Mathematical Modeling of Manufacturing Processes
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Lecture - 29
Powder Metallurgy

Hello everybody. Now I will start the second part of the casting and powder metallurgy technology. So the second part powder metallurgy will be covered in this module.

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And powder metallurgy if you see that this casting and powder metallurgy module. Here casting technology, we have already discussed. Now in this module we will try to discuss the principle of the powder metallurgy and what is the modeling approach in powder metallurgy product.

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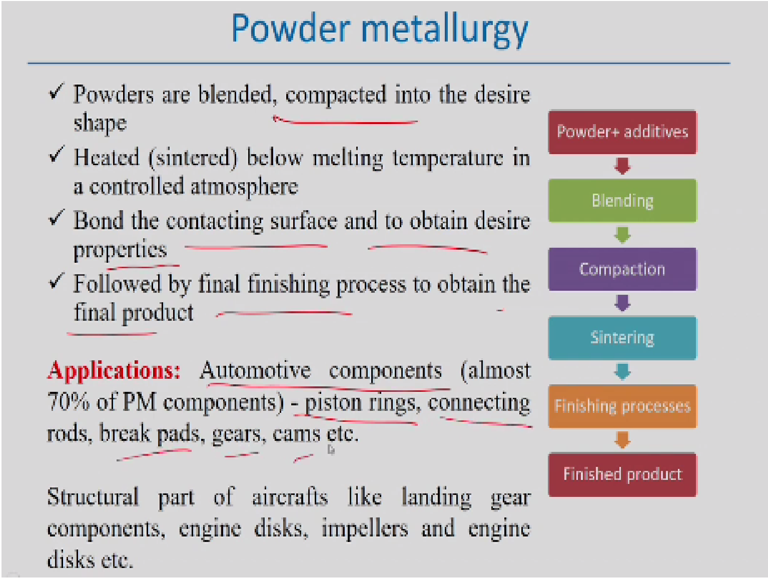

So powder metallurgy basically we understand from the terminology powder metallurgy that we made the compact product by using in the form of the powders. So the steps involved in powder metallurgy techniques if you look into this figure first preparation of the powders, making of the powders according to some desire size, shape and then we do some additives mixing or blending the powder along with the additives.

And then after blending there is a compact that means we need to apply some amount of the compact force, compaction is required. Once they are densely compact then we allow some heating to the substrate material and that steps is known as the sintering process. So one sintering done and then intimate contact between the powder particles normally happens and that is after sintering process the making the product then we do the finishing operations.

So that of course after sintering the product desire, shape depends on the die and the punch we are using for this things, but till we need some sort of surface finishing is also required. So after finishing then we get the final product using the powder metallurgy technique. So of course if you see and if you compare this technology as compared to the other conventional manufacturing processes probably in this case the loss of material is very less and maybe the energy consumption is comparable as compared to the other conventional manufacturing techniques.

And of course the shape complicated shape, desire shape it depends on what way we can design the shape of the product or shape of the mold basically shape of the die in this case of course mold is related to casting process. Now if you look into this steps first there is a powders are blended the water is blended and then compacted into the desire shape and that desire shape is predefined then heating the compacted product.

Heating means it is basically sintering, but remember sintering means the temperature remains below the melting point temperature near about and then sintering normally happens in a control atmosphere such that we can control the quality of the product. Then bond the contacting surface, the surface which are in powder particle which are in contact they can obtain and that surface are in contact and then obtain the desire properties.

And of course finally the final finishing process to obtain the final product. So of course there is a huge application of the powder metallurgy product normally we can find out the automotive components almost 75% of the power metal components normally used in the automatic. So is a very small thing, piston rings, connecting rod, break pad, gears, cams etcetera.

So many components we can made in terms of powder metallurgy technique because in this technique maybe it is more convenient way as compared to the other manufacturing technology. Apart from that automatic components the structural part of the aircraft for example landing gears components, engine disks, impeller and engine disk. Actually all this components we make using the powder metallurgy technique.

We can achieve the very good desired properties and even sometimes it is possible to control the properties also using the making the final product from the material particles or powders from that particular material rather than the making the components starting from the casted part specifically when you do the solidification on casting process and after casting we need to do some kind of the finishing operation, machining operation to get the design, shape and shape.

So apart from this all different type of techniques to produce a final product with respect to that powder metallurgy product is relatively easy, less loss because machining is minimal in this cases. So loss of material is very low in this case. So the costly material probably the powder metallurgy technique is the more convenient techniques to produce the final product.

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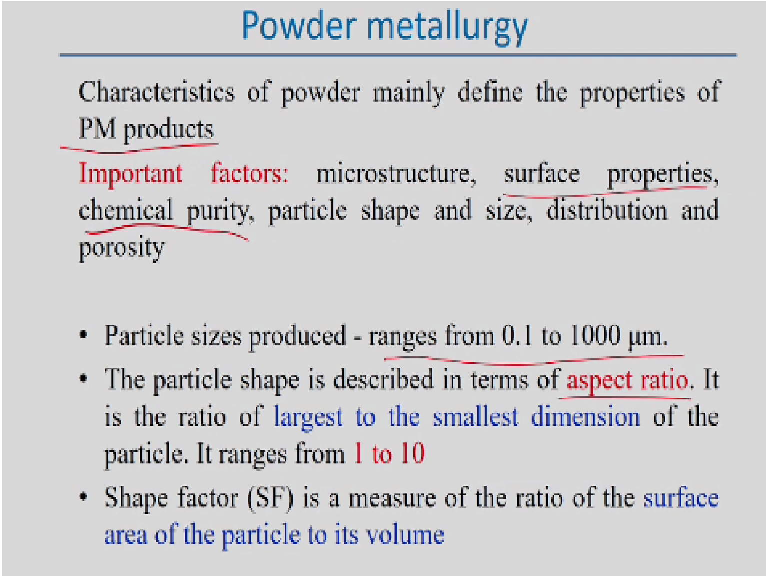

So characteristics of the powder define the properties of the PM products powder metallurgy products. So definitely what type of powders typical characteristics the microstructure shape, size, distribution, surface properties and specifically all the existence of the porosity that means when using the powder, the presence of the porosity that actually and chemical purity of the particular material and of course this properties of the powder is actually different from the same material, but from the bulk material.

So therefore this important factors need to consider when you are looking into the product of the powder metallurgy basically the surface properties. So surface properties can be influenced by adding some additive elements or some lubricant also we can add and we can modify the surface properties of the powder and of course chemical purity is almost free from any oxides and particles, shape, size.

And how it is distributed all matter to produce some kind of the powder metallurgy product. So normally particle size ranges from 01. to 100 micrometer, but particle shape is defined by the aspect ratio. So aspect ratio the maximum time the ratio mainly the maximum dimension to the minimum dimension of the particles and that can be range from 1 to 10 so based on that we can get the products, quality of the product mainly decided by is mainly influenced by the size of the powder particles.

And the shape also shape whether is a spherical shape, some irregular shape or other kind of shape all actually matter in powder metallurgy products and of course shape factor is sometimes measured which is when you are looking into the any particle formation then in that particle the ratio of the surface area to the volume of the particular particle is very significant and one is the important parameter.

