Metal Additive Manufacturing
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Lecture 28
Additive Manufacturing of Metal Matrix Composites (Part 3 of 4)

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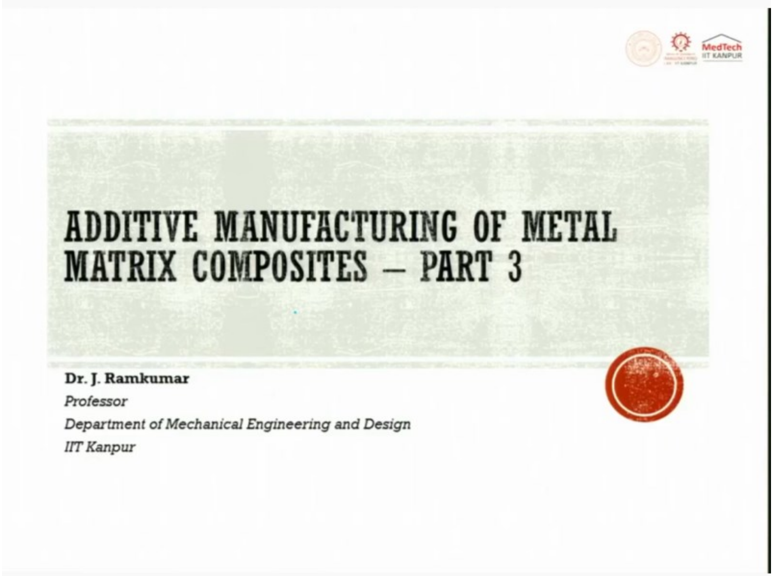

Welcome to the next lecture on additive manufacturing assisted for metal matrix fabrication. In the past, we have gone through conventional different ways of making metal matrix composite. Then, we studied how additive manufacturing laser assisted is useful in making such metal matrix composites. The big difference between conventional and additive manufacture metal matrix composites, is its microstructure.

Microstructure tries to dictate the property. Then, we studied various matrixes which are used for making composites, amongst them, iron, aluminum, titanium and nickel are very prominently used. How do you decide the matrix? The matrix is decided based upon the ductility it has, density and wear resistance hardness. So, all these things try to help in choosing the matrix.

Then for the reinforcements, predominantly for metal matrix composites, it is made of particulates. We saw how is TiC, TiN, B_4C, WC and VC all these are used for making reinforcement in the metal matrix. We discussed about iron matrix then we discuss about titanium matrix and the latest research which is going on is titanium reinforced with Hydroxyapatite.

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Now, in this lecture as part three, we will try to see two more matrixes. One is aluminum, the other one is nickel. Aluminum is very much common and very popular amongst metal matrix composites. For two simple reasons. One, it is lightweight, it is cost effective. And third it is ductile and you can tweak its properties to your own requirements easily. So, aluminum finds a lot of applications in automobile, aerospace, entertainment industry and in also the biomedical applications in terms of instrumentation. They find a lot of applications.

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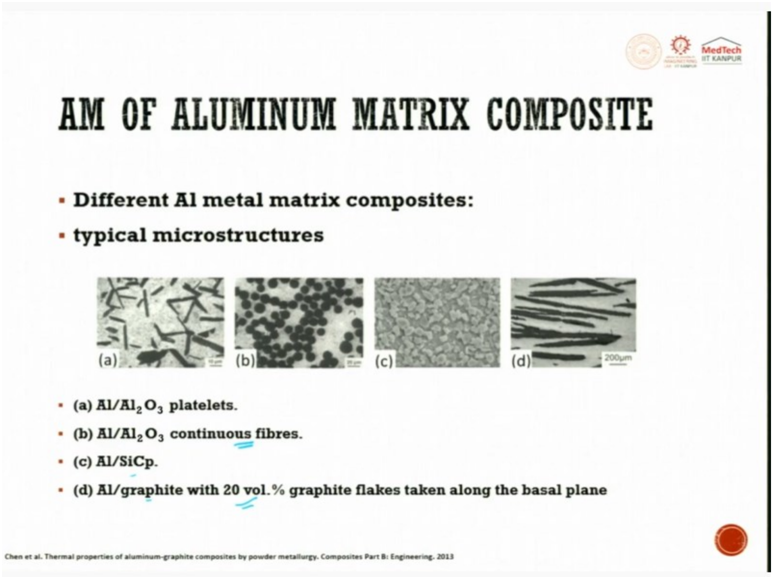

Next is Nickel, wherever it is high temperature and where they do not bother much about density, they go for nickel matrix composites. When we talk about metal matrix composites where aluminum is the matrix so, we see various types of microstructures. We see here alumina platelets type, then we see here continuous fiber alumina through which the metal is squeeze casted.

Then we try to see silicon carbide where alumina is the matrix, the next one is going to be graphite with 20% volume fraction, where graphite flakes taken along the basal plane. So, these are the different types of microstructures, you can also have continuous fiber, these fibers are ceramic fibers, they are again made as a preform and they can use it for squeeze casting.

