African Journal of Applied Research
Vol. 5, No. 1 (2019), pp. 132-147
http://www.ajaronline.com
http://doi.org/10.26437/ajar.05.01.2019.11

APPLICATION OF ADDITIVE MANUFACTURING TECHNOLOGY ADVANCES TO FOOD PROCESSING

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ABSTRACT

The additive manufacturing technology has not been used to process or build foods in the required shapes or patterns using raw or cooked ingredients of the food, especially in the varying ingredients ratio. The continuous expansion of additive manufacturing technology application requires that the materials application is expanded to enable it to widen its application. One of the key factors that is slowing down the fast development of the technology is the limited material application. This paper therefore looks at modifying the existing 3D Printer to print foods such as chocolate with varying taste at different layers, or labelling of pastries such already baked cake with inscriptions such as "HAPPY BIRTHDAY", "HAPPY WEDDING ANNIVERSARY", etc. The author has therefore undertaken a critical study of various processes of additive manufacturing technology and has come out with a modified system branded as "In-flight Mixing System", an attachment to an available 3D Printer (ReplicatorG). The modified system has been used to cross-mix to blend two ingredients of food (assorted colour of sugar syrup) on the surface of deposition to print layers of the syrup by the influence of compressed air. The In-flight mixing Additive Manufacturing technology avoids mixing of base materials before injecting through nozzles for building, hence preventing waste due to expiration of mixed ingredients.

Keywords: *Additive manufacturing; lightweight products; stereolithography; food processing; application*

INTRODUCTION

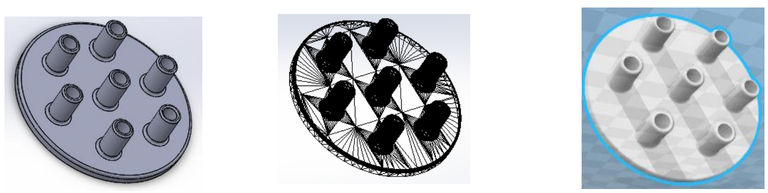
Additive Manufacturing (AM) has been described as a process by which digital 3D design data is used to build up a component in layers by depositing material source needed. AM takes a computer-generated design (Figure 1a) from Computer Aided Design (CAD) software, or obtained from Laser Scanning, Computer Tomography (CT), Magnetic Resonance Imaging (MRI), Mathematical Modelling software and stores it in stereolithography (stl.) file format (Guo

ISSN: 2408-7920

African Journal of Applied Research
Vol. 5, No. 1 (2019), pp. 132-147
http://www.ajaronline.com
http://doi.org/10.26437/ajar.05.01.2019.11

& Leu , 2013; Sreenivasan, Goel, & Bourell, 2010) which is the Rapid Prototyping's best possible tool path for the printer which then creates the object (Figure 1c) through selective placement of material in series of triangles (Figure 1b) (Campbell, Williams, Ivanova, & Garrett, 2011).

Even though many AM processes are in existence, the type of machine used determines the build or binding material (Guo, & Leu, 2013; Giannatsis, & Dedoussis, 2009). When building an object using any of the AM processes, choosing of the appropriate building direction is essential as it can influence the specifications of the object including quality, cost and lead time (Sreenivasan et al., 2010).



(a) (b) (c)

Figure 1: The 1 – 2 – 3 Major Steps of AM Technology

General Principles of Additive Manufacturing Technology

Even though several AM processes exist, they are all based on the same basic principles with various limitations such as build speed, interlayer adhesion, materials, and support structure (Dotchev, Dimov,Pham, & Ivanov, 2007).

The process starts by arranging the parts to be formed within a specified build area, and determining the suitable build direction of the part (Chua, Leong, and Lim, 2003). The factors that influence the orientation of the part to be built are: dimensional accuracy, clarity of detail, support and support removal, and build-time (Chua et al, 2003; Wendel, Rietzel, Kühnlein,Feulner, Hülder, & Schmachtenberg, 2008). Once orientation has been decided, the parts all run through "slicing" program, cutting the parts into "Z" layers. The "slice file" is then transferred to of the AM machines, where the parts are then formed layer by layer (Chua et al, 2003; Wendel et al, 2008).

