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Material Property Changes in Custom-Designed Digital Composite Structures Due to Voxel Size

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ABSTRACT
Advances in additive manufacturing enable fabrication of complex structures using functionally graded materials (FGMs) at a voxel level. Prior to developing voxel-based FGM designs using compatible dithering approaches, it is essential to first understand the basic principles of voxel-based digital composite designs. While several research studies exist regarding different representations of composition in voxel-based solid models, there is no extensive research on the material properties of voxel-based digital composite structures. This paper bridges this gap by investigating custom voxel-based designs of digital composite structures. The objective is to determine how the material properties of such structures are impacted by different voxel sizes using the material jetting process. In addition to the material properties, computational time taken to process different voxel sizes is analyzed. By doing so, we gain a better understanding of the relationship between material composition and voxel size in digital composite structures.

1. MOTIVATION AND BACKGROUND
Additive manufacturing (AM) offers a wide range of technologies that provide various opportunities in the aspects of design freedom and material complexity, including parts that can be manufactured in a single build using multiple materials [1]. Multi-material AM has led to the development of 3D printed objects fabricated using materials with heterogeneous compositions. This "free" material complexity within multi-material AM enables the processing of composites. Composite materials comprise two or more constituent materials with varying material properties, which are combined to produce a material with enhanced material properties [2]. Digital composites are materials of a heterogeneous nature defined by discrete voxels. A voxel is a "fundamental, physical, and self-aligning" volume element defined in a 3D space [3,4]. The actual physical size of the voxel indicates the resolution present in a three-dimensional image. Voxels have mostly been used in the development of data structures in computer graphics [5], however, based on recent advancements, researchers have explored different methods of designing digital materials in relation to voxels. Voxel-based designing involves "converting a geometrically represented 3D object into voxel models by digitally distributing multiple materials in a specific voxel region" [6].

Various research studies have demonstrated the capability of incorporating the voxel-based design approach to develop and analyze different structures. This approach has been used by Hiller and Lipson [3] to validate the manufacturability of digital composites by developing self-aligning voxels in 3D geometries. Conformal lattice structures as studied by Aremu and co-authors [7] were also developed using a voxel-based design method of tessellating and trimming. The discrete nature of the voxels caused a stair-stepping effect on the surface of the external geometry. In order to mitigate such problem, the authors proposed to increase the voxel resolution. Furthermore, Park and Rosen [8] used a voxel-based design method to assess the material properties of additively manufactured lattice structures. Similarly, another research study by Hiller and Lipson [9] explored a range of material properties of voxel-based fabricated digital materials by varying the voxel microstructure and the percentage of randomly distributed materials. The authors used simulations and demonstrated that the material properties of digital materials can be extensively tuned by randomly half-toning a percentage of two materials to create a desired material composition. In addition, by varying the materials' microstructure, material properties like stiffness were tuned, thus allowing for novel behavior within the digital materials.

Researchers have not only looked at how composites are designed but have considered various methods of processing these composites. Current AM technologies such as material extrusion, powder bed fusion, and directed energy deposition have demonstrated their capabilities in fabricating composite structures [10]. Researchers like Bakarich and co-authors [11,12] used a novel extrusion-based deposition system to print hydrogel composites directly into functional structures for a bio-inspired application. Fused deposition modeling (FDM) and directed energy deposition (DED) have also been explored by Ning and co-authors for their capabilities in fabricating parts with composites [13,14]. However, most of the manufacturing processes mentioned lack the capacity to control the material deposition at a voxel level and have comparatively low resolution for multi-material digital manufacturing.

The PolyJet process, a material jetting AM process, has the capacity to finely control the composition of multiple materials through its voxel-based design and manufacturing abilities. At high levels of spatial control, the PolyJet process selectively deposits droplets of photopolymer materials in a layer wise manner at a default resolution [15]. Within the scope of this research, voxel-based design abilities provided by the PolyJet process are used. The Objet350 Connex3 printer, a material jetting system, is a multi-material and multicolor 3D printer that can combine up to three model materials in a single build. With a large array of possible material compositions, objects can be manufactured with a variety of material properties. Regarding voxel-based deposition in the PolyJet process, it is important to note that materials are not mixed but are rather selectively suspended at a microscale within a structure's volume [16–18].

