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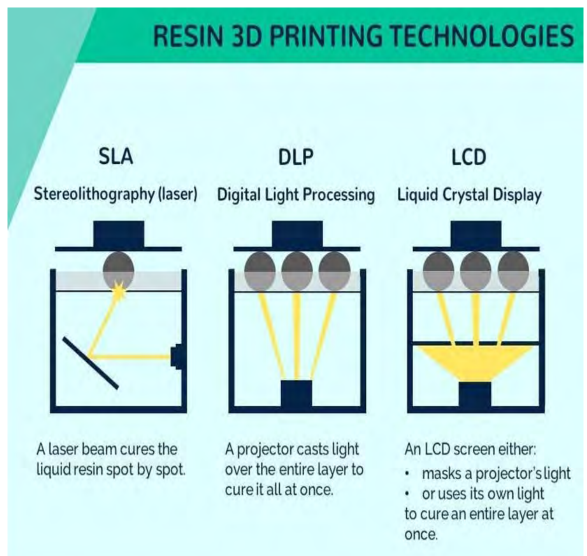
Radiometry

Background of 3D Printing

In the industry of additive manufacturing, the 3D printers themselves vary not only in the material used for printing, whether they print resin, filament, or even cement, but also in how things get printed, like positioning or differences in light sources. 3D printers are categorized into 4 different types: SLA, DLP, LCD, and FDM. FDM are filament based printers, which mean that they use a heated nozzle to melt the thermoplastic filament building layers on a build platform.

SLA, DLP, and LCD printers use a process called Vat Polymerization to cure the resin into layers by using a resin tank and a certain type of light source. This allows for ultra detailed pieces compared to the detailed abilities of FDM printers.



Stereolithography (SLA) started being commercialized in the mid 1980's, and uses a laser beam to selectively cure layers of resin on the bottom of the resin tank that then adhere to a print platform. The laser works by using galvanometers, which are little mirrors under the resin tank, to guide the laser to the precise position that needs to be cured.

In DLP 3D printing, they use a digital light projector to cure the layer of resin simultaneously. Using the color black or no light at all to get precise layers.

The last type of Vat printers are the Liquid Crystal Display (LCD) printers, which use LED lights that shine through LCD panels to cure the current layer of resin.

LCD/LED Light Sources

Liquid Crystal Display (LCD) printers have recently become a popular option for 3D printing, they provide a high quality product while also being cost effective, similar to a FDM 3D printer. In LCD 3D printers, an array of UV LCD panels are used as a light source which only allows light to pass

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through where resin needs to be cured, reducing the need for galvanometers and mirrors which simplifies the printing process. LCD based printers have a print quality that depends on the LCD density. The more pixels a display has, the better the quality of the print.

A common problem with LED lights is that they fade over time, and may take a couple days to a number of years. They start to dim towards the end of their life span unlike other traditional light bulbs that burn out all at once. Each light will age differently due to manufacturing, and there are thousands of LEDs within a singular array. Small imperfections in the LED chip semiconductor crystals can cause the LED to begin losing brightness. LEDs let out a small amount of heat when they are turned on, without proper cooling can increase the rate of which it decays.

> “The term degradation in connection with LED lighting describes the decrease in luminous flux over the course of a lifetime. The luminous flux slowly decreases due to material changes in the LED chip and clouding of the optics. Degradation is therefore an aging process in which an LED lamp loses its brightness over time and slowly becomes darker.”(LED Brightness Degradation: Do LED Lights Dim With Age? - LampHQ, 2022)

Common Printer Issues and Observations

When 3D printing, there are many parameters that need to be met for a successful print to take place. Print failures can occur due to anything from incorrect settings, to support placement, and equipment that needs calibration. As we have been using 3D printers, we have seen how important it is to include radiometry in the conversation of print issues as well.

We have observed that when printing, sometimes we would have failures on printers that had been consistently printing, were calibrated, cleaned, had correctly inputted settings, and with a known material. Sometimes these print fails were minor, a deformed support or an unlevel surface that was able to be sanded smooth, however other times it would be a complete fail with no model attached to the print platform or half the model missing. For a while we had these failures seemingly out of nowhere, and began investigating and learning more about our 3D printers.

We observed that lifting and uneven models were mostly printed if they took up a majority of the print platform, or were placed close to the edges. This star ship is a good example of what it looks like when it’s lifting. This print took up most of the print platform horizontally, the edges of the print lift more the closer you get to the edges.

