Finite Element Modeling of Welding Processes
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Lecture - 36

Heating of nano-film

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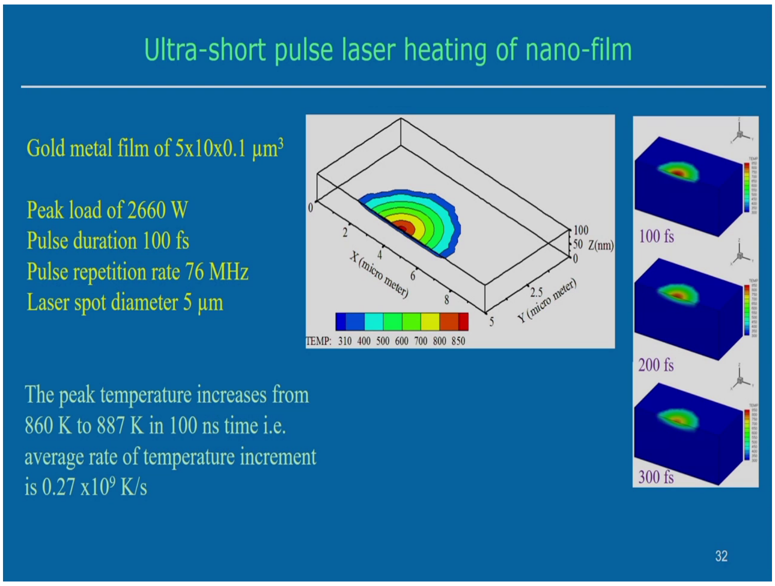

Hello everybody. Now, we will discuss the application of the non Fourier heat conduction model for the different heat transfer problem. Mostly we account this application of the either simply heating of the surface and we start with these things and then non-Fourier heat conduction model can be used for the welding of material, maybe I will try to show the joining of the dissimilar materials in this process.

And even non-Fourier heat conduction model how it is associated with the stress analysis that kind of analysis we will show in this particular module. So, let us start with, so application of the ultra short pulse laser of nano-film; so, simply heating up the nano-film. So, we have already shown that how the finite element model can be done. Now, if we look into the different using that particular developed model we can show the different results on this thing.

And the main objective here will try to identify how this thermal analysis or these results is different from the Fourier heat conduction model. So, we start with this thing, gold metal film of particular dimension the 5 micrometer by 10 micrometer by depth; depth is only 0.1 micrometer. So, that means, 100 nanometer thickness gold film, how it basically when it interact with the ultra short pulse laser. Then how heat transfer phenomena can we explain these things.

If you see in the particular situation this gold film, the peak load is very ipc on 2660. That means, I mean to say that if for 100 nanometer thickness layer it is subjected to that kind of the amount 2660 watt laser, but this laser this power this energy that is peak load is 2660 watt laser is actually apply with a very small duration of the time, such that pulse energy can be very small in the micro Joules.

I think in this case pulse energy is around I think 20 or 30 micro Joule if you estimate; we can estimate the pulse energy also. So, that amount of the small energy is applied on the nano-film then how it behaves or how it responds with respect to the ultra short pulse laser.

Assuming that there is no vaporization simply the heat transfer is there because this ultra short pulse laser is mostly used in case of the for ablation purpose, but in this cases we are discussing the different from just simply heating the surface without the ablation of the material.

See pulse duration is only 100 femtosecond then pulse repetition is a very high pulse repetition rate 76 megahertz and the laser spot diameter on the surface it is around 5 micrometer. So, in this situation we can see that if you do the simulation using that a non dual phase lag model we can reach the temperature distribution can be like this. So, temperature if you see the temperature distribution is mostly confined on the surface and depth heat affected zone is may be very small in the depth direction.

But we will see if you look into this simulation also right hand side see that at the different time or the 100 femtosecond, 200 femtosecond, 300 femtosecond, how? There is a progress of the heat affected zone specifically I am talking about the in the depth direction we can see.

So, although the pulse duration is 100 femtosecond it means that if we count the time from the 0 then within the 100 femtosecond that duration pulse energy is supplied to the sufficient material, but till that means, at 200 femtosecond there is no in this cases the in the that comes under the pulse of period. That means no pulse energy supply to this particular material and on this film at 200 femtosecond or even 300 femtosecond.

But till we can see that even if we reach the 200 femtosecond the depth of penetration; that means, depth direction or we can say the heat affected zone heat affected zone is increasing even it is 300 femtosecond it is more although the application of the pulse energy is stopped after 100 femtosecond. It means that we are concerning that the thermal relaxation that means some relaxation time is there.

So, it must account that not exactly reaching to the peak temperature immediately after ending of the pulse energy supply. But till beyond that it takes some time to reach the equilibrium condition, it means that it try to take some even after of the pulse energy, it takes some time 2 is the equilibrium condition.

That means, 2 is the peak temperature and that peak temperature can reach beyond the 100 femtosecond time. Therefore, we normally say that once the peak temperature even not exactly reaching exactly just end of the pulse duration rather much more time to reach this peak temperature.

So, this can be explained by assuming that there is a thermal inertia effect and the thermal inertia effect is basically try to act here in such a way that it takes some time to reach the peak temperature. So, here you can see the peak temperature increases from 860 Kelvin to 887

Kelvin in 100 nanosecond time. That means, if you look into that things only that 860 Kelvin to 887 there is a not much temperature change, but it happens only on within a 100 nanosecond time.

It means that average rate of the increment is around 0.27 into 10 to the power 9 Kelvin per second. So, in that scale this rate of temperature change is very high. So, that means, very rapid there is a change of the temperature. So, that kind of information we can get from this a non Fourier heat conduction model.