Because some frictional properties or other kind of properties actually depends on the surface area and volume ratio and of course we already observed and maybe we can see when you try to look into the any analysis manufacturing component at nanoscale, so nano particle the properties are completely different as compared to the bulk material because in the nanoparticle in that cases the surface area, volume ratio is very high in this case.

So the property when you analyze the properties of the particles specifically in powder metallurgy product the surface area and volume ratio is one important parameter we need to consider that actually influence the final product.

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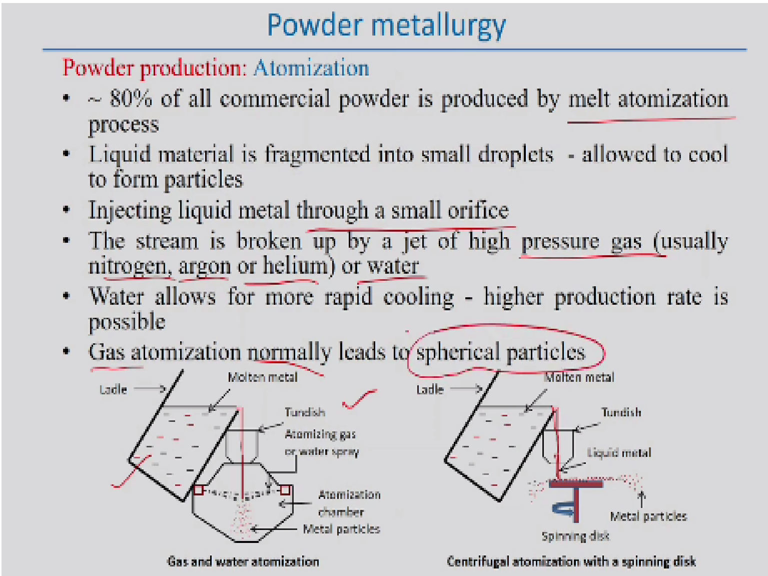

Now what are the different steps in powder metallurgy products. First is the atomization. Atomization melt, atomization we can say that means from the liquid molten metal we can produce the powder. So that is the most almost 80% of the commercially available powder is actually produced by the atomization process. So what is atomization process if we look into that and that liquid metal so directly liquid metal is fragmented to small particles, small droplets.

And of course that when creates a small droplets and finally allowed to cool to form the particles. So how it can be done so suppose this is the ladle source of the liquid molten metal and through the tundish we make a control of the liquid metal and such that we make create some kind of the jet of the liquid molten metal and on the jet directly the spring of the atomizing gas or we can spray the water also.

Such that the liquid metal actually creates the solid metal particles. So this is the one process to make from the (()) (09:43) impacting the water on some atomization gas such that the molten metal actually produce some kind of particles. Similarly, centrifugal atomization with a spinning disk that means look it metal passes here and flow of the liquid metal we can put the spinning disk and the disk is rotated with some rotational speed.

And of course when the molten metal is actually in contact in the spinning disk once it rotated through the centrifugal forces then metal particle is actually created and then comes out of this spinning disk. So using the centrifugal this is called the centrifugal atomization process and using some kind of spinning disk powders can be produced. Now let us look into the steps here.

First injecting the liquid metal through a small orifice actually the liquid metal it passes through a small orifice so that we can create kind of jet and that jet is broken by using high pressure gas or water of course the gas is normally used we can use the nitrogen gas, argon gas or helium gas maybe inert type of gas is more suitable here because there may not be any reaction with this molten metal.

And of course water can also be used directly such that atomization of from the liquid state to directly solid particles can be formed. So of course if we use the water allows more rapid cooling therefore high production rate maybe possible if we use the water, but there may be other difficulties. So if we use the water may be produce the powder particles, the quality of the powder particles may not be good enough.

But of course for high production rate water is more suitable to produce the solid particles, but if we follow the gas atomization process. So gas atomization of the nitrogen, argon and helium that type of gas if we use jet of the gas directly use that impacting on the liquid jet of the molten metal then in that cases it is more leads to more spherical particles. So more regular particles can be produced using this kind of gases.

Of course all depends the size of the particles actually depends on the what is the size of the jets and water is impacting the gas to the stream of the liquid molten metal. So all actually is a parameter to decide the typical the size of the particles, but in general in gas atomization we can expect the size of the particles are (()) (12:21) spherical.

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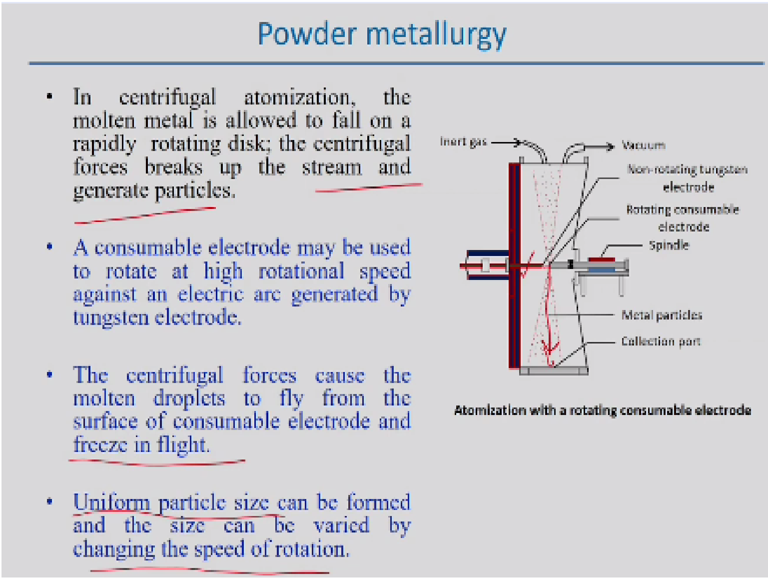

In centrifugal atomization the molten metal is actually allowed to fall on the rapidly rotating disk. So there is rotating disk and liquid molten metal actually fall on the that disk and then centrifugal force breaks the liquid metal up to the stream of the stream and that generates the particles actually. Now instead of directly looking to the molten of course there is one variation of this process use of the centrifugal forces here also.

Instead of using the liquid molten jet of the liquid molten pool we can use the consumable electrode here and that in this way maybe we can look into this picture. So inert gas under the vacuum then non rotating tungsten electrode. So there is a non rotating tungsten electrode is this one and this is a rotating consumable electrode. So tungsten is easily non consumable electrode.

And stationary electrode and we can use the other ones are rotating electrode, but that is consumable electrode. Now we can create the arc between these two and that arc is actually try to melt the consumable electrode and then through the centrifugal force this from the consumable electrode the source of the liquid metal here by the consumable electrode and then consumable electrode actually converted to the small particles.

And we collect the particles metal particles here. So this is another variation of the production of the powders solid powders or particles using the consumable electrode. So of course in this cases the centrifugal force caused the molten droplets to fly from the surface of the consumable electrode and freeze into the flight. So when it is flight from here then it is freeze basically.

