Finite Element Modeling of Welding Processes

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Lecture - 40
Modelling approaches of additive manufacturing

Hello everybody. Now, we will try to focus on that the Finite Element modelling of the Wire arc Additive Manufacturing process. So, in this case, we have already shown that how we can solve the heat transfer problem, how we can solve the fluid flow problem associated with the welding process and apart from that what way we can solve some kind of the stress analysis or in general you can see the thermo mechanical analysis associated with the welding process.

So, all kind of solution methodology strategy useful in the wire arc additive manufacturing process. There is no nothing specific to look into, you know different kind of the governing equation.

So, in this case only thing is that, there are applicable solution domain has to be defined in your in wire arc additive manufacturing process and then accordingly, we and you apply the arc conventional modelling method what we have done in case of the welding process all can be applicable in case of the wire arc additive manufacturing process. So, let us look into this thing.

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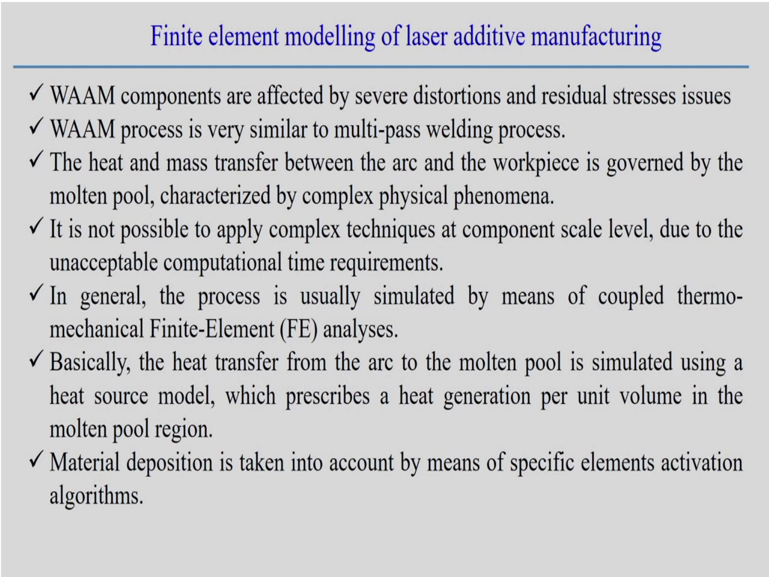

How it is different from the simple welding process. So, definitely wire arc additive manufacturing components are affected by the, in general talking about the severe distortion and the residual stresses generation. This is one genuine problem associated with the wire arc additive manufacturing process.

And if you look into compare with the welding process, the wire arc additive manufacturing process is basically the multi pass welding process is equivalent to the multi pass welding process. Only thing is the difference is there, is a very controlled way there is a deposition of the material can be done in additive manufacturing process.

Now, there is a heat as well as a mass transport between the arc and the workpiece is governed by the molten pool and characterized by the complex physical phenomena. So, definitely in this case, there is a heat transport by the arc creation of the arc as well as the molten metal transport to the domain is there any associated with this particular process. Now, it is not possible to apply very complex techniques to at the competence scale due to the unacceptable a computational time requirements.

If you look into the complete process in additive manufacturing, so, we have already explained in the material deposition process also, then in module 7, there you can find out that there are so many physical phenomena is actually interacting this process and considering all this together and solving all this. For example, solving the thermal analysis or in the flow analysis as well as the stress analysis in one common platform is really very time consuming, basically the computational time becomes very high.

So, may not be feasible in practical. So, rather we can focus on the individual domain of the analysis and then we can simply solve the heat conduction equation, if you want to know the temperature distribution, if you want to know the flow field then we can solve the Navier-Stokes equation and if you are interested to know the distortion residual stress, then we can use the thermo we can solve for we can look into the thermo mechanical model. So, that can be done individually.

Now, in general the process is usually simulated by means of the coupled thermo mechanical finite element model analysis to understand mostly the residual stress and distortion level in a wire arc additive manufacturing structure. So, basically the heat transfer from the arc of up to the molten pool is simulated using the heat source model, that also we do in case of the welding process and which defines a heat generation per unit volume in the molten weld pool.

With that we know that if you look into that what way we can solve the heat generation model or heat source model, the same heat source model also applicable in this particular problem. Now, material deposition is taken into account by means of the specific element activation algorithm. It is true that the strategy can be different as compared to the simple static welding process. So, in this case so, there is a continuous deposition of the material.

So, every time some activation when there is deposition of the material that can be in the in terms of the mathematical model, that can be considered as a there is a activation of the particular element which is synchronized with the deposition of the molten pool. And then problem can be solved in general, we can be it can be solved only heat transfer analysis or only the fluid analysis or only the stress analysis process.

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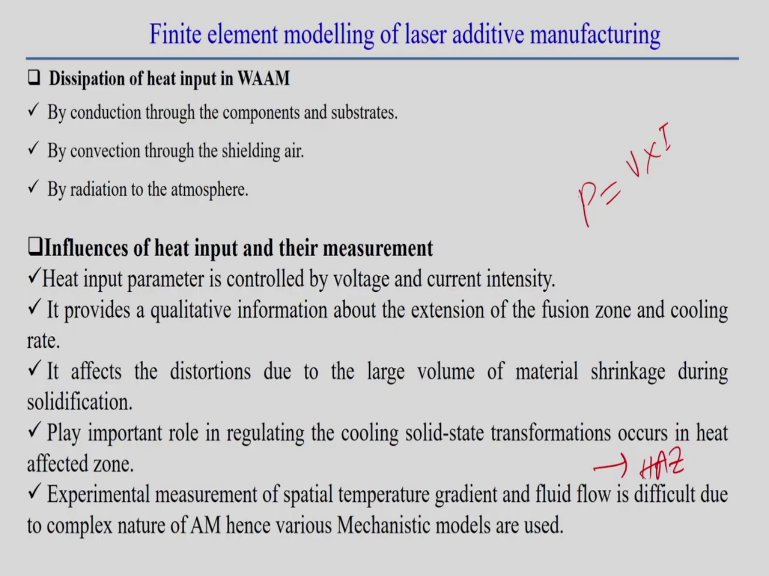

Now, it is very important to know the dissipation of the heat input to the wire arc additive manufacturing process. So, in this case the heat input by conduction through the components on the substrate so, heat input from the arc. So, there will be conductive heat transfer within the domain and at the same time the heat input from the molten droplet also and at the also there is some heat loss from the surface by convection through the shielding air.