African Journal of Applied Research
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Functional Parts and Tools by Additive Manufacturing

Even though many manufacturing industries are using the AM technology to solve a lot of complicated problems with material requirements ranging from plastics or ceramics to steel or titanium, the technology has not been able to solve all problems confronting the manufacturing sector (Gibson, Rosen, & Stucker, 2010). The technology is therefore not considered as complete substitute to conventional manufacturing processes, but rather suitably considered as their compliments (Gibson et al., 2010). The technology cannot produce parts in a wide enough range of materials to the entire spectrum of requirements of industry and science (Giannatsis, & Dedoussis, 2009). AM technology is used in two ways to make useful items, which include: *Direct and Indirect* or *Secondary Processes* (Guo, & Leu, 2013).

ADDITIVE MANUFACTURING DIRECT PROCESSES

Plastic Parts Produced by Additive Manufacturing Technology

With many processes of AM in use, some of the most significant ones thought to be for end-use directly fabricated products are Laser Sintering [LS] (Guo & Leu, 2013; Melchels, Domingos, & Klein, 2012; Murr, Gaytan, Ramirez, and Martinez, 2012), thermoplastic extrusion such as Stereolithigraphy [SL] (Zhang, Xu, Wang, 2003), or Fused Deposition Modelling [FDM] (Zhang, Xu, and Wang, 2003). Laser sintering extends its fabrication process to a wide range of engineering plastics such as glass-filled nylon, polysterene and PEE (Das, 2003; Kumar & Pityana, 2011). Examples of thermoplastic extrusion materials that are fabricated by laser sintering may include: ABS, polyphenylsulfone, polycarbonate, polyester, among others (Pityana, 2011; Kruth, Wang, Laoui, & Froyen, 2003). Parts produced by these processes possess higher strength and some added properties that are found currently in photopolymers (Campbell, Bourell, & Gibson 2012; Vaezi, Seitz, & Yang, 2013). Factors influencing the mechanical properties of parts built by AM process are: the direction, and the layered fabrication process itself (Campbell et al., 2012).

Metal Parts Produced by Additive Manufacturing Technology

Additive manufacturing processes that most often directly fabricate metal parts are Selective Laser Sintering (SLS) (Gu, Meiners, & Wissebach, 2012), Direct Metal Laser Sintering (DMLS) (Simchi, Petzoldt, & Pohl, 2003), Laser Powder Forming (Gu et al., 2012). Where necessary, porosity may be reached by secondary metal infiltration and secondary process applied when required (Gu et al., 2012; Gebhardt, 2007) to improve the surface finish.

Indirect or Secondary Processes

Despite the significant advancement in the growth of material in AM technology processes, its unmeasurable display of application requires that there is always the need to transfer AM fabricated parts into another material (Huang, Leu, Mazumder, & Donmez, 2015) based on the following factors: application, volume of parts to be produced, final material and accuracy requirements, and the additive process available (Huang et al., 2015).

ADDITIVE MANUFACTURING CATEGORIES, PROCESSES, AND MATERIALS

Even though there are several of AM processes available, researchers alongside the growth of the technology continue to work to add more of the processes and materials (Campbell, Bourell, & Gibson, 2012). The processes can be grouped into categories and differ in the way layers are built to create parts, and specific material application (Campbell et al, 2012). While some methods use softening, or melting of material to produce the layers, others lay liquid materials and then cure with different processes (Gebhardt, Schmidt, Hötter, Sokalla, & Sokalla, 2010). Others also use thin layers of materials such as paper which are cut to shape and joined together (Gebhardt et al., 2010; Chu, Engelbrecht, Graf, & Rosen, 2010).

Notwithstanding the uniqueness of the various AM processes, with varying characteristics, each method has its strengths or advantages and weaknesses or disadvantages (Chu et al., 2010; Pham, & Gault, 2009; Wong & Hernandez, 2012). These lead to several manufacturers a choice between paper, polymer, metal, etc. in the form of liquid, powder, or solid (Kruth, Wang, Laoui, & Froyen, 2003) for an object emerging from these materials (Wong & Hernandez, 2012; Hopkinson, Hague, & Dickens, 2006; Huang, Mokasdar, & Hou, 2013).

Liquid-Based Process

These processes characteristically use photopolymer resins and cure selected portions of the liquid vat to form each layer (Pham, & Gault, 2009). The most common liquid based process is stereolithography (Kruth et al, 2003). Parts produced by this process have high accuracy with appearance that are like moulded parts, but with poor mechanical properties that sometimes worsens overtime. Others include jetted photopolymer and Inkjet printing (Kruth et al., 2003; Pham, 2009) which may be single or multiple jet.