So uniform particle size so this method is more suitable if you want to produce the more uniform particle size can be produced and size can be varied by changing the speed of the rotation. Therefore, the size depends on the or as a function of the rotational speed or rotational velocity so that decides the size of the solid particles. So this is another method to produce the powders normally use the powder metallurgy technique.

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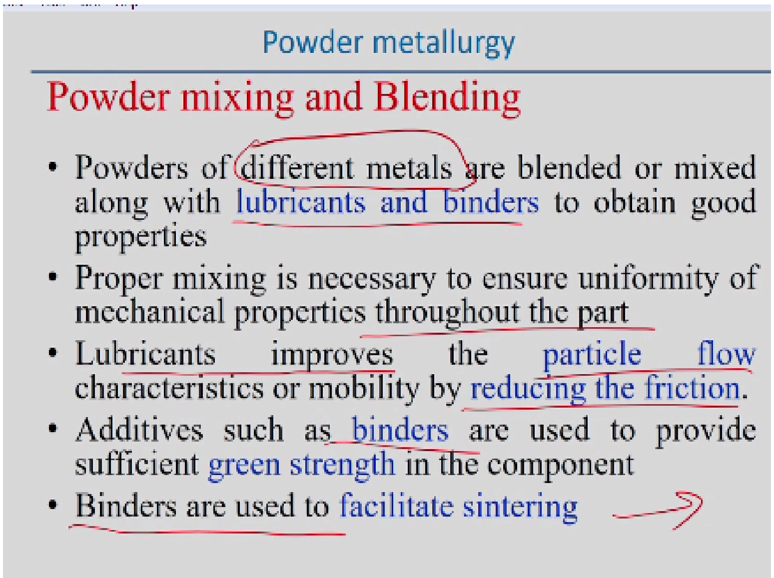

So once you produce the powders then we think about how to mixing and blending this powders. So powders of the different metals or similar kind of metals can be used are blended or mixed together and by using some lubricants and binders or additives to obtain good properties. Actually the lubricant and binders is normally mainly introduced along with the powder such that we can improve the properties of the powder metallurgy technique.

But of course this lubricant and binders takes a very small percentage of the total volumes of the particle maybe 5% to 10% we can use in the form of the lubricants and binders apart from 90% to 95% remains the solid metal powders, but one advantage of the powder metallurgy techniques so we can use the different metals also. So we can mix up the different powders, the different metallic components here or with a similar kind of the metallic powder can also both can also be used to produce the powder metallurgy product.

So proper mixing is necessary to ensure the uniformity of the mechanical properties and throughout the part. So definitely the mixing should be if you want to impart the uniform properties and of course the physical properties the uniformity so mixing should be uniform. So in that sense the mixing is very important and that localization of the properties maybe depends on the improper mixing of the particles.

And the role of the lubricant here actually we use improves the particles flow characteristics or mobility characteristics by reducing the friction. So definitely in between the particles the flow ability can be increased if we use some kind of the lubricant that is the purpose of using and additives such as binders can be used to provides the additives it impart the green strength, the strength of the component.

So normally we use in case of the casting process when you are making the (()) (16:48) there also we can use some kind of additive to bring the strength of the mold material. So here also the similar kind of role also observed in case of the powder metallurgy technique as a binder that actually impart some kind of the green strength of the component and binders there is another role the binders that actually facilitate that means improves the sintering process.

So that facilitate the sintering process during the (()) (17:18) that is the secondary role of the binding elements.

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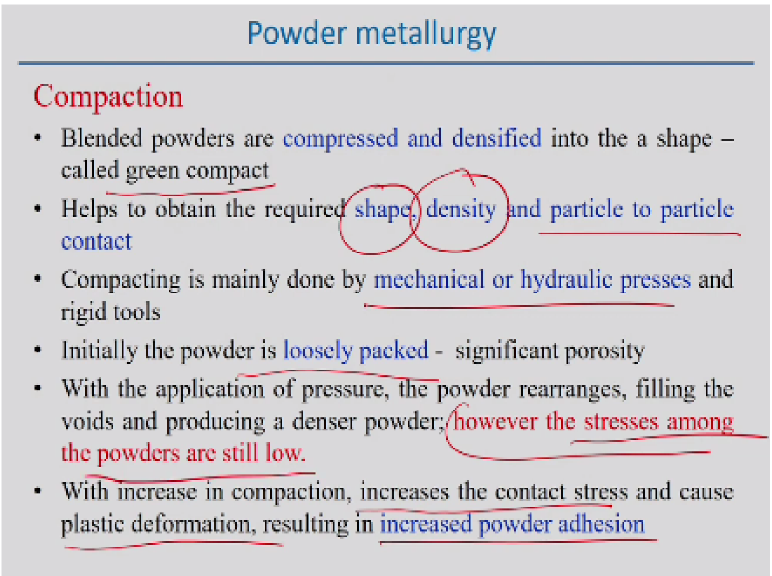

So once mixing and binding once mixing is done, mixing and blending of the powders are done then next step is the compact, compaction of the powders. So how we can do the compacting of the powders. So blended powders actually compressed and densified into the shape and that is called the green compact, but of course that is not sufficient once we make the that what way it makes we compressed the particle.

And we try to densified this things that is to produce the green compact. This is not the final step to make the product because the next step is to make the sintering, but what way we can do the compaction in powder metallurgy techniques. So it helps to desire, shape by the compaction we can get the desire shape, control the density of the component and of course there is a particle to particle contact happens during these process.

But compacting is mainly done by the mechanical or hydraulic press and of course press as well as using some kind of the rigid tool. So initially the powder is loosely packed initially the loosely packed and then once we apply the pressure then powder rearrange and definitely filling the voids and producing a denser powder, but till the stress among the powder becomes still low.

So to impart the strength bring this thing the strength of this powder particles then we need to go for the next step, but of course increase in the compaction that try to increase the contract stresses and cause the plastic deformation during the compaction process the plastic deformation and contact stresses also involve, but finally that actually increases the powder addition though that means addition between the two particles when we are trying to handle the powder components. But till the stresses becomes low even after the compaction steps.

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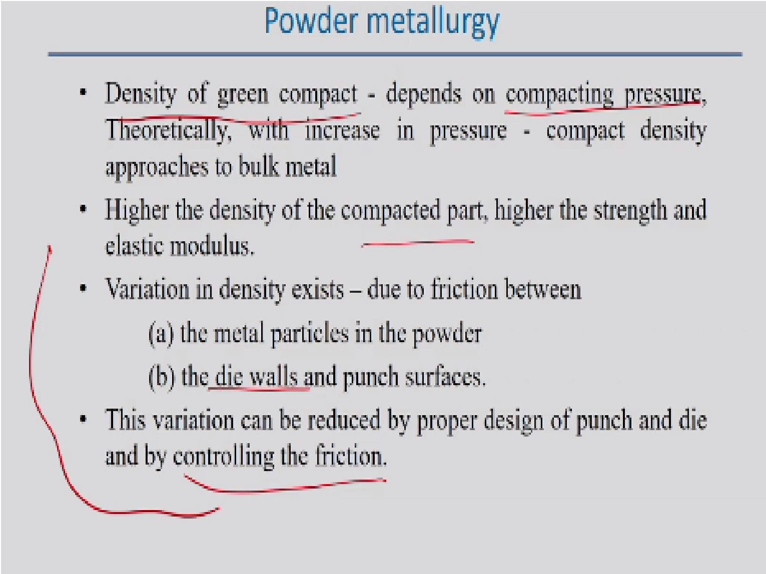

Then next step is that sintering process, but before that we can look into more on the compaction process. So of course the density of the green compact it depends on what pressure we are applying compacting pressure by the rigid tool and of course theoretically with increasing the pressure compact density approaches to the bulk metal in theoretically, but of course after compaction process it is sometimes it may not be possible to exactly achieve the density of the bulk metal.

