ROBOTIC COLOR GRADING FOR GLASS

Additive Manufacturing of Heterogeneous Color and Transparency

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Abstract. This paper presents a new additive manufacturing method for color grading of glass. Color-graded elements, ranging from product design to architectural scale, could filter light and view in a novel way through locally differentiated color and opacity, and produce color effects in space. Existing methods for manufacturing multi-colored glass are either not economic for building due to labor intensity, limited to surface applications or small scale objects made of resins or plastics. To allow for automated color grading of glass in two-and-a-half and three dimensions we propose a robotic multi-channel process. The multi-channel tool mounted on a Universal Robot consists of four compartments, containing red, yellow, blue and transparent glass granules. Colors can be mixed on the fly by implementing varying flow rate ratios along the print path. Loose granules are fused in a kiln at high temperature into color-graded glass elements. The goal of this research is to lay the basis for color-graded elements of larger size and volume with higher pattern differentiation for functional and aesthetic purposes.

Keywords. Color grading; robotic fabrication; multi-channel printing; glass.

1. Introduction

Traditional manufacturing of multi-colored glass for cultural and household objects dates back to antiquity (Wight 2011) including several methods such as kiln fusing, stained glass, and Murrina & Millefori or Vetro Pezzato (Chambers and Oldknow 1999). Kiln fusing, the oldest technique for making glass artifacts, was invented by the Egyptians around 2000 BC and relies on fusing small glass pieces under high temperature in a kiln. Glass pieces are manually assembled according to a pattern or the artisans design idea and fused into a three-dimensional or multi-colored glass artifact (Reynolds 1987). The artisan craft of stained

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glass, developed in ancient Rome, enables the manufacture of multi-colored glass elements of larger size suitable for buildings. The process consists of manually cutting and joining glass pieces of different colors into figurative or abstract patterns using metal joinery (The Metropolitan Museum of Art 2000). Resulting elements can perform as illuminated wall decorations and windows in churches. While the glass is colored inherently by adding metal oxides to the glass mixture, glass surfaces can also be painted by manually applying acrylic enamel paint onto the surface of glass (Wylie and Cheek 1997). Due to the labor intensiveness of these processes, the manual production of multi-colored glass and glass painting techniques are primarily used for exclusive luxury objects or in restoration projects until today. Contemporary techniques of adding color onto glass include silkscreen and ceramic digital printing onto glass. For the silkscreen printing process, a decorative layer of ceramic ink is applied through a screen mesh onto the glass. This technique is durable and suitable for application in building projects as realized in the Ricola building by Herzog de Meuron in 1993 (Herzog & de Meuron 1996). Digital ceramic printing onto glass is an automated technique for applying ceramic inks onto flat glass with a multi-head process (Hoffmann 2012). This technique is automated, but it remains a surface application of color onto glass that is not material-inherent or applicable to locally varying properties within a volume. On the other hand, latest multi-material printing shows the potential to locally vary material-inherent properties, colors and transparencies, within artifacts. Stratasys Objet Connex printers can produce high-resolution, geometrically complex, and materially heterogeneous 3D printed objects at product scale by locally jetting and curing drops of photo-curable resin as demonstrated in the Vespers II Series (Doubrovski et al. 2015). Nevertheless, multi-material printing methods are either limited to plastics (Grigoriadis 2018) or restricted in size due to the extremely high machine and material costs of resin-based multi-jetting techniques; thus not economic for application at architectural scale. Previous research for *Color and Transparency Grading in Glass* (Giesecke 2018) has demonstrated the potential for material-inherent color grading of granular glass according to computed gradient patterns. In summary, existing methods are either labor-intensive, limited to surface application of color or not suitable for up-scaling due to economic constraints. As a continuation of *Color and Transparency Grading in Glass* the goal of this research is to allow for the concept of color grading and multi-color printing to enter architectural scale and application enabled by an automated multi-channel printing process. We present a method for additive manufacturing of multi-colored glass elements with material-immanent color grading in two-and-a-half and three dimensions.

