Rapid Manufacturing

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Lecture - 31
Materials in Rapid Manufacturing (Part 1 of 2)

Good morning, welcome back to the course Rapid Manufacturing. We have discussed various rapid manufacturing processes in the previous weeks.

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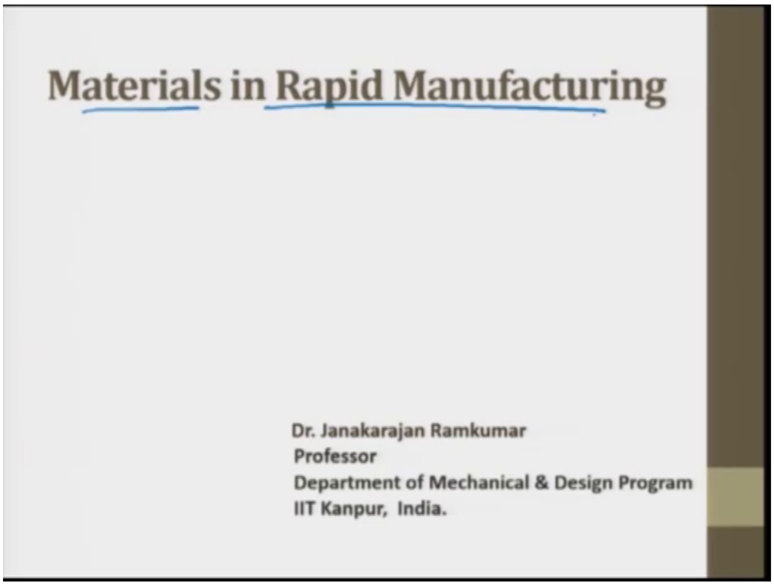

In this lecture, I will discuss rapid manufacturing materials or Materials in Rapid Manufacturing.

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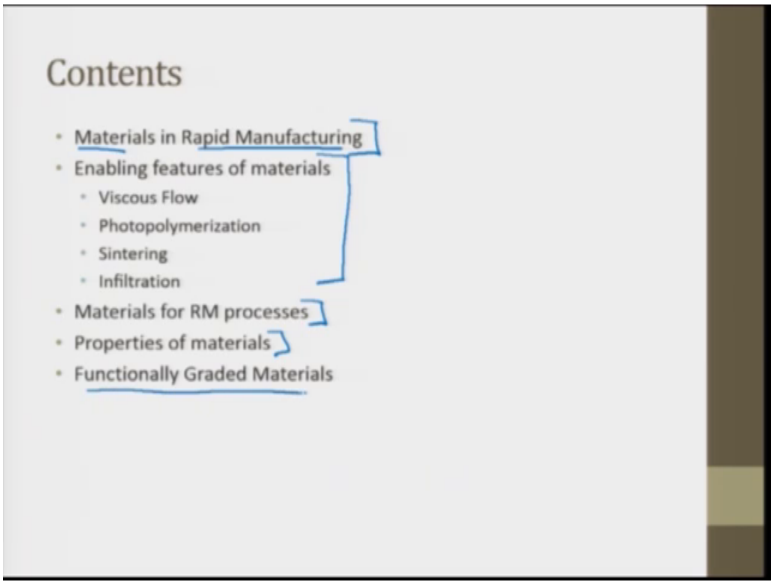

The contents of the lecture would go like this. First we will discuss the materials in rapid manufacturing, what are the general materials. Then we will discuss the enabling features for the materials, then we will see what are different kinds of materials for instance metals, ceramics different kinds of polymers composites, then we will see the properties of materials, then we will see what are functionally graded materials.

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Now, materials in rapid manufacturing, materials flexibility in rapid manufacturing along with accuracy and surface finish has been a critical factor in the technology from very beginning., You can see the appearance of different materials here this is nylon. This is stainless steel, this is aluminum, this is acrylic, this is high density acrylic and this is different colors embedded in a single material.

As it is said a craftsman is as good as his tools, similarly an additive manufacturing or rapid manufacturing process can be as good as its materials adds its feed stock that it has. So, materials are very important. There are different materials which have different properties associated with them and this there are specific manufacturing processes, that can be used only specific materials not all materials can be used with all the processes. So, there are certain things we will discuss those in this lecture.

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So, a major role of materials developer in rapid manufacturing is the tailoring of materials, alloys and multi component systems. This is all done to create processable materials with an acceptable performance acceptable end performance it is the final performance. So, as in the case of any manufacturing process, the choice of material is path dependent on specific of the process. For instance as fluidity is critical for casting plasticity is a requisite for forging rapid manufacturing process is imposed constraints on various range of valuable materials. So, the end user or end use of the product is the critical factor in this.

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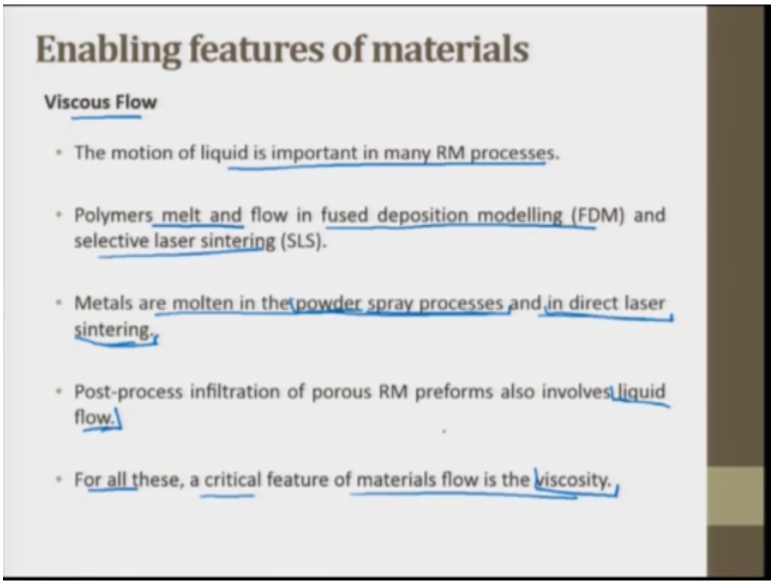

Some enabling features of materials number 1 is viscous flow, the motion of liquid is important in many rapid manufacturing processes because as we said the material has to be melted as a big sometime it is in the filament form some sometime it is in powder form. So, material has to be melted and has to be, then deposited layer by layer to form a final rapid manufacturing build.

So, viscous flow of the material is one of the enabling features. We will discuss about the properties of material separately, properties of rapid manufactured parts and the materials which they use that will be discussed separately in this lecture only this are only enabling features. So, polymers melt and flow in FDM process fused deposition modelling and selective laser sintering.

Metals are molten in powder spray processes and in direct laser sintering. Post process infiltration of porous rapid manufacturing preforms also involves liquid flow. This is all regarding the liquid based processes, those we discussed. For all these a critical, feature of material flow is viscosity. So viscosity flow becomes an important factor.

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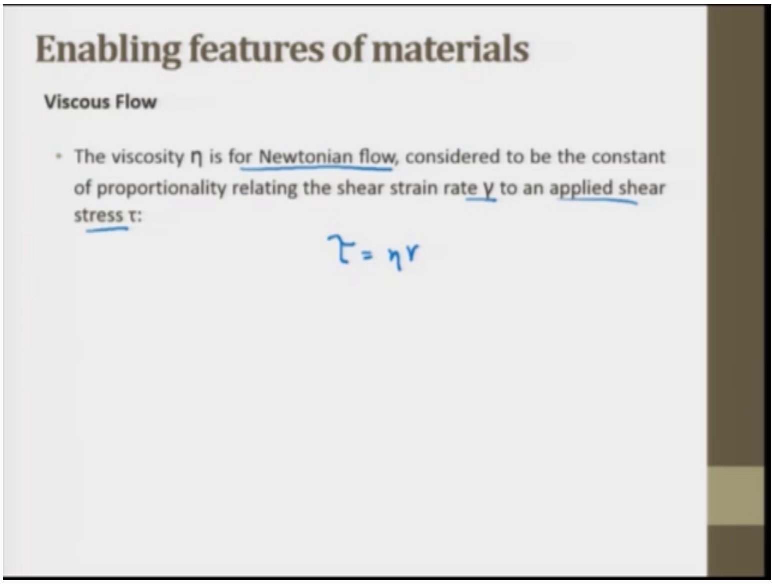

The viscosity eta for Newtonian flow considered to be the constant of proportionality relating to the shear strain gamma to an applied shear stress tau. So, this relation is directly like this then, tau is equal to eta into shear strain. Now many polymers obey a similar non Newtonian power law relationship in which gamma is raised to the power m or less than 1.

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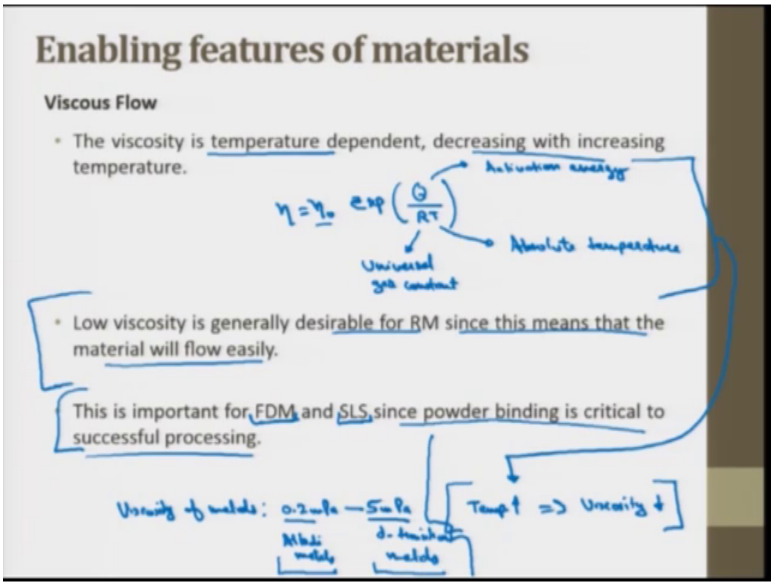

In viscous flow, viscosity is temperature dependent, decreasing with increasing temperature. Both polymers and liquid metals for there is a general relation this eta can be put as eta naught into exponential of Q by RT. So, where eta naught is again a constant and this Q is activation energy, R is universal gas constant this you people know and T is absolute temperature.

Low viscosity is generally desirable for rapid manufacturing since this means that the material will flow easily. So, the viscosity has to be low, but not much low, so that the material appears to be solid material itself. So, this is important for FDM and SLS since powder binding is critical to successful processing, so this is important for FDM and SLS it is very important.

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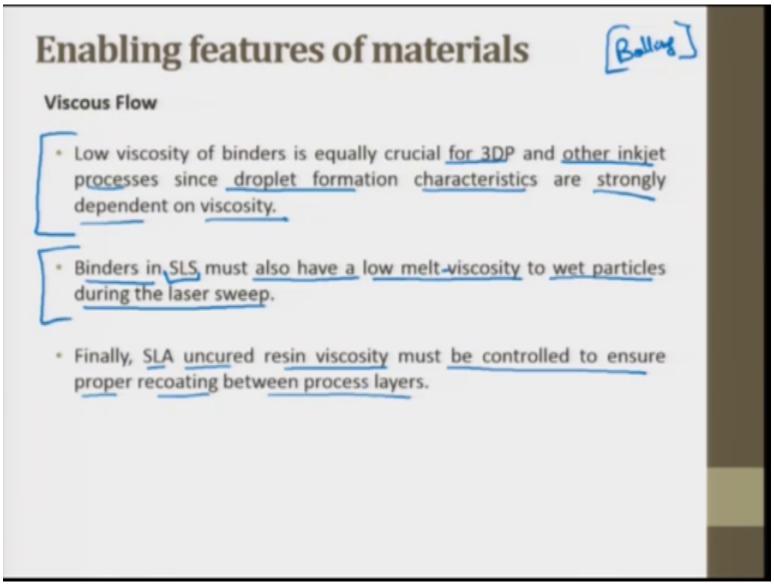

Low viscosity of binders is crucial for 3D printing as well and other inkjet processes. Since droplet formation characteristics are strongly dependent on viscosity. Droplet formation happens in certain processes like 3D printing and there certain defects like balling defects I will discuss about the defects, balling is one of the defect that is the function of viscosity only. What is balling?