Then higher the density of the compacted part definitely the strength and modulus will be more in this cases, but variation that there may be the possibility of the variation that is one issues in powder metallurgy product that the variation of the density may also exist. So due to friction between the metal particles powders, between the powders and of course in between the interface that means the die walls and the punch surface in that part.

There may be some density differences exist, but of course if you want to avoid the differences in the density then we need to properly design the die and punch and of course by controlling the friction between the metallic powder or in between the metallic powder and along with the boundary that means along with the interfaces. So all this parameters actually defines.

So in compaction process the most significant component here is that the to break the uniformity in the density of the components and of course till even after compaction it is not necessary that contact strength may reach the very high level and that actually impart the strength of the component. So in that cases still stress remains very low after the compaction process.

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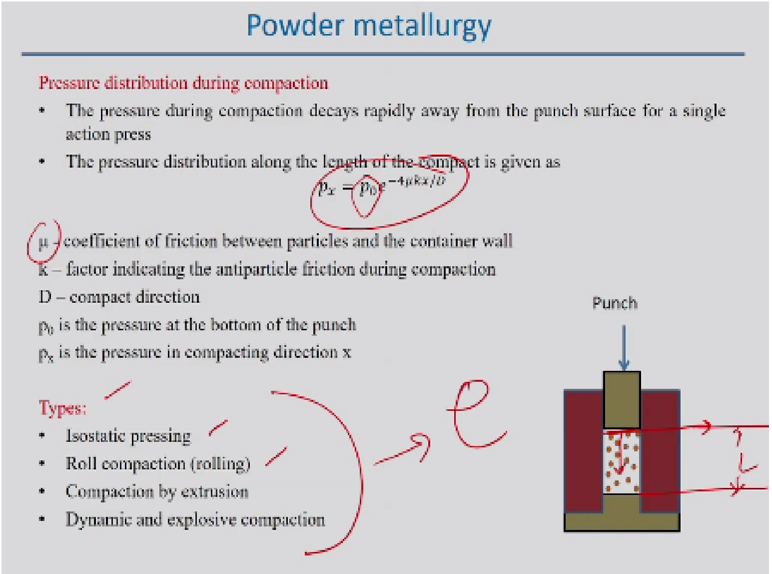

We can look into that the pressure distribution during the compaction process suppose this is the punch if you look into the this figure the powder particles are there. So definitely we can use the punch force here and such that powders can be compacted and they can rearrange among themselves we create the compacted with respect to each other of course it make some kind of voids maybe there in between.

But normally the pressure during the compaction actually rapidly away from the punch surface decays very rapidly. So and this contact surface the pressure the compacting density actually is very high compact pressure remains very high at this point of contact, but gradually decreasing, but that decreasing decays is very rapidly and normally that is represented by the hearing the negative exponential form.

So Px at any distance x the compact pressure is p0 is some constant exponentially varying we can see that mu is that exponential varying what are the different parameters the coefficient of the friction between the particles and the container wall and k is the factor indicating the antiparticle friction during the compaction and D is the compact direction basically in that compact diameter in this cases.

And P0 is the pressure at the bottom of the punch and Px is the pressure in the compacting direction. So in general this compacting pressure actually varying with respect in a exponential decaying way. So that means it is not necessary if we apply the length of the component, length of that means this length L is very high then it is quite possible that variation of the pressure from the top of bottom, good pressure variation may exist.

So therefore proper design of the punching is also necessary or sequence of the punching process. So maybe in that cases it is not necessary to punching from one direction it can be done from the other direction also. Now what are the different types of this compaction process one is the isostatic pressing the one type the roll compaction it is simply rolling, roll compaction can also be done.

And compaction by extrusion one kind of metal forming process so by extrusion also compaction can also be done and we can use the explosive compaction dynamic and explosive compaction. Normally the explosive compaction is mainly suitable and the product size is very big or area need to cover very big area in that cases maybe explosive is suitable process for the compaction.

But of course all this cases the main difficulty to bring the uniform density throughout the product that is the one difficulties.

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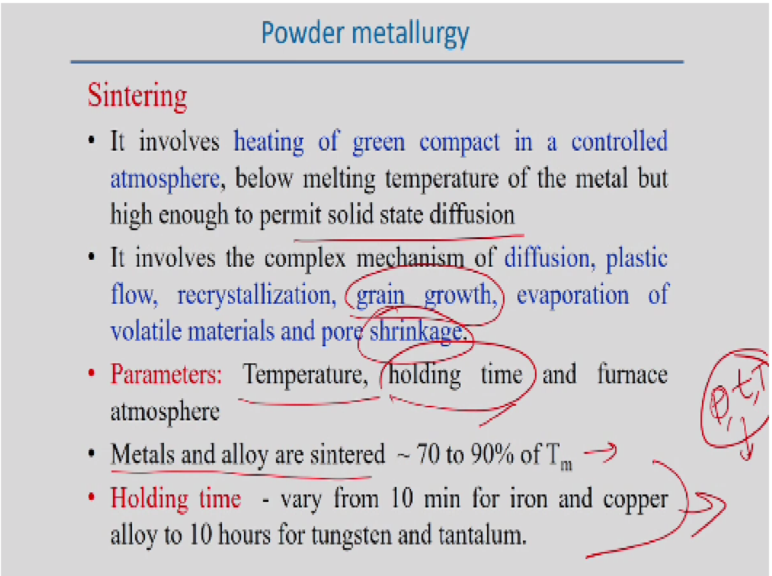

Now sintering process so once compaction done then we can go to the steps of the sintering process. So in sintering process it involves the sintering process simply the heating of the component, but heating in a controlled atmosphere and of course the temperature is less than the melting point temperature of a particular metal such that it should be high enough that temperature should be high enough that actually permit to solid state diffusion may happen during the process.

So this is the sintering process and of course in that sense the sintering process is actually different from the any melting process. So definitely the sintering process involves a very complex mechanism, diffusion happens here plastic flow during the because when you are applying the load plastic flow may happens and of course recrystallization may also happens at this temperature and with the application of the load.

Then grain growth also happens during this process and of course evaporation of the volatile materials and pore shrinkage because we use some kind of additives also here binder agent and lubricant as well we use during this process. So that can be easily evaporate at a very load at that temperature. So this may not be during the evaporation that actually creates kind of the pore.