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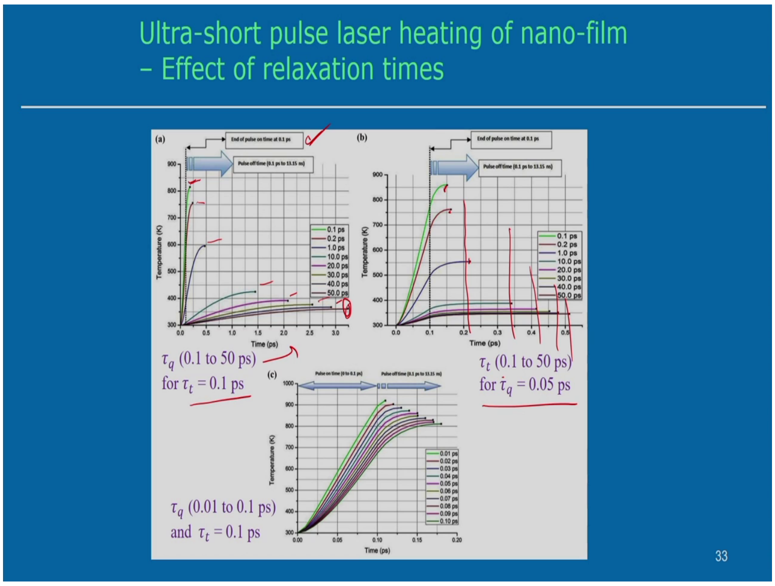

We can see then of course, one important part is that if you understand that how the non Fourier heat conduction model or temperature distribution is different from the Fourier heat conduction model; we can look into this figure. So, in this figure we have plotted the temperature distribution assuming that different value of the relaxation time. So, we have already defined there are two relaxation time, one is the relaxation type for the heat flux and the relaxation time for the temperature gradient.

Now, for a first figure it shows that temperature gradient we have T t. That means, for the temperature gradient relaxation time is considered 0.1 picosecond and, but relaxation time due to heat flux is changing from 0.1 to 50 picosecond within that range. Now, if there is a changing of the relaxation time in that such duration we can see that how temperature distribution varies.

So, if for a fixed value of the relaxation time for temperature gradient, but relaxation time for the heat flux changes from 0.1 to 50 second then peak temperature changes this value in gradually decreasing and if it is 50 picosecond then it is very low value, the maximum temperature of the system can be very low. And we can see this is obvious that the difference we have seen the graph is showing that at the different values of the relaxation time of the heat flux.

So, this we can see, but other point is that we are showing the at the which point at the what timestamp span it is actually reaching the peak temperature. In other sense we can say how much time is required to reach the equilibrium condition that means. So, if it is heat flux that means, tau 2 value is the very low 0.1 and near about this thing 0.1, 0.2 then after end of the pulse. So, this first dotted line we can see the end of the pulse is the very small that 100 femtosecond.

So, then pulse energy supply stopped after 100 femtosecond, but till it is evolving it trying to reach the equilibrium condition and it reach the peak temperature. So, that gap is very small even tau q means is that the heat relaxation time for the heat flux is low, but once the relaxation time heat flux is very high for example, it is 50 picosecond then it takes huge time to reach the peak temperature. So, that kind of information is required.

Now, the same kind of the analysis if we compare with the Fourier heat conduction there is no question of the relaxation time. So, in this case in Fourier heat conduction model if we solve then peak temperature will be reaching exactly after end of the pulse duration. So, that means, if we assume that Fourier heat conduction model is applied and even for the valid for the ultra short pulse laser welding cases it should reach the peak temperature after 100 femtosecond.

So, that means, just end of the pulse it should reach the peak temperature at this time duration just end of the pulse, but in case of non Fourier heat conduction you analyzing these things because of some thermal inertia effect it will not exactly reaching the or reaching to the maximum value of the peak temperature not exactly the end of the pulse. So, that kind of the information we can get and that is the difference of the heat transfer analysis as compared to the Fourier heat conduction model.

The same thing we have analyzed the different way also the effect of the different relaxation time. We can see that the temperature pattern are different maybe in this cases. The tau t is varying point 0.1 to 50 picosecond, but heat flux this thing tau q is the that mean relaxation time due to the heat flux is very small 0.05 and when you can reach this is the reaching peak temperature you can reaching and the at the same time at the corresponding time also you can see the corresponding time also.

That means, to reach the peak temperature it takes some the huge time and depends on the relaxation time. So, it means that correct choice of the relaxation time is one important thing when you try to develop the heat conduction model and it is very specific in case of the dual phase lag model because in these cases we are handling the two relaxation time.

One is the relaxation time due to the heat flux another relaxation time for the temperature development within this body.

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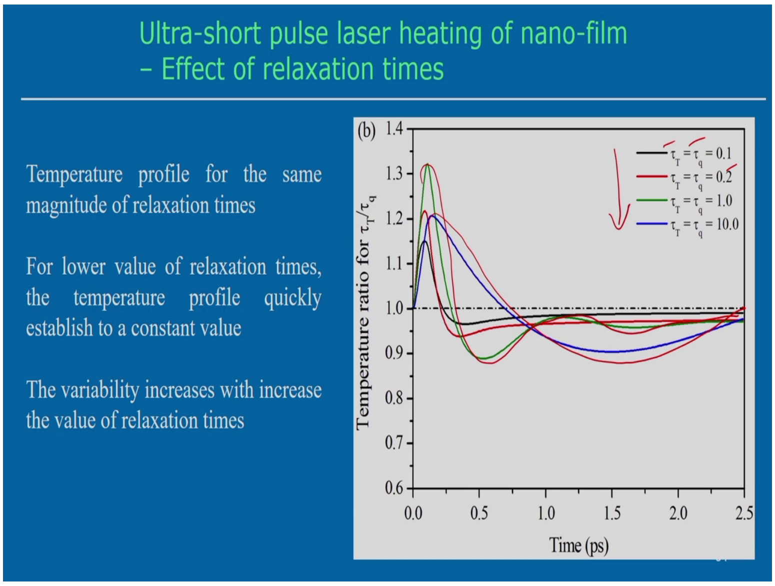

Similarly, we can see the effect of the relaxation time in other way also that means temperature profile for the same magnitude of the relaxation time. So, same magnitude of the relaxation time in the tau they both are the same magnitude 0.1 picosecond, similarly if this is other is the 0.2 picosecond, 1 picosecond, 10 picoseconds see or the different cases we have tried with this thing.

And then we can find out the temperature ratio with the ratio of the we can see for temperature ratio it is varying from 0.6 to 1.4, but if we look into the temperature profile for the lower value of the relaxation time. It is a very low value of the 0.1 is quickly try to establish the equilibrium condition try to reach some constant value of the temperature.

But this variability increases if the ratio or the value of the relaxation times is actually increases. That means the relaxation time is increasing these things, the variability temperature is actually increases, if you see the very high value this takes some more variability this touches with the relaxation then it try to reach the equilibrium.

