

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

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## **Lecture 06**

Welcome back to this course. In this lecture, I will be continuing my discussion on the overview of different engineering materials, material classes. However, before I do that, let me also show you how some of the materials are additively manufactured and then I will be first showing you some videos so that you continue to appreciate the additive manufacturing processes at the same times learn some of the key attributes of the material classes. This is first video. Now, let me go back to where I stopped in terms of my discussion on engineering materials is concerned. After showing you these 4 videos, let me revisit these key slides to remind you.

that engineering materials can be. categorically classified into 3 primary material classes metals and alloys, ceramics and glass and polymers. Each of having their own key advantages like metals and alloys have high toughness, modest hardness and lower melting point. Ceramics and glasses have low toughness and strength variability.

Polymers have high flexibility but low strength. If I want to show you this in one specific plots just to show you what is the comparative advantages of three different material classes. Then let me draw this plot. Along x axis it is strain is plotted, along y axis it is stress is plotted. In engineering terms, stress is force by original cross sectional area.

In engineering terms, strain is the change in length by original length. Just for your reference, I am showing you typical dog bone type of geometry which essentially follows the required ASTM guideline. And this dog bone type of geometry is pulled in tension, that means equal forces are being applied to opposite directions. It has a gauge length, gauge length means the part of this test coupon samples with uniform cross section area. In case of ductile metals it is linear so it is a straight line followed by non-linear part, cross sign essentially means it fractures.

In case of ceramics it is brittle, under tension it has a lower strength, so it fractures with very low strain to fracture. Now if you consider the elastic modulus  $E$  for metals is  $E_m$  elastic modulus of ceramics it is  $C$  so this is your metal. this is your ceramic behavior and

this is the thermoplastic polymers like polyethylene, ultramarine polyethylene and so on. I put a dotted bar, dotted bar essentially means this scale is large and many times it can go to greater than 100% strain to failure that is  $\epsilon_f$ . Now, if you look at one parameter elastic modulus that is the slope of the linear part of this stress strain response, you would agree with me that  $E_c$  greater than  $E_m$  greater than  $E_p$ .

what it means that elastic modulus of ceramics is much higher than metal is much, much higher than the polymers. How about strength? Suppose this is the strength of metal  $\sigma_m$ , this is the strength of metal  $\sigma_c$  and this is the yield strength which is kind of  $\sigma_p$ . If you consider the  $\sigma$  values, the strength that is maximum load bearing capability as I have mentioned in the last lecture.  $\sigma_a$  greater than certainly  $\sigma_c$  certainly greater than  $\sigma_p$ . So, this is the maximum measure of the maximum load bearing capability.

What is the strain to failure? Strain to failure is  $\epsilon_p$  is greater than strain to failure  $\epsilon_m$  is greater than strain to failure of ceramic  $\epsilon_c$  So from this description in this particular slide which is essentially describes tensile stress strain behaviour or tensile deformation response of metal, ceramics and polymer. I am sure you will be with me to appreciate the three facts. Fact number 1. is elastic modulus of ceramics is higher than that of metals is higher than that of polymers. Load bearing capability of metals in under tension is higher than that of ceramics is much higher than that of polymers.

Strain to failure of any thermoplastic polymer those who are from polymer background they know that there is a two broad classification one is thermoplastic one is thermosetting. What are those that I will be going to explain when appropriate time comes. In case of thermoplastic polymer the strain to failure or strain to fracture is much higher than that of metal and that of ceramics. As I said in the beginning of the lecture on engineering materials overview, I mentioned that each of the material classes has their unique advantages. And now we are in a position to appreciate that statement by the fact that for metals, strength is higher, for ceramics, elastic modulus is higher, for polymers, strain to failure is higher.

These three properties are not comparable for all the three material classes. Each of the material class outperforms other material classes in terms of one individual property. Whether it is elastic modulus, ceramics is the best. In terms of strength, tensile strength, metals is the best. In case of strain to failure, polymers is the best.

So strain to failure means what is the maximum deformation that the material can sustain without failure and that maximum deformation that the material can sustain without failure I think their polymer outperforms. However, their strength is very low that means that

deformation is possible only at low load So, I think these things should be clear to all of you. In the earlier lecture, I have also mentioned briefly about the metals and polymers. Let me explain to you little bit more.

on ceramics. Now ceramics, this is an important structural materials, it has excellent hardness and wear resistance, corrosion resistance, it has a good compressive strength. One of the things that I must mention that compressive strength wise, ceramics compression, under compression is much much higher than the tension. In fact, one can derive and show you that compression strength of ceramics is at least 8 times that of the tensile strength. In the last slide you have seen that the metals tensile strength is higher than that of the ceramics. Let us take the example.

example is stainless steel. Their tensile strength let us say 500 mega Pascal, some specific rate. If the tensile strength 500 mega Pascal, compressive strength is also around 500 mega Pascal. Let us say ceramics it is like 250 mega Pascal tensile strength of alumina. Let us take another example alumina.

Now as I said that compression strength of ceramics is 8 times higher than that of the tensile strength. What it means for the polycrystalline alumina , Compression strength is around 2 gigapascal, 2000 megapascal while the tensile strength can be as low as 250 megapascal. Again compression strength wise, ceramics are much better than that of the metals because metals have let us say one of the classic materials is stainless steel which has a compression strength can be as modest as 500 megapascal. This again places the importance that each material classes have their distinct advantages and that as a material scientist, as an engineering scientist, it is our responsibility to exploit these advantages properties of different material classes in the most thoughtful manner, right, to when you will design engineering components. This in biomedical applications many can be used for artificial joints and bearing components.