For example, the basic principle of Jetted Photopolymer is the photopolymerization, which is the process where a liquid monomer or a polymer converts into a solidified polymer by applying ultraviolet light which acts as a catalyst for the reactions; this process is also called ultraviolet curing (Pham et al., 2009). It is also possible to have powders suspended in the liquid like ceramics (Pham et al., 2009; Kruth et al, 2003).

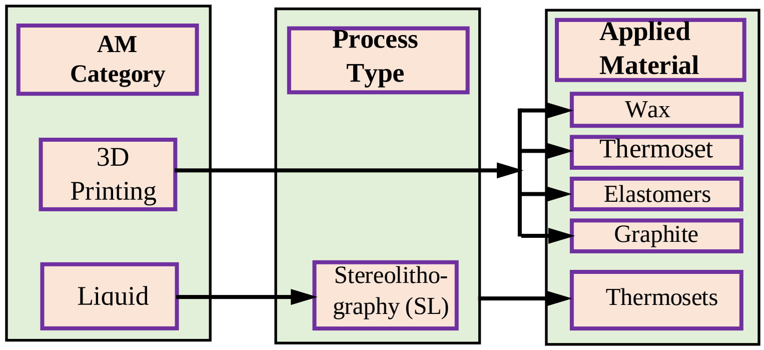

Figure 2: Liquid–Based Additive Manufacturing

(Source: http://www.custompartnet.com, 2013)

Powdered-Based Process

The powdered-based processes (Figure 3) operate on the principle of consolidating selected portion of powdered material which is sintered using a laser or electron beam to fuse scans of sliced CAD data layer by layer to create the geometry (Gibson, Rosen, & Stucker, 2010). After each layer, a re-coater mechanism lays down powder on top of each scanned area, which allows another layer to be built on top of the previous one (Gibson et al, 2010).

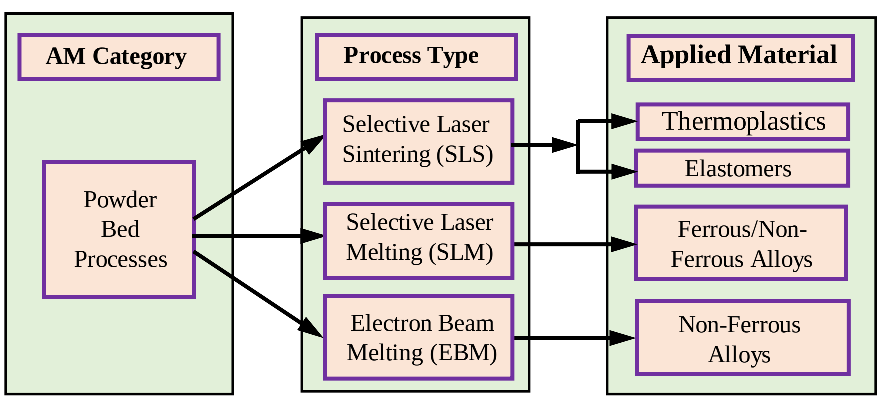

Figure 3: Powdered Based Additive Manufacturing Process

(Source: http://www.custompartnet.com, 2013)

African Journal of Applied Research
Vol. 5, No. 1 (2019), pp. 132-147
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http://doi.org/10.26437/ajar.05.01.2019.11

Material Deposition/Extrusion Process

The deposition processes (outlined in Figure 4) work by heating the material using a laser or electron beam source through a nozzle which extrudes it following a path which is pre-defined, depositing a layer on top of a platform, one on top of the other successively to create a three-dimensional geometry (Gibson et al., 2010).

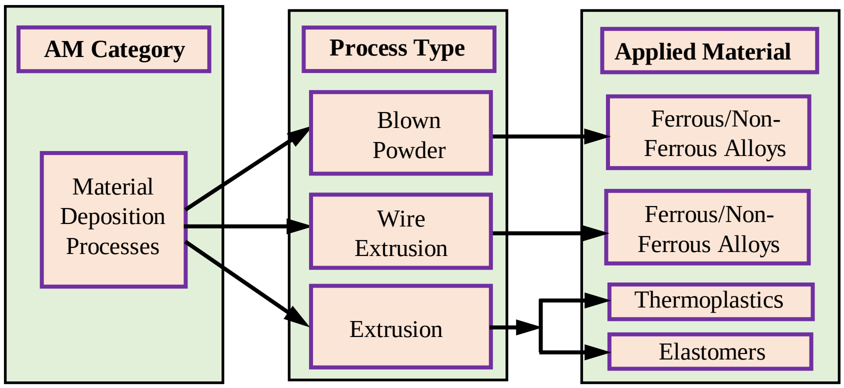

Figure 4: Material Deposition/Extrusion Additive Manufacturing
(Source: http://www.custompartnet.com, 2013)

