Experimental Analysis of Low Melting Metal Alloy for Fused Deposition Modelling based Process

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Abstract— Fused Deposition Modeling (FDM) is one of the rapid prototyping technologies which use an additive manufacturing approach. In recent years, FDM has become one of the most widely-used rapid prototyping methods for various applications such as bio-printed organs, piezoelectric components, etc. FDM, which offers the opportunity to design and introduce new materials, including composites. The material commonly used in FDM is Acrylonitrile butadiene styrene (ABS), Polylactic acid (PLA) and some low melting metal alloys. The low melting alloys containing bismuth, tin, and indium, etc. Many of the paper deals with 3D printing using thermoplastic only. And some papers suggest that printing could be possible with tin and bismuth. In this paper, Bi-Sn alloy is used in the composition of 50% bismuth and 50% tin. The Melting temperature of Bi-Sn alloy is between the ranges of 138^0c to 170^0c. Bi-Sn alloy is used as a filament of 3 mm diameter to do "Experimental Analysis of Low Melting Metal Alloy for Fused Deposition Modeling Based Process". This work is done to reduce material wastage and labour costs and manufacture the complex shaped object.

Keywords: 3D Printer, FDM, Bismuth, Tin, Low Melting Alloy

I. INTRODUCTION

Scientists and engineers regularly impress with innovative technologies that have transformed into the fact which was later regarded as science fiction or modern inconceivable. Such innovation rendering our life much more comfortable and more exciting. For instance, a single device is creating their own built glass screen, kid's furniture, or any other prototype, and it is named as 3D printing. 3D printing is a form of additive manufacturing technology where a three-dimensional object is created by laying down successive layers of material. It is also known as rapid prototyping; it is a mechanized method whereby 3D objects are quickly made on a reasonably sized machine connected to a computer containing G-code of the 3D object. The 3D printing concept of custom manufacturing is exciting to nearly everyone. This revolutionary method for creating 3D models with the use of inkjet technology saves time and cost by eliminating the need to design; print and glue together separate model parts. Now, you can create a complete model in a single process using 3D printing. The basic principles include materials cartridges, the flexibility of output, and translation of code into a visible pattern.

Fig. 1: 3D printer

A. *Types of 3D Printer*

The most common types of 3D printers used today are,
- Stereolithography (SLA)
- Digital Light Processing (DLP)
- Selective Laser Sintering (SLS)
- Selective Laser Melting (SLM)
- Electronic Beam Melting (EBM)
- Laminated Object Manufacturing (LOM)
- Binder Jetting (BJ)
- Material Jetting (MJ)
- Fused deposition Modeling (FDM)

1) *Fused Deposition Modeling (FDM)*

FDM is a 3D printing process developed by Scott Crump and then implemented by Stratasys Ltd., in the 1980s. It uses production-grade thermal plastic materials to print its 3D objects. It's popular for producing functional prototypes, concept models, and manufacturing aids. It's a technology that can create accurate details and boasts an exceptional strength to weight ratio.

Before the FDM printing process begins, the user has to slice the 3D CAD data (the 3D model) into multiple layers using special software. The sliced CAD data goes to the printer, which then builds the object layer at a time on the build platform. It does this by heating and then extruding the thermoplastic filament through the nozzle and onto the base. The printer can also extrude various support materials as well as the thermoplastic. For example, as a way to support upper layers, the printer can add unique support material underneath, which then dissolves after the printing process. As with all 3D printers, the time it takes to print all depends on the size of the object and its complexity. Like many other 3D technologies, the finished object needs cleaning. Raw FDM parts can show fairly visible layer-lines on some objects. These will obviously need hand sanding and finishing after printing. This is the only way to get a smooth, end product with an even surface. FDM finished objects are both functional and durable. This makes it an accessible process for use in a wide range of industries, including mechanical engineering and parts manufacturers. This method is used in this project.

