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Investigating the Effect of Modifying the Binder and Other Additives on the Printability of Ceramic Paste for the Direct Ink Writing (DIW) Technique

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ABSTRACT

Ceramic 3D printing, also known as ceramic additive manufacturing, is one of the new production methods based on 3D printers without the need for molds. This manufacturing method allows for the creation of ceramics with complex geometric shapes, hence cost reduction. Among the various additive manufacturing methods, extrusion-based printers have been well received by a large number of researchers and industrialists. In this study, the rheological behavior of ceramic pastes and their printability in the extrusion-based 3D printing process were investigated. Emphasis is placed on optimizing the parameters that affect paste printing, particularly for pastes containing a high weight percentage (wt%) of alumina powder. The current research used Direct Ink Writing (DIW) method to examine the impact of adjusting binder content and additives such as plasticizers and dispersants on the printability of the alumina paste. The results indicate that optimizing these parameters improves the printability of the paste which exhibited shear thinning behavior. Paste samples with varying weight percentages of alumina powder and Polyvinyl Alcohol (PVA) binder were prepared. After evaluating their printability and viscosity, the printing process was carried out. The printed samples were then sintered at a temperature of 1250 °C. The results revealed that increasing the printability of alumina pastes enhanced their density and strength. The best results were achieved with a 70 wt% alumina sample, which exhibited a density of 1.8 g/cm³ and a flexural strength of 2.9 MPa. These results confirm the significant influence of wt% of alumina powder on the mechanical properties of the printed parts.

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1. INTRODUCTION

The 3D printing of ceramics is one of the modern manufacturing methods that does not rely on the conventional manufacturing methods used in other manufacturing processes for shaping and constructing ceramic parts. Therefore, it is classified as an additive manufacturing process. The absence of molds brings about significant changes in the production of ceramic parts, as demonstrated by the above-mentioned method of constructing ceramic components. These changes include the elimination of defects associated with mold formation and the ability to create complex geometric shapes that were previously impossible to produce in a single piece due to the constraints of molds (Chen et al., 2019). These advantages highlight the benefits of using ceramic 3D printers. However, many researchers employ various methods to construct ceramic parts, such as Selective Laser Sintering (SLS), powder Selective Laser Melting (SLM), extrusion-based methods such as Fused Deposition Modeling (FDM), and Robocasting, as well as other techniques such as stereolithography and binder

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jetting (Lakhdar et al., 2021). Table 1 provides a classification of these Techniques.

Extrusion-based 3D printing of ceramic paste, often referred to as Direct Ink Writing (DIW) or Robocasting, is among the most effective techniques in this field (OKYAY & SAĞBAŞ, 2021). To prepare an appropriate printing paste, ceramic powder is first mixed with a polymer binder and other additional ingredients. The resulting paste is then put in the extrusion chamber, which functions similarly to a conventional printer, to print and build the part. Under the pressure generated by the extruder, the paste moves toward the nozzle, where it is extruded into a filament. The desired part is constructed layer by layer through the X, Y, and Z movements of the arm attached to the extruder, following a pre-made design map. Layer by layer, the desired portion is constructed. One of the advantages of Robocasting is that it does not require any sophisticated or expensive equipment, allowing for low-cost part production. This is because none of the steps involved require the use of heat or other auxiliary equipment. Instead, secondary methods, such as sintering the part in a furnace after printing, are used (Shahzad et al., 2013). A schematic of the steps involved in creating a ceramic item using the Robocasting 3D printing technique is displayed in Figure 1.

Of note, additive manufacturing methods for ceramics also have some limitations, including their inability to produce large volumes and relatively low production speed on an industrial scale. Additionally, the unique capabilities of these manufacturing methods have been underutilized in the industrial sectors due to a lack of awareness among a wide range of industrialists about the different 3D printing techniques for ceramics and the parameters that affect them (Rane et al., 2019).