Various research studies [16,19–22] have explored the capabilities of the PolyJet process regarding voxel-based deposition of multiple materials and the impact of such technology on the resultant material properties. Bader and co-authors [15] used the PolyJet process together with a multi-material voxel printing approach to visualize and convert data sets to dithered materials. Using high resolution dithering, material properties were characterized and matched to material mixing ratios. From their study, the voxel-based approach helped bridge the gap between digital information and physical material compositions. Doubrovski and co-authors [23] also used the PolyJet process together with a voxel-based approach to determine the material properties of additively manufactured prostheses. Using bitmaps to represent slices of voxel-based design, the desired material properties were translated into local material compositions at the default resolution. The authors highlight that controlling the geometry and the variation of the material properties at the resolution of the PolyJet system provides greater control over the material property, structure, and behavior relationships. Also, Swetly and co-authors [24] used the PolyJet process to explore voxel-based 3D printing. Their goal was to investigate the possible increase in the impact strength of AM parts fabricated with combined stiff and elastomer-like materials at a

50% material composition. The individual voxels of the materials were arranged in a chess pattern and aligned at different voxel edge lengths. Results showed that at larger voxel edge lengths, the impact strengths decreased. In addition, the material properties such as tensile strength and strain at break decreased as the voxel edge lengths increased. This research study is particularly significant to the research presented in this paper in that voxel-based design and manufacturing of digital composites is explored using the PolyJet process.

Whereas existing research mostly centers on processing composite materials for different application using various compatible AM manufacturing processes, limited studies have explored the use of a voxel-based dithering approach to develop complex composite structures. In addition, existing research that explores voxel-based design methods has only developed and studied material compositions at the default resolution [15,23,24]. There is also limited to no research literature regarding how the composite material can be represented at the voxel scale in terms of size and material distribution. The research presented in this paper seeks to investigate and understand the representation of composites specifically developed using a voxel-based design approach. By analyzing how size and composition affects the distribution of materials in a 3D space, we are able to understand the behavior of composite structures based on microscale representation decisions.

2. DESIGN AND EXPERIMENTAL APPROACH

To further understand the behavior of voxel-based digital composites, changes in the material composition and voxel size of tensile specimens were compared against the specimens' material properties. Particularly, this research study seeks to answer the following research questions:

1. How does changing the voxel size of digital composites impact their material properties?
2. Is there any interaction effect between different material composition percentages and voxel sizes for digital composite structures?

The work in this research is important because it helps us understand the trade-off between different voxel sizes and material compositions in relation to material properties. This also allows us to further understand if the computational time of digital composites at different voxel sizes can be saved without loss in material properties.

2.1 Experimental Design

In order to answer the presented research questions, a design of experiments approach was implemented. For this study, tensile specimens, shown in Figure 1, were designed according to ASTM D638-14 [25]. Digital composites were designed based on selected material composition percentages and applied throughout the specimen model design.

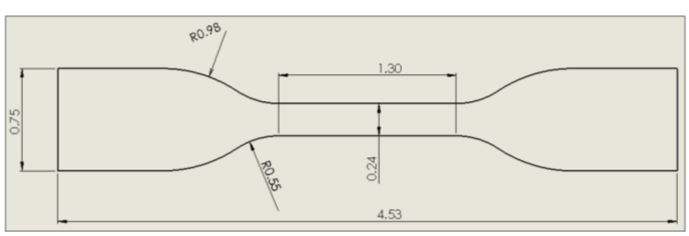


Figure 1. A CAD drawing of a tensile specimen. All units are in inches.