When we are depositing the material; material is not coming in one flow small drops and drop coming out of that. So, that drops are sometimes dispersed in a different way. It is not a continuous flow, so that is one factor that depends upon viscosity that is one defect. The binders in SLS must also have a low melt viscosity to wet particles during lasers sweep, is selective laser sintering process binders should have low melt viscosity; this is a factor here.

Finally, stereolithography apparatus uncured resin viscosity must be controlled to ensure proper recoating between process layers; this is important. So, viscosity is lower significantly by increasing the temperature as mentioned in this equation. When temperature rises this means, what does this mean? This means that temperature high implies viscosity low. The result is that most of the rapid manufacturing processes operate at elevated temperatures to maintain low viscosity that is the reason.

Viscosity of polymers varies significantly with temperature as I said viscosity of metal ranges from maybe 0.2 mega Pascal, for alkali metals to 5 mega Pascal for d transition metals. So, I can put viscosity of metals it ranges from 0.2 mega Pascal to 5 mega Pascal 0.2 mega Pascal is for alkali metals and this is for d transition metals right.

So, in the sense viscosity of water at room temperature is 1 mega Pascal. This is a kind of a field that is we are telling you 1 mega Pascal is water at room temperature lesser than that would be for alkali metals and more, than that should be actually for the d transition metals.

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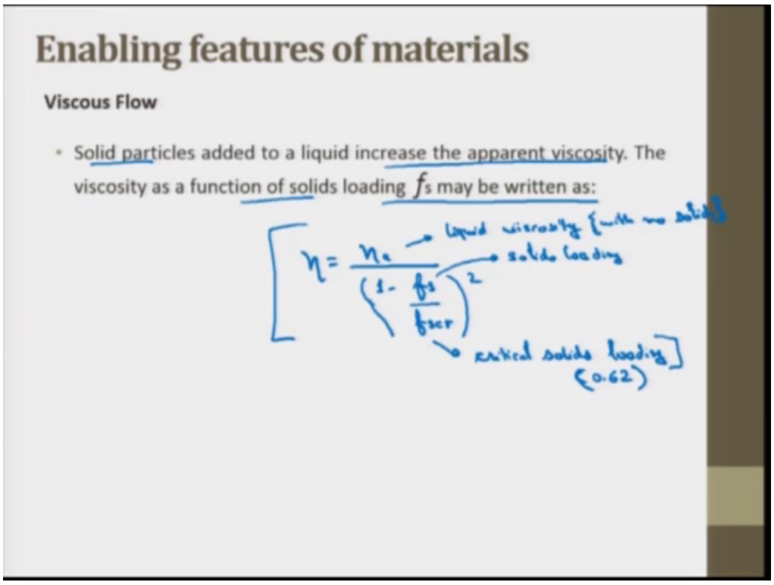

Now viscosity flow solid particles added to a liquid increase the apparent viscosity this is obvious the solid particles are added viscosity increases, the viscosity as a function of solids loading f s may be written as eta is equal to eta a by 1 minus f s this is solids loading the amount of solid that is added by f scr. What are these variables? I will just let you know whole square. So, here eta a is liquid viscosity and f s is the solids loading, f scr is the critical solids loading critical solids loading and this value is generally 0.62.

So, it is a critical solids loading at which the flow seizes at this point if this much solid is in the slot completely seizes and eta is the liquid viscosity this is actually the viscosity with no solids. So, because we need to add solid particles to obtain the specific properties of the final manufacturing rapid manufacturing part, the amount of solid that has to be put that can be determined in this formula.

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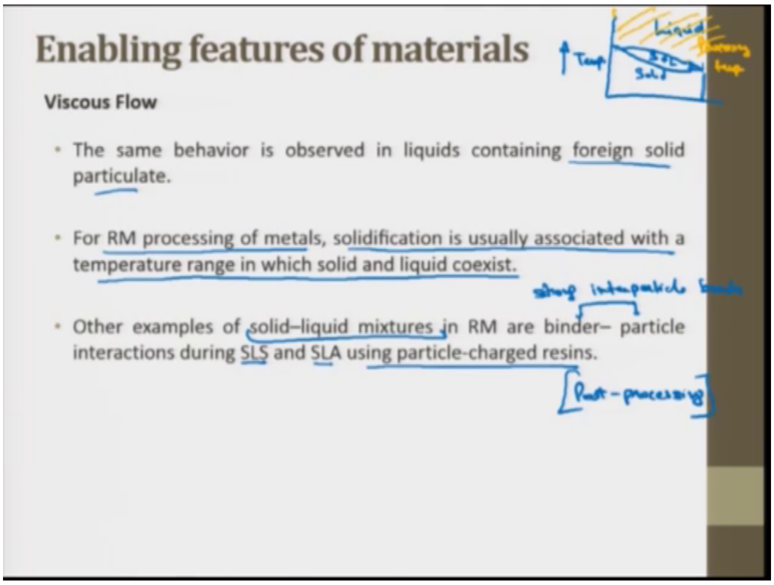

Now, viscosity is the same behavior is observed in liquids containing foreign solid particulate for rapid manufacturing processing of metals, solidification is usually associated with a temperature range in which solid and liquid coexist. So, there is a liquidous line, we I do not want move it much. So, if you know this is something like this is here, we have solid at lower temperature, here we have temperature rising this side. This is solid, this is liquid and this is solid plus liquid coexisting phase. This temperature raising at this point at lower temperature it is was complete solid.

So, the solidification is usually associated with a temperature range in which solid and liquid coexist, it is desirable to process at the temperatures above this slushy zone. So, the processing generally happens at this zone. So, this is processing temperature, in this zone the material is completely liquid and the viscosity is also low. Other examples for solid liquid mixtures in rapid manufacturing are binder particle interactions, in binder particle interactions we have combined solid and liquid mixtures.

So, as a binder particle interaction during selective laser sintering and stereolithography apparatus using particle charged resins. It is critical in post processing infiltration of rapid manufacturing porous parts to maintain strong inter particle bonds. So, post processing is important in rapid manufacturing as well and when we do post processing the certain ways infiltration is one of the ways. So, to maintain strong inter particle bonds that is the binder and particles we have the inter particles bond between them. So, these have to be strong. So, if this does not happen the liquid in filterant must not exceed about 50 percent or the part will slemp and lose the shape due to the low apparent viscosity. So, this is important point.

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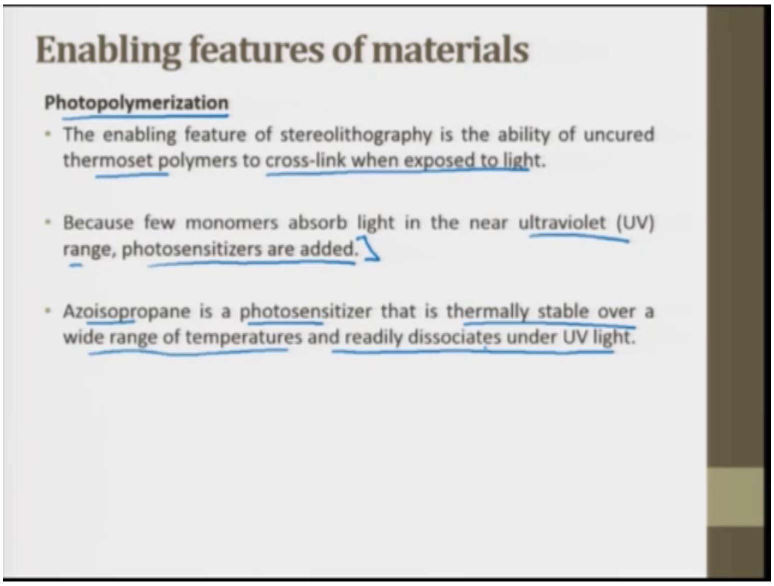

Next enabling feature for materials is photo polymerization; photopolymerization. This is discussed in detail in the previous lectures when we discussed photo polymerization based rapid manufacturing process is. The enabling feature of the stereolithography is the ability of uncured thermoset polymers to cross link when exposed to light this is just the recall.

Because few monomers absorb light in the near ultraviolet range photosensitizers are added, these are chemical that absorb light in the near UV range and dissociate into free radicals, so these are added here. Azoisopropane is a photosensitizer that is thermally stable over a wide range of temperatures and readily dissociates under UV light this is one of the examples here.

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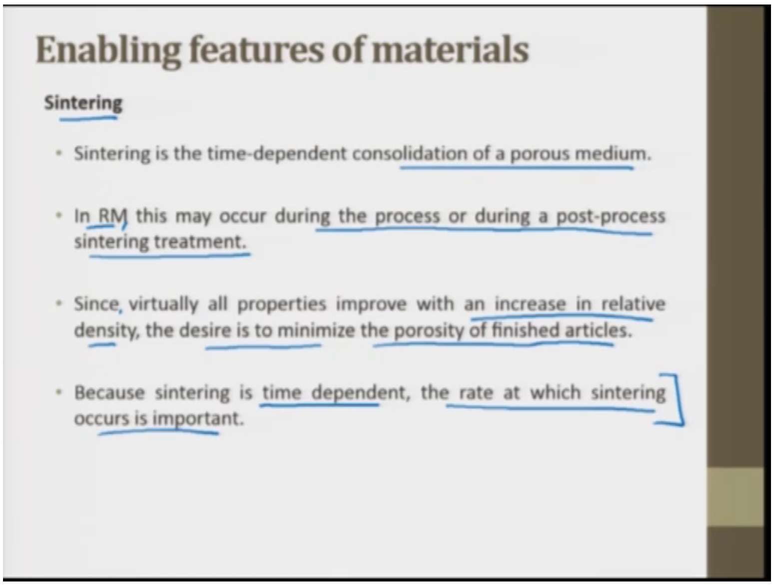

Next enabling feature is sintering; sintering is the time dependent consolidation of a porous medium, this also is discussing before in rapid manufacturing this may occur during the process or during a post process sintering treatment. Since virtually all properties improve with an increase in relative density the desire is to minimize the porosity of finished articles in sintering because sintering is time dependent the rate at which sintering occurs is important. So, this is one of the enabling features metals and ceramics sinter at rates much to slow for the phenomenon to occur during actual part build.

However polymers sinter at higher rates which may be consistent with the specific rapid manufacturing processes that is what polymer does. So, in any case, any of this case metals ceramics or polymers; it is generally desired to produce final products as quickly as possible whether the process step is direct rapid manufacturing processes or a pre process or a post process.

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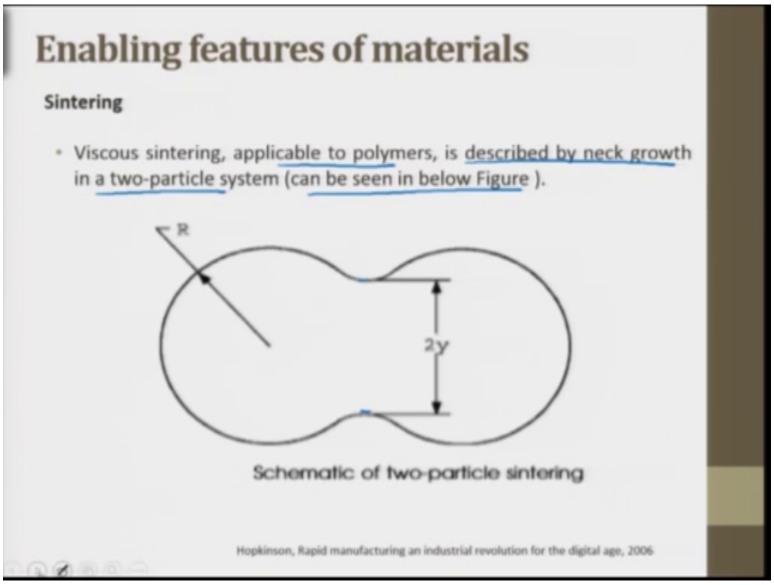

So, time and sintering parameters are to be defined. There are certain parameters or certain ways the sintering happens. One of the ways is now this is viscous sintering. That is applicable to polymers, this is it is described by neck growth in a two particle system and can be show in a below figure, this is viscous sintering in which this neck is formed this is radius of the particle two particles are sintering. So, this is the neck that is formed.

