Metal Additive Manufacturing

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Lecture 26

Additive Manufacturing of Metal Matrix Composites (Part 1 of 4)

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Welcome to the course on Metal Additive Manufacturing. In this lecture, we will predominantly focus on how to prepare metal matrix composite, which a lot of researchers are looking forward, making metal matrix composite through additive manufacturing route. The normal route is you do powder metallurgy, and then you mix up whatever ingredients you want depending upon your requirements. And then, they do sintering cycle to get the required output or they use a casting route to get the output.

But here in metal additive manufacturing, what we do is we try to mix it and then we try to use laser to hit at this spot. Now, what is a difficult problem? First is you have to simulate the process to do process optimization. So, when you have to do process optimization, there are a lot of parameters, which is still indecisive or the literature is not available. So, this becomes a great challenge.

Today, metal matrix composite through additive manufacturing is predominantly made by get and go. So, that means to say people do a lot of experiments, they try to get the local optima and then they report it and go. So, we will try to understand, how to make metal matrix composite through metal additive manufacturing.

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So, the content of this lecture is going to be conventional manufacturing techniques for metal matrix composite. This will try to give you a small insight what are all the different ways they do it. Next is additive manufacturing technique of metal matrix composite. What are the challenges and opportunity? Metal matrix composite preparation is also a challenge.

Today, what we get in the market is predominantly alloy powders. When we wanted to make metal matrix out of it, there are two ways of doing it. One while doing the process in situ, it tries to reinforce or you try to mix with a ceramic material, prepare the alloy and then use it. So, preparation for composite materials is a big challenge.

So, through mechanical mixing which is predominantly used, we will focus that, then we will try to see as usual four different types of materials. One is ferrous based, titanium based, aluminum based, nickel based and at the last we will see the factors affecting composite properties.

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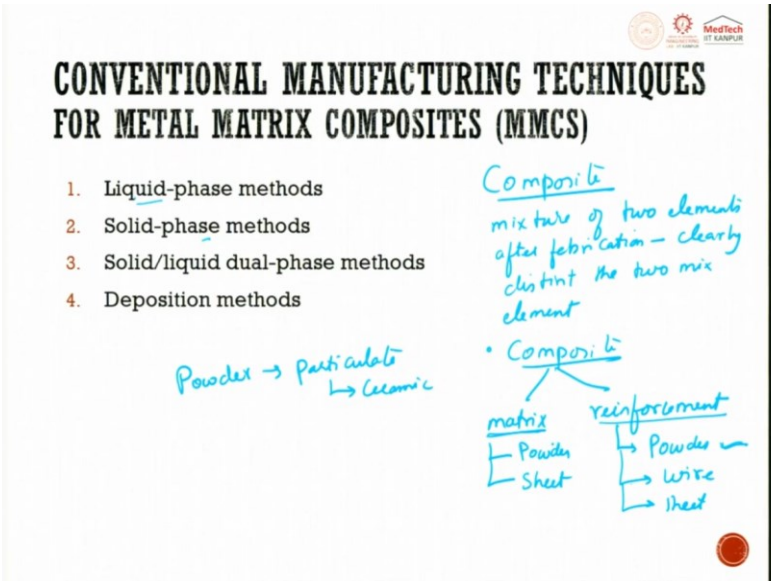

When we talk about conventional manufacturing techniques for metal matrix composite, it can be through liquid phase method, solid phase method or it can be a combination of solid liquid phase method, the last thing can be deposition. So, these are the four predominant techniques, the process names can be there, but the basics of the process falls in this four only.

So, liquid phase method, solid phase method. So, liquid phase the name itself says liquid so, one of it becomes liquid, the other one is solid so, it flows around and makes it or you try to add two powders it tries to react during the process and it tries to make one reinforcement and one matrix.

The next one is all are in solid, you do a sintering process you will try to get the output, the third one is a combination of these two, last one is deposition. So, before we understand all this process, let us try to look what is a composite material? A composite material is a mixture of two elements, where in which after fabrication, we can clearly distinct the two mixed element. So that is a composite.

So, there is a difference between composite and alloy. Alloy, you will not be able to clearly distinct the mixed element, but in composite you can clearly distinct the mixed element. Now what is the difference between a mixture and a composite? In a mixture, you can distinctly find out and extract it out. You can remove it off, but in composites it gets integrated into the material. So, it is placed there, it is very hard for you to disintegrate and then remove it off. So that is the difference between alloy, composite and mixture.

In composites what is all the ingredients of composite or what are all the elements of composite, you will have a matrix then you will have a reinforcing agent. This reinforcing agent again can be a powder. It can be a wire. Wire means it do not think in terms of ordinary wire what you see here, you will try to have very thin wires of microns. They try to form a preform, and that is how we use this wire.

But predominantly in metal matrix composite, we use powder. You can also you have sheet which over a period of time when you heat it, pressurize, this disintegrates and then gets into the powder. But most commonly used one is powder. And again, when you talk about matrix, there are two types. One is called as powder-based matrix, you start with powder, the other one is sheet.

Now you have a matrix powder, you have a reinforcing powder, if you can mix these two, what comes out, is a composite material. Matrix is those material where it is more as compared to that of reinforcement. When we try to talk about the powder or particle reinforcement, the maximum percentage generally which we do is up to 20% maximum. There are exception cases they go up to 50, but predominantly it is from 10 to 12 to 15, they go up to 20.

So, 20% of the powder will be reinforced in the matrix. So now the powder whatever we are talking about, it has nothing but a particulate. So, particulate is a powder, this particulate generally will be ceramic particulate. This particulate 20% will try to get mixed to a metal powder and then you can start making the composite.

When we do this, then what happens, we will try to get into these four methods. So liquid phase method, solid phase method, solid liquid phase, dual phase method and deposition method. Deposition method is very clear. What we do is, we try to take a preform made and then we try to deposit, spray metal and then deposit, that is deposition.

When we talk about liquid, the matrix is brought to the liquid form and then it is blunt. When you try to take it as solid, it both of them are solid and then you sinter it and then get it, that is solid phase. Then solid liquid one goes to liquid phase, the other is still in the solid phase. So, they form dual face methods.

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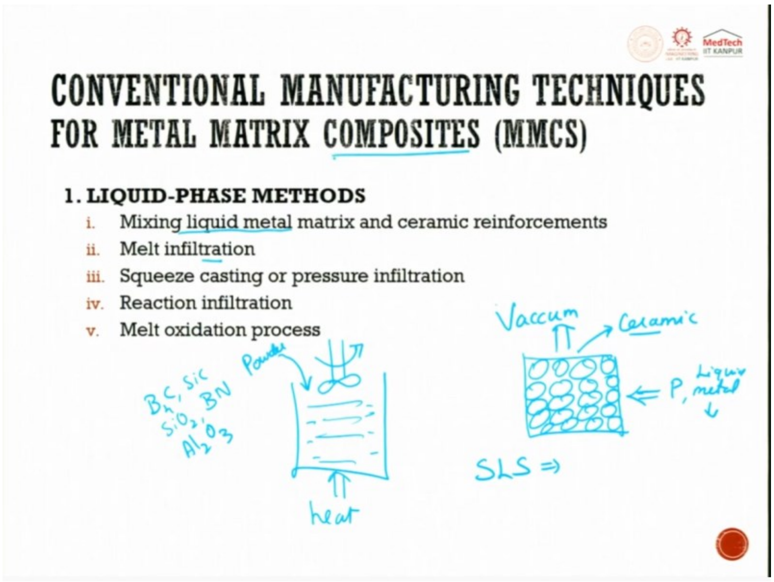

When we talk about liquid phase method, the mixing liquid metal matrix and ceramic reinforcement happens here. So, we try to mix liquid metals so liquid metals, it is not at room temperature, it happens at very high temperatures, these two are mixed or two a liquid metal matrix, whatever is there, aluminum alloy, you try to mix up a reinforcing agent. So that is what is called as liquid phase.