And in case of the 1 both are 1 then each reach the equilibrium then it try to reach the equilibrium condition. So, it means that variability increases with increase the value of the relaxation time as that we can observe this data we observe we obtained from the numerical model. That means, from the what we have developed for the analysis of the non Fourier heat conduction.

So, we can see this kind of conclusion that relaxation parameter has to be chosen it is very carefully because experimental is very difficult to measure the relaxation parameter for a particular system. So, sometimes we depend on this analysis, so that means, to depend on this or we can estimate from the other by from other way, in the sense that from the by relating to the other parameters we can estimate the relaxation time, but it is very much sensitive to the model results.

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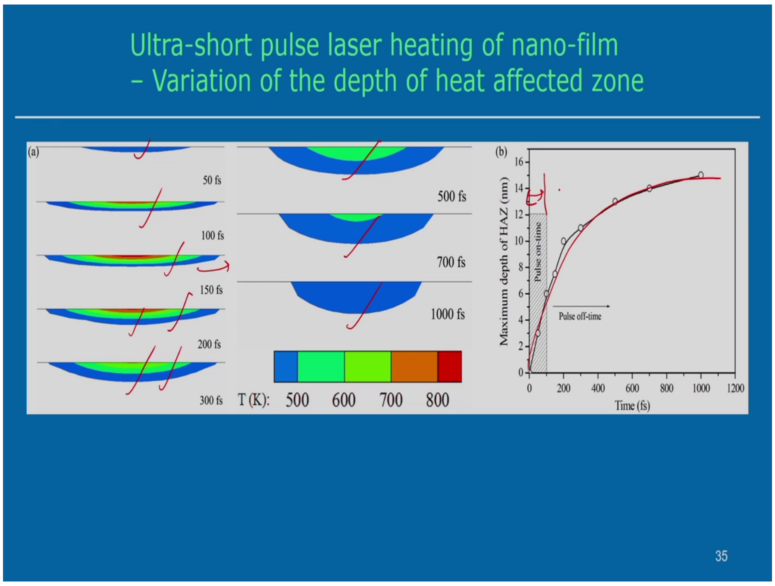

We can see the variation in the depth of the heat affected zone from this we have done some simulation we can see that how the depth of zone depth of heat affected zone is increasing. So, it is a 100 femtosecond this profile will reach the 100 femtosecond this we reach 50 femtosecond, but if you see 150 femtosecond even it is more than that depth of penetration is more than that although the stop supplying the pulse energy at this point after 100 femtosecond.

This is 100 femtosecond so, 150 this is 200 and this is 300 second femtosecond this is 500, 700 and then 1000 femtosecond. It means that if we see with respect to time the heat affected zone is actually increases and that is the typical nature of the heat affected zone in case of the ultra short pulse laser heating of a nano-film.

So, here you can see very clear the minimum maximum depth. So, heat affected zone is the in this case maximum depth of affected zone you see continuously increasing if you see that the increasing order. Although pulse up to pulse energy stopped at this point within first 100 second the all pulse energy has been stopped, but still there is a heat affected zone is gradually increasing and that increases because of the thermal inertia effect.

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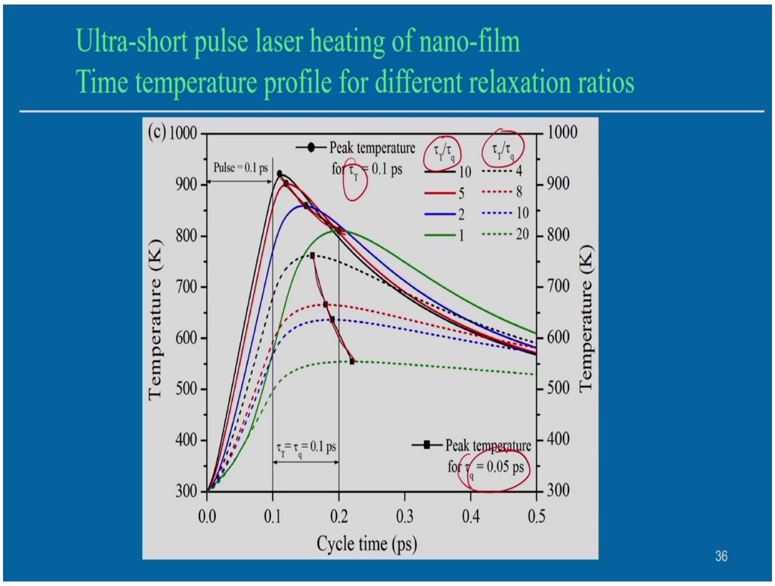

This we have we have tried to show that nano-film the time heating, but the time temperature profile for the different relaxation time. We can see for the different relaxation time, how the temperature profile actually varies? We see that solid line. So, 1, 2, 5 and 10 this is the ratio of the relaxation time and dotted line also, this is also represent the ratio of the relaxation time and peak temperature estimated for tau t equal to 0.1 picosecond and this 0.1 picosecond.

You see that the peak temperature is basically achieving this in this way the peak temperature is gradually decreasing and its achieve gradually decreasing and the ratio is very high then the peak temperature is the maximum when the ratio decreases then peak temperature is actually decreases. And other way also same thing also happen in case of this in case of the other ratio. That means, for 0.0 tau relaxation due to 0.05 picosecond here also you can see the peak temperature is actually decreasing and this thing.

And temperature profile are different. So, it means that the relaxation time is very much sensitive to the to obtain the this thing temperature profile and it has to be very carefully determine the value of the relaxation time and optimized value of the relaxation time is required or optimization of the relaxation time is required to get the very good results of temperature distribution when you apply the non Fourier based heat dual phase lag heat conduction model.