So once the pore creates that actually that space is occupied by the powder so that we can say the shrinkage actually happens of the metallic powder to accommodate that created the space created by the volatile materials during this process. Then of course parameters is the in the sintering process is the most the important parameter is what temperature we should use here, how long holding time we can keep during this process.

And of course the furnace atmosphere means the surrounding atmosphere we are using all this important parameters to get successful sintering process and that is the I think that is almost the last step of a powder metallurgy product. So metals and alloy normally sintered around 70% to 90% of their melting point temperature and of course we see 70 % to 90%, but below melting point temperature of this material.

And holding time it is a vary depending upon the type of the materials it can vary from 10 minute for iron and copper alloy to10 hours for tungsten and tantalum. So maybe in these cases for tungsten and tantalum that takes a very high time, very long time is required to hold that means we keep the sintering temperature for a long time during this process because all this time this actually depends the time actually decides the how the diffusion mechanism actually we know the solid state diffusion normally happens here.

So for a long time and temperature that actually influence the diffusion process and for a particular material. So that is why the pressure here welding times for a certain pressure may or may not may not required also certain pressure, but time T and of course and temperature are important parameters here and of course surrounding atmosphere to protect this thing because when we raise almost 90% of the melting point temperature of a particular component powder.

Then we need to surround this metal with some kind of inert gas type of atmosphere such that the sintering process can be more successful without any defects. So what way we use the shielding gas in case of the welding process the similar purpose we use the some atmospheric to avoid some atmospheric contamination we can use some kind of the shielding gas during this process.

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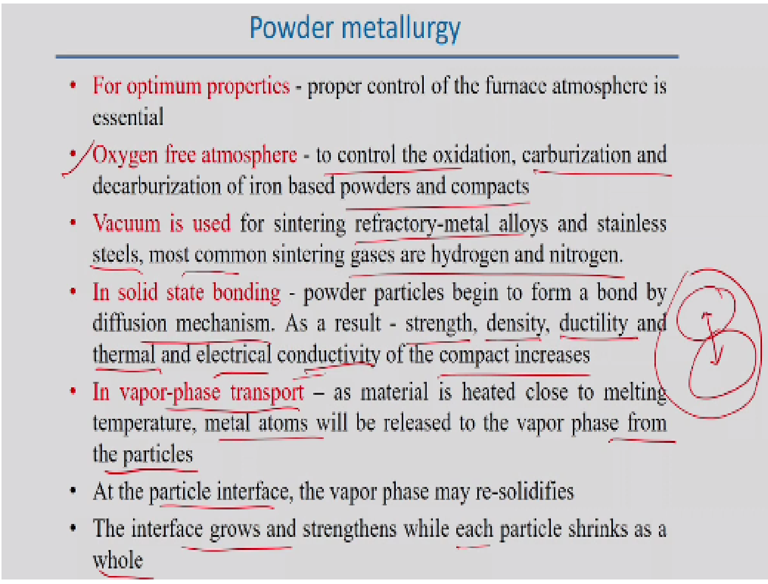

Now if we look into the powder metallurgy product so for optimum properties proper control of the furnace atmosphere is essential and of course controlling of the furnace atmosphere because it decides to optimum the powder metallurgy product then oxygen free atmosphere is mostly to control the oxidation, carburization, decarburization of the iron based powders and composites.

In this case definitely oxygen free atmosphere is required. Vacuum is used in some cases the sintering of the refractory metal alloy and stainless steel mostly because now in this cases, but apart from the vacuum other sintering gases we can use the hydrogen and nitrogen most of the cases hydrogen and nitrogen can be used as a sintering gas during this process, but during the solid state bonding powder particles in begin to form a bond by diffusion mechanism.

Definitely the powder particles are in contact and this (()) (29:37) is a certain temperature and for a sufficient time the diffusion of the atoms normally happens between this particles. So that means diffusion mechanism is responsible for solid state bonding between the particles. So results is that strength, density, ductility and the other properties, thermal properties, electrical conductivity of the compact actually increases.

So when the diffusion increases then that actually that results its impart its actually is modify the strength, density, ductility of a as a bulk component, but in vapor phase transport also happens in this cases because material is heated closed to the melting point temperature so it is possible some localized area metal atoms will be released to the vapor phase some localized area metal atoms can be released in the vapor phase from the particles that may also happen.

But at the same time at the particle interface the vapor phase may also re-solidifies this actually happens the localized distribution of the temperature. So based on that the interface finally grow and strength strengthens while each particle shrinks as a whole. So finally imparts the interface the grow and actually imparts the strength and may be some cases each particle shrinks as a whole during this powder metallurgy product.

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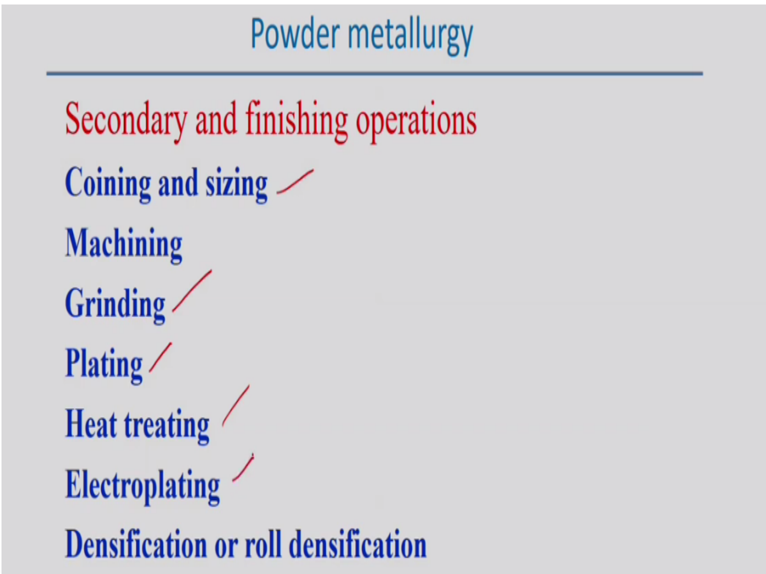

Now what are the after sintering process once the sintering process so then diffusion normally happens all the particles we can get some kind of product then finally the secondary and finishing operation may also happen of the final product, but these are the different type of the finishing operation we follow coining and sizing some machining may be required on this powder metallurgy product.

Grinding may also required, plating, heat treating, heat treatment maybe there and some electroplating may be there and of course densification and the roll densification maybe sometimes densification of the roll densification may also be needed as a finishing operation. So apart from that machining, grinding, plating some densification or roll densification may also be required as a finishing operation in the powder metallurgy product.

So this is in general the powder metallurgy product and this are the very simple 4 basic steps are involved in powder metallurgy product, but it had a lot of advantages as compared to other conventional processes because first advantage is that so the similar different types of the metals can be metallic powder can be combined and we can produce some kind of alloy that product.

And second thing is that the powder metallurgy product is not involved the melting point so the mechanism here the solid state diffusion normally happens through the sintering process. So this properties or this thing in powder metallurgy product maybe different as compared to the bulk material which bulk material is normally produced through the solidification process. Now looking into all this basic steps the powder formation then mixing and blending then compact then sintering.

