Laser Based Manufacturing

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Module # 03

Lecture # 09

Effects of Process Parameters During Laser Welding and Study of Defects in Weld Beads

Hello everyone. I welcome you all to the third lecture of Week 3 of NPTEL MOOC course on Laser Based Manufacturing. In this lecture, we will be studying the effect of various laser process parameters and other parameters associated with laser welding on the weld quality.

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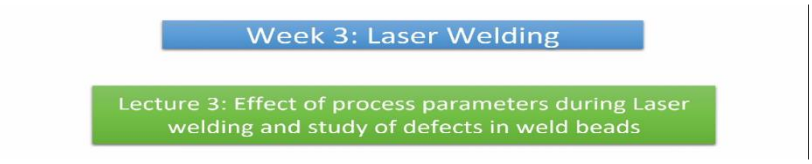

Moreover, we will also study the defects which are getting generated during the laser welding operation in the weld beads.

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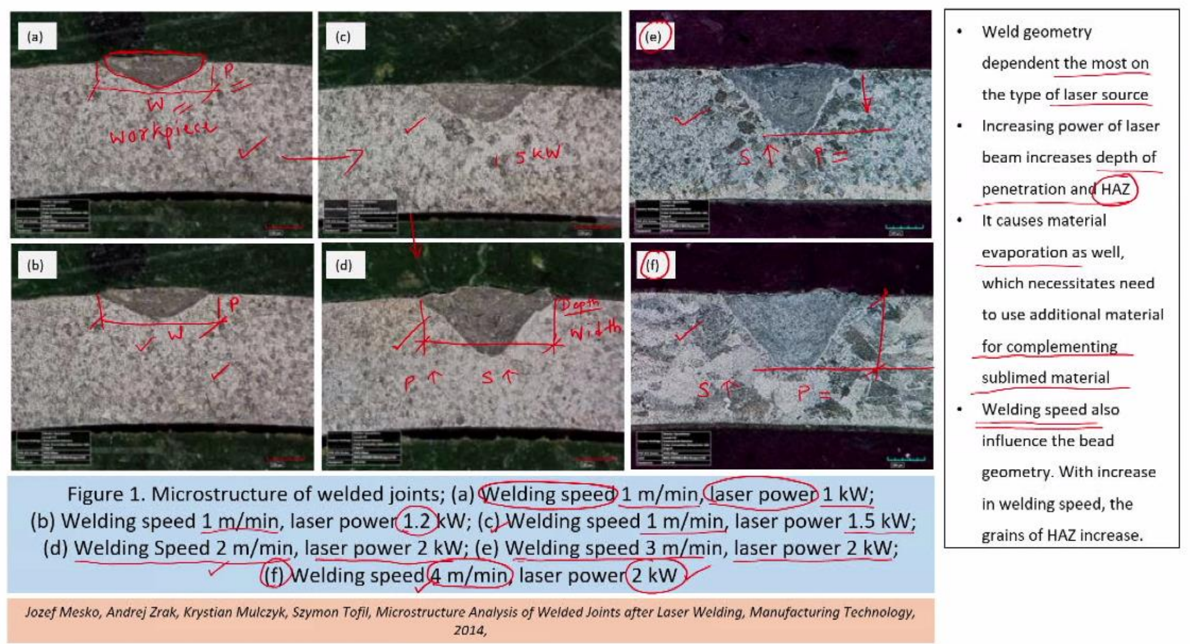

On your screen you can see a variety of optical micrographs and we will be studying this optical micrographs to understand the effect of two important laser welding parameters. The first laser welding parameter is welding speed-the speed of interaction between the laser and the work material and the second important parameter is laser power.

The first optical micrograph is an cross sectional cut of laser welded specimen. Here you can see the formation of laser bead. These dark grey colour is showing the laser bead and this is the workpiece or the specimen. I request you all to study or just observe the width in all such cases. This is the width of the laser bead and this is the penetration P. These two parameters we have already seen in our previous class. Similar, laser beads we can observe in all the pictures b, c, d, e and f. Now, you note the values of speed and power for all these cases. For case number 'a' the weld speed is 1 meter per minute and the laser power is 1 kilowatt that is for this case, for 'b' the speed is 1 meter per minute which is the same as 'a' however we have increased the laser power by 200 watts. It is 1.2 kilowatt for case number 2. In case number 3 the speed is again constant we have not increased the speed, but the power is further increased to 1.5 kilowatt. Here the power is 1.5 kilowatt. Then we increased the speed. Now, we are increasing the speed as well as the power. Speed has been increased from 1 meter per minute to 2 meters per minute and the power is increased from 1.5 kilowatt to 2 kilowatt. That you can see in 'd'. Here power is also increased and the speed is also increased.

In the next case that is 'e' the speed is further increased and the power has kept constant. Here speed is increased in 'e', but the power is same and in the last case the power is kept constant and the speed was further increased to 4 meters per minute. Here speed is further increased and power has kept constant, but note down this power is more than the power in case a, b, c.

Now, let us look at the geometry that we are getting. Now, you just observe when we are increasing the power by 200 watt there is no considerable change in the geometry, the width seems same in this case as well and the penetration is also almost same. The width and penetration seems almost same. By increasing power by 200 watt there was not considerable increase in the geometry parameters of weld beads. Now, you just look at 'c' you can observe that the width is increased as well as there is increase in depth as well. The width depth or the penetration has increased.

Let us look at why this has happened? Here the speed is remained constant, but power was further increased by 300 watt. From a to c if you observe when we increase the laser power by 500 watts then there is a considerable increase in penetration depth. Now, from c to d if we observe; now in this case we are increasing the speed that means we are reducing the interaction time and we are increasing the laser power as well. Laser power has further considerably increased and interaction time has been considerably reduced. When interaction time has been reduced the power density is more, you can notice over here that there is considerable enhancement in the width as well as the penetration depth. The speed is also affecting majorly and the power is also affecting majorly during the weldment formation during the laser welding operation.