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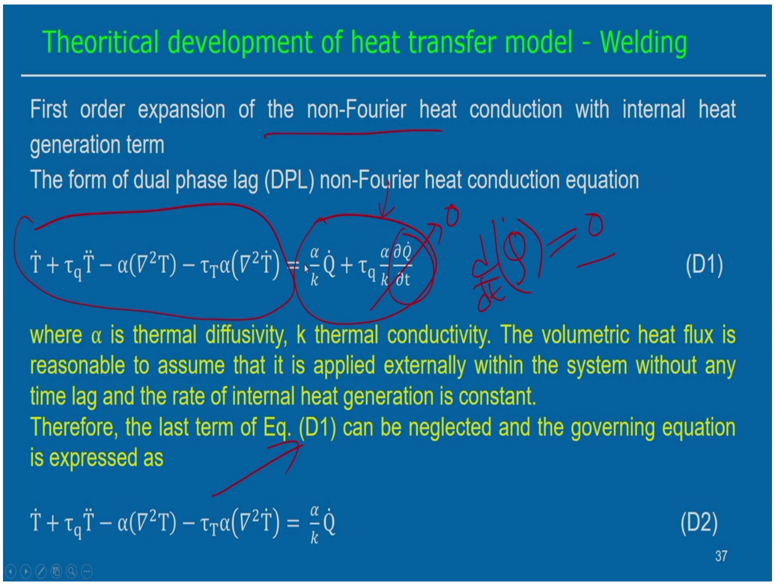

Now, we try to look into the theoretical development of the heat transfer model in case of the welding process. So, in case of the welding process is not much different as compared to the simply heating this thing only in terms of the heat source term we can in case of welding it is sometimes it is necessary to introduce the heat source from the volumetric heat source term. So, that has to be incorporated.

But when you try to analyze the nano-film, in that cases we represent the heat flux in the surface heat flux. So, in that way it is different whether we are in considering only the surface heat flux or whether we are considering the internal heat generation term what we have observed that in the Fourier heat conduction model there is internal heat generation term.

Now, if this if we consider the internal heat generation term in case of the non Fourier heat conduction model the expression can be different and that internal heat generation term may be significant when you try to analyze develop the model in case of the welding process, when you are using the some kind of the ultra short pulse laser source.

Now, first order expansion we have already seen that first order expansion of the non Fourier heat conduction with internal heat generation term incorporating this thing that dual phase lag model can be represented like this.

So, this term we have already seen and then since that we are using this Q dot term. So, internal heat generation term. So, this extra term will be there and the in the Fourier heat conduction dual phase lag Fourier heat conduction model considering the effect of the internal heat generation term.

But alpha is the thermal diffusivity k thermal conductivity that is there, the volumetric heat flux is reasonable to assume that it is applied externally within the system without any time lag and the rate of internal heat generation is constant. So, q dot term is the rate of internal heat generation we represent this thing the per unit volume per unit time.

So, therefore, further variation of the rate or in just the it is not a feasible. That means, variation of this with respect to time we take we neglect this term it is a variation is basically equal to 0; that means, we are considering the further variation of the internal heat generation term with respect to time that can be neglected and this heat generation term is not accounting any kind of the temperature lag.

So, from that point of view we can reach this kind of expression that is an equation D1. Now the last term of the d equation therefore, you neglecting this value. So, last term can be 0. So, then we reach this expression in case of the when you are considering the internal heat generation term. So, now, will be solving the same way what we have done the formulation in case of the simply assuming the heat flux on the surface the same way we can do the formulation in this particular case.

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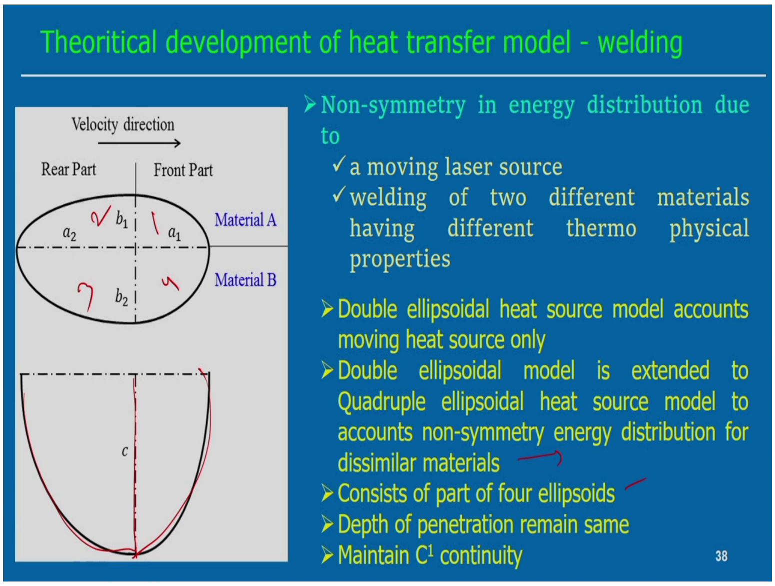

But theoretical level of the heat transfer model in case of the welding whatever we can represent that internal heat generation term. So, that quadruple double ellipsoid heat source model we have already discussed in the particular module, I think module 2 and then module 2 or module 3. And then after that what we have shown that how this distribution what we can develop some volumetric heat generation term that means, heat source model basically volumetric heat source model.

So, in that case we have shown that double ellipsoidal heat source model every any heat source model there are two terms are was important that one is the geometric shape geometric shape what kind of the regular geometric shape we can use and second how the energy is distributed with this the geometric shape.

So, that in the similar direction, in case of dissimilar material is the most non-linear. So, some modification of the double ellipsoidal heat source model was the quadruple ellipsoidal heat source model. In this case what we can incorporate this volumetric heat source term that we use the ellipsoid the part of the 4 ellipse ellipsoid can be merged and then we can make the quadruple ellipsoidal heat source model and then expression is already explained in that module.

But if you want to do the heat source model for the dissimilar material and along with the moving. So, along with the moving heat source. So, both can brings the non symmetric in the energy distribution and that is why there are four different kind of the a1 and this 1, 2, 3, 4 ellipsoids can be considered part of the ellipsoids can be considered, merge it then quadruple ellipsoidal heat source can be modeled.

Now, you can see the characteristic of this quadruple ellipsoidal heat source model is that. Double ellipsoidal heat source model is accounts only the moving heat source only, but double ellipsoidal model is extended to the quadruple model heat source model to accounts non symmetry energy distribution for the dissimilar material as well as the accounting the linear velocity in particular direction.

Therefore consists of the four parts of the ellipsoids, but depth of penetration remains the same. So, the depth of penetration remains the same. So, this profile can be merged in such a way and maintain the c1 continuity. With these assumptions it is possible to develop the quadruple ellipsoidal heat source model and that may be very much relevant to represent the volumetric heat source in case of the welding process.

