Laser Based Manufacturing

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Module # 02

Lecture # 04

Principle of Operation, Types of Laser Cutting and Kerf Geometry

Hello everyone. I welcome you all to the Week 2 of NPTEL online course on Laser Based Manufacturing. I hope you have enjoyed the three lectures of Week 1. Let us begin the Lecture 1 of Week 2.

In the first week of this course, we have seen the fundamentals of lasers, principle of generation of laser beam, its characteristics, applications in the manufacturing. We have also seen the construction of a typical laser and what are various the cavity designs. With these fundamentals of laser, let us begin our journey to know how the lasers are applied in the manufacturing industry.

In this week, we will be focusing on material removal processes how lasers are used to remove the excess material or specific material from the work part so that we can generate our desired cavities, desired shapes, desired features for the intended application in manufacturing.

In this lecture that is the first lecture of week 2, we will be studying the principle of operation of laser cutting and what is the meaning of kerf and what is the geometry of kerf and how it is important in the context of laser cutting.

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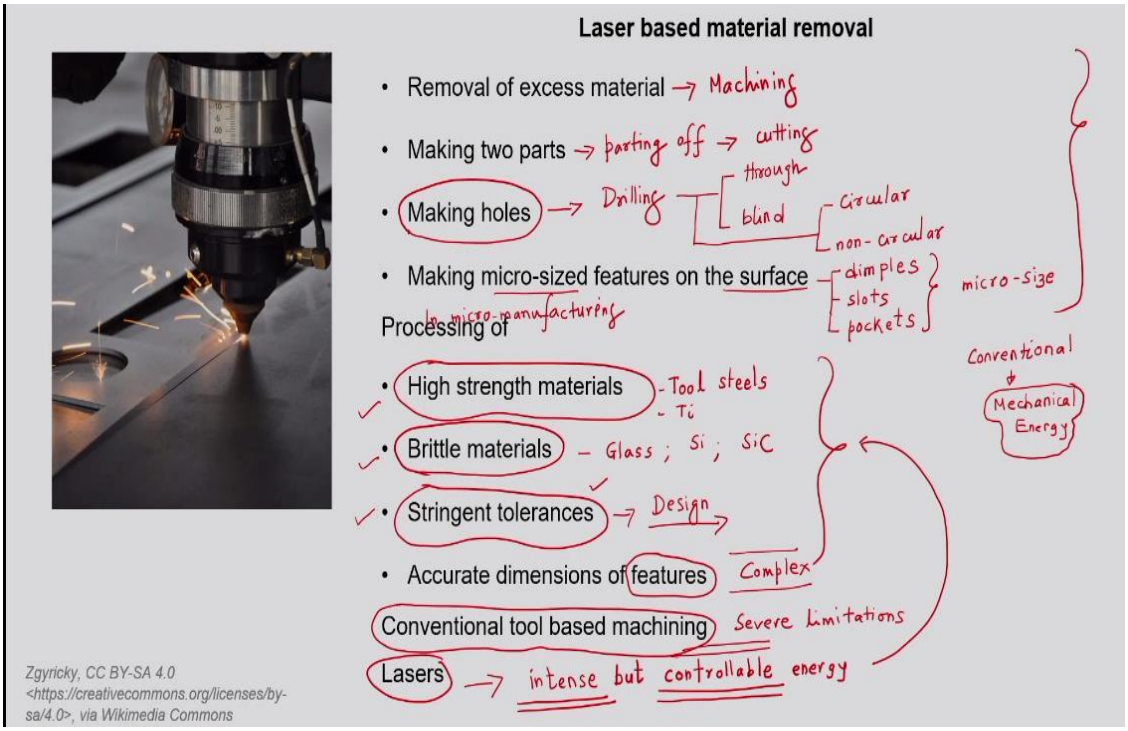

I hope you might have seen laser in manufacturing mode somewhere else in the industry or in tool room or in your laboratories. Basically, lasers are used in manufacturing industry for material removal. There are various applications of the lasers. The first application is removing of excess material, it is called as the machining operation, where we are transforming the bulk material into the required semi-finished product or the final product or the part which will be further utilized for some assembly and it can be take away for the shipping as well. The removal of excess material is called as machining operation. Not only machining, we also require to make two parts of a product or a one part or one system we have to cut it into two parts that we call the parting-off operation. Consider, we are having a thin sheet and that thin sheet has to be cut into two parts. That is called as parting-off which is very common general operation in the industry. This also people are calling as cutting operation, cutting of a thin or thick sheet. Then in the industry or in tool rooms there is a huge requirement to generate the required shape and size holes that we call the drilling operations. This is also very general and common manufacturing operation, that is, the drilling or making holes. We need to generate various types of holes which maybe through holes or we may have the blind holes. Even the drilling is being used to generate circular holes or non-circular holes.