So, that is also there through the shielding air there is a convective heat loss will also be there and apart from these thing some radiative heat transfer from to the atmosphere. It is also associated to the heat loss in this particular process is the similar to the fusion welding process.

Now, if we look into the influence of the heat input and their measurement, then heat input parameter is basically controlled by the voltage and current intensity that is there, because we estimate the power required of a particular welding process also and power equal to that volt into ampere.

So, that voltage into current that indicates the power input or it actually it controls the heat input. And it provides the qualitative information about the extension of the fusion zone and the cooling rate definitely the heat input will length that heat input is directly defined, what is the size of molten pool and basically what is the size of the fusion zone?

And of course, it influence the what is the cooling rate, it affects the distortion definitely the in a large structure large volume of the material shrinkage during the solidification so on. It influence the distortion pattern also and play important role in regulating the cooling a solid state phase transformation occurs in the heat affected zone. So, therefore, in the heat affected zone, it also this heat input also affects the influence the solid state deformation.

And apart from this thing experimental measurement of the spatial temperature gradient and the fluid flow is difficult due to the complex nature of additive manufacturing that we already know it is a although in case of simple fusion welding process, we can simply put the thermocouple and we can measure the temperature also, but in this case additive manufacturing it is very difficult to measure the on process measurement of the some kind of the temperature just simply putting the thermocouple as well as the to observe the flow field also here it is very difficult.

So, in that sense it is more useful to take the help of some kind of the numerical model also not only the heat transfer and the fluid flow even residual stress generation it is very difficult to measure, because one deposited layer is there and what will be the residuals for the next layer before next layer deposition it is very difficult to measure the residuals stress.

So, that kind of can be done only after in post processing of this particular sample. So, that is why it is a modelling of this particular phenomenon is actually helpful to design the this additive manufacturing process.

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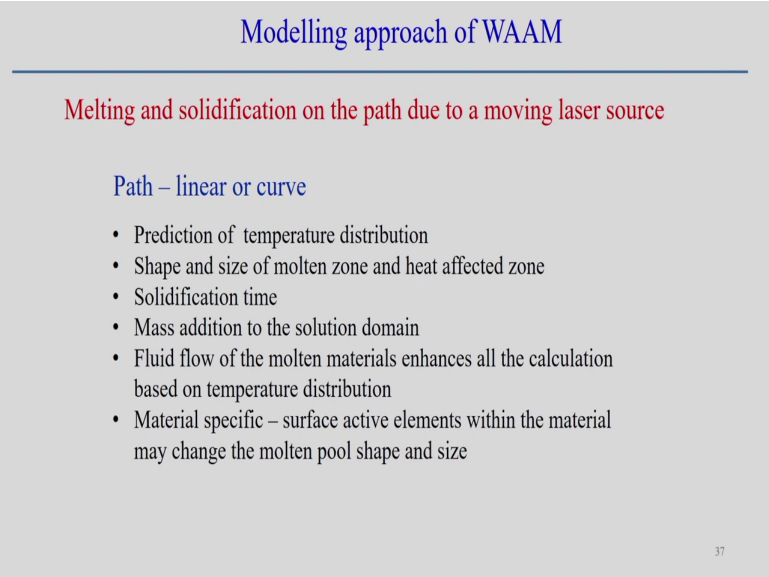

Now, modelling approach for wire arc additive manufacturing process. So, it melting and the solidification happens. So, it we can represent in this way also that there is a metal transfer, then metal is deposited on a substrate or may be deposited on the previous layer, but if you look into the physical phenomenon happen happens in this cases, the melting of the wire or melting of the already on the substrate material melting occurs.

Even once the heat source moves in forward direction, then back side there is a subsequent solidification will also occur. And on the path due to a particular moving source. So, it is associated with the melting and solidification of this particular process in general you can represent that way. Now, this path can be very linear path or path can be curved also.

So, look it depends on the what kind of the geometric profile you are handling. So, therefore, if you look into the modelling approach, what are the expected parameters or phenomena we should consider. One is the prediction of the temperature distribution.

That we are always interested to know if for a particular deposition what are the what is the maximum temperature achieved in during this deposition process and what is the size of the zone fusion zone and what is the size of the heat affected zone all kind of information are important.

Apart from this thing the shape and size of the molten zone and heat affected zone that actually decided by the temperature distribution. So, therefore, temperature distribution helps to define this heat affected zone and fusion zone dimension.

Apart from this thing solidification time is also important solidification time means once is moving one particular direction, then how much time is required to solidify such that the if a very small component is there. So, we if we calculate the solidification time, it will help to take the strategy when should be deposited for the next layer. Apart from this thing there is some mass addition to the solution domain, definitely the molten material transport to the domain or deposited on the workpiece surface.

So, if you look into the work piece, if you consider this workpiece as a control volume. So, within the control volume, there is a mass transport is also there as well as the heat energy transport through the molten material is also there. So, that has to be considered in the modelling also. So, now, fluid flow of the since it is above the melting point temperature. So, fluid flow of the molten materials has to be look into this thing.

But there the molten material characteristic can be more important, when one way it helps this fluid flow field that more precisely calculate the temperature distribution, that is one and apart from this thing the fluid flow phenomena can be material specific also, because if there is a presence of the surface active elements, it actually influence the flow pattern and when there is a change in the flow pattern, it influence the weld pool shape and size.