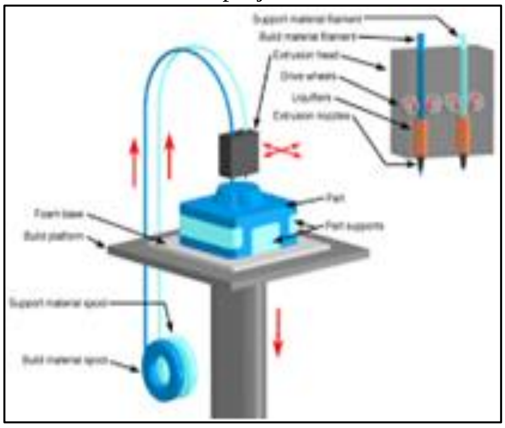

Fig. 2: Schematic Diagram of the FDM Process

II. SELECTION OF MATERIALS

Fused deposition modelling is an additive manufacturing process. This method is only suitable for thermoplastics and low melting alloys only. So the material studying and material selection is a valuable one while going for metal 3d printing. The extensive material investigation was conducted on eutectic and non-eutectic low melting metal alloys. Due to the temperature limitations of an FDM 3D printer, only low melting alloy systems with onset melting temperatures ranging from 100-300°C were considered. Additionally, the lead content was limited to a maximum composition of 10% to reduce the toxicity and possibility of leaching.

A. Eutectic Alloys

A mixture of metals having a melting point lower than that of any of its components. An example of low melting non-eutectic alloys is bismuth, indium, tin, and gold.

B. Non-Eutectic Alloys

Non-eutectic alloys melt over a range of temperatures; the material is usually slushy between their liquidus and solidus temperatures. An example of low melting non-eutectic alloys is indium, antimony, cadmium, silver, bismuth, and lead.

C. Nature of Materials

Bismuth alloy systems exhibit significantly low melting point and improved wettability. Indium alloys exhibit low melting points and high ductility, but it is rare and not readily available. Gold has excellent thermal fatigue properties but has comparatively high ranges of liquids temperature, and it is also very costly. Antimony alloys exhibit superior tensile strength and wettability properties. Silver alloys show sufficient mechanical strength, but has low ductility and also is highly toxic. Some of these alloy systems also contain traces of cadmium, copper, and zinc. The presence of copper in the alloy lowers its melting point and improves wettability. It also leads to increased resistance to thermal fatigue. The presence of zinc reduces the melting point of the alloy but is highly susceptible to corrosion and oxidation. Cadmium is considered highly toxic.

D. Composition and Properties of Eutectic Alloys

Composition and Properties of various alloys are described in this section. Physical properties, Mechanical properties, Thermal properties of eutectic alloys were reviewed, and its properties are analysed and described below.

ALLOY	NAME	MELTING TEMP (°C)	DENSITY (g/cm³)
Bismuth	58Bi42Sn	138	8.72
	100Bi	271.4	9.80
	50Bi50Sn	152	8.37
	52Bi48Sn	151	8.42
	42Sn56Bi2In	140	8.55
Indium	100In	157	7.02
	52In48Sn	118	7.30
	97In3Ag	143	7.38
Tin	98Sn8Zn	199	7.38
	96.5Sn3.5Ag	221	7.80
	91Sn9Zn	199	7.27
	99.3Sn0.7Cu	227	7.31
	95.5Sn3.8Ag0.7Cu	221	7.37
	99.85Sn0.04Cu0.03Bi	239	7.29
	93Sn3Ag4Cu	221	7.42
	48Sn46Bi2Ag4Cu	146	7.44
	100Sn	231	7.30
Gold	80Au20Sn	280	14.51

Table 1: Physical properties of the low melting eutectic alloy

ALLOY	NAME	ULTIMATE STRENGTH (MPa)	ELONGATION (%)	HARDNESS (HV5)
Bismuth	58Bi42Sn	55.4	46	23
	100Bi	1.96	-	7
	50Bi50Sn	61.8	53	39
	52Bi48Sn	60.9	57	-
	42Sn56Bi2In	66.1	47	116
Indium	100In	1.88	41	116
	52In48Sn	11.8	83	5
	97In3Ag	5.51	-	2
Tin	98Sn8Zn	-	-	-
	96.5Sn3.5Ag	55	35	-
	91Sn9Zn	53.1	33	22
	99.3Sn0.7Cu	29.4	21	9
	95.5Sn3.8Ag0.7Cu		64	-
	99.85Sn0.04Cu0.03Bi	18.6	57	3.9
	93Sn3Ag4Cu	-	-	-
	48Sn46Bi2Ag4Cu	69.4	3	-
	100Sn	13.2	268	4
Gold	80Au20Sn	-	2	274.6