One of the materials is in liquid. So, it can be ferrous, it can be aluminum, it can be titanium, it can be nickel, or it can be copper so many things are there. And why are all these things made? We are trying to make exotic materials to meet out to the customer requirements. Today we demand high strength, high ductility, high conductivity, high fatigue resistance. So, all these things if you ask high, so, then it is not possible by a conventional material or a conventional alloy.

So, we look for composite materials where these combinations can happen and the composite also need not give the same performance for a wide spectrum of range. Let it be temperature or let it be strength within a particular strength or within a particular working temperature, this metal matrix composite can give a better performance.

So, the mixing liquid metal matrix and ceramic reinforcement is one way in liquid phase material to do. So, what generally we do is we take a crucible and then we put aluminum alloy or titanium alloy, we try to heat it and then once it becomes a liquid, we try to put stirrer, this stirrer will try to rotate and once this stirrer is rotating, it tries to create war types action and it also makes sure that it does not solidify.

So now what you do is you start adding powder material, it can be ceramic or it can be another metal or it can be some powder, which tries to react and then form composite material. So, this is mixing liquid metal matrix and ceramic reinforcement. What are the ceramic powders? You can have B4C, SiC, SiO_2, then you can have boron nitride, you can also have alumina. So, you can have any of those things or you can have combination of these things to meet out to the customer requirements.

Next one is melt infiltration. What is melt infiltration? I tried to create a porous structure, a porous structure. This porous structure can be made from ceramic so, you can again use additive manufacturing route to build the preform structure. So, this preform structure is here in this case is made out of ceramic. So, you can also use SLS process for doing this preform porous structure of ceramics.

So SLS is a selective laser sintering process. So, in selective laser sintering we try to use a ceramic powder as against a metal which we are discussing in this course. We try to make this and then what we do is we try to pressurize the metal, liquid metal which is a liquid metal through this porous structure. So, these are ceramic and liquid infiltrates and tries to make a composite.

The other way around, you can also try to have a vacuum which is created, a vacuum which is created and this vacuum can suck the negative pressure, can suck and the metal can flow through and it gets filled. So that is called as metal infiltration. So here I have metal infiltration. So, using pressure to deinfiltrate is called as pressure infiltration or squeeze casting.

The next one is reaction infiltration. So here we have a ceramic preform made, the metal flows through it, it starts reacting and then it forms a composite material. The last phase or method is going to be melt oxidation process. In melt oxidation process, we try to make an oxide during the process in the melt and develop a composite material. So, there are so many processes which are available today. If you want to look at composite materials.

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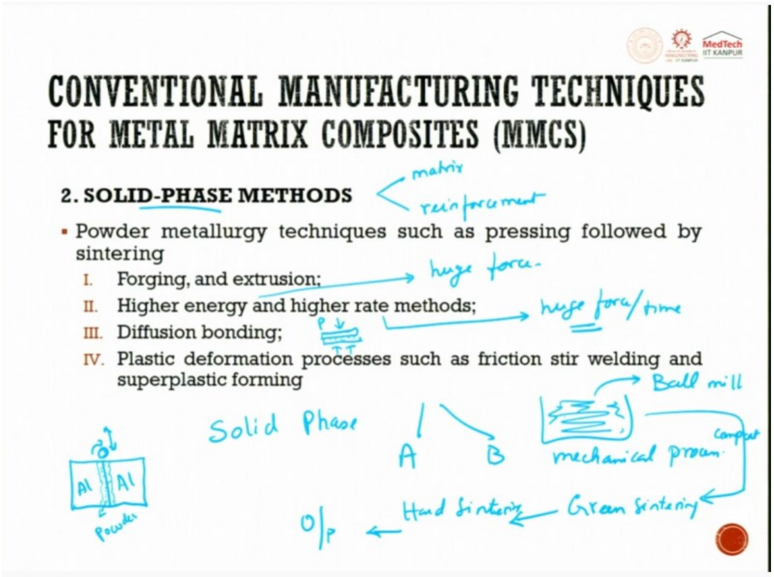

Next let us move to solid phase methods. In solid phase methods, what we have is we have a powder metallurgy technique such as pressing, followed by sintering. Solid, so that means to say both the material, matrix and the reinforcement are made out of or are powders. And they start with these two powders and then they go undergo a sintering cycle. So, the powder metallurgy technique such as pressing, followed by sintering is very, very common.

So, we try to do first so in solid phase what we do is, we try to take material A, material B, mix them in a mechanical mixture. So, this is nothing but a ball mill which is mechanical process. And now whatever we get is a powder where in which you have a blend of A and B so after mechanical blending, they undergo green sintering. So that means to say they compact it. So here in between you have compacts and process.

So, compacts and then they do green sintering. So, they remove all the ingredients whatever we used for binding, green sintering and then they do for hard sintering and finally, what they get is the output. Now after doing this green sintering or doing hard sintering they are also used for forging or extrusion methods are also used to make the part.

So here forging and extrusion, they use a lot of force in mixing of these powders before going sintering. So, extrusion is also there. High energy and higher rate methods. High energy means applying a huge force, huge force, high energy rate means here with respect to huge force with respect to time.

Say for example, it is more of hertz, frequency one by time so it is and here it is only the huge force is there so high energy is applied. This high energy can also be mechanical or it can be explosive, you can explode and create a very high pressure to mix it. So higher energy and higher rate methods both are used for making this, then diffusion bonding is also possible.

What is diffusion bonding? I will try to take a sheet of matrix then I will try to have a sheet of reinforcement. So, these two are there. Now I apply pressure and temperature so that there is a diffusion which is happening and it forms a composite material. The last one is plastic deformation process such as friction stir welding or super plastic and superplastic forming is also used.

In friction stir welding what we do is we try to take two materials. So here we can try to have friction stir is nothing but predominantly we have here block which is made out of aluminum. Now here there is a tool. This tool is rotated as well as is allowed to move forward. When it is moving forward, it tries to create a melt zone because of the friction and in this you try to disperse powder and that tries to make a reinforcement. So, that is what is called as friction stir welding.

And superplastic forming is also done in the same way. So, these are the different types of methods wherein which all falls under the category of solid phase method, which is used for making metal matrix composites. These higher energy and higher rate methods, the machine tool is expensive. Forging and extrusion it is also expensive. So, here you are trying to do a huge force, the machine tool has to be so stable to get to the output.