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Some 3D printer manufacturers offer replacement screens and instructional videos for their printers due to these inconsistency issues. Other 3D printing companies don’t offer any replacement option or even acknowledge the problem with their light sources. We understand that companies don’t want everyday people trying to do their own repairs on the printer and possibly worsening the problem but on the other hand, acknowledging the problem and addressing it is ideal.

Purpose of Experiment

One of the reasons we came up with this experiment was because we started to notice that we would have a print fail then try it on a different printer from the same manufacturer with the same print settings and it would print perfectly. While this was happening, we began to wonder what could be the cause of this. There are a couple different variables that we had to look at, like material, light source, or printer calibration. We have had issues in the past with prints peeling up at the edges but we thought that it was due to not having a high enough bottom exposure level. As we did more research into 3D printers, we learned that overtime the light sources begin to dim and don’t work at 100% power consistently or have inconsistency over the whole screen.

Overall, the main reason for this experiment is to do more research to better understand the printers, find out why there are inconsistencies in print quality, and figure out why after multiple successful prints we have a print fail when there are no obvious reasons for failure. We need to understand these things in order to develop materials at the highest quality possible for this industry.

Procedure and Equipment

We used a UV light meter (radiometer) to measure the output of energy the light in different 3D printers gives off when operating. First, making sure the radiometer is on and in the correct parameters of (uW/cm^2) for this experiment. While wearing proper PPE, we turned the display on or started the “print” depending on the printer. Then we took the probe and placed it on the printer's screen to take our measurement of the UV light output. We ran the probe for five seconds, and recorded the data. The process was then repeated, depending on which measurements were being taken, the probe was either kept in the same spot for more readings or moved to another

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spot on the printer's screen and recorded. The average was taken of three measurements to get the data reported for each particular printer.

For the experiments performed, we had several different printers we used. As the Cost Range table below shows, some printers tested were on the low end commercially, and some on the high end. The printers varied in how they allowed radiometry testing as well; some give measurement internally, however most don't. And some printers have an option to test the light's power without an actual measurement produced.

The point of this experiment was not to evaluate which printer or manufacturer had the best printer, but to create discussion about radiometry and 3D printing. We have assigned letters to the different printers within the experiment, and have categorized them by cost in ranges to give a scope of understanding for readers.

Cost Range	**Manufacturer**
under $1000	A, G
$1000-$5000	E, F
$5000-$10000	B, C
$10000+	D

It is also important to note that any printers that were tested were within the specification per the manufacturer at the time testing was performed.

We wanted to do a check on the precision with this radiometer. We did several experiments to understand the variation with respect to measurement. We did this by measuring printers in the same spot multiple times with the radiometer cycled on and off without moving the probe.

Testing of Radiometer: Consistent Spot on the Screen with Radiometer Turned on/off Between Samples		
Printer Number	**Avg. Per Printer (uW/cm^2)**	**Std. Dev. Per Printer**
#1	**4115.4**	7.7
#2	**4352.5**	2.8
#3	**4267.2**	1.3

#4	**4044.0**	6.8
#5	**4036.7**	0.6
#6	**4625.7**	12.7
#7	**4105.3**	9.0
#8	**4242.5**	15.9
#9	**4075.3**	3.6
#10	**4069.9**	2.2
#11	**4217.7**	2.5
#12	**3990.5**	0.1

As it can be seen above, the radiometers measurements are extremely consistent with low variability.

Challenge of Measuring Energy Outputs

When beginning the testing for this experiment, we noticed some manufacturers allow you to check the exposure levels and/or display an image that we can check the quality of the LED. There were a few that we had to start a print with a long exposure time and trick some safety features to be able to check the energy output. We have three printer manufacturers that have safety features, or are designed in a way that we weren't able to check their energy output.

With having to trick some of the printer's safety features or using a display, the total energy output for individual printer manufacturers is not being compared across manufacturers.

Data and Analysis

We will begin looking at data from Printer Manufacturer A. We have a total of 12 printers from this Manufacturer that we performed testing on, ranging in age from 1 month to 12 months old and the range in use from ~10 hours to ~200 hours.

When looking at Manufacturer A and the data reported for these printers, it is important to note that the assigned printer number is not significant to the age of a particular printer or amount of time used. The assigned numbers are purely for distinction between printers of this manufacturer within our lab.

