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OPACITY MODULATION IN ADDITIVE MANUFACTURING

Aja Hartman, Mary Baker, Ingeborg Tastl, Krzysztof Nauka
HP Laboratories, Palo Alto, CA, USA

Abstract

HP's powder-based technology, Multi Jet Fusion (MJF), uses a fusing agent to selectively melt polymer powder in a layer-by-layer fashion to create 3D parts. There are many applications that require variable opacity including signage, medical models, and backlit buttons and indicators on computers, vehicles, and instruments. The industry also needs to replicate different materials that have varying optical properties throughout their thickness, such as skin or tortoiseshell, and to enable techniques such as covert markings on parts. Although completely opaque parts are achievable by doping the base powder material with an opacifying material, this opacifying method makes the whole part opaque instead of allowing variability at a voxel level. By modulating both opacifying agent loading and the geometric design of the opaque part region in our MJF platform, we have achieved variable optical properties within parts, modulating optical transmission from 48 % to 1 %.

1. Introduction

Additive manufacturing (AM), the process of building a part layer-by-layer, has been identified as the leading technology of the Fourth Industrial Revolution, Industry 4.0 [1][2]. This revolution is characterized by the combination of automation and information technology in advanced production systems. 3D printers are the primary example of these advanced production systems, using data to improve production effectiveness and efficiency through product optimization and process control [3]. Additive manufacturing has the added benefits of enabling design complexity, small batch production, and short lead times compared to other manufacturing technologies, which has led to its adoption, shown by the additive manufacturing industry growing 33.5 % to 9.795 billion dollars in 2018 [4].

There are many different additive manufacturing technologies and materials, Multi Jet Fusion (MJF) being one of the powder bed fusion (PBF) polymer printing archetypes. The MJF print process starts, like many AM processes, with a CAD model that is sliced to form a stack of 2D images. The MJF machine then begins printing pre-print layers by spreading powder and warming it using overhead near-infrared (NIR) lamps in combination with fusing NIR radiating lamps vicinal to the powder. After an adequate warming base has been formed, the first CAD model 2D geometry slice image is printed using a black IR absorbing fusing agent on the powder and fused using the fusing lamps. A new layer of powder is spread on top of the previous layer and the process (print, fuse, spread) is repeated until the full object is formed.

The described printing process is used in the HP Jet Fusion 4200/5200 series 3D printing solution. However, MJF technology is not limited to using only one fusing agent. It has the potential to perform in-situ chemistry on a voxel (volumetric pixel) level by selectively jetting functional agents, hence the namesake "Multi Jet" fusion.

An example of one such functional agent is the opacifying agent (OA). This material can be dispensed at different loadings to scatter light and modulate optical transmission properties on the voxel level throughout a printed part. However, the OA must be used in combination with a clear fusing agent, different from the black fusing agent previously described. This OA can be used for many applications that require variable opacity including signage, medical models, and backlit buttons and indicators on computers, vehicles, and instruments. The OA can also address industry needs of replicating different materials that have varying optical properties throughout their thickness, such as skin or marble, and to enable techniques such as covert markings on parts. Although completely opaque parts are achievable by doping the base powder material with an opacifying material, this opacifying method makes the whole part opaque instead of allowing variability at a voxel level. By modulating both OA loading and the geometric design of the opaque part region in our MJF platform, we have achieved variable optical properties within parts.

2. Materials and Methods

2.1 Powder and agent materials

Opacifying Agents (OA) can be formulated using several different opacifying materials in combination with an ink vehicle to form a thermal jettable agent. Examples of such materials are: $TiO_2, ZnO, La_2O_3, BaO, CaO, MgO, SnO_2, BaTiO_3, Sb_2O_3, BaSO_4, ZnS$. In the experiments described, 0.01 wt% of opacifying material was used with an HP proprietary ink vehicle.

All experiments in this paper were conducted with HP 3D high reusability PA12 powder from HP Inc, Palo Alto, CA USA. PA12 material properties can be found in table 2 [5].

Table 2. HP 3D high reusability PA12 material properties.

	Value	Method
Powder melting point (DSC)	187 ℃ 369 ℉	ASTM D3418
Particle size	60 μm	ASTM D3451
Bulk density of powder	0.425 g/cm^3 0.015 lb/in^3	ASTM D1895

2.2 Sample Preparation

Samples were produced using an MJF experimental platform. This printer is outfitted with a multi-agent print carriage depositing a clear IR absorbing fusing agent and an opacifying agent, IR warming lamps, two 650 W IR fusing lamps mounted on either side of the print carriage, a print bed, a powder supply, and a spreader.

2.3 *Measurement Methods*

The transmission of the samples was measured with a spectrophotometer using an integrating sphere and an aperture of 6 mm in diameter (X-Rite Ci7800). The reported total transmission values are luminance factors quantifying the percentage of light being transmitted through the material at a specific thickness. High values indicate high transmission while low values indicate opacity. All the samples had a high degree of subsurface scattering.