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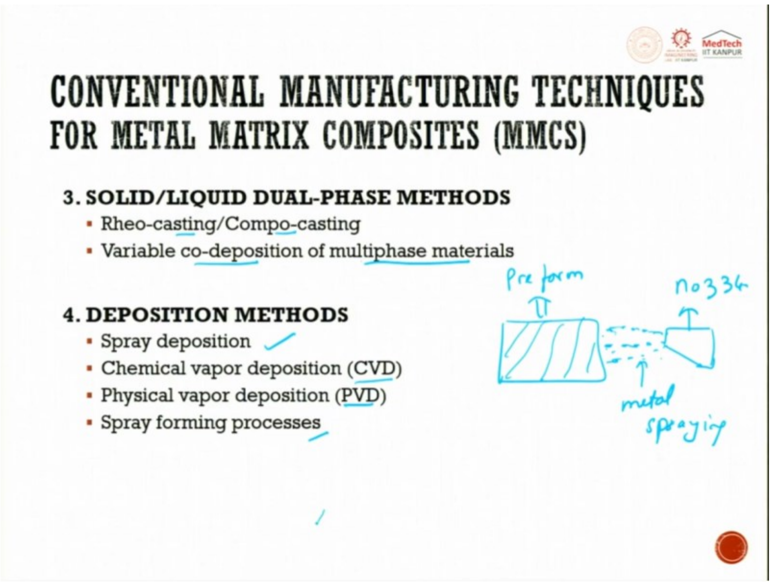

The next one is called a solid liquid dual phase casting. This is Rheo casting or combo casting, here you take it to a mushy state and then you try to disperse it, the liquid will be taken to a mushy state and you disperse it so, that is called a solid liquid dual phase method. And you also have variable co-deposition of multi-phase material. So, co-deposition is two deposition of multi-phase means, two different phases solid and liquid, you try to deposit and then try to make a composite.

When we go to the last technique of deposition technique, you can do it by spray deposition. So, you can have a preform of ceramic material and then you have a nozzle through this nozzle you try to spray metal. So, this is a nozzle, this is a preform which is made out of ceramic or some metal. So, then what you do is here there are metal which are getting sprayed, metal spraying we do it and then it gets deposited. So, spray deposition. This is what it is.

The other way around is you have a preform and then you can do a chemical vapor deposition. In chemical vapor deposition, there can be two gases used and these two gases react and then start depositing it. It will deposit molecules and that fills the preform. You get metal matrix composite.

You can also use the physical vapor deposition. Physical vapor deposition means you try to move atom by atom so, the accuracies of building is very high as far as PVD is concerned and PVD is slow process as compared to that of CVD, you can use chemical vapor deposition or physical vapor deposition, for depositing metals in ceramic matrix preform. So, the next one is spray forming process. In spray forming process what we do is we almost repeat the same and during the spraying also we try to give a form to get the output.

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So, MMCs are made from metal or alloys strengthened with diverse material to increase strength, toughness, thermal stability, wear resistance, fatigue property and application specific qualities. That is why we try to go for metal matrix composites. Additive manufacturing multi directional and freeform production makes it an attractive manufacturing approach for composites.

So, what all we saw in the four processes solid, liquid, solid liquid and spray, with these four techniques what we develop is metal matrix composites. Now, additive manufacturing is also playing a very important role in doing so. The ability to fabricate composites using additive manufacturing techniques allow for their use in industries that desire lighter, lower cost material such as automobile, aerospace and biomedical are looking forward for composite material metal matrix composite made through additive manufacturing.

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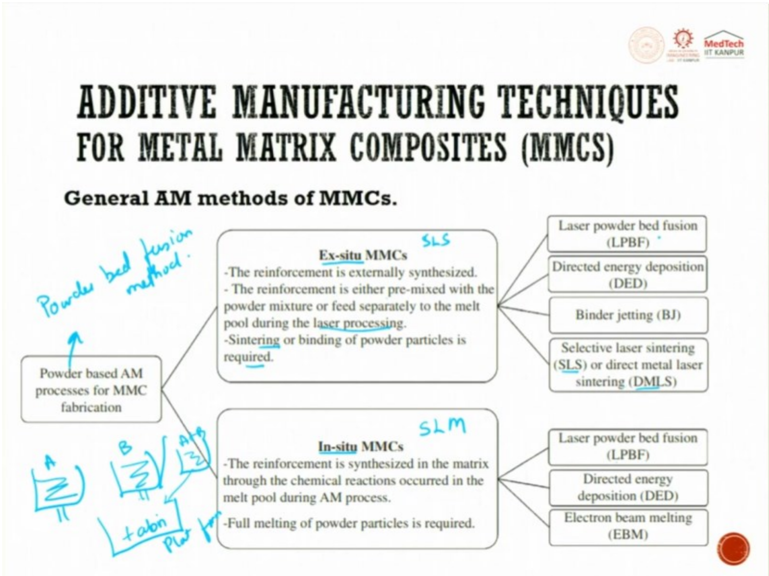

So, when we look into general additive manufacturing methods of metal matrix composite, you can start with a powder based additive manufacturing. So, what is powder based, you are talking about powder bed fusion method. So, here you have a container filled with A powder, container filled with B powder, you can try to mix on the platform where fabrication. This is a fabricating platform. So, fabricating platform, so you can have a mixture of this and this getting it done.

Or you can try to have one single, this one or one single mixed of A+ B and then directly taking to the fabrication. Powder bed is the most economical and easy to fabricate technique in terms of making metal matrix composite through additive manufacturing route. So, powder based additive manufacturing process for metal matrix composite fabrication, it can be ex situ, or it can be in situ.

Ex-situ is the reinforcement is externally synthesized. You make it outside and then you add it. The reinforcement is either pre mixed with the powder mixture or fed separately to the melt goal during the laser processing. So, it is like your DED, directed energy deposition.

Directed energy deposition, what happens? You will have a metal powder coming in one direction, it can be off axial it can be coaxial. It can come in one direction. It can come in both directions. You can have in one direction as ceramic, the other direction you can have it as metal and then you can start exactly focusing on the table and laser can be used for melting.

So, the reinforcement is either pre mixed with the powder mixture or fed separately to the melt pool during the laser processing. Sintering or binding of the powder material is required which is done either through selective laser sintering or selective laser melting process. What is in situ? The reinforcement is synthesized in the matrix through the chemical reaction occurred in the melt pool during additive manufacturing.

So here we try to mix material A and B together and we try to do a heating cycle while the heating happens, you will try to see this reinforcement getting formed. So that is what is called as in situ. During the process reinforcement getting formed in the metal matrix composite, fully melting of powder particles is required. So here it is required.

So predominantly we will use SLM here, we will use SLS here, predominantly but you can also use SLM here. So, what are all the different processes, we can use laser powder bed fusion method LPBF, we can use directed energy deposition method DED, we can use binder jetting, wherever we want to drop a jetting, so that is binder jetting, we can use selective laser sintering or direct metal laser sintering DMLS or SLS process in getting the required output.

When we talk about in situ, here also laser powder bed fusion can be used, directed energy deposition can be used, electron beam melting also can be used. So, all these things can be used and here also you can use electron beam, we can also think when laser and you can also think of using electron beam, but here predominantly electron beam is used.

