Metal Additive Manufacturing
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Lecture 29
Additive Manufacturing of Metal Matrix Composites (Part 4 of 4)

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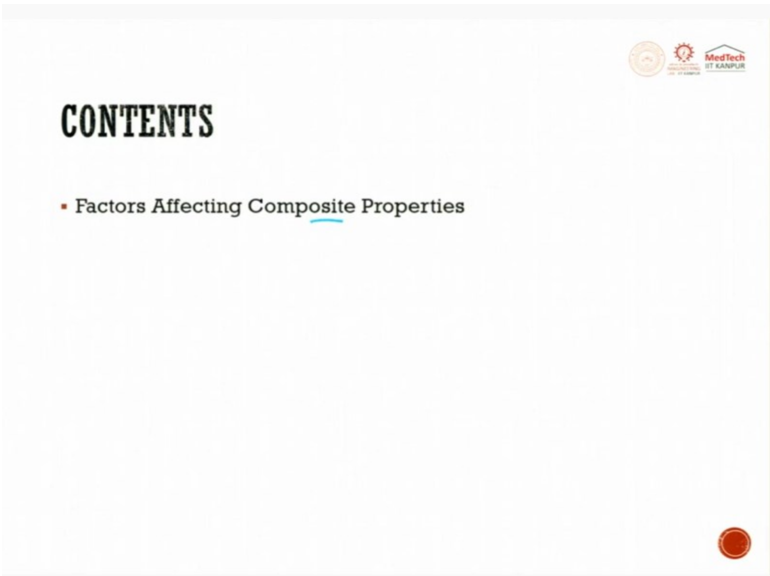

Welcome to the lecture on metal matrix composites fabricated through additive manufacturing process. This is part four and this is the last in this series of lecture. In this lecture we will try to focus on factors affecting composite properties. We will see all the factors, so, that when you start using the process, you will understand each factor what its influence on the final output is.

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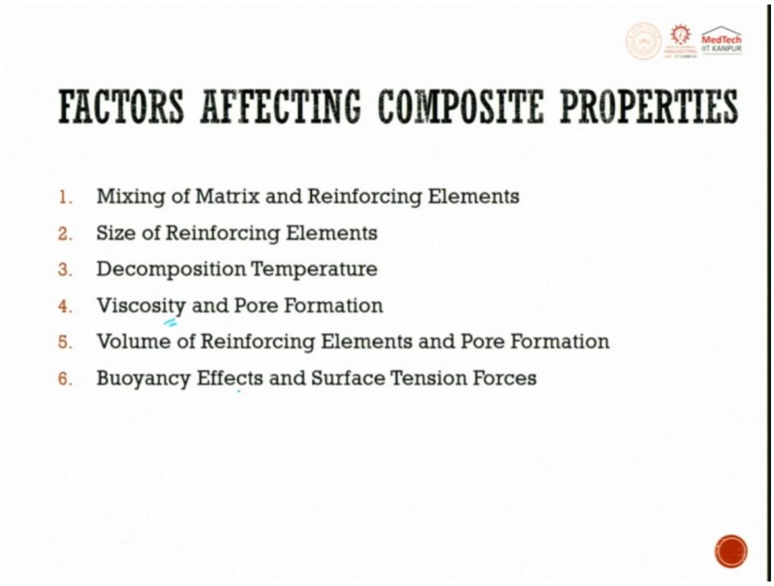

The factor affecting composite properties are mixing of matrix and reinforcing elements, the size of the reinforcing element, decomposition temperature, viscosity and pore formation, volume of reinforcing elements and pore formation, buoyancy effects and surface tension force.

So, first is mixing of matrix and reinforcing elements. So, here we are looking at volume fraction and we are also looking at how is the mixing happening between the matrix and the reinforcing. When we talk about size, what is the size factor of comparison between the matrix powder and the reinforcing powder, decomposition temperature at what temperature the matrix will melt and at the same temperature we should also make sure that TiC or the reinforcing agent they split, or they are stable at that phase.

Viscosity helps in deciding what will be the flowing property of the material, which is melt, the volume of reinforcing elements is very important, which we will try to talk about varying volume fractions, buoyancy effects and surface tension in turn we will try to talk about balling effects and other things.

