Open Source 3D Printing Filament (Rev 1)

Contents

Introduction – Why Open Source Hardware 3D Printing Filament?

IC3D's company mission is to "democratize manufacturing" in order to "unlock human potential." This concept simply means that anything can be made anywhere by anyone. The spirit of this statement is not unlike that of "open source" software and hardware which aims to allow anyone to modify, make, and sell products based on shared designs. In today's society, there are many good options for open source 3D printers in terms of hardware and software, thanks in huge part to the RepRap project (see below for more history). However, there is still a gap for "open source" that exists between the "readily-available … materials" and most of the desktop 3D printers available, which is in the 3D printing filament. One might look at the landscape of 3D printing filament and think that there are already numerous brands available today. However, there are still several issues:

1. Most brands are private labeled products supplied by just a few manufacturers.
2. Most manufacturers of 3D printing filament began producing their core product that serves a different industry that typically has standards insufficient for 3D printing filament (plastic welding rod, yard trimming line, etc).
3. The number of 3D printing material choices available in the market pales in comparison to the number of formulations and compounds available by the numerous resin manufacturers and toll compounders.

IC3D's goal for this document is to help solve some of these issues. If more people could understand the basics and components to making 3D printing filament, there could be more filament material options from high-quality manufacturers.

About RepRap

The RepRap project started in England through the University of Bath in 2005 and sought to develop a low-cost 3D printer capable of printing most of the constituent components. The term "RepRap" is short for replicating rapid prototyper. The team lead by Adrian Bowyer started a revolution in Open Source Hardware 3D printing and are responsible for the wide variety of 3D printers available today. Visit RepRap.org for more history of the RepRap project. [http://reprap.org/]

Open Source Hardware (OSHW) Statement of Principles 1.0 (by the Open Source Hardware Association)

"Open source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware's source, the design from which it is made, is available in the preferred format for making modifications to it. Ideally, open source hardware uses readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open-source design tools to maximize the ability of individuals to make and use hardware. Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs."

https://freedomdefined.org/OSHW#Open_Source_Hardware_.28OSHW.29_Statement_of_Principles_1.0, CC-BY-2.5

About IC3D

IC3D's Mission: To provide the highest quality 3D printing consumables and services that significantly reduce lead-time and cost over traditional manufacturing methods, thereby **democratizing manufacturing** which leads to **unlocking human potential.**

Timeline:

2003 – Michael Cao begins 3D-printing on commercial FDM and Polyjet machines as a design engineer of many plastic injection molded parts for a large automotive OEM

2011 – Michael purchases Makerbot Thing-O-Matic. Doesn't enjoy tuning process and quality. Finds the Reprap community. Falls in love. Decides to start with the MendelMax frame, makes several minor tweaks to the printed parts but redesigns the Y system to integrate electronics underneath the build platform. Shares designs on Thingverse. Discovers CORMUG (Central Ohio Reprap and Makerbot Users Group), one of the longest running regular 3D printer meetups in the nation (monthly since 2009).

2012 – With a small support team, ends up building, tuning and selling about 60 MendelMax's in about 1 year in a basement. IC3D is created in a basement in Columbus, Ohio.

2013 – With the struggle to find high quality US-made 3D printing filament, purchases first extrusion line dedicated to ABS. Decides to stop making 3D printers and focus on filament.

2014 – IC3D purchases second extrusion line to dedicate to PLA.

2015 – IC3D adds 3D printing service. Grows staff and in-house equipment.

2016 – Michael finally leaves corporate America to grow IC3D full-time. IC3D designs and builds several medium sized FFF 3D printers for in-house service bureau use and filament testing.

Polymer Resin Pellets

Plastics can be derived from a variety of resources such as coal, oil, minerals and even the cellulose found in plants. While many materials and methods are used today to produce a variety of products, several of the more common polymers used to produce filament include ABS, PLA and PETG. For the purposes of this document and due to the complexities and expenses in manufacturing from the petroleum or corn starch base, the polymer resin pellets are considered a "readily-available … material."

Plastic Extrusion of 3D Printing Filament

Terminology

Melt - polymer liquid above its glass and/or crystallization temperatures.