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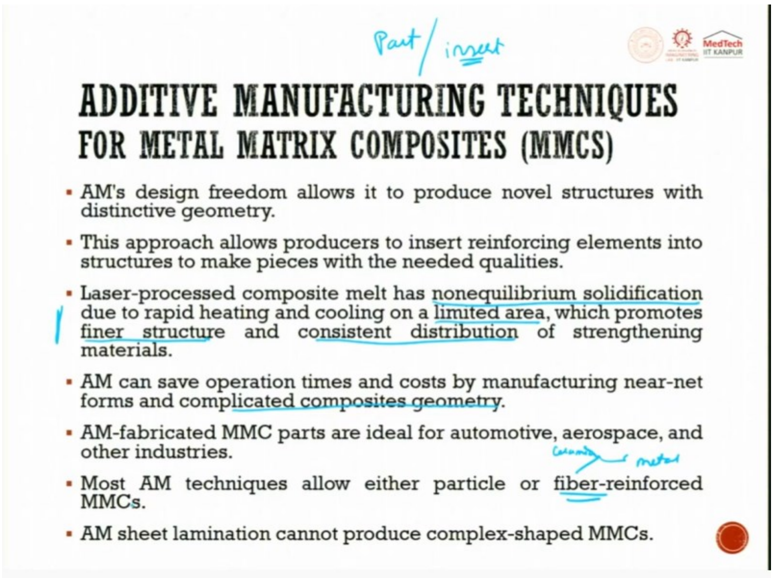

So, additive manufactures design freedom allows it to produce novel structures with distinctive geometry. This approach allows producer to insert reinforcing element into structures to make pieces with the needed qualities. Laser processed composite melt has non-equilibrium, we have already covered equilibrium and non-equilibrium solidification due to rapid heating and cooling on a limited area which promotes finer structure and consistent distribution of strengthening material.

So, this is very important. So, here we talk about melt has non-equilibrium solidification due to rapid heating and cooling on a limited area which promotes finer structure and consistent distribution of strength can be achieved. AM can save operation times and cost by manufacturing near net forming and complicated composite geometry.

So, you can make a complete part that is a composite part, through additive manufacturing or you can make an insert where metal matrix composites out of additive manufacturing, which can be used with other processes to manufacture the output. Additive Manufacturing fabricated metal matrix composite parts are ideal for automotive, aerospace and other industries.

Most AM techniques allow either particle or fiber reinforced metal matrix composite, this is what I said fiber, this fiber are two types it can be metal or it can be ceramic. Most AM techniques allow either particle or fiber reinforced metal matrix composites. AM sheet metal laminate cannot produce complex shaped metal matrix composite parts.

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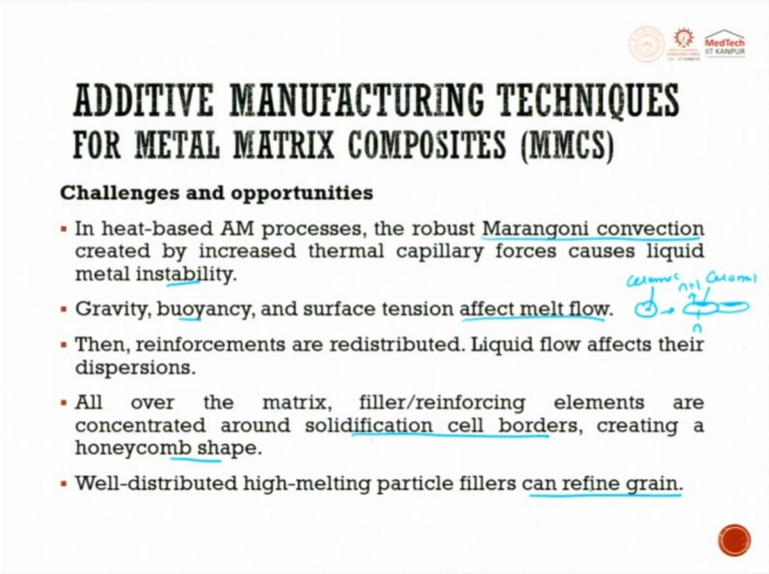

In heat based additive manufacturing processes, the robust Marangoni convection created by increased thermal capillary forces causes liquid metal instability. So, what causes instability, it is a robust Marangoni convection. It is also a good idea to go back and refer to what is Marangoni convection used in casting as well as in metal matrix composite, you please go through the literature you will understand more.

Gravity, buoyancy and surface tension affect melt flow because gravity the ceramic particles if it is very light, if it comes on top of it when the next layer is stretched it creates a lot of problems. So, gravity, buoyancy and surface tension, the liquid metal, the viscosity and the surface tension are predominant. So, gravity, buoyancy, surface tension affects melt flow.

So, and the other thing is when there is a ceramic particle there when it melts, maybe the metal will go like this and the ceramic particle comes to the top. So, this is ceramic. So, you have to be careful to make sure such things do not happen. Because if this happens in the entire layer, so in the next layer when it is getting formed, there will be a wettability problem between the ceramic and the metal.

And next thing is, there is a difference in viscosity between the previous layer and the next layer plus form. So, this is n and there is a viscosity in the n+1 layer. So, gravity, buoyancy, surface tension affects melt flow. Then, reinforcements are redistributed. So, when it floats because of buoyancy, it will get redistributed, the redistribution may also lead to agglomeration. So, you have to be careful.

So, that means to say the laser power whatever is used should not take it to such a high temperature such that the powder completely melts and it forms a liquid. This liquid when there is a slight variation in temperature, it tries to have varying viscosity that is what we are talking here. Then reinforcements are redistributed, liquid flow affects their dispersion. So, this forms the agglomeration effect.

All over the matrix filler slash reinforcement, reinforcing elements are concentrated around solidification cell boundaries. So, when there is a solidification happening, so, this material will be in between them and it will try to form a metal matrix composites, solidification cell boundaries, creating a honeycomb shape.

Well distributed high melting particle fillers can refine the grains. So, you have to decide the reinforcing agent with respect to matrix and make sure that distribution happens such that the grain refinement is also promoted while solidification.

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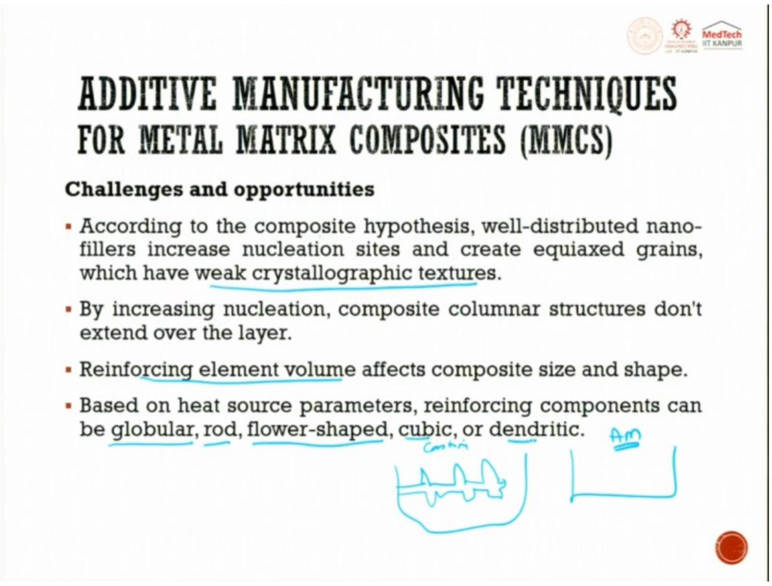

So, the challenges and opportunities according to the composite hypothesis, well distributed nano fillers, increase nucleation sites and create equiaxed grains which has weak crystallographic textures. This is a biggest challenge, which we have to make sure. So, well distributed nanofiller increase nucleation sites yes, and creates equiaxed grains that is also yes, which have weak crystallographic textures.