So, therefore, any presence of the any surface active elements can be better explained in the by the fluid flow analysis and that actually finally, it affects the shape of the weld pool. So, all this kind of phenomena is associated with this thing, but apart from this thing once the thermal and fluid flow field is known in the deposition process, then we need to know after the solidification what can be the distortion or what kind of the residual stress is generated within the structure.

So, therefore, for that purpose there is a need to know, the do some kind of the thermo mechanical analysis even in case of additive manufacturing process. So, all these phenomena are associated with the additive manufacturing process. Now, we know the transient suppose, we already mentioned this thing even simply we can use the heat conduction analysis to know the temperature distribution.

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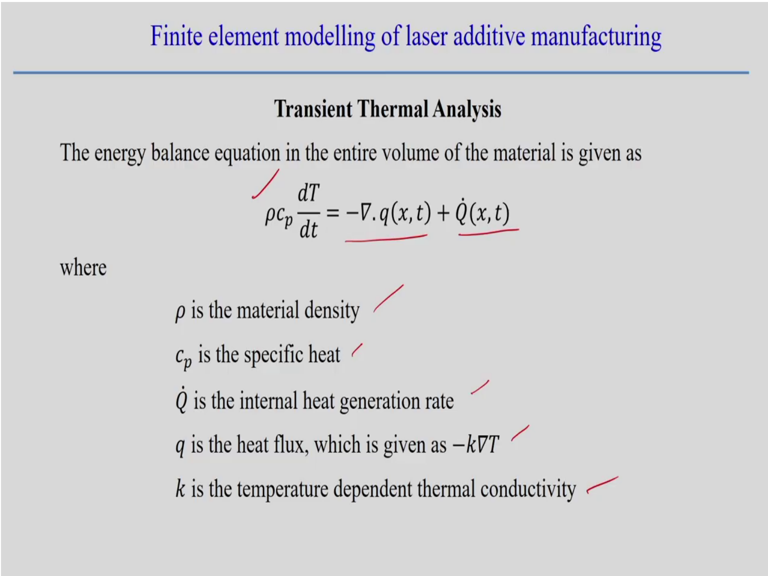

So, therefore, the energy balance equation for the entire volume of the material can be given as this thing. So, rho c p this is the transient component rho c p del T by dt. Now, this is the heat flux Q as a function of x t and this is the internal heat generation. So, this is simple the transient heat conduction equation. Now, to understand the temperature distribution, we need to solve this particular equation.

Now, this all the parameters are defined density, specific heat, internal heat generation, the heat flux and the thermal conductivity. Now, point is that this is the this has to be solved with the kind of the proper boundary condition. So, proper boundary condition, we can solve this heat conduction equation then, we will be able to get the temperature distribution even in case of the additive manufacturing process.

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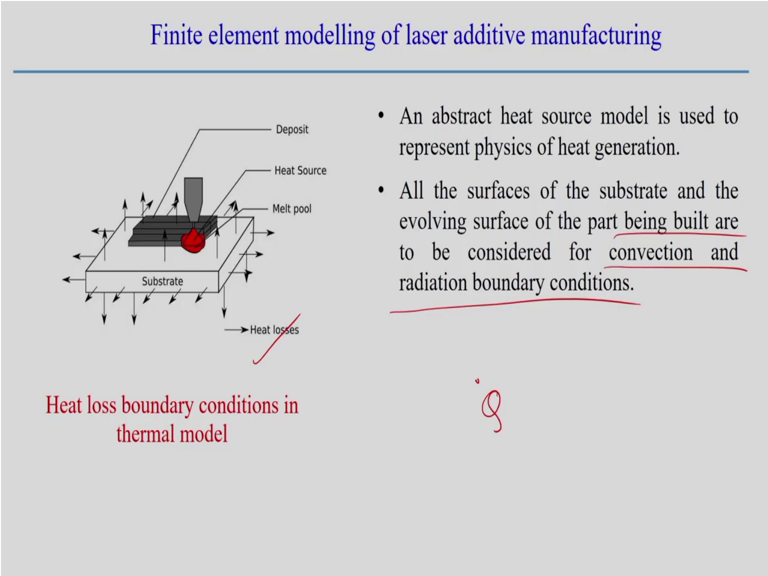

Now, here we can see that this is a deposit of the layers schematically, we can see the deposit of the layer and if we see the substrate material and from the substrate material there is a heat losses are there. So, deposit there is a melting molten zone and then molten zone representing when the laser or arc is interacting with the substrate material. Then that interaction can be represented in terms of the heat source model that we have observed in case of the fusion welding process also.

Then heat source modelling is also has to be developed here, then that heat source model can be incorporated in terms of the internal heat generation term the Q dot term, basically that we can heat source model can be represent the what is the energy per unit volume.

So, that amount has to be incorporated through the heat generation term, then we solve this equation, then we will be able to get the temperature distribution. So, therefore, an abstract heat source model is used to represent the all the physics of the heat generation in this particular process.

Apart from this thing, all the surfaces substrate on the evolving surface of the part apart from this thing all the surfaces of the substrate as well as the evolving surface of the part which are already built can be considered for the convection and the radiation boundary condition. That means, we can considered all the surface area that is also associated with some kind of the convective and radiative heat loss from this particular surface.