Regarding material distribution, the digital composites were a combination of TangoBlackPlus (TB+) and VeroWhitePlus (VW+). TB+ is an elastomeric material that simulates rubber with flexible material properties whereas VW+ is a rigid material with polypropylene-like material properties. The combination of both materials at different mixing ratios creates materials with a wide range of elastic properties. These materials were used as the main model materials in the Objet350 Connex3 printer [26]. For this printer, the default scale of voxels for the XYZ dimensions are 42μm × 42μm × 30μm based on the XY build resolutions of 600 drops per inch (DPI) and a layer thickness of 30μm (0.03 mm) [16]. Table 1 shows different variables considered for this research study. Five material compositions and six voxel sizes were selected for comparison. The smallest tested voxel size, 85μm (300 DPI) was based on the overall length of the tensile specimen.

Table 1. Selected variables for the custom-designed digital composites

Variables	**Parameters**	
Independent	Composition (% rigid material)	10, 30, 50, 70, and 90
	Voxel Size across the length (μm)	85; 150; 267; 479; 846; 1588
Dependent		Ultimate tensile strength, elongation at break, computational time

The design process of digital composites as well as the procedure for developing voxel sizes is presented in Section 2.2. Section 2.3 presents the printing and tensile testing procedure specifications of all fabricated tensile specimens.

2.2 Designing voxel-based digital composites

This section provides the methodical design process for custom-made, voxel-based digital material composites by combining different material compositions with different voxel sizes using a dithering approach compatible with the PolyJet process. Prior research work [16] provides the details of a similar design process for functionally graded materials. The design process was divided into two tracks; a part geometry track and a digital composite track. The part geometry and digital composite tracks are separated to allow effective dithering and changing of the material compositions and voxel sizes while maintaining the external geometry of the specimen. Within the part geometry track, the tensile specimen's STL model was sliced into individual layers using Netfabb slicing software. The images of the layers represented the specimens' external geometry and were saved in bitmap format (.BMP) for direct input into the Connex printer [16].

The digital composite track was divided into three phases. The first phase involved creating digital composites from selected material composition percentages. The material composition percentages ranged from 0% to 100% of the rigid material (VW+). A single color was developed in an in-house MATLAB algorithm using a binary scale from zero to one to represent the volume fraction of the material composition. A volume fraction closer to zero, such as 0.1, implied a material composition of 10% rigidity and 90% flexibility whereas a volume fraction of 0.7 implied a material composition of 70% rigidity and 30% flexibility. Figure 2 shows the different percentages of material composition selected.

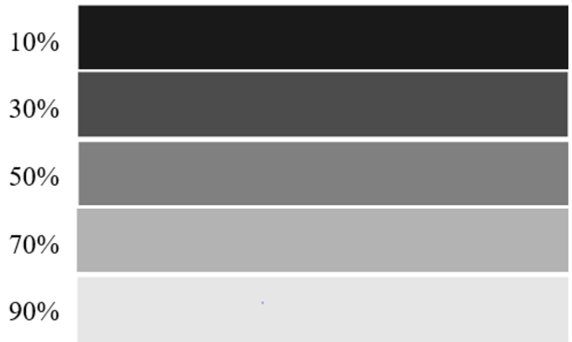


Figure 2. Selected material composition percentages for the digital composites.

The second phase of the digital composites track involved specifying the voxel sizes. Initially, the MATLAB algorithm was implemented for the selected material composition percentages at the 85μm voxel size. Thereafter, the voxel size was increased until the lowest resolution (16DPI) that could possibly fit throughout entire length of the tensile specimen and still maintain the quality of the external geometry was achieved. As shown in Table 1, alternating voxel sizes were selected to be compared at different material compositions.

The third phase involved using a Floyd-Steinberg error diffusion dithering algorithm [27] compatible with MATLAB. The dithering algorithm was used to develop grayscale images of the material compositions at different voxel sizes. The grayscale images were converted to dithered binary images (black and white) resulting in patterns of discrete droplets rather than a random mixture of volume fractions. In this phase, the individual bitmap layers from the part geometry track were then combined to the dithered binary images with different voxel sizes to form a final rendition of the tensile specimen. Figure 3 shows a grid of dithered images for all combinations of material compositions with different voxel sizes.