Now, let us look at e. Now in the case of e what is happening? The speed is further increased to 3 meters per minute and the power is kept constant then also there is further enhancement or further increase in the depth of the laser penetration. Here you can see that if we reduce the interaction time of laser with the work material we can get better depth or the deeper weldments during laser welding operation.

Now, in 'f' we have further increased the speed by keeping the power constant to reinforce or to verify the fact that as we reduce the interaction time we are getting deeper weldments. Here you can see that if you increase the welding speed then we are getting the deeper weldments. When there is a faster welding speed and larger the power we can get deeper and strong weldments during the laser welding operation.

The same things I have been summarized at right side of the slide. Weld geometry depended upon most of the type of laser source that is obvious Nd:YAG or the CO_2 laser power. CO_2 gas laser is producing higher laser powers, it is providing larger laser power. By using the high power lasers certainly you will get a better quality laser welds. Increasing the power of laser beam increases depth of penetration and HAZ. The depth of penetration is increasing because we are including more power, but there is a by-product of these increase in depth that we are increasing the heat affected zone. When there is more heat affected zone that would probably not desired because of degradation of material properties in the heat affected zone.

When we increase the power the evaporation will also increase and which necessitates the additional material to compliment the sublimed material. When we increase the power more amount of material will get vaporized in that case there is need to have some sort of filler material which will compensate for the vaporized material. The sublimation of the material will make some voids and that voids need to be filled up. The molten material can get deposited in the voids, but in case the vaporization is more then we have to have some filler material to fill up the gap between the joining parts.

As we have seen that welding speed is also playing a crucial role in the weld bead formation that we have already discussed.

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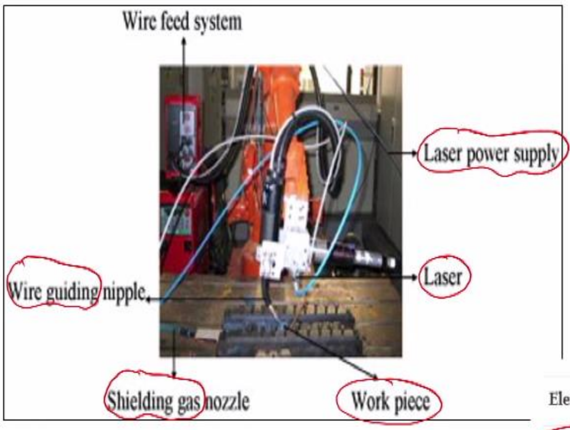
Laser welding with filler wire process



- Nd:YAG laser with maximal output power of 3 kW
- A six-axis robot
- The laser is transferred through a fiber and focused on the workpiece. The laser beam was 15 degrees leaning to the normal direction to prevent the fiber being burned.
- Two argon shielding channels (side shielding and back shielding) were also used to protect both the front and back of the welds.
- The wire feed system was constructed.

Element	Mg	Mn	Er	Zr	Al
Base metal	4.7	0.7	0.3	0.1	Bal.
Filler wire	4.9	0.7	0.3	0.1	Bal.

Yang DOngxia, Li Xiaoyan, He DIngyong, Nie ZUoren, Huang Hui, (2012), Optimization of weld bead geometry in laser welding with filler wire process using Taguchi's approach, Optics and Laser Technology, Volume 44, Issue 7, October 2012, Pages 2020 - 2025

Now, let us look at one case study and in this case study laser is used to join two plates of aluminum. However, in this case we are using a filler material and the filler material is of the same grade, same composition. The experimental setup can be seen on your screen. Here we are having the workpiece, this is the workpiece, there is a laser, this laser is of Nd:YAG type, solid state laser and it provides a highest power of 3 kilowatt.

Here you can see the laser power supply. Now, as I mentioned due to more vaporization there is need to have the filler material. We can have the same filler material, we can have a filament of the same filler material which can be used to melt and deposit at the junction of the joining. Now, this is wire guiding system, here through this wire guiding system the wire will come and that is getting melted and will be deposited. We also need the shielding gases, the inert gases to protect or to make the environment free of oxidation. We are using two argon shielding channels, one is from the side and the other one is from at the rear side or at the back side. The laser is transferred, it is conveyed by using fiber and it is focused on the workpiece and it has been given a deliberate angle of 15 degrees to prevent the fiber being burnt. If it is perfectly orthogonal there are chances of getting burn out of the fiber which is carrying the laser. Deliberate angle is given 15 degrees and the wire feed system was constructed. You can see the base material is an aluminum alloy and it has variety of other element such as magnesium, manganese, zirconium.

Now, after carrying out this process, after carrying out the laser welding we are seeing what are the observations or results. Now, these laser welding was operated by a robot. In our previous class we have seen that there is need to have a CNC based system, but in industry people are using the articulated robot as well 6 axis robots for the laser welding operation.

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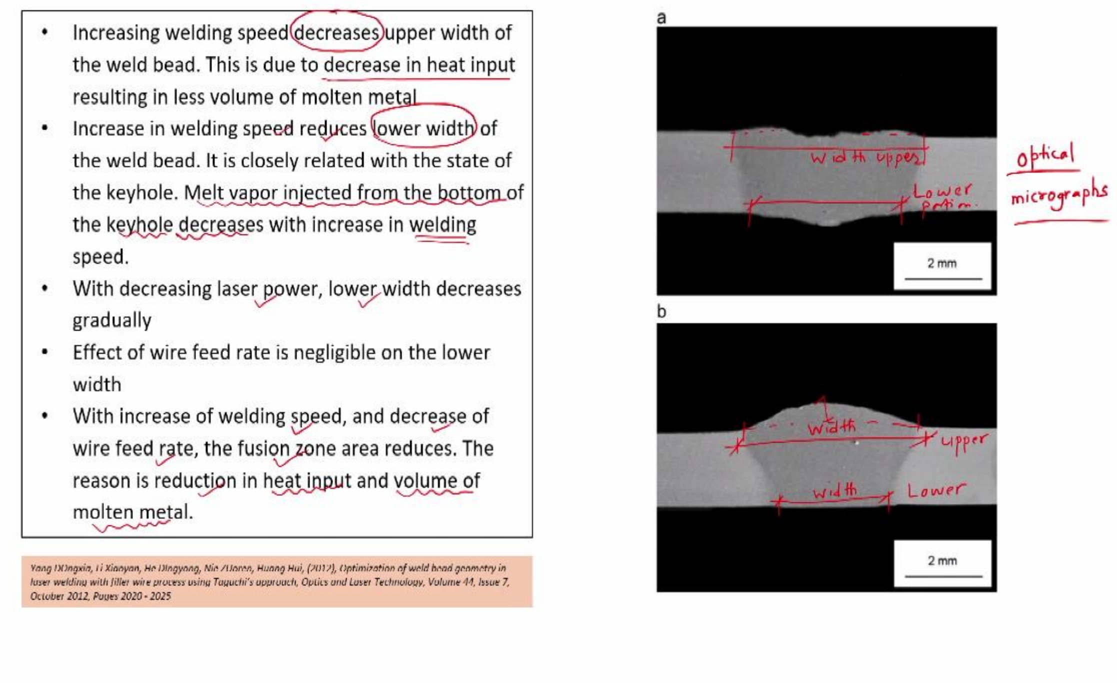

