The Future of Manufacturing Business:
Role of Additive Manufacturing

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Lecture-28
Additive Parameter Development

Hello all, in this session we will look into the factors considered for the additive parameter development work.

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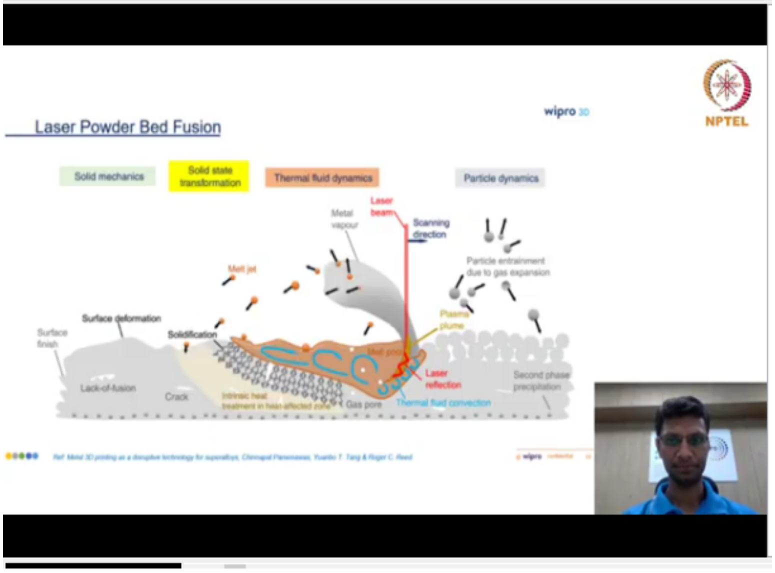

Laser Powder Bed Fusion

Ref: Metal 3D printing as a disruptive technology for superalloys, Chinnapat Panwisawas, Yuanbo T. Tang & Roger C. Reed

First going into the details of the LPBF process as you have already learned it is a layer by layer manufacturing process. I am not going into the details as it is already covered into the other session. But I am going into some details which are very important for the next session or next few slides. It involves selectively heating a thin layer of a fine metal powder with a moving focused laser causing it to melt and then solidify.

This intense localizer heating affects not just the metal that solidifies to form the part but the melt pool also emits a hot high-speed vapour plume that cools to form a fine mist of metal condensate nanoparticles. In addition, larger irregular spatter particles are rejected from the rolling melt pool. Both of these condensate and spatter will affect the laser interaction with the powder.

And cause the defect generation. Also with its melting and re-melting of fine powder size in micron, length and time scale lead to high cooling rates of 10^3 to 10^6 degree centigrade per second and a very different metallurgical response to processing and solidification can be seen. Triggering metallurgical defects which jeopardize mechanical properties.

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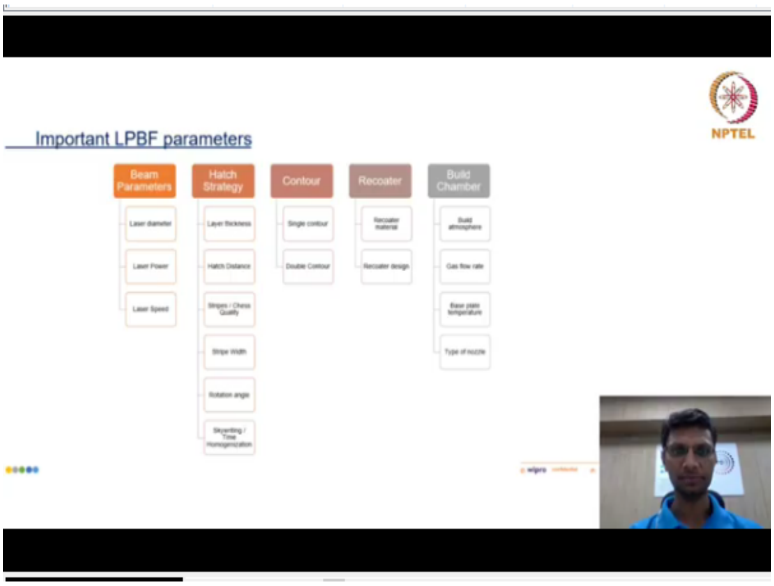