Ovality - the degree of deviation from perfect circularity of the cross section of, in this case, the filament strand.

Resin – a solid or liquid synthetic organic polymer used as the basis of plastics, adhesives, varnishes, or other products

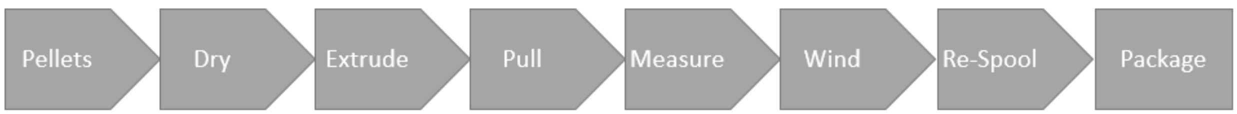
Masterbatch – colorant that is mixed with natural (colorless) resin to produce the desired final color

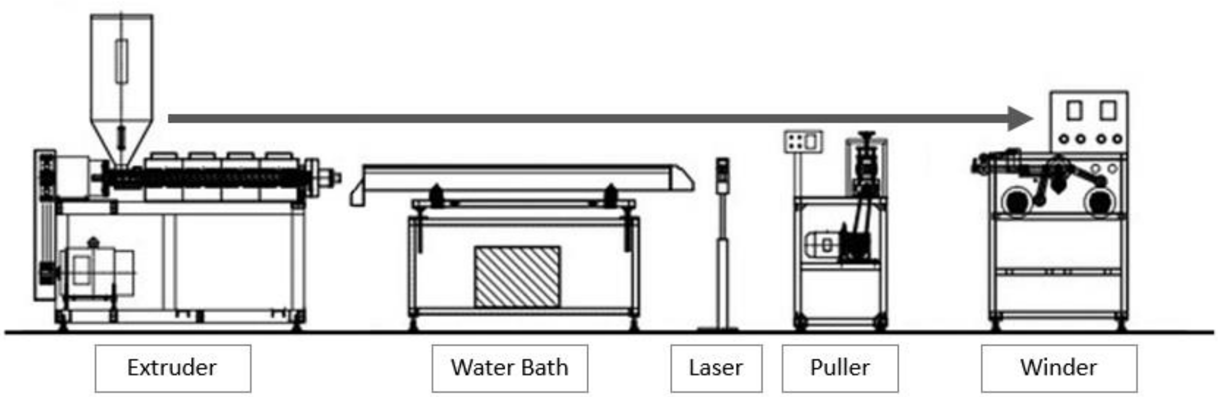
Stringing – the process of hand-pulling the initial polymer melt through the water bath and into the puller that is in operation

The consumable for most desktop 3D printers is in filament form. This is also called round rod profile extrusion: “round” since the cross-section is circular, “rod” as opposed to tubing or channel, and “profile” since the final shape is dictated by a die at the end of the extruder.

The following sections outline in more detail the equipment and process that IC3D uses to make filament.

Basic process flow:





Drying

Since nearly all polymers are hygroscopic (water absorbing), it is an important measure to properly dry resin pellets before putting into an extruder whether for injection molding or profile extrusion. If moisture is absorbed into the plastic resin, it will turn into a gaseous state while heated in the barrel of the extruder which will either form air bubbles in the filament or off-gas upon exiting the extruder die which may lead to an undesired surface finish as well as inconsistent dimensions.

In IC3D’s production process, a Novatec MD-50 commercial grade dryer is used. The resin pellets are dried at a certain temperature for a certain duration (please see Parameters section). Different polymers will require different temperature and / or drying time depending on factors such as grade, type of fillers, pellet size, and even the manufacturing environment.

Extruding

All plastic profile extrusion involves, by definition, an extruder. The basic components include a hopper, barrel, screw, motor and gearbox, screen pack, breaker plate, dies, pressure transducers, heating elements, and controls. Extruders come typically in either single-screw or twin-screw. IC3D utilizes single-screw extruders for both the production lines

Basic Components

Hopper – A hopper simply holds the plastic resin to consistently feed the throat of the extruder barrel. Some hoppers can incorporate a resin dryer as well as a vacuum delivery system that can move resin from a container on the factory floor to fill the hopper automatically. On IC3D's Line 1 that is described in this document, the dryer / vacuum system is a standalone unit. Other IC3D extrusion lines have integrated systems. IC3D plans to have an integrated system for Line 1 in the near future as a process improvement.