2. Methods

The research consists of the following steps:

1. Material Research and Kiln Fusing
2. Multi-channel Tool and Robotic Setup
3. Computational Modeling of Three-dimensional Color Gradients
4. Tool Path Generation for Multi-channel Grading
5. Grading Tests

2.1. MATERIAL RESEARCH AND KILN FUSING

When composed of its basic ingredients sand, soda ash and limestone, soda-lime glass is transparent. By adding different metal oxides one can add color. To fuse glasses of different colors, their compatibility needs to be assured. Compatibility is related to glass type, expansion coefficient, viscosity during the heating process and the types of metal used for coloring. Incompatibilities in metal oxides can evoke reactions that lead to unexpected coloring results. As a first proof of concept, we use off-the-shelf *Bullseye* and *Farbglas* glass which use non-reactive metal oxides and provide compatibility charts. Red, yellow, blue and transparent glass are chosen as exemplary channel inputs based on the traditional color wheel for mixing of physical colors (Baty 2017), from which secondary colors can be mixed and according to their intensity. These inputs can be varied in relation to the desired output. To test the color logic a set of manual tests is conducted to establish the color spectrum attainable with the primary colors. Transparent base granules of 3.3 - 5 mm ø and coloring granules of 0.5 - 1mm ø results in fine coloring resolution and high potential transparency. The maximum amount of colored granules used in a given location is 16% (see Figure 1, central triangle). The ratio of the 3 base pigments alternates with pure red, blue and yellow along the edges with a minimum of 4% of one type of pigment added.The color palette produced (see Figure 1) demonstrates that pigments do not share the same intensity. Red is clearly more dominant, mixing red with blue results in unexpectedly dark tones. Consequently, colors are dosed depending on their relative dominance: red is dosed at 1:6 parts, blue at 1:4 and yellow at 1:3 ratio. The local maximum saturation is reduced from 16% to the lowest percentage of color within the testing setup, 4% in further tests.

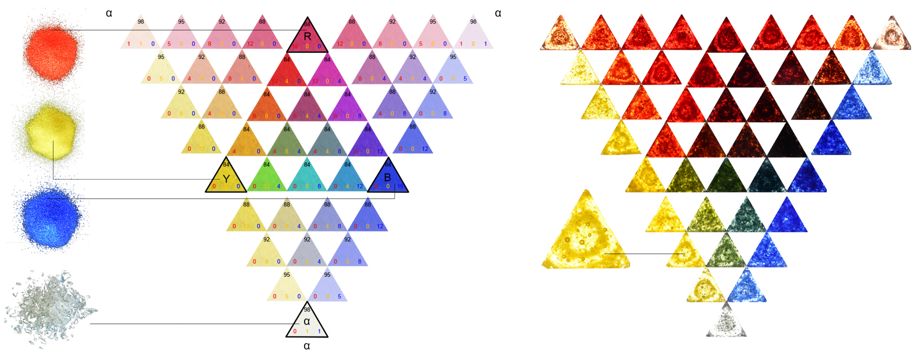

Figure 1. Exemplary color palette RYBα visualization of mixing ratios (left) and resulting materialized color spectrum in glass (right).

For identifying a suitable logic for the automated layering process in relation to the resulting coloring output. Alternating colored and transparent layers of glass granules facilitate transparent properties of resulting artifacts. From these tests is concluded that depositing dense layers of colored granules without transparent glass in between results in opaque optics while alternating colored layers of small granules and transparent large granules allow for light to pass through the artifacts. To fuse glass granules, they are placed in the kiln at room temperature (see Figure 2) and fused along a specific heating and annealing curve (see Figure 3), depending on the glass product and type used (Griffith 2014). The firing duration is related to the thickness and volume of the glass object. The fusing process fuses the granules, while the annealing process releases stress from the glass.

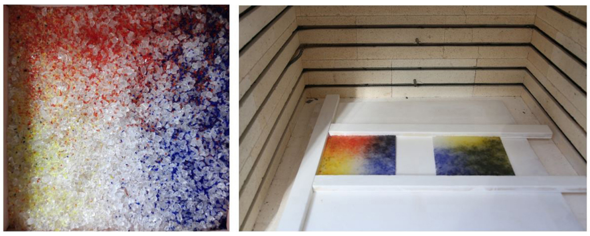

Figure 2. Loose granules robotically placed before kiln fusing (left) and after fusing in the kiln (right).