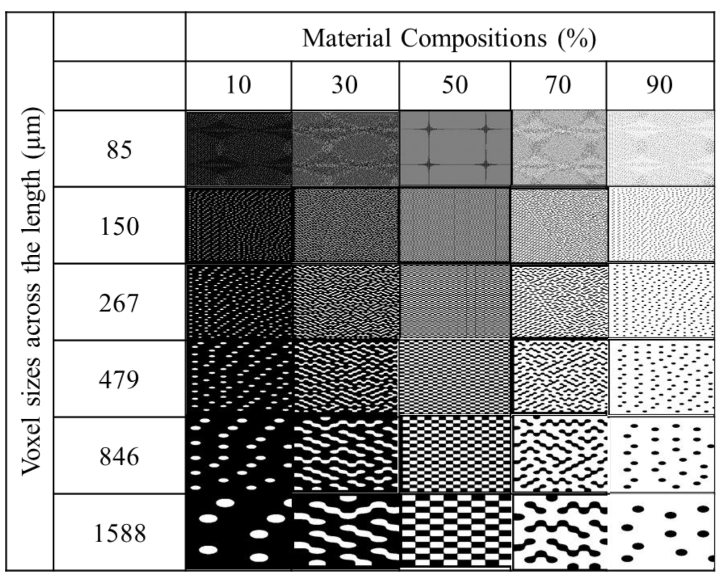


Figure 3. A grid of images showing representations of voxel sizes for different material composition based on percentages of the rigid material, VW+.

2.3 Printing and tensile testing specifications

All tensile specimens were printed using the Objet350 Connex3 printer with TB+ and VW+ as the model materials and FullCure SUP705 as the support material. The Voxel Print software provided by Stratasys was used in support of voxel by voxel deposition to fabricate the digital composite specimens. Individual bitmap slices of the digital material composites were printed in digital materials mode for an average of 45 minutes, with 138 slices per specimen and a uniform layer thickness of 30µm. A total of 75 specimens were printed and tensile tested. Examples of fully fabricated specimens are shown in Figure 4.

Figure 4. Fully printed specimens of different digital composites at 85µm voxel size.

All fabricated tensile specimens were tested for tensile properties using an AGS-X universal electromechanical test frame. A pair of mechanical grips were used to fasten the specimens onto the load frame during testing, shown in Figure 5. The specimens were tested in load control with a 1kN load cell and a 5.08mm/min pull rate. From the tensile testing procedure, the tensile stress (MPa) and break elongation (%) were recorded.

Figure 5. The AGS-X Universal Electromechanical Test Frame showing the mechanical grips.

3. DATA ANALYSIS AND DISCUSSION

This section provides the detailed analysis of the results obtained from the tensile tests performed as described in Section 2.3. This analysis provides information on the relationship between material compositions in digital composites as well as the relationship between different voxel sizes. Results for maximum tensile stress and break elongation were obtained and analyzed. The plot shown in Figure 6 is a graphical representation of the average maximum tensile stress for material composition percentages of digital composites at different voxel sizes. Previous research work [16] provides in detail the results comparing the tensile strength of material compositions at the default resolution.