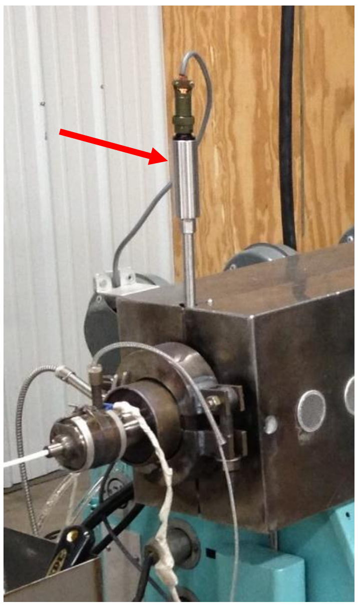
Barrel and Screw - the size of a plastic extruder is often expressed in two values, the diameter of the barrel and the diameter to length ratio. Small extruders, often called lab extruders, typically start from about one inch in diameter, and larger high output extruders can be found with diameters of several inches or more.

The extrusion screw has three zones: the feed, compression (or transition), and metering zones. The feed zone behaves as an auger to transfer material from the hopper to the compression zone. The compression zone has two primary functions. It builds pressure for the polymer to being shearing along the side of the barrel. The act of shearing the resin pellets is how about 90% of the heat is generated to reach melting temp. The other function of the compression zone is to force air and vapors rearwards and out of the polymer melt. The metering zone has the function of creating a consistent flow by creating constant pressure by controlling the volumetric flow rate of material.

Screen Pack – this is a single or multi-layer stack of steel wire mesh that is a filter for contaminants in the polymer melt. Mesh density comes in various densities chosen for the specific material being extruded. This is typically changed out regularly to prevent build-up that can lead to increase head pressures which could influence the final dimensions of the product. The IC3D extrusion lines use a 2-layer stack of a course and fine screen in order to catch smaller sized contaminants. The course screen is on the upstream side. The course screen is a size #20 while the fine screen is #40 (see BOM for more info).

Breaker Plate – the purpose of this component is to support the screen pack by serving as a backing. This resides immediately after the barrel and end of screw. It is a thick plate with many holes that offer support for the thin mesh of the screen pack while allowing melted plastic to flow through. Key design elements are chamfered holes to improve flow and reduce pressure (see included CAD files for the design of ours).

Pressure transducers- these are located at the end of the extrusion barrel and monitor the pressure. Reading the pressure and keeping it within a desired range is a key factor to consistent extrusion as well as being able to increase the production rate. There is one located on each extruder.



Heating elements – these come in primarily two forms, rod heaters and band heaters. Band heaters are found though the various zones of the barrel as well for various sections between the end of the barrel and the outlet of the die. Rod heaters can be used for extruders that include a melt pump which consists of a block of steel containing the gears to control volumetric flow. The rods would be found inserted into various locations of this block. IC3D's Line 1 does not currently incorporate a melt pump, however this will be a future upgrade. IC3D's Line 2 does incorporate a melt pump which allows for higher output due to the ability to stabilize the diameter and roundness.

Cooling

When the polymer melt exits the die of the extruder, it enters the water bath. It is in this section where the filament strand gets drawn down to the final size as it transforms from a liquid state to a solid state. It is critical to maintain a steady temperature of the water since this could drastically effect the diameter consistency as well as the ovality. Since the polymer entering the water is typically at a temperature near or above that of water boiling, much heat is introduced into the water gradually raising it. Therefore, a chiller is used in conjunction with a heat exchanger to introduce chilled water to maintain a steady water bath temperature. (more information in BOM)

Pulling / Drawing

The puller is the piece of equipment that moves the filament through the production process. It is comprised of upper and lower rubber treads with a smooth surface that are driven synchronously that pull the filament strand. The speed of the puller is also the primary method of adjusting and tuning the diameter of the strand, therefore, a high-quality and well-maintained puller is critical to dimensional accuracy.