Important LPBF parameters

Beam Parameters
- Laser diameter
- Laser Power
- Laser Speed

Hatch Strategy
- Layer thickness
- Hatch Distance
- Stripes / Chess Quality
- Stripe Width
- Rotation angle
- Skywriting / Time Homogenization

Contour
- Single contour
- Double Contour

Recoater
- Recoater material
- Recoater design

Build Chamber
- Build atmosphere
- Gas flow rate
- Base plate temperature
- Type of nozzle

Going into the details of the LPBF parameter here I categorized some important parameters into different heads. These parameters need to be developed or decided during any new development work. Parameter to the laser beam or the laser diameter, laser power, and laser speed. Parameter categorized under the head of hatch strategy is the layer thickness, hatch distance, stripes, stripe width, rotation angle, sky writing, and time homogenization.

Contour parameters and then recoater material and recoater design also are very important. Build chamber parameters for example selection of the build atmosphere, gas flow rate, build plate temperature and type of nozzle. So, these how it affects your properties?

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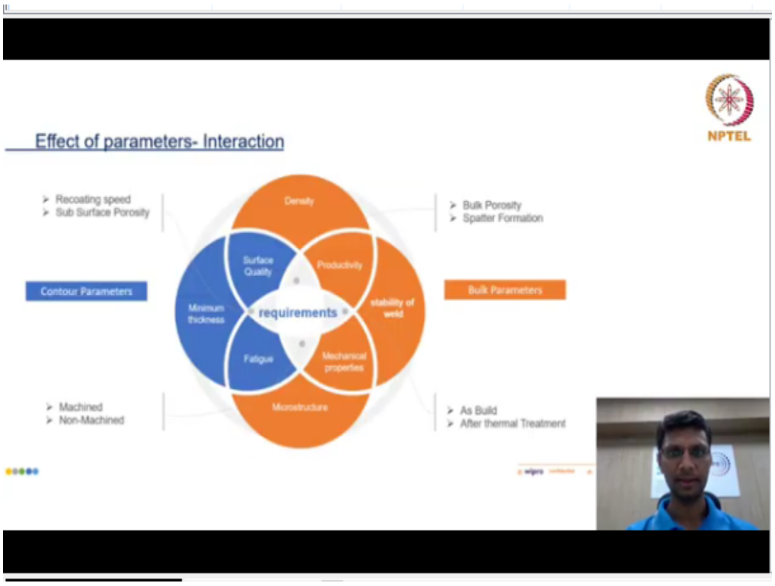

Effect of parameters- Interaction

- Recoating speed
- Sub Surface Porosity

Contour Parameters

- Machined
- Non-Machined

- Bulk Porosity
- Spatter Formation

Bulk Parameters

- As Build
- After thermal Treatment

Density

Surface Quality

Productivity

Minimum thickness

requirements

stability of weld

Fatigue

Mechanical properties

Microstructure

NPTEL

So, these parameters can be divided into two categories. First category is the bulk parameter and the second category is the contour parameter. These bulk parameters are directly affect your density productivity, stability of the well, mechanical properties, and microstructure, whereas contour parameters affect to surface quality, minimum thickness, and fatigue properties. During the parameter development there will always be some trade off between these different properties.

For example, if you need productivity you may need to compromise on the mechanical properties, same with the surface quality. If you need good quality surface finish in as build condition you need to compromise on the productivity. So, your AM should be clear while developing the parameters. So, this is regarding the parameters.

