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

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Lecture 19

In this lecture, I will be discussing on the microstructure development during laser based additive manufacturing processes. microstructure is the key aspect which determines properties of any materials In case of additively manufactured materials, the way laser beam interacts with the materials that determines the evolution of the microstructure. And microstructure as a result will influence the properties of the materials. This particular process like selected laser melting processes will be discussed in reference to their ability to generate microstructures in different materials. Particularly, I will show you mostly the examples from titanium alloys because titanium alloys it is not only used for aerospace applications but also for biomedical applications. Although, this particular video was shown before, I thought before I will show you this microstructure, it may be it is pertinent to show you again this specific video just to show you how the laser beam interacts with the powder bed during the SLM processes.

And, how the different components are being manufactured in a layer by layer manner, each time a new layer is exposed to the laser beam, the similar interaction processes involving melting and solidification of the materials will continue and then again the next layer is deposited, next layer interacts with the laser beam, again the same process you will continue. so that you know this entire component is being manufactured in a layer by layer manner After this video it should be more clear to you that how the material is experiencing thermal history and also material is experiencing repeated laser beam interactions. typical representative microstructures of Ti-6Al-4V You can see this is the oriented martensite plates. Those who are from metallurgical engineering background, they know this martensite is one of the metastable phases.

And this martensite in steel essentially results in high hardness of the material. Martensite, Martin was a German scientist on its name this martensite is mentioned. This is alpha, beta. biphasic microstructures and these different phases as you see this also appears with different morphology in this biphasic microstructures. you have a base metal.

This is the base metal. It is the equiaxed alpha grains. This is the heat affected zone. This heat affected zone is also developed during the welding of materials. In a way if you see

that many scientists or researchers who contributed quite significantly to additive manufacturing, they essentially come from welding community like those who are very busy like mechanical engineering or material scientists.

who have done substantial work in the field of welding, they found it much easier to translate their work, their thought process, their concepts, their ideas to understand and to exploit their understanding in developing new materials or new structures in the additive manufacturing sector. heat affected zone either is dominated by alpha plus beta alloys or beta grains and accordingly they are also referred as that heat affected zone beta and this is the deposit that is being, this deposit is mostly Wittmann-Straten alpha. This kind of description follows the conventional metallurgy or phase transformation description of the microstructure. titanium 6 aluminium and with addition of vanadium how the different phases and then how this temperature versus how the phase diagram evolves, the different phase boundaries evolves that is being shown. this phase is completely beta phase, this phase is alpha plus beta and this alpha phase and if you superimpose the martensite start temperature ms on this, this follows this kind of trajectory and this is Ti6Al4V, so if you draw this 4% vanadium on this particular binary phase diagram, then you can see that what is the temperature of the beta dominated heat affected zone or alpha plus beta dominated heat affected zone on this particular phase diagram.

Now solidification, now when this material gets melted, they eventually get solidified but in this particular case of the laser based IT manufacturing process, the solidification process is very rapid or so it is one of the rapid solidification processes. what are the two things that are important in this solidification? One is the temperature gradient G and one is the growth rate R. traditionally if you look at any kind of microstructure that is generated as a result of the solidification, the characteristics of the microstructure largely depend on the combination of G and R values. And for examples, if there is a liquid solid solidification front, so how this liquid solid solidification front traverses. For example, if you have a mold and then you are pouring this liquid metal into the mold, liquid metal.

During that conventional casting processes, this particular region essentially mold wall actually provides sites for the heterogeneous nucleation sites. And after this mold, then this interface actually grows in this direction. Same thing is true that this interface grows in these directions and also from the base, this interface grows to these directions. When they meet, then they will in the central zone, you can also see lot of equation. this is called, so some of the terminology that I am mentioning, you must have heard the word grain and grain sizes before in one of the previous lecture.

Equiaxed grains are essentially Equiaxed grains are essentially smaller sized, finer sized grains. I am just looking at the microstructure which is there, no. So, equiaxed grains are

essentially the sizes of the grains, for example, if you draw a hexagonal array of grains, so if you take the center of the grain, then if you say three different directions of this grain, then you can see that the dimension in three different direction is equal. that is why equiaxed means equal dimensions in three directions. Then there is a columnar grains, you can see that the description of the columnar grain like you can see this is a large columnar grain And this is the case for the large columnar grain and these columnar grains are seen in many classical microstructure and the central region of the mold is again equiaxed grains.