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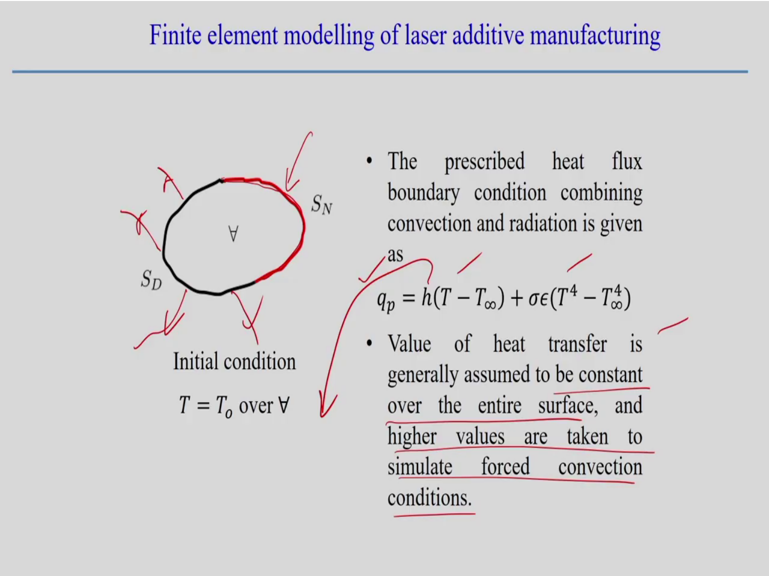

Now, in general we can see the prescribed heat flux boundary condition combining the convection and radiation. We can find out for example, this one part is the basically the domain this is the solution domain that part is there is a heat input for example, and there is a heat loss is there.

So, in general the heat flux boundary condition combining the convection radiation we can see, we can take a balance of the what is the heat input to the domain, what is the lost from the domain. So, that from that point of view, we can say the boundary mathematically we can represent the boundary condition is this q p is the heat flux the boundary interaction input and this is the heat loss by convection, heat loss by the radiation, we can make the balance this can be act as a boundary condition.

But imposing of the boundary condition, it depends on the what is the geometric shape because already built up shape from the surface also there is a heat loss. So, we can define that particular surface area and then the heat loss may also occur from this particular surface. Now, value of the heat transfer is generally assumed to be constant over the entire surface and the higher values are taken to simulate the force convection condition.

So, if there is a force convection condition, then we can simply modify the h value and if it is a natural convection accordingly, depending upon the whether it is forced convection or natural convection is there based on that we can define the what is the value of h in this particular process.

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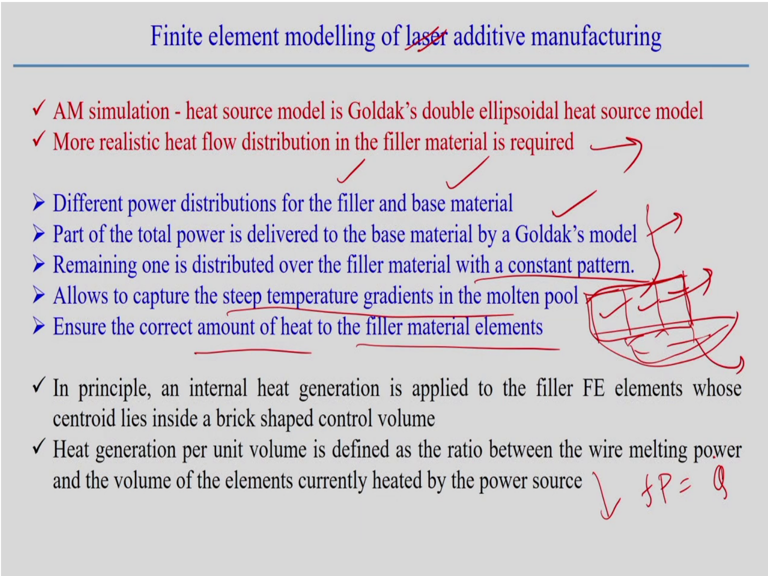

Now, we can say finite element modelling of the laser additive manufacturing process. So, in this case I think this is simply we can say the additive manufacturing process. So, in additive manufacturing simulation, the heat source model is basically Goldak's double ellipsoidal heat source model we normally use.

So, same thing what we have used in case of the welding process. So, these are the more realistic heat flow distribution, when in the distribution in the filler material is required. So, of course, this we apply the in case of the Goldak's double ellipsoidal heat source model for a moving heat source problem, but in this case there was no material addition to this particular welding process.

But when there is a material addition, then more precisely we need to modify the heat source model, but of course, it is possible to consider the simply by modifying the Goldak's double ellipsoidal heat source model that will be applicable in case of the additive manufacturing process, specifically for error additive manufacturing process. Now, what are the different aspects associated with the heat source model?

Different power distribution for the filler and the base material, so, filler material is there as well as the base material. So, power density distribution can be different in these two cases. Part of the total power is basically delivered to the base material by the Goldak's model. So, for example, not all the power is supplied by incorporated through the Goldak double ellipsoidal heat source model.

So, not all this energy is input to this particular model. So, some part has been incorporated that through the Goldak's model. Remaining one is distributed over the filler material with a constant pattern. So, remaining apart from this thing some part, we can incorporate to the Goldak's double ellipsoidal heat source model and remaining part can be incorporate some other that can be count on that the energy transport by the filler material.

And that can follow some kind of the constant pattern or some kind of the distribution as well. Now, this actually allow, if you follow this thing two different way. Heat source we can make into two different parts, then heat actually allows to capture the steep temperature getting is possible to capture in the molten pool apart from that ensure the correct amount of the heat to the filler material elements. So, basically the correct amount of the heat for the filler material elements.

So, filler material elements means, we are talking about the this model can be done some activation of the elements. So, when we are activating the particular element, that element can be considered as the volumetric heat source term can be incorporated in this particular element, apart from the Goldak's double ellipsoidal heat source part.

Now, in principle, we are following basically the internal heat generation term applied to the finite elements whose centroids lie inside the brick shape control volume. So, if we define for example, on the substrate material already deposited we can follow some kind of the Goldaks double ellipsoidal heat source model. So, this energy input on this thing, but apart from this thing we can say so, this is the this can be represented on the for example, the deposited material.