The next one is by increasing nucleation composites columnar structures do not extend over the layer. So, it is pretty interesting in casting and all what happens you can think of the columnar, dendritic structure like this right in casting, this is in casting. But what happens in additive manufacturing, it is a big challenge.

So, by increasing nucleation composite columnar structures, do not extend over the layers, one layer to the next layer it does not go. Reinforcing element volume affects composite size and shape, reinforcing element volume. So, that is why if you have more of ceramic, the reinforcement might give you a good strength but it will lead to improper solidification and a defective part.

So, reinforcing element volume affects composite size and shape based on heat source parameters, reinforcing components can be globular, rod, flower shaped, cubic or dendritic. So, use this also the shape is very important, the components can be globular, rod like, flower shape, cubic or dendritic. So, that they can try to form proper dispersion in the composite.

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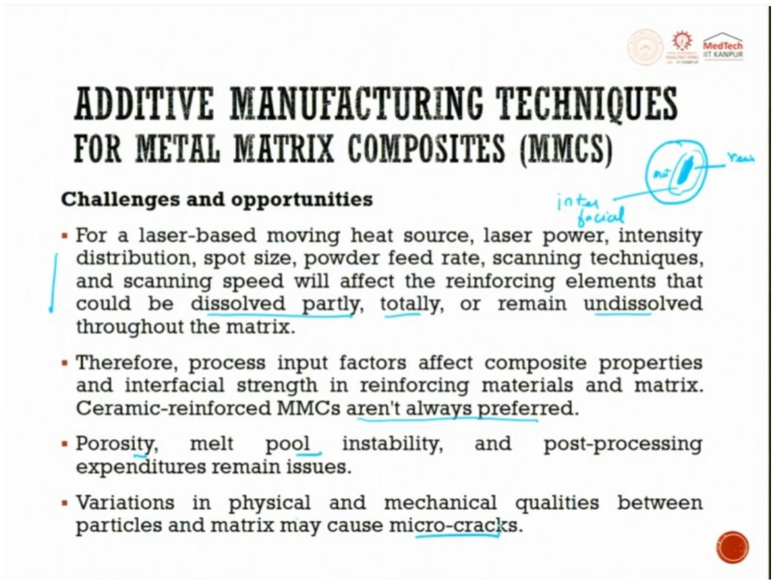

For laser based moving heat source, because the laser will be moving along the bed, moving heat source, laser power, intensity distribution, spot size, powder feed rate, scanning techniques and scanning speeds will affect the reinforcing element that could be dissolved partially, totally or remain undissolved throughout the matrix.

Laser power, intensity distribution, intensity distribution is Gaussian distribution curve by hat pattern all these things, then spot size, the diameter, powder feed rate, scanning techniques and scanning speeds all these things dictate the reinforcement whether it should be partially or totally or remain undissolved throughout the matrix.

So, reinforcing particle will be as it is, it will not change its shape, it will not change its size, it will just float and then it will try to solidify to create the composite. Therefore, process input factors affect composite properties and interfacial strength. So, if you have a composite this is the matrix, this is the reinforcement and between these two whatever you have this portion what you have is interfacial strength.

So, this is between the matrix and the reinforcement, the interfacial strength. Therefore, the process input factors affect composite properties and interfacial strength in reinforcing the material and matrix. Ceramic reinforced metal matrix composites are not always preferred, because what happens it tries to stay there or it tries to form agglomeration or it tries to come out of its space. So, it fails very fast.

And there is a difference, thermal distribution difference will be there. So, it always leads to porosity. Porosity, melt pool instability, post processing expenditures remains issue because of the porosity, melt pool instability. So, you have to do a lot of work in the post processing state. Variations in physical and mechanical qualities between the particles and matrix may cause micro cracks.

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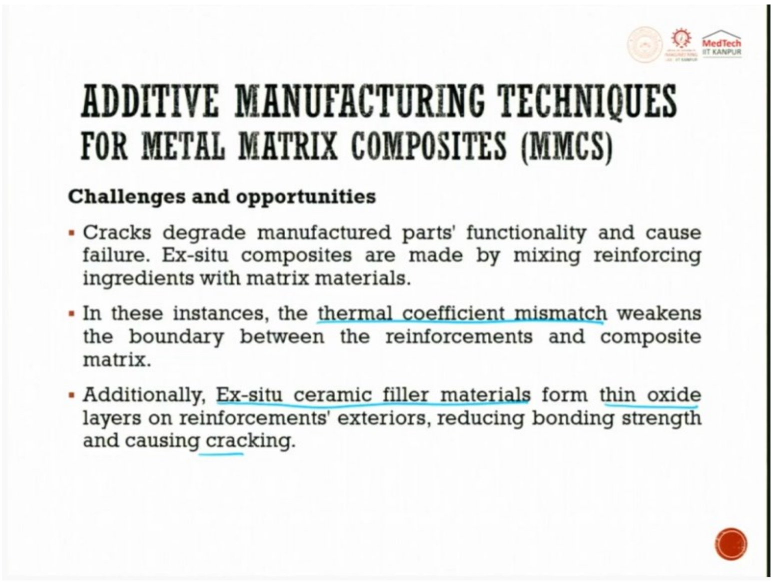

The cracks, degrade manufactured parts functionality and cost failure. Ex situ composites are made by mixing reinforcing ingredients with the matrix composite. In these instances, the thermal coefficient mismatch, this is very important. That is what I said, thermal property problems. The thermal coefficient mismatch weakens the boundary between the reinforcement and the composite matrix.

Additionally, Ex-situ ceramic filler materials form thin oxide, Ex-situ ceramic filler materials from thin oxide layer on reinforcement exterior reducing bonding strength and causing cracks. So, it is very clear when we try to use ceramic as Ex-situ there is a possibility of forming cracks defects. This has to be avoided.