TABLE 1. Types of Ceramic Additive Manufacturing Techniques

Ceramic Additive Manufacturing	Photo Polymerization	Digital Light Processing (DLP)		(Lee et al., 2015)
		Stereolithography (SL)		(Khecho et al., 2021)
	Extrusion Based	Direct Ink Writing (DIW) Or Robocasting (RC)		(Xia et al., 2019)
		Fused Deposition Modeling (FDM)		(Onagoruwa et al., 2001)
		Feezed form Extrusion Fabrication (FEF)		(Huang et zal., 2006)
	Jetting	Slurry Jetting	Direct inkjet printing (DIP)	(Bae et al., 2018)
		Binder Jetting	Powder Binder Jetting (PBJ)	(Farzadi et al., 2015)
			Slurry Binder Jetting (SBJ)	(Grau et al., 2022)
	Powder Based	Direct Energy Deposition (DED)		(Balla et al., 2008)
		Selective Laser Melting (SLM)		(Hao et al., 2009)
		selective laser sintering (SLS)		(Gao et al., 2013)
	Sheet lamination manufacturing	Laminated Object Manufacturing (LOM)		(Weisensel et al., 2004)
		Computer-Aided Manufacturing engineering materials (CAM-LEM)		(Cawley et al., 2022)

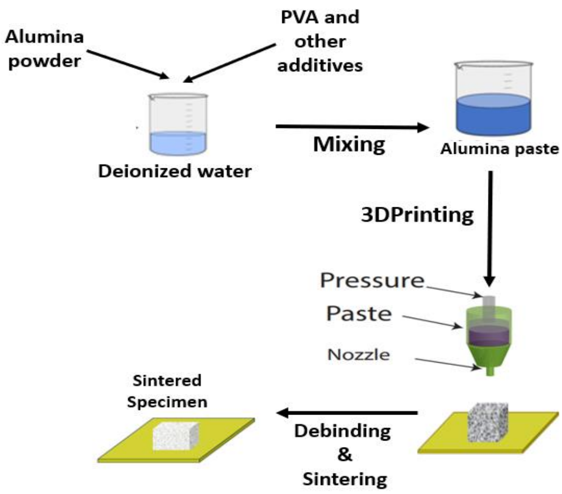

Figure 1. schematic of additive manufacturing ceramic parts utilizing extrusion based ceramic 3D printing.

In general, optimizing the paste used in robocasting can enhance the production of ceramic parts. This includes improving the printability of high-percentage ceramic powder pastes and increasing the quality of the resulting parts, such as their density and strength. In case either the integrity or the viscosity of the ceramic paste is low, the filament extruded from the nozzle will be of poor quality, and the layers of the printed part will not have sufficient strength and stability; hence, these layers will collapse on each other and disrupt the shape and dimensional accuracy of the part (Flores-Martinez et al., 2022a; Mamatha et al., 2021). In addition, if the paste has very stiff continuity or the high viscosity, the probability of it exiting the nozzle and forming a continuous filament will be quite low. Moreover, the final filament will lose its capacity to construct the part layer by layer in terms of both shape and application method. Therefore, identifying the optimal parameters and transition effects in suitable pastes for extrusion gains importance. These parameters include the amount and type of binder used as well as those of the additives such as dispersants and plasticizers, etc.(Lakhdar et al., 2021; Lamnini et al., 2022). Among ceramic materials, alumina which is a widely used industrial oxide ceramic, is particularly suitable for preparing water-based ceramic pastes. At high alumina loading percentages, the behavior of alumina powder-containing paste shifts toward non-Newtonian fluid behavior, exhibiting dilatant behavior (Cesarano TIl et al., 1997), modifying the behavior of alumina paste ultimately helps acquire knowledge about and a better understandhow to adjust the behavior of binders and other additives for the printability purposes of the desired paste. To date, several studies have been conducted to address these issues, investigating different binders and additives to print alumina pastes, with the alumina powder content varying depending on the research conditions. Some of these studies are summarized in the Table 2.

However, none of the previous studies have simultaneously investigated the effects of dispersants and plasticizers in PVA-containing alumina pastes at a specific ratio. Therefore, the aim of the present research is to study the effects of additives applied in alumina pastes designed for 3D printing using the Robocasting method. The goal is to achieve optimal additive percentages that not only improve printability but also result in final printed parts with desirable density and strength.