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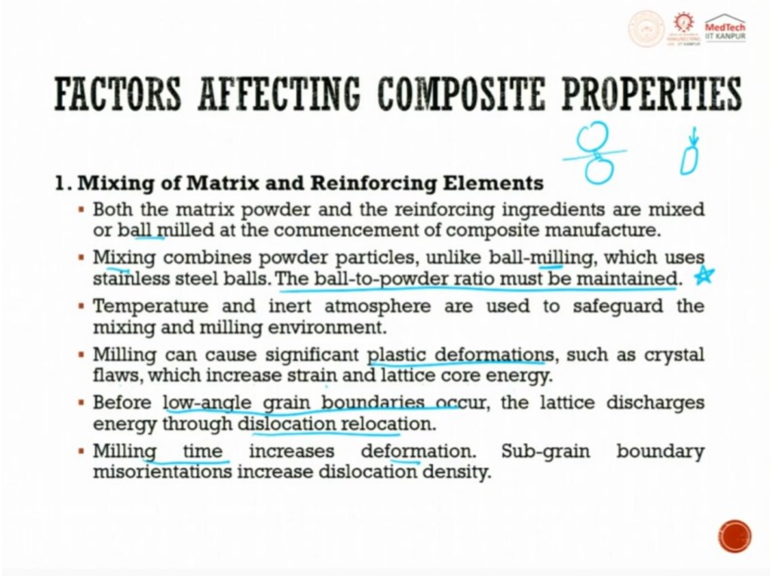

When we talk about mixing of the matrix and reinforcing agents, both the metal powder and the reinforcing ingredients are mixed, or ball milled at the commencement of the composite manufacturing. The mixing combines powder particle unlike ball mill which uses stainless steel balls. The ball to powder ratio must be maintained, that is an important factor which is called as ball to powder ratio.

The temperature and the inert atmosphere are used to safeguard the mixing and milling environment. Mixing is separate and milling is separate. Milling means you have a ball, between these two balls the particle goes in, it gets strain harden and then it shears into smaller particles. Milling can cause significant plastic deformation such as crystal flaws, which increases strain and lattice core energy.

So, when we are trying to take a particle, when you repeatedly hit it or do an impact load, it undergoes strain hardening, ductile material undergoes a lot of strain hardening and once it has reached a major strain hardening, it will then try to shatter. So, it converts from a ductile failure to a brittle failure. So, it shatters. When it shatters, it makes the size small. So, that is what we talked about is a plastic deformation. Such as crystal flaw which increases the strain and lattice core energy, before low angle grain boundary occurs the lattice discharge energy through dislocation, relocation before low angle grain boundary.

Low angle grain boundary is also one where in which they talk about with respect to an angle less than 20^0 or 30^0. The lattice discharge energy through dislocation relocation, milling time increases deformation. Sub grain boundaries misorientation increase dislocation density, more and more and more milling time, more and more, more deformation. Deformation leads to sub grain boundary misorientation and increased dislocation density.

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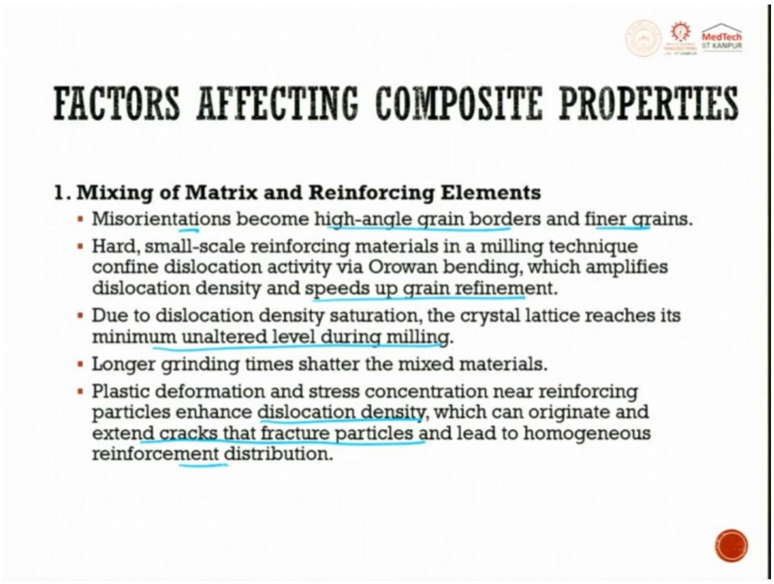

Misorientation become high angle grain border and finer grains. Misorientation is also an important parameter, when it tries to be milled for a longer time, it undergoes misorientation. Hard, small scale reinforcing material in a milling technique confined dislocation activities via Orowan bending, which amplifies dislocation density and speeds up the grain refinement.

When we have ductile it is going to take a longer time. When we have a hard small scale reinforced material, by milling it is going to break fast. Due to dislocation density saturation, the crystal lattice reaches its minimum unaltered level during milling. Long grinding time shatters the mixing material, the plastic deformation and stress concentration near reinforcing particle enhances the dislocation density which can or originate, extend the cracking of fracture of material leading to homogeneous reinforcement distribution.

