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Auxetic Cellular Structures for Custom Made Orthopedic Implants using Additive Manufacturing

Saied M. H. Darwish, Muhammad Usman Aslam

Abstract- ***Auxetic structures exhibit negative Poisson's ratios in one or more directions. When stretched, they will become fatter or become thinner when compressed, in contrast to conventional materials. The present work intends to provide an overview of the current state of the art in the area of auxetic cellular structures for customized orthopedic implants, using advanced AM techniques. The present work also highlights the existing limitations in addition to future prospects in fabrication via AM techniques.***

Keywords: Auxetic cellular structures, Additive manufacturing, Solid free foam fabrication, Orthopedic implants

I. INTRODUCTION

The word “auxetic” comes from the Greek word auxetikos which means “that which tends to increase”. Auxetic cellular structures have attracted considerable interest in recent years due to their unique mechanical properties resulting from a negative Poisson’s ratio.. A new field of endeavor is to study materials exhibiting negative Poisson’s ratio (NPR) [1]. These types of materials get fatter when they are stretched, or become thinner when compressed, in contrast to conventional materials (like rubber, glass, metals, etc.) as shown in figure 1. When a material is compressed in one direction, it usually tends to expand in the other two directions perpendicular to the direction of compression. This phenomenon is called the Poisson effect. Poisson’s ratio, is a measure of this effect [2]. The value of the Poisson’s ratio controls the elastic behavior of a material to the same extent as, for example, the Young’s modulus.. A negative value of Poisson’s ratio leads to higher indentation resistance, shear resistance, and fracture toughness to name only a few affected properties. Materials in form of 3D cellular solid [3] are found in many natural structural elements like bone, cork, and wood. Currently, man-made cellular solids such as foams and honeycombs had increasingly used in different Engineering applications, that require light weight, customized stiffness and impact resistance. Numerous research efforts have been made to analyze the mechanical response of periodic and non-periodic cellular solids in 2D and 3D under different loading conditions.

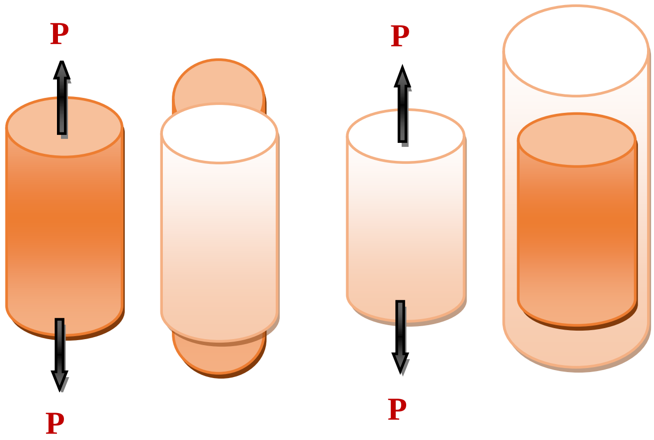

Figure 1. Poisson Ratio [4]

Additive Manufacturing (AM) [5] Techniques such as electron beam melting (EBM) and selective laser melting/sintering (SLM/SLS) allow the rapid fabrication of complex cellular structures with controllable architecture in metallic biomaterials like the commonly used Ti-6Al-4V alloy. The using of 3D Cellular structures fabricated by AM in orthopedic implants can enhance the bone in-growth and reduce implant stiffness. Additive Manufacturing (AM) techniques which are a group of advanced manufacturing processes can produce custom made objects directly from computer data such as Computer Aided Design (CAD), Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) data. A considerable amount of work is currently focusing on auxetic materials and their applications. The deformation characteristics of auxetic materials have made them appropriate candidates in biomedical applications. The purpose of the present work is to introduce a comprehensive review of the recent developments in the area of auxetic cellular structures, for custom made orthopedic implants using additive manufacturing techniques.