2. EXPERIMENTAL PROCEDURES

2.1. STARTING MATERIALS

In this research, alumina (Bohler, D50:1 µm, Germany) was used as the ceramic powder, PVA (Merck, Germany) as the binder, deionized water as the solvent, Dolapix CE64 (industrial grade, China) as the dispersant, and TM-HSP (TamamMavad co. , Iran) as the plasticizer.

2.2. FABRICATION OF CERAMIC PASTES AND GREEN BODIES

First, the PVA granules were weighed and placed in a beaker. The calculated amount of water was then added to the binders. The beaker was placed on a heater stirrer (IKA, Germany) to dissolve the PVA in water at 80 °C and a sintering speed of 400 rpm.

TABLE 2. Composition of alumina pastes used in DIW.

Ceramic powder	Solvent	Binder + Additives	Alumina powder content	Ref
Alumina	Water	Methylcellulose, Polyelectrolyte dispersant	73 .32 wt%	(Minas et al., 2016)
		Ethyl-hydroxyethyl-cellulose (0.42 wt.%), Ammonium acetate, Polyelectrolyte dispersant	81 wt.%	(Schlordt et al., 2012)
		Ethyl-hydroxyethyl-cellulose (0.42 wt.%), Polyethyleneimine (0.9 wt.%), Polyelectrolyte dispersant (0.4 wt.%)	79.6 wt.	(Fu et al., 2017)
		Polyvinyl alcohol (1 wt.%), Propionic acid	71.76 wt%	(Minas et al., 2016)
		Polyvinyl alcohol, Cross-linking agent, 1-octanol, Polyelectrolyte dispersant	70-73 wt%	(Morissette et al., 2000)
		Alginic acid, Polyelectrolyte dispersant	70.2 wt.%	(Glymond & Vandeperre, 2018)
		Pluronic F127 (25 wt.% a)	65 wt.%	(Feilden et al., 2017)

Once the binder solution was prepared, the alumina powder was weighed and added to the solution, followed by continuous manual stirring. If other additives are required, they are added while the samples were being stirred. After preparing the aluminum paste samples, the mixtures were placed in the chamber of the printer's extruder (Abtin 1, Abtinteb, Iran) and printed with a nozzle diameter of 2 mm and a pressure of 0.2 MPa, maintaining a nozzle-to-substrate distance of 1.5 mm. The desired 3D model was first created using SolidWorks software, from which the G-code file was extracted. The dimensions of the designed part were set at 15mm x 45mm x 10 mm with a 100% filling rate. The part design file was then transferred to the printer program execution software, Repetier-Host (V2.1.6-Germany), enabling the printer to build the desired part layer by layer according to the provided design.

2.3. DEBINDING AND SINTERING

To analyze the relationship between the printability of the pastes produced and the strength and final bulk density of the produced parts, the samples underwent debinding and sintering at a heating rate of 10 °C/min up to 1250 °C for 2 hours. The heat treatment diagram is shown in Figure 2. In this diagram, the specimens were held at 240 °C and 300 °C for 3 minutes to ensure that the gradual removal of binder and any excess material from the interior of the part, thereby preventing any defects or cracks in the structure of the part.

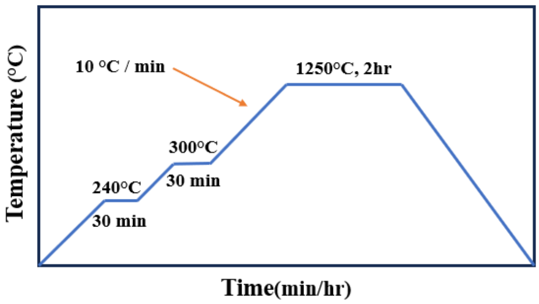

Figure 2. Heat Treatment Diagram of 3D Printed Samples

2.4. MATERIAL CHARACTERIZATION

2.4.1. EVALUATION OF THE PRINTABILITY OF THE SAMPLES

The printability of the pastes was evaluated based on the quality and manner of paste extrusion from the nozzle, as well as and the quality of the filament in terms of texture and structural integrity. Scores were assigned according to Table 3 Accordingly, each paste was assigned a number between 1 and 10, with 10 being the best score and 1 the lowest score. To study the viscosity of the prepared pastes, a rheometer (Anton Paar, MCR300, Astria) was used. The Archimedes method was used to determine the density of the sintered parts, and the three-point bending (3PB) test (Sanat Ceram, Iran) was done to determine the flexural strength of the samples.