2.2. MULTI-CHANNEL TOOL AND ROBOTIC SETUP

For the automated distribution of red, yellow, blue and transparent granules a multi-channel-dispenser is designed. The multi-channel tool attached to a UR robot consists of a dispenser body with four compartments, each containing glass granules of a different color (see Figure 3). An inverse-pyramid shape of the tool enables the collection of granules from different channels in the bottom center and refilling of the channels from the top. Vertical customized conveying screws transport and dose the granules (see Figure 4). To minimize the collection area, the screws are slightly tilted inwards. Every compartment consists of a container with a metal tube at the bottom, through which the granules pass. Each screw is connected to a stepper motor on top of the cartridge. The tubes, combined with the conveyor screw, create a section small enough for the granules to start packing. Their flow is enabled by spinning the conveyor screws. For the small granule color channels transporting granules of 0.5-1mm size off-the-shelf Ø 5mm steel drill bits are used, for the large granules of 3.3-5mm size a costume 3D printed plastic conveyor screw was designed in an iterative process. This iterative process includes testing various helix diameters and steepness to ensure dispensing process without clogging resulting in a 20mm screw diameter and 30° helix steepness. For both granule sizes, the relationship between tube size and screw shape is identified in calibration tests. Depending on the revolution speed of the motor more or less granules can be dispensed over time allowing the different colors to be mixed in specific ratios along the robotic tool path.

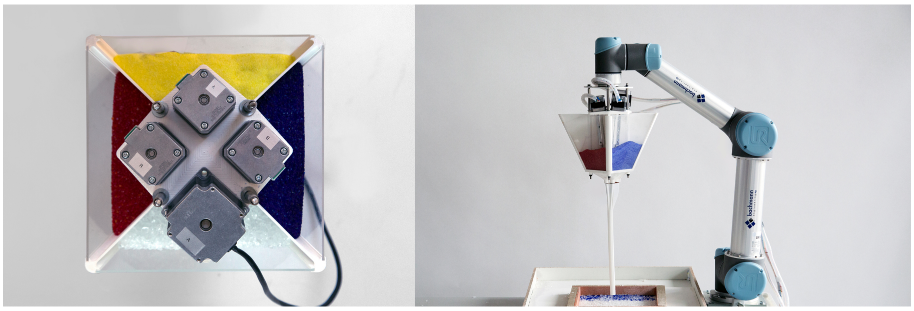

Figure 3. Top view (left) and elevation (right) of multi-channel tool and robotic setup.

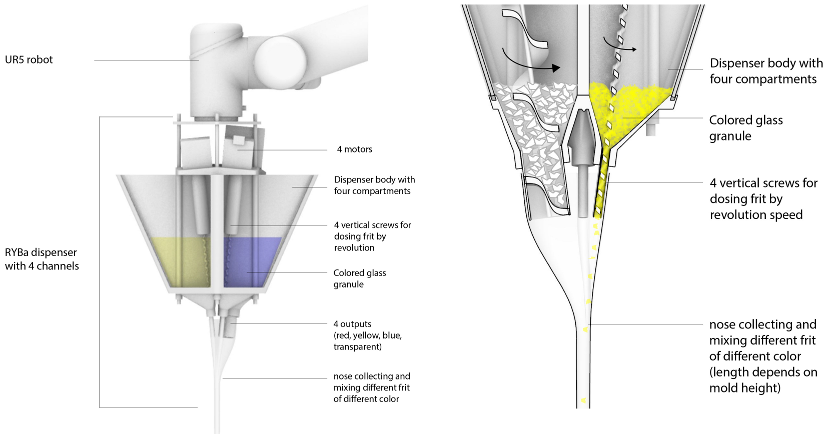

Figure 4. Multi-channel tool (left) elevation and detailed section (right).

2.3. COMPUTATIONAL MODELING OF THREE-DIMENSIONAL COLOR GRADIENTS

To model linear color gradients in plane and in volume, an axial grading model is set up using distance functions, with the start point of every axis being transparent (α) and the end point a primary color (RYB). Initial two-dimensional grading tests use the X- and Y-axis, while for the volumetric tests the same modeling logic is also applied to the Z-axis. To visualize a design, the volume of the object is discretized into dots/voxels for which the matching RYBα values are calculated. Those are then translated into RGBα using the color transformation matrices as found in *Paint Inspired Color Mixing and Compositing for Visualization* (Gossett 2004) values which are then rendered through Rhino's Grasshopper plugin.