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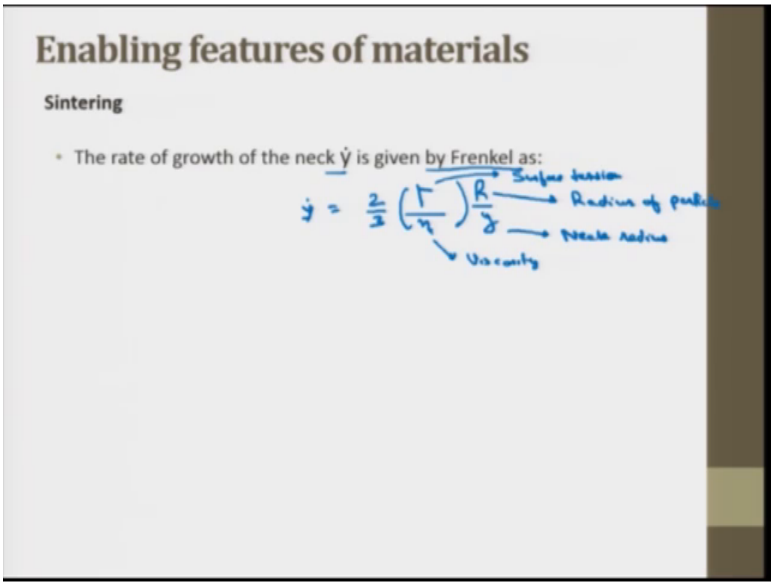

This neck that is formed can also be quantified the rate of growth of neck y dot is given by Frenkel as this relation, he says this y dot is equal to 2 by 3 capital gamma by eta then

R by y. What are different parameters here? This capital gamma is. So, it is proportional to surface tension and eta as we have discussed, in this lecture only this is viscosity, R and y are the dimensions R is radius y is neck radius this is radius of particle R.

So, solid state sintering of metals and ceramics is limited to the pre and post processing since the time required to complete significant densifications are long and rapid manufacturing of metals using processes involving powder spray, direct SLS provide higher energy for melting and flow of liquid metal.

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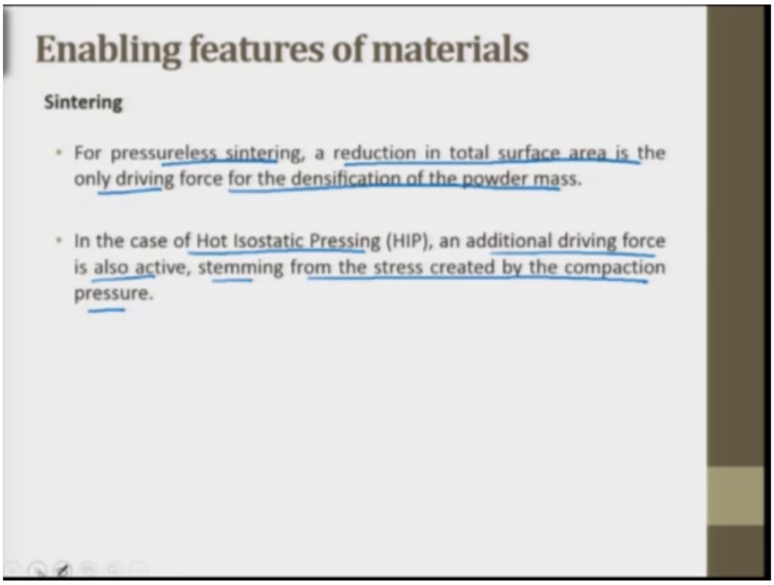

So, rather than solid state sintering that is being described here pressureless sintering is also one of the ways. For pressureless sintering a reduction in total surface area is the only driving force for the densification of the powder mass. In the case of HIP Hot Isostatic Pressing and additional driving force is also active, stemming from the stress created by the compaction pressure. So, this is sintering.

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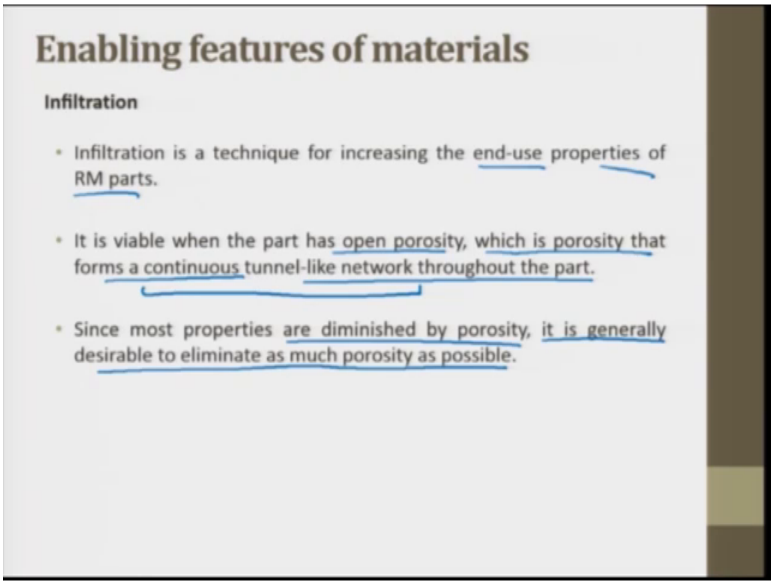

Next is infiltration; infiltration is a technique for increasing the end use properties of rapid manufacturing parts. It is viable when the part has open porosity, which is porosity that forms a continuous tunnel like network throughout the part. Porosity is also again one of the defects, porosity is a very common word and mechanical people who understand, porosity is the existence of pores in the core or the surface of the material that is produced. There are different kinds of porosities that can be spherical porosities, that can be unstructured porosity.

So, different kinds of porosities occur when porosities their infiltration helps to counter that. So, when the porosity is specifically it forms a continuous tunnel like network throughout the part, then infiltration helps to counter that since most properties are diminished by porosity, it is generally desirable to eliminate as much porosity as possible.

Several rapid manufacturing techniques such as fuse metal deposition; they can create the fully dense part that does not have porosity or a very negligible porosity. But, generally in metal sintering, in ceramics porosity is more prominent than glass and polymers other materials that we will discuss.

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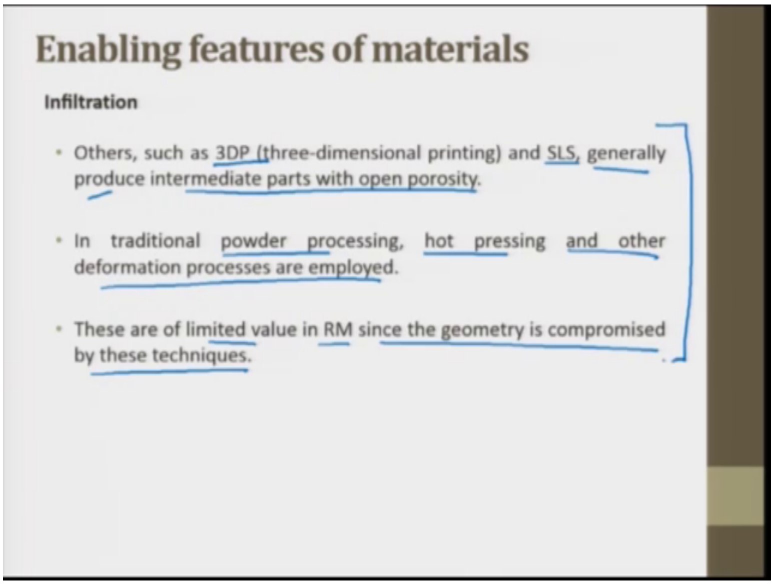

Infiltration others such as 3D printing and SLS generally produce intermediate parts with open porosity. In traditional powder processing hot pressing and other deformation processes are employed. These are of limited value in rapid manufacturing since the geometry is compromised by these techniques. So, high temperature post process sintering is sometimes useful if the kinetics for densification are acceptable and it is one of the criteria.

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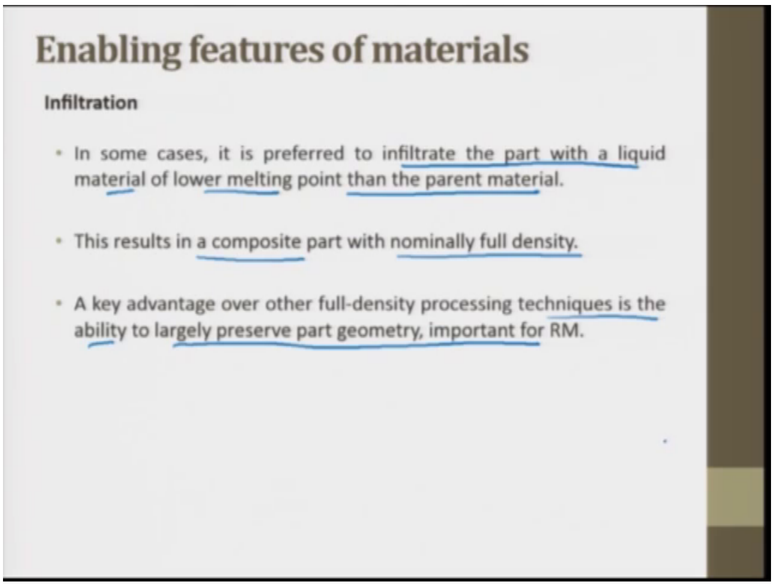

In some cases it is preferred to infiltrate the part with a liquid material of lower melting point than the parent material, these results in a composite part with nominally full density. So, it makes a composite part which has metrics and reinforcement in between. So, this infiltration helps us to have the composite part which has two parts, but it is completely dense there is no porosity left. A key advantage over other full density processing techniques is the ability to largely preserve part geometry important for rapid manufacturing.

Here infiltration is usually a post processing step that I am referring to, in this the porous part is heated that is in contact with infiltrant. It is heated to temperature at which the infiltrant is molten and will wet the part and will try to enter it and fill the pores to have the complete or a better part complete dense part or a better part that is obtained. So, these are enabling features of the materials rapid manufacturing materials, will discuss about post processing in the coming lectures.

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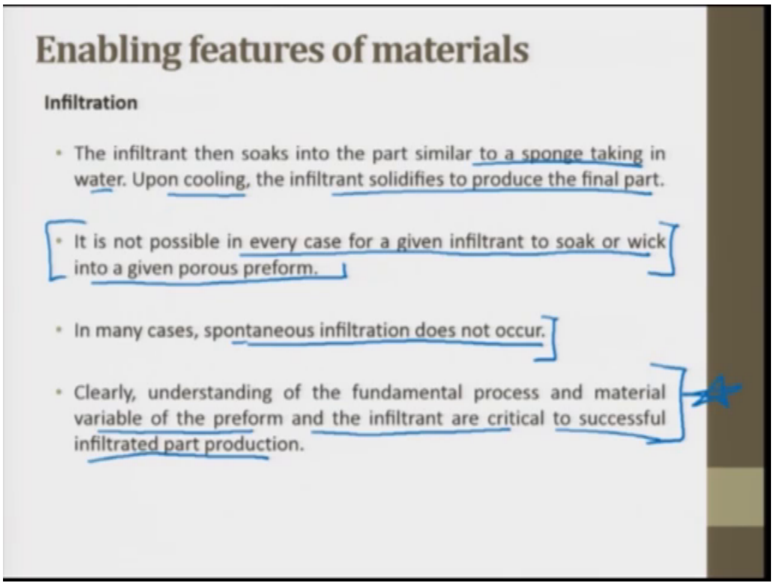

So, what happens infiltrant soaks into the parts similar to a sponge taking in a water, upon cooling infiltrant solidifies to produce the final part like we soak a sponge in water and sponge has a lot of pores in it. It looks like sponge does not have a space, but it has lot of pores in it and water is filled into that what if we filled; if we wet the sponge completely and immediately we solidify that we make ice of that water. It is a similar kind of pattern similar kind of thing that is happening here the infiltrant, then soaks the part in similar way as sponge taking in water upon cooling the infiltrant solidifies to produce the final part. It is not possible in every case for a given infiltrant to soak or wick into a given porous preform.