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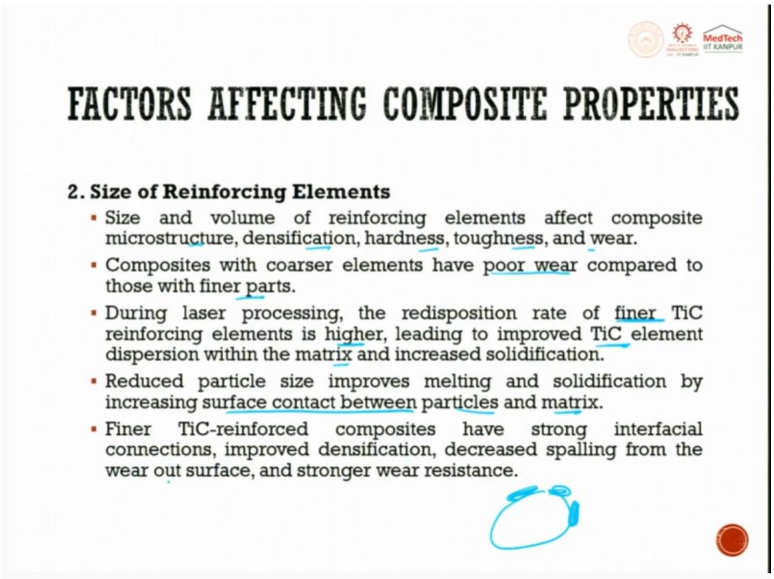

Next is size of reinforcing element, size and volume of reinforcing element affects the microstructure densification, hardness, toughness, and wear. If the size between the metal powder and the reinforcing are in some ratio, if the matrix powder size is large and the reinforcing is small, then it becomes a little easy for getting the required achievement.

The composite with coarser elements has poor wear compared to that of fine parts, because when there is a coarser abrasive, so, then what will happen is this coarse abrasive will have lots of ductility. So, this will undergo wear and once it is weared, these particles also will get along.

So, the composite with the larger core elements has poor wear resistance as compared to that of finer parts. During laser processing, the redeposition rate of finer TiC reinforcing element is higher so, if we have TiC, larger TiC, smaller TiC, coarser TiC finer TiC. Finer TiC reinforcing element is higher leading to improve TiC element, dispersion with the matrix and increased solidification. Reduced particle size improves melting and solidification by increasing surface contact between particles and matrix. Finer TiC reinforced composites have strong interfacial connections, improved densification, decreased spalling from wear out surface and stronger wear resistance.

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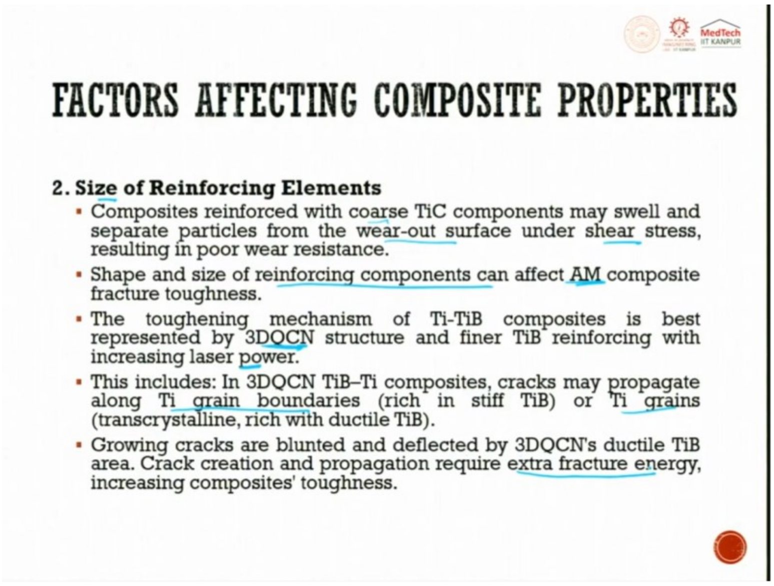

When we talk about the size of reinforcing element, composite reinforcing with coarser TiC components may swell and separate particles from the wear out surface under shear. So, pull out will happen very easily. So, under shear stress it will come out resulting in poor wear resistance. So, we will always look for a small finer TiC component.

The shape and the size of reinforcing component can affect the AM composite fracture toughness. Because the toughness is basically depending upon the size of the grain and the reinforcement. The toughening mechanism of Ti-TiB composite is best represented by 3DQCN which we saw in our lecture discussion. And finer TiB reinforcing with the increasing power.

This includes 3DQCN TiB TiN composites, cracks may be propagated along the Ti grain boundary and Ti grains through the grain bound or along the grain boundary or within the Ti grain. The growing cracks are blunted and deflected by 3DQCN ductile TiB area. Crack creation and propagation requires extra fracture energy and increases composite toughness.

