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14. ABSTRACT

We report on the development and characterization of a composite material to mimic the mechanical response of human cranial bones. Mimicry of the mechanical response of bone requires a material that can be formed into complex architectures while possessing physical and mechanical characteristics similar to that of bone. We are utilizing additive manufacturing, more generally known as 3-D printing, as a suitable process to reproduce the curvature, variation in thickness, and gradient in porosity characteristic of the human cranial bone. The simulant material consists of a photocurable polymer with a high loading of ceramic particulate reinforcement that is compatible with stereolithographic (SLA) additive manufacturing. Specimens produced by SLA printing were characterized under conditions of quasi-static tensile loading and demonstrated properties that fell within the experimental range of values measured for the human cranial cortical bone as previously reported in the literature. The simulant material demonstrated a tensile modulus of elasticity of 10.3±0.5 GPa compared to the cranial cortical bone property of 12.8±1.6 GPa, while the tensile strength was 78.0±9.7 GPa compared to 72.0±13.8 GPa. Tissue surrogates such as this enable bio-fidelic experimentation and evaluation of protection schemes without the variability and difficulties typically associated with using real human tissue.

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CHARACTERIZATION OF A COMPOSITE MATERIAL TO MIMIC HUMAN CRANIAL BONE

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Keywords: bone simulant, tissue surrogate, cranial bone, bio-mimicry

ABSTRACT

We report on the characterization of a composite material to mimic the mechanical response of human cranial bones. Mimicry of the mechanical response of bone requires a material that can be formed into complex architectures while possessing physical and mechanical characteristics similar to that of bone. We are utilizing additive manufacturing, more generally known as 3-D printing, as a suitable process to reproduce the curvature, variation in thickness, and gradient in porosity characteristic of the human cranial bone. The simulant material consists of a photocurable polymer with a high loading of ceramic particulate reinforcement that is compatible with stereolithographic (SLA) additive manufacturing. Specimens produced by SLA printing were characterized under conditions of quasi-static tensile loading and demonstrated properties that fell within the experimental range of values measured for the human cranial cortical bone as previously reported in the literature. The simulant material demonstrated a tensile modulus of elasticity of 10.3±0.5 GPa compared to the cranial cortical bone property of 12.8±1.6 GPa, while the tensile strength was 78.0±9.7 GPa compared to 72.0±13.8 GPa. Tissue surrogates such as this enable bio-fidelic experimentation and evaluation of protection schemes without the variability and difficulties typically associated with using real human tissue.

1 INTRODUCTION

Prevention of head injury is receiving growing attention in the sporting arena as well as the battlefield due to an increase in the frequency of diagnosed concussion and traumatic brain injury (TBI) events. The United States Department of Defence reports that between 2000 and 2014 there were over 313,000 Service members diagnosed with TBI, of those 83% were diagnosed as concussions, or mild TBI events [1]. Helmets and head protection devices are under development to reduce the frequency and severity of TBI injury. Bio-fidelic representation of the human head is important for assessment of these protective measures. Anthropomorphic test devices (ATDs), such as those used in the automotive industry for assessment of vehicle crashworthiness, provide a representative shape and mass of the human head on which devices can be tested. However, ATD headforms are typically constructed of metal covered in an elastomer skin for durability and as a result they do not flex, fracture or transmit stress waves the same as a human cranium. Alternatively, Post Mortem Human Surrogates (PMHS) may be used to assess protective devices, although the tissue frequently comes from older donors and may not represent the mechanical characteristics of the general population, particularly that of the

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soldier. Moreover there can be large variations in the mechanical response of the tissue depending on the age and health of the donor. Testing with PMHS also requires careful handling and preservation techniques after extensive planning to ensure availability at the time of testing.

Developing a synthetic material to mimic the mechanical response of the human cranial bone alleviates a number of these concerns. The response of the surrogate material can be tailored to represent a particular age population and the geometry of the surrogate can further be tailored to a specific anthropometry. Developments in medical imaging technology allow us to obtain detailed, three-dimensional renderings of the human cranium specific to individuals which may be used for representation of a general population. These file formats can be sent directly to additive manufacturing machines, generically referred to as 3-D printers, to replicate a human skull. In this work we utilize additive manufacturing to process a photocurable polymer and report on the tensile properties of the material and correlation to human cranial bone.