So, this affinity to the materials of in the between the materials important factor here, sponge can be put in water and it can be soaked completely, but can sponge can be sponge soaked in some high viscous material maybe engine oil or may be some other material that is not able to infiltrate into the pores of the sponge. So, those things are similar in the rapid manufacturing material as well.

In many cases spontaneous infiltration does not occur that is the immediate or instant infiltration does not occur. Clearly understanding of fundamental process and material variable of the preform and the infiltrant are critical to successful infiltrated part production. So, this is important this is the point I was referring, the properties the behavior of the material when they come in contact with the other material, so that is very important.

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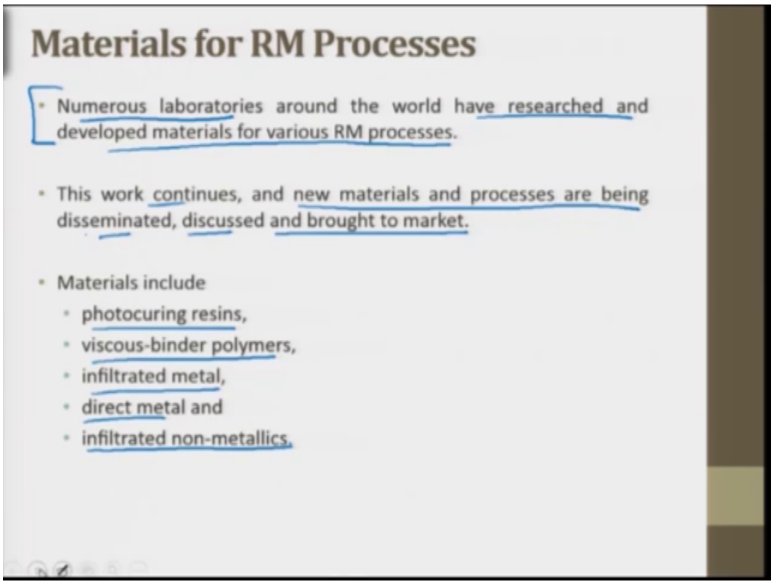

So, with this enabling features of materials are discussed and I will come to the materials for rapid manufacturing processes. Numerous laboratories around the world have researched and developed materials for various rapid manufacturing processes. This work is continuing and new materials and processes are being disseminated, discussed and brought to market this is continuing rapid manufacturing as it said by professor

Ramkumar is still is in its infancy and it has a great potential there are certain materials which are being developed such a processes are being developed, these days we can even get a 3D printer in less than 20,000 rupees.

So, there are certain developments which are happening and it is very fast. So, certain laboratories are working in this area these materials which are for rapid manufacturing processes is include photocuring resins, viscous binder, polymers infiltrated metal, direct metal and infiltrated non metallic.

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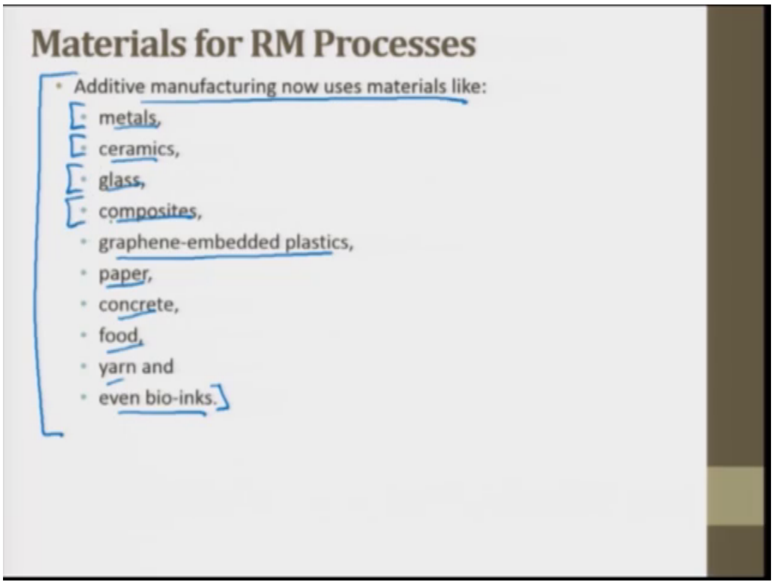

I will discuss the materials in this classification additive manufacturing now uses materials like metals, ceramics, glass, composites, graphene embedded plastics, paper in laminated processes, concrete maybe food, yarn and bio inks; bio inks as used to produce the parts for instance the air that we showed in the first slide for porting the direct and indirect rapid manufacturing processes the ear that we produce with is with a bio inks material cellulose based eggs. So, those bio eggs possible food; the furnishing of the cakes and the food that is manufactured is happening using additive manufacturing processes all those things are there.

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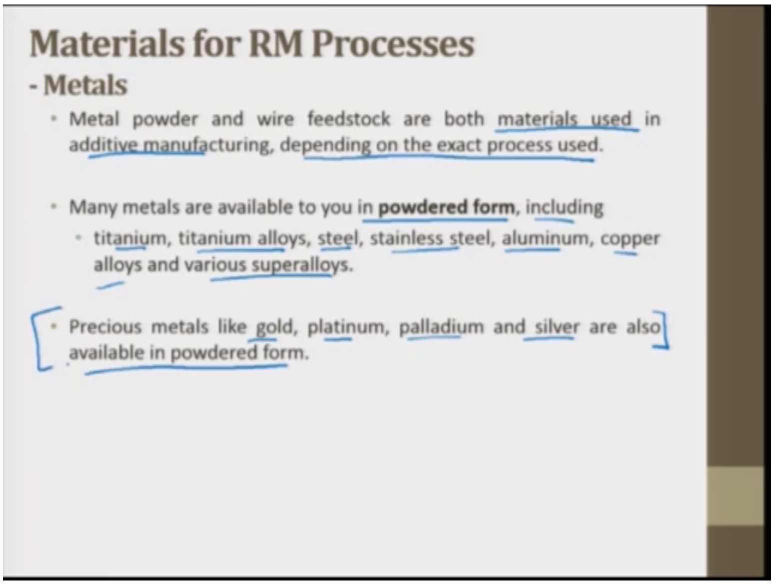

So, I will discussed the major parts here metals, ceramics, glass composites and some of the above materials, first is metals. Metal powder and wire feedstock are both materials used additive manufacturing depending on the exact process that is being used. Many metals are available to you in powdered form, including titanium, titanium alloys, steel and stainless steel, aluminum, copper alloys and various super alloys. Precious metals like: gold, platinum, palladium, silver are also available in powdered form and there is used to develop jewelry in different forms and also in integrated circuit those are being used in the electronics these days, so this is metals.

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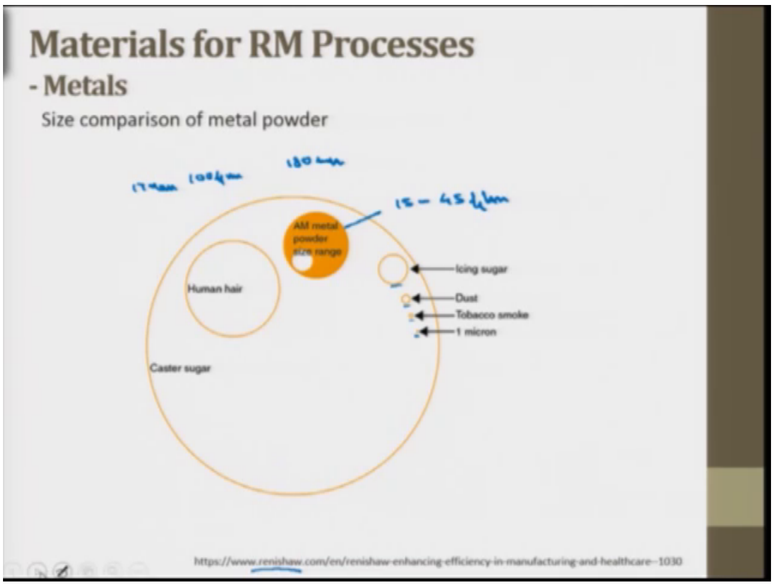

Now, size comparison of metal powder when metal is obtained in powder form this is the size comparison this is human hair; human hair generally the size of human hair is 100 micrometer. So, it varies from 17 micrometer to 180 micrometers, this is human hair actually.

Generally this is this is around 100 I mean micrometer this is 1 micron, this is caster sugar that you use in tea, this is the range of the additive manufacturing powder size that is available in the market, this is the figure that is taken from Renishaw and this range for additive manufacturing powders those are provided by Renishaw company varies from 15 to 45 micrometers.

So, in this regard, we can see this is icing sugar size, this is dust size, this is tobacco smoke, size the single particle and this is 1 micron size. So, this is 15 to 45 micrometers of metal powders size is those are provided by this specific company.

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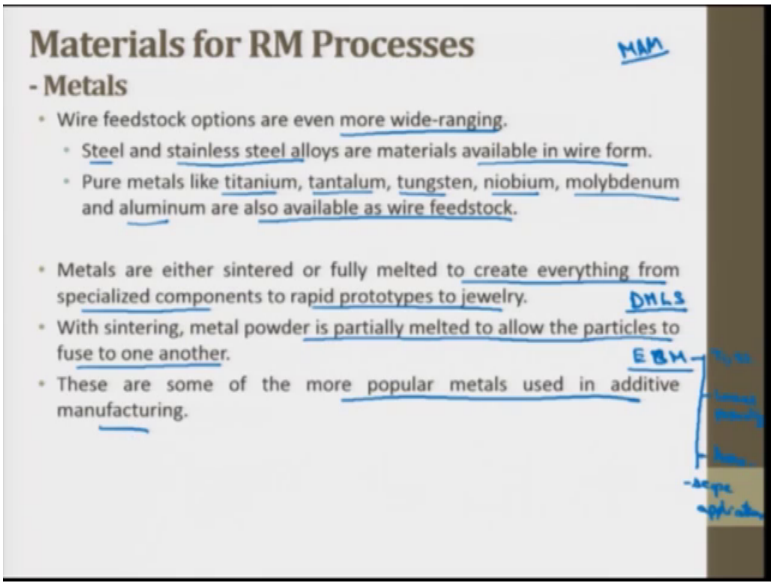

So, wire feedstock options are even more wide ranging as I said metals are available in 2 ways powdered forms and wire feedstock. Powdered form can be sintered in using different processes, wire feedstock can also be used in different processes like fuse metal like in MAMs the abbreviation used for Metal Additive Manufacturing and in MAM certain like selective laser sintering then fused deposition modelling FDM these are different ways to manufacture using different stocks feed stock. So, wire feedstock is one of the options there is available steel and stainless.

Steel alloys are materials available in wire form. Pure metals like titanium, tantalum, tungsten, niobium, molybdenum and aluminum are also available as wire feedstock. Metals are either sintered or fully melted to create everything from specialized components to rapid prototypes to jewelry. So, the metals have a big range of applications as is mentioned here with sintering metal powder is partially melted to allow the particles to fuse to one another.