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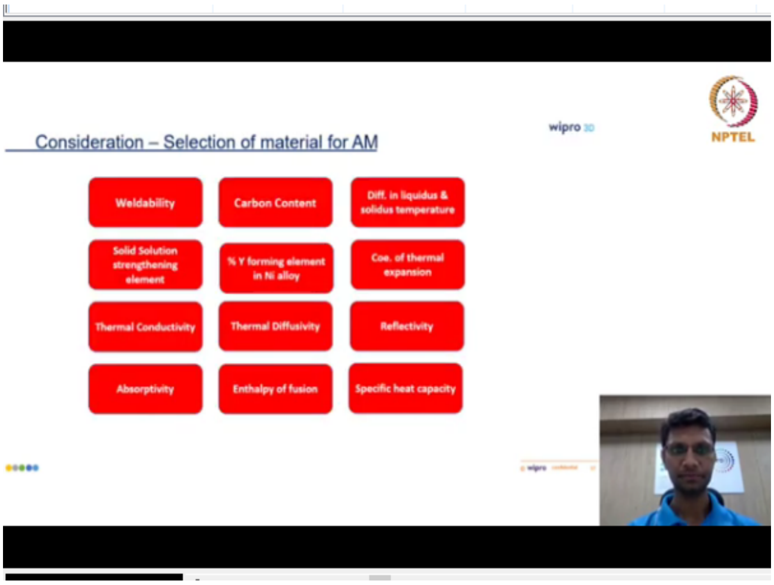

Consideration – Selection of material for AM

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Weldability	Carbon Content	Diff. in liquidus & solidus temperature
Solid Solution strengthening element	% Y forming element in Ni alloy	Coe. of thermal expansion
Thermal Conductivity	Thermal Diffusivity	Reflectivity
Absorptivity	Enthalpy of fusion	Specific heat capacity

And next slide is on the important considerations for the material selection. While selecting the material we are considering weldability, carbon content, difference in the liquidus and solidus temperature. Solid solution strengthening elements, percentage of gamma forming elements in nickel alloys, coefficient of thermal expansion, thermal conductivity, thermal diffusivity, reflectivity, absorptivity, enthalpy of fusion and specific heat capacity. So, why we are considering this?

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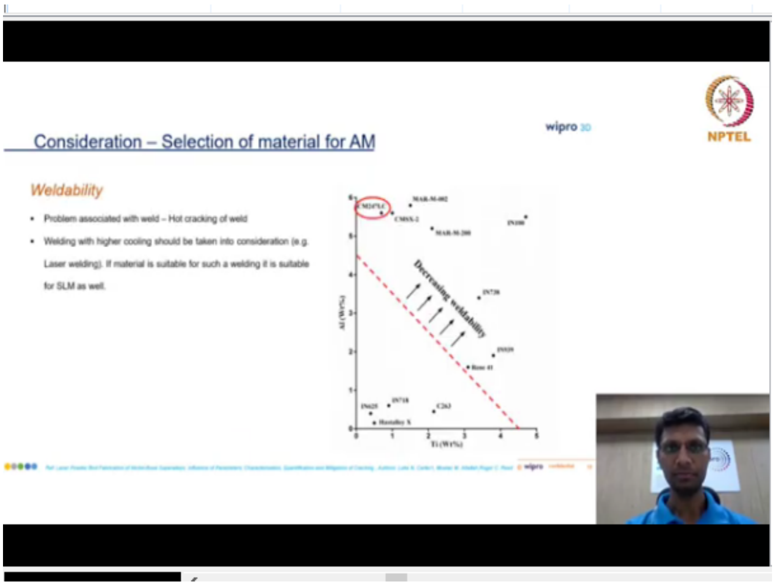

Consideration – Selection of material for AM

Weldability

- Problem associated with weld – Hot cracking of weld
- Welding with higher cooling should be taken into consideration (e.g. Laser welding). If material is suitable for such a welding it is suitable for SLM as well.

Because weldability is one criterion which we are considering because LPBF process is nothing but a welding process at micron level. It is very close to the welding technology. So, those steels having problem associated with the weld hot, cracking of weld will also face problems during the additive manufacturing. As cooling rags are very high and magnitude is of 10^4 to 10^5.

So, welding with a higher cooling rate should be taken into considerations. If the material is suitable for such a welding it is suitable for SLM as well. This is the part showing the Nickel alloys weldability, below this red line alloys are easy to weld and well established in AM industry. But above this redline these are some alloys which are difficult to weld due to their cracking tendency and because of the complex metallurgy phenomena.