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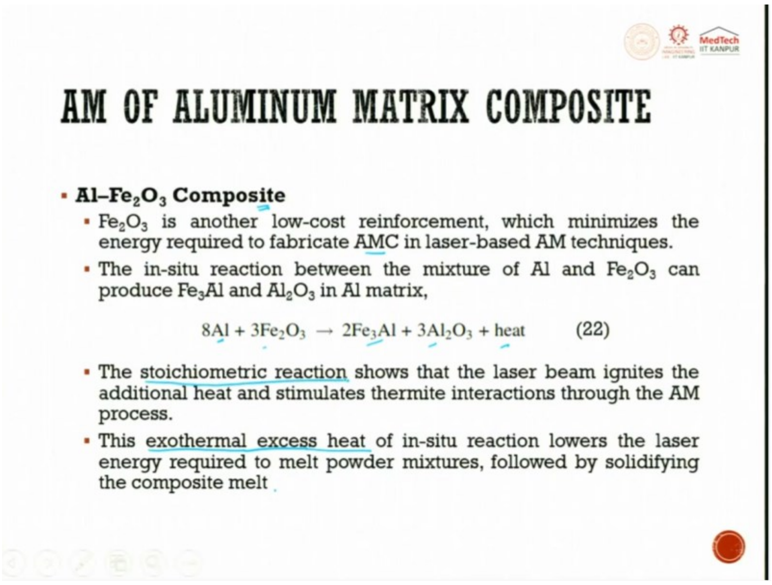

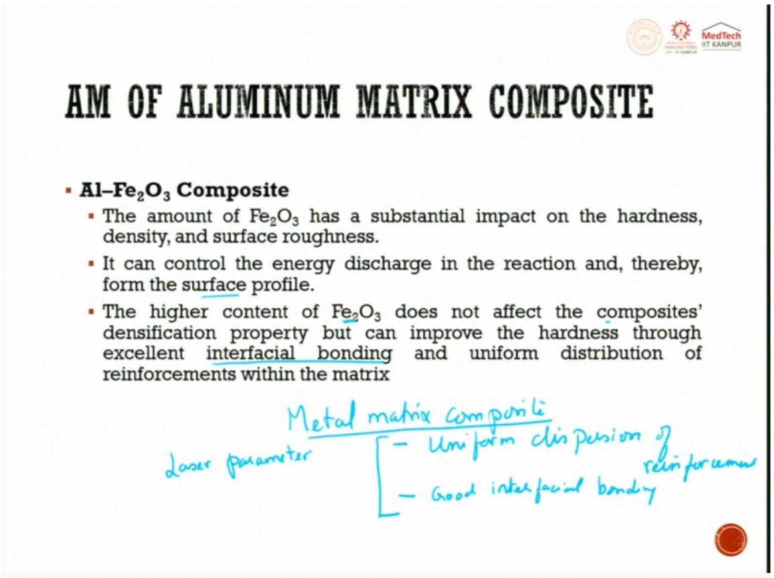

When we try to mix iron oxide in aluminum, so, we can also make such composites. Fe_2O_3 is another low-cost reinforcement which minimizes the energy required to fabricate AMC in laser based additive manufacturing techniques. The in-situ reaction, whatever it is, so that means to say you do not make iron powder, you try to have ingredients and that will try to reinforce and then get you.

$$8Al + 3Fe_2O_3 \rightarrow 2Fe_3Al + 3Al_2O_3 + heat$$

So, the stoichiometric reaction shows that the laser beam ignites the additional heat and simulate thermite interaction through the AM process. The exothermal excess heat of in situ reaction lowers the laser energy required to melt powder mixture followed by solidifying the composite melt.

So, this is very important exothermal excess heat, then stoichiometric reaction is maintained. The amount of iron oxide has a substantial impact on the hardness, density and surface toughness. It can control the energy discharge in the reaction and thereby form a surface profile.

The higher content of iron oxide does not affect the composite densification property, but can improve the hardness through the excellent interfacial bonds. Interfacial bond is also one important thing as far as metal matrix is concerned. Now that we have seen some amount of metal matrix's basics, let me list out what all are expected from a metal matrix composite.

So, the first thing is it should have uniform dispersion of reinforcement. The second thing is it should have good interfacial bonding. These two are very important. So, if you want to have this good interfacial bonding and uniform dispersion so, you must vary the laser parameters to get the required output.

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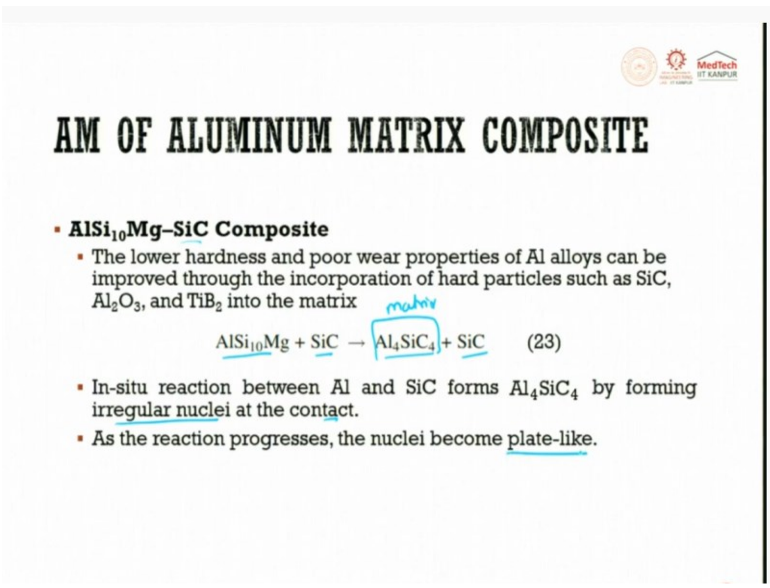

AlSi10 Mg with SiC composite, lower the hardness, poor wear properties of aluminum alloy can be improved through the incorporation of hard particles such as Si_3, SiC, Al_2O_3 and TiB_2 into the matrix.

$$AlSi_{10}Mg + SiC \rightarrow Al_4SiC_4 + SiC$$

So, this becomes the matrix and this becomes the SiC reinforcement. In situ reaction between Al and SiC forms Al_4SiC_4 by forming irregular nuclei at the contact. So, irregular nuclei, the nuclei which is formed and it has nuclei -- as the reaction progresses, the nuclei become platelet like.