2 HUMAN CRANIAL BONE

Human bone is a complex hierarchical composite material with variable mechanical properties throughout the different regions of the body. The basic constituents of human bone remain the same however: collagen fibers, hydroxyapatite mineral, and water. Each of these constituents are present in the hard outer cortical layer as well as the porous inner trabecular region of the bones. Long bones such as the femur exhibit increased strength and stiffness along the primary loading direction, whereas cranial bones are less stiff and exhibit transverse isotropy in directions tangent to the outer layer due to the absence of a predominant loading direction on the cranium [2].

The body of literature characterizing cranial bone properties is much smaller compared to that of long bones and properties can vary significantly for reasons mentioned previously. An extensive study of the tensile properties of the parietal, temporal and frontal bones was performed by Wood [3, 4]. The study utilized specimens from the craniums of 30 subjects ranging from age 25 to 95 years with an average age of 54 years. The study characterized the mechanical response of the outer cortical regions (tables) independent of the inner trabecular (diploë) regions at strain rates ranging from 0.005 to 150 sec^{-1}. The cortical cranial bone data from Wood serves as a basis for comparison to the surrogate material under evaluation in this work.

2 EXPERIMENTAL

2.1 Materials and Fabrication

Stereolithography (SLA) was chosen as a means to manufacture the specimen due to its ability to create high resolution parts. A schematic representation of the SLA process is given in Figure 1. A typical SLA machine cyclically raises and lowers a platform on which the parts are fabricated in a bath of photo-sensitive liquid resin. With each cycle, a blade is passed across the platform to create a uniform layer of resin. The resin layer is exposed to a ultra-violet laser that traces a cross-section of the desired geometry, thereby selectively curing the resin into a specific pattern. The process is repeated as the platform is lowered into the resin and the next layer is cured on top of the previous layer. A support structure, visible in Figure 2, is typically first built on the platform and serves as the foundation from which the part is built.

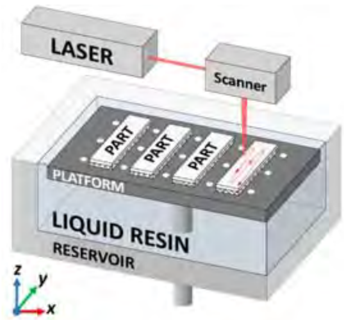

Figure 1. Illustration of the SLA additive manufacturing process.

The SLA machine used in this study to manufacture specimens was a Viper Si (3D Systems, Rock Hill, South Carolina). In ongoing work, we are evaluating the ability of additive manufacturing such as SLA to reproduce the curvature, variation in layer thickness, and gradient in porosity characteristic of bone [5].

Figure 2. Example parts fabricated by the SLA machine.

A photocurable polymer with a high loading of ceramic particulate reinforcement was chosen for its similar density and anticipated mechanical properties relative to the human cranial cortical bone [5]. Furthermore it was chosen for its compatibility with the SLA manufacturing process. Tensile testing specimens were printed in a dumbbell geometry in accordance with ASTM D638-10, Type I, with a nominal thickness of 3 mm [6]. The planar, non-porous specimens were manufactured in two orientations: *flat* type specimens were made such that layer-by-layer deposition coincided with the smallest dimension of the dumbbell tensile geometry (thickness), and *edge* type specimens in which the deposition occurred across the face of the geometry, as illustrated in Figure 3.

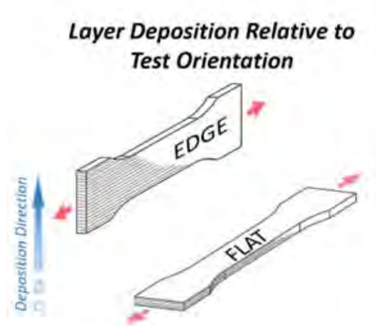

Figure 3. Orientation of SLA layer deposition relative to tensile testing direction for *edge* and *flat* specimens.

Upon removal from the SLA machine, the support scaffold on which the parts were built was removed from the specimen. A post process wash in isopropyl alcohol was performed to remove any excess material and the samples were abraded with 600 grit sandpaper to remove any residual scaffold that remained on the surface. The parts were then post cured at 160º C for two hours with a two hour heating ramp and two hour cooling ramp to room temperature. Upon removal from the oven it was noted that curvature had been induced in some of the *flat* printed samples.