These are the alloys difficult to weld but not impossible. So, major work is going on these alloys for bringing it into the AM bucket. We are also working on the CM247 alloy and is very near to the completion of the development work.

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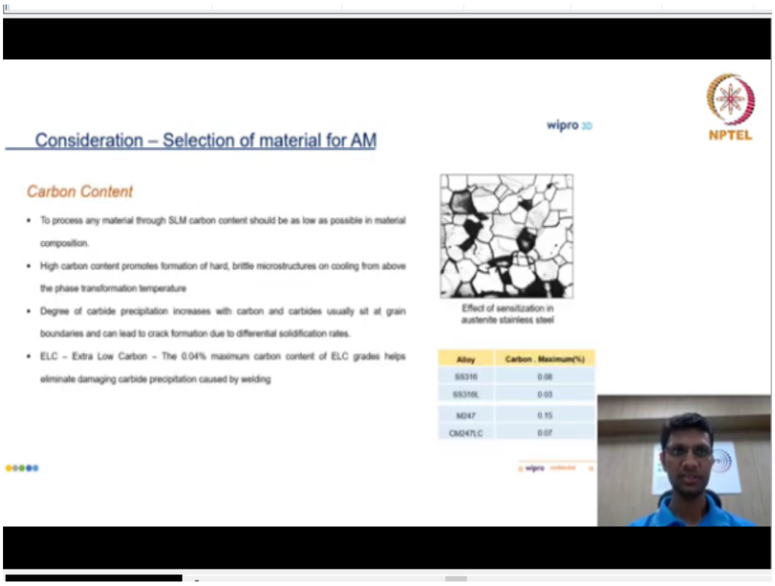

Consideration – Selection of material for AM

Carbon Content

- To process any material through SLM carbon content should be as low as possible in material composition.
- High carbon content promotes formation of hard, brittle microstructures on cooling from above the phase transformation temperature
- Degree of carbide precipitation increases with carbon and carbides usually sit at grain boundaries and can lead to crack formation due to differential solidification rates.
- ELC – Extra Low Carbon – The 0.04% maximum carbon content of ELC grades helps eliminate damaging carbide precipitation caused by welding

Effect of sensitization in austenite stainless steel

Alloy	Carbon . Maximum(%)
SS316	0.08
SS316L	0.03
M247	0.15
CM247LC	0.07

So, next consideration is the carbon content, to process any material through SLM carbon content should be as low as possible in the material composition. Because high carbon content promotes the formation of hard brittle microstructure on cooling from above the phase transformation temperature and degree of carbide precipitation increases with increase in the carbon content.

Carbides usually sit at the grain boundaries and can lead to the crack formation due to the differential solidification rates. Basically, it will embrittle your material to mitigate this nowadays AM material comes with a low carbon content. For example, in conventional SS316L, it comes with a low carbon content with the carbon content of 0.08, but the alloy available for the AM that is SS316L comes with the carbon content of 0.03.

Here in this SS316L meaning of L is the low carbon content grid, same is with the CM247 alloy, conventional CM2 for this 247 alloy still comes with a carbon content of 0.15%, but whereas in CM247 alloy available for the AM that is CM247LC low carbon grade it comes with a 0.07% of carbon. So, nowadays more and more alloys are coming with the low carbon content for the additive manufacturing.