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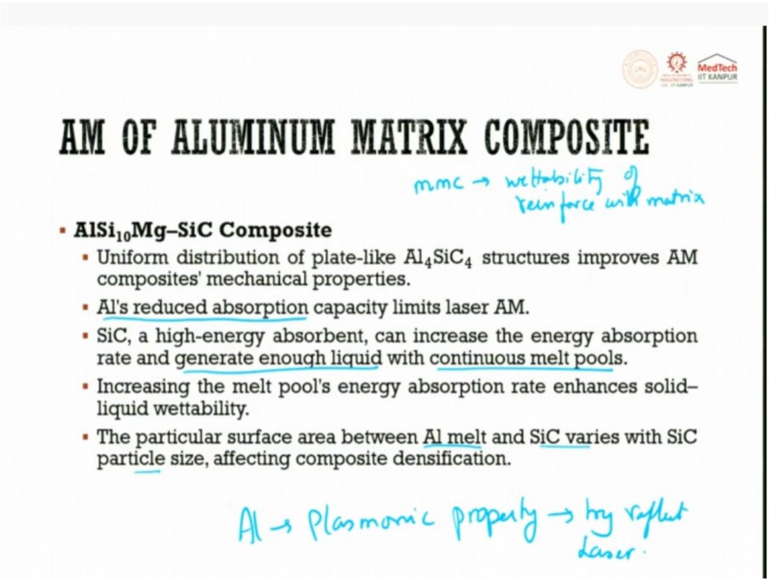

Uniform dispersion of plate like Al_4SiC_4 structures, improve AM composites mechanical property. Al reduced absorption capacity limits the laser processes. Al reduces absorption, why? Because the Al has a plasmonic property and this plasmonic property whatever it has tries to reflect laser. So that puts an issue with a laser additive manufacturing. SiC an energy observant so, in this SiC absorbs laser in a big way. So, SiC a high energy absorbent can increase the energy absorption rate and generate enough liquid with continuous melt pool. This is very important.

So, Al will try to reflect, but SiC will try to absorb so, now SiC temperature goes high, that in turn tries to transform Al from solid to liquid. Increasing the melt pool's energy absorption rate enhances solid liquid wettability. Solid liquid wettability is also very important. When we are looking at all these MMC, the wettability of reinforcement with matrix is very important.

If the wettability is not good so, then you will not have interfacial bonds. If the interfacial bond is not there, interfacial strength will not be there. If the strength is not there, then the particulates will get dispersed or it will get dislocated very fast when you try to put it into real time use. The particulate surface area between Al melts and Si varies with SiC particle size affecting the composite densification.

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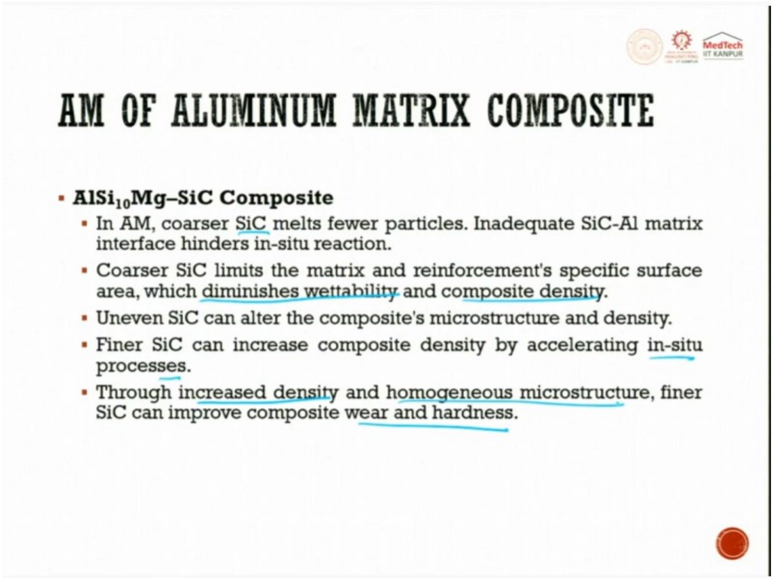

In AM, coarser SiC melts fewer particles. Inadequate SiC-Al matrix interface hinders the in-situ reaction. Coarse SiC limits the matrix and reinforcement specific surface areas which diminishes wettability and composite density. So, diminishes wettability and composite density. Uneven SiC can alter the composite microstructure and density.

Finer SiC can increase composite density by accelerating in situ processes. Though increased density and homogeneous microstructure finer SiC can improve composite wear and hardness, through increase in density. So, through increased density and homogeneous microstructure, finer SiCs can improve the composite structure.