2.4. TOOL PATH GENERATION FOR MULTI-CHANNEL GRADING

The computed volumetric design is sliced into layers. Based on this information a tool path is generated for each layer and the robotic movement is defined by a set of movement frames. Those frames provide sampling points to generate the RYBα values along the tool path. These RYBα values are then translated into GCode to operate the stepper motors of every color channel. For the final output, based on a range of process parameters identified through various tests (see Table 1), the time intervals for both the robotic movement and stepper motors are synchronized. The revolution of every screw corresponds to the ratio of each color channel at a specific location. Both the communication with the stepper motors driven by an Arduino board flashed with GRBL (Motion Control for Makers), and the UR5 robot is done in Grasshopper using GHPython components and the *Robots* plugin. Two different dispensing methods are identified to achieve grading the discrete process and the continuous process. In a discrete process, the robot moves from one point to the next, dispensing different amounts of color at each point (see Figure 5a). In the continuous process, the robot dispenses the required quantity of color along a continuous path allowing for the inscription of sharp lines (see Figure 5b) as well as for creating smooth gradients (see Figure 5c). When using the discrete method the amount of color can be varied by the amount dispensed in one spot. The continuous method allows for varying color intensity by changing robot speed, thus for producing smooth gradients at a higher speed.

Table 1. Process parameters.

Parameter		Min.	Typ.	Max
Robotic movement speed		10 mm/s	35 mm/s	150 mm/s
Path spacing		5 mm	10 mm	25 mm
Layer thickness		2 mm	5 mm	15 mm
Nozzle-surface-distance		2 mm	10 mm	50 mm
Channel pipe diameter	Color channels	-	6 mm	-
	Transparent channel	-	22 mm	-
Granule size	Color channels	0.5 mm	-	1 mm
	Transparent channel	3.3 mm	-	5 mm
Spindle speed	Color channels	0.05 rev/s	0.5 rev/s	6 rev/s
	Transparent channel	0.1 rev/s	0.3 rev/s	0.5 rev/s
Corresponding mass/time	Color channels	0.07 g/s	0.26 g/s	0.66 g/s
	Transparent channel	8.6 g/s	10.4 g/s	13.2 g/s

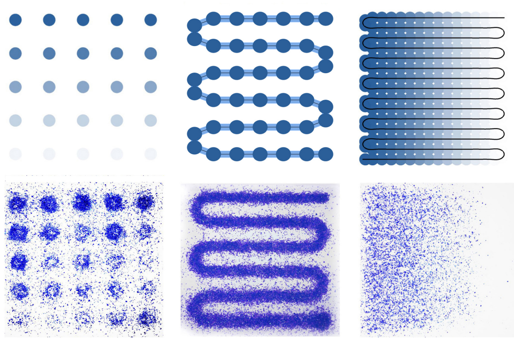

Figure 5. Dispensing a) discrete dots b) along a continuous curve c) along a continuous curve with varying speed and decreased distance.

2.5. GRADING TESTS

Material research and tool design allow for the gradation between two (transparent to blue), three (transparent to blue to yellow) and four properties (transparent to blue to yellow to red). As a first proof of concept, linear grading is tested in two-and-a-half dimensions. The loose granular material is distributed within reusable limitation ledges, reusable molds, consisting of coated vermiculite plates, and then fused in the kiln. Tiles of 15x15x1cm size and cubes of 10x10x10cm size are fabricated demonstrating the possibility to fabricate linear gradients, smooth transitions between color properties (see Figure 6) made from *Bullseye* (see Figure 6b) and *Farbglas* glass (see Figure 6c). The quality of the colors also depends significantly on the primary colors and the granule size used. Samples made from *Farbglas* and *Bullseye* glass result in different physical properties and aesthetics differing in resolution, color intensity, and transparency. Volumetric grading of cubes (see Figure 7) follows the same process logic as the linear grading of tiles. Layers with 2D grading patterns are built up vertically to fill the volume of the mold. The glass volume is compressed vertically by 45% throughout the fusing process. When layering the granules such shrinkage in volume can to be taken into account within the modeling and fabrication process. Fused cubes show a heterogeneous deformation with proximity to the edge caused by friction with the mold. Non-homogeneous deposition or taking these deformations into account in the computational model could mitigate this issue. Furthermore, the colors deviate slightly from the intended result, especially red is still dominating. This issue can be resolved by updating the current color modeling translation matrix used for translating the RYBa to RGBa.