And this heat source model is basically same whether it is Fourier heat conduction model or whether it is non Fourier heat conduction model. But I am showing you some variation of the volumetric heat source model. So, in this case we can see the variation may happen because the geometric shape is one fact and the other fact is the what way the energy is distributed within this particular geometric shape.

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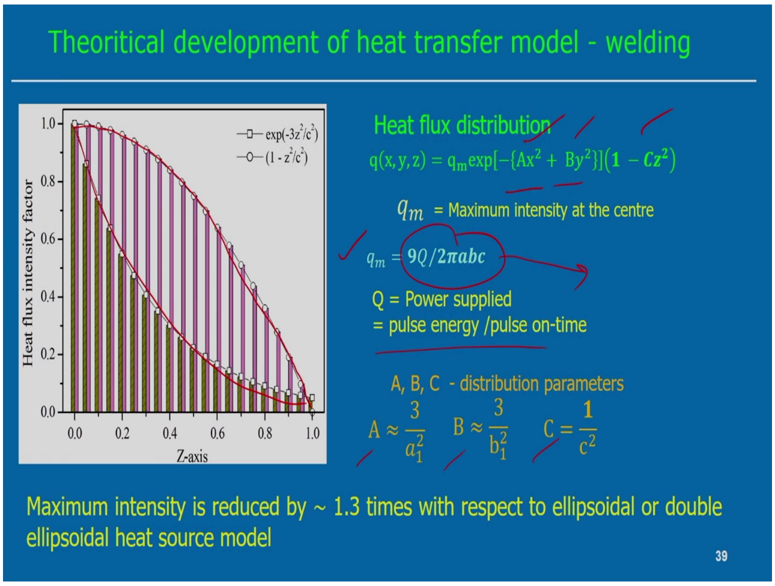

So, in this case we if we assume that it is a exponentially that we normally follow in case of the heat double ellipsoidal heat source model that is the exponentially varying the one distribution x is in along the x axis y axis, but along the z axis the some parabolic kind of distribution may happen. So, in this case we assume the 1 minus C by z square. So, this is the variation.

That means intensity varies with respect to this thing in that case if we follow what we can derive the any kind of the heat source model same methodology if we follow, then we can find out what is the maximum heat intensity at the center then we can find out the qm which expression is different from the double ellipsoidal heat source model. So, Q is the power supplied or pulse energy divided by pulse on time then expression is different.

And then in this cases the A, B, C distribution parameter can be different A approximated B approximated C is deterministic value 1 by c square, but we can see that distribution for example, 1 minus z square by c square distribution may happen in this way also. So, this is the expression for the this distribution, but other expression it can exponential way its varies like this way.

So, it means that that even if you follow the geometric shape and the regular geometric shape what way the distribution can be different and accordingly distribution can be different energy distribution and based on that we can estimate the what is the value of maximum intensity and the similar methodology can be applied for the heat source model.

So, maximum intensities reduce one point three times with respect to the ellipsoidal or double ellipsoidal heat source model and because this expression is different in case of the double ellipsoidal heat source model. So, in that cases this expression is 1.3 times. So, maximum intensity is 1.3 times with respect to the ellipsoidal or double heat source model.

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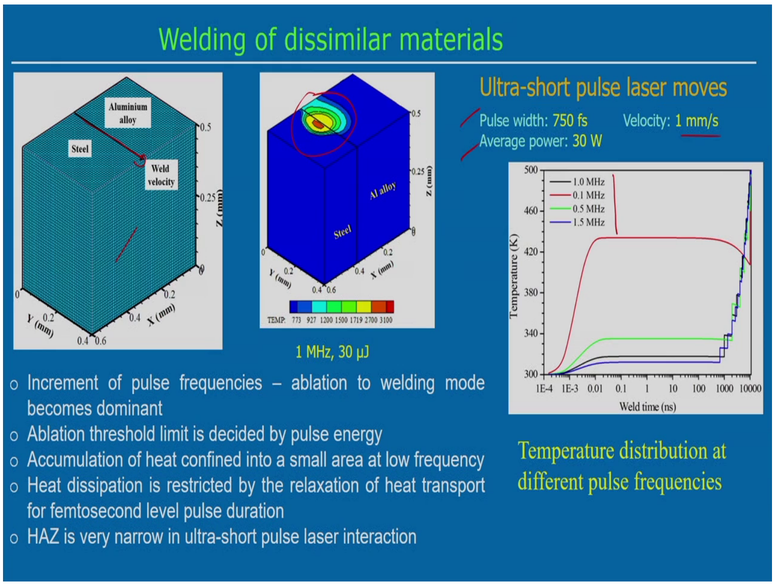

Now, we can show that simulation some results for the double in non Fourier heat conduction model applicable in case of the welding process and that is the dissimilar welding process we have done some simulation. So, welding of the dissimilar materials the steel and aluminum alloy.

So, steel and aluminum alloy first to create the domain the finite element this domain discretization of the domain using the some you can use a uniform mesh system or some additive mesh system can be done, but in this case we have used the uniform mesh system and the welding velocity is this along this direction heat source moves particular direction.

Then we can get the typical temperature profile is something like that we can see that dissimilar material that means, heat properties are completely different from the steel and aluminum, specifically the heat conductivity are different specific heat are also different and at the same time heat source is moving on particular direction. Then we can get that this non symmetric profile this thing.

So, some part will be if we see the maximum heat is concentrated towards the steel side and the aluminum side the that maximum that temperature is less as compared to the as compared to the steel part. Now, you see this kind of temperature profile we can expect in case of the dissimilar material.

But if you look into the other aspect, that means, how the maximum temperature varies on a particular in maybe we can stick any either steel or aluminum, the typical nature of the temperature variation with respect to the weld time. So, at the different frequency we can see our pulse repetition rate. We can start the pulse repetition in 1 megahertz 0.1, 0.5 and 1.5 megahertz.

We can see all this pulse repetition rate that how the temperature profile varies red color means the minimum pulse frequency pulse repetition rate. We can get the temperature distribution the domain is reach the temperature is very high as compared to the other frequency we follow this thing, but in this case pulse width that means, 750 femtosecond laser the pulse with the 750 second velocity is very small 1 millimeter per second. So, there is a possibility of the pulse overlapping and the average power is 30 watt.

