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3D Printing of Polyethylene

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ABSTRACT - Extrusion-based Fused Deposition Modeling is widely used for varieties of material. Ultra High Molecular Weight Polyethylene (UHMWPE) has extremely long chains resulting in a very tough material, with high impact strength. If UHMWPE can be made in freeform, lots of application can take the advantage of this novel material. Extrusion-based Fused Deposition Modeling, as an approach of Additive Manufacturing, it can cost-effectively fabricate complex three dimensional shape. In this project, an experiment setup for extrusion based 3D printing polyethylene is tested. This paper explores the experimental design for a 3D printing setup specific to UHMWPE, detailing modifications, challenges, and promising results for advanced prototyping. The study establishes a foundation for using UHMWPE in various high-demand applications, particularly in medical and defense sectors. Each component of the setup is introduced in detail, along with the modification of the components. The current result is shown, along with the challenges of the whole printing process, result also gives hints on the future scope of the experiment design.

**Keywords: Ultra High Molecular Weight Polyethylene(UHMWPE); Fused Deposition Modeling (FDM
); Additive Manufacturing (AM)**

1. INTRODUCTION

1.1 Background and Importance of 3D Printing technologies

3D printing, also known as additive manufacturing, has revolutionized industries by enabling the fabrication of complex shapes with high precision and minimal material waste. Unlike traditional subtractive manufacturing, 3D printing constructs objects layer by layer, providing significant advantages in prototyping, customization, and cost efficiency. Among various methods, Fused Deposition Modeling (FDM) is widely used due to its simplicity and compatibility with a variety of materials.

- **Significance of Ultra-High Molecular Weight Polyethylene (UHMWPE)**
  UHMWPE stands out as an exceptional material in additive manufacturing, offering unparalleled impact resistance, chemical **inertness, and** wear properties. Its ultra-high molecular weight enables its use in high-demand applications, such as medical implants and body armor, making it a strong candidate for advanced manufacturing techniques. However, the challenges of processing UHMWPE, such as its high viscosity and melting temperature, limit its widespread adoption in 3D printing.

1.2 Material Properties

With semi crystalline properties(mentioned in [1]) and very long chains (mentioned in[2]) , the molecular mass of UHMWPE is about: 2 million ~ 6 million Dalton(Da.)[3]. Now, comparing it with Low-Density Polyethylene which has weight ≤40,000 Da and High-Density Polyethylene which was weight of about 100,000 ~ 250,000 Da),[3] (1 Da≈1.66×10^(-27)kg) this material proves to be highly dense as compared to its counterparts. UHMWPE surpasses other polyethylene types, such as Low-Density Polyethylene (LDPE) and High-Density Polyethylene (HDPE), in terms of molecular mass, toughness, and impact resistance. With molecular weights ranging from 2 to 6 million Daltons, it significantly outperforms LDPE (<40,000 Da) and HDPE (100,000-250,000 Da), providing superior density and durability.
The long chains of UHMWPE make it one of the most tough material as well as distinguish it among all thermoplastics with highest impact strength.

2. CURRENT APPLICATIONS AND CHALLENGES

2.1 Applications

While UHMWPE is extensively used in traditional manufacturing, its integration into 3D printing processes has been limited. The primary challenges include maintaining its structural integrity during heating, achieving consistent extrusion, and preventing material degradation. Overcoming these obstacles would unlock transformative possibilities in medical, defense, and industrial applications. According the market research forecasting report, use of UHMW PE will increase rapidly in various applications in years to come. This makes it one if the most in demand material due to fast pace increase in its applications. Fig.1 shows the growth of the UHMWPE from 2012 to 2022. This growth forecast is for the various categories in which this material is used in which the topmost are the usage in medical grade and prosthetics, filtration and membranes. This increase in the years to come make it an ideal candidate for the use in rapid prototyping where it can be printed in various styles and shapes. The fields where it is mostly used is medical where it is used in knee, hip and spine implants. It is also used in defense purposes where its lightweight body armour can be very helpful to the soldiers

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and security personnels. Besides this, it is also used in manufacturing field in order to make hydraulic sealings and bearings. Forecasts predict a steady rise in UHMWPE demand, with substantial applications in medical-grade materials, filtration, and durable membranes. Its extensive applications include knee, hip, and spine implants in the medical field, as well as body armor manufacturing for military and law enforcement. [4,12]