TABLE 3. Examination of the printability of the pastes on the basis of the relevant variables and their evaluation

Score	Structural integrity of filament texture	Uniformity and homogeneity of filaments	Exit conditions from the printer nozzle
1	x	X	X
2	x	X	X
3	x	L	X
4	L	L	Very diff
5	L	M	Very diff
6	M	M	diff
7	M	M	Eff
8	M	O	Eff
9	O	O	M
10	E	E	E

L: Low, M: Medium, O: Optimal, E: Excellent, diff.: difficult, Eff.: Effortless.

3. RESULTS AND DISCUSSIONS

3.1. INVESTIGATION OF THE PRINTABILITY OF ALUMINA PASTES

To investigate the changes in the printability of the samples resulting from an increase in the amount of alumina powder, or to examine the effect of increasing the percentage of binder or other additives, the samples were prepared with different alumina wight percentages of 55 wt%, 60 wt%, 65 wt%, and 70 wt%. Additionally, polymer binders contents used in the samples were varied at 10wt%, 15wt%, and 20wt%. Finally, the optimized amounts of dispersant and plasticizer in the samples were investigated through controlled addition to the samples.
It should be noted that printability becomes more difficult with pastes containing high amounts of alumina powder. This difficulty results from not only the hard and uneven extrusion of the ceramic paste from the nozzle but also from the change in the paste behavior from a pseudo-plastic state to a dilatant state. This criterion can ultimately have a negative impact on the strength and density of the sintered parts. Therefore, studying the printability of the paste through the addition of binders and other additives plays a significant role in determining the print quality and properties of the printed parts.

3.1.1. INVESTIGATION OF THE PRINTABILITY OF THE PASTES PRODUCED ON THE BASIS OF VARIATIONS IN THE AMOUNT OF PVA AS A BINDER

In this section, varying weight percentages (wt%) of PVA were added to each specific alumina sample. These percentages were 10 wt%, 15 wt%, and 20 wt%, resulting in a total of 12 samples divided into four categories. The printability of these samples is demonstrated in the graph in Figure 3.

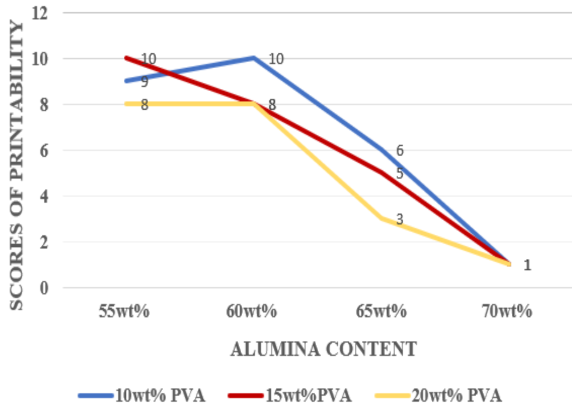

Figure 3. Investigation of the production samples with respect to the amount of dispersant and plasticizer additives

As shown in Figure 3, the quality of the filaments and the printability conditions decrease with an increase in the wt% of alumina. This decrease is particularly observed in the 70 wt% alumina sample, which can be attributed to the dilatant behavior of alumina pastes containing approximately 70 wt% alumina powder (Cesarano TIl et al., 1997). In contrast, for the 55 wt% to 60 wt% alumina samples, the printability of the pastes remained satisfactory and did not vary significantly with increasing wt% of alumina. Of note, in the 65 wt% and 60 wt% alumina samples, reducing the amount of PVA by 10 wt% improved printability, which can be attributed to the simultaneous absorption of water by the alumina (Minas et al., 2016). When the binder content increases, the water content in the paste decreases significantly, hence a reduction in printability.