So, average power is 30 watt in the sense in this case the frequency are different to maintain the average power, then peak power and the pulse energy can be different, but average power is same for all these four cases, but pulse repetition rate are completely different for all these cases. So, if you see that the temperature domain can reach on the single application of the single pulse is the very high temperature as compared to the low frequencies for the high frequency in this case.

See it means that increment of the pulse frequency is basically that indicates that its moves from ablation to the welding mode it means that the very low frequency pulse specific to ultra short pulses that is more suitable in case of the ablation process, but if you reduce the pulse frequency if the pulse frequency is low; that means, very small pulse frequency then its more towards the most suitable in case of the welding process.

We will see why it is suitable in the welding process. So, ablation threshold limit is decided by the pulse energy definitely in the in this case the policy energy can be high, in case of the high pulse repetition it once when it maintains the average power is the same because accumulation of the heat confined into the small area at the low frequencies.

Heat accumulation is there at the low frequency and that is why there is a once the heat accumulation there is a increment of the temperatures gradually, but not too high or not too much on the application of the single pulse. So, over the successive pulses then heat accumulation is there and gradually increment of the temperature. So, that way it is more suitable in case of the welding that means, melting of the material and the joining.

But if the pulse energy is very high and then with a short period of time this pulse energy is applied to this thing it can immediately that means, without reaching the equilibrium there is the very high temperature and the evaporated the material that is why it is very much suitable that means, low pulse frequency part is very much suitable in case of the material ablation process.

But heat dissipation is restricted by the relaxation of the heat transport for femtosecond level pulse duration that is obvious that is obvious, but heat dissipation is restricted by the relaxation of the heat because relaxation of the heat is basically restrict the heat dissipation.

So, once it restrict the heat dissipation then that is why it is more suitable the ultra short pulse in case of the material ablation process until and unless we control the parameter in such a way that lowering the pulse energy as well as the increasing the pulse frequency that is more suitable towards the welding of the material.

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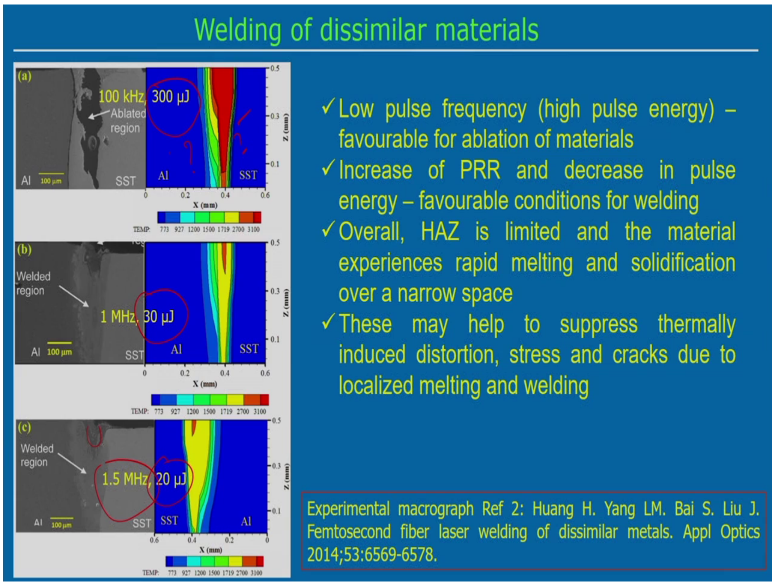

We can see that simulation we have compared the three different in this cases the three different pulse frequency and three different pulse energy and what is the accordingly what we can the temperature profile using the ultra short pulse laser. The first figure if we see this first figure this is 100 kilo hertz that means, very low pulse frequency and the pulse energy is 300 micro Joule.

So, definitely in this case we can see the mode of the ablated region we can observe; that means, it is a quickly vaporization of the materials happens ablated design, that is why similar kind of prediction is possible using this non Fourier heat conduction model and we can see this aluminum side and the stainless steel side.

So, if you see the aluminum side the heat diffusion or heat affecter zone is more or heat diffusion zone is more, but still there is not much heat diffusion zone and because the steel is having the thermal conductivity is very low as compared to the aluminum, aluminum is having very high thermal conductivity. So, that is why heat diffusion zone or heat affected zone is maybe more towards the aluminum side, but in not at that much of heat diffusion or heat affected zone in case of the stainless steel side.

Now, if you compare the pulse frequency first case and second case. Second case if you see that increment of the pulse frequency 1 megahertz and, but pulse energy is only 30 micro Joule which is 10 times less than that of the first one. In this case the ablated region is less rather the molten zone is well molten zone is more in this cases stable.

So, that means, if we gradually increasing the pulse frequency at the same time decreasing the pulse energy even for ultra short pulse result then it is possible to achieve the mode of the welding. Even if you reach the high pulsing is 1. 1. 1.5 megahertz, but pulse energy is only 20 micro Joule which is less than 50.

That means, pulse frequency is increasing and pulse energy is decreasing and of course, all these cases we maintain the same average pulse for that is 30 watt, but till you see the ablated region is basically decreasing and the molten zone is actually increasing. So, in that sense we can say that even if we increase the pulse a lowering the pulse energy as at the same time there is an increment of the pulse frequency, then it promotes the accumulation of the heat energy and that actually try to try to increase the temperature gradually and most suitable in case of the welding process.

So, therefore, low pulse frequency or high pulse energy is favorable for the ablation of materials increasing of the pulse repetition rate and decreasing in pulse energy which is favorable condition for welding. Overall heat affecter zone is limited and the material experiences the heat affecter zone is very limited we can see from this analysis the heat affecter zone is very maybe little bit more in case of aluminum side, but stainless steel heat affecter zone is very small.

But overall heat affecter zone is limited, even if you use the ultra short pulse and the material experiences the very rapid melting and the solidification and that is that normally happens very confined zone that is very small zone. This may help to suppress the thermally induced distortion stress cracks due to the localized melting and welding process.

At the same time even with dissimilar metal this is also advantageous because in this case is very rapid solidification that it can reduce the inter metallic formation as well also in that way it helps. So, therefore, in this case the dissimilar materials can be using the ultra short pulse result and of course, if you see that in this case a dissimilar material is only 0.5 millimeter thickness heat.

So, very small thickness heat it is possible to achieve, but practically if you want to achieve this welding of this only 0.5 millimeter using the ultra short pulse laser then it is necessary to some geometric groove is required. Otherwise the ultra short pulse laser may not be able to penetrate to the throughout this thickness direction.