Table 2: Mechanical Properties of the Low Melting Eutectic Alloy

ALLOY	NAME	Coefficient of thermal expansion (10^{-6}K)	Thermal conductivity (W/m.K)	Specific heat capacity at const. pressure (J/Kg.K)
Bismuth	58Bi42Sn	15	18.41	46
	100Bi	13.4	86	48
	50Bi50Sn	18.6	22	43
	52Bi48Sn	12.13	-	40
	42Sn56Bi2In	16.01	-	45
Indium	100In	29	83.7	44
	52In48Sn	20	34	-
	97In3Ag	22	73	-
Tin	98Sn8Zn	20.5	-	-
	96.5Sn3.5Ag	20.04	78	64
	91Sn9Zn	31.77	61	69
	99.3Sn0.7Cu	-	66	-
	95.5Sn3.8Ag0.7Cu	20.04	60	-
	99.85Sn0.04Cu0.03Bi	23.8	62.6	22
	93Sn3Ag4Cu	14.83	-	65
	48Sn46Bi2Ag4Cu	14.83	-	36
	100Sn	17.9	73	22
Gold	80Au20Sn	16	57	-

Table 3: Thermal Properties of the Low Melting Eutectic Alloy

From Table 1, Indium is the least dense of all the materials systems and has the least ranges of melting temperatures. Tin is as less dense as indium but melts a higher temperature. Bismuth alloy system exhibits high densities along with convenient melting temperatures, even lower than its lighter counterpart, tin. Gold is the densest of all and melts at the higher temperatures. From Table 2, pure indium is found to exhibit the highest range of percentage elongations among all the low melting eutectic systems considered. Bismuth alloys are found to exhibit a percentage of elongation values in the ranges of 45% to 55%. The percentage elongation values of tin alloys fall over a broad range of values, the lower elongation values corresponding to alloys with lower percentages of tin and the higher elongation values corresponding to elements with a higher percentage of tin. The gold-tin alloy is found to exhibit the lowest elongation value among all the low melting eutectic alloy systems considered.

From Table 3, it can be stated that bismuth alloys tend to exhibit the least thermal expansion values among all the low melting eutectic alloys considered. Bismuth is closely followed by the tin-bismuth and tin-silver alloys. The tin alloys, however, fall into a broad range of values from scales of 15 to 30, owing to the wide range of the tin-alloy compositions considered. The gold-tin alloy falls in the average thermal expansion ranges of all the eutectic systems considered. The highest values of thermal conductivity for the bismuth alloys correspond to their pure metal counterparts. Higher conductivity values of indium correspond to those alloys with higher compositions of Indium; pure indium exhibits the highest conductivity value of 84W/m.K. As a part of studying the feasibility of 3D printing metals using an FFF 3D printer, the material search was conducted on low melting alloys through metal reference books, research papers, and commercial websites. Due to the temperature limitations of an FDM 3D printer, only low melting alloy systems with onset melting temperatures ranging from 100-300°C were considered. Additionally, the lead content was limited. From some literature suggestions, Bismuth and tin are used for experimental analysis.

III. METHODOLOGY

In the FDM 3D printer, the filament is used in wire form. And their diameter is varied as 1.75mm and 3mm. It depends upon the 3D printer nozzle size. The wire is drawn by a wire extruder machine. Due to the unavailability of wire extruders, the casting process is used to make a filament.

A. Casting

Casting is a manufacturing process in which a liquid material is usually poured into a mould, which contains a hollow cavity of the desired shape, and then allowed to solidify. The solidified part is also known as a casting, which is ejected or broken out of the mould to complete the process.

1) Types of Casting

– Sand casting
– Centrifugal casting
– Investment casting
– Gravity die casting
– Shell mould casting

B. Sand Casting

Sand casting is a metal casting process characterized by using sand as the mould material.