The Competitive Dynamics of Additive Manufacturing

The ecosystem of AM will have major effects in each of the three main stages of the design-build-deliver model (Lipson & Kurman, 2013). It will change the nature of design, increase the interactivity between design and production, and radically localize manufacturing as consumers interact more directly with each other and with manufacturers, some of which act as printer hubs, offering services to anyone with a design to print (Lipson & Kurman, 2013; Petrick &Simpson, 2013).

Environmental Impact of Additive Manufacturing

Conventional manufacturing processes such as casting and moulding produce hazardous industrial waste, therefore, generating a lot of environmental pollutants (Ford, 2014), which many countries spend huge amount of money to control (Babatunde, Zhao, O'neill, & O'Sullivan, 2008). AM technology has emerged as a multidimensional tool used to alleviate these negative environmental impacts (Babatunde, Zhao, O'neill, & O'Sullivan, 2008). The constraints imposed

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on product design by AM are very few compared to the conventional manufacturing processes, as it enables previously separate parts to be combined into a single object with augmented functionality and decreased energy and natural resources required to operate it (Ford, 2014; Babatunde et al., 2008), which will in effect avoid material waste on every sub part, sometimes not recyclable and would therefore have to be thrown to the environment.

The Competitive Dynamics of 3D Printing

The 3D production ecosystem will have major effects in each of the three major stages of the design-build-deliver model (Lipson and Kurman, 2013). It will change the nature of design, increase the interactivity between design and production, and radically localize manufacturing as consumers interact more directly with each other and with manufacturers, some of which act as printer hubs, offering services to anyone with a design to print (Petrick and Simpson, 2013; Ford, 2014).

METHODOLOGY

The existing 3D printer (Figure 5) was modified to suit the production of fluid or semi-liquids. In this paper, the fluids used for the testing of the modified system were sugar syrup with high viscosity.

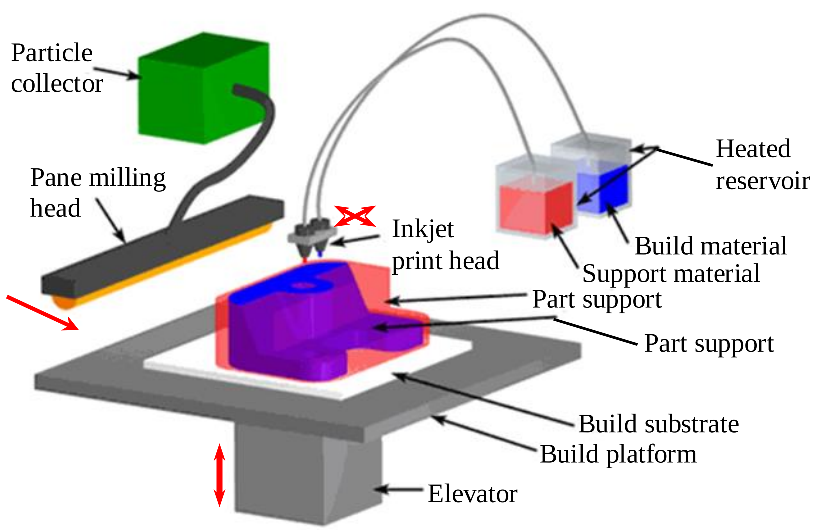

Figure 5: The Inkjet Additive Manufacturing Process

(Source: http://www.custompartnet.com, 2013)

ISSN: 2408-7920

African Journal of Applied Research
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Design of the In-flight System

Even though some existing 3D printers have more than one print nozzles, such as one having two nozzles (Figure 5) by which one of them prints the build material and the other the support material (the support material normally supports overhang or wide opening of a part), they do not print varied materials mixed together whilst printing. Where two or more materials are to be mixed printing, mixing of the materials takes place in a separate chamber by any possible means before feeding through the nozzle. This research looks at modifying the existing 3D printer by designing an attachment that would enable the machine print two separate fluids mixing on the surface of deposition with varying mixing ratio. An object of varying constituents of colours could therefore be realised based on how much of the ingredient is metered.

