Advances in Additive Manufacturing of Materials: Current status and emerging opportunities

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Lecture 20

 Welcome to this lecture on Introduction to Lattice Structures. I will be taking two lectures on this particular topic because of its emerging significance in the field of additive manufacturing. Now, to start with if you look at this particular structure, this structure is essentially made up of struts. and nodes and this structure can have specific unit cells which are regularly repeated in 3 dimensions to make a 3 dimensional structures. So, why is it important? First, I will show you that what is its relevance to biological structure of human bone.   For   example,   natural   bone   structure.

 Then I will introduce you to the lattice structure and crystalline material. Like I am a metallurgist by training, as a metallurgist we learn that crystal structure, unit cell and then crystallinity and amorphous materials and so on. those things actually I will be explaining you in details. Then I will introduce you to the structural optimization, classification of lattice   structures   and   topology   optimization.

  these particular three things I will put a star. The reason for me to putting this star is that these kind of materials may be little bit hard for one to understand without any specific knowledge in design. and as well as the mechanics of materials. But I will go little bit slow. But the first two topics essentially will give you foundation for these two lectures on the lattice structures for you to understand that why lattice structure is important, what are the different   components   of   this   lattice   structure   and   so   on.

  if you look at this human bone, this is the classic case of the long bone structure. like femur for example, okay. So, if you look at this femur bone structure and if you take the cross section, you will see these are like all spongy bone structure. spongy bone many times they are called cancellous bone structure or porous bone structure. And this is a medullary cavity you can see very clearly and then individual unit of this bone structure is called osteon.

  osteon you can consider is the smallest repeating unit of the bone. these osteons they are essentially distributed you can see this is one osteon, this is second osteon, this is third osteon, this is fourth osteon, this is fifth osteon and so on. So like that around the

circumference outermost circumference I will put the word use outermost circumference of a natural bone structure you will find this osteons are randomly distributed to form the cortical bone. And, this kind of osteo structure essentially give sufficient strength to the outer bone structure what is called cortical bone. The inner bone structure if you put your attention here, it is the highly complex porous structure.

And, these complex porous structure it is   In medical terminology, it is known as a trabecular bone or cancerous bone structures. And there are several canals in this bone structure like Haversian canal or Volkmann's canal and so on. So these canals, they perform their own responsibility in terms of either the process of nutrient and oxygen transport to the bone cells. or to essentially transport the waste products or to supply the blood vessels and so on. all those kind of biologically relevant performances are assigned to these different canals here in the bone structure.

Now, if you look at the 2D bone structure you can see it is little bit more this as I have told you a few minutes ago this is the osteon structure and this is the concentric structure and there are also lamellae of the bone and haversian canals is there and then also there is a cement line that boundary of osteons and so on. And this is what I was talking about the 3D porous structure. Now if you look at this structure you would agree with me that one cannot describe this porous structure in a most simplistic manner because this structure is made up of the struts and then two struts they join they form a kind of a nodes and these struts are actually distributed in a more stochastic manner or more random manner at different parts This kind of unique structure to mimic in the design world, one has to have significant understanding and insight into the key design principles of the lattice structure design and that was the reason that these two lectures are very important to get the fundamentals right and so that one can essentially design and construct this kind of lattice structures using 3D printing. first step is the design and then comes 3D printing. But then design to printing also there are some challenges that I will address it quite soon.

 from materials perspective, this bone structure has collagen and hydroxyapatite. these are like collagen fibrils and these are like hydroxyapatite. crystals. And these hydroxyapatite crystals, they are like hexagonal structure, hexagonal platelets. It has a thickness of 1 nanometer and then size of this hexagonal crystals is 70 nanometer.

 And this collagen fibers, this kind of bundles, they have a length of around 300 nanometer and collagen has a very characteristic of the triple helix pattern. And these osteons, if you look at the size of these osteons, these are like 100 to 500 micron and this is the bone structures and you can see this is the specific osteons that it is being produced, it constitutes the entire bone structure. what are the point that I was trying to make is that the design of natural bone structure demands the knowledge of lattice structures and topology

optimization, that is number 1 point. Number 2 point, even if you design the most complex structure which can very closely mimic the natural bone structure, then one of the challenges that one can possess is that how to manufacture this kind of complex structures with good dimensional tolerance and also good safe fidelity compliant structures. this can pose a considerable challenge even with the use of the state of the art additive manufacturing   techniques.