So, sintering can also be used here as I said versatile direct metal laser sintering in sintering specifically I can put direct metal is a laser sintering, MAM is Metal Additive Manufacturing, this is direct metal laser sintering which is one of the MAM processes. This partially melts many of different metals and alloys yielding observable degree of porosity, so this can be number one of the processes.

Then is EDM can also be used, that is Electro Beam Melting, EBM uses powerful beams of electrons to fully melt the various powder metals this can be used to melt titanium steel, stainless steel. It is more popular with porosity is to be very less such as high stress, high temperature, aerospace applications. So, I can put this can use titanium, stainless steel and it gives less porosity less porosity then lesser porosity, then other processes because the. So, lesser porosities application in aerospace; aerospace applications; so, there are some of the more popular metals use in additive manufacturing, a few of them can be number one is titanium.

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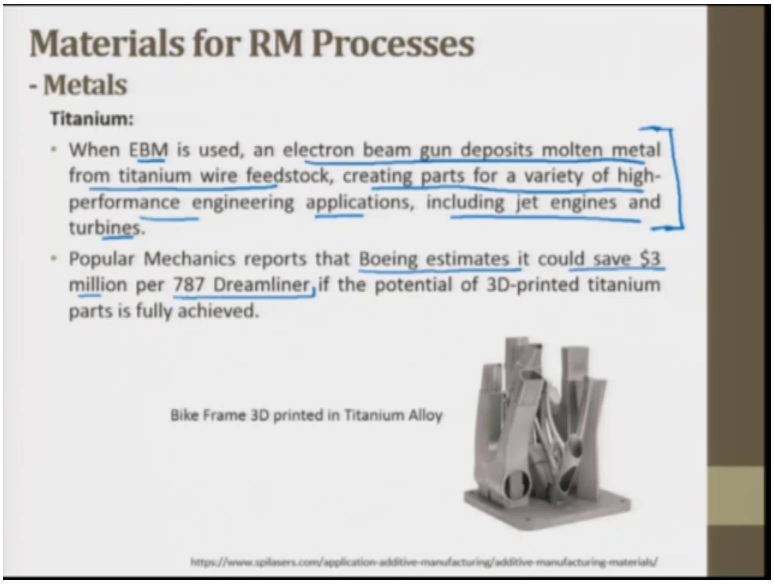

When EBM is used, an lectron beam gun deposits with molten metal from titanium wire feedstock, creating parts of a variety of high performance engineering applications, including jet engines and turbines. Waste reduction is the key advantage with expensive titanium and other alloys as titanium is expensive we know the waste reduction or high waste cannot be afforded. So, EBM is the process that is used that does not produce a big waste or a huge waste and titanium can be used to develop parts using this process.

Popular mechanics reports that Boeing estimates it could save 3 million dollars per 787 dreamliner aircraft, if potential of 3D printed titanium parts is fully achieves for this is one of the statements given in the certain reports. So, this is a bike frame that is 3D printed from titanium alloy the bike frame different parts of a bike are printed using titanium alloy.

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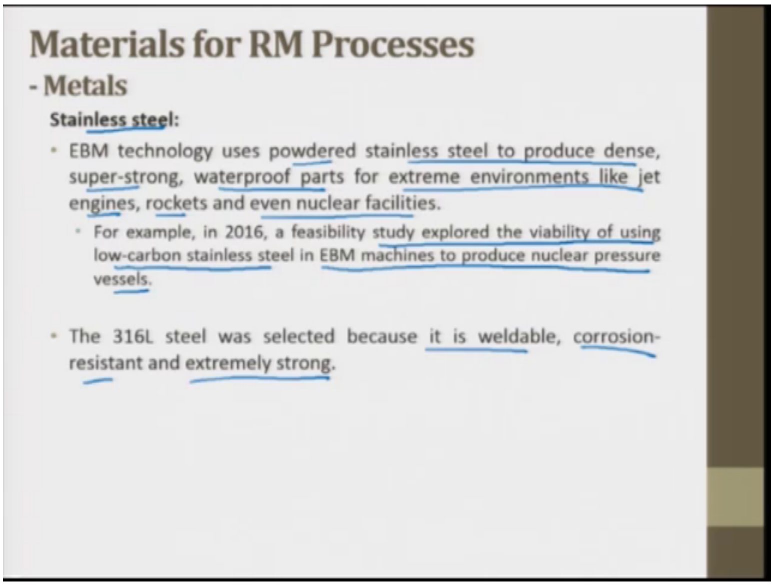

Next is stainless steel so when fusion is involved the metals generally must weldable, to be successfully processed in rapid manufacturing the small moving melt pool is significantly smaller than the dimensions of final part. So, EBM is the one of the processes that help to get this small or the very minimum melt flow. So, as to produce the components using stainless steel as well EMB technology uses powder stainless steel to produce dense, super strong waterproof parts for extreme environments like jet engines, rockets and even nuclear facilities.

For example, in 2016 a feasibility study explored that viability of using low carbon stainless steel in EMB machines to produce nuclear pressure vessels, this is one of the examples that is quoted. The 316 steel was selected because it is weldable, corrosion resistant and extremely strong. So, stainless steel is one of the materials that is used in rapid manufacturing.

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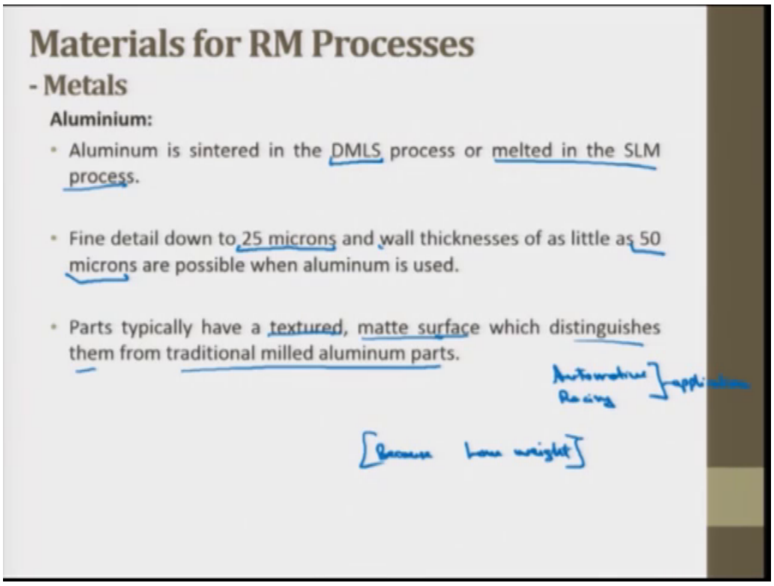

Next is aluminum; aluminum is sintered generally in direct metal laser sintering process and also it can be melted in other processes as well. Fine detail down to 25 micron and wall thickness of as little as 50 microns are possible when aluminum is used. Parts typically have a textured on matte structure which distinguishes them from the traditional milled aluminum parts generally milling happens on aluminum. But the texture that is obtained is not there after milling in corelation processes, we have to do some grinding some finishing of this surfaces.

But in this case the parts have a good texture and sometimes surface finish is required depending on the process because staircase effect is there. So, this those effects and not their surface, so it can also avoid the post processing. So, due to the low weight of a aluminum 3D printed aluminum is used for automotive and racing parts. So, it as applications over there, automotive and racing applications because of low weight and also bentness is high in the case of aluminum.

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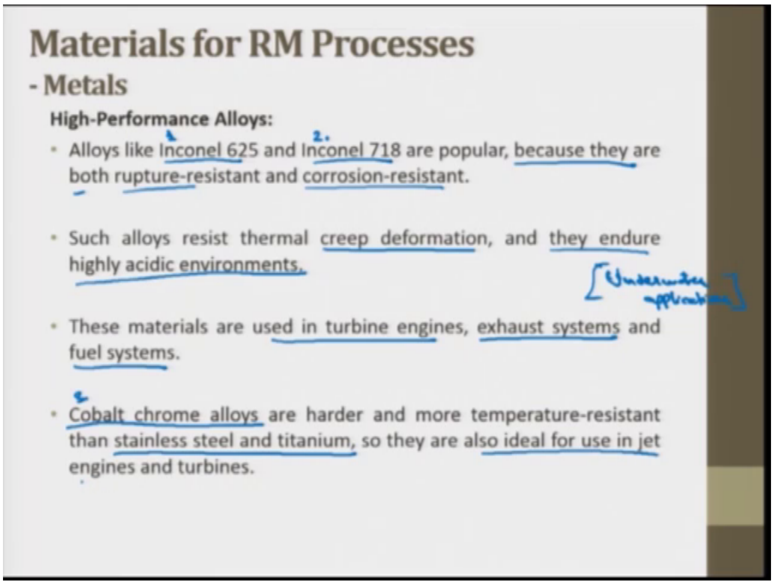

Next is high performance alloys; high performance alloys like inconel 625. Such alloys resist thermal creep deformation and they endure high acidic environments. They are very less reactive, so they can endure high acidic environments and also at high temperature is the creep deformation is very less. These materials are used in turbine engines, exhaust systems and fuel systems, their resistance corrosion also make them popular to be used in underwater applications for in the sense saltwater application, naval applications where the corrosion happens very rapidly.

In those cases I can put it here in underwater applications, this can be used in underwater applications where salt water is there are for naval applications. So, cobalt chrome alloys are harder this is another alloy in this inconel that is one discussing second is inconel 718 cobalt and chrome alloys. Cobalt chrome alloys are harder and more temperature resistant than stainless steel and titanium, so they are also ideal for use in jet engines and turbines.

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Next is precious metals, it is possible to sinter powdered gold, silver platinum, palladium using direct metal laser sintering machines. Extremely fine metal powder is partially melted to create jewelry. At the conclusion of the process the object is removed from the remaining metal powder akin to an archaeological dig.

So, these fine parts can be produced using the direct metal laser sintering process you know this is direct metal laser sintering this is the parts that is produced, these are the small you can say rings those are produced, these are the tips of the rings, this is the powder that is being removed, this is post processing step one of the step is support material or the powder removal.

So, unique and beautiful pieces of jewelry feature interlocking or interwoven designs are only possible with additive manufacturing which was not possible before by manual or traditional manufacturing.

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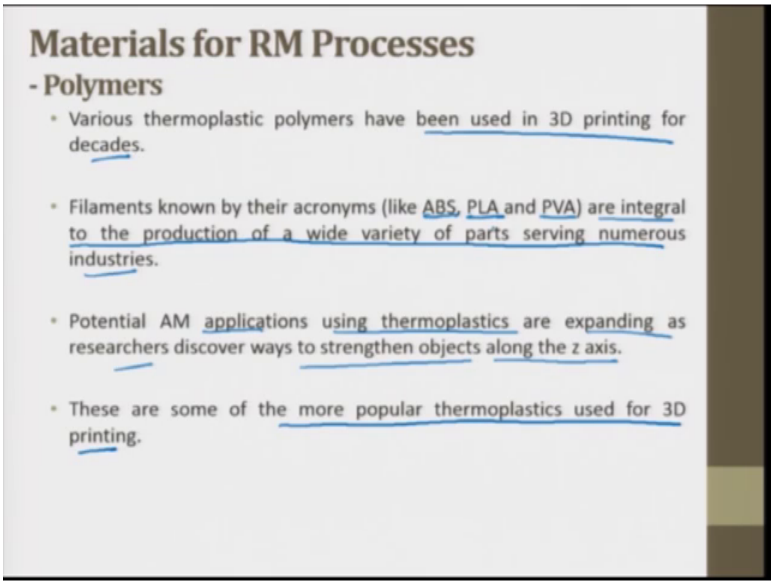

Next is polymers various thermoplastic polymers have been used in 3D printing for decades filaments known by their acronyms ABC PLA, PVA are integral to the production of a wide variety of parts serving numerous industries. Potential additive manufacturing applications using thermoplastics are expanding as researchers discover ways to strengthen objects along the z axis.