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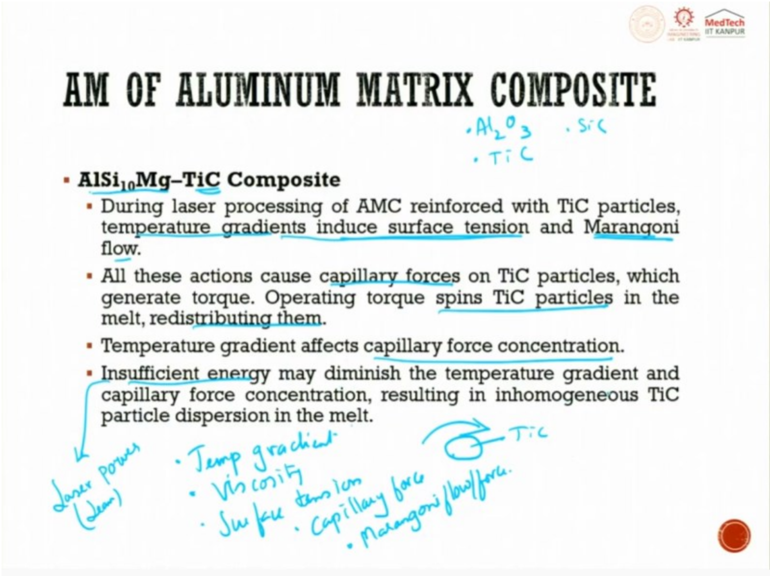

Now, AlSi Mg with TiC, we saw with alumina. Then now we are going to see with TiC. We also saw with SiC, the previous one was SiC. During laser processing of additive manufacturing composite reinforcement with TiC particles temperature gradient induced surface tension and Marangoni flow is very important.

Everywhere it is the same story, temperature induced, surface tension, Marangoni flow is important. All these actions cause capillary force on SiC particles which generates torque. The operating torque spins the SiC particle in the melt and redistributing them. So, TiC particle, this will spin. So, all these actions cause capillary forces on TiC particles, which generate torque.

Operating torque spins the SiC particle. Where is this spinning and all happening? Induced surface tension and Marangoni flow. These two people try to bring in the spin, in the melt and redistribute them. Temperature gradient affects capillary force concentration. So, in variably if you see what they talk about is temperature gradient. Important parameter. Then from there you try to talk about viscosity.

Then we talk about surface tension. Then, we try to talk about capillary force. Then we talk about Marangoni force, flow slash force. So, these are the things which are there. So, temperature gradient affects the capillary force concentration. Insufficient energy may diminish the temperature gradient and capillary force concentration, resulting in inhomogeneous TiC particle dispersion in the melt.

So, insufficient energy means here we are trying to talk about laser power poor, or laser power lean. Lean laser power you use. So, there is an improper or inhomogeneous TiC particle dispersion in the melt.

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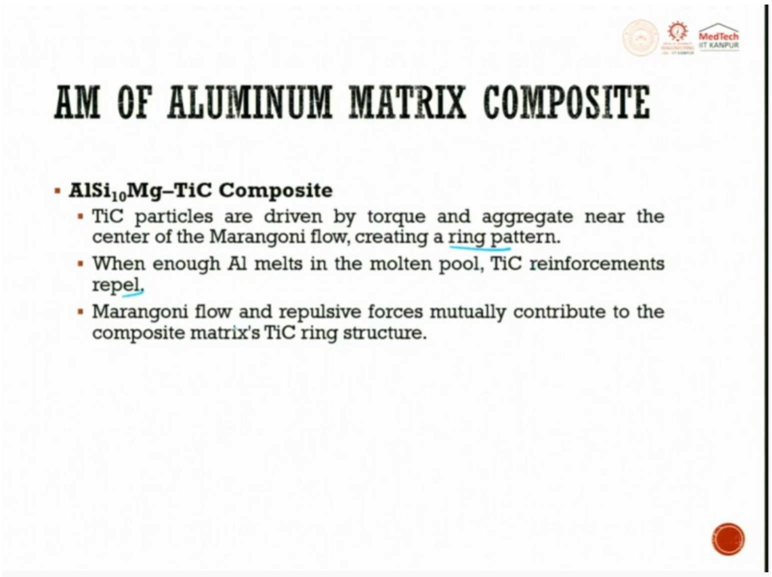

TiC particles are driven by torque and aggregate near the center of the Marangoni flow creating a ring pattern. So, this is the same thing when you see, when iron also TiC ring pattern, the same thing. Al melts in the molten pool, TiC reinforcement repels them. Marangoni flow and repulsive forces mutually contributes to the composite matrix TiC ring structure.

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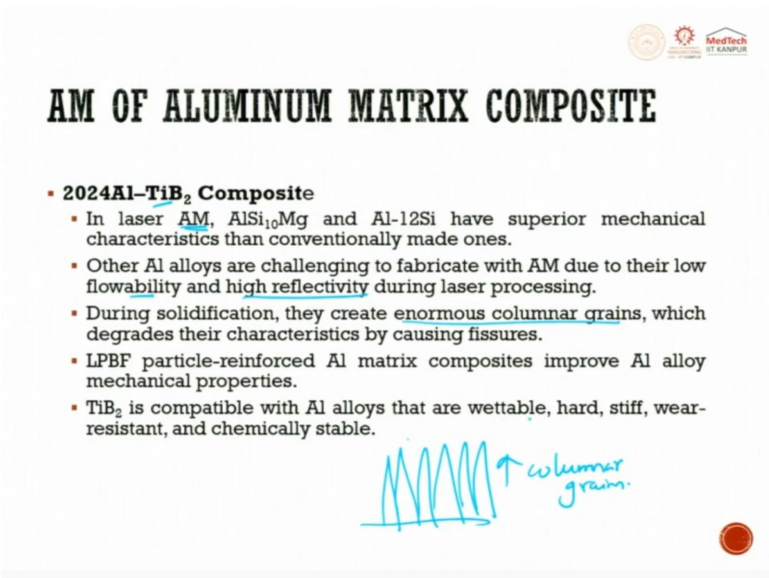