II. AUXETIC CELLULAR STRUCTURE

Back in 1984, auxetic behavior had been predicted to exist in a laminate composite oriented in specific ways [6]. However, wide acknowledgment of auxetic structures was not established until 1987 by Lakes [7]. In his work, Lakes described a simple structure that could exhibit isotropic negative Poisson's ratios in the three principle directions.

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The key point for creating an auxetic behavior is to generate re-entrant angles in the structure, which results in an inward movement when the structure is under compression or an outward movement when the structure is in tension. In his article, Lakes also stated that auxetic structure has higher ductility, higher toughness and very high indentation resistance. During the last two decades, an increasing interest can be observed for auxetic cellular materials which are a class of materials with negative Poisson's ratio (NPR) [8]. In spite of the statement in some textbooks that negative Poisson's ratio does not exist in nature, auxetic behavior was observed in both micro and macro scale. By changing the design of a honeycomb unit cell structure, a sandwich panel could exhibit negative Poisson's ratio and form synclastic curved panels [9]. A type of Polytetrafluoroethylene (PTFE) structure, that could achieve negative Poisson's ratio through the control of extrusion and drawing process [10]. Considerable investigations have been carried out to study the behavior of auxetic structures. Detailed reviews about recent research work related to auxetic structures are reported by [11], [12] and [13]. Ultra high molecular weight polyethylene (UHMWPE) auxetic foam can be produced using powder [14]. During this process, the UHMWPE powder is filled into a heating tube and compressed gradually at elevated temperature to perform sintering. After sintering, the pre-form is air cooled and reinserted into the heating tube for a secondary extrusion in order to generate the final parts. Auxetic structures possess higher fracture toughness [15], which has been verified experimentally [16]. With smaller Poisson's ratio values, the fracture toughness of the structure increases. This could be explained by the ready deformation of the re-entrant cell struts which gives rise to a significantly larger amount of dimensional change [17]. It is analytically proved that the out-of-plane elastic modulus could be higher than conventionally predicted for the laminates consisting alternatively laid isotropic auxetic laminates and regular laminates. By designing the auxetic laminates in certain ways, the in-plane modulus of the structure could exhibit the modulus of the stiffer phase [18].
Auxetic structures possess higher energy absorption and dissipation ability than regular structures. Auxetic foams tested that were made from polyurethane (PU), and both compressive and tensile tests showed a significant increase of total energy absorption [19]. In the same series of work, it was also demonstrated that the total energy absorption of the auxetic structure under cyclic loading was also significantly higher than the regular structure [20].

III. AUXETIC STRUCTURE PROPERTIES

Considerable amount of work has been done to evaluate the properties of auxetic structures. Most of the work was either numerical or experimental. With the decrease in Poisson's ratio values, the in-plane effective elastic modulus of auxetic structures decrease through the elastic analysis based on their analytical model [21]. In another simulation based analysis, [22] suggested that with the decrease of Poisson's ratio, the in-plane modulus of the 2D re-entrant honeycomb structure increases. The out-of-plane modulus [23] showed the opposite trend, which was also observed during the experiments. Numerous research efforts described that the auxetic foam structures possess superior mechanical properties as compared to the regular foams. Indentation tests were performed with copper auxetic foams, and the results suggested that the indentation resistivity of the auxetic foam increases significantly with the relative density [15]. Auxetic foam exhibited about 300% higher compressive strength as compared to the regular foams [24]. Some work was also done specifically on the 2D extruded re-entrant honeycomb structure. Finite element analysis used with the extruded 2D re-entrant honeycomb structures and concluded that, unlike the regular structures; the thickness versus strut length ratio has a significant effect on the shear modulus of the auxetic structure [22].