Now typically fused filament fabrication demonstrate better strength along x and y axis than z axis typically fused filament fabrication x and y axis strength is higher, but research has to be done now in z direction where the strength is also required. So, research into thermal welding techniques provides a way to provide the all important z axis strength which is what the products like load bearing or prosthetics. So, in that case z direction is very important. So, in that case polymers are very helpful. So, there are some of the more popular thermoplastic used for 3D printing.

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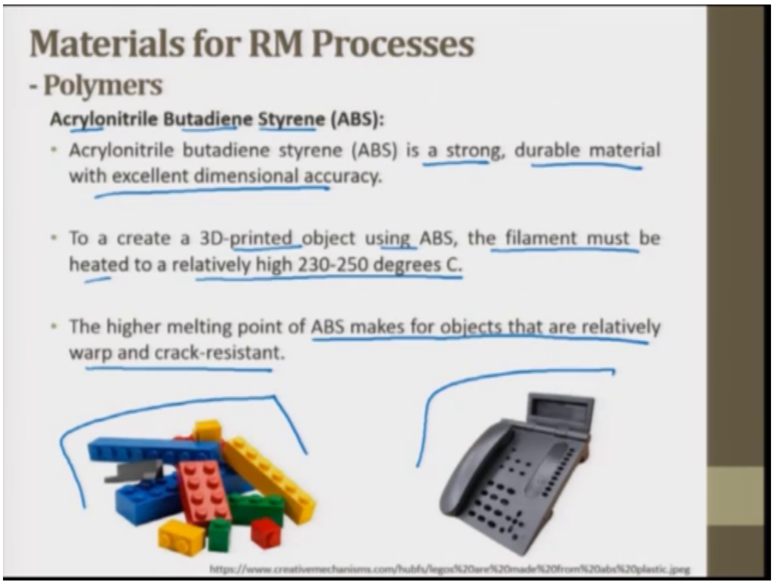

So, let us this try to discuss these polymers ABS PLA and PAV what is ABS? It is a acrylonitrile butadiene styrene. So, this ABS is a strong durable material with excellent dimensional accuracy. To create a 3D printing object using ABS the filament must be heated to a relatively high temperature, I have discussed the difference of ABS and PLA in the demonstration that we had in 3D printing.

So, I would not detail much about ABS about these two materials here in this lecture. So, the difference that one of the material that PLA is PLA can be melted at low temperatures and other strength and all the properties a droplet size the resolution that we can obtain or discussed. So, high melting point ABS makes for the objects that are relatively warp and crack resistant, these are the toys or the LEGO which are made from ABS and this is the casing.

So, this is specifically using casing and toys which makes ABS is a very good choice for producing these products. So, ABS is also using rapid tooling for creating concept motors rapid tooling as I said the tools that are used to make a mold for rapid manufacturing those are also developed using ABS because the strength of ABS is higher than the other polymers that we are discussing PLN and PVA. So, this is acrylonitrile butadiene styrene that is ABS.

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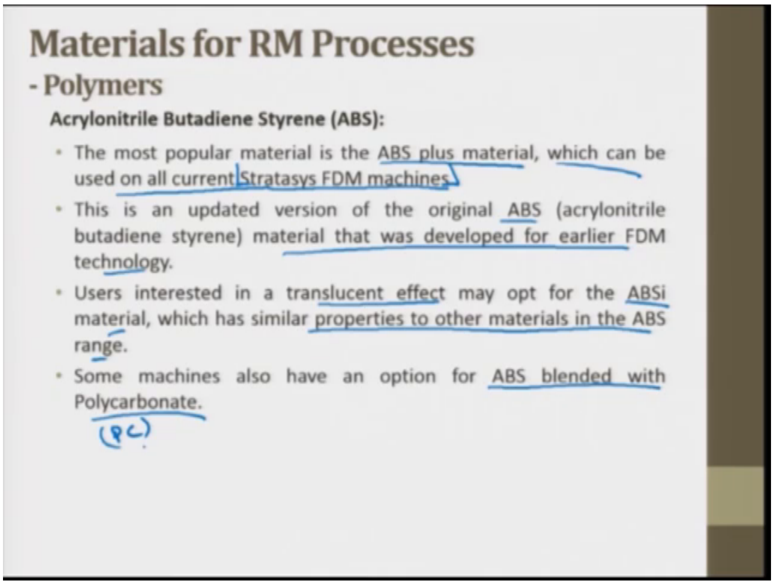

The most popular material is ABS plus material, which can be used on current stratasys FDM machine. This is a company that has these machines it is an updated version of the original ABS material that was developed earlier FDM technology. Users interested in a translucent effect may opt for ABSi material, which has similar properties to other materials in the ABS range. Some machines also have an option for ABS blended with polycarbonate which is PC also known as PC.

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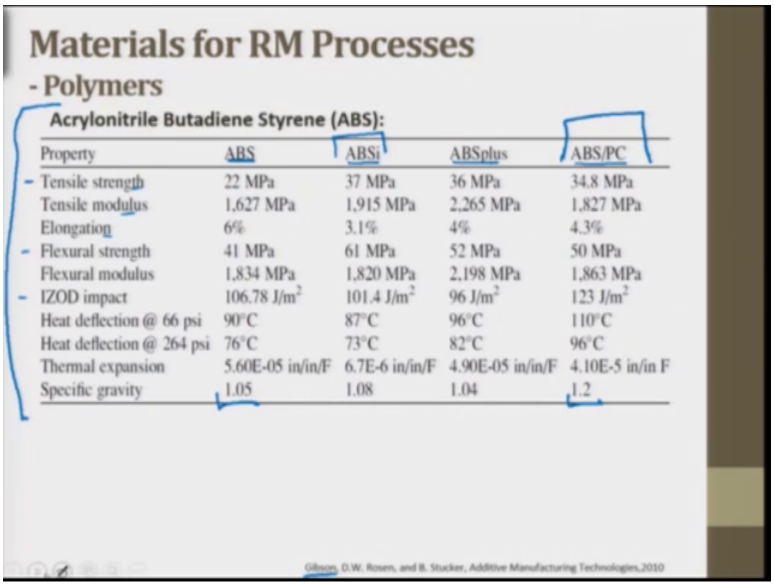

Property	ABS	ABSi	ABSplus	ABS/PC
Tensile strength	22 MPa	37 MPa	36 MPa	34.8 MPa
Tensile modulus	1,627 MPa	1,915 MPa	2,265 MPa	1,827 MPa
Elongation	6%	3.1%	4%	4.3%
Flexural strength	41 MPa	61 MPa	52 MPa	50 MPa
Flexural modulus	1,834 MPa	1,820 MPa	2,198 MPa	1,863 MPa
IZOD impact	106.78 J/m^2	101.4 J/m^2	96 J/m^2	123 J/m^2
Heat deflection @ 66 psi	90°C	87°C	96°C	110°C
Heat deflection @ 264 psi	76°C	73°C	82°C	96°C
Thermal expansion	5.60E-05 in/in/F	6.7E-6 in/in/F	4.90E-05 in/in/F	4.10E-5 in/in F
Specific gravity	1.05	1.08	1.04	1.2

So, there are certain materials and their properties is taken from the book, now tensile strength, tensile modulus, elongation these are the strength actually tensile flexural, tensile flexural and impact are the strengths. So, we can see that this is a general ABS, this ABSi, this is ABS plus, this ABS along with polycarbonate.

So, we can see that the maximum strength is when poly carbonate is incorporated in the ABS material and elongation is also average here, but the least elongation here is ABSi material. So, it all depends what do we need? We do we need high tensile strength or lesser elongation or a impact strength. So, what do we need do in a specific gravity or specific density has to be very low; however, the specific gravity close it varies from 1 to 1.2 it is close here. So, different properties are here and different variants of ABS are available that can be used.

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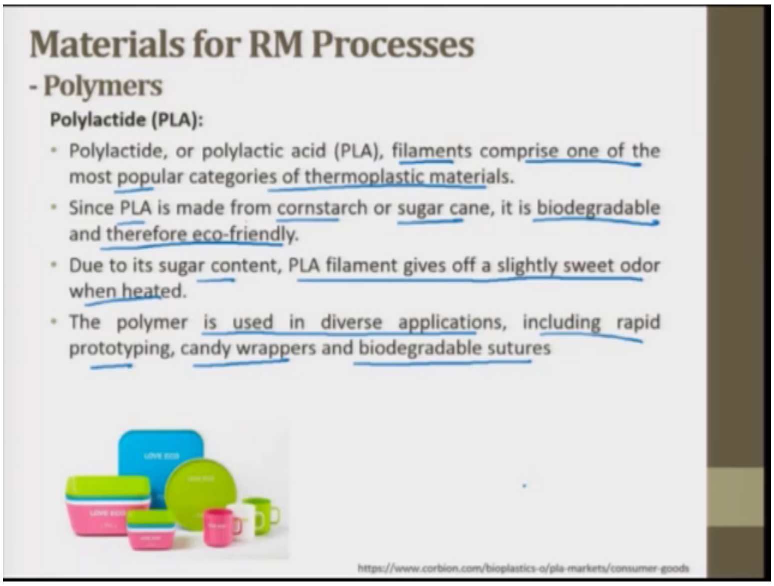

Next is PLA; PLA is polylactic acid or polylactide, so this is again filament material. So, these filaments comprise one of the most popular categories of thermoplastic materials, since PLA is made from the cornstarch or sugar cane, it is biodegradable and therefore, eco friendly this is discussed previously in the 3D printing laboratory demonstration lecture. Due to sugar content PLA filament gives of slightly sweet odor when heated, the polymer is used in a diverse applications including rapid prototyping candy wrappers and biodegradable sutures.

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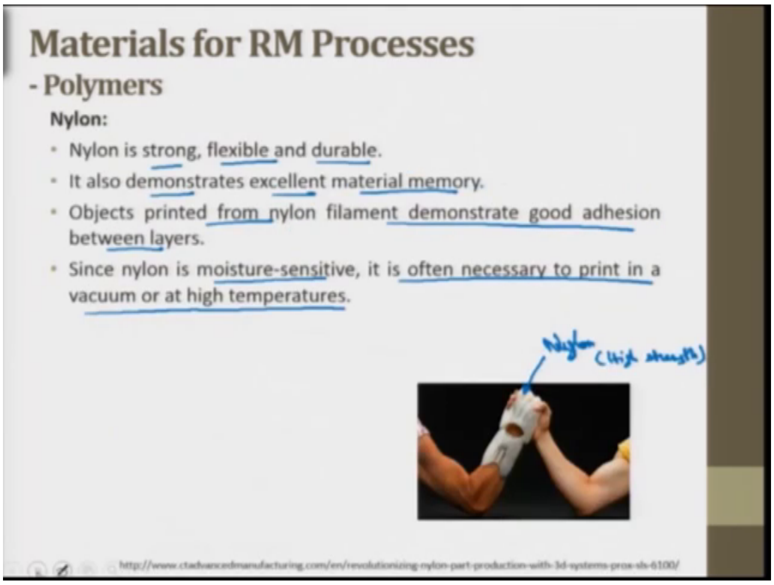

Next is nylon; nylon is a strong flexible and durable material, as you can see here in figure the prosthetic arm is made of nylon and this figure demonstrates that it has high strength. So, they are into arm wrestling, so nylon also demonstrates excellent material memory. Objects printed from nylon filament demonstrate good adhesion between layers, designers and engineers performed test using functional prototypes printed from nylon.

So, prototypes are generally printed and test are conducted on them. So, since nylon is moistures sensitive it is often necessary to print in a vacuum or at high temperatures to avoid any of the water to get in to the material and produce defects such as pores again. Now low run and smooth finish nylon parts are used in everything from consumer electronics to adventure sports, so this is also one of the material. Next is polycarbonate, as we have discussed PC as one of the alternative material here to ABS and FDM.

