

# **Advances in Additive Manufacturing of Materials: Current status and emerging opportunities**

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## **Lecture 18**

In this lecture and then in a subsequent lecture, I will be discussing the process science of the laser based additive manufacturing processes. This process science as you will notice will be very different from what you have learnt from the binder jet 3D printing because in binder jet 3D printing essentially no external heat source is used. It takes place at room temperature or physiologically relevant temperature. And also it involves mostly the binder or ink, aqueous ink and their interactions with the powder bed. And then we have also seen that how to develop more mathematical framework based analysis of the binder jet 3D printing by simple geometry based calculations and also using some of the established models like from Washburn model or Karmans models and so on. Laser based 3D printing in general is very different from binder jet 3D printing.

If you remember from one of the previous lectures that where we have discussed about the laser engineered net shaping which is in practice or reality since 1997. I have also mentioned in the earlier lectures that typically selected laser sintering, selected laser melting, these are all synonymous. And what you see here in both these processes of selected laser sintering, selected laser melting, these are all laser powder based fusion processes and these laser powder based fusion processes you are essentially focusing the laser beam. and this laser beam is scanning like this and this powder bed here powder particles they are being constantly melted and solidified according to this laser beam, Beam parameters and so on this way you can essentially fabricate layer by layer fabrication processes and then you can make the engineered part at the end of the selected laser sintering.

This is one of the videos that you can see that how SLM based 3D printing of Ti6Al4V is actually taking place in industrial scale production processes. One layer is gone now another layer will be melted then solidified on the above that on the top of the previously solidified layers. that in the layer by layer process this material will be developed they will be built up and at the end of the process you can see how different components are essentially fabricated . this is again another layer that is being deposited. this is all about SLM based 3D printing of Ti6Al4V.

What are the specific advantages of SLS or SLM technique? The complex shaped parts can be manufactured without any support structure and no post curing and no tooling cost is incurred and no wastage of materials, unused powder is also reprocessed. This is just an example of corderite that is one of the ceramic which has been printed using selected laser sintering. This is another example of SLM based 3D printing of aluminium, silicon, tin, magnesium alloy. This is one of the most widely investigated aluminium alloys and these materials are used in aerospace and automotive applications and you can see that how these materials are being printed using selected laser melting method. This is one layer is being printed, now another layer is deposited and again laser beam will be in action and you can see this laser beam is essentially interacting and slowly they will be melting and solidifying the layer as per the design.

contained in the STL file and according to this design this particular component will be fabricated. this is second layer is being printed, now if you further continue this video you will see that during that individual layer according to the component shape and size The entire part will be scanned and they will be melted and solidified and then only next layer of powders will be displaced and then this next layer of powders will be printed. this is how the subsequent layers are being printed and solidified. This material is aluminum silicon 10% magnesium alloy which has been extensively used in aerospace and automotive applications. Now, directed energy deposition as a process has been introduced in one of the earlier lectures and direct energy deposition this is relatively less explored or less investigated when compared to SLS or SLM technique.

However, this has distinct advantage and the direct energy deposition, as far as its functionality concerned or as far as operation concerned is very similar to that of the laser engineered net shaping technique. But however, they are being known in the community with different names. And, what you see in the directed energy deposition process which is quite widely used in Indian Institute of Science as well and this is one of those few machines that which are currently available in India. where laser beam is focused on a substrate at specific locations or in a moving locations and then this particular substrate is rotated. in a specific manner according to the part to be printed using this directed energy deposition and coaxially powders are also being delivered to the laser beam, laser substrate interaction zone.

And these powders they will interact not only at the laser beam stream but also they will constantly melted or they will be instantly melted and solidified on the structural parts where these powders are being constantly deposited. Now these two videos when you see you should be able to observe that on a complex shaped part when you are depositing these powders they will take the contour of this particular parts outer boundary and they would

be able to essentially get the material solidified. And then you can see on the left panel that towards the end how these kind of parts are being manufactured very rapidly in this particular video. Another material which is being printed using selected laser melting, this is the copper, chromium, zirconium alloys and these are widely used as radiators and heat exchangers and you can see that how this material is being printed in these heat exchangers using that copper, chromium, zirconium. just to show you that how the different materials are being printed using these techniques Now, coming to the process science involved in these processes, so essentially laser material interactions is the central theme of these process science in both these processes.

Now, SLM is the powder bed based processes, directed energy deposition is not powder based processes, here laser beam also interacts with these powders on its path of interactions. But here laser beam is incident on this particularly powder bed and then they are melting constantly this powder bed or very thin layer and subsequently this melting and solidification takes place. SLM essentially uses lower laser power and higher laser scanning speed whereas DED you can go for the maximum build size with lower dimensional accuracy. In terms of the different process parameters which are used in these two techniques like in DED technique you can use the power as 0.1 to 3 kilowatt whereas SLM it can go up to 50 watt to 1 kilowatt.