On your screen you can see two optical micrographs and these two optical micrographs are generated after the welding operation and you can see or you can observe the bead at the top or you can see at the upper portion and there is a lower portion as well. There are two widths that we can notice: one is at the upper portion of the bead and the other one is at lower portion. This is upper portion and lower portion. And here is some sort of reinforcement can also be seen. This is a reinforcement.

Now, this is another micrograph. Here you can see there is no reinforcement or there is a minor reinforcement at little sides and we can clearly distinguish between the width at the upper portion and the width at the lower portion. Width at upper portion and at the lower portion. This is root basically and we can see that this is root opening.

Now, after carrying out multiple number of experiments and studying this optical micrographs of all the specimen some of the observations are there on your screen. When we increase the welding speed the upper width of the weld bead is reducing or it is decreasing. An interesting phenomena is occurring when the speed is getting increased the width is getting reduced. This is due to decrease in the heat input and resulting in less volume of molten metal.

When we increase the welding speed the lower width of the weld bead is also reducing. As the upper width is also reducing certainly there would be reduction in lower width as well, due to low amount of heat energy that we are passing through.

When there is increase in welding speed as well it has been noted that the melt vapour injected from the bottom of the keyhole is reducing it is decreasing with the increasing weld speed. The injected melt vapour at the bottom of the keyhole, its amount is getting reduced and that is affecting due to increase in welding speed.

When we decrease the laser power there is reduction in the lower width which is quite obvious. Effect of wire feed rate is having a negligible effect on lower feed. The wire feed that we are using or when we are feeding the wire during the laser operation, its effect - the rate of deposition it is not that much affecting during this laser welding operation that has been noted.

With increasing welding speed and decrease of feed rate the fusion area reduces. When the speed is getting increased the fusion zone area is getting reduced and this reduction is attributed to the lower heat input and the lower volume of molten metal which is getting generated.

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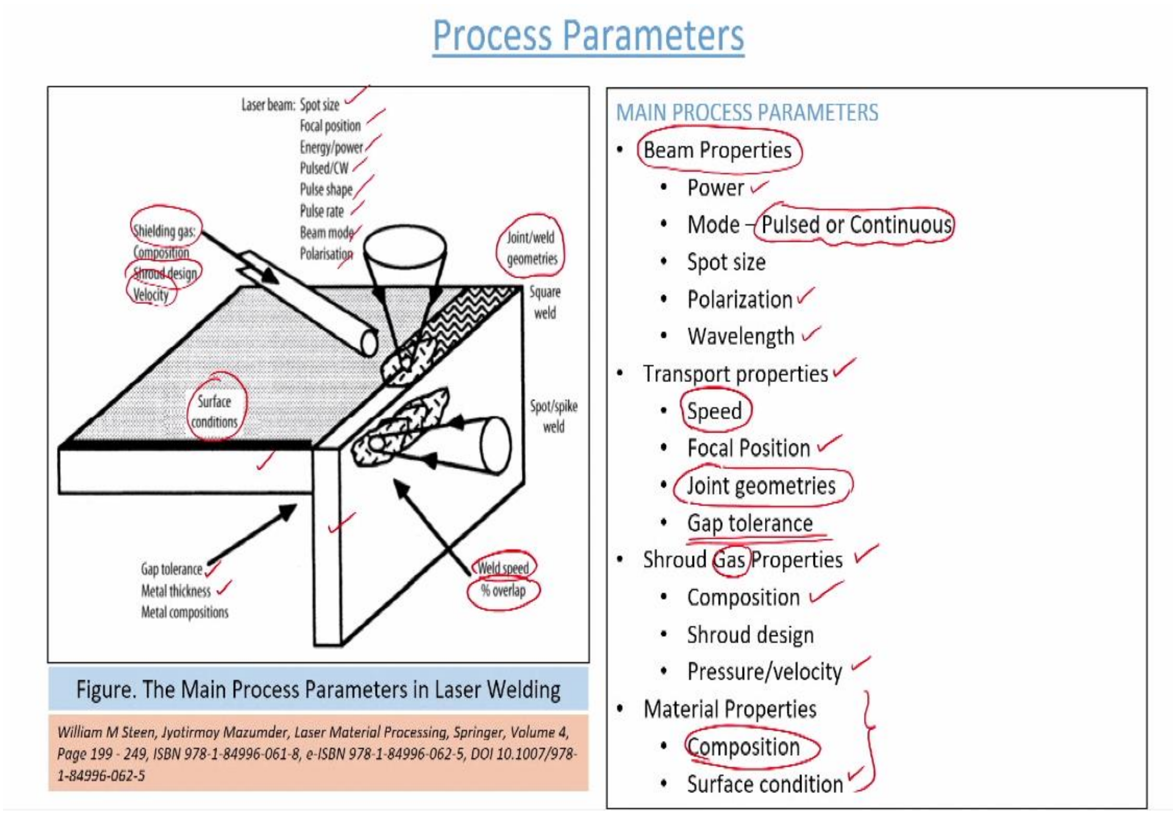

Now, just look at in a comprehensive way what are the various parameters affecting the laser welding process. There are various groups of process parameters.