1) Types of Sand Casting

– Greensand casting
– Sodium silicate casting
– Resin sand casting

a) Green Sand Casting

These castings are made using sand moulds formed from "wet" sand which contains water and organic bonding compounds typically referred to as clay.

b) Sodium Silicate Casting

Sodium silicate is a viscous liquid. It is produced by dissolving silica gel in sodium hydroxide. Sodium silicate is the most popular method used in casting slips for many years.

c) Resin Sand Casting

The resin sand casting process is a kind of floor moulding process by using the resin sand as the moulding material. Resin sand is a kind of mixture of quartz sand and resin.

2) Tools of Green Sand Casting

– Cope box
– Drag box
– Greensand
– Runner
– Riser
– Shovel
– Trowel
– Strike of bar

a) Cope Box
It is the top part of the sand casting. This flask is made of wood or metal frame, which contains moulding sand providing support to the sand as the metal poured into the mould.
b) Drag Box
It is the bottom part of the sand casting. This box is made up of wood or metal frame for casting the product.
c) Green Sand
Greensand is the type of sand that is used to cast the product. It consists of clay, pulverized coal, and water.
d) Runner
The runner is used to provide a passage for a material to flow from the sprue busing to the gate.
e) Riser
The riser is used to passing the molten metal into the mould cavity. It is used to identify whether the metal is filled or not.
f) Shovel
A shovel is a tool that is used for lifting and moving bulk materials such as soil, coal, etc. It is made up of sheet steel or hard plastics.
g) Trowel
The trowel is a small hand tool used for digging, applying, moving a small amount of particulate material.
h) Strike Off Bar
Strike off the bar is used for striking off the excess sand from the mould to provide a smooth surface. It is made up of wood or steel.
i) Crucible
A crucible is made up of sand in which metals or other substances may be melted or subjected to very high temperatures. It withstood very high temperature and used to deposit the melting metal into the mould.
j) Tongs
Tongs is an instrument with two movable arms that are joined at one end, used for picking up and holding things.

3) Muffle Furnace

It is a type of furnace which radiantly heats the material. The material cannot direct contact with the flame. It usually works by putting a high-temperature heating coil in an insulating material. The insulating material effectively acts as a muffle, preventing heat from escaping.

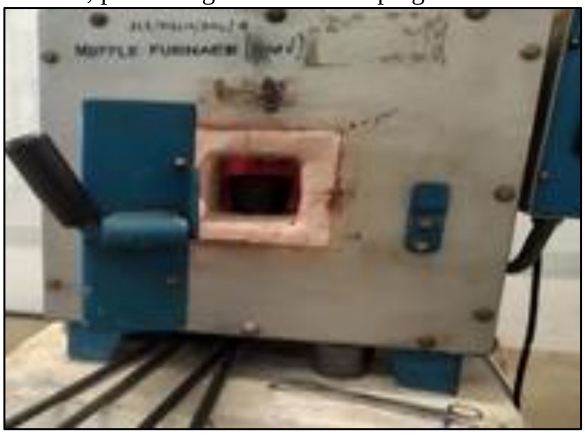

Fig. 3: Muffle furnace

C. Fabrication Method

The fabrication process of filament is described in this topic; this process contains various steps they are explained as follows.

1) Step 1: Material selection

From chapter 3, Bismuth and Tin are used as a feed material. They are used to fabricate the filament, and it is used in the composition of 50% Bismuth and 50% tin by weight. Materials are taken in the form of powder and grain.

Fig. 4: Tin Powder

Fig. 5: Bismuth

Fig. 6: Bi50Sn50

2) Step 2: Mould preparation

In the sand casting process, mould preparation is the first and foremost step. The drag box is clay washed, and the mould is placed in the bottom of the box. The green sand, which is a mixture of clay and sand, is poured inside the box. After that ramming is taken place for tight packing of sand. After that Excess amount of sand is removed from the drag box by using the strike-off bar. Then the box is turned back by placing the die portion placing upside. And die is removed.