Speed wise, SLM is much higher speed like it can go up to 10 to 1000 millimeter per second, this very-very high speed like 10 millimeter per second to almost like 1 meter per second that is quite high whereas in DED it is 5 to 20 millimeter per second. Maximum feed rate it is 0.1 to 10 gram per second. Maximum build size it can go 2000, 1500 and 750 whereas SLM it can go up to 500, 280, 320. if you look at that maximum build size this DED process is more advantageous.

Also, if you look at the dimensional accuracy and particularly surface roughness, surface roughness is little better in DED compared to the SLM. And in both the cases, you need to do heat treatment, And then speed of laser scanning speed SLM process is much faster compared to the DED but power wise DED process essentially can use more power like 100 watt to 3 kilowatt. in the directed energy deposition process like process property structure correlation that is important concept in the material science and that has been introduced to you in an earlier lecture. what are the major important facets in 3D printing? We want to get fully dense parts particularly for structural applications or non-biomedical applications fully dense parts with near net shape. like without so that we do not need much of machining and much of other post surface treatment.

Material gradient, surface modification, higher build rates and build volumes these are also important. And then surface roughness and post processing these are also required,

these are the major disadvantage of some of the laser based additive manufacturing techniques. one of the important aspect in this powder based additive manufacturing or laser based additive manufacturing which are essentially involving powders or powder bed is the powder characteristics. Like this powder characteristics is very important and that determine the quality of the products and also the process kinetics also to some extent of the 3D printing processes. Now, typically metal powders or metal alloy powders are printed using multiple techniques in a commercial scale production.

And one of the most widely used techniques is gas atomization. In gas atomization essentially liquid metal is dispersed by a high velocity jet of air, nitrogen, argon or helium. And gas atomization powders contain entrapped gas bubbles leading to porosity in these components. Then there is another kind of processes called PREP plasma rotating electrode process and this leads to most uniform size distribution and this has lower porosity than gas atomized powders. And prep is a centrifugal atomization process where the end of a consumable metal bar is melted while being rotated about its longitudinal axis.

And third one is a water atomization. In the water atomization process, we get the powders in irregular shape. As you can see here, this D is the water atomization process. It is very irregular shaped powders and that can lead to the nozzle blocking and so on. A is perfect plasma rotating electrode processes.

You can see perfect spherical shaped powders. C is that gas atomization processes. Now, these are the powders which are alloy powders, there is also inconel 718 powders, this is that gas atomized powders and this is like prep powders. Depending on which processes you use, you will be able to get powders with different morphologies and different size distribution. it is not only the size distribution but also powder shape, powder morphological characteristics that actually determine the 3D printing processes.

what are the laser characteristics and laser powder interactions? laser power density is essentially it shows more or less like a Gaussian type of distributions and if you look at that power density distribution when powder is absent in the absence of powder. this power density distribution essentially follows this kind of expression like  $P_d$  is equal to  $F_p$  by  $\pi R_b^2$  that is the beam radius exponential minus  $F_p \cdot r^2$  by  $r_b^2$   $f$  is the distribution factor. Now, depending on the  $f$  value you will be get the different distribution this is  $f$  value is equal to 1, this is  $f$  value equal to 2, this is  $f$  value equal to 3. more is the  $f$  value the peak in the distribution increases.

and then width of the distribution also decreases because if you see that  $f$  is equal to 1 much broader it is becoming more and more narrower and if you look at this trend it will be clear to you at  $f$  equal to 4 and all this peak is much more sharper and much narrower.

energy becomes more focused and high peak temperature that is very clear because if you look at that peak density here it is power density is close to 1 kilowatt per millimeter square. Now in a process like DED or the laser beam will have the opportunity to interact with the powders during the flight itself. And in case of powder bed processes, the laser beam will be falling on the powders and depending on the powder particle size distribution, they will be interacting with these powder particles. Now, same laser power distribution function in the presence of powders that will be modified.