These are the 4 basic steps and finally the finishing operation which will apply the powder metallurgy product. So looking into all this steps now look into that what way we can model this powder metallurgy component.

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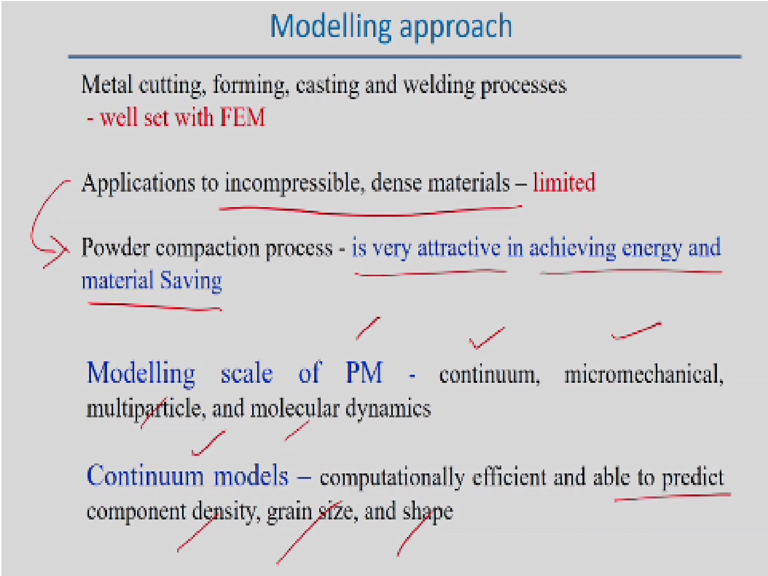

So now we look into the modeling approach. So in modeling approach we see the metal cutting, forming we have discussed the metal cutting forming and welding processes, casting processes and their modeling approach, heat transfer material flow, and of course stress analysis all these kind of modeling approach we have seen that means it is well set and we have seen in most of the cases we do some kind of the static analysis.

And using the finite element method, the modeling can be done, but of course if we look into in general the application of the incompressible flow may be in compressible of course some dense material, but of course there may be some variation of the density also in powder metallurgy product. So analysis of this kind of situation using the finite element is very limited.

So we look into that different approaches in powder metallurgy product and first is that, but in this cases the modeling approach means we understand that compaction process and maybe the sintering process these two parts that we can model, we can express the parameters, the variable output in the density variation, grain size or maybe distribution, grain formation all this kind of output we can get from this modeling approach.

But of course powder compaction process when you are compacting the powder is very attractive in achieving the energy and material. This is a very general comment the powder compaction process because in this cases it is a very energy saving process as compared to the other conventional manufacturing process, but of course most of the cases if you look into the modeling approach of the manufacturing process.

So we need to define in which scale we should do modeling. So modeling scale of the powder metallurgy process can be done even from starting from the continuum scale to micromechanical scale, multiparticle even molecular dynamics also we can use. So in this case is micro continuum, micro then multiparticle, molecular dynamics that means from starting from the continuum to microscale, grain scale basically that is grain scale and nanoscale all different scales the modeling can be done of a powder metallurgy product.

But of course most of the cases it is easier approach can be more easier using the continuum models because continuum models is computationally efficient as compared to the other components and other scale at the same time able to predict density, grain size and shape also if we follow the continuum models. Let us look into the approaches we can look into.

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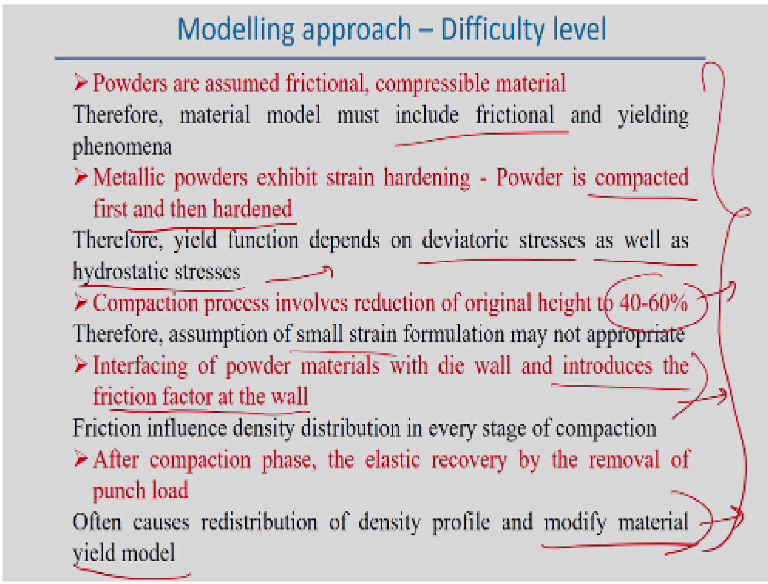

But before the approaches we can look into the in modeling of the powder metallurgy technique may be what are the difficultly levels we can look into that aspects first. So first point is that powders are assumed frictional and compressible material because we are compacting variation, so there is a powder initial volume (()) (36:47) accompany this is some kind of the voids between the powders when they are loosely packed.

So from loosely packed to the densely packed we will convert during the compaction process that we can say it is a compressible material in the sense. and of course the particle flow with respect to each other. So there must be some kind of the friction force between the two particles. So then frictional force involve as well as the compressible material involve during this process.

So therefore in this cases when you try to do the material model definitely it must include the frictional effect and as well as the yielding phenomena because it is a compressible material. Second point is that material powder so define material powder like bulk material many application some kind of the load it exhibits the strain hardening behavior. Similarly, metallic powder also exhibits some kind of the strain hardening behavior.

Because powder is compacted first and then hardened. So initially we compact it and then it becomes harder strain hardening mechanism becomes active with the application of the load. So compacted and hardening so with this sequence therefore when you define the yield function that depends on the deviatoric stress component because when it is compacted but at the same time it depends as well as not only the deviatoric stress.

At the same time, it is the yield function also depends on the hydrostatic stress components. So normally when we do the elastoplastic analysis or mechanical behavior of the bulk material. When you test we analyze this thing we will develop the plasticity model there we look that is strain hardening behavior also there, but yielding phenomena actually happens independent of the hydrostatic stress component.

So yielding phenomena actually only depends on the deviatoric stress components, but in powder metallurgy product it is a different it depends the yielding actually it depends on both deviatoric stress components as well as the hydrostatic stresses component. So therefore to define the yielding function is little bit complicated in this process. Then compaction process also involves reduction of the original height around 40% to 60% in general average is a 50%.

So during this process there involves the loosely packed powder particles during the compaction processes. So it reduce within the container it reduce the height around 40% to 50% to 60%. So this involve the strain generation. So therefore assumptions of the small strain formulation when you look into the plasticity theory by application of the or when you try to define the yield function by application of the small strength theory is not applicable in this cases.