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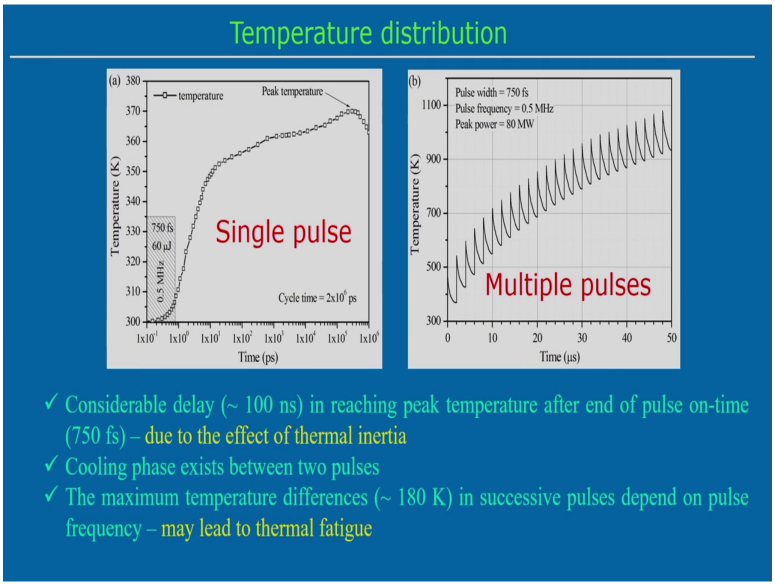

We can explain that whatever you can this thing there is a if you see the temperature single pulse what is the temperature distribution, in case of the single pulse we can see the temperature increasing and this at the particular point at the peak temperature. Although the cycle time is 2 into 10 to power 6 picosecond, but only pulse energy is applied only for the 750 femtosecond within that range.

We can say remaining term, we can say that is the pulse of time, but till even at the pulse of time, but till there is a high time to reach equilibrium the peak temperature that is very much obvious. And this is a typical temperature profile for the multiple pulses consequently multiple pulses.

In this case you see there is a increment of the with the application of the pulse energy there is a rapid increment of the temperature, but gradually it is decreasing this thing that, but decreasing temperature is the basically the gap between the application of the next pulse.

So, this way with the multiple pulse there is a this way there is a fluctuating fluctuation of the temperature it is the very high value then gradually decreasing to the lowering the value it depends on the what is the lowering the value depending upon the, what is the gap between the application of the next pulse? Therefore, you can see considerable delay almost 100 nanosecond in reaching the peak temperature after end of the pulse on time that is very often even in this case 750 femtosecond.

And due to the effect of the thermal inertia that means, it reach even after the peak temperature is even after the application of the pulse duration pulse energy then that happens due to the effect of the thermal inertia effect. So, cooling phase exists between the two pulses that is obvious and that because during the time between the application of the next between the two pulses there is a cooling may happen and there is a lowering of the temperature.

Now, maximum temperature differences we can see the 100 Kelvin that means, in the successive pulses it depends on the pulse frequency that means. So, that is way we can take the advantage of these things that exactly what may be the gap between the maximum minimum value and during the application of the one pulse to next pulse that internally depends on the, what are the frequency is normally following.

So, therefore, maximum temperature difference in this case is the 100 180 Kelvin and in successive pulses and entirely depends on the what are the pulse frequencies normally using. So, if the pulse frequency is very high then this the gap between the temper maximum temperature differences can be reduced.

But when there is a continuously practicing of the temperature increasing and then decreasing within the material subjected to this with the application of the ultra short pulse this may induce lead to the thermal fatigue. So, that may be the different issue associated with the one wave issue associated with the ultra short policy result processing.

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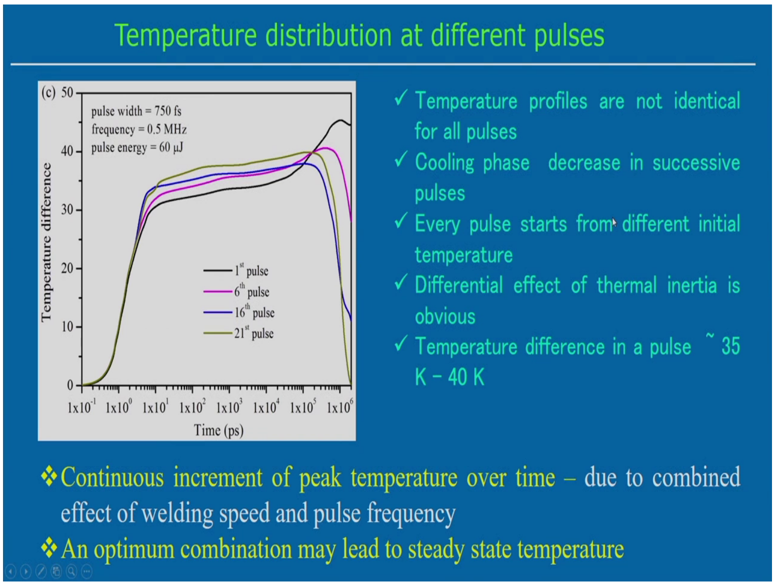

Here you can see the temperature distribution at the different pulses we can see that we have although the application we just individually estimating the with some references value, that what are the what is the effect of the individual pulse, how? The first profile is something different and what is the 16th pulse and 21 pulse. So, all these cases temperature profile are different and this can be explained like this thing temperature profile are not exactly identical for all the pulses.

Therefore cooling phase decreases in the successive pulses; that means, and the cooling phase decreases definitely in the successive pulses because there is maybe some accumulation of the pulses. So, every pulse starts from the different initial temperature that is fine, but we just scaling it to starts from the 0 to make compare what is the temperature distribution associated with the individual pulses.

So, therefore, definitely the temperature affects temperature distribution different in this case therefore, differential effect of the thermal inertia is obvious because all pulses are not behave in the form of a temperature distribution identical. So, that is mean thermal inertia effect are different in all these different pulses.

Temperature differences in a pulse its can be around 35 Kelvin to 40 Kelvin normally you observed. Therefore, continuous increment of the pink temperature over time due to the combined effect of the welding spin and pulse frequency. So, it means that pulse frequency is there, but at the same time the welding speed is an important parameter. So, if welding speed is very small in these cases.