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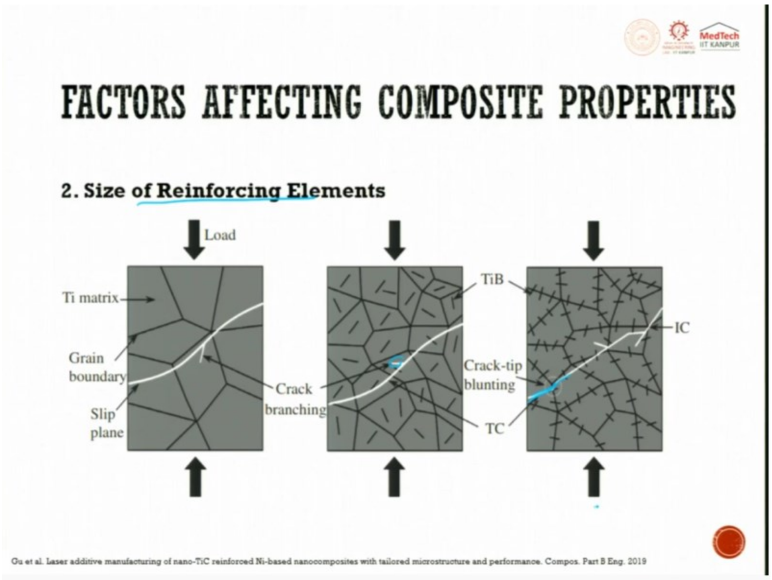

So, this is what it is a load there. So, you have Ti matrix. These are all the grain boundaries, and this is a slip plane which happens. So, you can see here is the crack branching. So, right these are crack branches which are there. So, in the same way when I have a load with TiB and TC so, TiB is this. So, you have TiB which is there and then you see the crack that is going the branching whatever happens and how does it go. So, these are all crack branching.

And the crack tip blunting, this is the TC. This is the inter cracking, IC, this is transverse cracking. So, you see here there is a blunt tip crack blunting. So, the crack blunting is happening here. So, the sides of the reinforcing element are more focused towards the TiB formation coarse or fine and then it tries to divert the crack and take it for a longer distance. So, the failure will not happen so, easily.

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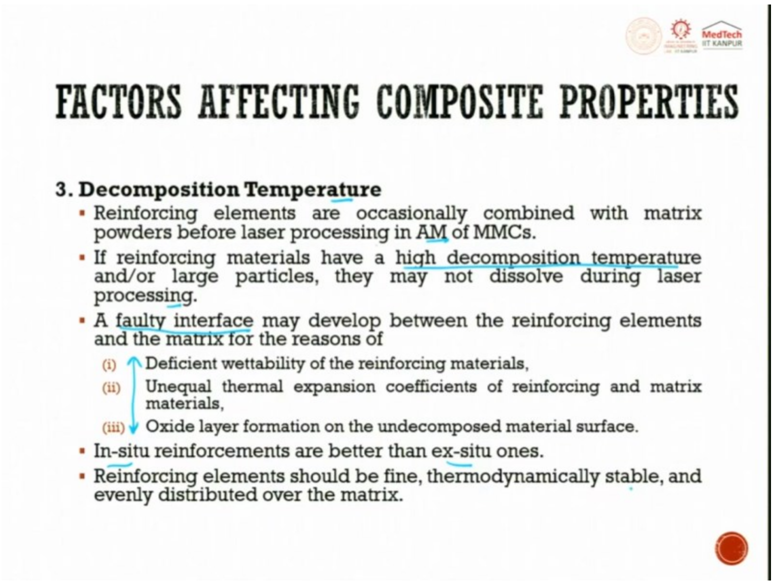

The third point of discussion is going to be composite temperature. Composite temperature or decomposition temperature. The reinforcing elements are occasionally combined with matric powder before laser processing in AM process. If reinforcing material have a high decomposition temperature and a large particle, they may not dissolve during the laser processing. If they are high decomposition temperature, then they will not dissolve during the laser processing.

A faulty interface may develop between the reinforcing element and the matrix for the reasons of, deficient wettability of reinforcing material, unequal thermal expansion coefficient of reinforcing and matrix material, oxidized and layer formation on the undecomposed material surface. So, these are the three things which are there.

Deficient wettability of the reinforcing material, unequaled thermal expansion coefficient of reinforcing and matrix material. The third one is oxide layer formation on the undecomposed material surface. So, these three things are important for creating a faulty interface. So, this faulty interface in turn depends upon the temperature.

In situ reinforcement are better than ex situ reinforcement. So, ex situ, you mix it outside and then bring it to the process. But when we do in situ, it tries to take care of everything within the material itself while the processing is going on. Reinforcing elements should be fine, thermodynamic stability and evenly distributed over the matrix. Viscosity and pore formation once the temperature comes then the viscosity comes.