Because here the strain is very high almost 40% to 60% length actually reduce during the compaction process. Therefore, small strain formulation may not be applicable during this process. Then next point if you look into that interfacing of the powder materials if we look that normally interface of the powder material with the die wall and normally die wall and of course when there is a interfacing of the die wall definitely it introduces some kind of the friction factor at the wall.

So then we need to incorporate the friction factor and the friction factor in friction influences actually the distribution of the in and every stage of compaction. So the initial stress to the final stress of the compaction at every point the interaction between the die wall and the powder component there is friction is introduced and friction is basically influenced friction influences the density distribution.

Therefore, we need to incorporate the effect of the frictional force when you try to look the modeling approach so that brings the complexity in the modeling approach. So definitely after compaction phase so once compaction over since the powder normally the elastoplastic behavior it exhibit so therefore it must some kind of the elastic recovery will be there so by the removal of the punch load.

So once we remove the punch load some elastic recovery must be there. So therefore once the elastic recovery is there then for it redistribution of the particles may happens, redistribution of the density profile. So modify the density profile and of course when there is a modify of the density profile it finally modify the material yield model. So therefore at the last stage if you want to incorporate the elastic recovery we need to incorporate the elastic recovery that actually impact on the redistribution of the density profile.

And finally basically impact on the material yield model. So that is also one complicated situation normally happens in this modeling approach in the case of powder metallurgy product. So these are the issues when you try to look into the modeling component. Of course in this cases we are not talking about the during the compaction process so of course there is no component of the temperature here.

So all this is the deformation behavior during the compaction process. These are all the difficulties in the modeling approach during the powder metallurgy product.

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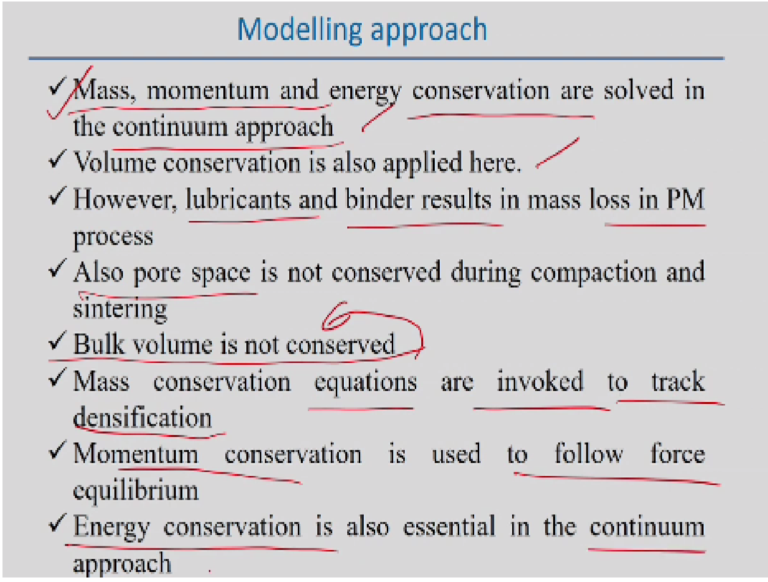

So what are the way to do in the continuum scale if we try to look into the modeling approach. So definitely that looks the conservation of the mass, momentum and energy and that is (()) (42:24) to solve the governing equation in the continuum approach. So this is the first step definitely we look into all this equations, but volume conservation is also important and that also applied here

So that also need to solve we need to consider the volume conservation during the modeling approach, but you use the lubricant and binder results but during the process powder metallurgy process maybe you can the sintering process there will be loss of this binder results lubricant. So to capture loss of the mass so from the solution domain there is a loss of the mass.

So we need to incorporate the loss of the mass during this process and that also that is we have to be careful when you try to look into the model of the powder metallurgy product of course also pore spaces is not conserved the spaces is not conserved during the compaction and sintering process. So once the pore spaces changes actually during the compaction process and definitely it changes during the sintering process.

So that space is not conserved that means volume is not also conserved during this process. So here also we have to look that the volume conservation issues during this process so that definitely bulk volume is not conserved during the powder metallurgy product. So definitely that is the one issue and which is normally different from what is other welding process and other process there we assume the total volume, the solution domains remains the same.

Volume of the domain remains the same based on that we do some kind of the distribution of the distortion all this things that means distortion behavior we analyze this thing, but here is not the case. Here there is a loss of the pores and there is a change of the volume during this process. Of course mass conservation also equations are invoked to track the densification. So mass conservation equation because in this cases during the compaction process there is a distribution of the density.

And there maybe localization change of the density may also happen so that definitely density and volume is relevant to the mass say for mass conservation is actually we need to look into the mass conservation during this processes of course force equilibrium we need to look into the momentum conservation when we try to do the modeling, model of this process and finally the energy conservation is also another essential component in the continuum approach.

So when you do some kind of the modeling mass, momentum and energy conservation are the main issue, but along with that mass momentum, the energy conservation we need to find a suitable governing equation need to solve getting the distribution all this things apart from that the energy conservation is also necessary during this modeling approach of course continuum scale modeling approach.

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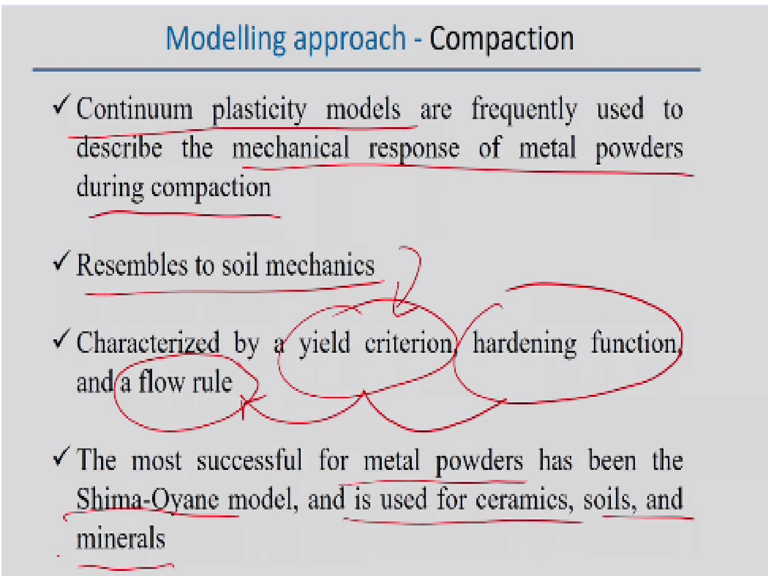

So apart from this if you look into the compaction modeling approach another way the compaction process if we look into the deformation behavior during the compaction process we normally accept the continuum plasticity models mostly used continuum plasticity models to describe the mechanical responses of the metal powders during the compaction process. So deformation behavior of the or mechanical response of the metallic powder.

Here we need to consider the some sort of plasticity model to analyze the mechanical response of this thing. So of course actually the compaction process is powder metallurgy which resembles the soil mechanics problem. So this idea of this modeling from the compaction process may also comes from the what way we model the soil mechanics problem.

But of course in general we adopt the plasticity model therefore that is must characterized by the yield criterion we need to decide the yield criteria and it follows some hardening behavior. So therefore hardening function need to define and of course along with the hardening function some sort of the flow rule during the plastic deformation process, some flow rule should be adopted.