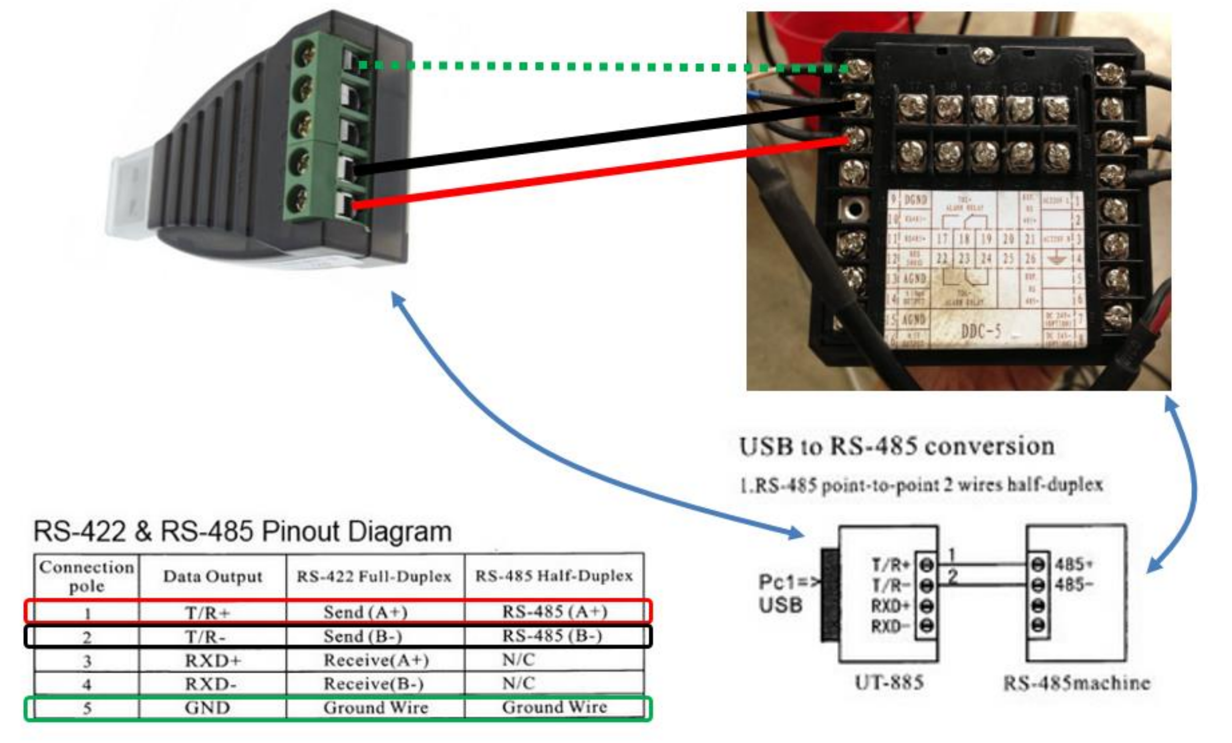
Measuring

One of the most important aspects of high-quality 3D printing filament is dimensional accuracy. Having dimensionally out-of-spec filament will lead to inconsistencies in layer adhesion, surface quality, and can lead to insufficient driving force from the extruder on the 3D printer. A non-contact dual axis laser gauge is used to measure the instantaneous diameter at a high frequency as the filament passes through. The two axes are typically offset by 90 degrees. From these two measurements, the average diameter and ovality can be calculated. IC3D's filament extrusion lines use a Mercury-Tech LDM-25XY dual axis laser gauge.

The Mercury Tech LDM-25XY includes the DDC-5 Display Controller which displays the instantaneous diameters along both axes. IC3D has developed in-house a monitor app for PC that takes these two inputs and displays them graphically. In order to achieve this, a USB to RS485 / RS422 Converter is used. See the below instructions on wiring as well as more details in the BOM.