The first group is beam properties. In beam properties we can note here the laser power is affecting, then the mode of the laser: whether the laser is pulsed or a continuous that is also effecting the laser welding operation, the spot size or the spot diameter is also affecting - if the spot size is less with constant laser power the heat power density would increase. The diameter of the spot or the size of the spot or the area of the spot is also affecting the laser welding process. Then laser related parameter such as polarization and the wavelength. If the wavelength of the laser is low then its absorptivity would be high and reflectivity would be less and then we can achieve a better quality weld. Then the transport related properties, conveyance related properties, the speed of interaction of the laser with the work part, the focal position of the laser with respect to the work part, then the geometries of the joint, the geometries of the work samples is also affecting, then the gap tolerance is another parameter that to be considered during the application of laser particularly in butt welding.

Then the inert gases which are being used during the laser operation, their composition, the design of application of the gases during the laser welding operation, the velocity of the passage of the gases during the laser welding operation.

As far as the material properties are concerned the composition of the work material itself and the surface condition. If the surface condition is reflective then certainly we will not get the proper welding operation. Composition means the alloying elements, their effects, because the alloying elements are controlling the thermal conductivity of the work parts. They decides whether the conduction mode of heat transfer or the conduction based laser welding is able to generate the required weld or not.

All these process parameters can be seen or can be summarized in a graphical way. On your left side of the screen you can see the variety of parameters associated with laser and laser welding process are there. Here we have taken two workpieces, this is workpiece number 1 and workpiece number 1 and we are going for the edge joint, sorry, here we are going for the corner joint. During this corner joint various parameters are enlisted here: spot size, focal position, energy or power that we are applying, mode of the laser whether it is a pulsed or continuous wave, shape of the pulse, rate of the pulse that is the pulse frequency, beam mode and the polarization. This is the shielding gas or the inert gas that we are using here, the design, the angle at which we are applying the shielding gas at the joining place or at the joint, its velocity that to be also considered. Again the surface condition whether the surface is having any irregularities or the surface is having some sort of dirt or the surface is uneven that also is affecting the laser welding operation.

Then the gap which is provided in between the two parts that are to be joined, the thickness of the metal. If the thin sheets are there then we can easily weld, but when we are dealing with two thin sheets or very small thickness sheets, then we have to be very careful for setting up the laser power or the scan velocity and if the sheets are too thick then also we have to consider whether we are applying the conduction mode of laser welding or we have to go for the keyhole based laser welding. Accordingly, the parameters need to be set.

Then speed of the weld and the overlap, that percentage of overlap is to be considered when we are using the pulsed type of laser welding and the geometry here you can see the geometry or the joint condition. Here we are going for the corner joint. The process conditions may be different than the process conditions we are using for butt joint or the edge joint.

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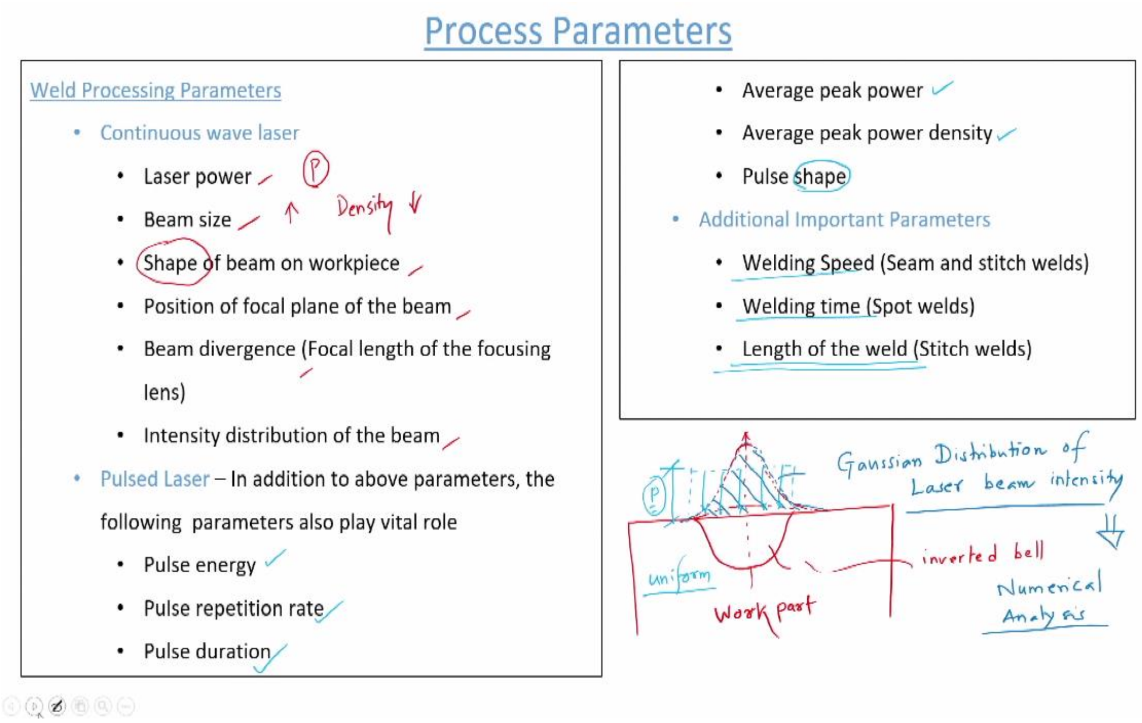

Well let us look at these parameters little more in details. As we have already seen that power, beam size, the shape of the beam, position of the focal plane of the beam divergence and intensity distribution of the beam these are affecting. The power is quite obvious that we have seen, the beam size is deciding the density. If the beam size is more with constant power than the density would be low.