When equiaxed grains forms and when equiaxed grains actually undergo transformation to columnar grains, these are all dependent on the combination of these G and R values that is the temperature gradient and growth rate. what happens this is called planar solidification front. when this planar solidification front that breaks down then it gives rise to some kind of undulation or perturbation in the structure. When it grows this undulation essentially also grow with time. It grows and then it becomes very unstable, then this is broken.

this actually gives rise to more or less like a dendritic type of structure. what is dendrites? Dendrites are essentially can have a primary dendritic arm. And from the primary dendritic arm, you can have a secondary dendritic arm. And from secondary dendritic arm, you can have a tertiary dendritic arms. And depending on that what is the spacing of the secondary dendritic arms and primary dendritic arms, this kind of dendritic arm spacing also important in the context of microstructure characterization.

what you see here, this is a planar front. And this planar front is essentially in this particular space like this is the combination of G and R. This is cellular microstructure. And this is the lower cooling rate and higher cooling rate and finer structure that is being developed. And G / R essentially determines the morphology of solidification structure whereas G cross R, the product of the G and R that determines the size of the solidification structure like what is the length scale of the solidification microstructure.

And what you see a different region is divided into columnar dendritic, equiaxed dendritic and so on and you have a high G by R ratio and you have a low G by R ratio that has been also mentioned in this part. I repeat the ratio of G to R determines the morphology while product of G and R that determines the size of the solidification structure. when fully equiaxed microstructure develops that is in the combination of the lower G value and then higher E values. When fully columnar grain structure develops that is the combination of very high growth rate. that there is anisotropic structure, because the moment if you see this is the dendritic structure, it should remind you that it is highly anisotropic in nature, these highly anisotropic grains are developed in this kind of microstructure and there is a

transition between fully columnar to fully equiaxed, it is the mixed type of structure.

this is the microstructure property relationship in a typical SLM process, what you see typically both the columnar and the EQS grain morphology that develop and this is the nucleation sites of the powder nucleation, this is the base plate nucleation. And this kind of contours that you can see outer layer curved columnar grains, these contours develop and that facilitates the columnar structure. Actually, this is the depth of the melt pool and this is the spread of the melt pool and this is the laser scanning directions. you can see that you can visualize now that how the laser beam interacts with the melt pool and then how this microstructure develops and then it also undergoes transition from columnar to aqueous grain by varying G/R. So, you understood the two important parameters here.

I must remind you that this is not a course on metallurgy or material science. This is a particular course on additive manufacturing. Therefore, I am not getting into too much details in the microstructure development which requires your in-depth understanding in the phase equilibria into the phase transformation. But I am trying to explain you in a manner which is most relevant from the additive manufacturing standpoint for you to know and to know that why equiaxed microstructure and columnar microstructure develops as a function of G and R. I reiterate that combination of G and R that determines overall microstructure development and G by R ratio essentially determines the morphology where G cross R that means product of G and R determines the scale of the microstructure.

So, these are like different characteristics and different grain characteristics of this microstructure. This is a different type of alloy. This is a Ti-6.

5Al-3.5 Mo-1.5Zr-0.3Si Remember, those who are non-material scientist and non-metallurgist, this alloy essentially the mixture of 2 or multiple metals in a specific ratio. The advantages of alloys is that you can achieve a quite different microstructure and you can achieve perhaps better material properties compared to single component metals. Now, titanium and aluminium is the base material. you know it has titanium 6 aluminium then you can add vanadium or instead of vanadium you can add combination of molybdenum zirconium and silicon. each time small alloying element is added.

And that leads to the development of very different microstructures. For example, here instead of 0.3 silicon, if you add 2% or 3% of silicon, certainly you will see a completely dramatically different microstructures that is being generated. you have this alpha prime martensite here that you can see that you know how the martensite develops. This is the fine columnar grains and Widmanstatten structure.

top region is the colonies of parallel very fine lamellae and larger laths and bottom region

is the thicker lamellae structure. So, you can see this is the weld pool, this is the heat affected zone. This heat affected zone typically develops during the welding and this welding can take place in different processes and those who are from mechanical engineering background they remember this welding processes can be MIG welding, TIG welding and so on and so forth. typically you have that equiaxed grain zone.

Then, you have a columnar zone. columnar zone constitutes a large part of the microstructure of the welded microstructure and you can see the size of these columnars or the aspect ratio of the columns. equiaxed grains can be described by one single number but columnar grains needs to be described aspect ratio and also longer size you know that what is the size of the columns in one direction compared to the width. What are the different factors that affect metal 3D printing? different factors essentially determine the quality of the metal 3D printing products. different factors means mostly the defects like gas porosity, lack of fusion, melt pool instabilities and so on and melt pool instabilities lead to key-holing, random power fluctuations and so on. In this slide what you see the evidences or occurrences of different type of defects like lack of fusion here .

Balling, this is also one type of defect. Then keyholing, keyholing means that during due to this marangoni flow these keyholes that is being produced and these keyholes there is a vapor entrapment and that means there is a large elongated porosity that is being generated. this particular arrow essentially indicates how the heat is conducted away to the surrounding material. this is the laser power distribution that in case of high laser power when the melt pool forms there are chances that keyhole evolves. And because of this high heat that is being generated and also this heat is being conducted away, there is a chances that residual stresses also will develop.