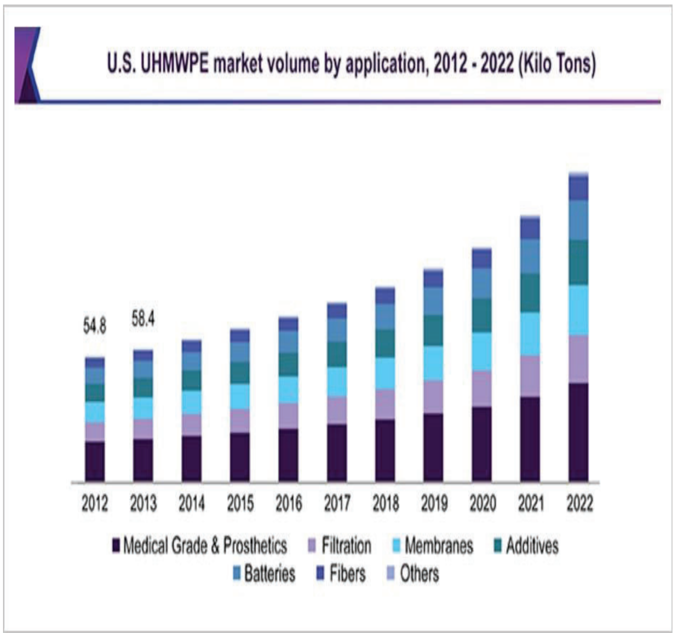

Fig.1 Market Trends of UHMWPE[5]

2.2 Relevant Research

UHMWPE exhibits exceptional tensile strength and resistance to abrasion, making it suitable for load-bearing applications. The material maintains stability across a wide temperature range, with a melting point near 130°C and excellent performance under cryogenic conditions. Its inert nature allows it to withstand exposure to corrosive chemicals, expanding its use in harsh environments. Few papers have realized 3D printing of this material. In 2018, Borges et al.[6] made a breakthrough in manufacturing filaments with small percentage of UHMWPE involved to achieve tradeoff between printability and best usability in biomedical area, validated by comparison with non-UHMWPE printed samples and differently manufactured samples in [6]. Advancements in additive manufacturing techniques, such as the integration of solvents and improved extruder designs, are poised to enhance the usability of UHMWPE, further expanding its market presence. Prior to this, Panin et al.[7] investigated the possibility of increased printability among different grades of UHMWPE from quantitative and mechanical testing in [7]. Besides, Cheung et al.[8] used solvent to restructure the material and evaluated the importance of using solvent by mathematical modeling with test results in [8]. Also, Rein et al.[9] extended the application of solvent into fabrication chance of fibers in [9]. Both researches[8,9] obtained the gel form. In this paper, we have used the solvent, o-Dichlorobenzene(o-DCB), and the magnetic stirrer as [9], but to put the gel form inside the extruder. The aim is to try to extrude the gel form of the mixture from the extruder onto the 3D printer bed by heating it with the attached heating rod. The compressional force required will be applied using the electric air compressor.

3. EXPERIMENTAL SETUP

The experimental setup for this experiment is shown in Fig.1. The air compressor and the air pressure regulator are attached to the regulator that has a long pipe and a blue adapter connected to the top of the extruder assembly. The experiment involves a custom 3D printing setup using a pneumatic extruder adapted for UHMWPE. Modifications were essential to handle UHMWPE's unique properties, such as high viscosity and specific melting behaviors. This section details each part of the setup, including temperature regulation, pneumatic controls, and solvent-based preparation techniques.

A detailed description of the experimental setup is provided here, focusing on modifications necessary to adapt standard FDM processes for UHMWPE. Custom extruders, temperature regulation systems, and the use of solvents were critical in managing UHMWPE's extrusion flow. Tests were conducted over various temperatures and pressures to identify the optimal extrusion environment.

Challenges included managing material oxidation at higher temperatures and ensuring a continuous flow through the extruder. The use of o-Dichlorobenzene as a solvent improved the material's flow by reducing viscosity, which enabled smoother extrusion at lower pneumatic pressures. Detailed findings indicate that an optimal extrusion temperature of 175-180°C minimizes oxidation and allows for consistent extrusion.