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Printer Manufacturer A: 3 Spots on the Screen					
Printer Number	**Left Spot Measurement (uW/cm^2)**	**Middle Spot Measurement (uW/cm^2)**	**Right Spot Measurement (uW/cm^2)**	**Avg. Per Printer (uW/cm^2)**	**Std. Dev. Per Printer**
#1	4393	4199	4309	**4300**	97
#2	4521	4463	4488	**4491**	29
#3	4233	4165	4145	**4181**	46
#4	4180	4063	4536	**4259**	247
#5	4331	4101	4688	**4373**	296
#6	4823	4943	5290	**5019**	243
#7	4420	4417	4775	**4538**	206
#8	4375	4276	4564	**4405**	146
#9	4120	4490	4550	**4387**	233
#10	4293	4231	4621	**4382**	210
#11	4116	4277	4141	**4178**	87
#12	4385	4208	4313	**4302**	89
Avg. Per Side (uW/cm^2)	**4349**	**4319**	**4535**		
Std. Dev. Per Side	194	238	312		

Manufacturer A's printers show a range of variation across the print platform. We have not done a correlation study for light exposure vs. print issues, and faster chemistries will be more robust with respect to this error. However, for this system based on some calculations we expect less than 2% to be great, less than 5% to be acceptable, 5-10% could possibly start causing issues and >10% probably print issues. For these 12 printers 6-7 could have significant print issues across the surface. The variation is also very high from printer to printer, so if you were trying to reproduce a method over these printers it could be very challenging.

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Printer Manufacturer B: 3 Spots on the Screen					
Printer	**Left Spot Measurement (uW/cm^2)**	**Middle Spot Measurement (uW/cm^2)**	**Right Spot Measurement (uW/cm^2)**	**Avg. Per Printer (uW/cm^2)**	**Std. Dev. Per Printer**
New Printer	11739	12304	12151	12065	292
12 Months Old	9922	11462	11426	10936	879
Avg. Per Side (uW/cm^2)	**10285**	**11630**	**11571**		
Std. Dev. Per Side	1384	377	338		

Printer Manufacturer B: Consistent Spot on the Screen					
Printer	Sample1	Sample2	Sample3	**Avg. Per Printer (uW/cm^2)**	**Std. Dev. Per Printer**
New Printer	12326.6	12327	12326.8	**12326.8**	0.2
12+ Month old	11457.8	11452.9	11442.5	**11451.1**	7.8
			Avg. of Printers (uW/cm^2)	**11888.9**	
			Std. Dev. of All Printers	**619.2**	

Looking at the data produced by Manufacturer B's printers, we can see how the older model has had more and more issues with consistent prints as it aged. Due to this, we bought a new one. The older printer meets the manufacturer's specifications and the new printer is fairly consistent with prints. The data clearly shows the new printer has significantly less variation then the old printer by greater than a factor of 3 across the print surface and even higher difference in irradiance.

Printer Manufacturer C: 3 Spots on the Screen					
Sample	**Left Spot Measurement (uW/cm^2)**	**Middle Spot Measurement (uW/cm^2)**	**Right Spot Measurement (uW/cm^2)**	**Avg. Per Printer (uW/cm^2)**	**Std. Dev. Per Printer**
1	11925	11842	11850	**11872**	46
2	11899	11834	11838	**11857**	37
3	11889	11821	11835	**11848**	36
Avg. Per Side (uW/cm^2)	**11904**	**11832**	**11841**		
Std. Dev. Per Side	19	10	8		

Manufacturer C is the only machine that does calibration of its own light internally. Though the data we displayed was a measurement we did take with our own radiometer as per the method listed above to keep consistent with the rest of our data. The printer is amazing with respect to the precision of irradiance as shown through the data in the table.

Printer Manufacturer D: 3 Spots on the Screen					
Sample	**Left Spot Measurement (uW/cm^2)**	**Middle Spot Measurement (uW/cm^2)**	**Right Spot Measurement (uW/cm^2)**	**Avg. Per Printer (uW/cm^2)**	**Std. Dev. Per Printer**
1	2856	2425	2920	**2734**	269
2	2808	2415	2901	**2708**	258
3	2852	2424	2890	**2722**	259
Avg. Per Side (uW/cm^2)	**2839**	**2422**	**2904**		
Std. Dev. Per Side	27	5	15		

A great example of you don't always get what you pay for, Manufacturer D produces a very expensive printer, and its consistency across the build platform is poor.