Wiring Instructions for the USB to RS485 / RS422 Converter:

Connect #1 on the USB adapter to #11 (RS485+) on the Laser Controller.
Connect #2 on the USB adapter to #10 (RS485-) on the Laser Controller.
Connect #5 on the adapter to #9 on the Laser Controller



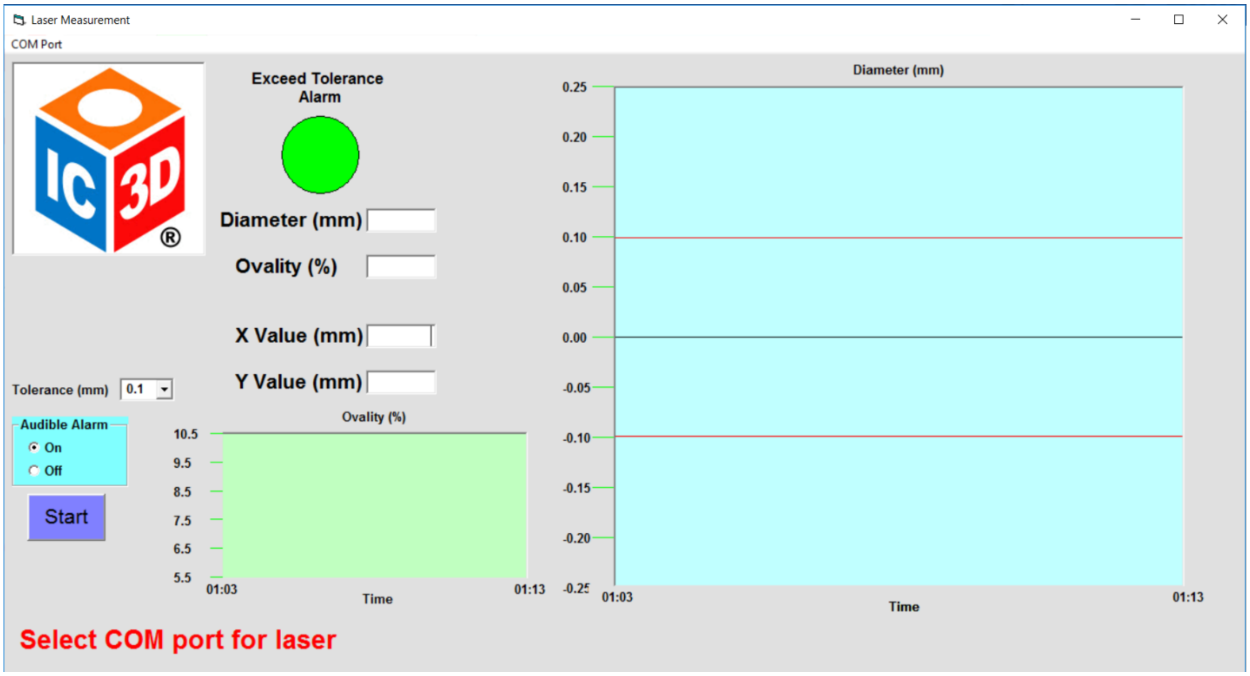
Connection pole	Data Output	RS-422 Full-Duplex	RS-485 Half-Duplex
1	T/R+	Send (A+)	RS-485 (A+)
2	T/R-	Send (B-)	RS-485 (B-)
3	RXD+	Receive(A+)	N/C
4	RXD-	Receive(B-)	N/C
5	GND	Ground Wire	Ground Wire

Due to the speed at which the filament strand travels as well as the span between the water bath and the puller, the filament can vibrate while going through the laser gauge. IC3D has designed "filament stabilizers" that comprise of a fixed bearing and a tensioned bearing that hold the filament steady as it travels through the laser measuring zone to obtain a more precise reading. (Plans and BOM included. Licensed CC BY-SA 4.0 IC3D Inc. 2017)


Laser Monitoring Software

The Mercury Tech LDM-25XY includes the DDC-5 Display Controller which only displays the instantaneous diameters. Relying only on this is makes it difficult to monitor data. IC3D has developed in-house a Windows app that takes in the two diameter inputs from the laser gauge via the DDC-5 and has the following features (d1 = diameter 1, d2 = diameter 2):