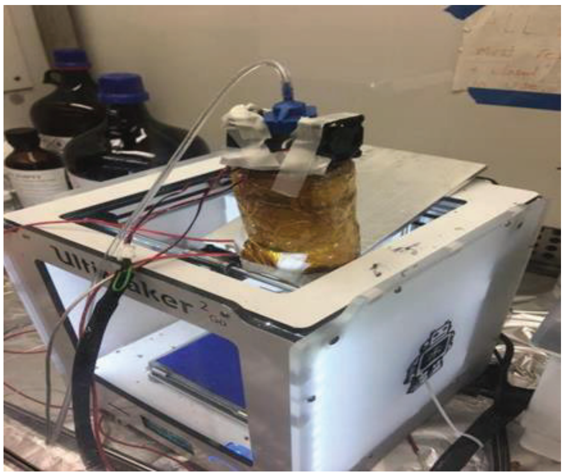

Fig.2 Printer with Extruder Under Experiment

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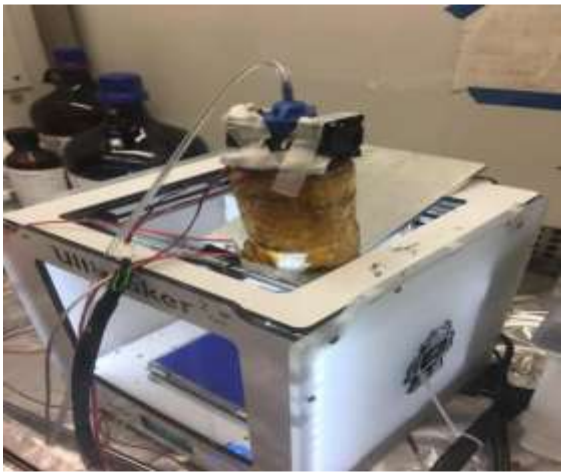

Fig.2 Printer with Extruder Under Experiment

The complete equipment list is shown in Table 1.

Table 1 Experimental Setup List

S. No	Equipment	Remarks
1	Printer	Ultimaker 2 Go FDM Printer (shown in Fig.3)  Fig.3 Ultimaker Printer
2	Extruder Cap	Printed using Envision TEC SLA printer. Material mixing with Formlabs High Temp Resin and Formlabs Tough Resin at volume ratio 9:1 (shown in Fig.4)  Fig.4 Extruder Cap (printed using EnvisionTec printer)

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3	Insulation Layer	Made of PEEK (Polyether Ether Ketone) (shown in Fig.5)  Fig.5 PEEK Insulation Layer
4	O-Ring (2)	On top and bottom sides of the insulation layer individually (shown in Fig.6)  Fig.6 O-Ring
5	Steel Screws	Used to tighten the assemblies between the extruder cap and the extruder(shown in Fig.7)  Fig.7 Steel Screws
6	Teflon Tubes	 Fig.8 Teflon Tubes
7	Washers	The ones previously used are made of PEEK (shown in Fig.9)  Fig.9 PEEK Washers

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8	Fans (3)	12V DC, 0.12 A (shown in Fig.10)  Fig.10 Fans
9	Extruder	Made of Aluminum, the drawing shown in Annex A.1(using Autodesk Fusion 360 Software), machined in UB Machine Shop (The machined extruder is shown in Fig.11)  Fig.11 Extruder
10	Heater	24V, 40W (shown in Fig.12)  Fig.12 Heater
11	Temperature Sensor	 Fig.13 Temperature Sensor

12	Polyimide Tape	 Fig.14 Polyimide Tape
13	Fiberglass Tape	 Fig.15 0.5 inch wide Fiberglass Tape
14	Mineral Wool Insulation Sheet	 Fig.16 Mineral Wool Insulation Sheet (Manufacturer: McMaster- Carr)
15	Foam	Previously used (shown in Fig.17)  Fig.17 Burned and Deformed Foam After High Temperature Experiment(230 ℃)
16	Holder	Printed using another Ultimaker printer, previously used, drawing shown in Annex A.2(using PTC Creo Parametric)  Fig.18 Holder Model in PTC Creo Parametric
17	Air Compressor	Maximum 100 psi (shown in Fig.19)  Fig.19 Air Compressor (Brand: Central Pneumatic®)

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18	Air Pressure Regulator	 Fig.20 Air Pressure Regulator (Manufacturer: Nordson EFD, Inc.)

19	Nozzle	 Fig.21 0.8mm Diameter Nozzle

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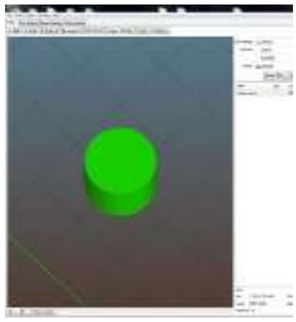
20	Other Mechanic Tools	Plier, Wrench, Hexagonal Allen Key, Torchlight(shown in Fig.22)  Fig.22 Wrench, Plier(Left), Hexagonal Allen Key(Right Top), Torchlight(Right Bottom)
21	Solvent (suggested in [9])	o-Dichlorobenzene(o-DCB) （shown in Fig.23）  Fig. 23 Solvent o-Dichlorobenzene (Manufacturer: Fisher Chemical)
22	Heating Platform	 Fig. 24 Heating Platform (Model Type: C-Mag HS 7, Brand: IKA®)
23	Magnetic Stirring Bar (suggested in [9])	Helps stir the solvent uniformly on the heating platform.  Fig.25 Magnetic Stirring Bar
23	Slicing Software	Slic3r  Fig.26 Screenshot of Slic3r Software