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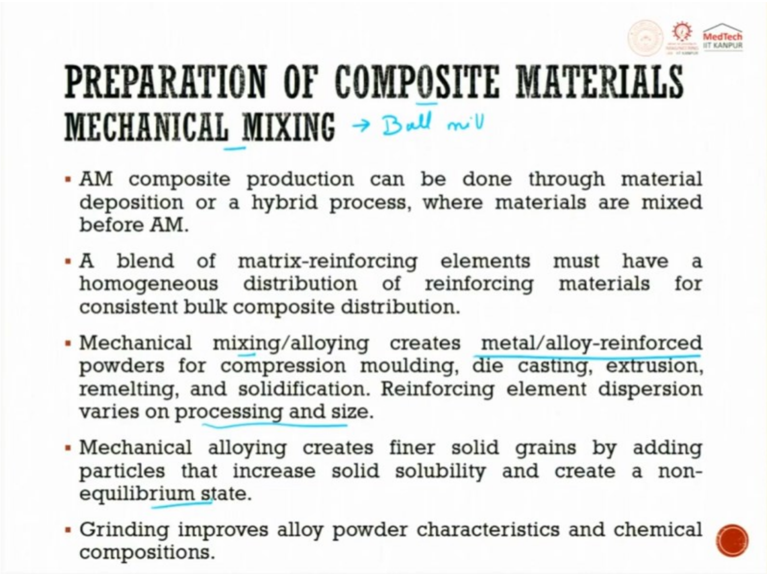

When we are discussing about preparation of composite material, we will always use mechanical mixing method. This mechanical mixing method is using a ball mill. AM composite production can be done through material deposition or a hybrid process. Whereas materials are mixed before AM. A blend of matrix reinforcing element must have a homogeneous distribution of reinforcing material for consistent bulk composite distribution.

See earlier it was very easy you pour one half of the liquid metal then stir it, add reinforcing agent, then pour 1/3 add reinforcing agent, then pour last 1/3 and then you close it and then you try to add the complete reinforcing agent. So, you will see a distribution can happen. But whereas when you start looking from the additive manufacturing route, it is every layer.

So, in this every layer means there has to be a homogeneous mixing of the reinforcement and the matrix in the powder itself. It can be inside or it can be around the metal powder depending upon the requirements. But blending of matrix reinforcing elements, ceramic materials must have a homogeneous distribution. Otherwise, what will happen? All melting will happen, buoyancy force will come, then all these fellows, the reinforcing agent will flow to one side, they will create agglomeration.

For reinforcing material, for consistent bulk composite distribution, mechanical mixing, alloying creates metal alloy reinforced powder for compression moulding, die casting, extrusion remelting and solidification. Mechanical mixing alloying creates metal alloy reinforced powder for compression moulding, sintering right compression moulding, then die casting, then extrusion, re melting and solidification, reinforcing element dispersion varies on processing and size.

Mechanical alloying creates finer solid grains by adding particles that increase solid solubility and create a non equilibrium state. Grinding improves alloy powder characteristics and chemical composition. So, grinding, all these things happen in ball mill.

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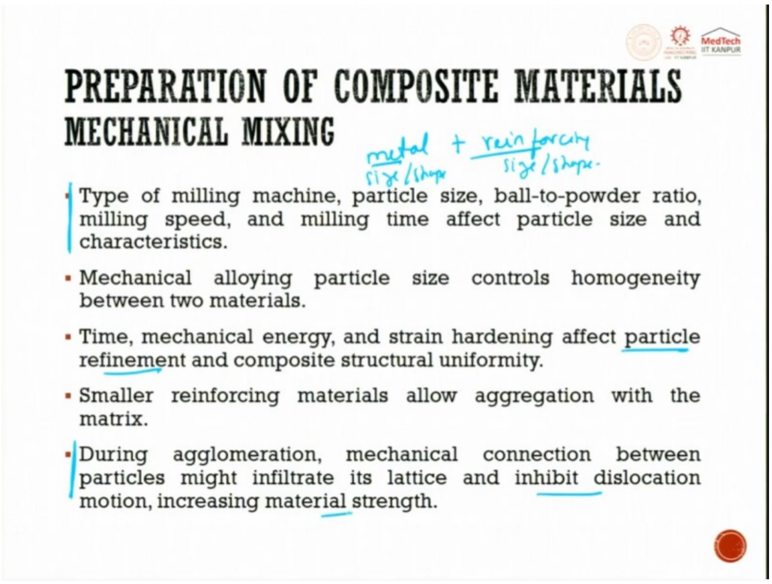

Types of milling machine, particle size, ball to powder ratio, milling speed and milling time affects particle size and characteristics. So, this is very important. So, ball milling so and also it is very important to have a metal and reinforcing size, shape in some ratio. Otherwise, we will not try to get the required mixing. So, for this we use a type of milling machine, particle size, ball to powder, number of balls there and you can do dry milling, wet milling, then milling speed, milling time and milling environment all these things are there, affects particle size and characteristic.

Mechanical alloying particle size controls homogeneity between the two materials. So, time mechanical energy and strain hardening affect particle refinement and composite structural uniformity. So, particle refinement also happens, smaller reinforcing materials allow aggregation with the matrix.

During agglomeration, mechanical connection between the particles might infiltrate its lattice and inhibit dislocation motion increasing mechanical strength. So, this is strengthening mechanism which is generally formed in metal matrix. During agglomeration mechanical connection between the particles might infiltrate its lattice and inhibit dislocation motion, arresting the dislocation motion, thus increasing mechanical strength, it is the same phenomena like arresting the dislocations at the grain boundary for displaying strain hardening behavior.

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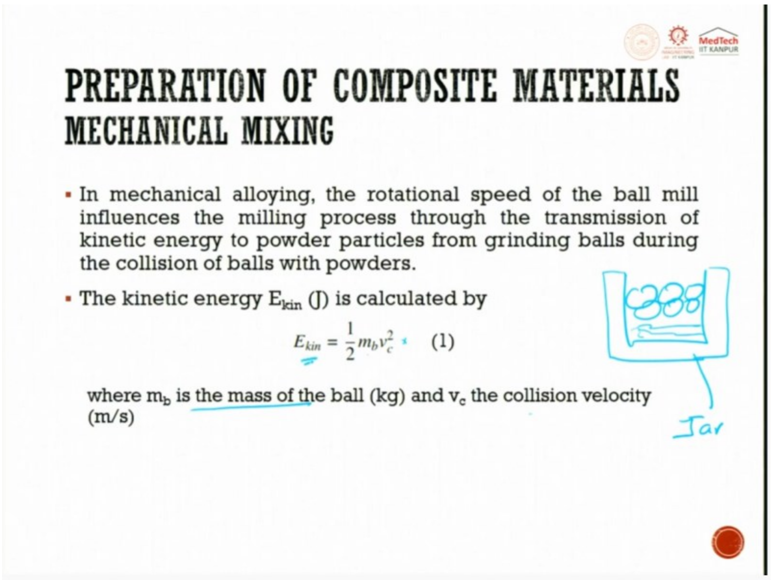

The mechanical alloying, the rotation speed of the ball mill influences the milling process through the transmission of kinetic energy to powder particle from grinding balls during the collision of balls with powder. So, what we are trying to say is, you will have a container, you will have all these metal powders, then you will have ceramic balls, these ceramic balls also will rotate, it will try to collide with each other and in between when it rotates at high speeds, these powders will go up and down.

So, this will come in between the collision, it will try to strain harden the powder, and it will try to fall down. So, repetitive of this action can try to reduce the particle size. This is a jar or a container. So, the kinetic energy is calculated as

$$E_{kin} = \frac{1}{2} m_b v_c^2$$

where m_b is the mass of the ball (kg) and v_c the collision velocity (m/s)

So, this is very important, with this you try to find out what is the kinetic energy you get in ball mill.