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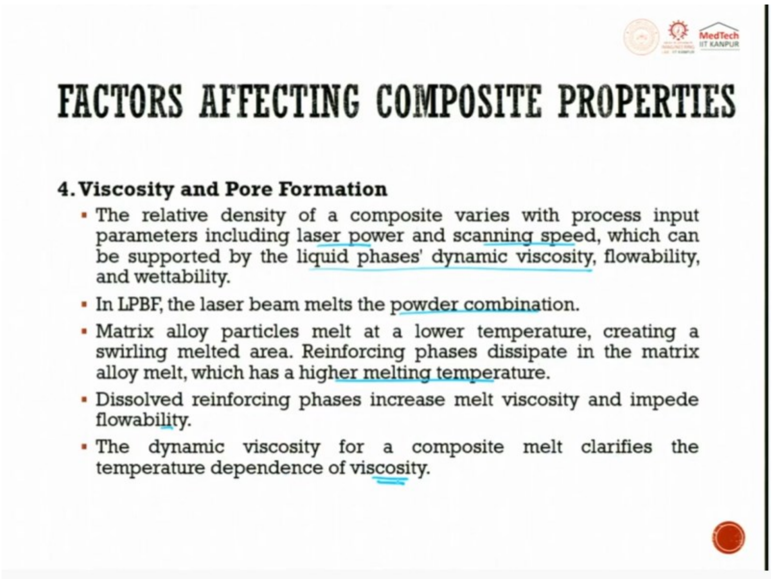

A relative density of a composite varies with the process input parameter, including laser power and scanning speed, which can be supported by the liquid phase dynamic viscosity. Liquid phase dynamic viscosity, flowability and wettability. A relative density of the composite varies with the process input parameters including laser power, scanning speed, and which can support the liquid for dynamic viscosity, there is something called as static viscosity, there is something called as dynamic viscosity.

In laser powder bed fusion, the laser beam melts the powder combination. There are two things right, the matrix is there, the reinforcing is there, both gets melt and then the laser beam melts the powder combination. The matrix alloy particles melt at a lower temperature creating a swelling melting area which we have discussed in plenty, reinforcing phase dissipate in the matrix alloy melt which can have a higher melting temperature.

So, this reinforcing agent just moves in the melting area. Dissolved reinforcing phase increases melt viscosity and impedance flowability. The dynamic viscosity for a composite melt clarifies the temperature dependency of viscosity. So, the dynamic viscosity for a composite melt clarifies the temperature and dependency of viscosity.

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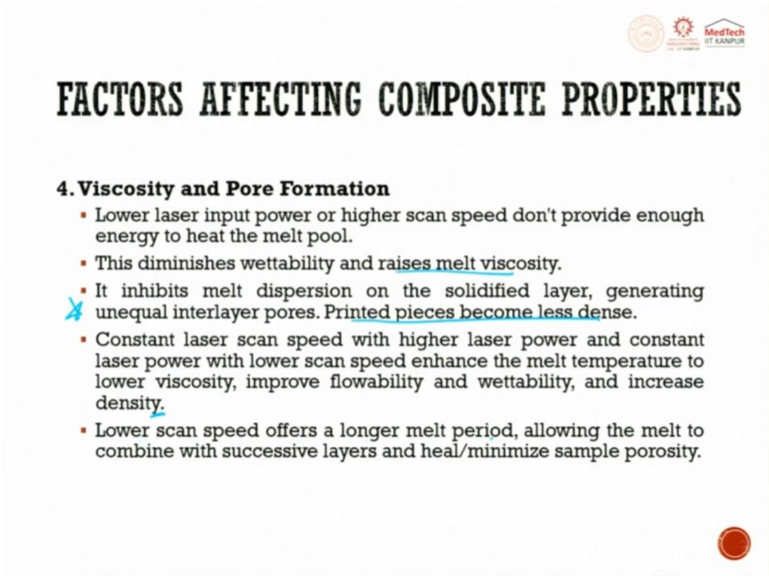

The lower laser, the viscosity and pore formation. The lower laser input power or higher scanning speed do not provide enough energy to heat the melt pool. This diminishes wettability and raises viscosity. The inhibit melt dispersion on the solidified layer generating unequal interlayer pores, printed pieces become less dense. This is also an important point.

The melt dispersion of the solidified layer generating unequal interlayer pores, they are formed here. Constant laser scan speed with higher laser power and constant laser power with lower scan speed enhanced the melting temperature to low viscosity, improved flowability, wettability and increased density. Finally, the lower scan speed offers a longer melting period allowing the melt to combine with a successful layer and heal minimize the sample porosity.