Further, in micro manufacturing or generation of micro parts, it is required to generate micro size features on the surface. It maybe dimples of various shapes such as circular, diamond dimples or we may have some slots on the surface or we may have some pockets on the surface. All are in micro size.

These are basic requirements which are there in the industry and for that we are in generally using conventional manufacturing processes where mechanical energy is being applied. In conventional manufacturing we have seen that mechanical energy is applied, for example, the

turning operation or milling operation, drilling operation. In micro-sized holes again the micro milling operation. In all these operations the mechanical energy is applied.

But consider a case when we want to process high strength materials such as tools steels, high strength alloys or biomaterial such as titanium or we want to process the brittle materials such as glass or semiconductor materials such as silicon or silicon carbide and we need to control or we need to achieve the stringent tolerances on the design. The design parameters or the dimensions are to be carefully attained, achieved with the stringent level with a very high precision.

Moreover, there are many complicated features they are to be generated on the surface - complex features are to be manufactured. When we talk about generation of complex feature with stringent tolerances on brittle materials or high strength materials, the mechanical energy or tool-based manufacturing processes are not sufficient. We are finding it difficult to manufacture or we are finding it difficult to satisfy all these requirements by using the mechanical energy.

The conventional processes, conventional tool-based machining processes are finding it difficult. They are having severe limitations for these requirements. Severe limitations are there. Here the answer is lasers.

Why lasers? Because lasers are providing us intense, but controllable energy. These two important characteristics, that intense energy that we are getting and moreover it is controllable which can cater or which can solve all these problem that we can go for processing of high strength materials, we can process brittle materials because it is non-contact process, tool less process, we can achieve stringent tolerances because we can control the process, we can control the site of application and we can achieve the accurate dimensions for complex features.

With this, the lasers are finding huge applications, wide applications in the material removal.

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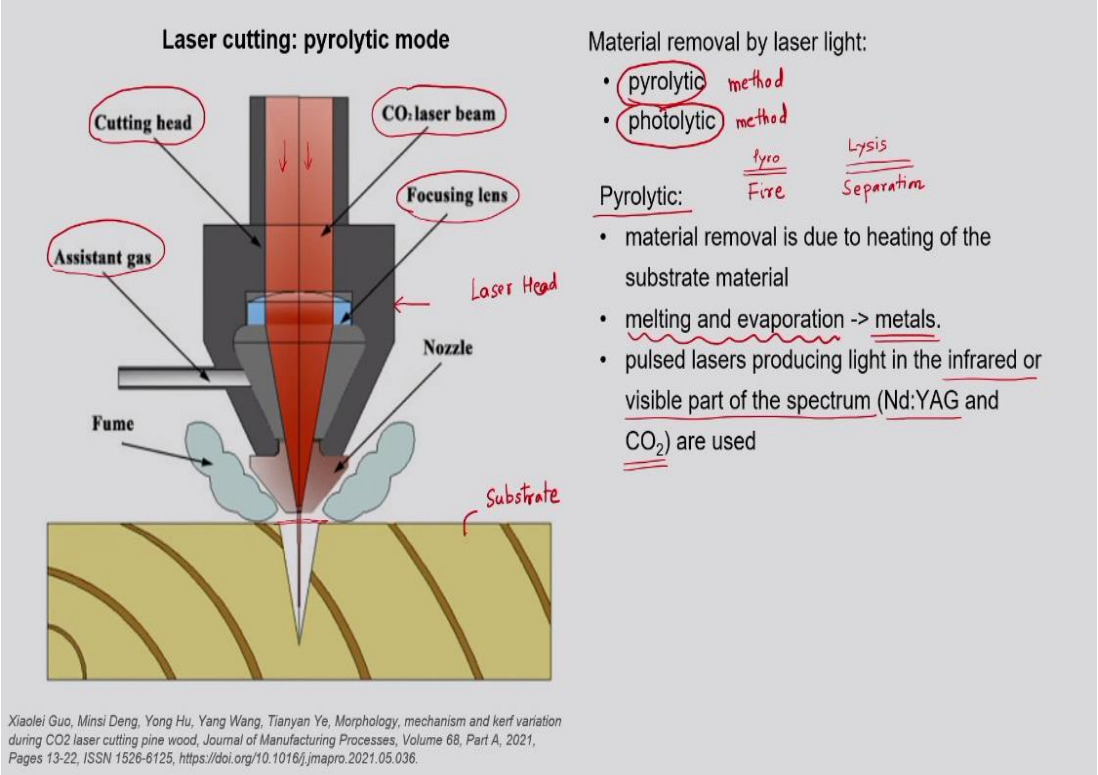

Now, let us see how the laser cutting is carried out. There are basically two ways in which the laser cutting is carried out. The first method or way is called as pyrolytic process or pyrolytic method and the second one is called as photolytic method.