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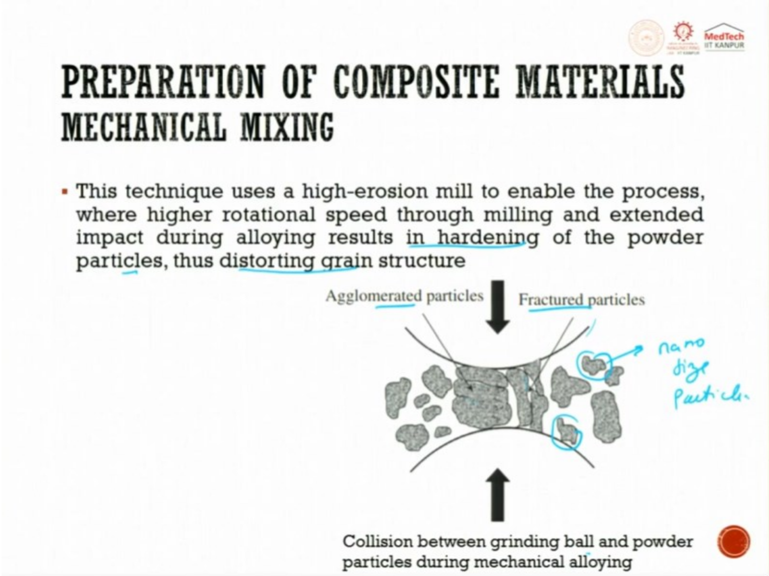

So, this technique uses a high erosion mill. This is collision between the grinding ball and the powder particle during mechanical alloying. So, you will have one ball, you have another ball, two balls and they will be rotating and they will be also trying to collide with each other. So, you will have the powder particle which comes in between when it has got maximum strain harden.

Next what it undergoes is fracture, it fractures into small particles and gets disintegrated. So, agglomerated particles are there, these are agglomerated when the strain, fracture happens it tries to split. This technique uses a high erosion mill to enable the process where higher rotational speeds through milling and extended impact during alloying results in hardening of the powder particle, thus distorting the grain structure. So, when we start doing it, it tries to split and try to get smaller particles. So, here you can even get nano sized particles.

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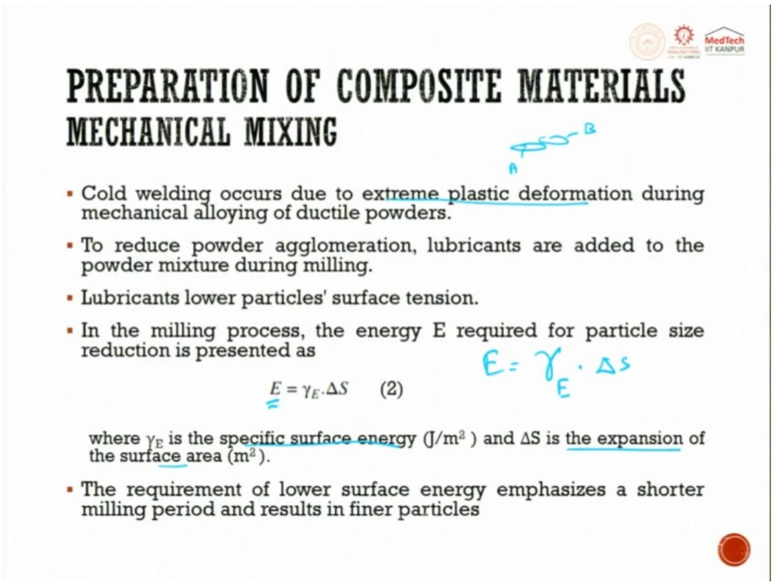

The other one is cold welding. In cold welding occurs due to extreme plastic deformation during mechanical alloying of ductile powders. What is cold welding? So, cold welding is you have one powder, you have another powder so, now, when there is a hammering happening, so, extreme plastic deformation happens and these two fellows join. So, this is A, this is B, metal powder.

To reduce the powder agglomeration lubricants are added to the powder mixture during milling, that is what I said you have a dry milling or wet milling. In dry milling, you will have extreme plastic deformation behavior will be more because of that welding will happen. The lubricant lower particles surface tension and because of that, so, there is a slipping action happening and the cold welding will not happen.

In a milling process the energy E required for particle size reduction is presented as

$$E = \gamma_E . \Delta S$$

where γ_E is the specific surface energy (J/m^2) and ΔS is the expansion of the surface area (m^2). So, with this what you get is you try to get the E, the requirement of lower surface energy emphasizes a shorter milling period and results in a finer particles.

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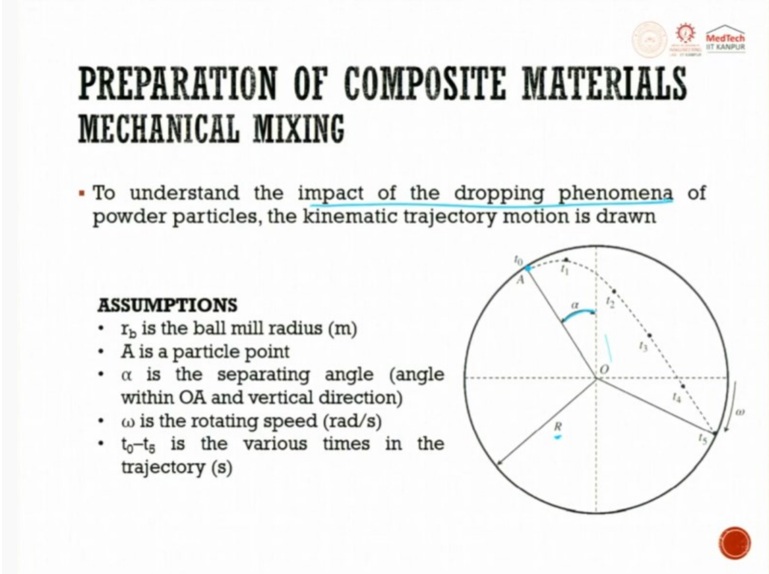

To understand the impact of the dropping phenomena of a powder particle, the kinematic trajectory motion is drawn here. You can see this is what is the kinematic trajectory motion, r_b is the ball mill radius, A is a particle point and α is the separating angle between OA and the vertical direction this is the angle, this is the point. So, α is a point here.

Now, ω is the rotation speed and t_0-t_5 is the various times in the trajectory (s). So, this is all done to understand the impact of the dropping phenomena of a single powder.

