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

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## Lecture 05

Welcome back to this course. In this lecture, I will introduce you to various classes of engineering materials, metals and alloys, ceramics and glass and polymers. These three are called primary material classes. I will be also describing in a brief manner on some of the key attributes or advantages of these material classes, three material classes as well as a derived material class composites which have been playing many which have been essentially used in different important application areas. The background to engineering materials is important across all engineering disciplines because any functional structures which are used for engineering. applications ranging from electronics to mechanical to medical to chemical engineering to civil structural, infrastructural applications.

Materials have been playing an important role for many decades. This has also necessitated in the development of new materials using a combination of all the 3 different primary material classes in a synergistic manner in the most thoughtful manner and that have resulted in the class of materials called composites. Second aspect is that why this lecture is important in the overall context of additive manufacturing. Additive manufacturing is essentially used to manufacture components.

of metals, ceramics, polymers or composites right. But we need to know what are the key attributes of these materials and that may not be necessarily taught in all non metallurgy material science courses in a manner and to the extent what would be useful to exploit additive manufacturing to make components of these materials . I think this places a importance unique importance for this particular lecture Metals and alloys have been used perhaps for as soon as the civilization has started and human civilization has started or from the onset of human civilization, it is known for high toughness, dislocation, plasticity. Now what is toughness? Toughness is essentially a measure of crack growth resistance. let me explain you some of these terms in the next slide.

suppose you have a rectangular plate of materials and this rectangular plate of materials has an edge crack. This plate is placed under tension. Let us say you are applying that extensional force F. Now what would happen, this is the crack opening mode and this edge crack will essentially increase in length with time. Now the question is that if material does not have a good toughness, toughness is essentially crack growth resistance.

If the material does not have a good crack growth resistance or material does not have the ability to offer sufficient resistance against the crack growth, this plate will be fractured into two pieces. But if it has a good resistance, then these cracks will propagate to certain extent and then that will be stopped. So, this is also another thing that you must remember that for example, if the material has good resistance, this crack will essentially grow to a certain extent but it will be unable to grow across the width of the plate leading to fracture. Second thing that I have mentioned in the last slide is the strength. The strength is essentially load bearing capability of a material structure.

So what is the maximum load that the material can withstand without fracture that is the corresponding stress which is being indicated as the strength of that material. And then strength can be measured in different mode. One would be tension. A material can also experience compression. Then it is called compressive strength.

For example, cements which are used in infrastructure or civil applications, their compression strength is important. And these both the tension and compression is by far the most widely used the loading mode that the material will experience under any given applications apart from that there is a third is more on the what we call shear force but that is most used for the shape distortion. It will deform the material but then when you call about the strength, it is mostly tension, tensile and compressive strength and also shear strength. But the shear in case of the metals, it also follows linear and non-linear behavior, linear following non-linear behavior. The slope with the linear part is called shear modulus.

I think these are very brief understanding that is very important. The third one that I have mentioned is the hardness. Many times I have seen the students are confused about hardness and strength. Hardness is essentially resistance against permanent deformation. Hardness of a material is a measure of the resistance against permanent deformation.

Hardness many times is synonymous with strength but however their value or the measure of hardness measure of strength is not equal or not equivalent. Hardness and toughness certainly is not the same and many students they make mistake in these mentioning these terms. A hard material may have a low toughness and often people use the word fracture toughness. Classic examples is ceramics. What I mentioned a hard material or a material with high hardness can have low toughness.

I am making such statement to make you understand essentially how these different terminologies like hardness, strength and fracture toughness they are to be understood and they are to be interpreted in describing the materials properties. The modest hardness and dislocations is the essentially a line defect in metals or in materials and these dislocations are primarily responsible for the deformation of materials. Dislocation induced plasticity is very important in the context of metals. And this dislocation, what is plasticity? Now this is the typical stress strain plot of a metal. Typical under tension.

For a ductile metal, it goes from linear behavior. This slope is essentially elastic modulus, then it goes to nonlinear region. This is up to the point of linearity. This is called plastic part. Elastic to plastic transition, so this plasticity essentially is due to the dislocation movement in metals.

In more scientific language it is called dislocation glide in the materials at room temperature or at ambient temperature. So what is stress? Stress as you know from the basic physics load divided by the area that is the classic description engineering stress but true stress is different that is load divided by the instantaneous area of cross section. Load is essentially P by A load divided by or F by A whatever way you define the load as P or F. Strain is essentially change in length divided by the original length. What it means that suppose this is a dog bone type geometry of a metal and this is a gauge length.

You are pulling it in the tension. This is the gauge length where there is a uniform cross section. So, what is the change in length? Delta L divided by original length that is the measure of strain. In the most simplistic terms I am trying to explain to you. Now you mostly understand that different terms.

Metals has high toughness that means it has a much higher crack growth resistance than ceramics which are known for its brittleness. And strength variability, strength variability means suppose you take 10 or 20 or 100 of alumina samples, you break it under tension or flexure that every alumina sample will break at different loads. Polymers have a low density, it has a high flexibility but it really lacks high temperature applications. These are some of the key attributes of these 3 different material classes and composites actually is a derived material class combining advantageous properties of metals and ceramics or ceramics or polymers or metals and polymers. With an aim to achieve a property which is higher than the sum total of individual phase property.

Three distinct composite classes include MMC metal matrix composite, CMC ceramic matrix composite, PMC polymer matrix composite. Now, at some point in previous lectures I have mentioned that I am going to show you what are the conventional manufacturing processes. This slide essentially gives you some introduction to that and the next slide will give you more details of this conventional manufacturing. You have a raw material is very important that what is the raw material it is important for many critical sectors like medical materials, medical implants and all raw materials. This material transformation process, what it means that this raw material is now being transformed to an engineering component by machines and automations.

