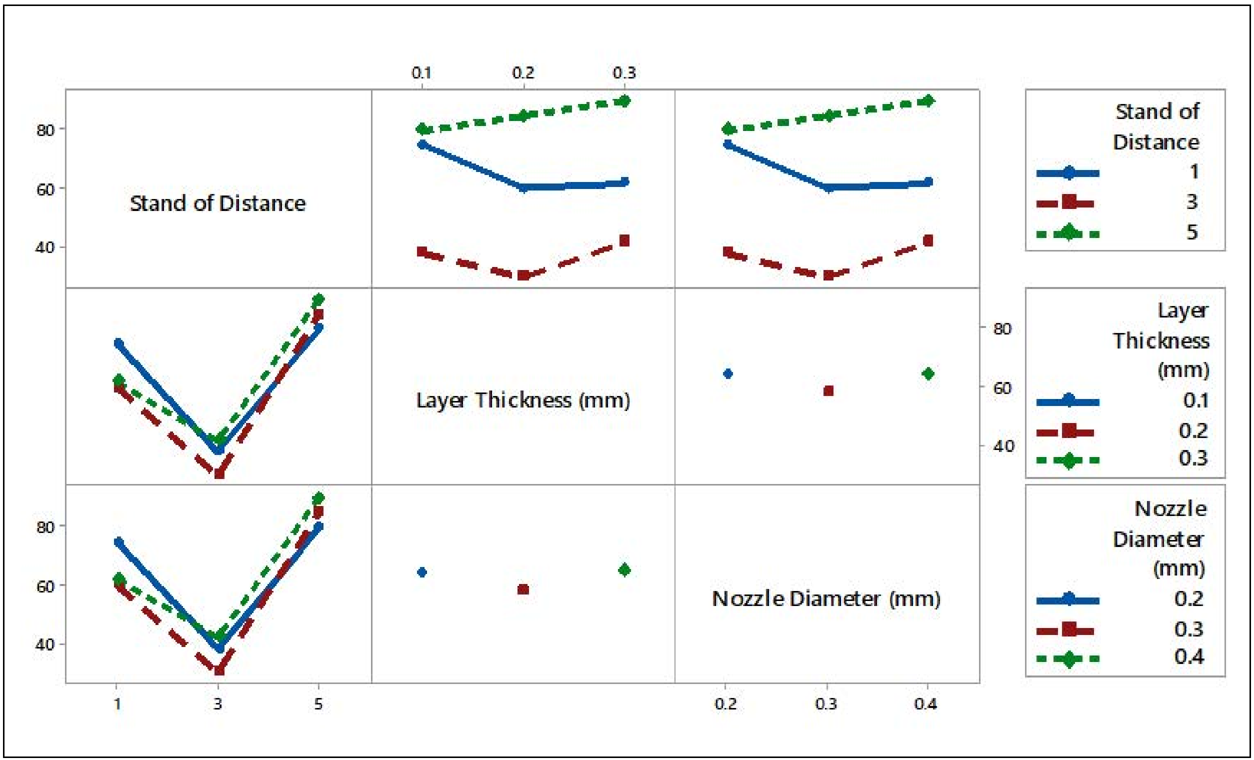

Fig. 14: The final output values

This image illustrates a study examining the impact of nozzle diameter, layer thickness, and stand-off distance on a specific dependent variable, potentially a printing or mechanical feature such as strength, precision, or quality. Compared to the 3 mm and 5 mm distances, the blue line (stand-off distance of 1 mm) usually yields larger values on the y-axis. Additionally, the greater stand-off distance (red and green) results in poorer quality or performance, possibly due to irregular adhesion or substance deposit irregularities.

4. CONCLUSION

One of the cleanest additive manufacturing processes is direct ink writing (DIW). Biological, dental, and surgical fields are among its many potential uses. As a by-product of this 3D additive manufacturing process, the Taguchi approach outperforms competing methods concerning the quality of the input values, the ease of analysis, and optimization. The direct ink writing equipment manufactured the component within 30 to 60 minutes, yielding the desired result.

The DIW machine didn't turn on until the CAD software converted these designs into G-codes. Among the best materials for dental and biomedical uses, aluminum ceramic Nanopowder is biocompatible, non-toxic, and does not alter tissues.

Aluminum ceramic is an excellent choice for determining the stand-off distance, build time, layer thickness, and nozzle diameters among the many available materials in this process. It can withstand temperatures up to 2072^0 C and has a high thermal conductivity and compressive value. One of the most incredible ways to make dental implants, bridges, and crowns is via the additive manufacturing technique of 3D printing, which employs this aluminum ceramic.

The cross-disciplinary materials science research, AI-driven process optimization for printing, and biocompatibility testing are required to improve DIW's suitability for application in biomedicine. The ultimate objective is to improve integration and reduce surgical risks while also generating personalized implants that last a long time and function well.

DIW will become scalable for biomedical applications with the assistance of automation, multi-nozzle systems, AI-driven optimization, and hybrid manufacturing. Research efforts further forward should concentrate on improving post-processing efficiency, developing high-speed DIW systems, and ensuring regulatory compliance.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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