Let us see what is the meaning of pyrolytic method and the photolytic method in the context of laser cutting.

In pyrolytic method, the material is basically removed by using intense heating due to the laser beam. The laser beam is applied on the material surface and due to the interaction of the photons, high speed photons with the atoms of the substrate material, there is melting and evaporation of the substrate material particularly the metals and then we are getting the cutting operation or the separation operation. Here the pyro is called as fire and the lysis is the meaning separation. When we are using the heat which is generated by the lasers for the separation operation that is called as the pyrolysis. In general, the pulse lasers producing the infrared or the visible part of the spectrum in particular the Nd:YAG or CO_2 lasers are widely used for the pyrolytic operation or pyrolytic method of metal separation in the industry.

On your screen you can see a typical arrangement of laser cutting. Here we are having a substrate and there is a laser head. This is the laser head the entire assembly of the laser head. It has the cutting head part and there is a focusing lens. We are getting the CO_2 laser beam, we are getting the coherent, collimated, monochromatic beam of light from the CO_2 lasing medium here. This beam of light is impinged on the focusing lens and through the focusing lens we are getting the focus beam which is applied on the substrate.

Here we are applying the focused beam. Now, when the heating is occurring, when the heating is carried out, there is lot of material being melted, vaporized and that molten material or the

vaporized material has to be taken out from the site of evaporation or melting. For this purpose we are using some sort of inert gases which are helping us to carry away, to flush away the molten material, that we call the assistant gases or the assist gases.

These gases are inert, they are not reacting with the molten material and they are protecting the molten material from getting oxidized.

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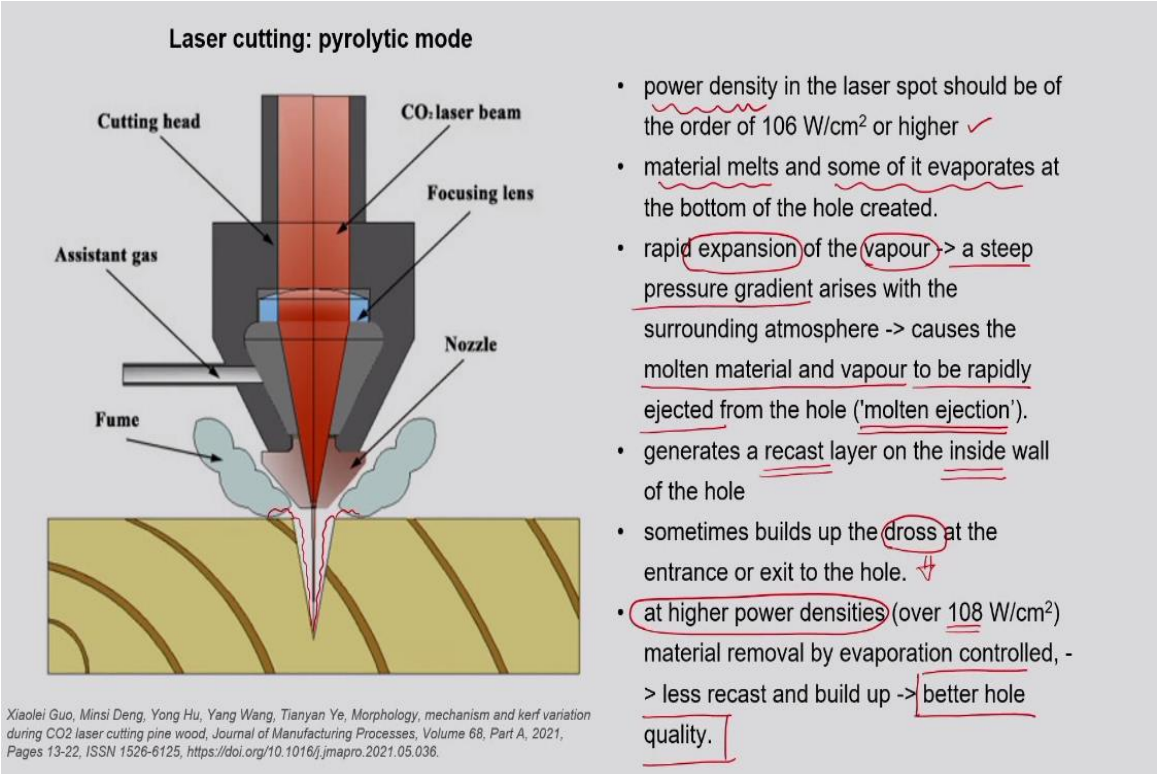