Now, let us look into TiB_2 composites. In laser, AlSi Mg and AlSi have superior mechanical characteristics than conventionally made ones in laser AM. Other aluminum alloys are challenging to fabricate with AM due to their low flowability and high reflectivity for the laser processing. During solidification, they create enormous columnar grains. What are columnar grains? These are columnar grains, where the heat is dissipated, they create columnar grains. These are columnar grains, which degrades their characteristics by causing fissures.

The laser powder bed fusion particle reinforced aluminum matrix composite improves aluminum alloys mechanical property. TiB_2 is compatible with aluminum alloys that are wettable, hard, stiff and wear resistant and chemically stable.

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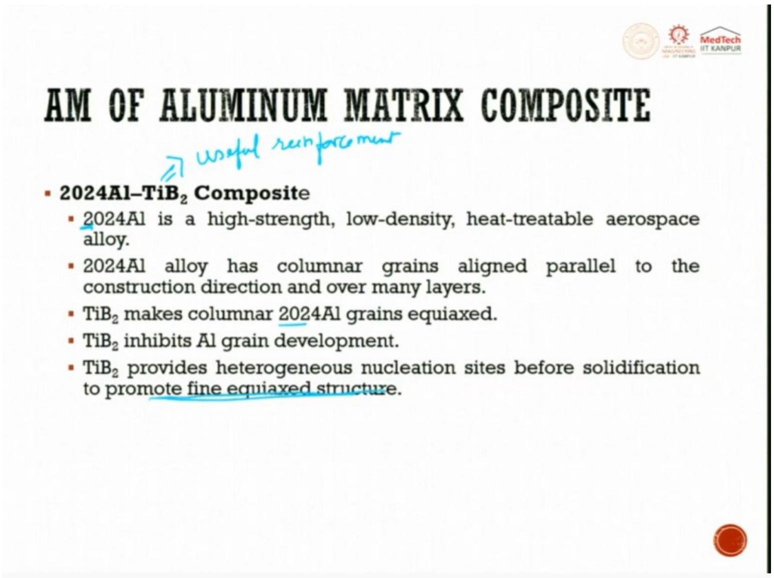

2024 Al is a high strength, low density, heat treatable aerospace alloy. It is two series basically, two series are aluminum alloys have columnar grains, aligned parallel to the construction direction and over many layers, making columnar 2024 aluminum grain equiaxed. TiB_2 inhibits aluminum grain development, TiB_2 provides heterogeneous nucleation sites before solidification to promote equiaxed structure. So, this is very useful reinforcement. It tries to create fine equiaxed structures.

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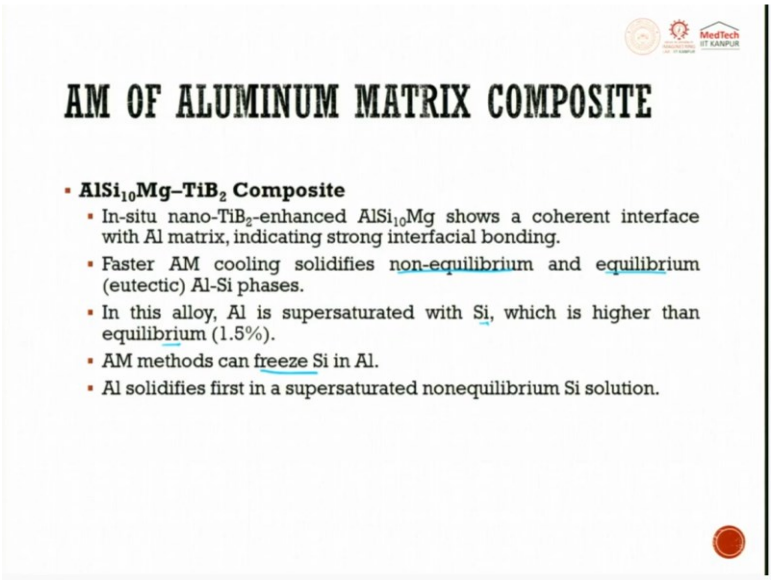

In situ nano TiB_2 enhanced $AlSi_{10}Mg$ shows a coherent interface with Al matrix indicating strong interfacial bonds. Faster AM cooling solidifies non-equilibrium and equilibrium Al-Si phases. It is very important to know what is the difference between non-equilibrium and equilibrium Al Si phase. In this alloy, Al is supersaturated with Si, which is higher than the equilibrium of 1.5%. AM method freezes Si in aluminum, Al solidifies first in the supersaturated non-equilibrium Si solution.