Printer Manufacturer E: 3 Spots on the Screen					
Sample	**Left Spot Measurement (uW/cm^2)**	**Middle Spot Measurement (uW/cm^2)**	**Right Spot Measurement (uW/cm^2)**	**Avg. Per Printer (uW/cm^2)**	**Std. Dev. Per Printer**
1	3992.5	3790.5	3779.7	**3854.2**	119.9
2	4000.4	3780.3	3784	**3854.9**	126.0
3	3996.4	3719.5	3789.2	**3835.0**	144.0
Avg. Per Side (uW/cm^2)	**3996**	**3763**	**3784**		
Std. Dev. Per Side	4	38	5		

One of the largest printing surfaces comes from Manufacturer E. This printer is less than a month old with minimal hours printed on it at the time of testing. The data from the table above illustrates the difficulty with making a large printer. The variation will make it challenging to use the whole surface especially as the printer ages.

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Printer Manufacturer F: 3 Spots on the Screen					
Sample	Left Spot Measurement (uW/cm^2)	Middle Spot Measurement (uW/cm^2)	Right Spot Measurement (uW/cm^2)	Avg. Per Printer (uW/cm^2)	Std. Dev. Per Printer
1	3459	3233.1	3464.6	**3385.6**	132.1
2	3435	3219.8	3416.8	**3357.2**	119.3
3	3432.4	3163.4	3441.1	**3345.6**	157.9
Avg. Per Side (uW/cm^2)	**3442**	**3205**	**3441**		
Std. Dev. Per Side	15	37	24		

Manufacturer F's printer is relatively new, and out of the box it is not great with respect to irradiance over the entire surface of the printer.

Printer Manufacturer G: 3 Spots on the Screen					
Sample	Left Spot Measurement (uW/cm^2)	Middle Spot Measurement (uW/cm^2)	Right Spot Measurement (uW/cm^2)	Avg. Per Printer (uW/cm^2)	Std. Dev. Per Printer
1	1107.8	1222.2	1022.3	**1117.4**	100.3
2	1108	1210.4	1011	**1109.8**	99.7
3	1101.5	1203.5	1006.2	**1103.7**	98.7
Avg. Per Side (uW/cm^2)	**1106**	**1212**	**1013**		
Std. Dev. Per Side	4	9	8		

Finally, we have Manufacturer G, which is one of the older printers in our lab at over 15 months old with pre-2020 technology. The measurements from the data table show what we expected with respect to the variability.

Conclusion

In conclusion, when selecting a 3D printer, it is important to understand the quality of the light the machine has and how that light might age in the future. This study has shown that the most expensive 3D printers don't guarantee a light source that is the best option. Money doesn't necessarily buy quality in the light source.

Having consistent radiometry across the entirety of the screen is important to try and achieve, but also hard due to structural differences or age between light sources. As seen by the printers from Manufacturer A, seven of them have significant differences between the middle and edges on the screens.

Understanding the radiometry can also make a difference in print quality and success. Worst case scenario is failed prints occur with a failing light source, but it might also be causing different printed models to have different conversion levels if printed on different parts of the print platform. Or even a singular model to have different conversion on different areas of its surface if it spans across a print platform. Uneven curing across the entire print can also cause added stress and embrittlement when undergoing post cure.

After doing this study, we do have some recommendations and guidelines for people looking to purchase a new 3D printer or create a method for a material. When setting up a method that is consistent for a material on a 3D printer, it's important to take into account lowest light settings that work for the material, not the average or highest, as not all print platforms give good results across the surface.

By looking at Manufacturer C, which had the best light consistency, it was the only printer we tested that had internal radiometry metrics. Therefore, we would recommend printer manufacturers that have an internal option to check the radiometry, however simply having a printer that includes a display or some kind of test or calibration that a user could perform testing with a radiometer themselves is also a good option.

This is our first in-depth look into the radiometry of the 3D printers we have access to, and have found the entire study to be very interesting.

Through doing this study, we do have some questions that we have begun asking that we would like to investigate in the future. One question that has arisen is if a printer is producing good

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prints, but there is variation across the surface of the printer, how does post cure affect the materials properties? Do material physical properties change with the 10% difference in light, or does post cure bring all printed models to the same state? Our lab has done work on effects of over-curing and under-curing materials during development, and have seen negative results when a material becomes overcured and has embrittlement. Could this be happening to parts if a post process is optimized for prints that have been exposed to less energy from a particular printer? Another question that has arisen is what is the correlation between the light's age and how many hours it has been used to print?

Resources

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