 Now, let us move on to the next point. up to this point, this is the first one that is that what is the natural bone structure, why this kind of lattice structure is relevant in the context of the natural structure. Now, next point that I mentioned about the crystallinity or crystalline materials. crystalline materials they have long range order and short range order in regular periodic arrangement of atoms. I underline this particular point regular periodic arrangement   of   atoms   in   3D   space.

 Amorphous materials On the other hand, they do not have any long range order but very short range order and random arrangement of entities like glasses. Even polymers also have a small crystalline domain where all the polymer chains they are organized in a particular directions, in a specific directions, in an identical direction in the local region of the polymer. Concept of crystallinity, in a crystalline solid the lattice is made up of repeating units of atoms and a repeating array of atoms in a lattice is called the unit cell,   lattice is made up of repeating units of atoms. And a repeating array of atoms is in a lattice. repeating array   of   atoms   in   a   lattice   is   called   the   unit   cell.

 this unit cell I kind of put a box around it. And smallest repeating array of atoms is called the primitive unit cell. And the lengths of the size of the unit cells are called the lattice parameters. I will explain to you with some of the schematic presentation. lattice is the 3-dimensional framework onto which the atoms are placed at the intersections.

 And typically, atoms are considered as a non-deformable solid sphere or atoms or ions or molecules have a finite diameter. And unit cell is a convenient means of representing, characterizing and communicating the structural properties of the repeating pattern that is the crystal. And the unit cell represents the symmetry of the crystal. for example, what is the symmetry element? You start from the point O, you go along the X direction, so let us say this is the Y and this is the X direction, along the X direction by a unit A, then you reach   this   point.   This   is   another   identical   point.

 You go to 3 times X direction, the 3 A distance, then go to two times along these particular directions, then you reach this particular point. This is also another identical points. So these are essentially all the identical points. These nodes are all the identical points in this array of atoms, in this particular array of the lines. the intersection of two lines is called

the nodes here and then they have some unit length which is repeated in 3 dimension.

if you go by translation process from one point to another point you will reach the identical point then that translation process is correct in the unit cell theory. The fundamental concepts of the crystal structure is, crystal structure is the combination of lattice plus motif. What is the lattice? Lattice is essentially this array of intersecting lines, as you can see, the specific lines. And these lines, they will intersect, this will be called the lattice points. you can call this lattice points, it is all are unique, these two dimensions you can call it as the 0-0 points, for example.

The motif is, for example, this is motif. This motif is distributed in the two-dimensional space like that. Now, when this particular motif is being placed in a very regular manner at all the lattice points, then we call it as a crystal structure. crystal structure is here, again lattice plus motif. motif or basis is that an atom or a group of atoms associated with each point, lattice point So one should not get confused.

It should be borne in mind that crystal structure is the combination of lattice and motif. Many times people in the textbook they use the word basis. Sometimes in certain textbook they use called lattice plus basis. basis can be one atom or can be group of atoms like which are placed at different lattice points. This is also another such examples, these are like individual lattice points, the way I am identifying and this is your essentially motif or basis and you see this motif or basis essentially two field circle and one lens kind of an object.

this motif is arranged symmetrically in 2-dimensional space and repeated at each point in the 2D net to create the regular periodic pattern and hence the lattice structure is also symmetric. you can use the word lattice structure is also symmetric, this is the motif or basis, this is the lattice points and these are really organized. any periodic regular arrangements of motifs in 2 dimensional space at the different lattice points will result in a crystal structure and each of this crystal structure should represent the most distinguishable manner of arranging or organizing the motifs or bases in all the lattice points. One crystal structure is distinguished from another type of crystal structure simply because of the fact that motifs or bases are organized or arranged in different manner in these two crystal structures under consideration.

I hope this point is clear. Now this is like a packing of atoms. You can see this is the base layer. This is that intermediate layer. In base layer, these atoms are colored differently. Intermediate layers, where these atoms are placed? Now, if you consider that, for example, 1, 2, 3, these 3 atoms are there.

Now, these red balls can come here. at the interstials of this first 3, of the 3 atoms on the

base layer. Now here again you have this red balls here 1, 2, 3. here again you can have interstials here and here again yellow balls are essentially can be placed here. like that multiple layers of atoms can be stacked up to make this all crystalline materials and each layer is characterized by a regular periodic arrangement of atoms in two dimensional space.