- Average diameter = (d1+d2)/2
- Ovality % = d1-d2/((d1+d2)/2) * 100
- Diameter selection: 1.75mm or 2.9mm
- Tolerance band: ± 0.1mm or ± 0.05mm
- Graph of average diameter over 10 mins
- Graph of ovality over 10 mins
- Visual alert if average diameter surpasses tolerance threshold
- Audible alert if average diameter surpasses tolerance threshold

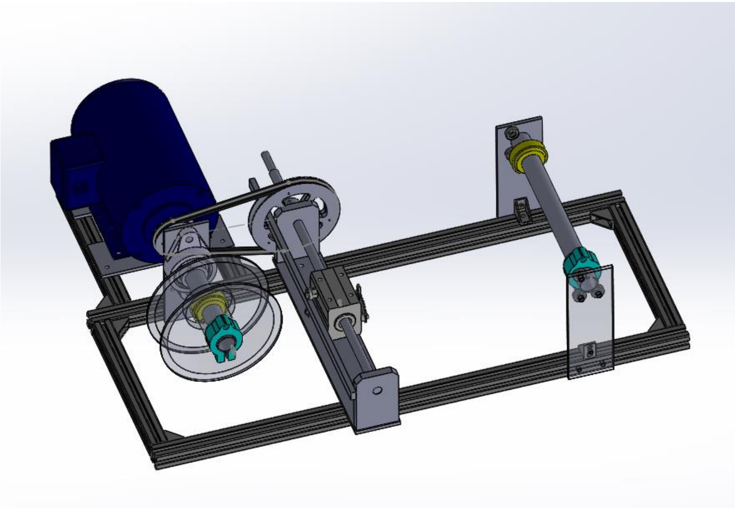


Winding

Winders can be set up to produce various sizes of spools. However, it can be tricky to adjust the end limits of the traversing mechanism while running at production speeds on-line. Therefore, IC3D's production lines are set up to run their largest product of 10kg (22lb) spools. These large spools are then taken over off-line to a respooler to create the 1kg (2.2lb) and 2.3kg (5lb) products.

Respooling

As mentioned in the previous section, a Winder can be used to create the final spool. However, IC3D has chosen to use an optional respooler to increase production flexibility. A respooler simply has one drive motor to drive a shaft where the empty spool mounts, a traversing mechanism that lays the filament neatly onto the spool to prevent overlapping strands, and a pay-off where the larger 20lb units are mounted. IC3D uses a respooler that is designed in-house. There are also commercially available units from various manufactures. (Plans and BOM included. Licensed CC BY-SA 4.0 IC3D Inc. 2017)



Stringing

When starting up the extrusion line for the first time or at the start of a production period, the filament needs to be "strung." After heating up the extruder properly (per instructions from the manufacturer) and slowly turning on the extruder motor, polymer melt will begin to come out of the extruder die and droop to the ground. It will be necessary to take this melt (carefully with high temp resistant gloves) and get it pulled through the water bath and into the puller and then connected to a spool on the winder.

Parameters

Component	Parameters		
	ABS on IC3D "Line 1"	**PLA on IC3D "Line 2"**	**PETG on IC3D "Line 2"**
Extruder Zone 1 heat (feed)	360 F (182 C)	160 C (320 F)	200 C (392 F)
Extruder Zone 2 heat (transition)	395 F (201 C)	165 C (329 F)	205 C (401 F)
Extruder Zone 3 heat (mix)	395 F (201 C)	175 C (347 F)	210 C (410 F)
Extruder Zone 4 heat	n/a	180 C (356 F)	215 C (419 F)
Extruder Zone 5 heat (melt pump)	n/a	185 C (365 F)	220 C (428 F)
Extruder Zone 6 heat (melt pump)	n/a	185 C (365 F)	220 C (428 F)
Extruder Die Zone heat	300 F (149 C)	225 C (437 F)	210 C (410 F)
Extruder screw speed	16 RPM	42%	42%
Extruder head pressure	3000 psi (20.7 MPa)	15 MPa (2175 psi)	15 MPa (2175 psi)
Water bath temp	152 F (67 C)	52 C (125 F)	68 C (154 F)
Puller Speed	30.2 ft/min	36.4 M/min	31.6 M/min
Winder Speed	Set at 100%	Set at 100%	Set at 100%
Resin drying temp	79 C (175 F)	79 C (175 F)	65 C (150 F)
Resin drying time	≥ 4 hrs	≥ 4 hrs	≥ 8 hrs