Description of the Designed In-flight Mixing System

The system consists of compressed air supply which is distributed to two reservoirs, one containing ingredient 1 and the other ingredient 2. Two pressure controls are connected on each pipeline after the distribution junction to control the pressure acting on the ingredients. Each reservoir is covered with heater blanket which pre-heats to maintain the ingredients at the required temperature to reduce its viscosity to enable easy flow. Two pipelines, each for one of the constituents are connected from the reservoirs A and B to the individual nozzles. Between the fluid reservoirs and the nozzles are connected two needle valves with each on one side to regulate the flow of fluids from the reservoirs to the nozzles which enables variation of mixing ratio. The nozzles are held in their housings which are extruded cylindrical portion normal to the Y-arm of nozzles holder. They are made to be screwed in and out to increase or decrease the distance between the nozzle tip and the build platform. Heated air would be distributed to the housing environment which heats the substrates to facilitate the solidification of the laid substrate to enable another layer to be deposited on the previous one at the required rate. The platform is made to lower a height equal to thickness of a layer after each layer cycle to enable another layer built on top of the previously laid one as applied to any other additive manufacturing process. The schematic diagram of the designed in–flight system is shown in Figure 6 and the detailed attachment is shown in Figure 7.

ISSN: 2408-7920

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Vol. 5, No. 1 (2019), pp. 132-147
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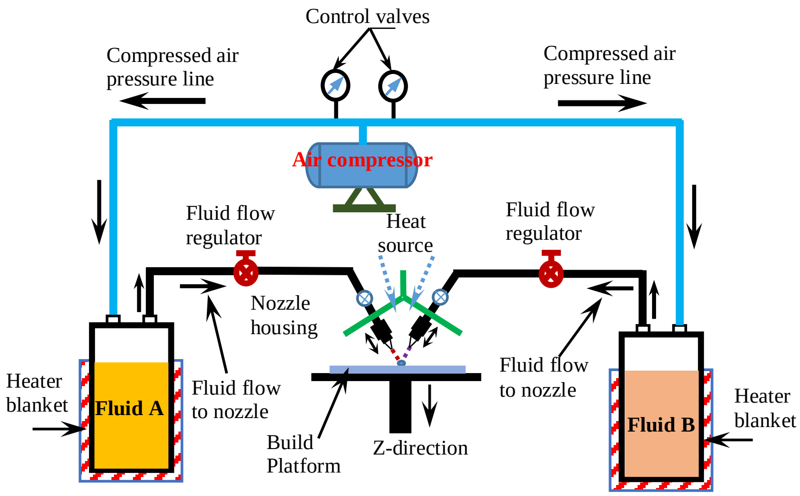

Figure 6: Circuit Diagram of the Modified 3D Printing

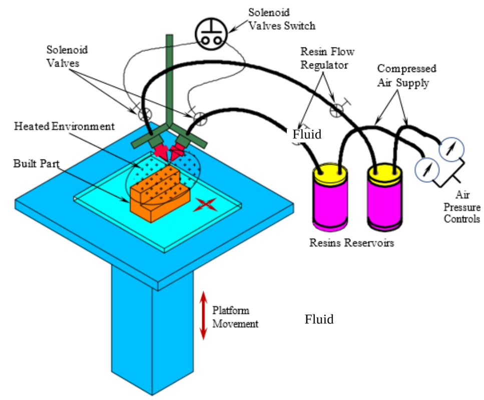

Figure 7: Modified 3D Printing System

Testing of the Designed In-flight Mixing Process

The final designed system tested using the Syrup was to be mixed to obtain a homogenous colour which would solidify to obtain a toffee when exposed to the atmosphere and enhanced by heated environment.

A simple rectangular hollow block with internal dimension (80 mm x 60 mm) and external dimension (84 mm x 64 mm) shown in Figure 8 and ring of internal diameter (60 mm) and external diameter (64 mm) as shown in Figure 9 were modelled using SolidWorks with extrusion of 3mm and saved in sldrt file (a), converted to slicing file (b), and subsequently to stl file (c). The model was transferred to the modified MakerBot Replicator 3D printer for printing.