2.2 Testing

Tensile testing was performed in accordance with ASTM D638-10, *Standard Test Method for Tensile Properties of Plastics* [6]. A servo-hydraulic universal testing machine (model 1331, Instron Inc.) equipped with 50 kN load cell was used to perform testing. Pneumatic grips were used to hold the ends of the specimen and No. 80 grit sandpaper was placed between the grip and specimen to reduce slippage and the likelihood of grip failure. Tensile testing was carried out under displacement control at strain rates of 0.0007 sec^{-1} and 0.007 sec^{-1}. Six samples of *flat* and six samples of *edge* printed specimens were prepared for testing at each strain rate, however excessive curvature induced into two of the *flat* printed samples caused them to break during installation into the grips and thus were excluded.

For the purpose of measuring strain by digital image correlation (DIC), a speckle pattern was applied to each specimen. The speckling process consisted first of applying a continuous layer of white acrylic spray paint, followed by a mist of larger droplets of black paint to create a pattern, as shown in Figure 4. A digital camera (Grasshopper model, Point Grey Inc.) was used to acquire images every 0.12 seconds during testing, and strain was calculated by digital image correlation (VIC 2-D Version 6, Correlated Solutions).

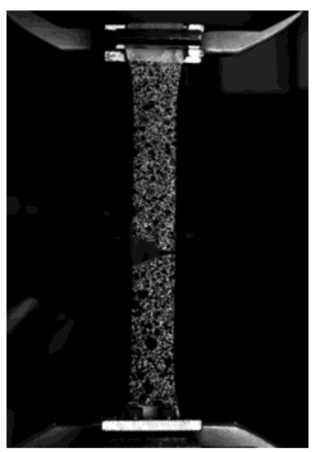

Figure 4. Tensile specimen undergoing fracture during testing.

3 RESULTS AND DISCUSSION

The tensile elongation curves for the *edge* printed samples and *flat* printed samples tested at 0.0007 sec^{-1} and 0.007 sec^{-1} are shown in Figure 5. Young's modulus was calculated below 0.2% strain and Poisson ratio was calculated based on analysis of the DIC images between 0.1 and 0.4% strain. The average values for tensile strength, modulus and Poisson ratio are reported in Table 1 along with the cranial cortical bone values from the literature.

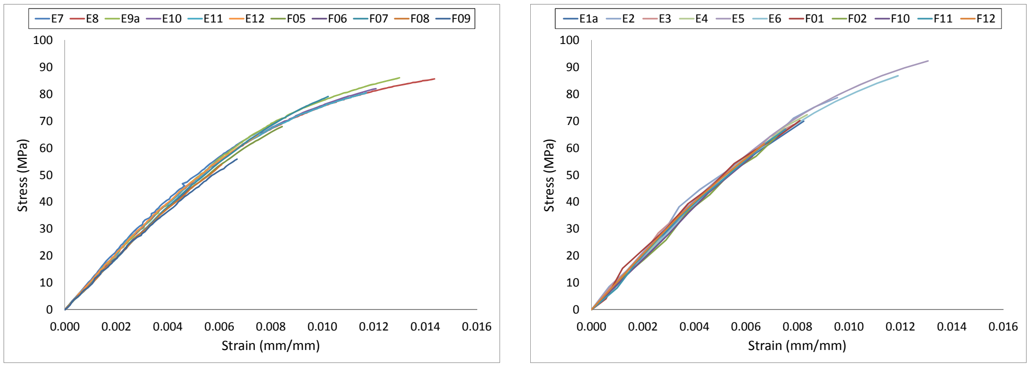

Figure 5. Stress vs. strain response of *edge* (denoted E) and *flat* (denoted F) printed samples at strain rate 0.0007 sec^{-1}(left) and 0.007 sec^{-1} (right).