IV. AUXETIC STRUCTURE APPLICATIONS

Because of their unique properties, auxetic structures have high potential in many different applications. Applications have been proposed from wine bottle corks [7] to redone sandwich panel cores [17]. Auxetic structures could be used as robust shock absorbers, fasteners, air and mass filters, air seat cushions. They could also be used in piezoelectric devices to maximize the acoustic-to-electrical energy conversion [23]. In many applications, core shear is the leading cause of structural failure. On the other hand, it is highly anticipated that the sandwich structures absorb more energy, and exhibit conforming bending when subjected to the bending moments. Auxetic structures could potentially provide all the advantages, which make them ideal candidates for the core structures. Auxetic structures could also be potentially used in large scale structures. The superior stiffness of auxetic structure makes them desirable in the design of tall buildings and bridges. Considerable amount of work is currently focusing on auxetic materials and their applications [13]. The deformation characteristics of auxetic materials have made them good candidates in biomedical applications. Little research in the literature has been done in the area of 3D FEA and fabrication of functionally graded auxetic structure [25]. A self-designed three-dimensional auxetic structure and its build up in the SEBM process using Ti-6Al-4V [1]. The unusual behavior of Auxetic structure under different loading condition by FEM as shown in Fig. 2, to examine the possibility of fabricating this type of structure using advanced AM techniques and to propose a novel design of femoral component of total hip replacement using Auxetic structure [3].

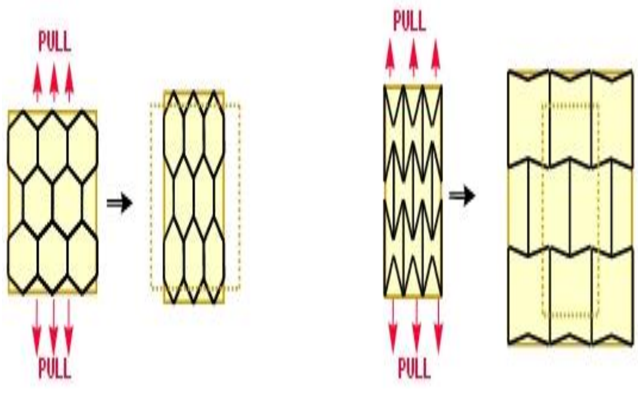

Figure 2. Behavior of Auxetic structures [9]

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Recent advancements in medical imaging and image processing have enabled custom design of biomedical implants based on patient specific Computed Tomography (CT) data by [26- 27].

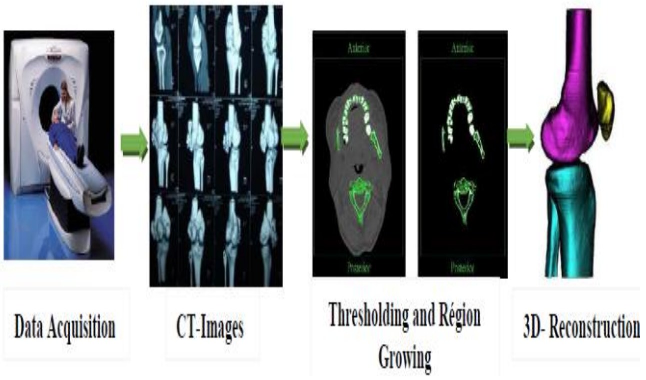

Figure 3. Data Acquisition [28]

The CT data is edited, and an accurate 3D-model of the joint is created and exported as a STL-file. Different software are used to convert the STL-file into a CAD-model that can be used as the base for the custom designed implant components. Several Solid freeform fabrication (SFF) technologies can also be used to produce a master pattern for investment casting, but producing a finished implant component is still time consuming and labor intensive. With the introduction of the Electron Beam Melting (EBM) machine by Arcam (Sweden), a new possibility for fabrication of custom implant components has become available. Initially, the EBM technology was only available with tool steel, which is not a biocompatible material. In theory, the EBM machine can process most materials that are electrically conductive, and a collaborative effort between North Carolina State University and Arcam AB was initiated to develop titanium for the EBM process.