The solenoid valves connections to the 12V DC battery were checked in accordance with the solenoid valves' operating specification by the manufacturer. The two resin reservoirs were connected to a TC2000 compressor was set at 1.5 bar. In all cases the solenoid valves were opened after all preliminary movements of the dispensing unit (print head) and the machine just starting to print the real object.

ISSN: 2408-7920

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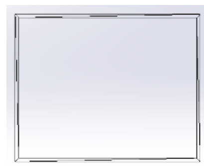
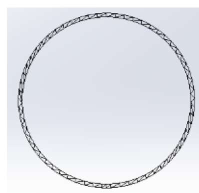



(a) Sldrt. File for sample **(b)** Slicing File for sample **(c)** Stl. File for sample

Figure 8: Modelled sample for testing of the designed/modified replicator


(a) Sldrt. File for sample **(b)** Slicing File for sample **(c)** Stl. File for sample

Figure 9: Modelled test sample by the designed/modified replicator

Testing of the Designed In-flight Mixing Process Using Syrup

The reservoirs were filled with the Syrup which had a clear colour and mixed with water (50 ml of syrup to 5ml of water) to reduce the viscosity to ensure that it would flow through the nozzle orifice under pressure. One of the syrup in the reservoirs was dyed with deep green food colouring liquid, and the other yellow which did not have effect on the viscosity when re-tested. The viscosity measured was 550 cP approximately.

The three selected angles (60º, 50º, 40º) between the nozzles (based on previous analysis for angle selection) were used for the dispensing using the available nozzle of orifice diameter 0.6 mm each of the two nozzles for the printer to print both the rectangles and the circles. Each test was carried out three times for repeatability. The widths and depths of the printed rectangles and circles were analysed by comparing measurements at three points on each side of the rectangles and six different points on each of the circles.

ISSN: 2408-7920

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Vol. 5, No. 1 (2019), pp. 132-147
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http://doi.org/10.26437/ajar.05.01.2019.11

TEST RESULTS/DISCUSSION OF THE DESIGNED IN-FLIGHT MIXING SYSTEM

Two–Dimensional Print of Syrup

Figure 10 – Figure 12 (a) – (c) illustrate three samples each of the two figures (rectangular and circular) printed using the 60º, 50º, 40º holders.

The rectangular and circular tracks printed using the 60º nozzle holder are shown in Figure 10 and the dimensions are illustrated in Table 1.

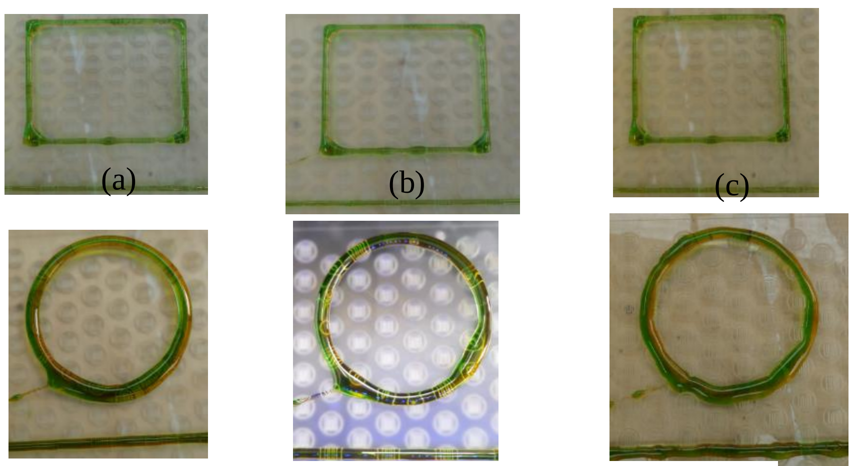

Figure 10: Printed samples using 60º nozzles holder

Table 1: Measurements of syrup tracks printed using 60º nozzle holder

	Layer Thickness (mm)		Layer Heights (mm)	
Track	Maximum	Minimum	Maximum	Minimum
Rectangular	3.1	3.9	1.5	1.9
Circular	3.6	4.3	2.7	3.4

ISSN: 2408-7920

African Journal of Applied Research
Vol. 5, No. 1 (2019), pp. 132-147
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http://doi.org/10.26437/ajar.05.01.2019.11

The rectangular and circular tracks printed using the 50º nozzle holder are shown in Figure 11 and the dimensions are illustrated in Table 2.