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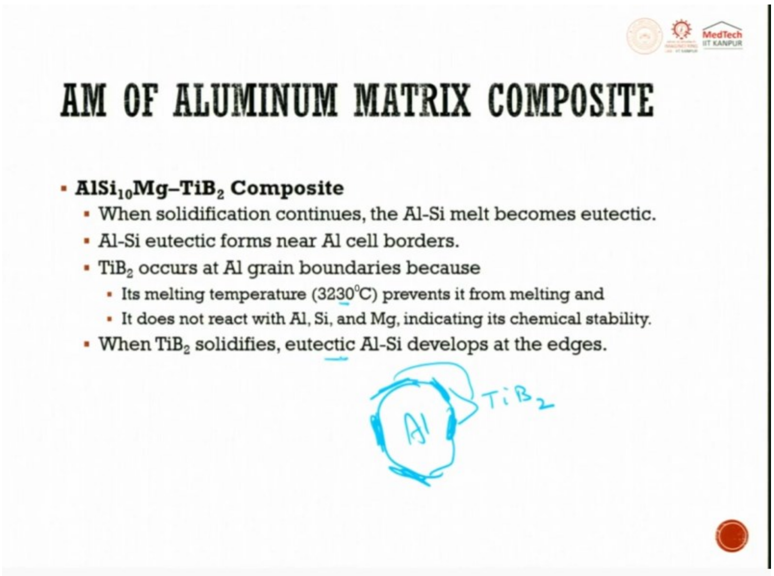

When the solidification continues, the Al-Si melt becomes eutectic. Al-Si eutectic forms near Al cell boundaries. TiB_2 occurs at Al grain boundaries because Al grain boundary you will have TiB_2. This will be Al. All these things are TiB_2. TiB_2 occurs at Al grain boundaries because the melting point is 3230^0C preventing it from melting, TiB_2 will not melt.

It does not react with Al Si Mg indicating its chemical stability. So, it will be all pushed out. So, once that is pushed out it will be all the grain boundaries. So, all the dislocations will be arrested by the TiB_2 which is there along the grain boundary. When TiB_2 solidifies eutectic AlSi develops at the edge.

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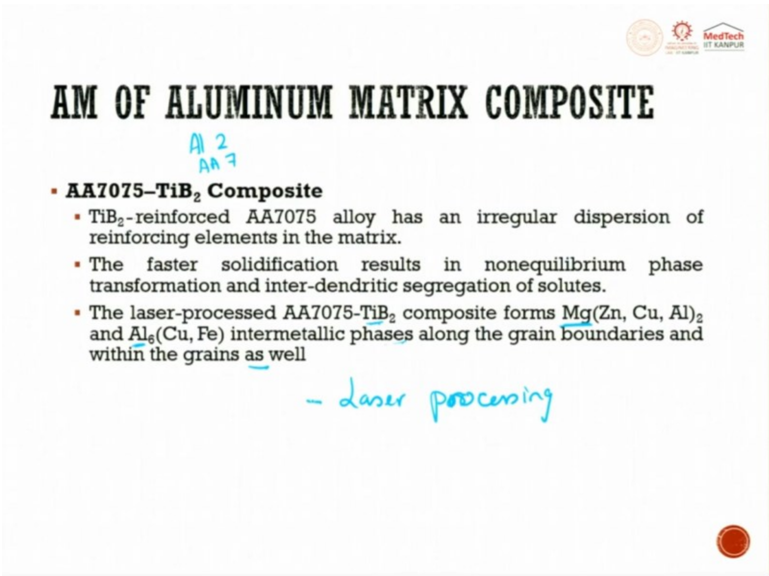

TiB_2 reinforcement AA7, so earlier we saw two series, Al two series, now we are going to see seven series, TiB_2 reinforced AA7075 alloy has an irregular dispersion of reinforcement elements in the matrix. The faster solution results in non-equilibrium phase transformation and inter-dendritic segregation of solutes. The laser processing of AA7075 TiB2 composite forms Mg and Al_6 intermetallic phase along the grain boundaries and within the grain as well. This is all possible because of laser processing. This is all because of only laser processing, if not also you can get but that is not an energy efficient way.

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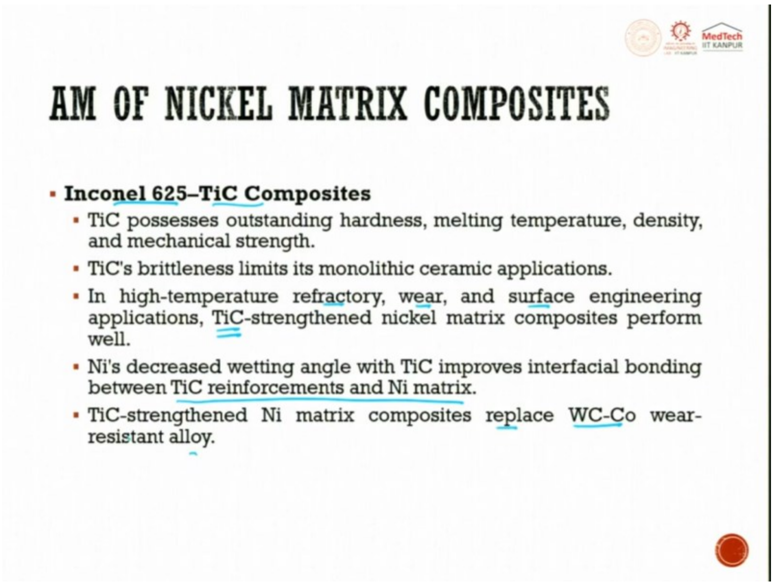

Now we will move on to nickel-based alloys. Nickel based alloys are Inconel 625 reinforced with TiC. TiC possesses outstanding hardness, melting temperature, density and mechanical strength. TiCs brittleness, limits its monolithic ceramic application. In high temperature, refractory wear and surface energy applications, TiC strengthened nickel matrix composites perform very well.