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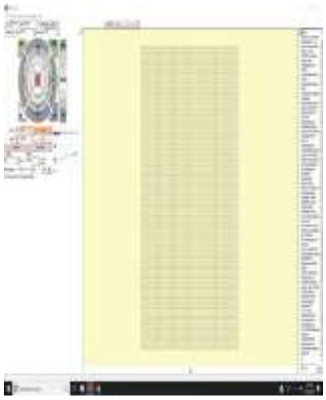
24	Printing Software	Pronterface  Fig.27 Screenshot of Pronterface Software

Fig.28 Extruder Assembly

In Fig.28, the holes for the bigger heater(right side) and smaller heater(left bottom side) are placed at the bottom of the extruder. The bigger heater is measured at 0.234 inch in diameter, and 0.802 inch in length. The smaller heater is measured as 0.157 inch in diameter, and 0.801 inch in length. The smallest hole is for the temperature sensor, measured as 0.118 inch in diameter, and 0.577 inch in length. Those dimensions are considered in the design of the extruder (shown in Annex A.1) to make the connections as close as possible.
The experiment is done inside the fume hood, because the solvent o-Dichlorobenzene is used.

4. RESULTS

Pre-liminary findings
Fig.29 shows the setup used with normal foam and was tested at high temperatures. We designed the pneumatic based extruder. As is shown in figure, it is machined in the machine shop. The extruder has a material cavity, the material will be put in the cavity before the experiment begin. At the top of the extruder body, four holes are designed for place the screws, the screws will connect the cap, insulation layer and extruder together. At the surface, two holes are drilled for fitting the heater and sensor. The size of the hole is exactly match the size of the heater and sensor, to make sure it is not loose. At the bottom of the extruder, the hole for the nozzle is drilled and threaded, overall the machine method including milling, drilling, turning, tapping and threading.

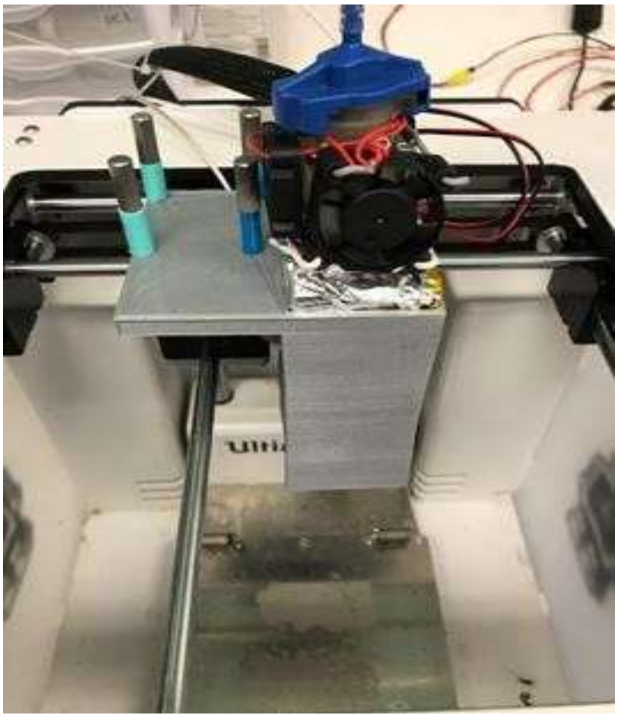


Fig.29 Previous Setup

The cap, as is shown in Fig.4, is 3D printed by SLA printer. The material is Formlabs “High temp” resin, blended with “Tough” resin with volume ratio of 9:1. We used to only printing with “High Temp” resin; however the printed cap is crispy, it is easy to break when applying large force, therefore we want to combine high temperature resistance with tough characteristic.

To avoid heat dissipation of the extruder, we choose to use foam to wrap the extruder at the beginning. The heat insulation of the foam is effective, however the foam can not withstand very high temperature, as can be seen in Fig.29, the foam is burned, generating a lot of smoke.

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Therefore, we change the foam to mineral wool insulation sheet, shown in Fig.16. The insulation effect is even better than the foam, and the wool insulation sheet can withstand temperature as high as 230 ℃, which satisfies our experiment condition.

As can be seen in the assembled figure, we also mount three fan around the cap, which can dissipate the heat, preventing the cap from heat deformation.

4.1 Material Morphology

We also did material morphology study to find a good state of material for extrusion. In room temperature, the polyethylene powder maintains the powder state. Then in order to extrude it, we heat up to 230 ℃, the powder is melted around 230 ℃, however the viscosity is too high to extrude out from the nozzle. Also oxidation of the material is apparently showed after heating up, the oxidation will lead to change in properties of polyethylene. Then we plan to dissolve the powder in o-Dichlorobenzene (o-DCB), o-DCB is an organic solvent, when heating up to 170 ℃, the PE powder begin to dissolve in the DCB. Around 175 to 180 ℃, the dissolved material is in very soft state, if keep heating up, it becomes hard. In this case we would prefer the soft state material, since it is easier to extrude out.