3.1.2. INVESTIGATION OF THE EFFECT OF ADDITIVES ON THE PRINTABILITY OF ALUMINA PASTES

Dispersants generally act as spatial inhibitors by dispersing particle agglomeration in the paste through electrostatic repulsion. When added to pastes with high ceramic powder content, dispersants increase fluidity, which is very important for the printability of these types of pastes (Lee et al., 2021). Therefore, it is important to study the increase in paste fluidity due to the addition of different amounts of dispersants (Abbasian, 2018). However, a significant challenge, as noted by other researchers, is the rapid and excessive changes in fluidity due to the addition of small amounts of dispersant, making it very difficult to control the fluidity of the paste (Landek et al., 2021). For this reason, many researchers also use plasticizers, which can be used independently or simultaneously with dispersants to enhance the printability of the paste in a controlled manner (Ananthakumar et al., 2004; Nie et al., 2021). Plasticizers mainly disrupt hydrogen bonds and van der Waals forces between the alumina particles and reduce the friction between the particles, hence a decrease in the viscosity of the ceramic paste, making it act as a lubricant (Wu et al., 2023).

Based on the obtained results in the previous section, a 65 wt% alumina paste containing 20 wt% PVA was used as it offered the highest alumina powder loading under conditions of acceptable printability and the maximum binder content. At this stage, four samples with varying additive levels were prepared. The first sample contained no additives, the second included one drop of dispersant (0.016 g), the third had two drops of dispersant (0.032 g), and the fourth combined one drop of dispersant (0.016 g) with 0.16 g of plasticizer. It was observed that increasing the amount of dispersant improved printability, and when dispersant and plasticizer were used in a 1:10 ratio, their combined effect significantly enhanced the print quality. All reported results are reported in Figure 4.

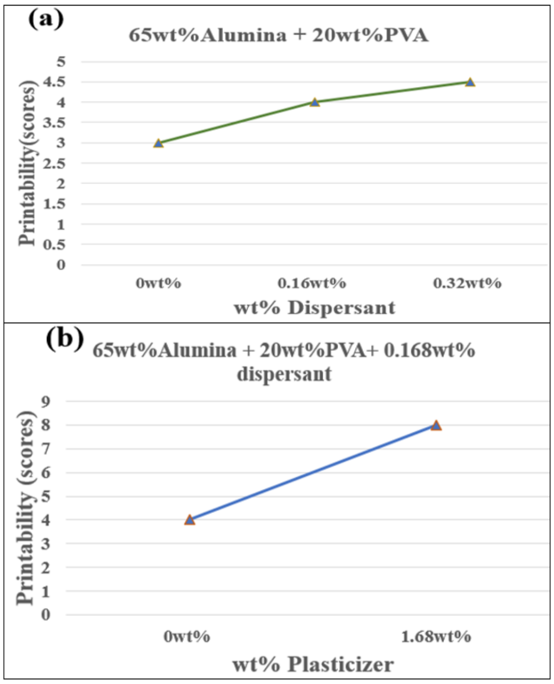

Figure 4. Investigation of the effect of adding a) dispersant and b) plasticizer in samples containing 65wt% Alumina + 20wt% PVA.

In general, addition of higher amounts of PVA to the ceramic pastes enhances the green strength of the printed bodies However, this increase must be optimized. In the case of low amount of PVA, the strength of the produced bodies will decrease while increased amount of PVA will in turn increase the viscosity and reduce the sample printability, potentially causing high pressures during the printing process (Ananthakumar et al., 2004; Nampi et al., 2011). Following the study of the effects of dispersant and plasticizer in a sample containing 65wt% of alumina, the effect of dispersant was investigated in samples containing 70 wt% alumina. For this purpose, a second series of samples was prepared with varying binder percentage of 10 wt% and 15 wt%. In both series, different amounts of dispersant were added. It was observed that in all samples, the printability improved upon increasing the dispersant. As clearly shown in Figure 5, samples containing 10 wt% PVA exhibited better printability than those containing 20 wt% PVA.

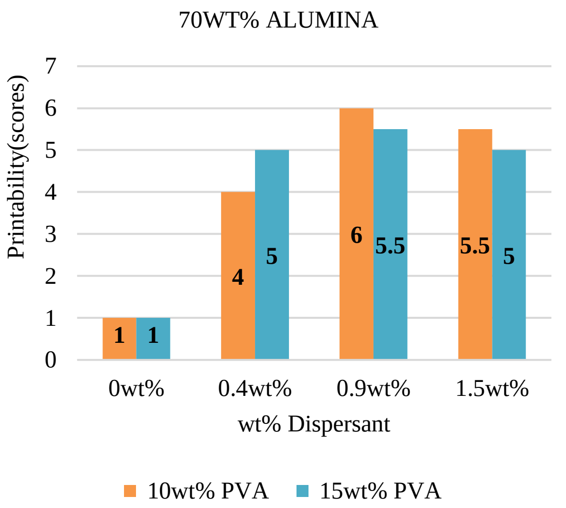

Figure 5. Graph of changes in printability versus weight of dispersant in 70 wt% alumina pastes at different PVA ratios.