TiC performs very well because it tries to give a refractory wear and surface engineering. Ni decreases wettability angle with TiC improves interfacial bonding between TiC with Ni. Ni decreased wetting angle that means to say it can easily spread with TiC improves interfacial bond between TiC reinforcement and Ni matrix. TiC strengthen Ni matrix composite replace tungsten carbide cobalt wear resisting alloys. So, these are very heavy but these are all not very heavy.

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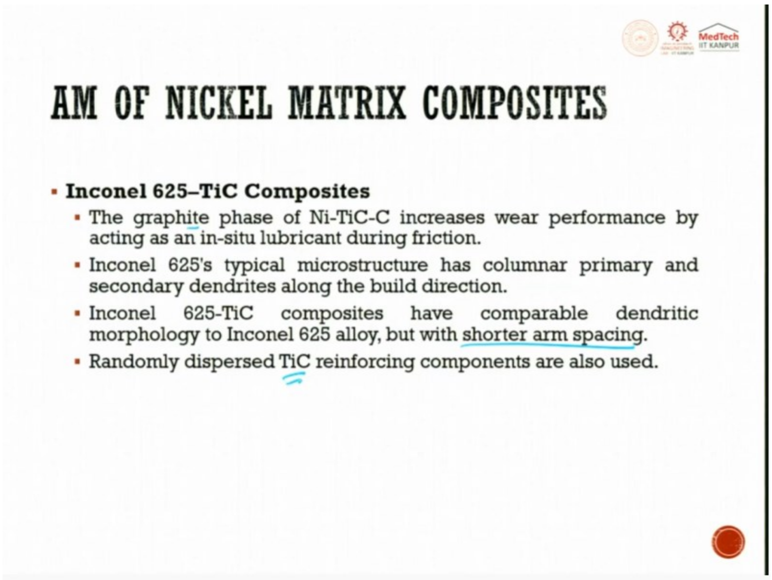

The graphite phase of Ni TiC C, we are bringing the C through the graphite phase. Increases wear performance by acting as an insitu lubricating between friction or during friction. Inconel 625's typical microstructure has columnar primary and secondary dendrite along the build direction.

Inconel 625-TiC composites have comparable dendritic morphology to Inconel 625 alloys, but with shorter arm length spacing. Random distribution of TiC reinforcing components are also used today.

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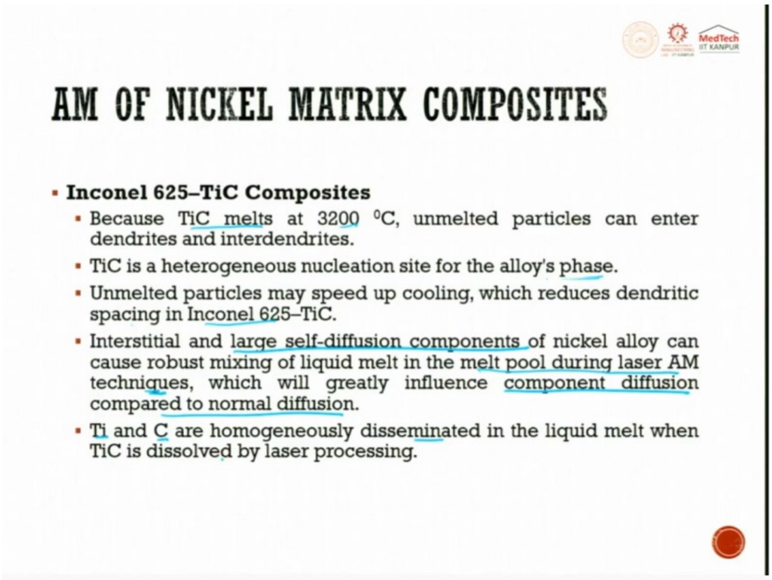

Because of TiC melt is around about 3200^0C unmelt particles can enter dendrites or inter dendrites. TiC is a heterogeneous nucleation site for the alloys phase. Unmelted particles may speed up cooling, which reduces dendritic spacing in Inconel 625 TiC. Interstitial and large self-diffusion components of nickel alloy can cause robust mixing of liquid metal in the melt pool during laser additive manufacturing techniques, which means greatly influenced the components diffusion as compared to that of normal diffusion.

Melt pool during laser additive manufacturing technique is self diffusion components. Interstitial and self-diffuse components of nickel. Ti and C are homogeneously disseminated in the liquid metal when TiC dissolved by the laser. Ti and C are homogeneously disseminated in the liquid metal when TiC is dissolved by laser power.