3) Step 3: Melting of metal

The metal is melted in the muffle furnace by mixing the bismuth and tin metal in the crucible each is mixed at the ratio of 1:1 by adding 50% of bismuth and 50% of tin in the crucible. This mixture is placed in the muffle furnace, and it is heated at the temperature of 250°C. When the required temperature is reached the molten metal is taken out from the muffle furnace by using tongs the crucible is taken out from the furnace, and it is poured in the sand die casting, and it is allowed to solidify.

4) Step 4: Solidification

The total solidification time is the time required for the casting to solidify after pouring. This time is dependent on the size and shape of the casting by an empirical relationship known as Chvorinov's rule. That relates the solidification time for a simple casting to the volume and surface area of the casting. The relationship can be written as:

$$T_{TS} = B\,(V/A)^n$$

Where,

T_{TS} -Total solidification time (min)

V -Volume of the casting (cm^3)

A - Surface area of the casting (cm^2)

n - Exponent is usually taken to have a value 2 the mould is constant.

The units of "B" is min/cm^2, and its value depends on the particular conditions of the casting operation, including mould material (e.g., specific heat, thermal conductivity),

After the solidification, metal is removed from the mould.

Fig. 7: Cast Rod

5) Step 5: Surface Finishing Process

Surface finishing is a process that alters the surface of a material for aesthetic or a functional purpose. There are various methods of surface finishing process like,

– Surface Lapping
– Buffing
– Honing
– Polishing
– Grinding
– Wheel Grinding

In that wheel grinding process is used in this project. Grinding wheels are composed of thousands of small abrasive grains held together by a bonding material. Each abrasive grain is a cutting edge. As the grain passes over the work piece it cuts a small chip, leaving the smooth surface.

IV. Experimental Work & Results

A. Mechanical Testing

Mechanical testing reveals the properties of a material under dynamic static force. Designed to ensure that materials are suitable for their intended applications, mechanical testing includes methods such as tensile strength, compression strength, impact resistance, fracture toughness, and fatigue. The most widely used hardness test is the Rockwell hardness test. This test utilizes the depth of indentation, under constant load, as a measure of hardness. Since it is the fastest and most accurate form of testing. The Rockwell hardness test used to find the hardness value of the bismuth and tin composition.

1) Rockwell Hardness

The Rockwell hardness test measures the hardness of the material in the simplest way possible by pressing an indenter into the surface of the material with a specific load and then measuring how far the indenter was able to penetrate. The indenter is made of either a steel ball or a diamond.

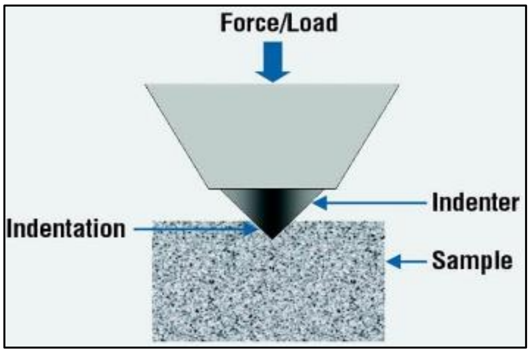

Fig. 8: Schematic Diagram of Rockwell Hardness

There are three stages to the Rockwell hardness test. A preliminary load is applied by a diamond or ball indenter for a short period of time. The preliminary load is then removed, and the indentation is measured. The load is subsequently increased and applied, known as a major load. The major load is then released, and the preliminary load re-applied for a short time. The indenter is removed and the final indentation measured.

The Rockwell hardness (HR) is calculated by measuring the depth of an indent after an indenter has been forced into the specimen material at a given load. The hardness of the bismuth and tin material is to be measured.

Alloy	Rockwell Hardness Value		
50%Bi-50%Ti	I	II	III
	38.1	37.9	38.2

Table 4: Rockwell Hardness Test

– Rockwell Hardness Value = $\frac{39.1+38.9+39.2}{3}$
– Rockwell Hardness value of
– 50%Bi and 50%Ti = 39
– The Rockwell hardness number of the 50%bismuth and 50%tin composition is 39

B. FDM 3D Printing

There are various steps involved in the process of printing a part or model using a 3D Printer. Here all the steps involved in the printing process in the 3D Printer are explained in detail.