So, deposited material so we can activate this element at this time and this volume of the element we can calculate such that this can act as a source of the heat. So, apart from this double ellipsoidal this is the another brick element, we can consider that as a source of the heat also. So, that is why, but elements how many elements? It depends on the whose centroid lies inside the brick shape control volume, we define the control volume suppose this is the control volume. So, within this control volume, there are three elements for example.

So, we consider only this three element, we can activate these three elements and these three elements will be counted to calculate the volumetric heat generation. Now, heat generation per unit volume is defined as the ratio of the between the wire melting power and the volume of the elements currently heated by the power.

So, that is means definitely, this can be what is the total power part of the power is utilized here for example, the fraction of the power is utilized these things. So, this thing and then this fraction of the power that can be incorporated in term of the internal heat generation the volumetric term. So, the internal generation term the total or divided by the volume. So, that indicates the over per unit volume that heats heat input can be represented.

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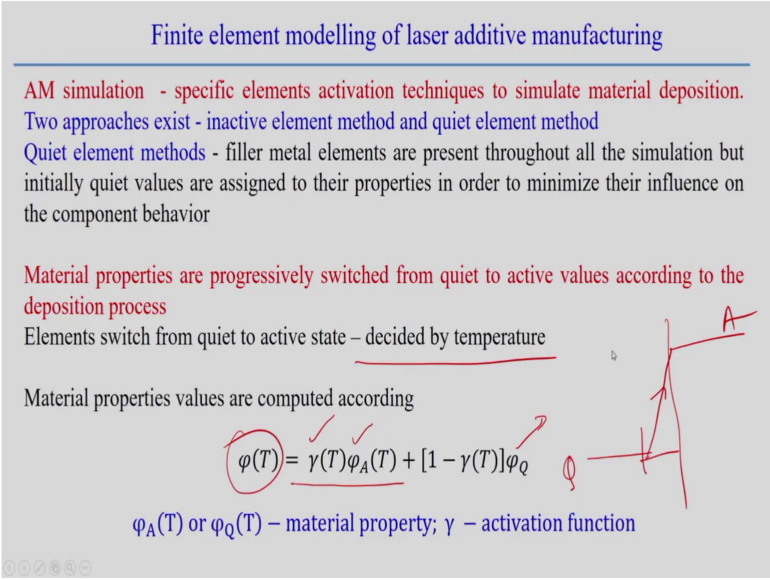

Now, additive manufacturing simulation the specific elements activation techniques to simulate the material deposition. So, normally we follow specific elements activation techniques we normally use, but there are two approaches exist. One is the inactive element method and the quiet element method.

So, quiet element method means, basically the filler metal elements are present throughout the simulation, but initially the quiet values are assigned to their properties in order to minimize their influence on the component behavior. So, it simply basically the activation and deactivation normally you can say in terms of the inactive elements and the quiet element method.

And accordingly, we can provide some kind of the one particular active element, then we insert this particular properties in this category and remaining which is not inactive element.

We can simply assign the properties in the very low value of the properties are almost it is a convenient way, we can basically depending upon the behavior component behavior, we can apply the material properties.

So, material properties are progressively switched from quiet to active values according to the deposition process. So, the material properties has to be vary depending upon the deposition process, it can be switched on by following some particular equation also. So, each elements switch from the quiet to active state and that actually decided by the temperature.

How you can decide that which is the quiet element which is the active element, maybe that can be calculated by as a function of the temperature. So, temperature or the maximum temperature, if we know the melting temperature or some other transformation temperature based on that temperature flag, we can decide when to activate the or element.

So, or other we can say the quiet to active state, we can decide by the temperature value. Now, material properties can be decided in this way also. So, for phi equal to these material properties as a function of temperature, it can be we can introduce some kind of activation function, which is also a function of temperature. And activation function in the one property, this is the activation activated property and that this is the Q phi Q is the quiet property. So, therefore, and this 1 minus the gamma.

So, gamma is the activation function in this case. So, it is a simply step wise, we can find out this function such that this gamma can vary something like that. So, this is transition from here to here and then during the activation stage and accordingly we can define the properties. So, it is a we can say that quiet property and it is the active property. So, like that and between there is a transition.

So, depending upon the value of the activation function can decide the to activate kind of property. So, this way we can handle the activation and deactivation part or maybe we can other we can say the this particular active element the quiet elements or transformation from active element a quiet element to the active element, simply by looking into the properties, but that properties we can put as a temperature flag.

As a temperature dependent properties or of course, we can define this transformation from one to other form that can be a function of the temperature.

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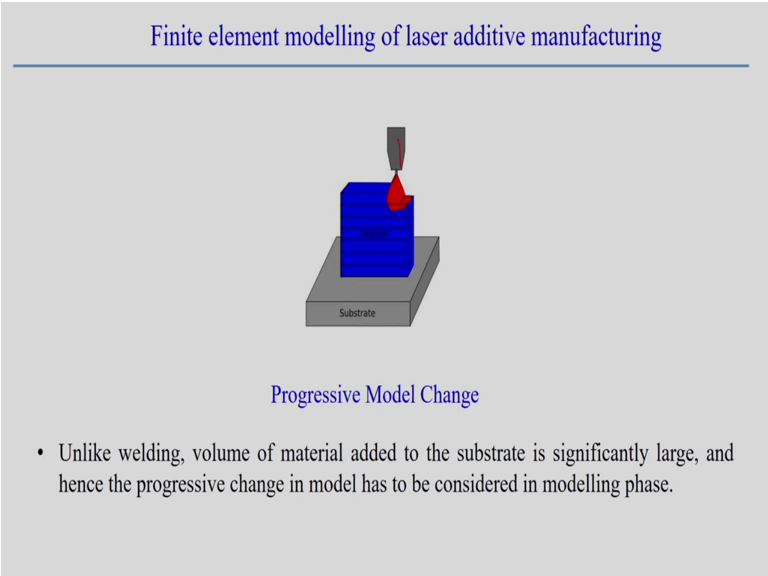

Here, you can see that we see the substrate material and the with the application of the arc deposition then progressive model change. So, gradually there is a layer by layer. So, domain actually increases. So, unlike welding volume of the material added to the substrate is significantly large and hence the progressive change in the model has to be considered in the modelling phase.