And if you look at this equation, what is the important things that you notice, it is these particular parameters is there and  $t$  is also another parameters that is the time of interactions.  $\eta_p$  is the fraction of the laser power being absorbed by the powder during flight and  $\eta_L$  that is this particular parameter it is the absorption coefficient of the deposit. these two part is important here and these two part is contained in this particular equation. that this laser power density functions is also modified by this particular expression All other parameters remain constant except you have a  $t$  term and you have also a function of  $\eta$  term where function of  $\eta$  is  $\eta_p + 1 - \eta_p \exp(-\eta_L L)$  where  $\eta_p$  is the fraction absorbed by powder during flight and  $\eta_L$  is absorption coefficient of deposit. Now in this particular slide what you see that this powder particle shape is important powder morphology.

not only size and size distribution, laser powder interaction either in flight or you know after deposition, heat and mass transfer and fluid flow like Marangoni flow and also Marangoni convection flow and also laser characteristics. This part of the slide it is kind of should be clear to you. left part of the slides is clear to you. Let us focus on the right part. Right part also this particular equation I have described to you in the last slide that how laser power distribution function is changed in the presence of powders and that what you can see that these particular parameters is actually present which is not there in case of the laser power distribution without powders.

Now, what you see in terms of the heat and mass transfer, so essentially there is a heat absorption or reflection by the powder and there is a molten pool formation. The molten pool formation what you can see not that clearly, there is a fluid vector that will be created which will be rotating in the laser melted pool and the heat will be lost from the molten pool by radiation. heat will be conducted away to the substrate or the corresponding powder bed also and also there will be likelihood of the formation of the Marangoni convection. Therefore, you have to utilize the fundamental heat transfer equations as part of the study of the process science understanding of this SLM process or DED process and some of the equations that you see in this particular slide, it comes from the mass momentum conservation laws and also if you see this is the fundamental heat transfer equations like  $-\nabla \cdot \mathbf{q} = \nabla \cdot (\mathbf{K} \cdot \nabla T)$ . So, that is the temperature gradient  $\mathbf{K}$  is a conductivity  $\sigma$   $S_b$

$\epsilon T^4 - h_c(T - T_a)$  to the power 4.

You can see that any times fourth power of temperature that would remind you of the Stephen Boltzmann equations and  $h_c$  that is heat transfer coefficient into  $T - T_a$ ,  $T$  is the melt pool temperature,  $T_a$  is the ambient temperature. There are other equations and detailed description of these equations is beyond the scope of the study based on course, however all the viewers and students of this course can look at some of the authoritative review papers which are published in this area and one such review paper has been mentioned here from the group of Professor T. DebRoy at Penn State. This review paper was published in Progress in Material Science in 2018. this is in one such review where you can find all these descriptions in a very authoritative manner.

As I said during the discussion of the previous slide that you are essentially following the mass, momentum and energy balance equations. mass balance is essentially  $\frac{d\rho}{dt} + \frac{d}{dx}(\rho u) = 0$ . So  $\rho$  is the density. Momentum balance is also mentioned here. this is the velocity factor  $\frac{d\rho}{dt} + \frac{d}{dx}(\rho u) + \frac{d}{dy}(\rho v) = \frac{d}{dx}(\mu \frac{du}{dx}) + \frac{d}{dy}(\mu \frac{dv}{dy})$  and similarly energy balance equations are also mentioned.

if you look at that combination of convective and radiative heat transfer, this part is the radiative heat transfer. This part is the convective heat transfer. and this is the thermal conductivity and then temperature gradient. Maragonii flow  $\tau_m$  is equal to  $d\gamma$  by  $dt$  into  $dt$  by  $dr$  is equal to  $-\mu \frac{du}{dx}$ . So, these are the non-dimensional number or non-dimensional number or dimensionless number like heat input, it is  $Q^*$ , Marangoni number is  $Ma$ , Peclet number  $Pe$ , Fourier number  $F_0$  and strain parameter  $\epsilon^*$ .

Now, if you remember well that during the binder jet 3D printing also when I was discussing process science of the binder jet 3D printing, there also I use the different dimensionless parameters. And these dimensionless parameters are Ohnesorge number, Reynolds number and so on. Now, when I have been discussing now in this particular lecture, laser powder bed interactions or laser powder interactions during the DED process where we have been invoking mass balance, momentum balance, energy balance to describe the total process signs. There again in order to develop a complete understanding we are using multiple such dimensionless number. So, from all this discussion one thing that should be very clear to you additive manufacturing truly or the science of additive manufacturing truly is a multidisciplinary field where you can bring together concepts and ideas from fluid dynamics that is core into the mechanical engineering and mechanical sciences discipline.

with the material science, with optical science for when the laser beam is interacting, what

is the laser material interactions, that is the core of this optical or physical sciences. all these integration of the ideas and concepts truly make this additive manufacturing an interdisciplinary area. I will come back to you in the next lecture to show you how the microstructure that develops during the additive manufacturing processes particularly laser based additive manufacturing processes and to show you to an extent possible the different materials which are being widely investigated in this additive manufacturing processes. how their microstructures evolved during the process of additive manufacturing. Thank you.