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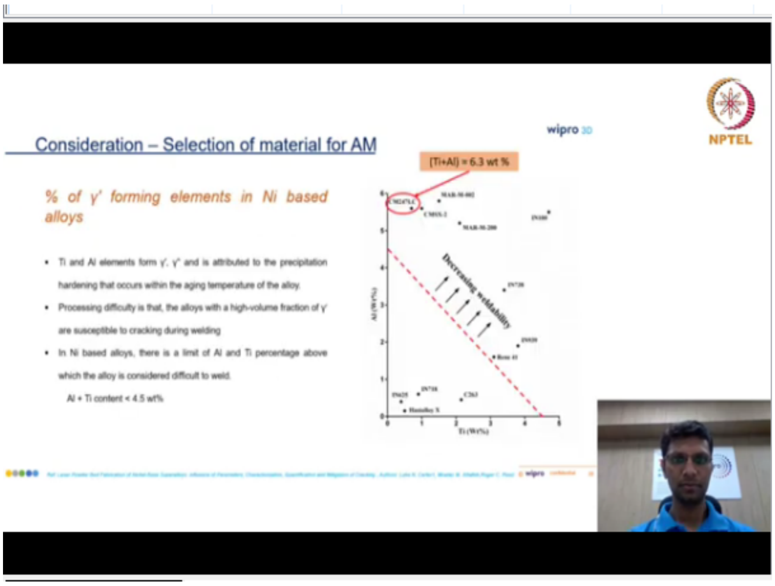

Consideration – Selection of material for AM

% of γ' forming elements in Ni based alloys

- Ti and Al elements form γ', γ" and is attributed to the precipitation hardening that occurs within the aging temperature of the alloy.
- Processing difficulty is that, the alloys with a high-volume fraction of γ' are susceptible to cracking during welding
- In Ni based alloys, there is a limit of Al and Ti percentage above which the alloy is considered difficult to weld.

  Al + Ti content < 4.5 wt%

Going to the next consideration that is percentage of gamma forming elements in nickel-based alloys. Titanium and Aluminium elements form gamma and gamma prime and gamma double prime. The chemical formula of the gamma prime is the Ni3 Ti or Ai. These are the precipitates gamma prime and gamma double prime which are part of strengthening mechanisms alloy, but with excess precipitation susceptible for cracking.

In this case processing difficulty increases with a high-volume fraction of gamma prime. In Nickel base alloys there is a limit of Titanium and Aluminium percentage, above which the alloy is considered difficult to build. If Aluminium and Titanium combine content is greater than the 4.5% it is considered as a difficult to weld material. We discussed this graph in the earlier slide. Here in the weldability slide here you can see the CM247 alloy is having 6.3% of combined Titanium and Aluminium content.

But still can be possible to print difficulty level increases and care needs to be taken while choosing the alloy.

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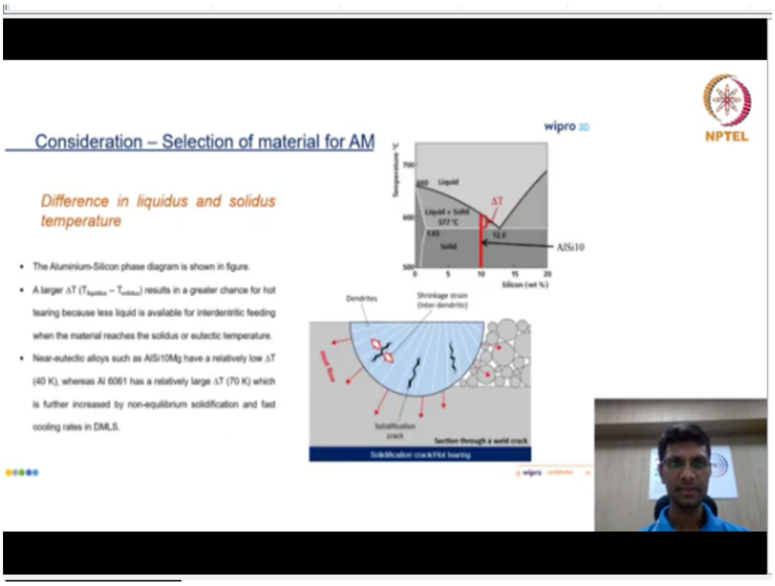

Consideration – Selection of material for AM

Difference in liquidus and solidus temperature

- The Aluminium-Silicon phase diagram is shown in figure.
- A larger ΔT ($T_{liquidus} - T_{solidus}$) results in a greater chance for hot tearing because less liquid is available for interdendritic feeding when the material reaches the solidus or eutectic temperature.
- Near-eutectic alloys such as AlSi10Mg have a relatively low ΔT (40 K), whereas Al 6061 has a relatively large ΔT (70 K) which is further increased by non-equilibrium solidification and fast cooling rates in DMLS.