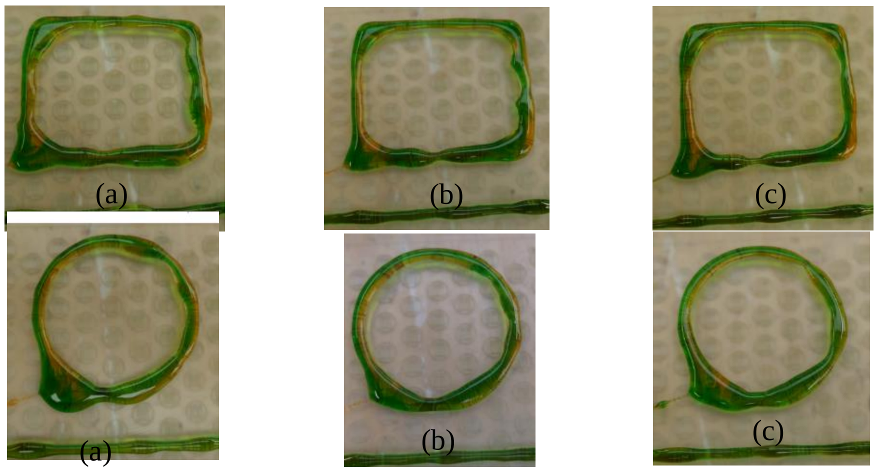

Figure 11: Printed samples using 50º nozzles holder

Table 2: Measurements of syrup tracks printed using 50º nozzle holder

	Layer Thickness (mm)		**Layer Heights (mm)**	
Track	Maximum	Minimum	Maximum	Minimum
Rectangular	3.1	4.3	2.5	2.7
Circular	3.8	4.5	2.8	3.5

ISSN: 2408-7920

The rectangular and circular tracks printed using the 40º nozzle holder are shown in Figure 12 and the dimensions are illustrated in Table 3.

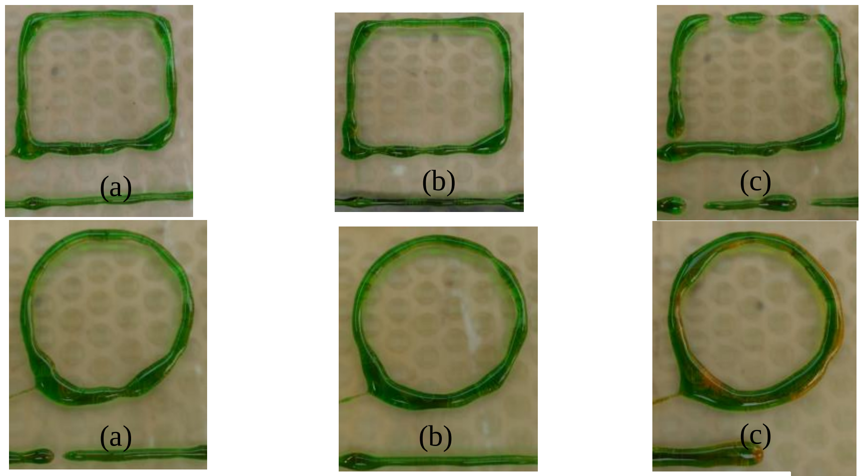

Figure 12: Printed samples using 40º nozzles holder

Table 3: Measurements of tracks printed using 40º nozzle holder

	Layer Thickness (mm)		**Layer Heights (mm)**	
Track	Maximum	Minimum	Maximum	Minimum
Rectangular	3.4	4.1	1.6	2.1
Circular	3.7	4.4	2.8	3.5

In all the tracks printed, even though the designed thickness was 2 mm, the layer thicknesses and heights depended on the nozzle diameter and the fluid flow. The starting point for both the circular and circular tracks had more build material as the dispensing unit stops therefore the valves are closed to stop the flow of flow completely.

CONCLUSION

To add to the material spectrum of additive manufacturing technology, this research has developed AM system which could print food products using some randomly selected ingredients at different mixing ratios to obtain different tastes at various parts in the same printed food. The designed attachment enabled the printer to cross-mix (In-flight mixing) of two or more fluids outside a mixing chamber on the surface of deposition under the influence compressed air. The rate at which the printer will build could be adjusted by the valve controller and, the nozzles could be replaced with ones of bigger nozzle orifice diameter in the case of a more viscous fluids or food ingredients.

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