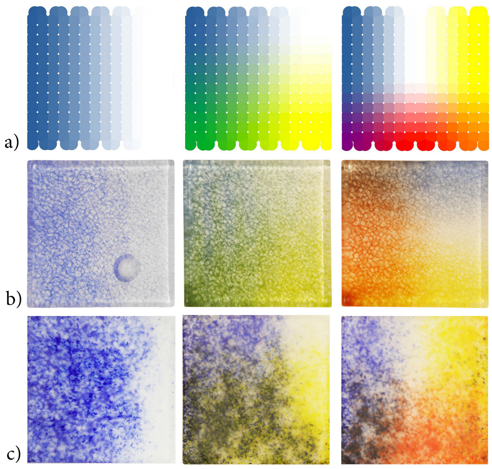

Figure 6. RYBα tiles from top to bottom (a) digital visualization (b) in Bullseye glass and (c) in Farbglas color spectrum.

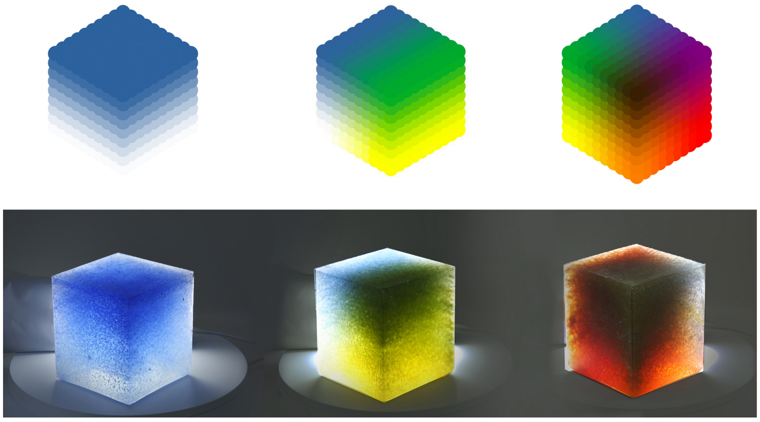

Figure 7. Color gradient visualization (top) and color graded glass cube (bottom).

3. Results

Grading tests (see Figure 8) provide a small scale proof of concept for *Robotic Color Grading of Glass*. The following list will summarize and critically reflect the research contributions made:

Material system. As widely used material with a long history in multi-colored objects and architectural applications such as stained glass windows, glass has great potential for automated color grading. Further research could expand the knowledge on using recycled glasses or testing cheaper glasses for their compatibility.

Multi-channel tool. Augmenting the robot with a multi-channel tool opens up new possibilities for various multi-property printing processes. The presented tool remains a first iteration and requires further development in terms of robustness, precision and variability of grain sizes.

Precision. Colors showed deviations from the intended results which require updating the color translation matrix. The precision of the process is lower than the one of multi-material printing processes due to the spreading of granules. This material behavior requires either further calibration of process parameters (e.g. surface distance) or the intentional implementation of process parameter dependent material behavior as part of a design tool.

Computational modeling. The computational methods applied allow for modeling and fabricating gradients between two or more properties and linking the digital and physical color model of the glass through a translation matrix. Deviations described above will require small adjustments of this translation. The use of other computational modeling techniques will allow the method to expand beyond printing of gradients to other multi-coloring approaches.

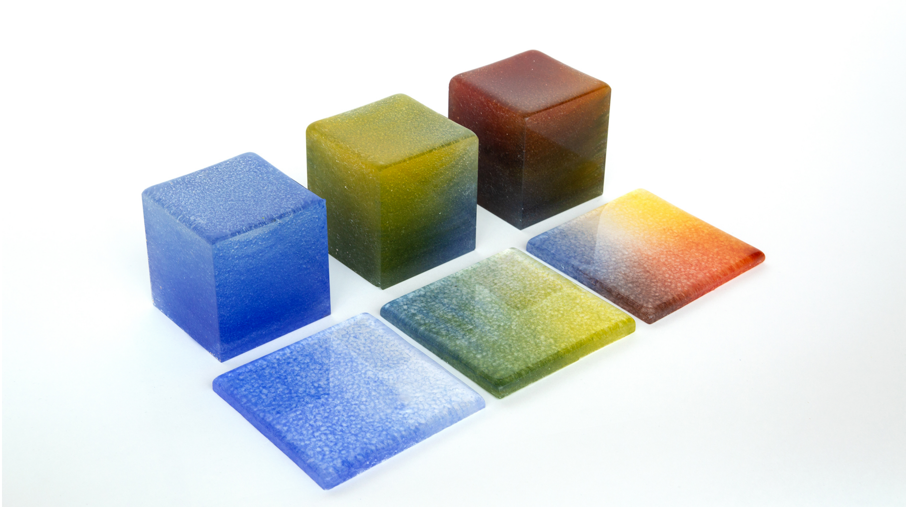

Figure 8. Tile and cube prototypes.