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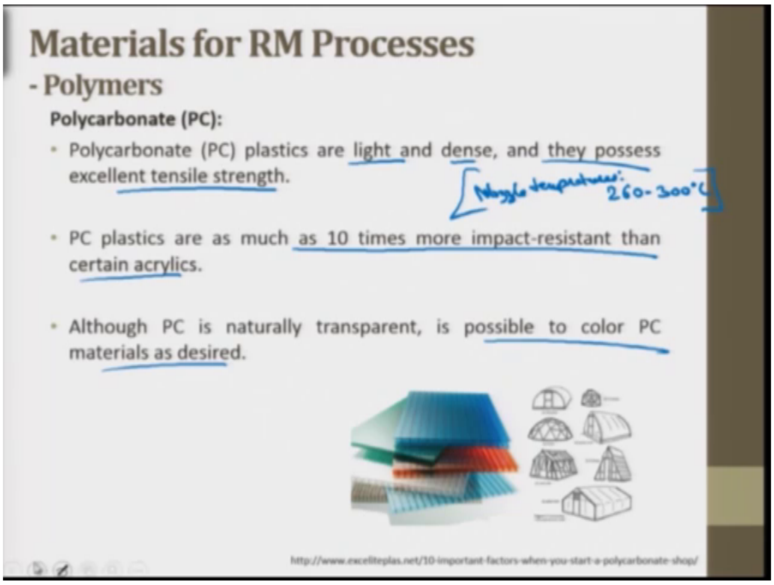

Polycarbonate plastics are light and dense and they possess excellent tensile strength. Polycarbonate plastic are as much as 10 times more impact resistant than certain acrylics. All though PC is naturally transparent it is possible to color polycarbonate materials as desired, carbon reinforced polycarbonate plastic are strong and heat resistant enough to use in manufacturing intake, manifolds and other parts subject to high temperatures.

Now polycarbonates are relative new comers to additive manufacturing because in additives it is also necessary to maintain high nozzle temperatures here, again the temperatures of the nozzle should be from 260 to 300 degree centigrade, this is nozzle temperature, but it has make a very good material to be used in rapid manufacturing.

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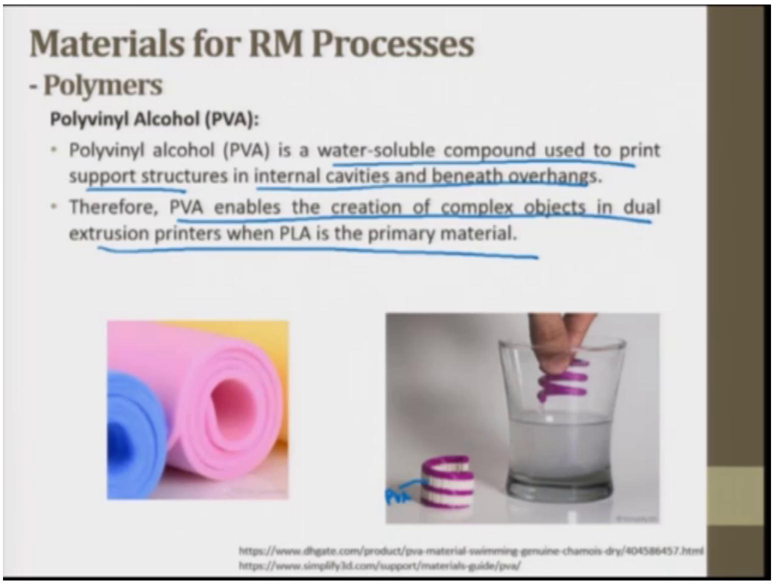

Next is PVA polyvinyl alcohol is a water soluble compound used to print support structures in internal cavities and beneath overhangs, you can see as it is given in the figure this white color PVA. So, it is dissolved in warm water as we showed you the two kind of nozzles were there in the laboratory demonstration one is support material another is the base material.

The base material can be any that has high strength, support material can be PVA that can be dissolved in warm water or other solvent that has to take it away. Therefore, PVA enables the creation of complex objects in a dual extrusion printers when PLA is the primary material. Once the primary objective fully printed the PVA is simply dissolved away by warm water.

So, there are certain benefits it has a great water dissolvable support material, there are no very special solvents required, no additional hardware required, but this properties also bring certain limitations such as it is moisture sensitive, it has to be kept in airtight storage containers which are required to keep it. Then greater chances of clogging in the nozzle is left hot when not extruding. So, this is it is also expensive material; so, they certain properties of this material.

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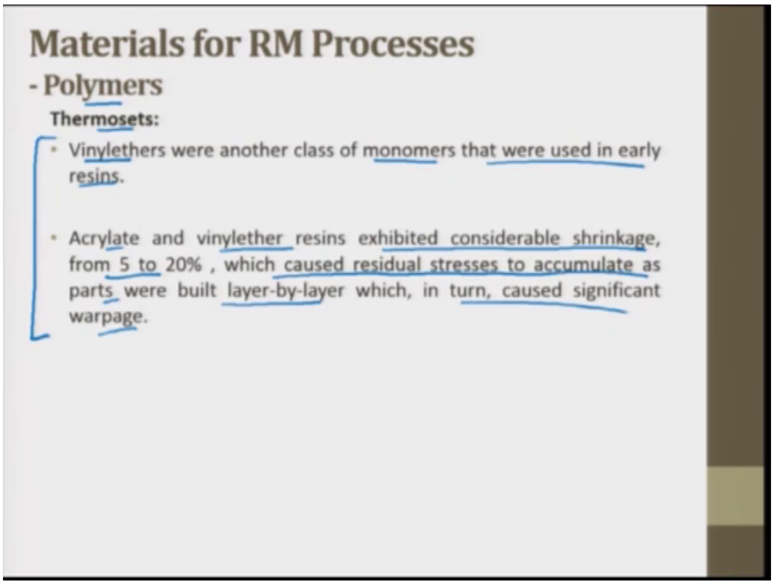

Next is thermosets materials which I have discussed before nylon, PLA, ABS these are polymers these are thermoplastic. Next is a range of thermoset materials such as vinylethers, now vinylether were another class of monomers that were used in early resins. Acrylate and vinyl ether resins exhibited considerable shrinkage from 5 to 20 percent which caused residual stresses to accumulate as parts were built layer by layer which in turn causes significant warpage.

So, these are certain disadvantages with these thermoset materials, but these are still used another disadvantage of acrylate resin is that their polymerization reactions are inhabited by atmospheric oxygen. So, to overcome these disadvantages of vinylether and acrylate certain other thermosets, are now being used such as epoxies.

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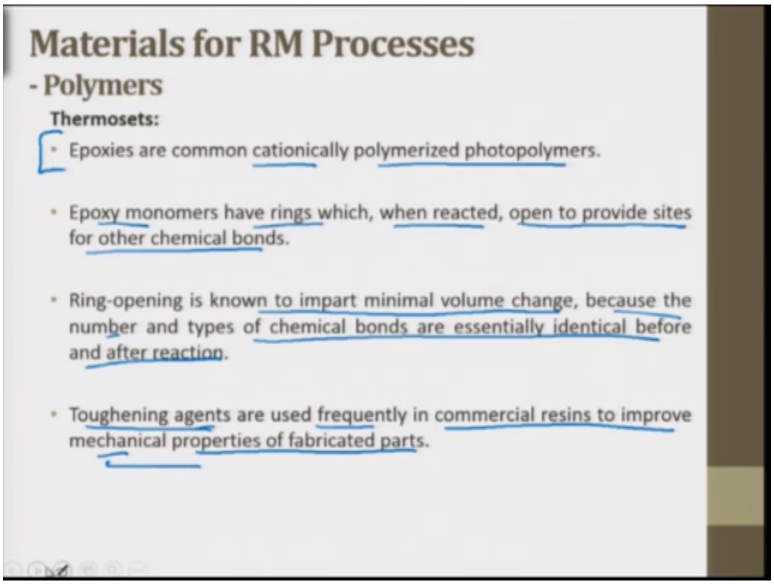

Epoxies where introduced in early 1990s and they were brought in to significant advantages to vat polymerization processes so, but they completed the formulation of resins also this is a little expensive than the other resins. So, epoxies are common cationically polymerized photopolymers. Epoxy monomers have rings which, when reacted open to provide sites for other chemical bonds. Ring opening is known to impart minimum volume change because the number and the types of chemical bonds are the essentially identical before and after the reaction.

Toughening agents are used frequently in commercial resins to improve mechanical properties of the fabricated parts. Epoxy stereolithography resin; typically shrink less than acrylates and have much less tendency to warp and curl defects are less and shrinks less, so that is why warping and curling is lesser. All most all commercially variable stereolithography resins have significant amounts of epoxy these days.

So, these mechanical properties are improved the toughening agent are added, these toughening agents may be reactive or nonreactive may be in the form of phase separated liquid or particles. So, these are the thermosets and thermoplastic polymers.

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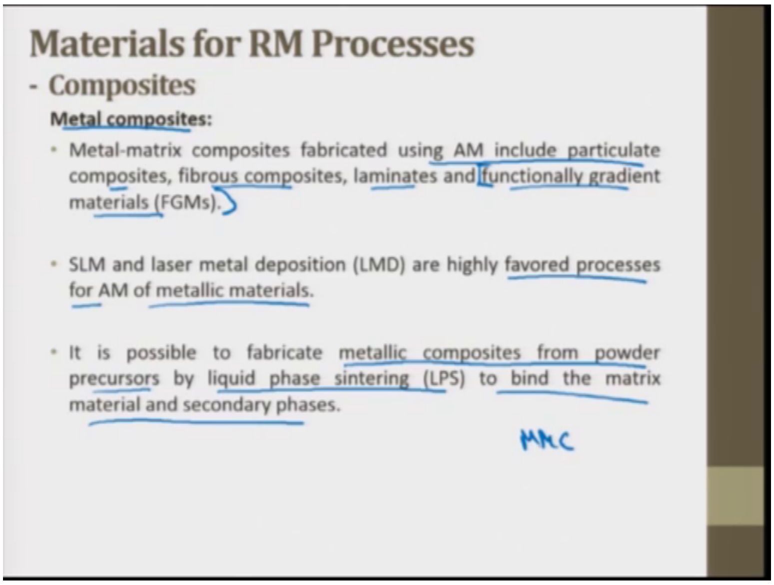

Next is composites, metal composites; metal composites fabricated using additive manufacturing include particulate composites, fibrous composite, laminates functionally gradient materials, FGMs would be taken separately in this lecture. So, SLM and laser metal deposition are highly favored processes for additive manufacturing of metallic materials.

It is possible to fabricate metallic composites from powder precursors by liquid phase sintering to bind the matrix and material and secondary phases. So, this technique has been applied to obtain MMC which are Metal Matrix Composites; metal matrix composites are now manufactured using the additive manufacturing techniques MMC I will put it here.

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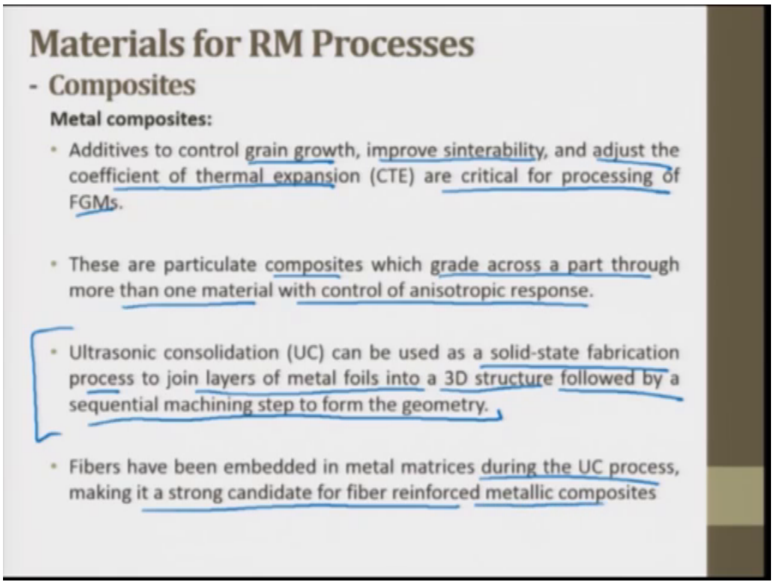

Additives to control grain growth, improve sinterability and adjust the coefficient of thermal expansion are critical for processing of functionally graded materials. These are particulate composites which grade across a part through, more than one material with control of anisotropic response. Ultrasonic Consolidation which is UC can be used as a solid state fabrication process to join layers of metal foils into 3D structure followed by a sequential machining step to form the geometry.