Now, let us see what are the various peculiarities of this pyrolytic mode of operation? Here, in general, a power density of about 106 watt per centimeter square or higher is generated and by using this higher energy the material is getting melted and some of the material is getting evaporated at the bottom of the hole. But during the evaporation process there is formation of vapour and vapour is rapidly is getting expanded. There is a rapid expansion of the vapour and due to this there is generation of steep pressure gradient, there is steep pressure difference between the rapid expansion of the vapour and the ambient pressure and due to that the molten material or vapour to be rapidly ejected out. This molten material or the vapour will get flushed away or ejected out due to this pressure gradient. It is called as the molten ejection.

During this pyrolytic mode there is generation of recast layer as well. Not all the molten material will get ejected out. There is no 100% ejection efficiency of this molten material. Some of the material will get re-deposited, recasted on the cavity itself. Some of the portion here will get recasted or redeposited on the site of action inside the wall. That is called as the recast layer. In some of the cases some dross is being generated, some portion will get deposited at the top side as well - at the opening of the cavity. If we go for much more higher power density say more than 108 watt per centimeter square this dross can be reduced, but some

minimum amount of dross will certainly be there, but by applying higher power density we can easily reduce it and this will certainly generate a better quality hole.

We can say that the pyrolytic process, here we are using the heat energy which is generated by using the collision of photons with or interaction of photons with the atoms of the workpiece material and due to that we are getting the required melting and evaporation of the material. This in general, we are using for the separation of metals, work removal of metals or the parting of the metals.

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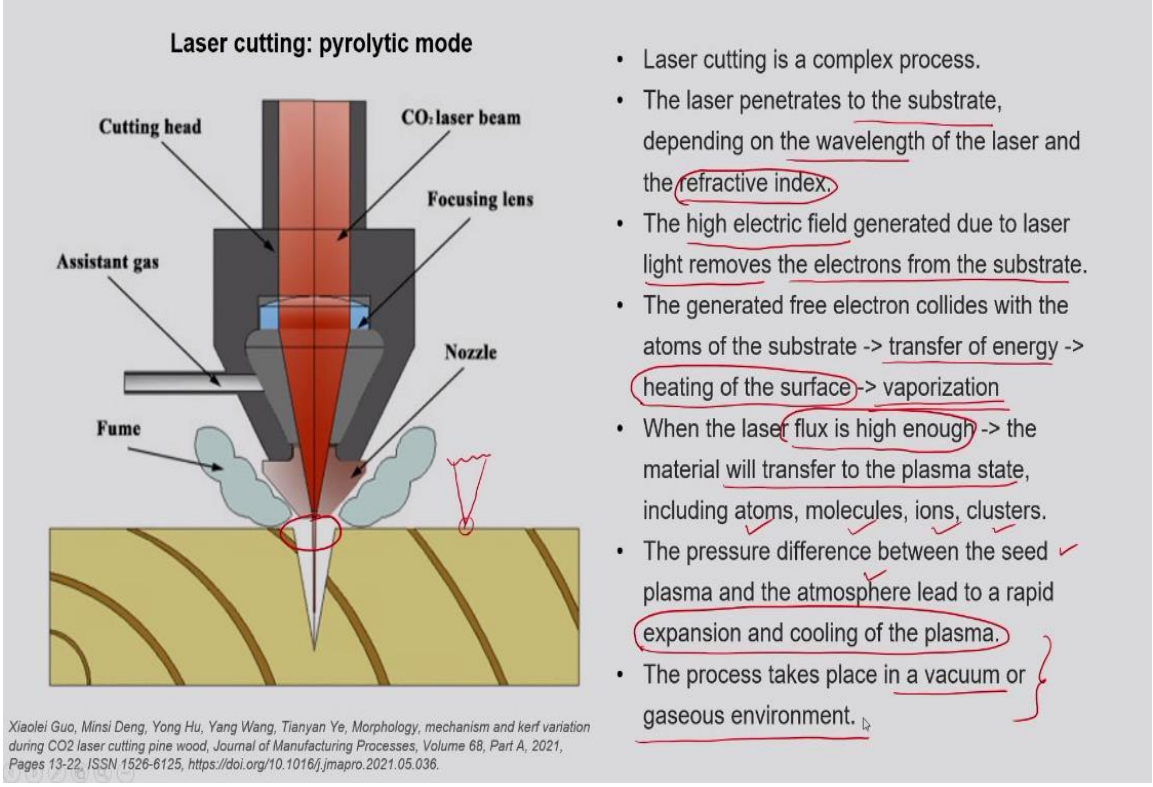