3. Results and Discussion

We enable opacity control of voxels in 3D parts by modulating OA loading in a single layer and modulating opacifying depth to create different levels of opacity throughout a part. Figure 1 shows illustrations of different ways to modulate the opacity in different areas of a part with the observing measurement device located at the top facing downwards. The first method of varying opacity is by changing the amount of the opacifying agent. The second method of varying opacity is by modulating the section thickness while maintaining the distance from the top of the part. The third way of modulating opacity is by varying distance from the top of the part while maintaining section thickness. These methods can be used in combination with each other to provide many different gradations of opacifying effect. An example of which is shown in the last illustration, where both opacity section thickness and distance from the top of the part are varied.

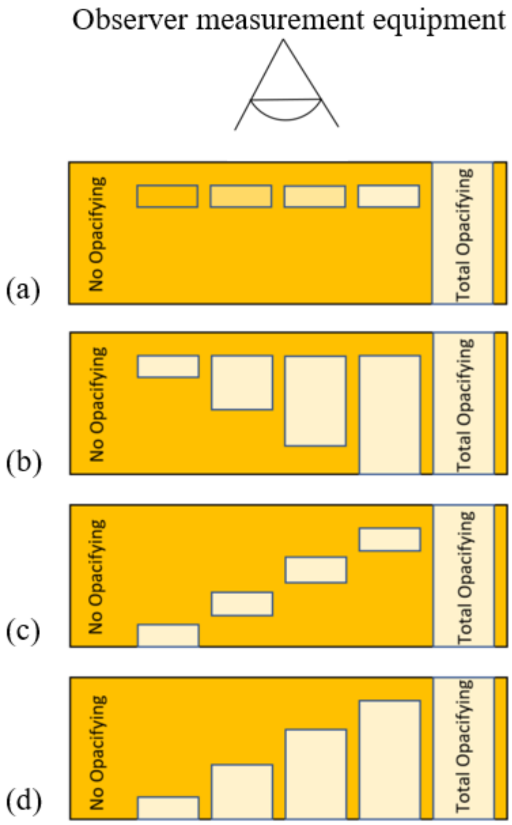

Figure 1. (a) Varying opacity by changing the amount of the opacifying agent. (b) Varying opacity section thickness while maintaining the distance from the top of the part (c) Modulating opacity section distance from the top of the part while maintaining section thickness. (d) Varying both opacity section thickness and distance from the top of a part.

We characterized the design space of opacity modulation and measured the change in transmission across four printed plaques. Each plaque contained four patches with 2 cm x 2 cm top surface area geometry with the overall part dimensions of 2 cm x 8 cm. Pictures of these plaques are shown in Figure 3. The 4 mm plaque had varied opacity material weight percentage with a maintained 4 mm thickness, the 2 mm patch had varied opacity material weight percentage with a maintained 2 mm thickness, “SS 4 to 1 mm” had a stair step (SS) geometry with constant opacifier weight percentage across the plaque with different step thicknesses of 4 mm, 3 mm, 2 mm, 1 mm, and the “SS CL 4 to 1 mm” plaque had both varied opacity material weight percentage achieved by changing contone level (CL) and different step thicknesses. Figure 2 illustrates these part designs. Table 3 shows these transmission values for each patch of each plaque and Table 4 shows the weight percentage of opacifying material needed to achieve these results.

a) SS CL 4 to 1 mm – Modulating both opacifying agent and thickness of opacifying part.

b) SS 4 to 1 mm – Modulating just the opacifying part thickness.

c) 2 mm – Modulating just opacifying agent across a 2 mm sample.

d) 4 mm – Modulating just opacifying agent across a 4 mm sample.

Figure 2. Side view of the design with varying opacity and thicknesses for the 3D printed plaque samples tested.