And these residual stresses can be if that can be contraction in nature that means equal stresses from two opposite directions. Then, it will lead to shrinkage of the solidification and then it can lead to the cooling solid well track. And this has also finally lead to the failure due to the residual stress of these components. in the laser based powder bed fusion processes, one of the things that one has to very clearly understand that there is something called linear heat input and powder feed rate. depending on this combination of the linear heat input and powder feed rate.

various defects that evolve and these defects are indicated here, this is lack of fusion zone, this is the mid porosity zone and key holding zone. Any time in any material these defects will evolve that will compromise essentially the mechanical properties, whether it is a strength properties, whether it is a hardness properties and so on. Second one, the powder bed characteristics or powder bed properties. powder bed properties. powder bed properties essentially means there is a packing density like how powder particles, smaller

particles or combination of coarser and smaller particles they are being packed together in this kind of materials.

and then how layer by layer material is getting deposited on this material and what is the build directions like you know theta and what is the layer thickness. All these attributes essentially influence the quality of the additive manufactured parts and essentially to recap what I have been discussing last few minutes is the defects, multiple defects of different types can be generated. as a result of the use of different combination of laser power and powder feed rate. At this point I must mention that whenever you are developing any new material composition and you are using laser based additive manufacturing processes then you have to utilize the combination of different process parameters. And this kind of intuitive optimization always follows trial and error approach.

And therefore, you need to do hundreds of experiments and also evaluate that material properties in a manner to see that whether these kind of defects are there or not. And these combination of defects not only depends on what is the combination of process parameters, but also depends on the metal powders, their characteristics and so on. Layer thickness and build orientation are essentially interdependent. These couple of important messages one has to bear in mind. as I mentioned that this is the classical example of the two different type of microstructures that evolved as a result of a laser based additive manufacturing process.

One is a columnar microstructures, one is equiaxed microstructures. And these columnar microstructures, equiaxed microstructures when they develop, they will essentially result in different properties. This is the case for the directed energy deposition. where H13 tool steel has undergone directed energy deposition and if you look at hardness and how the properties evolve from the top of the deposit and then you see that there is a gradient in the hardness properties that it essentially means there must be gradient in the microstructure. Defect wise there is a lack of fusion wires and surface roughness these also evolve in this kind of materials.

Now correlation between powder properties and printability, now typically surface roughness of the as printed structures that typically depends on the layer thickness. As the layer thickness increases, surface roughness also increases. And for many engineering applications, surface roughness need to be contained within 5 to 10 micron. there should be consistent effort to reduce the surface roughness.

Therefore, layer thickness must be minimized. lower the layer thickness, lower is the average surface roughness. Higher is the energy input or linear heat input, lower is the surface roughness. lower is the powder particle diameter, lower is the surface roughness.

these are the data points which are taken from different kind of materials, stainless steel 316L, inconel 625 and this kind of aluminium alloys and so on. changing the angle of build orientation or increasing laser power or decreasing powder particle diameter essentially decreases the surface roughness.

As I said if it is less than 10 micrometer surface roughness that is much better for engineering applications. What are the different process induced defects in the metallic parts and which determines the product quality? Now, this is the porosity, long crack and short crack as you can see and what you can see as a function of laser power and scan speed, if you plot in the higher laser power, there will be always probability of the key-holing porosity, there will be fusion errors, there will be balling type of defects and in between these are the essentially good parts. Good parts essentially means less number of defects or minimal defects in these particular things. In the worst cases, you can see the 3D printed parts can undergo delamination And also these materials can undergo balling or lack of fusion.

These are like some of the problems. with the additively manufactured parts which are commonly reported in the literature. You can also develop porosity in the structures like mid-range porosity and then under extreme cases if the pores they coalesce together they will form the large cracks. These printed components are also used in different binder applications. For example, in the binder jet printing like monotite scaffold, when they are used in animal models, for example, it is the rabbit calvaria, what we have seen that bone regeneration is being clearly shown in this printed that is being accelerated using this printed scaffold. This anti-cancer immunomodulatory drug which is loaded to tricalcium phosphate it is one of the calcium phosphate based materials which are being printed using the binder jetting and after that this bone tissue engineer scaffolds is placed in the animal models and this particular work essentially showed that immunomodulatory drugs were consistently released during these binder jetting based techniques.

Many of the processes and some of the process science that I have been teaching you for last few lectures, whether it is related to the binder jet printing or selected laser melting, these are being reviewed very extensively and also published in some of our review papers. One such paper is mentioned here. And this is the paper which is also written with the German group of researchers and this is another paper which is the Current Opinion Biomedical Engineering, this is also 3D powder printing. Thank you.