Now, let us understand, how the laser is getting interacted with the substrate material? We have seen in our previous slide that in pyrolytic process, the laser beam is removing the substrate material, but this process or this operation is quite complex. The laser interaction or the laser penetration to the substrate is majorly dependent upon the wavelength of the laser and the refractive index.

When we apply the laser the high electric field that is generated due to the laser light is removing the electrons from the substrate. When laser is being applied on the surface the high electrical field is removing electrons from the substrate and these electrons are colliding with the atoms of the substrate. These free electrons will interact with the atoms of the substrate and they are transferring the energy. Due to this transfer of energy this kinetic energy, there is heating of the surface, the surface is getting heated up and that is leading to vaporization of the substrate material. When the flux is sufficiently high then the material will transfer to the plasma state and as we know the plasma state is having atoms, molecules, ions and the clusters. This plasma is a high pressure, high temperature zone or state of the material and due to the

pressure difference that is occurring in between the seed plasma and the atmosphere there is a rapid expansion in cooling of the plasma. In general the pyrolytic process may be carried out either in vacuum or in gaseous environment, inert gases can be applied.

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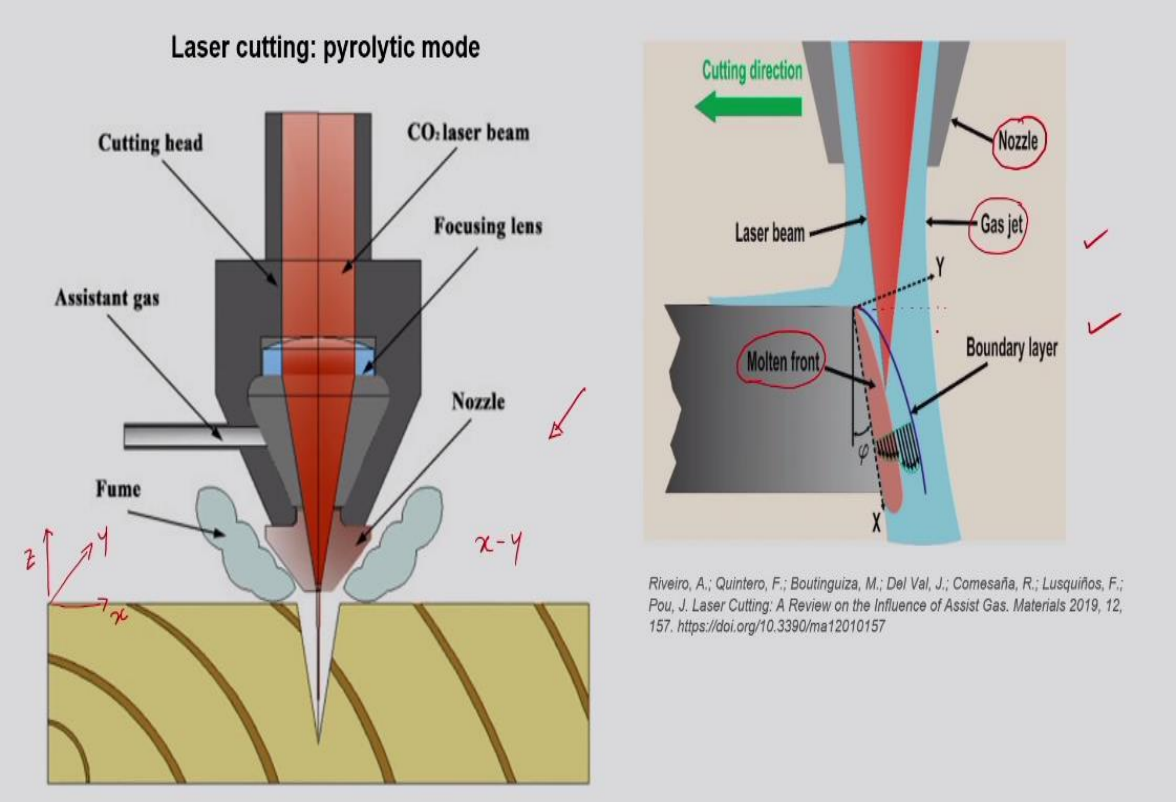