The solution shows different morphology under different temperatures. So the initial testing showed that the temperature range of around 170-220 ℃ would be good to work upon. However, after testing the material above 200 ℃ it turned to be bro wn due to oxidation and resulted in reduced fluidity. So, the temperature was tested from range 175-180 ℃ which provided the best morphology for the material mixture to be extruded for printing. Below shows the table describing the above with the various figures of the material at different temperatures.

Table 2. Material Morphology at different temperatures

27℃ No change Just the white powder	175-180 ℃ (Preferred) Ratio- 2.6 g PE powder with around 7 ml DCB	200-220℃ Brown and white powder due to burning and oxidation

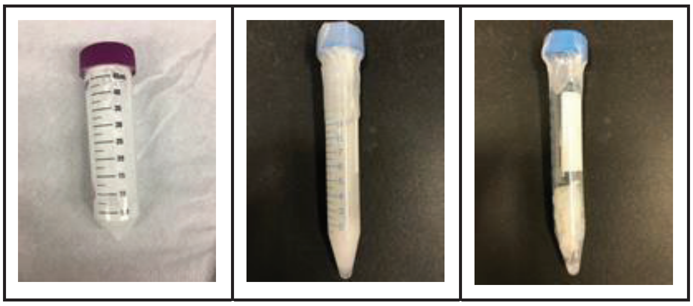

Fig.30 Powders at Different Temperatures

4.2 Extrusion Result

PE powder - The powder is barely melted around 240 ℃, liquid PE is too viscous to extrude from the nozzle, with the pneumatic pressure as high as 70 psi. Oxidation of PE is apparently showed when heating up to 240℃. Oxidation will lead to change in properties of the material, the strength of PE will decrease.

PE solution - The fluidity of PE solution is better than the melted PE at 180 ℃. Some of the material comes out of the nozzle, but in small amounts. However, we are looking for continuous and stable extrusion to print some pattern and part.

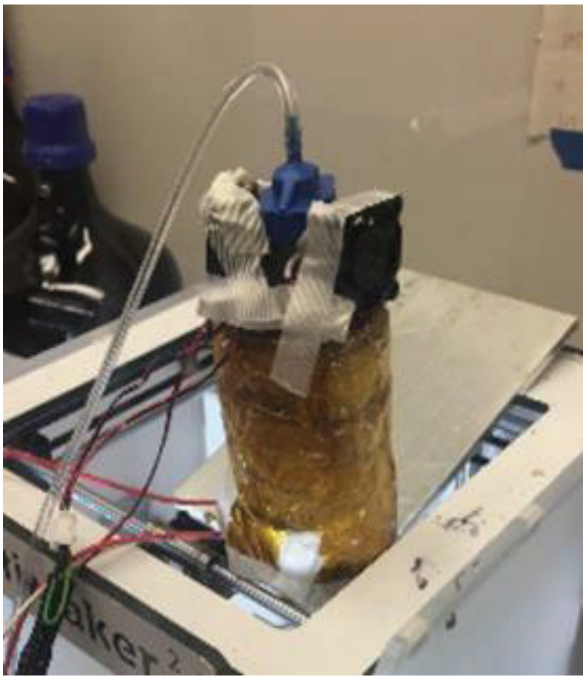

Fig.31 Current Setup

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5. MIXTURE FLOW

5.1 Compressional Force Required for Extrusion

One of the critical parameters for the extrusion process is the compressive force required to push UHMWPE material through the extruder nozzle. The force depends on the material's viscosity, the nozzle geometry, and the applied pneumatic pressure. The relationship can be expressed as:
F= $\Delta P * A$, where: F is Force required for extrusion (N), ΔP is the pressure difference across the nozzle (Pa) and A is the cross-sectional area of the nozzle (m^2).
Now, for a nozzle with a diameter d, the cross-sectional area is, $A = \pi * (d/2)^2$. Calculation: Now, the maximum pressure applied by the compressor attached here is 100psi. The atmospheric pressure at sea level is 14.7 psi. So
ΔP will be 100- 14.7 = 85.3psi = 588122.8 Pa.------ (I)
The diameter of the nozzle used is
d= 0.8 mm= 0.0008 m.—(II)
Area of nozzle will be **$A= \pi * (0.0008 / 2)^2 = 5.027 \times 10^{-7}$ m^2. --- (III)**
Therefore, force F= $588122.8 * 5.027 \times 10^{-7} = 0.295$ N.