V. ORTHOPEDIC IMPLANTS

Bone typically is a complex structure made of outer dense cortical bone and an inner spongy region [29]. Implants made from dense metals such as stainless steel, titanium or cobalt chromium are much heavier than bone. Titanium is the most biocompatible material [28]. Adding complexity to the geometry, implant requires having varying mechanical properties in different regions of a single implant. Some examples of load-bearing implants wherein the mechanical properties could be varied to effectively reduce weight without functional compromise would be a hip implant and a mandible implant. The best method to achieve weight reduction in this case would be to generate cellular structures. Voids generated in the internal architecture design primarily reduce the weight of the part with a trade-off in strength [28]. Analysis performed aids in the fatigue testing of implants and/or base the designs for tested materials at a suitable fatigue life. Subsequently, the stems that had the highest stress and displacement models were then optimized for a lower stress and displacement combination [30]. Re-evaluation of several hip stems and finite element analysis was conducted for each of the stems with various cross-sections applied to them. This analysis may explain the conditions favorable for stress-shielding in hip implants that need to be avoided. More anatomical designs are needed in the design of the total joint replacements [31]. Femoral stem developed which maintains appropriate mechanical properties for clinical use and provides enough medullary space for revascularization. Hollow and drilled stems were designed to gain sufficient medullary space [32]. A hip-joint implant with a graded lattice material can improve the load sharing capacity of the implant with the surrounding bone tissues as well as decrease the amount of bone resorption. Lattice microarchitecture of a 2D proof-of-concept implant against fatigue fracture designed to support cyclic loads in the hip joint [33]. The numerical results obtained have been verified via a detailed FE analysis. Square and kagome lattices have been used in a multi-objective optimization procedure to simultaneously minimize bone resorption and interface failure. Design and fabrication of titanium implant components, having tailored mechanical properties that mimic the stiffness of bone to reduce stress shielding and bone remodeling. Finite Element Analysis was used to design the tailored structures, and results were verified using mechanical testing [34]. The potential of EBM process for fabricating Ti6Al4V parts with controlled internal pore architecture meeting the requirements of orthopedic implants has been evaluated [35]. Feasibility and evaluation of the compressive properties of Ti6Al4V implants with controlled porosity via electron beam melting process were conducted. This process might be a promising method to fabricate orthopedic implants with suitable pore architecture and matched mechanical properties [35]. Biocompatibility of Ti-alloys for long-term implantation investigated and they are highly recommended the low-cost Ti-alloys such as Ta, Nb, Mo, and W due to their mechanical and biological biocompatibility [36]. Commercially Pure Porous Titanium can be used for surgical implants to avoid the stress shielding effect due to the mismatch between the mechanical properties of titanium and bone. Therefore develop and characterize such a specific porous structure is highly encourged. An elementary pattern of the porous structure was then designed to mimic the orthotropic properties of the human bone following several mechanical and geometrical criteria. Finite Element Analysis (FEA) was used to optimize the pattern [37]. A kind of porous metal-entangled titanium wire material has been investigated in terms of pore structure (size and distribution), strength, elastic modulus, and the mechanical behavior under uniaxial tensile loading. Its functions and potentials for surgical application have been explained [38]. It is well known that the completely understanding of stress' distribution in the hip joint is beneficial for both pre-operative planning and post-operative rehabilitation. Initially, the artificial hip joint implants are used in orthopedic surgeries without prior pre-clinical testing that may lead to inadequate clinical results. The pre-clinical testing helps in improving the clinical performance of the total hip joint replacement and controlling the possibility of joint revision operations [39].

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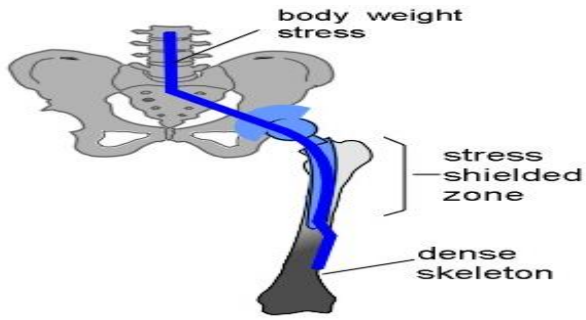

Figure 4. Body weight Stress [40]