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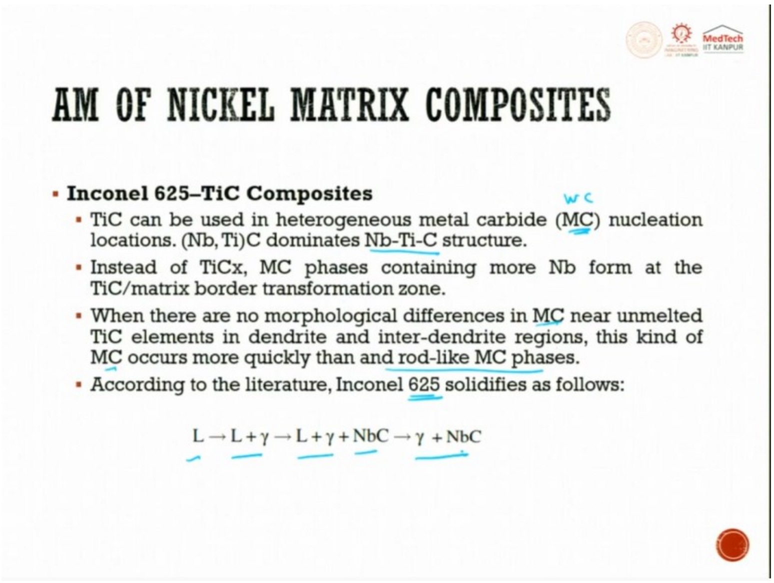

When we look at the entire thing TiC can be used in heterogeneous metal carbide, MC that can be WC, TiC, TaC, SiC, nucleation location Nb TiC dominates Nb TiC structure. Instead of TiC_x, MC phase containing more niobium form at the TiC matrix border transformation zone. When there are no morphological differences in metal carbide, nearly unmelted TiC elements in dendrite and inter dendrite region, this kind of MC occurs most quickly than the rod like structure in this.

From the literature, Inconel 625 solidifies,

$$L \rightarrow L + \gamma \rightarrow L + \gamma + NbC \rightarrow \gamma + NbC$$

So, this is what it is, when the laser is hit, it tries to form structures like this and these are columnar. When you form the composite like this, so you have these TiB_2 forming and they can form structures like this.

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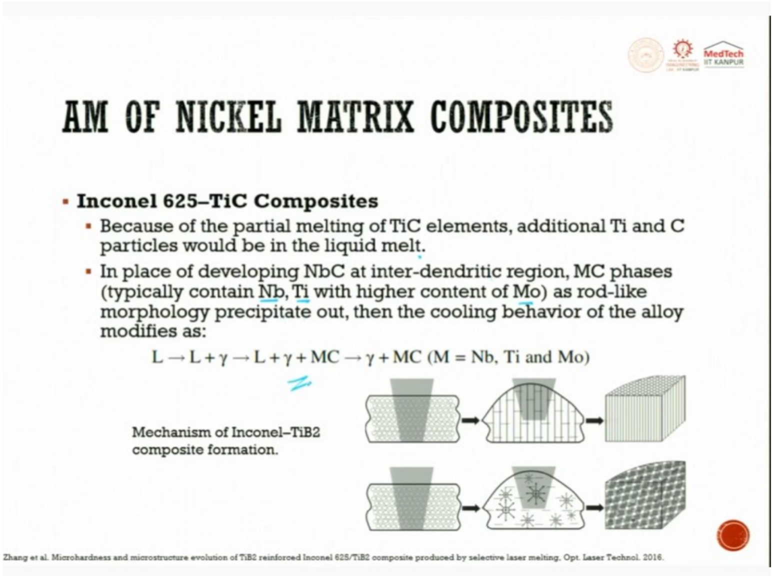

Inconel 625 TiC composite, because of the practical partial melting of TiC element, additional Ti and C particles would be in the liquid melt. In place of developing NbC at inter inter dendritic region, metal carbide phase containing NbTi and higher contents of Mo has rod like morphology precipitates out then the cooling behavior of the alloy is written like this.

$$L \rightarrow L + \gamma \rightarrow L + \gamma + MC \rightarrow \gamma + MC \text{ (M = Nb, Ti and Mo)}$$

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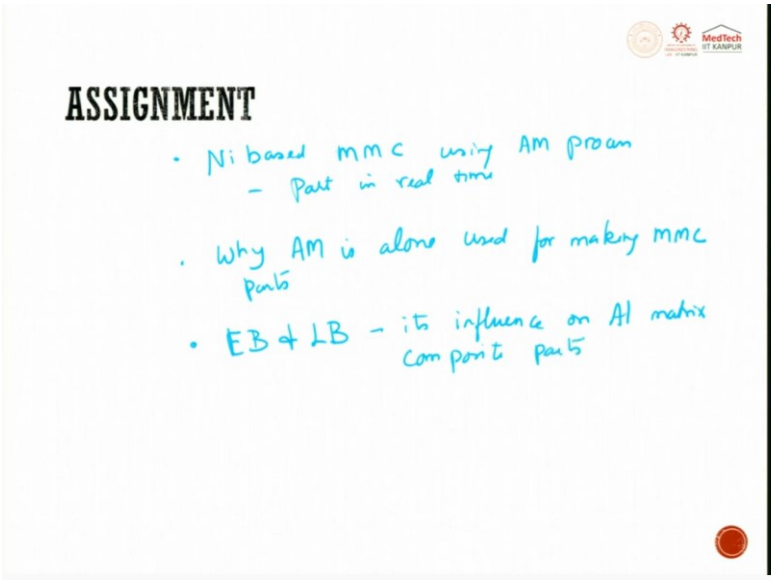

So, in this chapter, we tried to look out of applications of nickel-based metal matrix composite using additive manufacturing process part in real time. Second thing, why AM is alone used for making MMC parts? Electron beam and laser beam, its influence on aluminum matrix composite parts. These three questions are very important, that will give you more insight to understand what we discussed till now. Thank you very much.