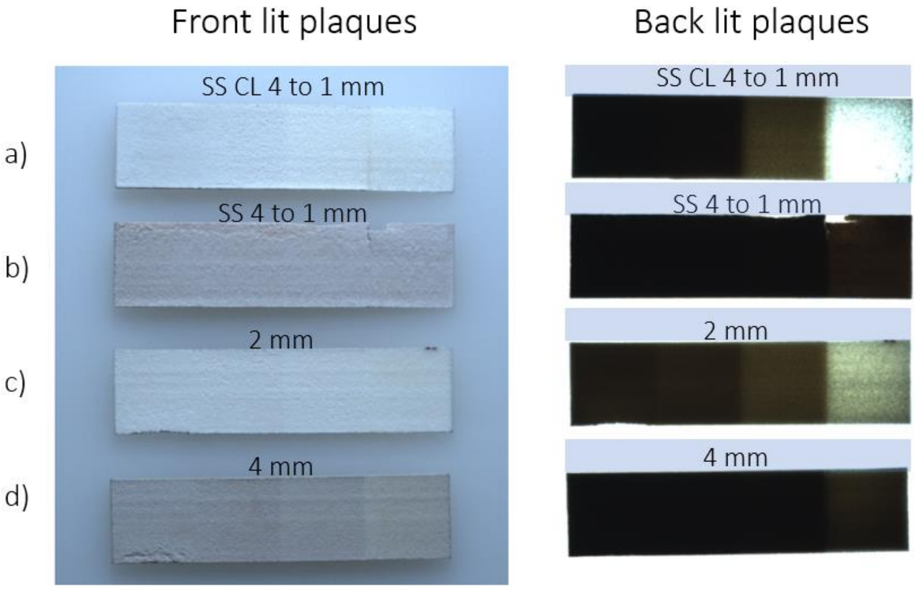

Figure 3. Parts printed on Multi Jet Fusion platform using opacifying agent both with normal lighting conditions on the left and backlit on the right. (a) Modulating both opacifying agent and thickness of opacifying part. (b) Modulating just the opacifying part thickness. (c) Modulating just opacifying agent across a 2mm sample. (d) Modulating just opacifying agent across a 4mm sample.

Table 3. Transmission measurements (in percent) across four different opacity modulated plaques.

Plaque	Patch 1	Patch 2	Patch 3	Patch 4
SS CL 4 to 1 mm	0.81	0.98	7.31	48.76
SS 4 to 1 mm	0.75	0.74	0.77	2.12
2 mm	2.08	2.64	5.52	22.60
4 mm	0.71	0.67	0.70	3.00

Table 4. Weight percentage of opacifying material for each plaque patch.

Plaque	Patch 1 [wt%]	Patch 2 [wt%]	Patch 3 [wt%]	Patch 4 [wt%]
SS CL 4 to 1mm	2.1	1.4	0.7	0.0
SS 4 to 1 mm	2.1	2.1	2.1	2.1
2 mm	2.1	1.4	0.7	0.0
4 mm	2.1	1.4	0.7	0.0

The characterization of OA loading in relation to transmission changes was used to design a part with varying optical properties internally to test the application space and ease of processability. This test part is shown in Figure 4, where a trace of a snail is imbedded into a color textured plaque. The snail trace design width is 0.945 mm and the depth is 0.8 mm. Here, we can see the capability of hiding and exposing information under different lighting conditions. With backlighting (a) the increased opacity snail trace appears white; with equal front and back illumination (b) the increased opacity snail trace is invisible; and with front lighting (c) the increased opacity snail trace appears black.

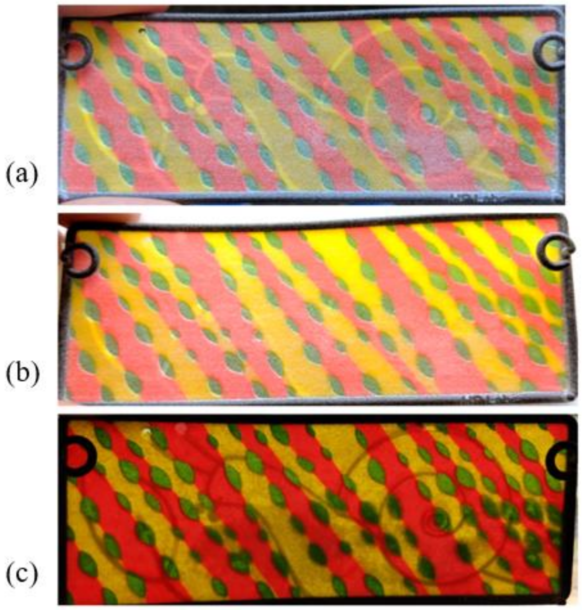

Figure 4. One sample under different lighting conditions producing variable snail trace colors. Front illumination (a) opaque trace of snail appears light, equal illumination from front and back of sample (b) creates "invisible" snail, and back illumination (c) creates dark snail trace.

Figures 5 and 6 show example applications of both material replication and active changing signage messages OA is able to achieve. Figure 5 shows an example of replicating optical properties of a material, in this case a stained-glass window. Figure 6 shows an example of signage that under normal front lit conditions, has a picture of flowers and under back lit conditions, shows a hidden message. This feature could be used in marketing, but also safety where advertisements or other displays could become backlit in case of an emergency and show directions to an emergency exit.

Figure 5. Back-lit stained glass window panels.

Figure 6. Sign with hidden message back-lit on the left and front-lit on the right.

4. Conclusion

In this work, a voxel level variable opacity method using Multi Jet Fusion 3D printing technology is presented. By using a clear fusing agent, modulating opacity agent loading in a single layer and modulating opacifying depth, we achieve different levels of opacity throughout a part. Printed parts underwent optical characterization, where variable optical transmission was measured from 48 % to 1 %. Demonstration parts were achieved to verify the application space and processability. Moving forward, we are exploring different polymer base materials with increased inherent translucency, so that larger opacity modulation can be achieved and enable more applications. Future work also includes designer tools that enable users to access these capabilities, for example, a library of textures with opacity information encoded to replicated textures such as skin.

5. Acknowledgements

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6. References

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