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

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Lecture 08

In the last two lectures, I have introduced you to the basic material classes that is metals, ceramics and polymers and then I have also emphasized that how their properties are different with few examples. While going through this lecture, I recognized that you know that some of you may not have sufficient understanding on the fundamentals of mechanics of materials or mechanical properties of materials which are essential for you to grasp what I have taught in last two lectures. Considering this aspect I have prepared a few more additional slides and then I will be showing I will be discussing them in this lecture and if it is not completed I will continue with the next lecture on the mechanical properties of relevance to materials. This would allow you to realize how mechanical properties play an important role in the performance of materials and then if additive manufacturing techniques are not sufficiently optimized to get the right combination of mechanical properties that may cause lot of challenges in their real life applications. Now one of the major things in the material science is the structure property correlation. What you see in this particular slide that there is two materials that has been mentioned.

One is the aluminum alloys and one is the magnesium alloys. Aluminum alloys are quite extensively used for aerospace applications for many decades. They have a proven track record of their successful applications in those niche areas. Magnesium alloys have also attracted lot of attention because of the lightweight and also good specific properties, specific strength properties and so on.

But, one of the issues is also magnesium is the degradation of corrosion. However, these alloys their composition their properties are being constantly improved in last one decade or so and their application also spans you know several engineering applications right up to biomedical applications. Now, what you see here this is the tensile coupon samples like what we call dog bone type of samples and this is that aluminium in the left and magnesium in the right. If you pull them in tension by applying equal forces into opposite directions. Now, there is a cup and cone type of fracture that means prior to the fracture the material has undergone extensive deformation and this undergoes necking.

And this deformation is clearly observed the way the fracture surfaces appear. But in magnesium metal if you look at the fracture there is hardly any significant deformation that you could notice. I hope you would agree with me that there is no significant deformation in case of magnesium material. And so this has something to do with the underlying structure of these metals. Now if you look at the aluminium, aluminium is a face centered cubic structure and magnesium has a hexagonal close packed structure.

Essentially this structure arises the way these atoms are organized in 3 dimensional space. If it is a face centered cubic structure, if you draw a cube and it is on the surface, each center of the faces there will be atoms as well as the corner of the atoms. Any close packed structure you have your corner of the cubes are occupied by atoms and in addition either body centered positions or face centered positions will be occupied by these atoms. This gives rise to the ability of this kind of materials to undergo deformation by a process called slip and slip was possible by the movement of dislocation which is known as dislocation glide. I am going to show these things in the next few slides.

Magnesium on the other hand as a completely different type of structure as I said that it is a hexagonal close packed structure and in this hexagonal close packed structure essentially you have a hexagonal top face and bottom face. So, your cube corners will be occupied by magnesium atom. as well as the centre of the top and bottom face, the basal planes. And in addition, there is atoms that will be occupying in the one-third, two-third half and two-third, one-third half. I mentioned it is one-third, two-third, half or two-third, one-third, half positions.

These atoms will occupy this crystal structure. This does not allow the magnesium, this kind of atomic arrangement does not allow magnesium to undergo slip induced deformation which is possible in case of the face centered cubic materials. And therefore, magnesium does not have sufficient ductility or it cannot undergo deformation. So, it is not only magnesium some of the mild steel also you can see that it is broken into two pieces. So, you can see this is the circular cross section.

maintained or circular cross section remain. Whereas in this particular cases you can see that cup and cone type of fracture and this cup and cone type fracture there is extensive deformation area right at the centre. This is again for the materials like ductile metals like aluminium. Now one of the question is that you know I have mentioned it in the last lecture also, how to define stress. Now this is a solid with arbitrary shape.

I am interested to define the stress at the point O. under the application of a combination of forces which are acting from all different directions and those are hypothetically mentioned as they are P1, P2, P3, P4, P5, right. These forces can have different magnitude and these forces are certainly being applied in different directions to this particular solid. First thing what you need to do, you need to construct a hypothetical plane around the point O that is point of interest. And this hypothetical plane, around this hypothetical plane, you consider a free body diagram.

And this free body diagram and this is your hypothetical plane with a dotted red line and this is your point O here, okay. This is the point O. So, what we have done since P1, P2, P3 are the forces which are acting on the bottom half of the solid and which are now not existing. We consider that these are replaced by a resultant of this P1, P2, P3 by P resultant force and P4, P5 is still there. First we need to find out that around this point O, what is the stress? This stress sigma is equal to limit delta A tends to 0, delta P by delta A.