This force is sufficient for low-viscosity materials. However, for UHMWPE, the viscosity increases drastically at extrusion temperatures, requiring higher pressures or modified nozzle geometries to achieve smooth flow.

5.2 Material Viscosity and Flow Rate

The flow rate of the material through the nozzle is influenced by its viscosity (η) and the shear stress (τ) exerted by the applied force. Using the Hagen-Poiseuille equation for a cylindrical nozzle: **$Q = \pi R^4 \Delta P / 8 \eta L$ ---- (IV)**
Where: Q is the Flow rate (m^3/s), R is the Radius of the nozzle (m), ΔP is the Pressure difference (Pa), η is the Dynamic viscosity of the material (Pa·s) and L is the Length of the nozzle (m). **For UHMWPE, η is estimated at 10^4–10^5 Pa.s** at extrusion temperatures, significantly higher than standard polymers like PLA or ABS.
This necessitates precise control of ΔP and L to ensure a steady Q. Now, for values of
R = 0.4mm = 0.0004m, ΔP = 85.3psi = 588122.8 Pa, η = 10^4 Pa. s [13] and L = 0.71inches [Annex A] = 0.018m,
$Q = 3.14*(0.0004)^4*588122.8 / 8*10000*0.018 = 0.032$ mm^3/s.

Now, flow rate for FDM printing varies from 10mm^3/s to 30mm^3/s [14] . To increase the flow rate from current setup, the values that can be varied are – R, ΔP, L and η. Now, according to [15], viscosity of mixture, **$\eta_{mixture} = \phi_1*\eta_1+\phi_2*\eta_2$ -----(V)**
we are adding 2.6g of UHMWPE in 10ml of DCB.
$\Phi_{UHMWPE} = m_{UHMWPE} / (m_{DCB} + m_{UHMWPE})$ ---- (VI)
$\Phi_{DCB}=1-\phi_{UHMWPE}$, mass fraction of DCB. Density of DCB = 1.304g/ml, so mass of DCB = 1.304 * 10 = 13.04g.
Mass fractions = $\Phi_{UHMWPE} = 2.6 / (13.04+2.6) = 0.1662$. $\Phi_{DCB} = 1-0.1662 = 0.8338$. So, the resultant viscosity is

$\eta_{mixture} = \phi_1*\eta_1+\phi_2*\eta_2 = 0.1662*10000 + 0.8338 * 0.0003 =$ 1662 Pa ----- (VI)

The table below (Table 2) shows the different scenarios of the permutations and combinations of various values of variables that when changed provide the optimum value of viscosity for extrusion.
The results illustrate how the viscosity of UHMWPE-DCB mixtures is significantly influenced by the ratio of polymer to solvent. As the proportion of DCB increases, the mixture's viscosity decreases, reflecting the dilution of the highly viscous UHMWPE by the low-viscosity solvent. This trend highlights the dominant effect of the polymer's properties on the mixture's behavior, which diminishes as the solvent becomes a more substantial component. The data clearly demonstrate the relationship between composition and viscosity, emphasizing the critical role of solvent content in tuning the flow properties of the mixture. The optimal values of length of the nozzle , Radius of the nozzle , and the pressure applied are necessary to get the optimum flow.
Let the pressure applied is assumed to increase to 120psi and the length of nozzle L is decreased to 10mm. The radius of nozzle is increased to R = 0.85mm. With the above values, Flow rate is calculated again for the mixture.
$Q = \pi R^4 \Delta P / 8 \eta L, = 3.14*(0.00085)^4 * 827371.2 / 8 * 1662 *0.01 = 10.2$mm^3 / s ----- (VII)
This flow rate is within the range of FDM printing rates required for the continuous flow of the material from the nozzle. The calculations can be verified by the further experimentation which will be covered in the next phase of the research.

6. CONCLUSION

The 3D printing of the UHMWPE has the potential to bring down the overall manufacturing time. It should be more effective body armour due to layered alignment in 3D printing as compared to conventional methods used nowadays. This will not only help to meet the increasing demand of this product but also 3D print various designs which was not possible earlier. It will open wider applications in medical field as well as more and better opportunities in other fields too.

6.1 Summary of Findings

This study explored the feasibility of 3D printing UHMWPE using a custom pneumatic extrusion setup. Key findings include: UHMWPE's unique properties present significant challenges for additive manufacturing, particularly in achieving consistent extrusion. Dissolution in o-Dichlorobenzene enabled partial success in material deposition, highlighting the importance of solvent-based preparation techniques. Optimum flow rate can be obtained by varying the values of solvent volume, radius of the nozzle, length of the nozzle and pressure applied over the holder. 3D printing offers unparalleled flexibility in design and manufacturing, enabling the production of intricate shapes and reducing material waste. The integration of UHMWPE into 3D

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printing processes would further enhance its applications in high-demand fields such as medicine and defense.