Warning

Pressure

With operating pressures being as high as 5000 PSI, it is a very real scenario for the extruder die to burst and fly off like a projectile if the die clamp or any other component is not properly tightened, inspected or maintained. IC3D's extrusion lines include a "rupture disk" that is designed to give way and relieve pressure when the pressure reaches about 9500 PSI as to not cause damage to the equipment or surrounding people.

The purpose of this document is to educate the general public on the basics of manufacturing 3D printing filament including settings and parameters. IT IS NOT a comprehensive guide for installation, maintenance, and all safety precautions. Since there are many manufacturers of new and rebuilt equipment, it is vital for your operation to consult with the manufacturer regarding these aspects.

Heat

It may be obvious to take extreme caution when around the extruder at operating temperatures as well as the polymer melt. However, there will be times when the operator or technician will be required to handle components at operating temp such as during die changes, screen pack changes, and screw removal during maintenance. During the stringing process, melted plastic will burn the skin. Use high-temperature gloves and tools and take extreme care.

Tuning of the Filament

When talking to most plastic extrusion experts, the terms "art" and "black magic" may commonly be heard. This is because there are numerous variables that can affect the outcome of the filament. It is not practical (some may even say possible) to explain exactly how each environmental and equipment parameter effects the settings in which exact way to produce in-spec filament. Below are lists of common variables that effect both basic settings as well as the outcome of the filament:

Common filament quality problems:

- Diameter variation
- Ovality (roundness) variation
- Bubbles inside filament
- Bumps or bulges on outside of filament
- Rough surface
- Brittleness
- Contaminants
- Color inconsistencies

Basic settings that control filament output:

- Pellet drying temperature
- Pellet drying time
- Extruder temperature of various zones
- Extruder speed
- Puller speed
- Water bath temperature
- Water bath inlet and outlet flow speed / currents relative to filament strand

Variables that effect "basic settings:"

- Condition of resin from manufacturer

- Temperature of air in factory
- Humidity of air in factory
- Pressure in the room of the factory
- Exact dimensions of the manufactured extruder components even for the same model (barrel, screw, dies, adapter plates, etc)
- Efficiency and wear of the components in the extruder (motor, gearbox, heater)
- Surface roughness inside various components in the extruder
- Puller / belt efficiency and wear and tear over time

Variables that can lead to a sudden spike in poor quality:

- Draft across polymer melt (ex. garage door opening in the room or HVAC turning on)
- Ambient pressure change (ex. large door or window opening in the room)
- Surges in electrical (ex. poor electrical service or large piece of equipment turning on that is on the same circuit as puller, laser monitor, etc)
- Stability of floor that the equipment is installed on (ex. vibrations from nearby forklift)
- Contaminants (ex. debris falling into box of pellets or hopper)
- Color inconsistencies (ex. wrong color of resin or colorant pellet dislodged from edge in dryer, hopper, inside extruder, etc.)

Masterbatch (Colorant)

Masterbatch is a concentrated mixture of pigments and/or additives encapsulated during a heat process into a carrier resin which is then cooled and cut into a granular shape. Masterbatch allows the processor to color raw polymer economically during the plastics manufacturing process. Masterbatch is primarily comprised of two components: the dye and the carrier resin. The carrier resin should be of the same type of polymer (i.e ABS if being used with ABS) as well as ideally the same grade to ensure consistent properties of the final product. IC3D filament uses masterbatch that is mixed to match a specific color when combined with the base “natural” (colorless) resin. Any colorant producer will also provide the exact “loading,” or mixing ratio, of colorant granules to the natural resin. This ratio is typically expressed by weight.