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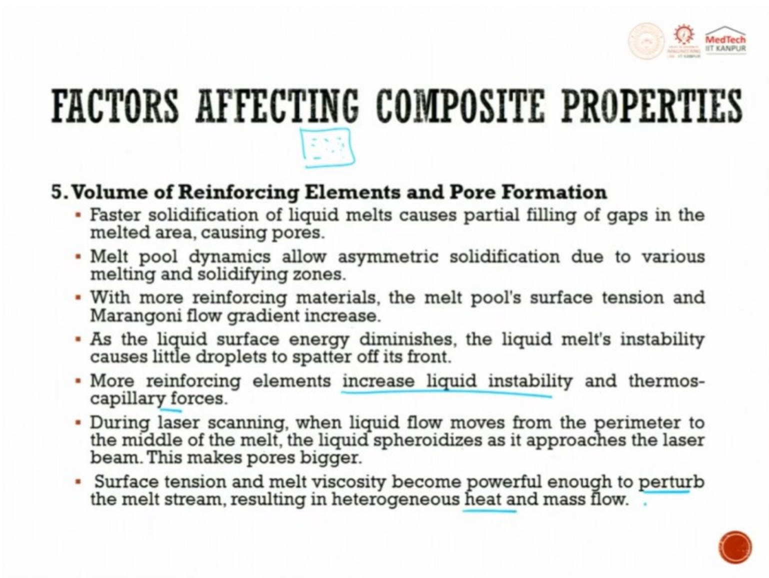

The volume of the reinforcing elements and pore formation. What is the volume? The reinforced number of reinforcement particles present in a unit area. Faster solidification of liquid melts causes partial filling of gap in the melted area causing pores. The melt pore dynamics allows asymmetric solidification due to various melting and solidification zone, with more reinforcing material, the melt pool surface tension and Marangoni flow gradient increases.

As liquid surface energy diminishes, the liquid melts instability causes little droplets to spatter off its front. More reinforcing element increases liquid instability and thermo capillary force. During laser scanning when the liquid flow moves from the perimeter to the middle of the melt, the liquid spherodizes as it approaches the laser beam, this makes pore bigger. The surface tension and the melt viscosity become powerful enough to perturb and melt stream, resulting in heterogeneous heat and mass flow rate.

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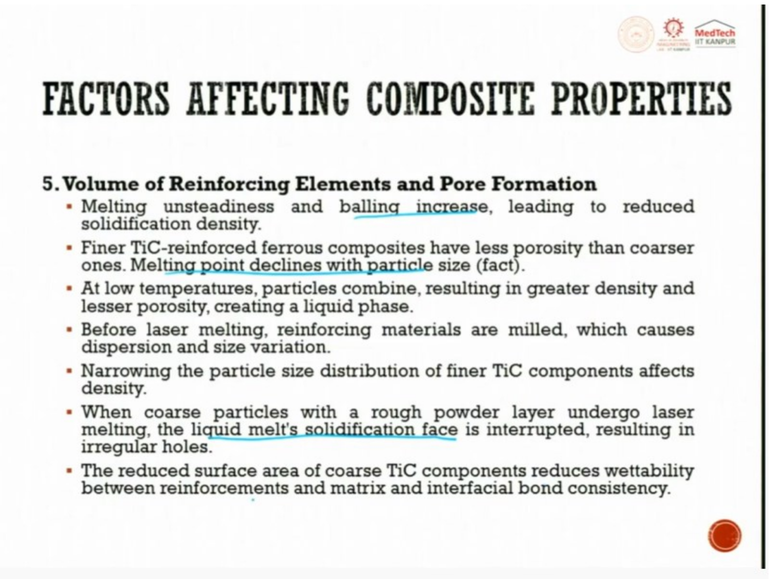

The melting unsteadiness and balling increases leading to reduced solidification density. What is balling? We discussed when we talked about the various parameters. Finer TiC reinforced ferrous composite have lesser porosity than coarser ones, melting point declines with particle size. All at low temperature particles combined resulting in greater density and lesser porosity creating a liquid phase. Because of liquid phase it can flow, it can get consolidated.

Before laser melting, reinforcing material are milled, which cause them dispersion and size variations. Narrowing the particle size distribution of finer TiC component affects density. When coarse particles with a rough powder layer undergoes laser melting, the liquid melts solidify phase is interrupted, resulting in an irregular hole. So, liquid metal solidification phase is interrupted. The reduced surface area of coarse TiC component reduces wettability between reinforcement and matrix and reinforcement bonding consistency.

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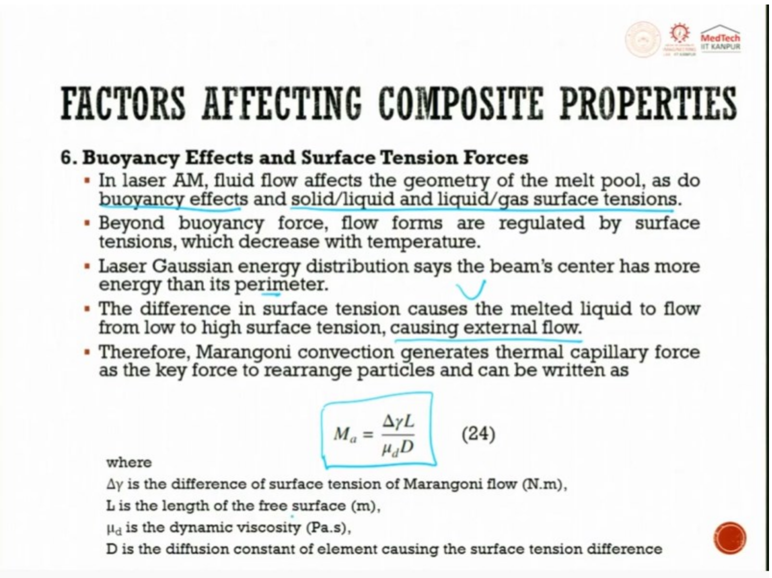