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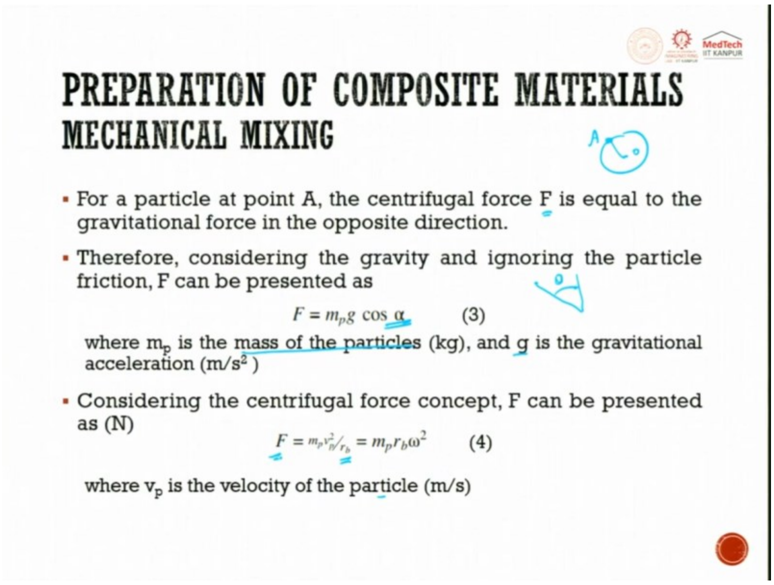

For a particle at a point A, the centrifugal force F, particle at a point A, the point is here, the particle at a point A, the centrifugal force is equal to this A, is equal to the gravitation force in the opposite direction, this is O, this is A. Therefore, considering the gravity and ignoring the particle friction F can be represented as

$$F = m_p g \cos \alpha$$

where m_p is the mass of the particles (kg), and g is the gravitational acceleration (m/s^2) and the cos α is that α between the line and the vertical angle. This is α.

If you see here this is α. So, considering the centrifugal force concept F can be represented as N. So, centrifugal force F is equal to:

$$F = m_p v_p^2 / r_b = m_p r_b \omega^2$$

where v_p is the velocity of the particle (m/s)

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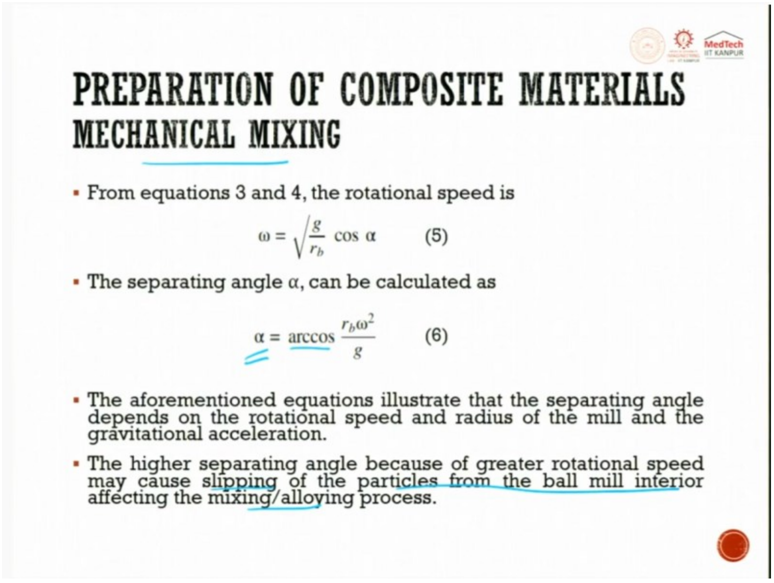

Now, the equation three and four, the rotation speed between these two we will try to take out.

$$\omega = \sqrt{\frac{g}{r_b}} \cos \alpha$$

Now separating the α we can calculate

$$\alpha = \arccos \frac{r_b \omega^2}{g}$$

The aforementioned equation illustrates that the separating angle depends on the rotating speed and the radius of the mill on the gravitational acceleration. The higher separating angle because of greater rotational speeds may cause slipping of the particles from the ball mill affecting the milling or the alloying process. So, all these things are very important until you do a proper mechanical mixing or preparation of the powder, you will not be able to get the required output when a laser beam or an electron beam is used.

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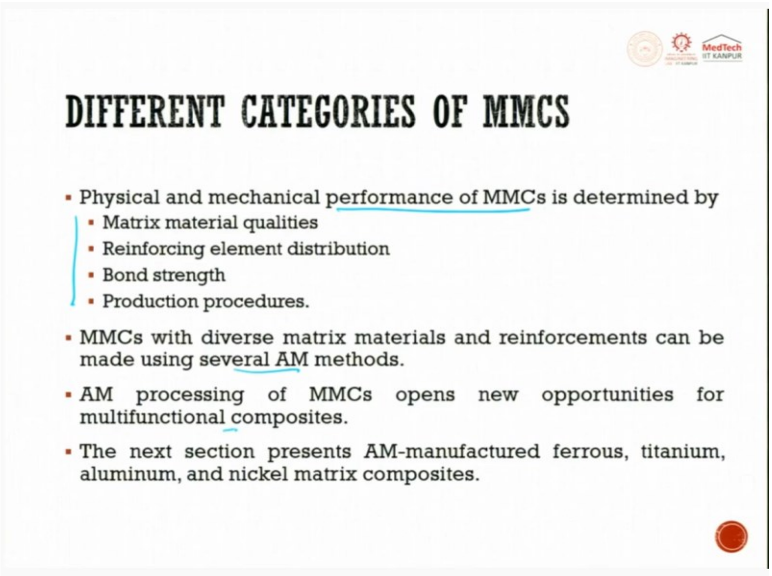

So, different categories of metal matrix composites are physical and mechanical preforms of metal metric composite is determined by matrix material quantity, reinforcing element distribution, bond strength and the production process. These four tries to dictate the performance of MMC in AM process. MMC with diverse matrix material and reinforcement can be used in several of the AM methods, AM processes of metal matrix composite opens new opportunity for multifunctional composite material. In the next section, we present the additive manufacture ferrous, titanium and nickel matrix composites for your understanding.

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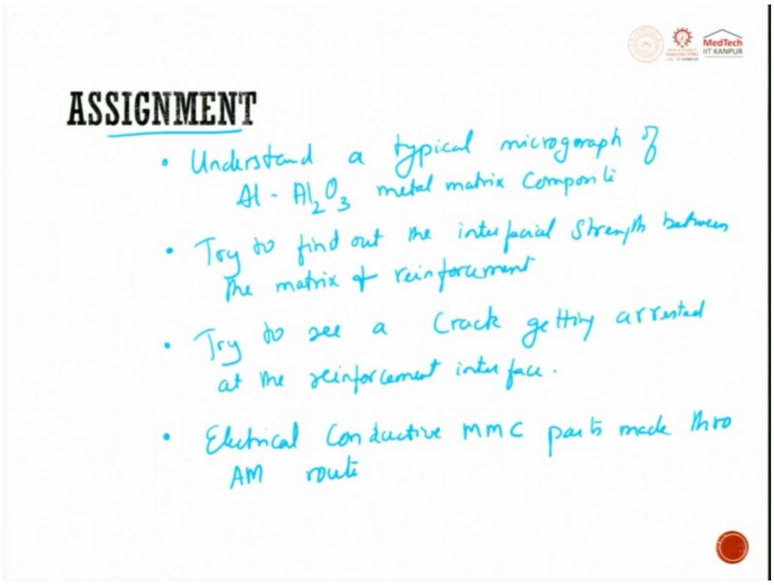

So, the assignment what we have here will be understand a typical micro graph of aluminum Al2O3 metal matrix composite. Second thing, try to find out the inter facial strength between the matrix and reinforcement. Third one is try to see a crack getting arrested at the reinforcement interface. Look forward for electrically conductive metal matrix composite parts made through AM route.

So, all these assignments you can try to do Google and try to note down all these things. When you see this figure or when you see that crack growing, when you see the interfacial strength which is reported in the paper, you will understand how important is, all these things. Thank you very much.