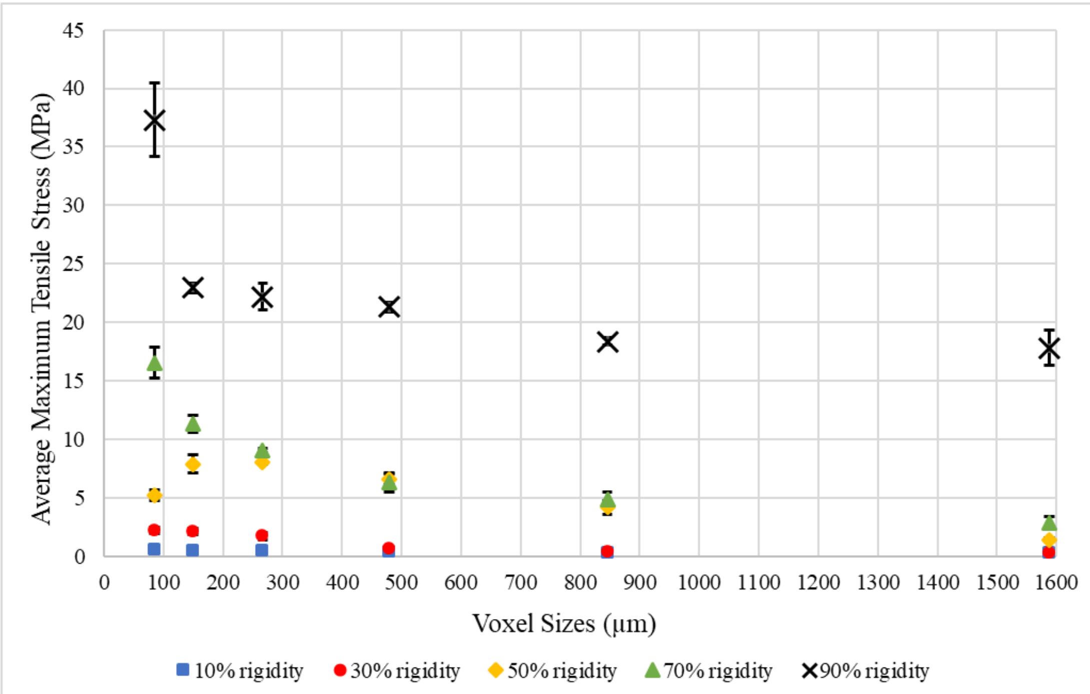


Figure 6. Average maximum tensile stress for different material compositions at different voxel sizes.

The data represented in Figure 6 was analyzed for statistical significance using a two-way analysis of variance (ANOVA). The purpose of the analysis was to determine the main effects of the digital composites and the voxel sizes on the tensile strength as well as the interaction effects between the digital composites and the voxel sizes on the tensile strength. Before two-way ANOVA was performed, all assumptions made for the analysis were verified with an exception of the test for homogeneity of variances, which was violated. Considering an equal sample size, ANOVA is generally robust against any violations of the homogeneity of variances test, thus statistical analysis was still conducted. Results from two-way ANOVA showed a statistically significant main effect of material compositions on the tensile strength ($p<0.001$) as well as a significant main effect of the voxel size on the tensile strength ($p<0.001$). There was also a significant interaction effect between the digital composites and the voxel sizes on the tensile strength ($p<0.001$). This analysis is confirmed in Figure 6 where the maximum tensile strength decreases as the voxel sizes (µm) increase. This trend implies that the behavior seen in the material properties is dependent on the material composition percentage.

Besides the maximum tensile strength, break elongation was also analyzed for the specimens as represented in Figure 7. The purpose of analyzing the elongation at break for different digital composites was to verify the behavior of different material compositions and determine any interactions between different voxel sizes.