Next consideration in the selection criteria is the difference in the liquidus and solidus temperature. This needs to be considered as a powder of aluminium and molybdenum alloy such as a ALSi12 or ALSi10 mg are relatively suitable for laser melting due to the small difference between their liquidus and solidus temperatures compared to the high strength rot aluminium alloys.

Here is the Aluminium Silicon phase diagram is showing in the figure you can see for ear eutectic alloys such as ALSi10 mg have a relatively lower ΔT which is 40 Kelvin. So, ALSi 10 mg can be possible to process with LPBF. But whereas AL6061 has a relatively large ΔT and around 70 Kelvin and difficult to process through the LPBF which is; further increased by non-equilibrium solidification and fast cooling rates in a DMLS.

So, what happens if the ΔT is higher, a large ΔT results in a greater chance of hot dating, because less liquid is available for the interdendritic feeding when the material reaches to the solidus or eutectic temperature. So, we look into the interdendritic feeding. So, far we have considered the melting aspects of the LPBF process and the effect on the part density.

Now we will look into the solidification process that is most critical to establishing the performance characteristics of the metal component, because solidification defines microstructure and which in turn drives mechanical properties. Many alloys are complex and can exist in multiple phases at different temperatures and compositions and so the solidification does not happen all at once.

Relatively little heat is lost into the neighbouring un-melted powder or via radiation into the chamber. As a molten metal cools the outer region of the melt pool falls below the liquidus temperature and one or more phase of the alloy will start to solidify, the remaining liquid phases are trapped between these primary dendritic frames, only solidifying once their lower melting points are reached.

Opposing cellular dendritic growth frames from the individual grain boundaries where the remaining liquid phases can also accumulate. The cooling process places strain on this cellular and grain boundary region which can results in a unwelcome porosity through a process known as a hot tearing or solidification crack in some materials. This is a waste where there is a large difference between the temperatures at which the different phases solidify.

So, that is why we are considering this ΔT difference in the T_{liquidus} and T_{solidus} temperature as important selection criteria for the metal layer.

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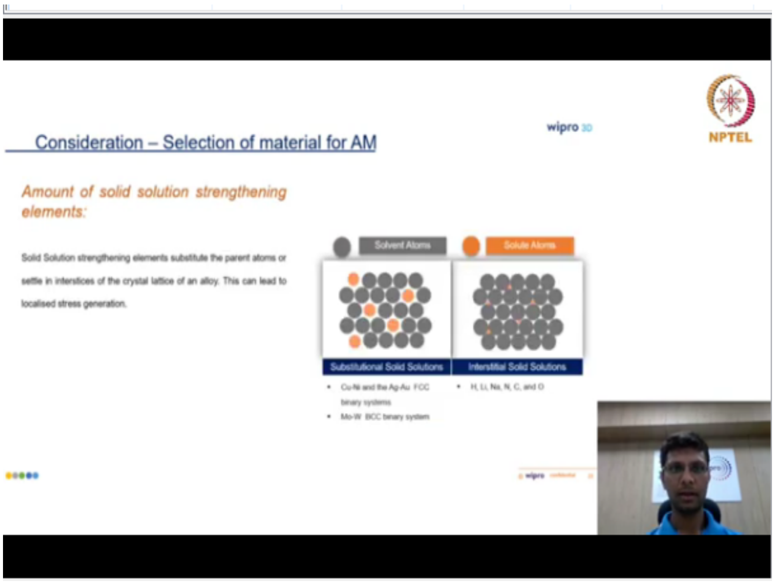

Consideration – Selection of material for AM

Amount of solid solution strengthening elements:

Solid Solution strengthening elements substitute the parent atoms or settle in interstices of the crystal lattice of an alloy. This can lead to localised stress generation.