The success of this research could pave the way for broader adoption of UHMWPE in additive manufacturing, opening new avenues for innovation and efficiency across industries.

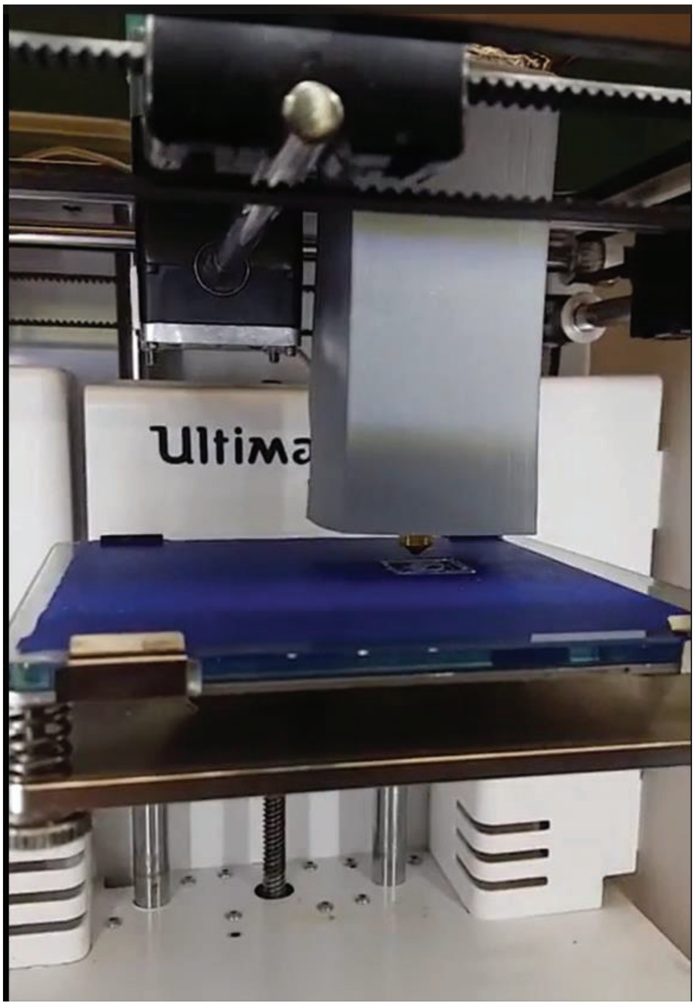

Figure 32 : Setup Testing using PCL material

Figure 33 : Melted UHMWPE in Extrusion form

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Table 2- Flow Rate Values for various variables

S. no	UHMWPE (g)	DCB (ml)	Viscosity η (Pa.s) mixture at 170degree C	Radius of nozzle (m)	Pressure difference P (Pa)	Length of nozzle (m)	Flow rate Q (m^3 / s)
1	5.0	0.0	10000.0	0.0004	588123.0	0.018	0.03
2	5.0	5.0	4339.0	0.0004	588123.0	0.018	0.08
3	4.0	5.0	3802.3	0.0005	620528.4	0.016	0.25
4	4.0	5.5	3580.4	0.0005	689476.0	0.016	0.30
5	3.8	6.0	3269.1	0.0006	827371.2	0.015	0.86
6	3.5	6.5	2922.5	0.0007	689476.0	0.015	1.48
7	3.2	6.8	2651.8	0.0008	758423.6	0.014	3.28
8	3.0	7.0	2473.6	0.0008	758423.6	0.014	3.52
9	3.0	8.0	2233.5	0.00085	827371.2	0.012	6.32
10	2.6	9.0	1813.6	0.00085	827371.2	0.011	8.50
11	2.6	10	1662.4	0.00085	827371.2	0.01	10.2

7. FUTURE PLANS

The extrusion of this material can be explored in various ways such as: -

Pneumatic Extrusion
This method will be applied on the current setup, finding the best morphology of the material. The focus should be on precisely controlling the temperature so that best results can be obtained Mechanical Extrusion (suggested by Valkenaers et al., 2013

[10]) This can be further improved by changing the setup to use mechanical pressure to squeeze the material so that the extrusion force can be used which we are expecting to be strong enough to have a stable extrusion result.

Filament Extrusion (suggested by Kishore et al., 2016[11])
This method is the mass manufacturing method in which making the PE material into filament, then using commercial FDM printer to print is explored. This can boost the manufacturing industry of this material to great extent.