The effect of adding a specific amount of dispersant and plasticizer on the printability of 70 wt% alumina samples with two different weight percentages of 10 wt% and 15 wt% PVA binder was then investigated, the results of which are shown in Figure 6. It was observed that, in both series of samples, the printability improved with the addition of dispersant and that the printability conditions were further improved by simultaneous addition of plasticizer. It is important to note, however, that as the amount of plasticizer increased, the amount of dispersant used was significantly reduced while the printability conditions were improved. It has been suggested that reducing the amount of dispersant used can lower the production cost of alumina pastes (Maillard et al., 2023).

3.2. INVESTIGATION OF THE VISCOSITY OF PASTES WITH DIFFERENT ALUMINA AND PVA CONTENT

The printability of alumina pastes is influenced by several rheological parameters, including viscosity. Therefore, in addition to increasing the alumina particle content, researchers have focused on adjusting the binder and other additives (Maillard et al., 2023). By analyzing the effects of these variables on samples with different alumina levels, the optimal use of dispersant and plasticizer was determined. The optimal amount of dispersant was found to be approximately 0.045 grams (equivalent to 4 drops) while the amount of plasticizer was 0.48 grams, with the plasticizer-to-dispersant ratio of - approximately 10 to 1. To examine the viscosity and shear rate of the produced samples, four samples were selected for rheological testing. After conducting the experiments, the shear rate and viscosity of these samples, with the formulations specified in Table 4, were obtained.

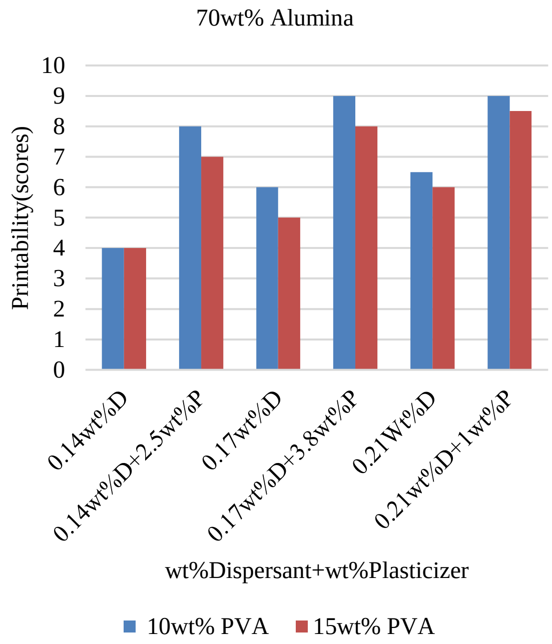

Figure 6. Comparison of 70 wt.% ceramic pastes with different amounts of binders, dispersants and plasticizers.

TABLE 4. Investigation of the viscosity of modified pastes at different amounts of binder and constant values of plasticizer and dispersant.

Sample No.	Formulation
A60P10	60wt% Al_2O_3 +10wt%PVA
A65P10	65wt% Al_2O_3 +10wt% PVA
A65P20	65wt% Al_2O_3 +20wt% PVA
A70P10	70wt% Al_2O_3 +10wt% PVA

Figure 7 illustrates the viscosity changes of the samples as a function of shear rate. As observed, the viscosity of all samples decreased upon increasing shear rate, indicating that despite the high wt% of alumina powder, the behavior of the produced pastes was pseudoplastic rather than dilatant. This characteristic is considered a positive aspect, as it indicates shear-thinning behavior of the paste, which results in reduced viscosity when exiting the nozzle. This property plays an important role in facilitating the printing process (del-Mazo-Barbara & Ginebra, 2021; Cesarano TIl et al., 1997). Conversely, as the part is built up layer by layer and the applied force on the pastes is removed, their viscosity increases, preventing the formed layers from collapsing, a behavior contrary to the dilatant materials. Therefore, the simultaneous use of dispersant and plasticizer in the production of pastes proved to be very positive and important.