1) Step 1: Part Design in PTC Creo

The first and foremost step in the process of 3d Printing is to design the part or model to be printed in any of the 3D Modelling Softwares such as Pro-E, Catia, Solidworks, PTC Creo. In our case, we had used PTC Creo 3D Modelling Software to design a part drawing. For example, a 3D cube. Required dimensions for the part to be printed is decided in the design stage for example the side of the Cube is 20 mm.

2) Step 2: Saving the Design in STL format

The designed file is saved as STL format (Stereolithography). Many software packages support this file format; it is widely used for rapid prototyping, 3D Figure-9 printing and computer-aided manufacturing.

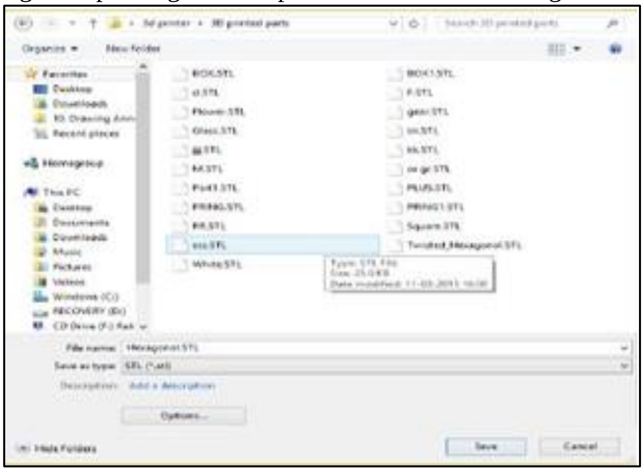

Fig. 9: Saving the File in STL Format

3) Step 3: Opening file in Slic3r and Export G-code

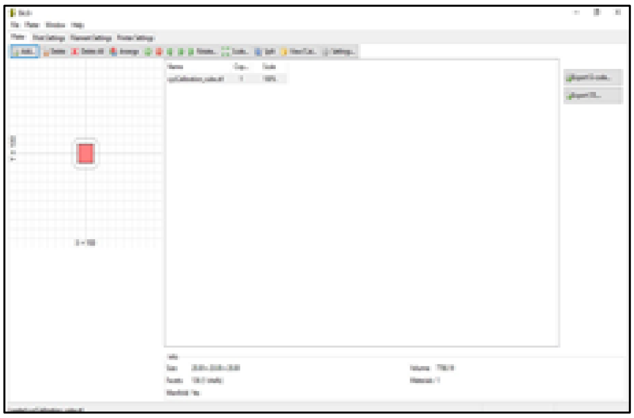

Fig. 10: Slic3r Software

The STL file is opened in Slic3r Software where the view of the object or the position in which the object would be printed can be seen. After checking the view, the G-code of the design, in this case, a 3D Cube can be generated by clicking on the option 'Export G-Code'.

4) Step 4: Importing the G-code file and Printing in Pronterface Software

The file created is then loaded in the pronterface which connects Arduino with the computer. From the pronterface software, we can give print command. The Arduino mega will thus send a command to the stepper motor & we get a 3D model. The figure below is a snapshot of pronterface software showing the wagon wheel through which the motions of the 3D printer can control.

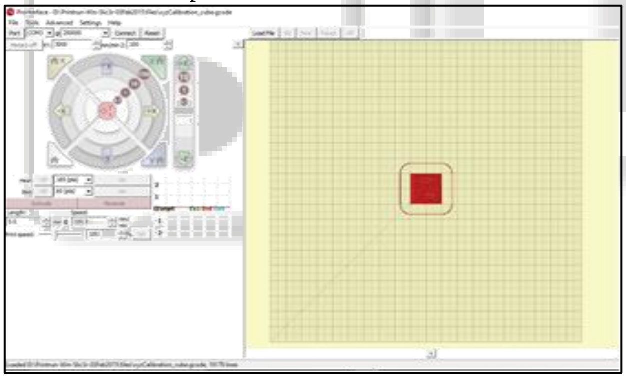

Fig. 11: Pronterface Software

In this methodology, the low melting Sn50Bi50 alloy in the form of wire was fed into the FDM 3D printer and heated in the nozzle to deposit material layer by layer to fabricate a 3D geometry. Since the extrusion characteristics of metals are different from that of polymers, optimization of the printer process parameters was necessary for the uninterrupted printing of the low-melting Sn50Bi50 material.