Ceramics can be typically or traditionally they are classified as oxide ceramics and non-oxide ceramics. Oxide ceramics means alumina zirconia, non-oxide ceramics means all the carbides, nitrides, borides and so on. These are non-oxide ceramics. Some of the popular examples of the ceramics for biomedical applications include hydroxyapatite, alumina, these are ceramics which are used for hard tissue replacement applications. These are commercially used as powders, as granules, hydroxyapatite I am talking about and these are clinically used in human patients.

as in many regular surgeries. Alumina is used as femoral ball heads in many orthopedic devices. What are the ceramics? This is a textbook type of definitions. It is a compound of metallic and non-metallic elements like I mentioned, alumina.

Aluminium is metal. and then you have a oxygen in 2 is to 3 ratio. Alumina is different than aluminium metal. Aluminium is metal, alumina is its oxide form that is ceramic. Where the inter atomic bonding this is very important can be either ionic or covalent bonding like oxides or carbides. Carbides examples is titanium carbide, zirconium carbides and so on.

Ceramics are well regarded for high compressive strength I have mentioned, high temperature properties I will come back to this point in the next few slides. Refractoriness that is also result of high temperature, ability to sustain high temperature without compromising on the structurally relevant properties that is what is important for refractoriness wear resistance properties. The key point is that engineering broad spectrum engineering applications of ceramics often restricted by low fracture toughness. I remind you that fracture toughness is essentially a measure of crack growth resistance. Ceramics is a low density material.

This particular slide also shows you density of different metals like iron or steel has a density around 7.8 gram per cc, copper is little high more than 8, molybdenum is kind of 10 and tungsten is as high as close to 20 gram per cc. alumina as a ceramic it has a density that is model ceramic or classical ceramic density of 3.

9 gram per cc. Iron has 7.8 gram per cc. What it means that density wise alumina is half of that of the steel. Therefore, if you take a component of equal volume of steel and alumina, alumina is lighter, almost like half of the weight that of the steel. Now if you look at the polymers, many polymers like polyethylene, thermoplastic polymers and all, they have a density of 1 gram per cc. When you compare to that of the roughly 0.

9, 0.8 and all, which you compare with that of the steel, it is like one-eighth of that of the steel. Again, if you take an engineering component of certain volume and then if you compare with a polymeric component of similar design, shape and also identical volume that of the steel counterpart. The polymeric component will weigh one-eighth time that of the steel. Therefore this example essentially shows you that how important is this density. It has also better hardness ceramics and elastic modulus hardness wise you can see that micro hardness that some of the ceramics cubic boron nitride, boron carbide it has much much higher hardness that of the tungsten, molybdenum and some of the refractory materials.

Elastic modulus wise, tungsten carbide has much higher elastic modulus. So this places the importance that why these materials are sought after or why these materials are quite widely used for many engineering applications. This will be my last slide in this particular

lecture. You have come across the term nanotechnology and in nanotechnology the materials processing is done either by two approaches, one is that called top-down approach, another one is called bottom-up approach. These two approaches are quite judiciously used to make materials of different sizes and also different shapes also.

Nanomaterial is classically defined as the class of materials with sizes in at least one dimension in the range of 1 to 100 nanometer. If you look at the particles, all these particles should have diameter as 1 to 100 nanometer, then we call nanomaterial or at least the majority fraction of the particles. If you plot the distribution and this is 100 nanometer, so majority of the particles in this 1 to 100 nanometer then we call it nanoparticles. One dimensional nanomaterials like you just see a alternate layer of the coatings. The coatings are oriented in different orientation and if each layer of the coating or alternate layer of the coating, it has a thickness of 1 to 100 nanometer then you call a nanostructured coating.

The two-dimensional materials here if you see that individual grain size of this coatings can be of 1 to 100 nanometer, then you call it as a nanostructured materials. In three-dimensional, any bulk materials where the individual grain, what is grain? Grain is the microstructural region where atoms are being placed along a specific planes and this is called lattice orientations. And along these planes these atoms are placed and if you go from one grain to another grain that along the lattice planes atoms are oriented differently. Within a grain, lattice orientation is same. across the grain, lattice orientation changes and this particular area of misorientation is called grain boundary.

Now when you say it is a nanomaterial what I am saying at least one of the grains should have sizes in the range of 1 to 100 nanometer then only you can call is a nanostructured material. This nanoparticles have been used for multiple applications and this nanostructured materials are also used for many classical engineering applications. Therefore, I thought this basic definition of 0 dimensional, 1 dimensional, 2 dimensional, 3 dimensional nanomaterials is important and this nanostructured materials are also manufactured using the additive manufacturing technique. To recap, I have covered in this lecture the rest part of the engineering materials classes with a particular focus on how the three different material classes metal, ceramics and polymers they are different and each of them have unique advantages in terms of the some properties and here I have given examples of the mechanical properties for the elastic modulus, strength and strain to failure. I have also discussed one of the important material classes called ceramics, how they are different, how to define ceramics, what are the different examples of ceramics and then how the ceramics have better properties than metals and polymers and so on.

And at the same time towards the end I have also shown you examples of nanoparticles and nanomaterials and at the beginning of this lecture I have shown you four videos just to

show you some examples of additive manufacturing. This course is on additive manufacturing. Every now and then I wish to remind you about either the definitions of additive manufacturing or the different ways or different machines that are used in the field of additive manufacturing to fabricate different classes of materials but at the same time This lecture and previous lecture essentially emphasize that what are the key attributes of the different material classes. Thank you and I will come back to the next lecture with particular topic which is relevant to additive manufacturing. Thank you.