The effect of using 2D-Functionally Graded Material cementless hip stem material in the reduction of bone resorption around cement-less hip implants studied [41]. The results showed that the recommended Functionally Graded stem minimize the stress shielding and reduced the maximum interface shear stress at the horizontal and medial sides of the femur in comparison with Ti stem. Gong H. et al. [42] identified the effects of using Functionally Graded materials as cementless femoral stem on the functional adaptive behaviors of bone. The results indicated that 2D-Functionally Graded Material stem might produce more mechanical stimuli and more uniform interface shear stress as compared to the stems made of other materials. 3D Finite Element model of a Functionally Graded femoral prosthesis developed. The model consisted of Functionally Graded femoral prosthesis, femur and bone cement. The results showed that using Functionally Graded stem resulted in uniform stress on the cement mantle layer and reduction of stress shielding in the joint [43]. Finite element analysis (FEA) has become common place in recent years. Numerical solutions to even very intricate stress problems can now be obtained normally using FEA The fatigue analysis is used to predict the fatigue life at any location of a structure. For multiple locations the process is repeated using geometry information appropriate for each location. An integrated Finite Element based durability analysis is considered as complete analysis of an entire component. Fatigue life can be estimated for every element in the finite element model and contour plots of life. Geometry information is provided by Finite element results for each load case applied individually, i.e., the Finite element results define how an applied load is transformed into a stress or strain at a specific location in the component. Applicable material data are also provided for the desired fatigue analysis method. The basic requirements for hip joints include: mechanical properties (yield stress, fatigue strength, Young modulus, plasticity etc.), chemical properties (wear degradation and resistance to different forms of corrosion), physical properties (density, magnetic properties etc.), biological properties (biocompatibility), and price [44].

VI. ADDITIVE MANUFACTURING

Additive manufacturing or 3D printing is a process of making a three-dimensional solid object of virtually any shape from a digital model. 3D printing is achieved using an additive process, where successive layers of material are laid down in different shapes [45]. 3D printing is also considered distinct from traditional machining techniques, which mostly rely on the removal of material by methods such as cutting or drilling. Electron beam melting (EBM) is a type of additive manufacturing for metal parts. It is often classified as a rapid manufacturing method. The technology manufactures parts by melting metal powder layer by layer with an electron beam in a high vacuum. Unlike some metal sintering techniques, the parts are fully dense, void-free, and extremely strong [46]. The EBM machine reads data from a 3D CAD model and lays down successive layers of powdered material. These layers are melted together utilizing a computer controlled electron beam. In this way it builds up the parts. The process takes place under vacuum, which makes it suited to manufacture parts in reactive materials with a high affinity for oxygen, e.g. titanium.

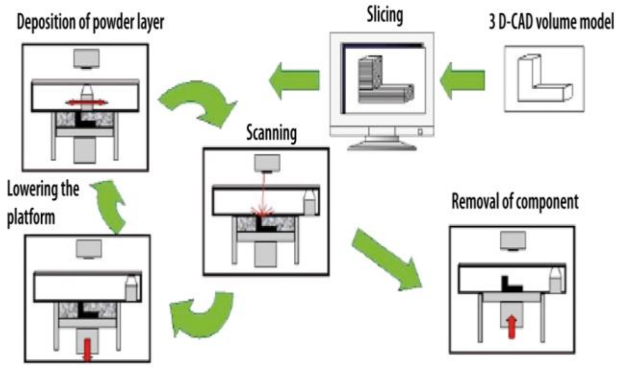

Figure 5. Steps of Fabricating an EBM part [47]