Then shape of the beam on the workpiece that also influencing parameters, we can have a circular shape of the interaction or a square shaped. It is based upon the focal lens or the optical instrumentation that is getting used. Then beam divergence - the beam if it is properly focused on the work part then we are getting the intense localized temperature and if the beam is getting diverged then probably we will not get the proper localized temperature to generate the keyhole type of drilling. The divergence is to be considered during deciding the laser welding parameters.

The intensity distribution of the laser beam. If you are considering the circular laser beam interactions, circular area of laser beam then it has been noticed that the shape of the weld bead is very similar to an inverted bell. The inverted bell shaped is considered as the opposite or the reverse image of the Gaussian or the normal distribution of the bell shape. If we consider that we are getting a inverted shape of the laser bead over here, this is the work part and the laser bead which is appeared to be of inverted bell shaped, then it can be assumed that the maximum amount of laser energy has been passed or it has been disseminated or it has been dissipated along the axis. I can consider that maximum amount of energy was this much and it was reduced with the distance of the application of energy from the axis. Here if we try to approximate the power of laser which is getting applied over here. This comes very similar to the Gaussian distribution or the normal distribution. This is the Gaussian distribution of the laser beam intensity application. The consideration of Gaussian distribution is very much essential when we use the numerical analysis to compute the temperatures during laser welding operation, so numerical analysis. What kind of laser beam intensity profile to be considered ? Most of the people do consider the Gaussian distribution.

Some of the people are considering uniform distribution. Instead of considering bell shape type of application of heat we can also consider a constant or uniform heat application over the area of application. This is the area of application and the power is applied uniformly over this area that we call uniform distribution. If the laser bead width or the application of laser beam is very small in microns then it is easy for computation to use the uniform distribution of heat application.

Well the pulse energy, then repetition rate that is the frequency of the pulse are also affecting the pulse duration. If the pulse duration is long, if the pulse application time is long then generally we are getting more dissipation of heat energy inside the work material, so we may not get sufficiently good quality weld because the heat will get dissipated and there is a chances of having more HAZ, that is the heat affected zone. Average peak power, then average peak power density which is again the function of various other parameters, shape of the pulse that is also affecting. In general we are approximating the shape of the pulse is rectangular shape, but in certain cases it has also be considered as a trapezoidal shape of the pulse as well. The welding speed, the welding time in case of the spot welds and the length of the weld which are designed parameters as far as the laser welding is concerned.

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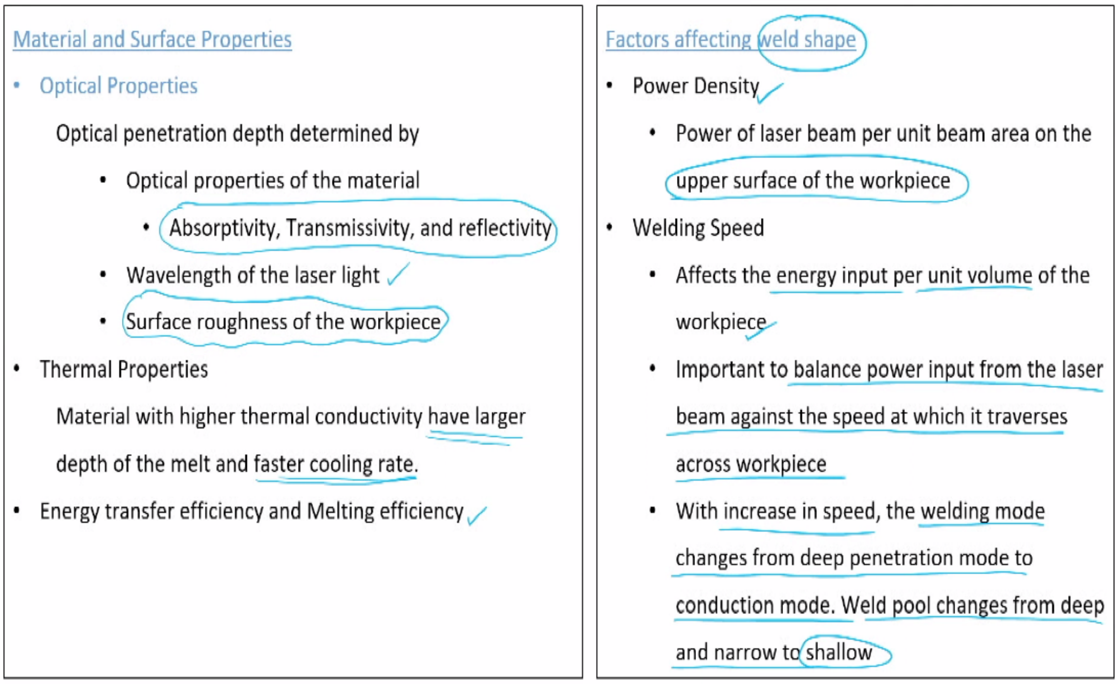

When we consider the material or surface related properties, the optical properties and the three properties which are affecting the laser welding is absorptivity of the material, transmissivity and the reflectivity. The wavelength of the laser light is also affecting, as I mentioned shorter wavelengths will get absorbed easily at a faster rate. Roughness, if the surface roughness is very high then the laser is getting reflected and the local reflections are also helping to increase the absorption.

Higher thermal conductivity will have larger depth of the melt and it will have faster cooling rate. So, higher conductive material can easily be weld. Heat transfer efficiency and melting efficiency these two are again the parameters which are affecting the laser welding operation.

The factors which are affecting the weld shape. The first parameter is the power density. Power of the laser beam per unit area on the upper surface that is affecting. If power is more then more energy will be there to get dissipated, more energy will be available for the laser welding. In case of the speed, the speed is affecting the energy input per unit volume of the workpiece and it is also important to balance the power input from the laser beam against the speed at which it traverses across the workpiece. The speed is also modulating, fine tuning the balance or it is modulating or fine tuning or balancing the power input from the laser beam to the workpiece.