C. Results & Discussion

The printing parameters such as the velocity of extrusion, rate of feeding, the temperature of the nozzle, print bed temperature and layer height play a significant role in the continuous deposition of the material, adherence to the bed (and subsequent layers) and build quality of the fabricated part. Each of these parameters was iterated in order to successfully 3D print Sn50Bi50 alloy using the FDM technology.

For better results, 3 Trials was conducted in the 3D printer. They were explained below.

- Trail 1 was conducted with the Nozzle temperature of 180 °C and Bed temperature of 40 °C. Extrusion Velocity of 7 mm/s and feed rate of 200 mm/s.
- Trail 2 was conducted with the Nozzle temperature of 180 °C and Bed temperature of 40 °C. Extrusion Velocity of 5 mm/s and feed rate of 230 mm/s.
- Trail 3 was conducted with the Nozzle temperature of 180 °C and Bed temperature of 40 °C. Extrusion Velocity of 1 mm/s and feed rate of 250 mm/s.

Printing Parameters	Trial 1	Trial 2	Trail 3
Nozzle temperature (°C)	180	180	180
Bed temperature (°C)	40	40	40
Extrusion velocity (mm/s)	7	5	1
Feed rate (mm/s)	200	230	250

Table 4:

Reducing the extrusion velocities, it provides additional time for depositing the material on to the print bed. Consequently, increasing the feed rate to a higher value, it assists in the faster extrusion of the material. Probably due to the lack of molten material available for immediate extrusion. Increasing the feed rate by a percentage of 20% along with a decrease in 28.57% in the extrusion velocity addressed this issue, reducing the discontinuities over the entire area of the geometry. Reducing the extrusion velocity further to an allowed minimum of 1 mm/s further reduced the voids and discontinuities between the layers and paved the way for the successful fabrication of Sn50Bi50 using FDM technology. In the initial Stages, the continuous printing does not take place. After many attempt the continuous printing was take place.

1) Advantages

- Better Quality
- Reduce metal wastage
- Reduce Labour cost
- Tangible Design
- Ability to print the Complicated shapes

2) Disadvantages

- Expensive method of Fabrication
- Chance of clogging
- Limited materials

3) Application

The capability of fabricating metals using an FDM 3D printing paves the way for the fabrication of prototypes for applications in fields such as automobile, aerospace, healthcare, etc.

V. CONCLUSION & FUTURE WORK

A. Conclusion

From the above details, it is concluded that the Eutectic alloy of Bismuth and tin in the composition of Bi50Sn50 is also suitable for the FDM 3D printing technology. And their parameter is the main factor for the printing process like Nozzle temperature, bed temperature, printing speed, feed rate. Bi50Sn50 alloy is melt in the temperature of 158 °C, and suitable Nozzle temperature is 180 °C, Bed temperature is 40°C with Extrusion velocity of 1mm/s and feed rate of 250 mm/s.

Increasing the feed rate by a percentage of 20% along with a decrease in 28.57% in the extrusion velocity addressed this issue, reducing the discontinuities over the entire area of the geometry. Thus it is concluded that the selected material (Bi50Sn50) is suitable for FDM 3D printing, and it is used in the application of the Automobile sector, Aerospace industries.

B. *Future Work*

Future work will focus on optimizing the process parameters of the FDM 3D printing approach for improving the geometric tolerances and densities of the fabricated part to improve the mechanical properties of the product. The setup will be placed in a controlled atmosphere to reduce the possibility of oxidation and contamination during the fabrication process. The characterization will be performed on the FDM 3D printed specimens to study the internal cracks within the specimen. The new nozzle design is created to reduce the chance of clogging. Furthermore, the feasibility of fabricating eutectic alloys using FDM 3Dprinter will be investigated.

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