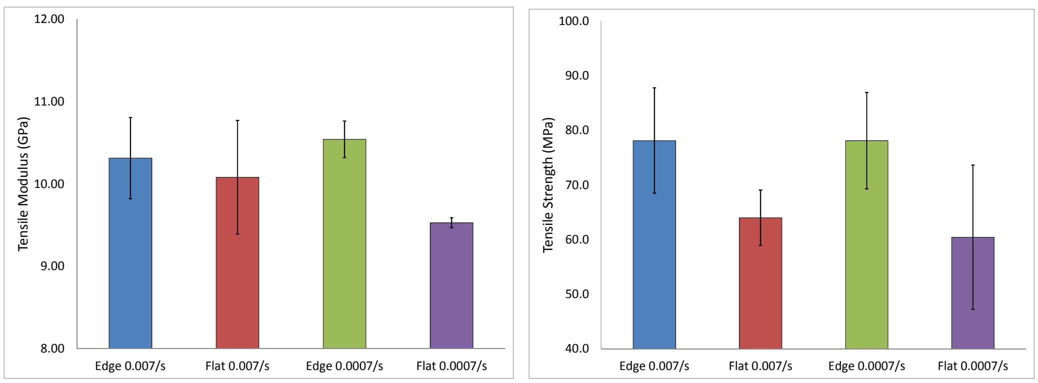

Figure 6. Young's modulus (left) and tensile strength (right) for *edge* and *flat* printed specimens at 0.0007 sec^{-1} and 0.007 sec^{-1}.

Specimen Type	**Strain rate**	**Tensile strength**		**Strain to failure**		**Tensile modulus**		**Poisson ratio**	
	[sec^{-1}] nominal	[MPa]		[%]		[GPa]		N/A	
		Avg	±	Avg	±	Avg	±	Avg	±
Edge	10^{-2}	78.1	9.6	0.98	0.22	10.3	0.5	0.26	0.02
Flat	10^{-2}	64.0	5.1	0.72	0.07	10.1	0.7	0.27	0.02
Edge	10^{-3}	78.1	8.8	1.11	0.27	10.5	0.2	0.30	0.03
Flat	10^{-3}	60.4	13.2	0.73	0.21	9.5	0.1	0.24	0.03
Cranial cortical bone [4]	10^{-2}	72.3	14.4	0.69	0.11	12.8	1.6	0.19-0.48 [7]	

Table 1. Properties measured for *edge* and *flat* print orientations of cranial simulant material.

The *edge* and *flat* printed samples show a similar tensile modulus at the two relatively low strain rates reported here. The *edge* samples exhibit a higher tensile strength and strain to failure compared to the *flat* samples. This difference may be a result of thickness and reinforcement content variations in the initial two or three layers deposited, as revealed by inspection under a microscope. In the *flat* samples the deposition of sequential layers occurs in the thickness dimension of the sample. Asymmetry between the upper and lower surfaces in the *flat* printed specimens likely created internal stresses, as evidenced by the curvature observed after the post-cure thermal treatment, and resulted in premature failure during tensile loading. In the *edge* samples however, this asymmetry occurs on the sides of the specimen geometry and had a much smaller negative effect on tensile properties.

Considering the *edge* printed samples alone, the simulant material demonstrated a tensile strength of 78.0±9.7 GPa compared to 72.0±13.8 GPa for the cranial bones as measured in the study by Wood [4]. While the mean strength value of the simulant is approximately 8% higher, it is well within the standard deviation of the bone property and represents a significant improvement in correlation compared to a cranial cortical simulant material reported previously in the literature (tensile strength 53±4.88 MPa) [8]. The tensile modulus of elasticity of the edge printed simulant was 10.3±0.5 GPa compared to the cranial cortical bone property of 12.8±1.6 GPa. The simulant material modulus is within approximately 20% and exhibits over 50% reduction in coefficient of variation compared to cranial cortical bone. Overall the variability of the simulant material is lower than that of the bone property and we expect to reduce variability further through refinement of the SLA processing parameters.

9 CONCLUSIONS

We have evaluated a composite material consisting of a highly filled photocurable polymer to serve as a surrogate material for human cranial cortical bone. Tensile specimens were produced by SLA additive manufacturing and characterized under conditions of quasi-static tensile loading. Specimens manufactured such that the layer-by-layer deposition coincided with the thinnest dimension of the dumbbell tensile geometry (*flat* type) exhibited noticeable warping after post cure compared to specimens where deposition occurred across the face of the geometry (*edge* type). As such, the variability in tensile properties of the edge type specimens was lower and provided a closer correlation to the experimental range of values measured for the human cranial cortical bone. Studies are currently underway to evaluate the dynamic fracture response of the material in comparison to human tissue. Additive manufacturing coupled with medical imaging is also being utilized to fabricate specimens that include curvature, porosity and variation in layer thickness mimicking the human skull.

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