If we increase the speed then welding mode may get changed from deep penetration mode to the conduction mode and weld pool changes from deep and narrow to shallow. If the speed is constant with higher power, in case of very high power laser of 2 kilowatt and if the speed is getting increased then we may not get the keyhole type of laser welding. In that case as the speed is getting increased there is a transition from the keyhole type of welding to the conduction mode of the welding.

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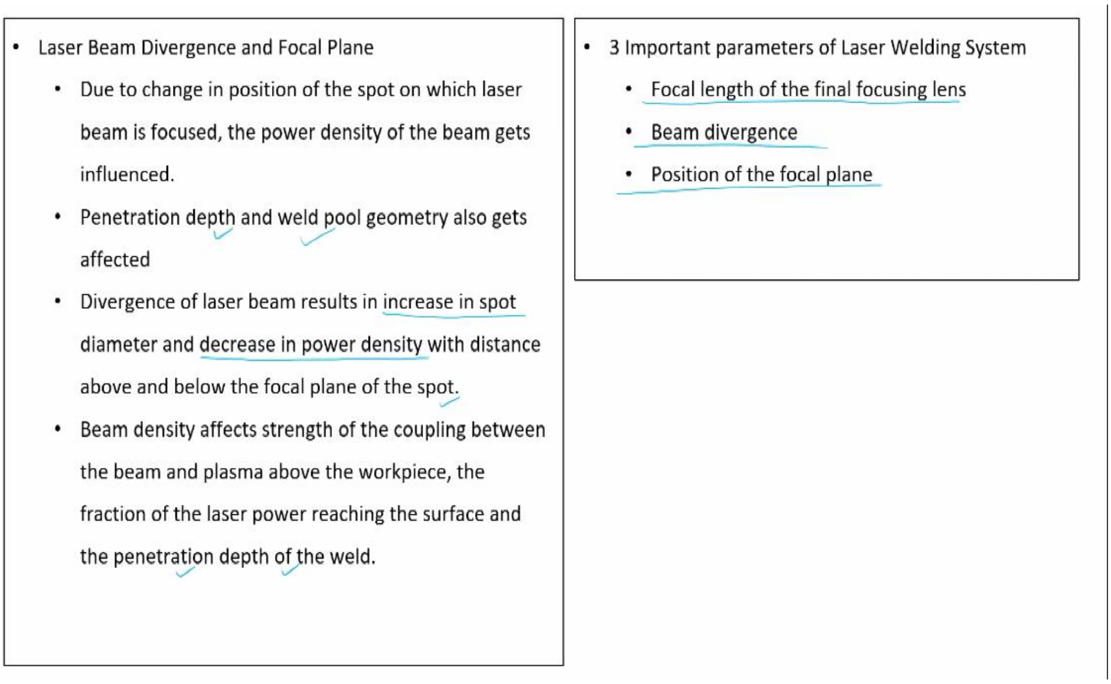

Now as far as the beam divergence and focal plane are concerned, due to change in position of spot on which laser beam is focused, the power density of the beam gets influenced as the laser beam focusing is getting changed it is affecting the power density, the focal plane is to be set properly based upon the requirement. If you want to have more intense localized temperature then the focusing should be very accurate and in case of heating up the workpiece then we can even have the diverged laser beam on the workpart. The divergence is also affecting the width and the weld pool geometry that we have already seen. Divergence of the beam, results in increasing in spot diameter and thus reduces the power density with distance above and below the focal plane of the spot.

The beam density affects strength of the coupling between beam and plasma above the workpiece and the fraction of the laser power reaching the surface and it is also affecting the penetration depth of the weld.

There are three parameters which are quite important in welding system. Based on this we can say that the three important parameters which are affecting the laser beam welding, that is focal length of final focusing lens, beam divergence and position of the focal plane.

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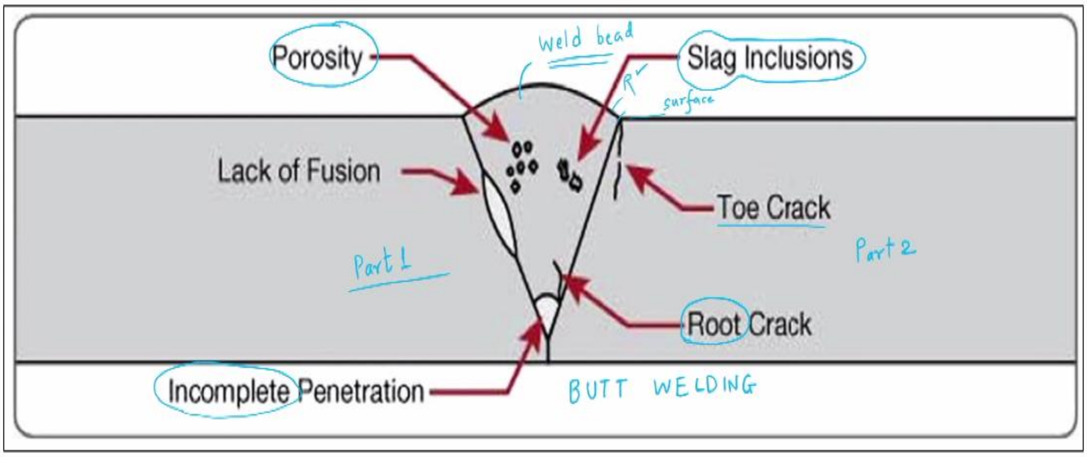

Figure. Possible Defects in Laser Welding

Stavridis, J., Papacharalampopoulos, A. & Stavropoulos, P. Quality assessment in laser welding: a critical review. Int J Adv Manuf Technol **94**, 1825–1847 (2018). https://doi.org/10.1007/s00170-017-0461-4

Now, let us look at what are the various possible defects in laser welding. On your screen you can see there is a part 1 got welded with part 2 and this is butt welding operation. Various types of defects that you can notice here. The first type of defect is porosity and this porosity is occurring due to various vapours which are getting liberated during the process of welding itself. As we have seen that most of the material is getting vaporized in keyhole type of laser welding and these vapours are high temperature, high pressure vapours, they will get sometimes entrapped inside the work material and slowly they will get release. Due to release to these entrapped vapours there are chances of having pores inside the weld material which is not good, which is not desired.