4. Discussion

The current results present a first small scale proof of concept for the possibility to automate the process of color grading. However, as the long-term goal of this research is to provide a manufacturing process for large scale applications, several steps need to be taken:

Material research. Glass research in a larger kiln will evaluate if the method is scalable to large elements with the current material system used, or if a change in glass type or size is required.

Molding. The process requires reusable ledges to keep the granular material in place during printing; further research will tackle mold-free printing.

Tool adaptation. Augmenting the robot with a multi-channel tool opens up new possibilities for various multi-property printing processes. The presented tool is a first iteration and requires further development in terms of precision, robustness and compartment size.

Computational design. Color patterns and color-form relationships can be explored in addition to process parameters and their implementation in a simulation tool.

Cost and accessibility. The fabrication process can be executed with a low cost tool attached to a motion system or universal robot and a conventional glass kiln. For up-scaling, further material and market research could contribute to more economic solutions for glasses and decrease cost.

Speed. The relatively high speed of the process increases the probability of applying it at large scale.

Architectural application. This research opens up a wide design space that could include facade elements, windows or interior separations.

The steps above could lead to large architectural elements that filter daylight and view through locally differentiated properties such as colors and opacity in an unprecedented manner, animate architectural space dynamically through controlled light conditions and produce sophisticated color effects in space.

5. Authorship Information Statement

Giesecke and Michopoulou are both equally first authors of this paper as they contributed equally to the written content including abstract, introduction, methods, results and discussion. Giesecke has provided the research framework based on initial material research executed, formulated the research topic, and supervised the experiments and tool development. Michopoulou has provided further material research and tool development. W. Van den Bulcke has developed the tool and computational workflow, and provided the process parameters. Odaglia supervised the research experiments and provided the electro-mechanical components of the tool. Dillenburger has contributed to the contextualization of the research and edited the text.

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References

"Herzog & de Meuron: Ricola-Europe SA, Production and Storage Building Mulhouse-Brunstatt" : 1996. Available from <www.herzogdemeuron.com/index/projects/complete-works/076-100/094-ricola-europe-production-and-storage-building.html> (accessed 18th July 2020).

"The Metropolitan Museum of Art: Stained Glass in Medieval Europe" : 2000. Available from <http://www.metmuseum.org/toah/hd/glas/hd_glas.htm> (accessed 22nd September 2020).

Baty, P.: 2017, *Anatomy of Color. The Story of Heritage Paints and Pigments*, Thames & Hudson, London.

Chambers, K. and Oldknow, T.: 1999, *Clearly Inspired: Contemporary Glass and Its Origins*, Pomegranate Communications, San Francisco.

Doubrovski, E. L., E.Y., T., D., D., Geraedts, J. M. P., Herr, H. and Oxman, N.: 2015, Computer-Aided Design Voxel-Based Fabrication through Material Property Mapping: A Design Method for Bitmap Printing, *Computer-Aided Design*, **60**, 3-13.

Giesecke, R.: 2018, "Grading Color and Translucency in Glass" . Available from <https://dbt.arch.ethz.ch/research-stream/grading-material/> (accessed 3rd May 2020).

Gossett, N. and Chen, B.: 2004, Paint Inspired Color Mixing and Compositing for Visualization, *Proceedings of the IEEE Symposium on Information Visualization*, 113-118.

Griffith, B.: 2014, *Kiln-formed Glass: Beyond the Basics*, Lark Crafts, New York.

Grigoriadis, K.: 2016, *Mixed Matters: A Multi-material Design Compendium*, Jovis, Berlin.

Hoffmann, B.: 2012, Ceramic Digital Printing - Customized Glass Facade Design, *Challenging Glass 3*, 943-955.

Reynolds, G.: 1987, *The Fused Glass Handbook*, Hidden Valley Books, Arizona.

Wight, K.B.: 2011, *Molten Color: Glassmaking in Antiquity*, Springer, Los Angeles.

Wylie, E. and Cheek, S.: 1997, *The Art of Stained and Decorative Glass*, New Line Books, New York.