This is one of the distinguishable way of organizing motifs in a crystal lattice. for example, you have this is a cube, cube has 4 and 4, 8 vertex points or these identical points. each identical point you put 1, 1 atom. And at the center, body center of this, this is a half, half, half positions.

You can put a comma. This is half of positions and this is your 0, 0, 0 positions. in the body centered cubic structures in the 0, 0 positions that is the cube corners are occupied by one type of atom and in the center of the body centered lattice this half of half position this another type of atoms. this will distinguish this kind of arrangement of the atoms in 3 dimensional space from another type of arrangement that I am going to show you in few minutes. this is the structure, this is the total number of atoms is 2 because each atom will be shared by 8 such unit cells. therefore, in each unit cell it will contribute only one-eighth of this total of the spheres and there are 8 such cube corners.

one-eighth into 8 is 1 plus body centered atom which is essentially contained well within the unit cell that will essentially contribute to only this particular unit cell and this contribution has to be taken as unit 1. there is 2 atoms actually, this unit cell has 2 atoms that I have explained to you. Now as I said that you know this is the different type of organization of these atoms in the 3 dimensional space. This is called face centered cubic structure. Now face centered cubic structure again you have this kind of a 8 cube corners and let us say 2 diagonal opposite cube corners here will have similar type of atoms, let us say A layer.

Now, this particular layer contains a B type of layer, this particular layer contains a C type of layer. essentially A, B, C, A, B, C type of stacking are essentially followed in this kind of face centered cubic structure. from this basic description it should be clear to you that BCC structure and FCC structure they are characteristically different. this is that like two different type of a crystal structures. with this background let us move on to the more in the design principles which are used to describe these lattice structures and also what is topology or topology optimization that I am going to introduce you now.

isotropic material, the word isotropic essentially means homogeneous properties independent of spatial orientation. this is relevant for manufacturing AM parts, additive manufacturing parts with lightweight and robust designs, that is very important. Then topology optimization and lattice structure designing, these are the two major concepts

which emerge as the two major lightweighting strategies while exploiting the design freedoms offered by additive manufacturing. additive manufacturing as you know that it has lot of freedom of design. Lattice structures adapted for weight reduction in high safety factor   parts.

these are like 3 different aspects in design specification. One is what is the performance requirements for a particular lattice structures, what is the initial CAD model and what is the functional requirements. Then those specifications are given to this further one, further final granulation it is shown the design process. You start with the functional integration assessment, then go to the structural optimization And then you check the design specification vis-a-vis what is the design specification that you wanted. If that is not satisfied, if no compliance is achieved, then you say no, then it starts with the function.

this is an iterative process. Once at the end of the iterative process its compliance is achieved then it goes to design solution outputs and redesign structure. And what is the process constraints? These are manufacturing constraints, these are assembly constraints, these are standardization constraints. Manufacturing constraints is very important because you remember every additive manufacturing technique is kind of appears to be very nice in certain aspects but it also has certain limitations either in terms of operating parameters or in terms of the resolution of the structures that can be printed. And here this resolution is very important because you have to see that what are the different 3D printing related parameters like layer spacing or hatch spacing, infill patterns that you can utilize as an input parameter to the 3D printing machine. But when you give a complex lattice structure to be printed to the machine whether the machine will be able to print that kind of a complex lattice structure that depends on what is the pushing limit of the machine that it can print actually.

if it is beyond that pushing limit then the machine cannot print even if the structure is very novel and medically important or biomedically attractive structure. I hope I have made this point in a clear manner. now let us move on to the cellular structure. Cellular structures are essentially defined as a solid material containing a high volume fraction of the pores and it offers advantages that cannot be availed by homogeneous structures such as the ability to locally tune properties and to add multifunctionality to the design components. There are two   requirements   of   the   cellular   structure.

One is the unit cell. Now, what is unit cell? That you have already learned few minutes back. Second one is the repetition. Repetition is that unit cell is repeated in three-dimensional space and then resulting pattern need not be regular and can include more than one unit cell. For example, if you look at the unit cell, I told you the unit cell has a lattice parameters, So, here it is 4 nanomillimetre for example and these are like 4 such unit cells

are contained here. that it makes 16 millimetre and you can see these are large number of sturts and nodes that it will contain and that will make that unit cell very important and very complicated also structurally.

what are the different attributes of the cellular structures? That I am going to explain to you in the next lecture. we will start with more description or more discussion on the cellular structure and topology optimization in the next lecture. Thank you.