So any plasticity model these are the three yield criteria hardening model as well as the flow rule need to adopt to make a plasticity model of the compaction process, but in general the most successful model for metal powders model has been the Shima Oyane model and is used for the ceramics, soil and minerals. So apart from the ceramics, soils and minerals for metallic powder also this model can also be used during the compaction process of the powder metallurgy product.

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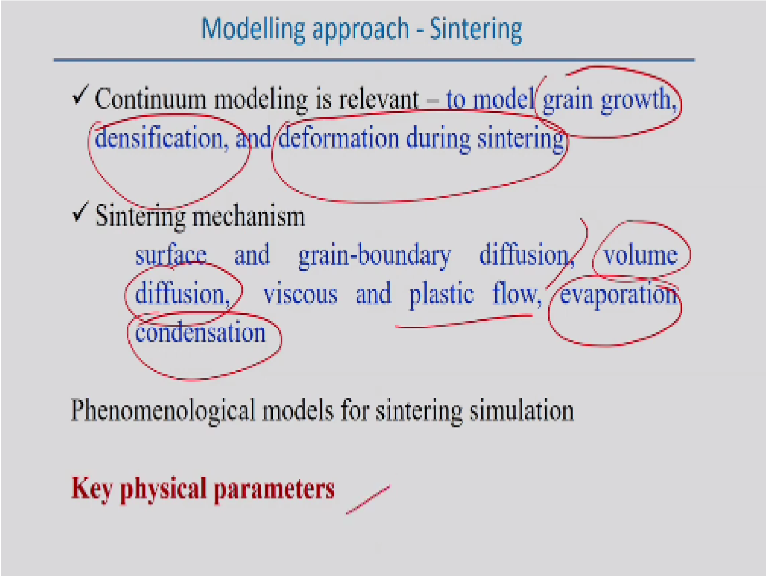

Now once compacting process is done then sintering process during this cases of course in the sintering process it is more relevant to consider the look into the grain growth, modeling of the grain growth densification normally happens because you predict the density of the product and the of course the deformation behavior during the sintering all this three are important aspect, physical aspects it is possible to model during the sintering process.

But if we look into this modeling process for the grain growth, densification and of course deformation behavior during the sintering process, but we look into the mechanism of the sintering process. If we look very carefully this powder metallurgy products since we are telling it is a powder metallurgy products. So metallurgy issues is that surface and grain boundary diffusion.

How surface and grain boundary diffusion happens and in particular temperature in particular atmosphere how volume diffusion also happens, volume diffusion means all particles the diffusion with respect to each other and create on the bulk volume. So therefore volume diffusion happens from the particles and then flow of the particles that flow of the particles we assume the viscous medium or viscous flow or we can assume the plastic flow also.

Both can also be done so by assuming the viscous flow by assuming the plastic flow so that we can analyze the deformation behavior during the sintering process and of course apart from that the evaporation, condensation, evaporation and condensation may also locally happen during this process and that we need to incorporate if we look into the good modeling approach of the sintering process.

So of course if we look into all this mechanism it is a very complicated situation to model the sintering process, bur of course if we look into phenomenological modeling approach for sintering process what are the different physical parameters we need to consider.

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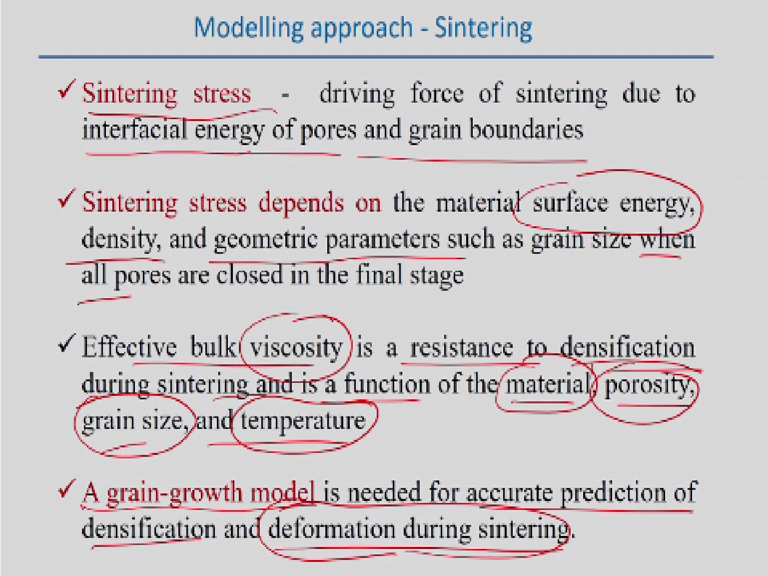

First is the sintering stress because we are looking into the stress because when deformation behavior we are looking into that, that deformation behavior if we analyze from there we can create the sintering stress also that stress the driving forces of the sintering due to the interfacial energy of pores and the grain boundaries that actually creates the sintering stress. The sintering stress will actually creates the interfacial energy and the grain boundaries of course and this sintering stress depends on the material surface energy.

Surface energy is a factor what is the density is another factor and the geometric parameters such as grain size when all the pores are closed in the final stage at the final force that grain size is also important parameters and that decides the sintering stress during the sintering process and of course either we can look into the bulk viscosity or plasticity model. So effective bulk viscosity we can assume it is a resistance to the densification during the sintering process.

Therefore, we need to define the viscosity and different viscous flow model, material model we need to consider assuming the particle flow as a viscous flow or viscoplastic flow. So that in that case is different, material models need to adopt for that and of course this (()) (50:54) is a function of the material, porosity, grain size and temperature. So therefore this viscous flow can also be used represents as a function of the material, what type of material model.

What type of the material porosity or we say the properties of the material and temperature all this can be a function and we can develop some kind of the viscosity model here then we can analyze the flow behavior also and of course and this we can estimate the sintering stress as well also. Of course a grain growth model is needed to need the accurate prediction of the densification and the deformation during the sintering.

So we need to consider the grain growth because it is a thermally activated process because temperature is applying there so some maybe some sort of grain growth may be there then in that cases we need to adopt the grain growth to accurately predict the densification basically what way the densification happens during the sintering process that we are able to predict and of course deformation behavior also able to predict during the sintering process.

So all this sintering process in grain scale model basically is more important and this metallurgical aspect is more important here as compared to the other thermomechanical or maybe only thermal aspect is less significant here. So therefore in powder metallurgy product the modeling approach is actually different as compared to the other conventional processes because most of the other conventional processes what we do.

For example, in welding process or casting process the flow of the material we assume the viscous flow, but we predict the velocity field, but in this powder metallurgy product the metallurgical behavior during the sintering process is more important and all the variables relevant to the metallurgical that mechanism that means surface energy, grain growth all this matters and based on that we can define.

We can decide some kind of the model to predict the powder metallurgy product during the sintering process. So this is all about of the powder metallurgy. So far we discuss the basic steps of the powder metallurgy and then what maybe the modeling approach in powder metallurgy product. So thank you very much for your kind attention.