When we discuss about buoyancy effects and surface tension in laser additive manufacturing fluid flow affects the geometry of the melt pool and do buoyancy effects and solid liquid, liquid gas surface tension. So, this is important. There is a buoyancy effect. Beyond buoyancy force, flow forms are regulated by surface tension, which decrease with temperature.

Laser Gaussian energy distribution says that the beam center has more energy than its perimeter, which is a fact. The difference in surface tension causes the melted liquid to flow from low to high surface tension causing external flow. Therefore, Marangoni convection generates thermal capillary force as the key force to rearrange particles and can be written as:

$$M_a = \frac{\Delta\gamma L}{\mu_d D}$$

where

$\Delta\gamma$ is the difference of surface tension of Marangoni flow (N.m),

L is the length of the free surface (m),

μ_d is the dynamic viscosity (Pa.s),

D is the diffusion constant of element causing the surface tension difference.

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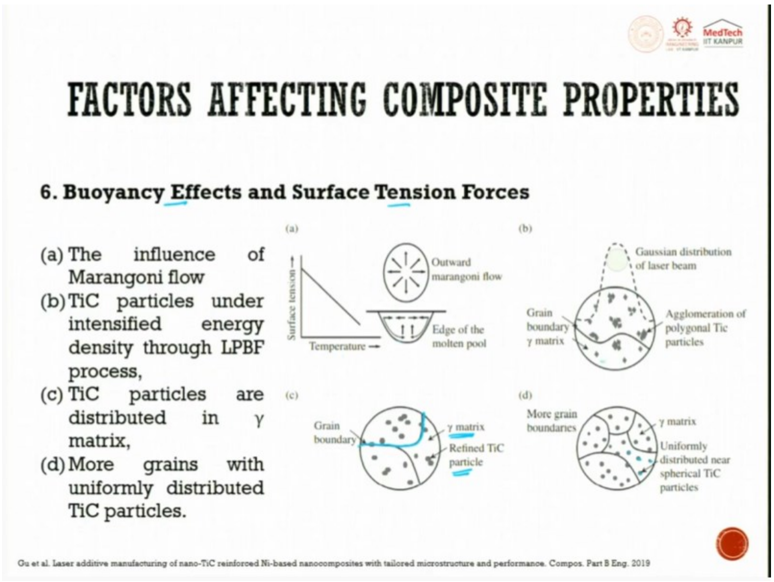

The buoyancy effect and surface tension in a, you can see the influence of Marangoni flow, outward flow and this is end of the edges of the melt pool, this is what it is, outward flow Marangoni. And this is on the top surface, this is on the side view. The surface tension reduces drastically with respect to temperature. Next is b, the TiC particle under intensified energy through laser. So, this is the Gaussian distribution of the laser. This is the grain boundary. These are agglomerated TiC particles which are there. The grain boundary gamma matrix is this.

Next TiC particles are distributed in gamma matrix. So, this is the grain. And these are the reinforcement, and this is the gamma matrix, and the reinforcement of TiC is here, and this is what is a grain boundary. So, TiC particles are distributed in the gamma matrix. More grains with uniformly distributed TiC particles are here. So, you can see gamma matrix, these are the grains, and this is uniformly distributed near spherical TiC particles are here.

These are the near TiC particles. So, these are the four things which is very nicely drafted here which talks about buoyancy force and surface tension. Surface tension decreases with temperature which tries to talk about how the TiC particles is getting fabricated in laser powder bed fusion, then TiC particles distributed in gamma and more grains and uniform distribution of TiC particles.

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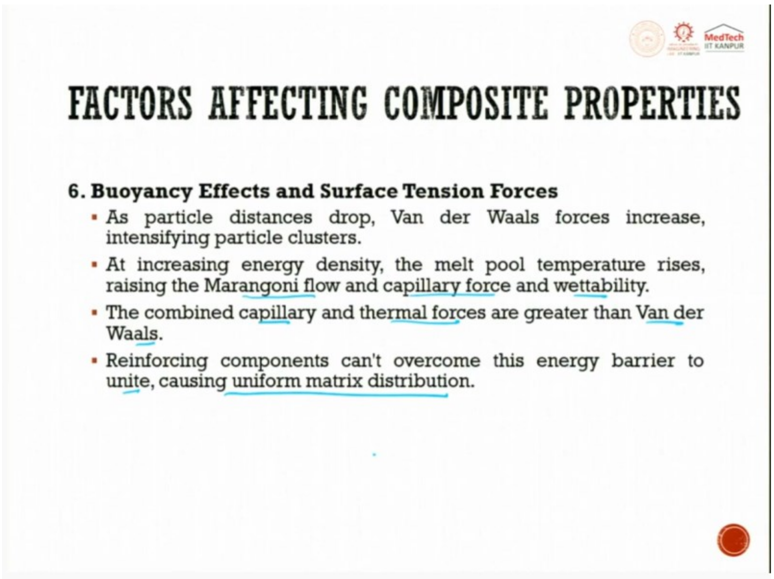