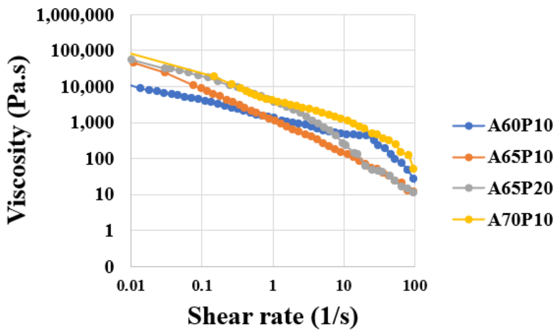

Figure 7. Investigation of viscosity alumina paste as a function of shear rate.

Based on the viscosity examination of the sample pastes shown in Figure 8, it is evident that as the wt% of alumina increases, the viscosity increases correspondingly. In particular, the sample with 70 wt% alumina shows a significant increase in viscosity, which is also common for alumina pastes with 70 wt% and higher (Rueschhoff et al., 2016). In addition, in Samples 2 and 3, which contain 65wt% alumina and varying amounts PVA (10 wt% and 20 wt%) as the wt% of PVA increases, the viscosity increases as well. This can be attributed to the excessive bonding between the particles and the binder, which in turn leads to the formation of clusters of coagulating alumina particles, hence an increase in the paste viscosity (Xiaotong Fang et al., 2023). Nonetheless, the fluidity of the produced pastes was of suitable quality, resulting in the overlapping of the printed layers and formation of a cohesive structure with a very smooth surface and no visible defects, a phenomenon also observed in the research by Maillard et al. (Maillard et al., 2023).

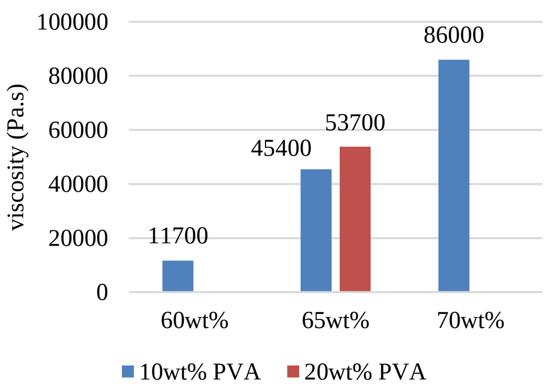

Figure 8. investigation of the effect of the viscosity of alumina pastes based on the wt% of alumina and PVA used.

3.3. DENSITY AND FLEXURAL STRENGTH TESTING

After printing the pastes prepared according to Table 4, the samples were sintered at a temperature of 1250 °C. This process allowed for evaluating the final density of the printed parts and understanding the relationship between suitable printability and the final raw density of the parts and, consequently, the strength of the samples. Based on the calculated density, it was observed that as the wt% of alumina powder in the printed samples increased, the density of the parts increased, as expected. For samples 2 and 3, which contained 65 wt% alumina, the density of the samples decreased as the amount of PVA increased from 10 wt% to 20 wt%. This reduction of density may be attributed to the increased viscosity of the printed paste and the lower printability quality of the paste, resulting in the part with a lower printed density. Similar observations have also been reported in other studies (Maillard et al., 2023; Cesarano TIl et al., 1997). This issue is also observed in the strength of the specimens. As the wt% of alumina powder increased, the density of the specimens increased as well, resulting in decreased porosity and enhanced compaction (Flores-Martinez et al., 2022b). Similarly, in samples 2 and 3, the addition of PVA, which reduced their density, also decreased the strength of the part. This indicates a direct relationship between the strength of the printed parts, their density, and ultimately the printability of the pastes. This problem has also been addressed in some studies conducted by other researchers which is attributed to insufficient adhesion and bridging between the particles and the binder caused by excessive saturation of the binder used (Xiaotong Fang et al., 2023). In addition, using higher percentages of PVA reduces the possibility of complete debinding of the parts during the process. However, this would result in large pores and voids in the final sintered parts due to uneven binder removal, which negatively affects the final strength of the parts (Maillard et al., 2023; Xiaotong Fang et al., 2023). The flexural strength and density of the final printed samples are shown in Figure 9.