Then the next, is slag inclusion. We may have some dirt on the surface of the work part and that dirt may get included inside the weld zone. This is the weld zone or weld bead this is also not desired naturally. Toe crack - this is the reinforcement and there is a joint of the reinforcement with the surface. This is the reinforcement and this is the surface and at the juncture of the reinforcement and the surface we are getting a toe. There is a good chances of having certain cracks at this junction.

We may also have incomplete penetration during the laser welding operation. If the process parameters are not properly set, there are chances of having poor or incomplete penetration during the laser welding operation. Moreover, there may be chances of having certain cracks at the root. During all these operations we must able to understand the various defects which are getting generated and accordingly we have to modulate or fine tune the process parameters.

There are lot of research being done in various universities across the world, lot of MS, M Tech projects, PhD projects being carried out to find out the defects and to analyze the causes for these defects and how to mitigate these defects during laser welding operation.

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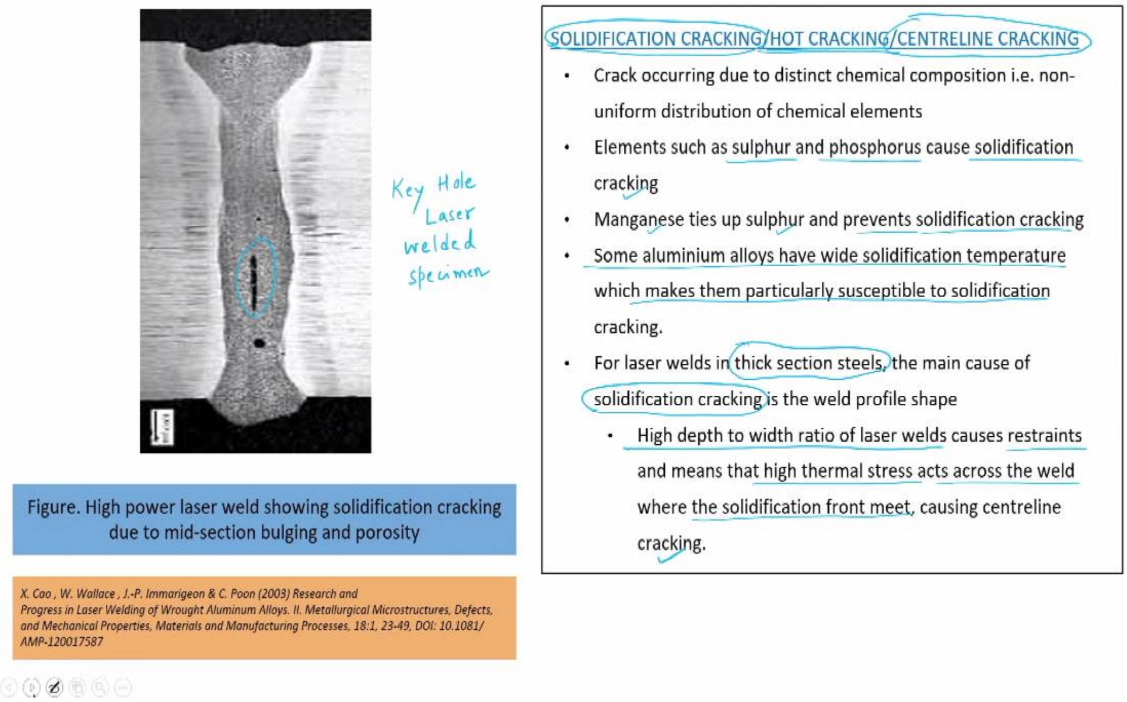

One such defect can be seen on your screen. It is the solidification cracking. This is solidification cracking or it is called as the hot cracking or in sometimes it is also called as the centre-line cracking. Now, on your screen you can see a keyhole type of laser welding - laser welded specimen. Now, here you can see the solidification cracking due to the mid section bulging or the porosity. This is the solidification cracking due to the mid section bulging or the porosity. Crack is occurring due to distinct chemical composition that is non-uniform distribution of chemical elements.

Laser welding we are using for joining the alloys and they do have the elements and diverse chemical compositions. Non-uniform chemical composition, non-uniform distribution of chemical elements and when these elements are thermally processed, due to their material properties we may not get uniform expansion of these elements that is leading to some sort of cracking or defects during the laser welding operation.

What are these elements? The elements such as sulphur or phosphorus are causing the solidification cracking. When we use manganese that is getting tied up with sulphur and it is preventing the solidification cracking. When we add the manganese it is reducing the chances of having the solidification cracking. Solidification cracking can also be understood by its name itself. The cracks which are generated during the solidification process.

Some aluminum alloys have wide solidification temperature. The temperature of solidification is varied from material to material from element to element. And when such wider solidification temperature materials are getting laser welded, then there are chances of having more cracking due to solidification. During the welding of thick section steels we can observe the solidification cracking, the solidification cracking is observed at a larger extent.

Why there is more solidification cracking when the thick section sheets are getting welded? The reason is that due to high depth-to-width ratio of laser welds, there is restraint and that restraint is nothing, but high thermal stresses which are acting across the welds where the solidification fronts are meeting. Two materials, they are having different state of thermal stresses and due to that there is generation of solidification cracking. When these two solidification front meets, their state of stresses is different and that leading to the cracking.