So, definitely the change in the model has to be considered, because every time one deposited layer is there and before the next depositing layer. So, there is a domain is basically increasing gradually. So, that one the change in the model has to be considered in this particular modelling phase.

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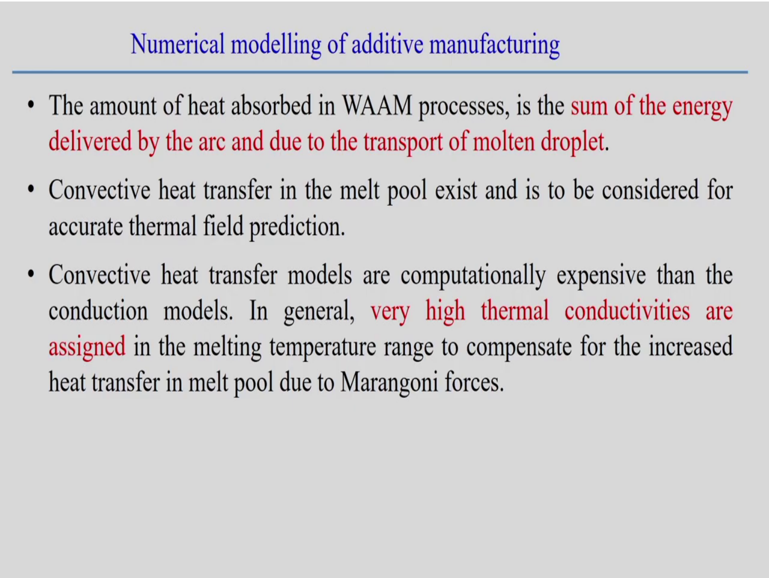

Now, the amount of the heat absorbed in case of the wire arc additive manufacturing process normally, we can consider this from the two different part. One is the sum of the energy delivered by the arc plus the energy due to the transfer of the molten droplet. That we had already mentioned, but in this case convective heat transfer in the melt pool exists and is to be considered for the accurate thermal field prediction.

If we want to ensure the very good thermal prediction of additive manufacturing process also, then we can convective heat transfer I am talking its equivalent to the flow behavior within the small weld pool or small pool molten pool that has to be considered. But apart from this thing, see this convert in general the convective heat transfer or may be fluid flow phenomena is computationally very much expensive than the simple conduction based model.

But in general if we want very high thermal conductivities are assigned in the melting temperature zone to compensate for the increase heat transfer in the molten melt pool due to the Marangoni forces.

So, definitely if we want to suppress the if you do not want to consider the material flow within the molten pool, then other way on a conduction based model simply use the high value of the thermal conductivity some arbitrary value we can enhance, such that it can takes care of the material flow behavior within the weld pool.

So, in that way we can simplify the modelling approach, if we do not want to incorporate any kind of the material flow in a conduction based heat transfer model. Even that is true in case of the additive manufacturing process.

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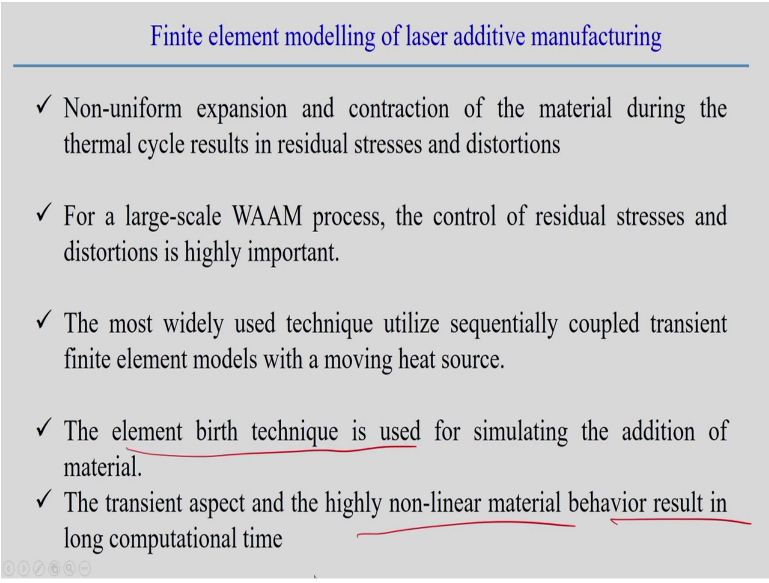

Now, if you look into the stress analysis part also, the non uniform expansion and contraction normally associated with the material during the thermal cycle, that we are already observed even it is true in case of the welding process. So, that can induce some kind of the residual stress and distortion in additive manufacturing process.

So, specifically for a large scale wire additive manufacturing process, the control of residual stress is an issue and maybe distortion is very much significant in this specifically for the last structure. Now, most of the cases we use the sequentially couple the thermo mechanical analysis and it is a most convenient computational time as compared to the other approaches.

So, that is why if you follow some kind of the thermo mechanical analysis sequentially coupled, then that can produce some kind of the stress analysis result associated with the wire arc additive manufacturing process, but we already mentioned this thing that element birth technique is normally used to simulate the addition of the material process.

Actually this terminology element birth, element activation, the philosophy is the same, but terminals are different because in different kind of the commercial software they use the different kind of the terminology. So, definitely transient aspect and the highly non-linear material behavior result in the long computational time, that is also very important because if stress analysis model in general, if you take the temperature dependent properties then computation times becomes very high.

That is the inherent problem associated with the or in any kind of the thermo mechanical analysis. Even in welding process even it becomes more computationally expensive for the additive manufacturing process.