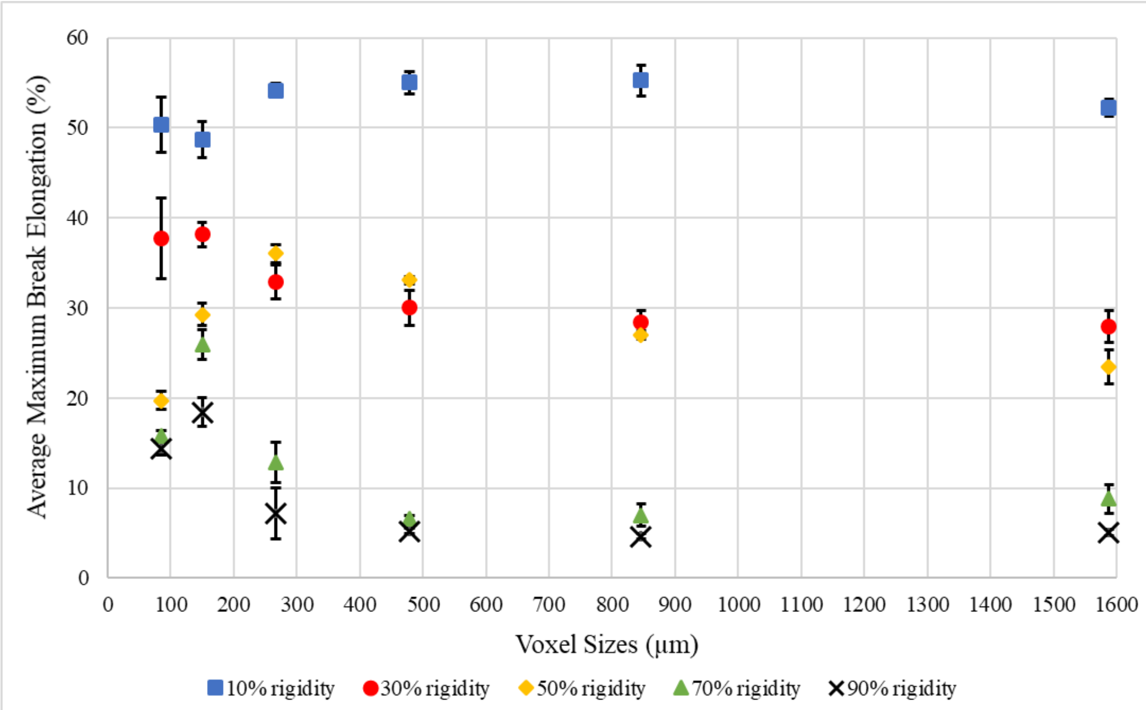


Figure 7. Average elongation to break for different material compositions at different voxel sizes.

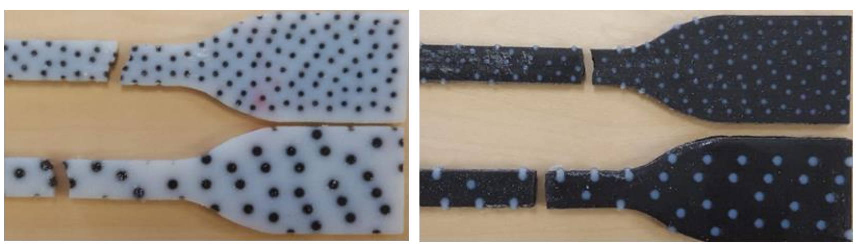
This data set was also analyzed for statistical significance using two- way ANOVA. Similarly, results from the analysis showed statistically significant main effects for both material composition and voxel size on the tensile strength ($p<0.001$). There was also a significant interaction effect between the digital composites and the voxel sizes on the tensile strength ($p<0.001$). The data represented in Figure 7 show the expected behavior for different material compositions whereby specimens with a 10% material composition were the most flexible thus had the highest break elongation with an average of 53% elongation. On the other hand, specimens with a 90% material composition had the lowest break elongation with an average of 8% elongation. This is confirmed in the research work done by Bass and co-authors [28] where they compare the elongation at break between rigid and flexible materials among other material properties. Their findings also indicate that indeed the flexible material should experience the highest elongation and the rigid materials have the lowest elongation. The data represented in Figure 6 and Figure 7 not only show how changing the voxel sizes affects the material properties but also how these changes cause the specimens to behave based on the dominant material. For instance, we see that specimens with a 10% material composition increase in elongation whereas at a 90% material composition we see a decrease in elongation.

In addition to the tensile strength and break elongation patterns shown in the digital composites, failed tensile specimens were observed to further investigate any unexpected behavior. Figure 8 shows a series of failure interfaces of different tested tensile specimens. Cracks propagated at the flexible material, TB+, and extended through the area of the weakest resistance leading to failure.

(a) (b) (c)

Figure 8. Tested specimens showing the failure interfaces at voxel sizes; 846μm (top) and 1588μm (bottom) for different material composition percentages; (a) 70%, (b) 50%, and (c) 30%.