So, UC and machining; machining becomes is a post processing step here, they can help to develop metal composites as well. So, fibers have been embedded in metal matrices during the UC, process making it a strong candidate for fibers reinforced metallic composites.

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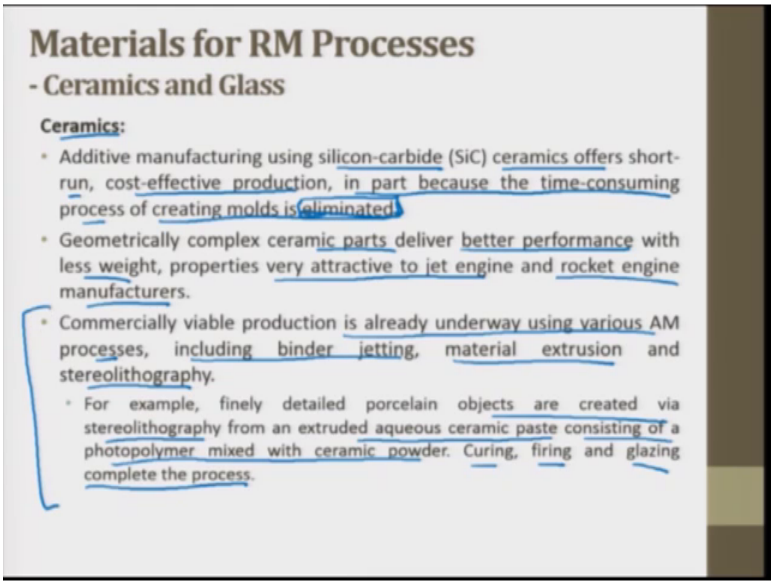

Next we have here is ceramics and glass; ceramics and glass or another additive manufacturing materials, so additive manufacturing using silicon carbide ceramics offers short run cost effective production in part because the time consuming process of creating molds is eliminated. So, the molds are not to be made, so these are cost effective. Geometrically complex ceramic parts deliver better performance with less weight, properties very attractive to jet engine and rocket engine manufacturers.

Commercially viable production is already underway using various additive manufacturing processes, including binder jetting, material extrusion and stereolithography. For example, finely detailed porcelain objects are created via stereolithography from an extruded aqueous ceramic paste consisting of a photopolymer mixed with ceramic powder. Curing, firing and glazing complete the process. So, ceramics can also be used as additive manufacturing materials.

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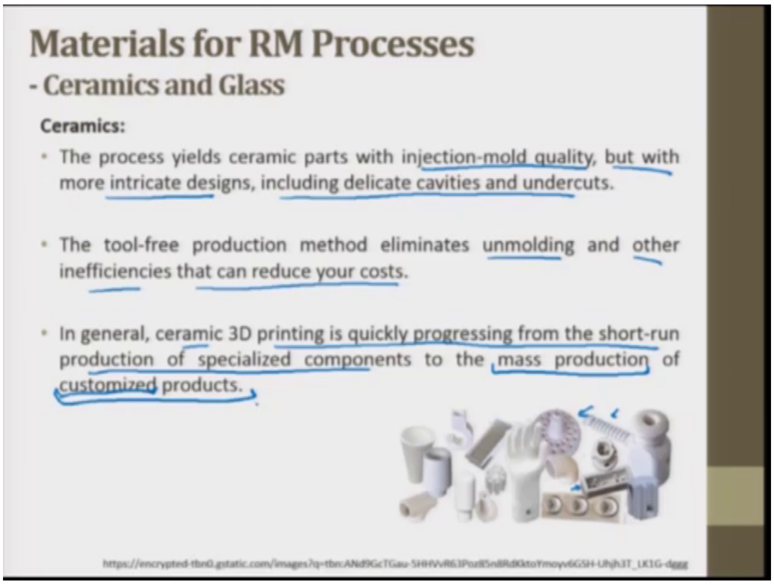

The process yields ceramic parts with injection mold quality, but with more intricate designs, including delicate cavities an undercut you can see the intricacy of these parts these are all ceramic parts; these are all ceramic parts, the intricacy of these parts those are produced using ceramics and this is produced using additive manufacturing. Tool free production method eliminates unmolding and other inefficiencies that can reduce your cost again.

In general, ceramic 3D printing is quickly progressing from the short run production of specialist components to the mass production of customized products because ceramic production is usually happened using molds and the manual kind of potters used to develop parts using ceramics. Now additive manufacturing machines are able to produce the parts in a large number, so customized parts and mass production is possible in ceramics now as well.

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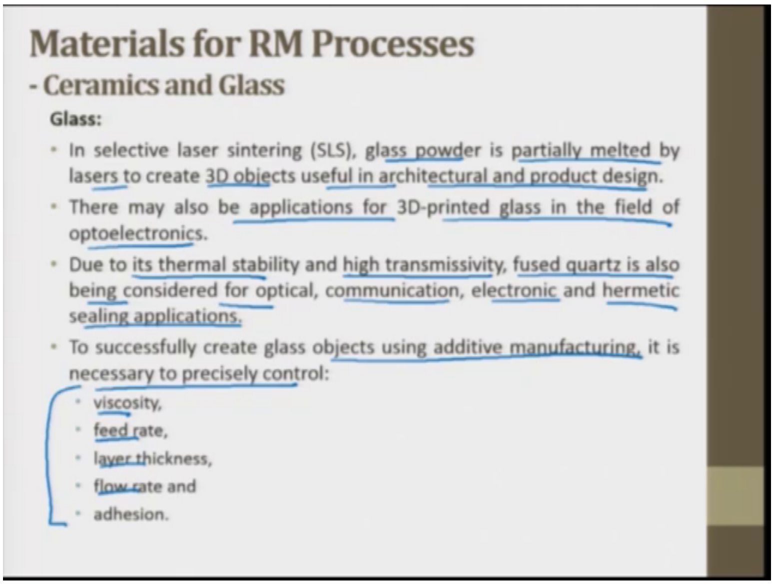

Next is glass; glass is another material in selective laser sintering, glass powder is partially melted by lasers to create 3D object useful in architectural and product design. There may also be applications for 3D printed glass in the field of optoelectronics. Due to it's thermal stability and height transmissivity fused quartz is also being considered for optical, communication, electronic and hermetic sealing applications.

To successfully create glass objects using additive manufacturing, it is necessary to precisely control these parameters viscosity, feed rate, layer thickness, flow rate and adhesion. The 3D printed optically transparent glass requires high temperature processing of glass powder into fully annealed product. So, optical properties are important in the products those are produced using rapid manufacturing, so, glass plays as vital candidate for that.

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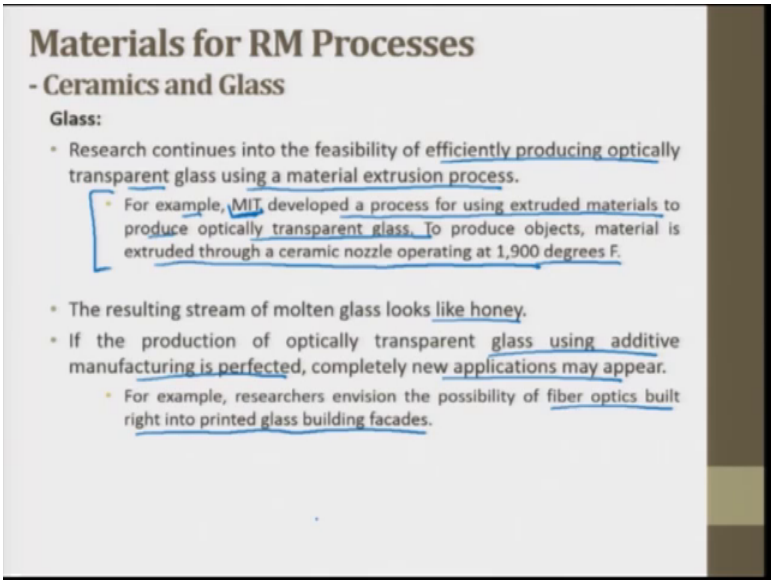

Research continuous into the feasibility of efficiently producing optically transparent glass using a material extrusion process. For example, MIT developed a process for using extruded materials to produce optical transparent glass. To produce objects material is extruded through a ceramic nozzle operating at 1,900 Fahrenheit. So, this is one of the research that is carried out in MIT institute.

The resulting stream of molten glass looks like honey. If the production of optically transparent glass using additive manufacturing is perfected, completely new applications may appear. For example, researchers envision the possibility of fiber optics built right into the printed glass building facades. So, this is the application of the glass. So, these are the materials in general materials which are used in additive manufacturing other than this there are bio materials which are being used.

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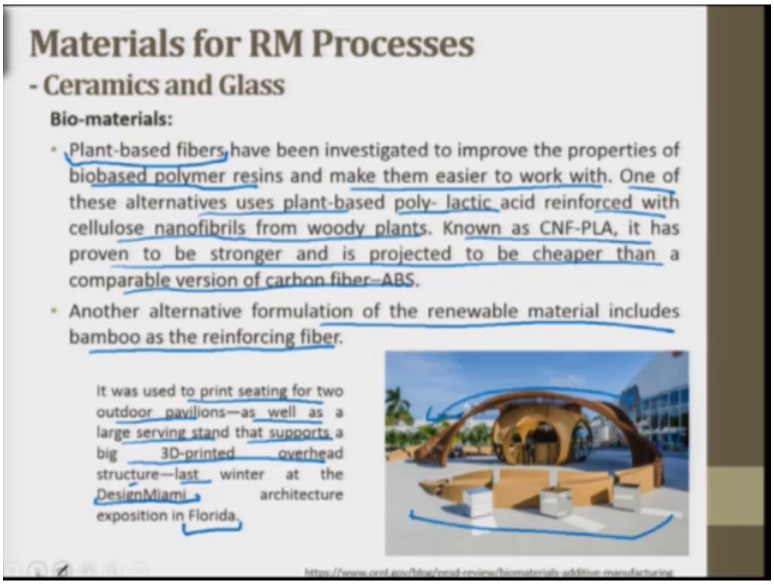

Bio materials, plant based bio fibers have been investigation to improve the properties of bio based polymer resins and make them easier to work with. One of these alternatives use plant based poly lactic acid reinforced with cellulose nanofibrils from woody plants known as CNF PLA. It has proven to be stronger and is projected to be the cheaper than a comparable version of carbon fiber ABS material.

So, plant based fiber are being used, the certain materials which are being developed even in the filament that is PLA filament or the ABS filament those are being used in 3D printing people have developed the filaments or the spools of filaments which have some biodegradable material in it. For instance, the carvings of wood and the wood powder and certain materials which helps us to produce some if not complete some part as biodegradable part, so those things are there.

Another alternative formulations of the renewable material includes bamboo as the reinforcement fiber, this complete seating outdoor pavilion is constructed using additive manufacturing process using bamboo as the material. So, it was used to print seating of two outdoor pavilions as well as a large serving stand that supports a big 3D printed overhead structure, this structure they talk talking about.

So, this is the reference from this is taken, these are bio materials some example of biomaterials are there are still many materials which are still coming and which are available in the market. So, these were some of the common materials which have been used in additive manufacturing or rapid manufacturing processes, let us meet in the next lecture.

Thank you.