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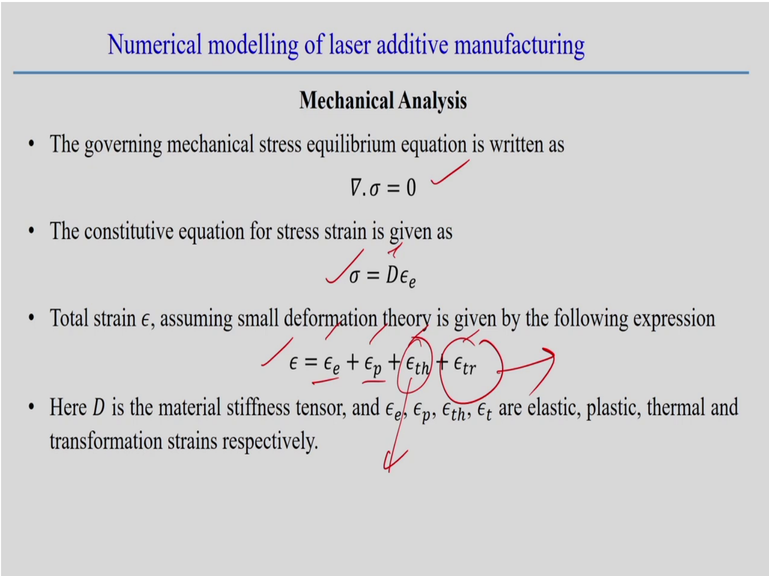

We know the mechanical analysis simply we can perform this thing that we have already mentioned in case of stress analysis model, which the mechanical stress equilibrium equation, here also we can follow the similar kind of the stress equilibrium equation. Then we can follow the constitutive equation between the stress and strain relation between the stress and strain within the elasticity matrix or maybe stiffness, you can say the stiffness tension depending upon elasticity of stiffness tensor.

Even if you look into the small strain and even if you follow the small deformation theory, then total strain component can consist of the elastic part, elastic part, thermal and the transformation induced plasticity. So, transformation though it can be transformation strain. So, there is a phase transformation that transfer strain also you can incorporate.

Now, see this is the general way we are talking about what way we can do the stress analysis even in the simple welding process, the same kind of the stress analysis we can follow in case of the additive manufacturing process as well. Now, even also if you do elasto plastic analysis, so, in that cases we have to look into the von Mises yield criteria and the Prandtl-Reuss flow rule and that can be following this thing.

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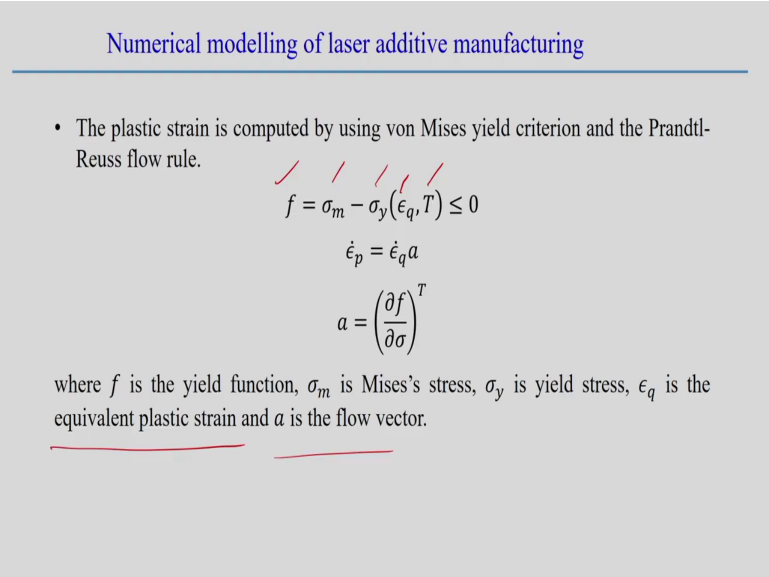

The f functional form of the yield surface can be like that, it is associated with the f sigma m is the Mises stress and sigma y is the yield stress and which is a function of the is the equivalent plastic strain and flow vector. Equivalent plastic strain, flow vector and the as well as a function of temperature.

So, these are the different plasticity model we can follow in general, we can follow the different plasticity model for the stress analysis. If we want to do thermo mechanical stress analysis or if we assume the material behavior should follow the elastoplastic. So, in that cases we can look into all these aspects.

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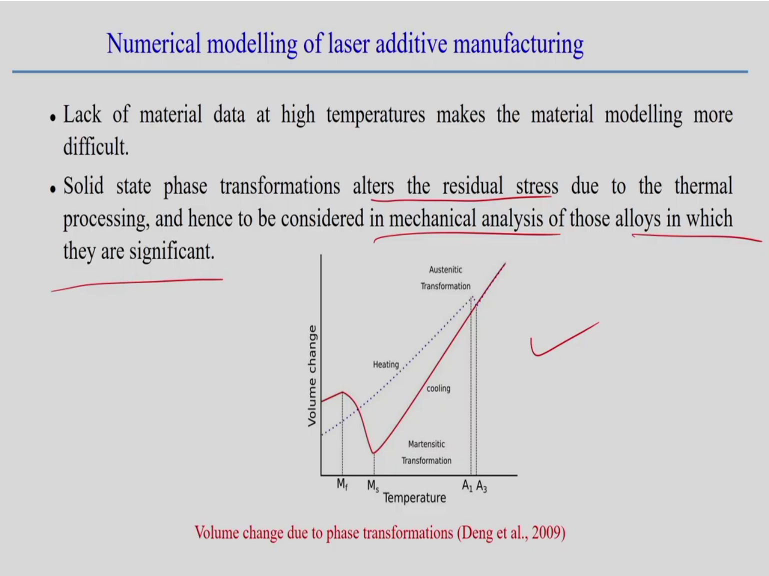

So, already mention this thing that of course, the transformation strain is also another important aspect associated with the stress analysis. Even if you want to enhance the accuracy of the stress analysis model, then it is better to consider the transformation strain that is also important. Now, of course, this transformation strain is maybe in few particular material it is very significant, but in other cases it may not be significant.