- Cu-Ni and the Ag-Au FCC binary systems
- Mo-W BCC binary system

- H, Li, Na, N, C, and O

Next consideration in the list is the amount of solid solution strengthening elements. When the atoms of the base metal that is solvent and the alloying element which is solute completely dissolve in each other and become an integral part of the solid phase of an alloy, the resulting phase is called as a solid solution. There are two types of the solid solution. One is a substitutional solid solution and the second is an interstitial solid solution.

In substitutional solid solution solute atoms such as are roughly similar to the solvent atoms, due to the similar size solute atoms occupy a vacant site in the solvent atoms. For example, copper and zinc, copper and nickel are some examples of substitutional solid solution and in interstitial solid solution solute atoms are much smaller than the solvent atoms.

So, they occupy interstitial positions in the solvent lattice. Carbon, Nitrogen, Hydrogen, Oxygen, and Boron are the elements which commonly form interstitial slide solid solutions, due to this substitution of the parent atoms or settle in the interstitial stress of the crystal lattice of an alloy. This can lead to the localized stress generation. This is also one of the strengthening mechanisms. But stress generation is what you need to take care during the processing.

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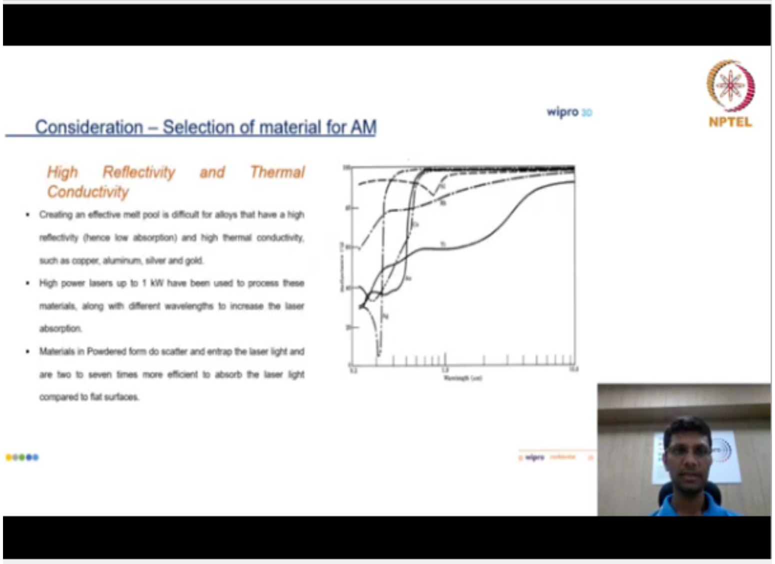

Consideration – Selection of material for AM

High Reflectivity and Thermal Conductivity

- Creating an effective melt pool is difficult for alloys that have a high reflectivity (hence low absorption) and high thermal conductivity, such as copper, aluminum, silver and gold.
- High power lasers up to 1 kW have been used to process these materials, along with different wavelengths to increase the laser absorption.
- Materials in Powdered form do scatter and entrap the laser light and are two to seven times more efficient to absorb the laser light compared to flat surfaces.

Next consideration is the high reflectivity and thermal conductivity. So, creating an effective melt pool is difficult for the alloys which have high reflectivity and high thermal conductivity, such as a Copper, Aluminium, Silver and Gold. High power lasers up to 1 kilowatt have been used to process these materials along with a different wavelength to increase the laser absorption.

For processing of ALSi10 mg we are using the highest power almost near to 100% utilization of laser power on our USM 290 machine, whereas other materials can be processed with only 60 to 70% of laser capacity. Materials in the powder form do scatter and interrupt the laser light and are 2 to 7 times more efficient to absorb the laser light compared to the flat surfaces.

Because of this at least it is possible to process these materials with LBPF technology. Otherwise it is very difficult to process these alloys because of this high reflectivity. So, these are the some of the important consideration factors we have seen in this session which will guide you for the right material selection for the AM and what are the difficulty levels with the different types of the materials will get to know and maybe you will be prepared for the same.

So, this is all about the parameter development and considerations factors for the material selection. In the next session we will go into the details of the common defects in LPBF and what mitigation strategies can be used to remove these common defects on to mitigate these common defects. Thank you for attending the session.