Development of the titanium powder for the EBM process as well as the initial fabrication of the first custom implants components, are shown in Fig.5. The traditional investment casting process of implant components is compared to the EBM fabrication [48]. Discussion an image based micro structural analysis and mechanical characterization of porous Ti6Al4V structures, fabricated using the EBM rapid manufacturing process is also considered [49]. Compressive Ti6Al4V and pure copper samples were manufactured via the electron beam melting (EBM) process and were then evaluated via mechanical testing. The results support the validity of the analytical models and the difference in behavior between the Ti6Al4V and the pure copper are also discussed [50]. Description of the mechanical properties such as compressive strength and fatigue life of three different cellular structures have been investigated [51]. The geometries examined include hexagonal, octahedral and rhombic dodecahedral. Test specimens were made of Ti-6Al-4V, fabricated via the Electron Beam Melting (EBM) process. Four different design configurations (two negative Poisson's ratio values x two relative densities) were manufactured and tested under compressive stress [50]. Fabrication of patient specific, monolithic, multi-functional orthopedic implants using EBM along with microstructures and mechanical properties characteristic of both Ti-6Al-4V and Co-29Cr-6Mo alloy prototypes; including both solid and open-cellular prototypes manufactured by additive manufacturing (AM) using EBM [52]. Finite element (FE) models that could predict the mechanical properties of porous titanium produced using selective laser melting or selective electron beam melting, are also considered. The irregularities caused by the manufacturing process including structural variations of the architecture are implemented in the FE models using statistical models [53].

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Also they have concluded that manufacturing irregularities significantly affect the mechanical properties of porous biomaterials. AM technologies manufacture directly from digital information of the part (digital files with 3D geometry) and do not need supplementary tooling during the manufacturing process. Normally, the use of tooling (molds, machining tools, etc.) makes vital influence on the product geometry, since desirable product features cannot be produced. These manufacturing constraints are not present in AM processes. Using AM processes, designers are not limited by conventional manufacturing constraints and can focus only on the optimum design of the product according to its application. AM technologies allow greater freedom in product design, enabling the manufacturing of much more complex geometries and in many cases, geometries that are difficult to manufacture with another fabrication method. The most important advantages of Additive Manufacturing are:

1. Time-to-market is reduced for customized products.
2. Fabrication of free form enclosed structures: AM technologies are capable of fabricating free form channels as well as different forms of latticed structures.
3. Maximum material is saved.
4. Product customization with complete flexibility in design & manufacture of a product.
5. No porosity of final parts: Unlike other powder based processes (powder metallurgy),
6. No tools, molds or punches are required.

VII. CURRENT LIMITATIONS

In spite of EBM process advantages, some issues remain unsolved. The first problem is the surface quality. Due to the unavoidable heat dissipation during the process [54], some loose powder around the part geometry is heated and partially sintered during the melting process, therefore it may stick to the outer surface of the part, generating somewhat “sandy" surface features. Most of the powder could be removed by the successive powder blasting recovery process. However some particles are more significantly sintered and will be partially melted together with the actual part [55]. This reduces the aesthetics of the part and creates surface defects. The heat affected zone also reduces the dimensional accuracy of the part, which becomes a serious issue when the part features are small such as the case for mesh structures. Another issue is the microstructure [56]. Although EBM can produce fully dense solid parts, mesh structures with small strut diameter due to the large surface area have more serious heat dissipation issue. As a result, there is a much higher chance to form defects such as voids or partial melting inclusions. Although not a serious problem for static mechanical properties, these micro-defects might serve as crack initiation sites that greatly decline the fatigue life of parts [55]. Because the electron beam scanning occurs at the top layer of the part, strong temperature gradients are formed in the direction normal to the layer. The grain growth will be favored in this direction, resulting in very elongated grain morphology in the building direction [57]. As a result, it is expected that parts made by EBM will exhibit anisotropic properties, and will have a generally lower strength compared with the wrought parts because of the relatively coarse grain size.

VIII. CONCLUSION AND FUTURE PROSPECTS

Medical Implants with auxetic cellular structures have better bone ingrowths and higher stability in the functioning body. Additive Manufacturing (AM) technology easily combines auxetic structures and solid parts in the same technological process and also can produce custom made objects. The present work intends to provide an overview in the area of auxetic cellular structures for customized orthopedic implants, using advanced AM techniques. To overcome the mentioned limitations, researchers have a vast area to work on how to improve the surface finish of the EBM parts. Also on the micro-defects which create cracks and deteriorate the fatigue life of parts.

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