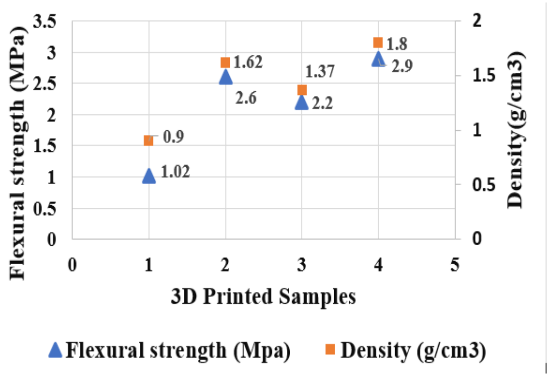

Figure 9. Investigation of the strength and density of samples sintered at a temperature of 1250 °C.

4. CONCLUSION

3D printing of aluminum parts makes it possible to create components with complex geometric shapes while reducing defects caused by the molds used in traditional methods. One of the additive manufacturing methods preferred by researchers and industrialists is extrusion-based additive manufacturing, of which DIW is the most important. In this process, a ceramic paste containing ceramic powders, a polymer binder, and other additives is printed layer by layer by a 3D printer to create a part based on a 3D-designed model. However, the printability of high-alumina pastes presents several challenges, including increased viscosity due to the higher weight percentage of alumina in the pastes, which ultimately leads to inadequate printing of ceramic parts. This in turn results in the inability to create a continuous and uniform structure, making successful sintering of the parts impossible and increasing the likelihood of defects in the printed parts, as well as reducing the mechanical properties of the final components. On the contrary, if the modified ratio between the amount of dispersant and plasticizer used in the alumina paste is not achieved, the possibility of dilatant behavior in the paste greatly increases.

In this regard, the present research investigates the effect of changing the weight percentages of ceramic powders along with finding the optimal amount of binder used and other additives such as dispersants and plasticizers. According to the results obtained from the printability diagram of the samples, the printability was high at low wt% of solid ceramic particles. However, due to the low wt% of alumina powder, the produced parts exhibit lower density and strength than other samples. However, as the wt% of alumina increases, the printability of the samples decreases, which is exacerbated by the simultaneous increase in the weight percentage of binder used. Moreover, as the amount of binder increased, the amount of water in the paste, which acts as a solvent, decreased. Given that alumina absorbs water, the printability of the paste decreases as well. To improve the printability and modify the behavior of the paste, the effects of dispersants and plasticizers were then studied separately and simultaneously. The best additive amounts at high wt% alumina usage were measured as 0.045 g for dispersants and 0.48 g for plasticizers. Followed by optimizing the additive levels, four samples were selected to study the rheological behavior.

According to the observations, upon increasing the weight percent of alumina, the viscosity increased. In addition, at the same wt% of alumina, the viscosity of the samples with lower amounts of PVA decreased, hence easier printing. While having the density and flexural strength of the samples examined, those containing 70 wt% alumina exhibited the highest strength at 2.9 MPa and the highest density at 0.8 g/cm^3. In the series of samples containing the 65 wt% by weight of alumina, the sample containing 10 wt% of PVA exhibited lower viscosity and better printability and density than the sample containing 20 wt% of PVA. In this summary. 3D printing of ceramic pastes using the Robocast method presnets many advantages and disadvantages. Among the advantages are the possibility of loading high percentages of ceramic powders by weight, possibility of changing different binders depending on the ceramic powder used, use of environmentally-friendly polymeric binders such as PVA, and simultaneous application of different ceramic materials with different particle sizes. However, these methods have some drawbacks namely the requirement for examination of the particle size distribution in the alumina paste, high sensitivity of the viscosity to the weight percentage of alumina powder or the amounts of additives, sensitivity of the paste printability to equipment parameters such as nozzle diameter and nozzle speed, need for proper design of the sintering and debinding curves to reduce potential defects, and necessity of post processes. It is anticipated that the future research will address these issues.

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