This observation is similar to that investigated in a research study by Moore and Williams [19]. Though their study focused on investigating the fatigue properties of 3D printed elastomers, their failure analyses of the multi-material specimens showed that failure mostly occurred in the flexible material region. This confirms the findings observed in the Figure 8 that cracks propagated in localized regions closest to the flexible material thereby causing failure. Though the specimens with 10% and 90% material compositions have minimal rigid and flexible material interfaces, as seen in Figure 9, in observing the failure interfaces, we see a similar behavior whereby cracks developed in the flexible material and followed the path of least resistance. By analyzing the specimens' failure interfaces, we gain a better understanding of how material is distributed. We also understand how changes in the material composition and voxel size impacts the tensile strength and elongation of tensile specimens.



(a) (b)

Figure 9. Tested specimens showing the failure interfaces at voxel sizes 846μm (top) and 1588μm (bottom) for different material composition percentages; (a) 90%, (b) 10%.

Following the analysis of the material composition and voxel sizes in the fabricated digital composite specimens, the authors compared the findings with those from the research study performed by Swetly [24]. For the purposes of this research study, the authors were more interested in their findings pertaining to the influence of voxel edge lengths on the elastic properties specifically tensile strength. Based on the rule that "material properties decrease as the voxel edge length increases", their results experienced a slight deviation in that the 400μm voxel edge length had the highest tensile strength followed by the 300μm voxel edge length whereas the lowest tensile strength is observed at the 600μm voxel edge length. Whereas their results imply that changes in the voxel edge length does not necessarily affect the material properties of multi-material specimens, the research presented in this paper addresses and reports the effects of changes in voxel sizes and material compositions on the tensile strength and break elongation for similar specimens. As mentioned previously, Swetly and co-authors [24] arranged the voxels in a chess pattern while the voxels analyzed in this study were developed through dithering using a variety of material compositions.

Finally, the authors analyzed and reflected on the computation time of voxel-based digital composites. The computation time was the total amount of time it took to simulate the dithering algorithm and generate the digital composites with the various voxel sizes across the length of the specimen. Table 2 presents a compilation of the average computation times at the different voxel sizes. Here, we see that as the voxel size increases, the computation time decreases consistently. Analyzing the computation time helps suggest a trade-off between saving the computation effort and designing at different voxel sizes with different material compositions while providing better results in terms consistent material properties.

Table 2. Average computation time for different voxel sizes.

Voxel size across the length (μm)	Average Computation Time (s)
85	99.18
150	87.30
267	85.10
479	84.50
846	84.07
1588	83.62

4. CONCLUSIONS AND FUTURE WORK

This research study has demonstrated the applicability of digital manufacturing within AM and the ability to utilize the voxel-based deposition technique provided by the PolyJet process. Digital composites have been developed by dithering two materials at different concentrations. The dithering approach was also used to adjust the voxel sizes in each digital composite. The goal of this research study was to analyze the changes in material composition and voxel size and how material properties of custom designed digital composites can be affected by such changes. Based on the results obtained from the tensile testing procedure and the results' analysis, it can be concluded that:

- Due to significant interaction effects, changes in material compositions and voxel sizes affect the material properties.
- Changing the voxel size may shift the material properties towards the properties of the dominant material for any given composition.
- Larger voxel sizes for any material composition can save computation effort thereby ensuring consistent material properties.

The research findings presented in this paper offer a wide scope of recommendations for future work involving multiple materials and voxel-based design methods within AM. In addition to the recent studies mentioned regarding the manufacturability of various composites, it is important to investigate and understand how the spatial resolution of composites within a structure's volume affects their behavior and structure at a microscale. This research work could benefit from the macroscopic analysis via optical scanning of the specimens' surface and overall geometry to further verify the manufacturability of the custom voxel-based digital composites. Furthermore, analysis of custom voxel-based digital composite structures designed using different dithering patterns and different build orientations would provide a better understanding of how the voxels are aligned and how the material properties are impacted. Finally, performing finite element analyses of voxel-based designs would assist in the evaluation and verification of the performance of voxel- based composite structures.

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