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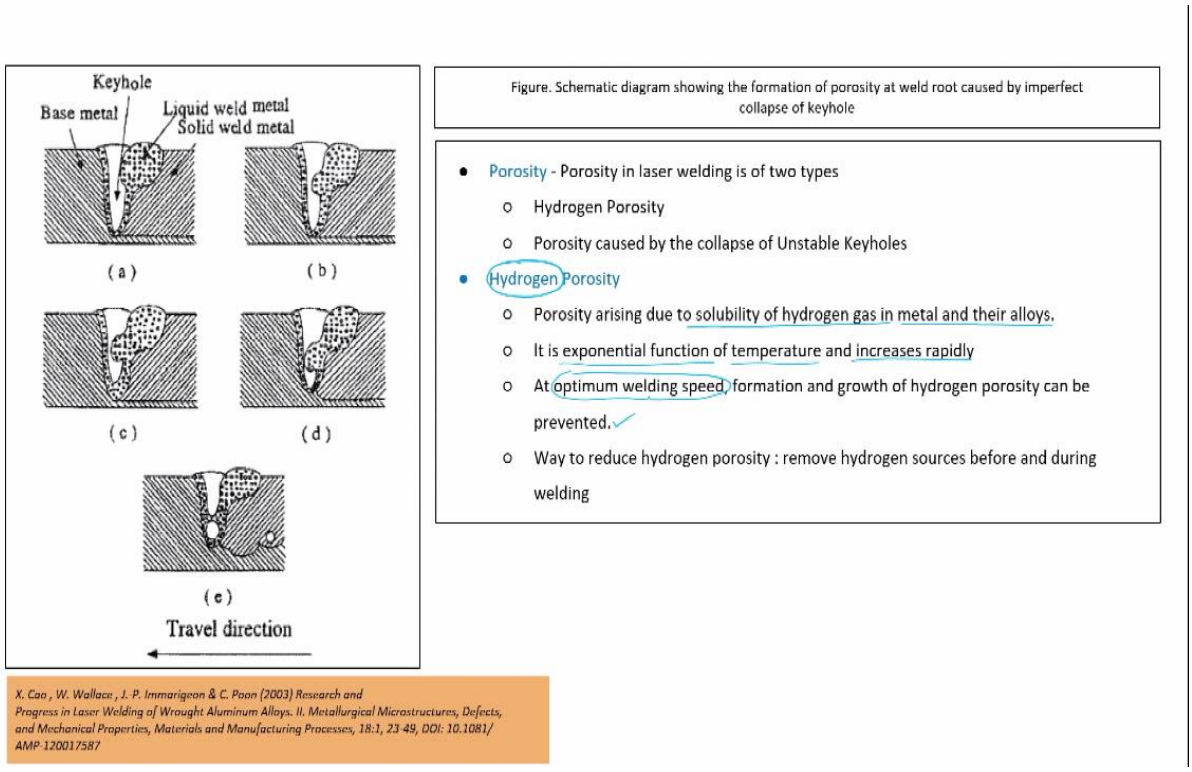

Now, in case of keyhole type of laser drilling, there is another defect which is quite prominent that is the porosity and the porosity is generally happening due to the hydrogen. On your left side of the screen you can see that there is a formation of porosity of the weld root by imperfect collapse of the keyhole. It is expected that the molten metal in the keyhole should get mixed with each other and to have the proper mixing so that the pore should be as less as possible, but if the collapse of the molten metal inside the cavity during the vaporization or the cooling of the keyhole, if the collapse is improper, if there is a sudden collapse then there are chances of entrapment of the gases would be more and that will generate the porosity. The porosity is arising due to solubility of hydrogen gas in metals and their alloys and it is exponentially varying with temperature and increases rapidly. If we set the welding speed at optimal level then we can certainly prevent the formation of hydrogen porosity.

Well with this I would like to summarize today's lecture that is on the process parameters of laser welding, its effects on the weld quality and various defects which are getting generated during the laser welding.

My friends we have seen at introductory level only the various process parameters and the defects. The detail analysis of the laser weld parameters and the defects can be done as part of some small projects you can take up this as a project and carry out the analysis in the greater extent.

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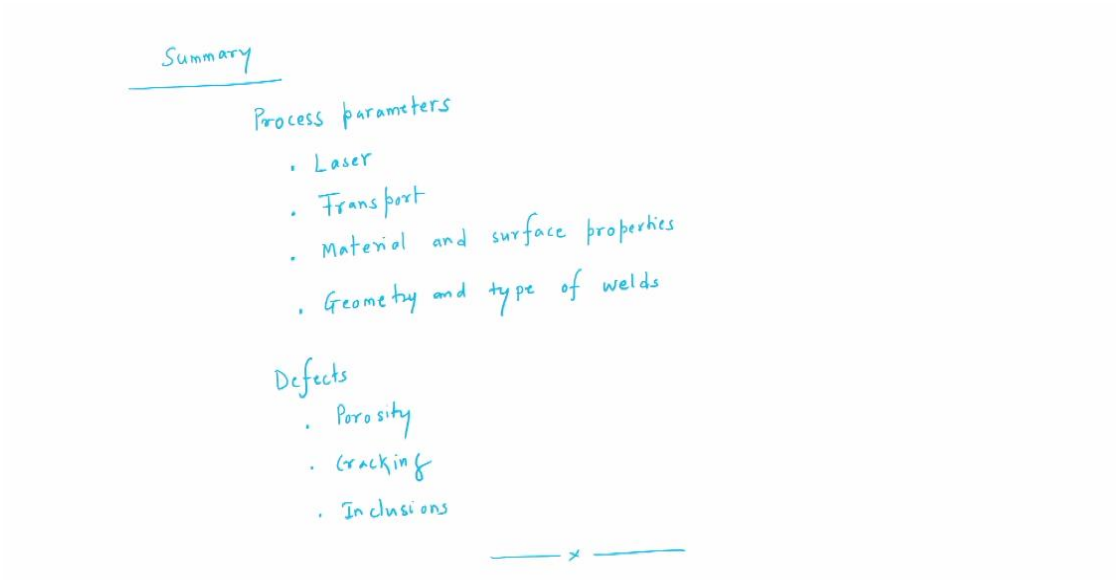

Let me summarize here. Various process parameters we have seen and these are related to laser, then transport of the laser, then material and surface properties and geometry and type of weld and we have also seen the defects which are getting generated, various defects such as porosity, cracking, inclusions etc.

With this I would like to stop for today's lecture. Thank you for listening and watching this video. Thank you.