What is delta P? Delta P is the resultant force acting on plane which plane this is the plane and what is delta A? Delta A is the area of the hypothetical plane constructed around point of interest and that is O. If delta A tends to 0 that means what would be the concentration of the resultant forces that would be acting on the point O at the infinitely small area around point O that is nothing but the stress around the point O. I hope that is clear to all of you. Next these stresses can be three different nature generic nature one is the tensile equal forces to opposite directions, compression equal forces in the same directions, shear equal forces on two parallel planes in two opposite directions . Always remember that when you show shear you have to show shear by single headed arrow and then shear essentially will make some shape change.

Shear essentially will make shape change and this tension and compression essentially will make changes on the sizes of this material. Tension essentially elongates the material and contracts the material in other directions. Compression essentially shortens the material but essentially expands the material in the transverse directions. In all these cases, volume remains constant. Volume of material will not change under the application of tension, compression or shear, these are fundamental things.

Now, the way deformation is measured either the change in area due to the application of tension and compression or change in the length because of the application of tension and compression. In case of the shear forces, the deformation is essentially indicated by the angle of distortion or essentially that how the angle changes between these two planes compared to the original position in the undeformed state. So this is what I have already mentioned. Now engineering stress, this is typically the stress which is used in most of these applications and this is more for engineering applications. Force divided by original area of cross section.

AO, A subscript O or A0 is essentially indicates the original area of test specimen, F is the applied force. Normally in literature either force is used by either F or A or B. Engineering strain, this is defined at a point in the stress by delta L by L0. Delta L is your change in the length, L0 is your original gauge length. Now one of the things that you might remember from the last lecture I said that stress and strain and I mentioned that typically for metals it is essentially linear and then it goes non-linear and then goes fracture.

This part from yield strength to maximum point on the stress-strength plot, what is called as UTS, ultimate tensile strength, this part of the curve where uniform deformation takes place. This is the place where uniform deformation takes place. This is the region that stress and strain will follow this kind of equations that is sigma is equal to k epsilon to the power n. What is n? n is very important that is strain hardening exponent. n value is typically lies between 0 less than n less than 1, okay.

n value lies between 0 and 1. Ductility, it is the ability of a material to be deformed plastically without fracture. Elongation up to the point of necking as I mentioned before, this is up to the point of necking, this is the onset of necking. onset of necking, this elongation up to the point of necking that is taken as a measure of the metal working processes like rolling. What is the metal working processes? I think I mentioned when conventional manufacturing was discussed like rolling, forging, etc.

These are like metal forming processes like you want the metal to give a very useful shape for specific applications you need to use these metal working processes. Toughness this also I have mentioned. As I said in the beginning of this lecture that it is important for me to show this slide so that you have better understanding of what has been taught also in the last few lectures. This is toughness to absorb energy in the plastic range without fracturing. I remember plastic range essentially means from elastic to plastic range.

Typically if you look at the fracture toughness in many metals if it is the stress versus strain, and if it is a typical ductile metal, so many material the fracture toughness is a measure of the area under the cross stress strain curve. And this is very important this parameters like railway tracks for materials which are used for railway tracks, some steels, train couplings, these are again steel materials, gears, crane hooks and so on. Compression test, now compression as I said that compression is the equal forces in the same directions and this essentially means that initially the height of the metal is H0, area is under A0, so after the compression H0 becomes H and A0 becomes A at any instantaneous point, so therefore engineering strain is defined by Current height H-H0 that original height divided by the original height. Since height is reduced during compression value of E is negative.

This you have to remember. Negative stress or strain means it is compression. positive stress or strain means it is tension This particular stress-strain response of materials was described earlier and then what you remember that ceramic, metal and polymer they behave completely different manner and each of them have their distinct advantages and this particularly elastic modulus has been shown but if you look at the strength wise metals has higher strength then comes ceramic and then comes polymers. However, that strain to failure epsilon f for metal polymer is number 1, epsilon F for metal is number 2 in terms of ranking and epsilon F is very very low for ceramic. Polymers outperform metals whenever very large deformation is required compared to metals but metals have typically much higher tensile strength. Remember this is tensile strength than polymers.

Typical compression response of materials, here again in the elastic regime if you see that slope that is the compressive modulus but then it undergoes non-linear deformation up to failure. In the shear response as I said that this is the theta and tangent of theta essentially is delta by b so that actually is measure of deformation. b is the distance between the 2 planes and delta is the relative displacement of the top plane with respect to the bottom plane and theta is the angle of distortion. This is the shear stress this definition is very simple tau is equal to F by A and shear strain is typically denoted by gamma is equal to delta by B. So typical shear stress of shear response of metals and irrespective of whether is tension compression on shear that That initial linear response is essentially determines that what is the modulus of the tensile compression and shear modulus.