As the particle distance drops, Van der Waals forces increase, intensifying particle clustering. At increasing energy density, the melt pool temperature rises, rising the Marangoni flow and the capillary force and wettability. The combined capillary and thermal forces are greater than the Van der Waals force. Why is that important? You can go back here. As the particle distance drop the Van der Waals force increases, intensifying particle clustering.

Now, the counter trait is the combination of capillary and thermal force are greater than the Van der Waals force. Reinforcing components cannot overcome this energy barrier to unite causing uniform matrix distribution. So, in this metal matrix composite and additive manufacturing, you have so many phenomenas which come into existence thus providing you a sound quality output.

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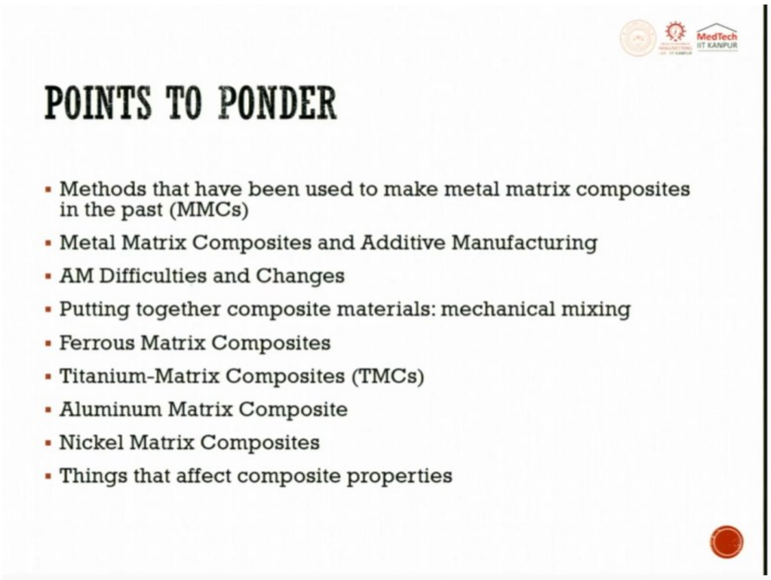

So, points to ponder, what all have we seen in this lecture, four lectures. Methods that have been used to make metal matrix composites in the past, that metal matrix composite and additive manufacturing, additive manufacturing difficulty and changes, putting together composite materials such as mechanical milling. So, then we have seen four alloys, metal matrix composites which are made iron matrix, Titanium matrix, aluminium matrix, and nickel matrix. And the last we saw factors affecting the property of the composite material fabricated through AM.

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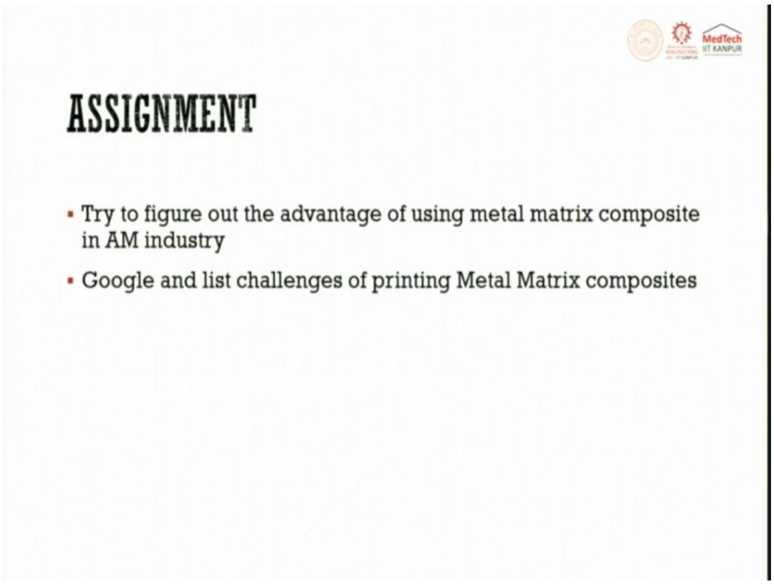

Try to figure out the advantage of using metal matrix composites in AM industry, and Google lists the challenges of printing metal matrix composites. These two are the assignments from this lecture. Thank you very much.