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Mechanical Extrusion and Pressure Analysis
To transition from pneumatic to mechanical extrusion, the required compressive force can be recalculated based on screw-based mechanisms. For UHMWPE with high friction coefficients (μ=0.3\mu = 0.3μ=0.3 to 0.50.50.5), the design of the screw extruder becomes critical for minimizing resistance while maximizing extrusion consistency.

Long-Term Industry Adoption
Future studies can focus on reducing material viscosity through novel solvent blends or developing high-temperature filament extrusion techniques. Advances in adaptive nozzle designs, such as variable-diameter nozzles, can also support continuous 3D printing of UHMWPE for complex geometries.

8. ACKNOWLEDGMENTS

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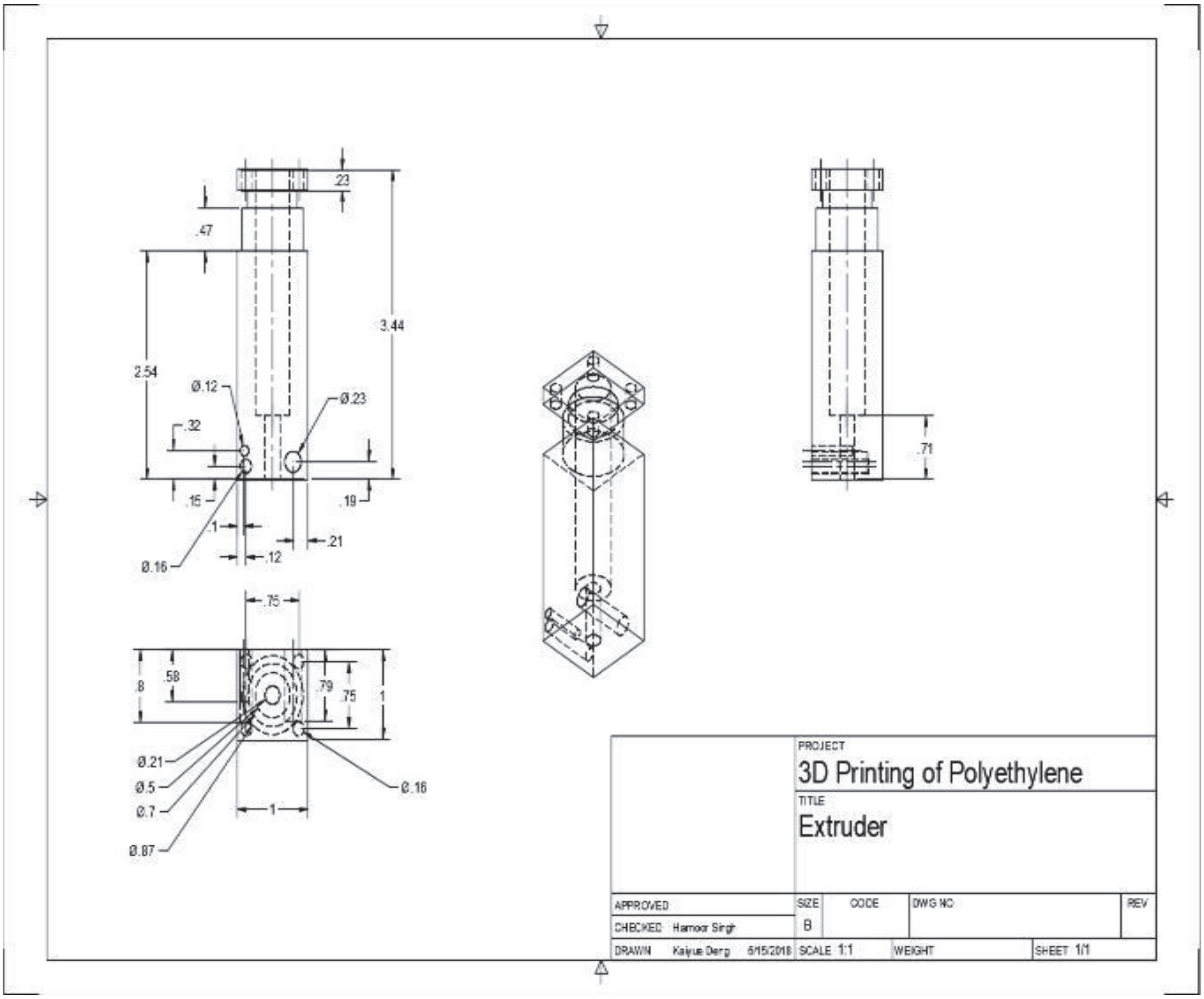
ANNEX A

DRAWINGS OF EXTRUDER AND HOLDER

A.1 Drawing of Extruder (designed using Autodesk Fusion 360)



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A.2 Drawing of Holder (previously used, designed using PTC Creo Parametric)