Reference

- IC3D Open Source Filament Documentation
  - https://consumables.ic3dprinters.com/open_source_filament
- RepRap
  - http://reprap.org/
- Open Source Hardware Statement of Principles
  - https://freedomdefined.org/OSHW#Open_Source_Hardware_.28OSHW.29_Statement_of_Principles_1.0, CC-BY-2.5
- Extruder Screen Mesh Size Explanation:
  - http://www.espimetals.com/index.php/online-catalog/327-technical-data/stainless-steel/334-understanding-mesh-sizes

BOM (Bill of Materials)

Polymer Resin

Item	Description	Supplier	Type / Model	Reference
ABS Resin	100% virgin resin	Chi-Mei	PA-747	http://www.chimeicorp.com/en-us/products/plastics/abs/

			(CAS 9003-56-9)	
PLA Resin	100% virgin resin	NatureWorks	Ingeo 4043D (CAS 9051-89-2)	https://www.natureworksllc.com/~/media/Files/NatureWorks/Technical-Documents/Technical-Data-Sheets/TechnicalDataSheet_4043D_3D-monofilament_pdf.pdf?la=en
PETG Resin	100% virgin resin	Eastman	Eastar 6763 (CAS not given)	https://www.eastman.com/Pages/ProductHome.aspx?product=71040786&pn=Eastar+Copolyester+6763
Masterbatch	Colorant	Chroma	---	http://www.chromacolors.com/

Other Components

Item	Description	Supplier	Type / Model	Reference
Spool	Plastic spool	ABC Plastics	MC-008-W	http://www.abcplasticslodi.com/products-page/one-piece-wire-spools/15-lb-spool-one-piece-wire-spool-8-inch-flange-4
Polybag	12 x 14" 6 Mil	Uline	S-11030	https://www.uline.com/Product/Detail/S-11030/Poly-Bags-Flat-Open/12-x-14-6-Mil-Poly-Bags
Dessicant	Gram Size 3, 1 1/16 x 2 1/16"	Uline	S-3904	https://www.uline.com/Product/Detail/S-3904/Desiccants/Silica-Gel-Desiccants-Gram-Size-3-5-Gallon-Pail

Equipment List

Item	Description	Brand	Model Number	Reference
Pellet Dryer	Dessicant dryer	Novatec	MD-50	http://www.novatec.com/parts/MD-MDM-50/
Extruder (Line 1)	1.25", 24:1 LTD	Killion (owned by Davis Standard)	KL 125	http://www.davis-standard.com/extruders
Extruder (Line 2)	40mm, 28:1 LTD	Kingswel Machinery	SXB-40T	http://www.kingswel.com.cn/english/
Extruder Screen-Course	Extruder Screen, Circular, Stainless Steel, 1-1/4" x 20 Mesh	IMS	159934	https://www.imscompany.com/ProductNavigation/ItemDetail?ItemNumber=159934
Extruder Screen-Fine	Extruder Screen, Circular, Stainless Steel, 1-1/4" x 40 Mesh	IMS	159935	https://www.imscompany.com/ProductNavigation/ItemDetail?ItemNumber=159935
Water Chiller	36000 BTU/hr, 3 ton capacity	Skyline	SAC-03	http://skylineinternationalco.com/Air-Cooled-Chillers.php
Water Heater	16 kW, ¾ HP, 35 GPM	Advantage Engineering	SK-1635-G	https://www.advantageengineering.com/temperatureControllers/units/temperatureControlUnit-skg1635.php
Water Bath	10' length	AMS	Economy- 10'	http://www.ams-plasticextrusions.com/
Pressure Transducer	10,000 psi range	Gefran	M30-6-M-P10M-1-4-0-000	http://www.swhc.com/pdf/Spec%20Sheets/Gefran/Gefran_M3_0208_ENG.pdf
Laser Gauge	Dual axis laser gauge	Mercury-Tech	LDM-25XY	http://www.cnmeasure.com/52/i-465.html
USB to RS485 / RS422 Converter	Connects Laser Gauge to PC USB	GearMo	GM-482422	http://www.gearmo.com/shop/usb-to-rs485-rs422-converter-ftdi-chip-with-terminals/
Puller	435 x 30	AMS	435 x 30	http://www.ams-plasticextrusions.com/
Winder	Dual Shaft Winder	AMS	Dual Shaft Winder	http://www.ams-plasticextrusions.com/