So, there is a chances of the overlapping of the pulses, but if welding speed is very high then maybe overlapping gap between these two pulses or temperature distribution can be different. So, therefore, optimum combination may lead to the steady state temperature it means that combining the linear speed and the pulse frequency they may reach to some steady state temperature distribution; that means, towards the reaching towards the identical temperature distribution. So, individual pulses.

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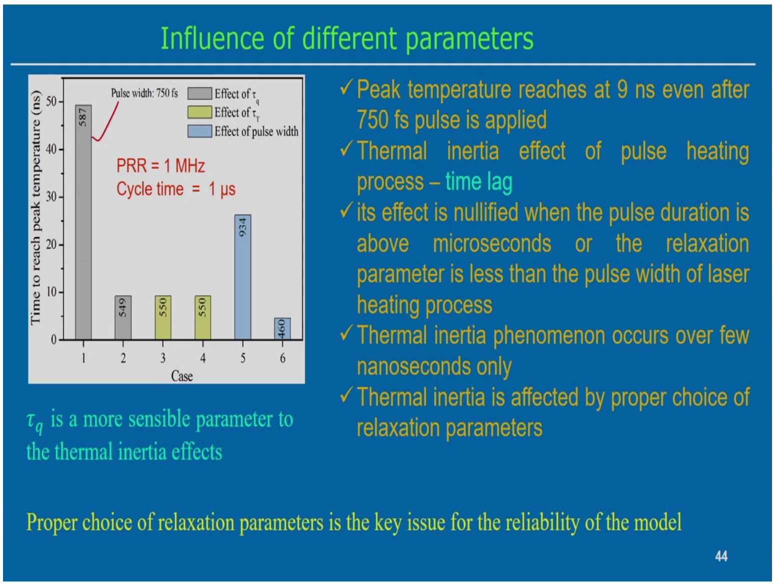

We can observe that influence of the different parameters that we have already explained this what are the effect of the in case of the simply heating on a nano-film, but in case in this particular cases we can estimate the what are the effect of the different relaxation parameters and that we can see the for pulse repetition 1 megahertz and the cycle time one micro second of this particular phases pulse with the 750 femtosecond.

We can see the what is the value of the time to reach peak temperature the peak temperature is 587 Kelvin in the 549 Kelvin that means, 1 and 2 effect of the relaxation time the. In this case relaxation time due to heat flux other cases relaxation time due to the temperature gradient.

And of course, you have shown the effect of the pulse width definitely pulse with this more than it is possible to reach to a high temperature or maybe temperature profile can be different. It means that peak temperature reaches at nanosecond 9 nanosecond even up the 750 femtosecond pulses is applied that kind of position you can see and of course, we represents the thermal units effect is more if time lag is more to reach the peak temperature then we can say the thermal inertia effect is more.

But the its effects can be nullified when the pulse duration is the above the microsecond it means that that we are getting the thermal inertia effect, but thermal inertia effect can be reduced if the origination is comparable with respect to the relaxation time. That means, per pulse duration in the of the order of micro second or millisecond then we cannot observe this kind of the thermal inertia effect in case of the pulse laser processing or pulse laser welding.

Now, thermal inertia phenomena occurs over the nanosecond in this particular investigation, we can see its thermal inertia effect is there, but it depends on the other parameter also, but we in this particular case the thermal inertia effects with the few nanoseconds only, but the thermal inertia is affected by the proper choice of the relaxation parameters.

So, definitely the relaxation time is important that actually decide or that play the role what are the thermal inertia effect can be can be observed in a particular system. So, therefore, from this analysis we can say that tau; that means, relaxation time due to the heat flux is more sensible parameter to the thermal inertia effect and that we can we can see from here also that it is the very high temperature it can achieve depending upon the this thing.

But of course, it depends on the what are the with respect to what other parameters is considered. So, therefore, proper choice of the relaxation parameters is one of the key issue for the reliability of the model. So, reliability of the model entirely depends on the proper purchase of the relaxation parameters.

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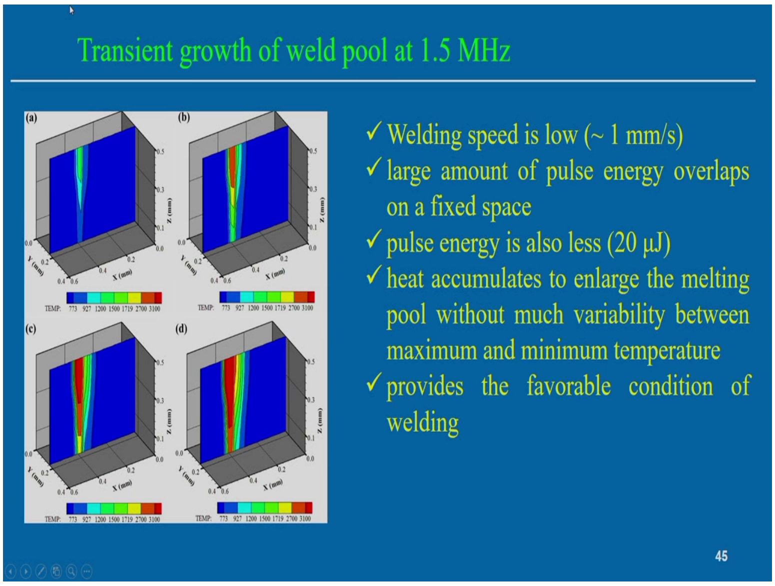

Even you can see the transient growth of the weld pool in a welding process we can see we can get some observation also and the weld pool at 1.5 megahertz you see the welding speed is very low in these cases only 1 millimeter per second. So, there is a possibility large amount of the pulse accumulation or pulse energy overlaps over a fixed space.

So, therefore, but in these cases pulse energy is also less only 20 micro Joule and heat accumulation heat accumulates to enlarge because in this cases the pulse frequency is very high. So, heat accumulation happens to enlarge the melting pool without much variability between the maximum minimum temperature in this particular cases and it is actually provides the favorable condition for the welding process.

We can see these 4 different cases and that what are the in this case we can see that that there is a gradual development a, b, c, d gradual development of the molten zone in case of the in dissimilar welding process. And this thing and this shows that transient growth of the weld pool as a particular pulse frequency.