Now, lack of material data at high temperature makes the material modelling more difficult. So, there is a one very good material modelling is requirement for the stress analysis, if you want to incorporate the effect of the transformation strain. Now, solid state phase transformation alters the residual state that we know due to the thermal processing and hence the consider for the mechanical analysis, those alloy in which they are significant.

So, the particular alloy system in that cases the transformation strain is significant, in that cases we can consider the transformation strain. For example, the volume change, during the heating cycle and during the cooling cycle if you follow this particular figure also, there is a change in the this thing.

During the solid state phase transformation, there is a it may not follow the same path during the heating and the cooling path. So, therefore, because of this thing it means that the transformation from one phase to another phase having some influence and they induce the transformation strain and then from there from the transformation strain.

If the transformation strain is significant, then it actually enhance if you the that calculation of the residual stress. So, point is that maybe if you do the simple stress analysis model and then we in that cases particular material, if follow the phase transformation effect then accuracy of the stress calculation or distortion can be enhanced.

And sometimes to handle one particular material for example, titanium alloy or I can kind of the maybe high carbon steel in that cases this transformation strain is very much significant. So, therefore, once you want to develop stress analysis model even for the wire arc additive manufacturing process, it is better to consider the component of this transformation strain.

Here, you can see the transformation strain, because see elastic plastic and this thermal strain is defined this is this from the thermal model and elastoplastic behavior we know in a particular material, but transformation strain from the phase transformation effect, it is possible to develop the model and incorporate the strain in the strain component for the stress analysis part. And remaining the way methodology of stress analysis parts is the same as the welding process that we have already explained this thing.

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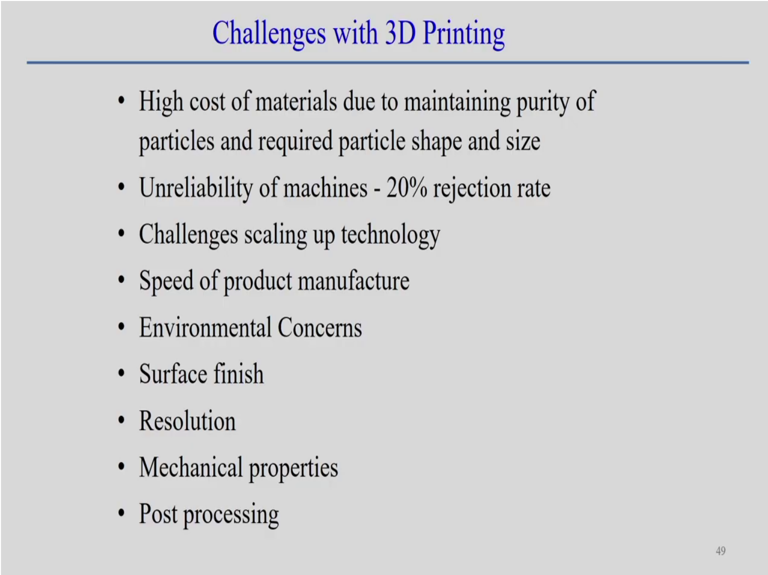

Now, finally, we can look into this thing, the looking to the additive manufacturing process. In general, we are talking about this thing. The there are so many challenges associated with the 3D printing process or additive manufacturing process that I think it is necessary to cover here. First is that high cost of the material due to the maintaining the purity of the particles if you look into the powder based technology and require particle shape and size.

If you want to make maintain the particular shape and size, even same thing is also true, even if you want to use some wire or additive manufacturing process the wire the quality of the wire is an issue. So, such that the quality of the additive manufacturing components it depends on the what kind of the wire quality we are using. Unreliability of the machine, so, most of the cases 20 percent rejection, because the feasible parameter domain is actually exist even additive manufacturing process over a very narrow domain.

So, very narrow zone, so that is why over a narrow zone, the exactly we are getting very good the component we can develop the component. So, that is why there is a chances for the rejection rate simply if you just outside of the narrow domain. Challenges scaling of the technology definitely, if you large scale if there is a scaling of the technology also there is a challenging time, even wire arc additive manufacturing if we lower down the scale then also it creates lots of challenges.

So, that is why both way it is also face lots of challenges associated with the powder based technology as well as the wire arc additive manufacturing technology. Speed of the product manufacturing can be an issue. So, build rate, build volume rate everything is an issue. Environmental concern depending upon the material all these things, shielding gas we are using and even following some kind of the melting. So, environment issue associated with this thing.

Surface finish has very much issue associated with the wire arc additive manufacturing process, because we cannot expect that very good surface finish in wire arc additive manufacturing process. But when there is a need to full a large component and large amount of the deposition rate as compared to the powder based technology, then the wire arc additive manufacturing is more suitable.

Resolution of this particular process depends on the; that means, how sensitive one particular parameter all this thing or how what way we can achieve the very good surface finish that is called the resolution of the process is one issue associated with this thing. Because to establish the resolution of the process they need to consider so many aspects so many effects, so many parameters has to be considered.

Mechanical properties so, layer by layer deposition process most of the cases the it can maybe the weak in the one layer to another layer may be due to the shearing action of the component so, that why mechanical properties can be an issue. And of course, in additive manufacturing component most of the companies associated with some sort of the post processing technology.

So, therefore, this post processing to get a better surface finish, the post processing means the some sort of the machining process is required associated with the additive manufacturing process, but it is more large amount of the machining process is required in case of the wire arc additive manufacturing process as compared to the powder based technology.

So, this all about the additive manufacturing process and their modelling approaches and what are the difficulties issues associated wire arc additive manufacturing process that I have tried to in general discuss in this particular module, so now.

Thank you very much for your kind attention.