That initial linear response is common to all and that is followed by nonlinear response. This is a more generic description of the stress strain response of metals this is I must mention this is tension and you have the elastic region and then you have a plastic region and this is that S versus E curve. Typically engineering stress strain curve they are defined as S and E and what is the true stress true strain curve it is more sigma versus epsilon. Now, why do we need true stress true strain curve? True stress true strain curve essentially is needed because if you look at engineering stress strain curve this particular description essentially tells you that as the load increased stress increases it reaches the maximum point but beyond maximum point stress falls before it fractures but in reality it never happens right. If you keep on increasing the load that material will undergo more and more strain harden but that concept is not captured in the engineering stress strain curve and therefore we need true strain true strain curve where is true stress is essentially denoted or defined by F by Ai where Ai is the instantaneous cross sectional area not the original initial cross sectional area because remember your cross sectional area goes through considerable decrease in the cross sectional area This true stress concept is very important.

Some of the things as we look at that maximum load also can be referred in the sigma epsilon and S versus E curve and the fracture point is typically on the right hand side of the fracture point of the engineering stress strain curve. Shear stress shear strain tau is equal to g gamma. Dislocations, dislocations is a essentially line defect. Since it is not a course of material science, I cannot teach very-very details of each of the important components of material science, but I have picked up most important concepts from material science and briefly mentioned so that you can follow this course, you can understand this course in a much better manner. So, if you apply shear stress to any metal block and independent of whatever processing or whatever way this you make this metal block you manufacture this metal block it must contain defects and this one of this important defects is dislocation as I said it is a line defect.

Why it is called line defect? Now, if you look at these particular things carefully, on the left of this defect, this atomic plane is continuous from top to bottom. On the right of this defect, this atomic plane marked as B, C, D, and continue in this towards the right, all the atomic planes are continuous from the top to bottom. Only the plane marked as A which is shown hypothetical plane, this does not continue from top to bottom and therefore, these particular dotted atoms are missing which should otherwise lie on a complete plane. Essentially dislocation is also described as a line defect and also incomplete plane of atoms. Now if you look at the 3 dimensions, so along this perpendicular to the plane of this board, now we can see that this also this is complete, right, this goes from front to back, right, these atomic planes.

Now if you apply the shear stress tau that what would happen this shear stress applications will drive the dislocation from more from left to right and now this plane is reached now B. Typically this is called edge dislocations because once this plane goes on at this complete right hand side, so this is your dislocation line and this is your unit slip vector and typically it is denoted as B, Burger vector also. What is the result if you see the dislocation line it moving from left to right as a result top part of the block is displaced with respect to the bottom part of the block by an amount b and this is something characteristics of this dislocations. Top part of the block is deformed with respect to the bottom part of the block, deformed or displaced whatever way you can describe with respect to the bottom part of the block and this is only possible if you have dislocations in a material. Some of the other properties which are important I mean which needs to be measured is like hardness.

Hardness as you know and I have mentioned and I will essentially remind you is this resistance to permanent deformation. Resistance to permanent deformation, how it is measured in case of metals, this is called Brinell hardness tester, you have a steel ball or cemented carbide ball of 10 millimeter diameter, it is forced to press it against a let us say metallic plate and then you measure that what is the shape of the indentation. And from shape of the indentation and from the initial diameter of this steel or cemented carbide ball, you can essentially find out that what is the hardness. Second one is the Rockwell indentation. Rockwell is a pyramidal kind of a indenter and this pyramidal indenter is forced to penetrate So, here that if this indenter penetrates to a large depth, that means the metal has certainly low hardness, so it is softer metal.

If the penetration distance is very small, that means metal has a high hardness. This is the two opposite things, high hardness and low hardness. In ceramics typically this Vickers indentation method is used and this is square base pyramidal indenter and then here again if it is pressed into a ceramic then what would happen in a polished surface, perfectly polished surface it will give an impression. And that impression is essentially is a measure of this how this impression expands that is measure of 2 diagonal D1 and D2 you take the average of this and this is kind of 1.854 P by D square this is the Vickers hardness of the ceramic material.

Essentially in case of ceramics, the brittle fracture is very common and how this brittle fracture takes place and what is the consequence of brittle fracture that I am going to teach in the next class. Thank you.