You can use an automated machine, machine tools. And their material science, thermodynamics, fluid dynamics all play some role with a varying degree of significance to convert or to transform this raw material to a functional engineered component. These components can be assembled to make a product which can be used for certain applications. I repeat what is the meaning of material transformation processes. Material transformation processes essentially means the conversion of raw material to an engineered component and these components were manufactured as per the design of the components under interest.

Then these are to be assembled and then products are to be marketed. Here material science concepts, concepts of thermodynamics, concepts of fluid dynamics play an appropriate role which is most relevant to the manufacturing process under interest. What is the conventional manufacturing? Raw material can be either in the powder and the molten material. The classic example of the molten material based manufacturing is the metals like either through casting or continuous casting and all. Classical example of the powder based raw materials also can be metals like you know powder metallurgy also can be ceramics for example ceramic based sintering techniques also can be polymers like many melt compounding starts with the polymers in the powder form.

Then molten metal, it can go through either ingot casting, so then it has to be poured into a mold and then mold inner cavity dimensions will be replicated on the outer surface of the as-cast product or it can be go through or it can go through continuous casting or rolling that is typically done in all integrated steel plants. across the world like you melt the steel and then you directly pour in the continuous casting machine which is integrated with the rolling units and then rolled products then it will undergo further deformation process and then make into a useful products or rolled products are marketed directly to the customers. Multimeter can be directly goes to the casting shapes or single crystal pooling that is more of research interest or sometimes in the turbine blades and so on. After continuous casting it goes through rolling or extrusions, ingot material or it can go through forging like where large compressive stresses or forces will be applied to the ingot and then it can undergo and this forced component can be used for many components. Now when it goes through all the series of operations, final operation is the machining.

Machining is a must because all these components which are manufactured through this conventional manufacturing, they may not have the direct dimensional tolerance, their surfaces may be extremely rough and therefore it has to be machined to make the smooth surfaces or make the surfaces of roughness with the acceptable limit. powders can go through pressing, injection molding and then it can be firing or sintering and there are also some of the processes it can go through either sheet metal forming then directly go to the finishing operations. After the finishing it goes to the assembly and product is launched in the market. This is in a snapshot actually the entire conventional manufacturing processes. Let me give you some more examples or more description of the metals and alloys.

As I mentioned, it has a high ductility and malleability. Some of the popular examples of metals which are used for various applications including aerospace is maraging steel. Its toughness can go up to 90 to 110 MPa square root meter. Titanium 6% aluminum 4% vanadium 105 to 120 is more than 100. And popular examples of metals and alloys, steels for example, structural applications, aluminum, lithium alloys, aerospace applications.

Steels, titanium alloys, cobalt-chromium-molybdenum are the popular examples of metallic materials. What are the major concerns why metals are not perhaps the best option for all the applications because corrosion and wear resistance are some of the limiting factors which restrict the lifetime which restrict the performance of metals in various applications. In the context of more engineering applications or in particular relevance to biomedical applications, why use metals? Because its properties and fabrication processes are reproducible and reliable. It is time tested. This is very important time tested means this has been used for decades all these forging, rolling, casting this has been used for decades.

People have developed the highest level of confidence, industry has developed highest level of confidence on this conventional manufacturing processes. This must be kept in mind. And when you look at that many of the most sophisticated, most state of that additive manufacturing machines, unit machine can be quite expensive. But when you consider the complexity of the parts to be manufactured, how many stages, what is the time spent, what is the labour intensive operations and human involvement is required in this inter-commission manufacturing process, then you would be able to appreciate the key advantages of the additive manufacturing. Remember, additive manufacturing is the newest entry into this entire manufacturing world.

Conventional manufacturing has been there for decades now. Metals are stiff and strong like that which has good elastic modulus, it has good strength property. Typically, metals have the tensile strength and compression strength is almost similar. For example, if a stainless steel particular grade has a tensile strength around 500 megapascal, it has the same strength in the compression also around 500 megapascal. Now various joining metal forming processes which are adapted for metals to obtain desired size and shapes that can be fitted and joined to biological structures is again reproducible.

And most commonly used metals are titanium alloys, 316L stainless steel, cobalt chromium, nitinol, nickel titanium for shape memory alloys. This is some of the examples. Now you can see this is the bone plate or bone screws here, bone plate or bone screws and you can see that how this standard plates with holes they are used during the orthopedic surgeries. And this is the hip processes I have made a brief mention in one of the earlier lectures like you have a femoral stem, you have a femoral ball, you have a cup, acetabular liner and so on and so forth. Those are in direct articulation particularly femoral ball and acetabular liner and that constitutes total hip joint replacement.

Polymers are long chain molecules, low density and extremely flexible, low friction, high damping capacity and these polymers are polytetrafluoroethylene and polystyrene. These are some of the examples. Polytetrafluoroethylene perhaps has very low coefficient of friction most among all known solids. What are the different materials which are used for different polymers which are used for many of the biomedical applications like high density polyethylene, polymethyl methacrylate, polylactic acid, polyglycolic acid copolymers. These are some of the examples of the polymeric biomaterials.

These are like examples of the polymers which are used is the hard valves. These are like hard valves which are used in cardiovascular applications and these hard valves are again tested for clinically tested for a long time. In the next lecture, I am going to explain little bit in more details. About the other material classes, I will be discussing how their properties are different, to what extent they are different and so on. So that you will get an overview of different material classes.

You will be able to appreciate the advantages and disadvantages of the different material classes. Thank you. Thank you.