Now please refer this particular diagram. Here a diagram has been shown with respect to this picture. If I consider this as Z axis and this as X axis and this is the Y axis. Now, let us consider that the laser is moving in XY plane and the movement of the laser is along the Y axis. When the laser is moving along the Y axis that is perpendicular to the plane of this PPT, then how exactly the processing is getting occurred. Now, here through the nozzle the gases are coming and the same nozzle is being used to apply the beam of laser over the work material. This is the laser beam which is focused on the work material here. As the work material is getting interacted there is vaporization in melting and this molten front is getting generated. This molten front has to be taken away. For that purpose we are using the high pressure inert gas jets so that this material can be removed from this material.

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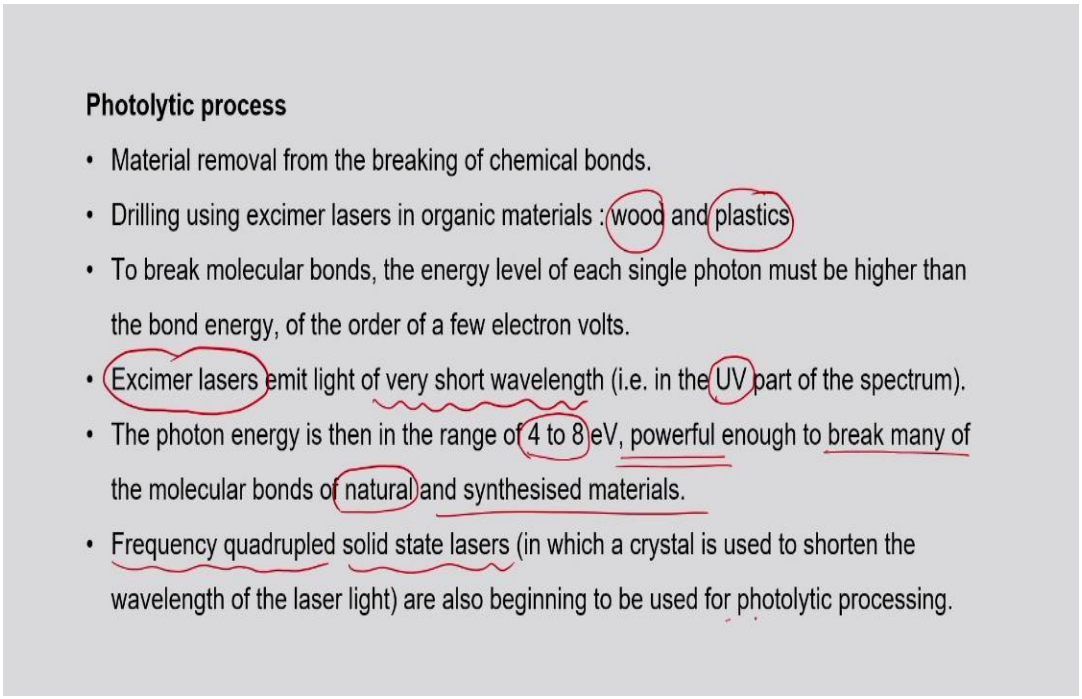

The next process that we call is a photolytic process. Here there is no heating up the substrate material, here there is breaking of chemical bonds. In general the wood or plastic or the polycarbonates when we process by using lasers, these materials are getting processed by using this photolytic version of laser interaction.

Now here there is no melting that is getting occurred. There is the chemical bond which is there in between the molecules that will be broken by the laser beam. To break that molecular bond, energy level of single photon certainly must be higher than the bond energy and it is in general of the order of few electron.

When we take the excimer laser which is having a very short wavelength that is in the ultraviolet part of the spectrum. It is having a energy level between 4 to 8 electron volt which is powerful which is more than sufficient to break many molecular bonds of natural and synthesized materials. In general when we use excimer laser which can be used to carry out the photolytic version of the laser interaction with such material such as wood, plastic, polycarbonates. Moreover, if we consider the frequency quadrupled solid state lasers such as Nd:YAG lasers where we are using shortened wavelength of the laser light that also can be utilized for this photolytic processing.

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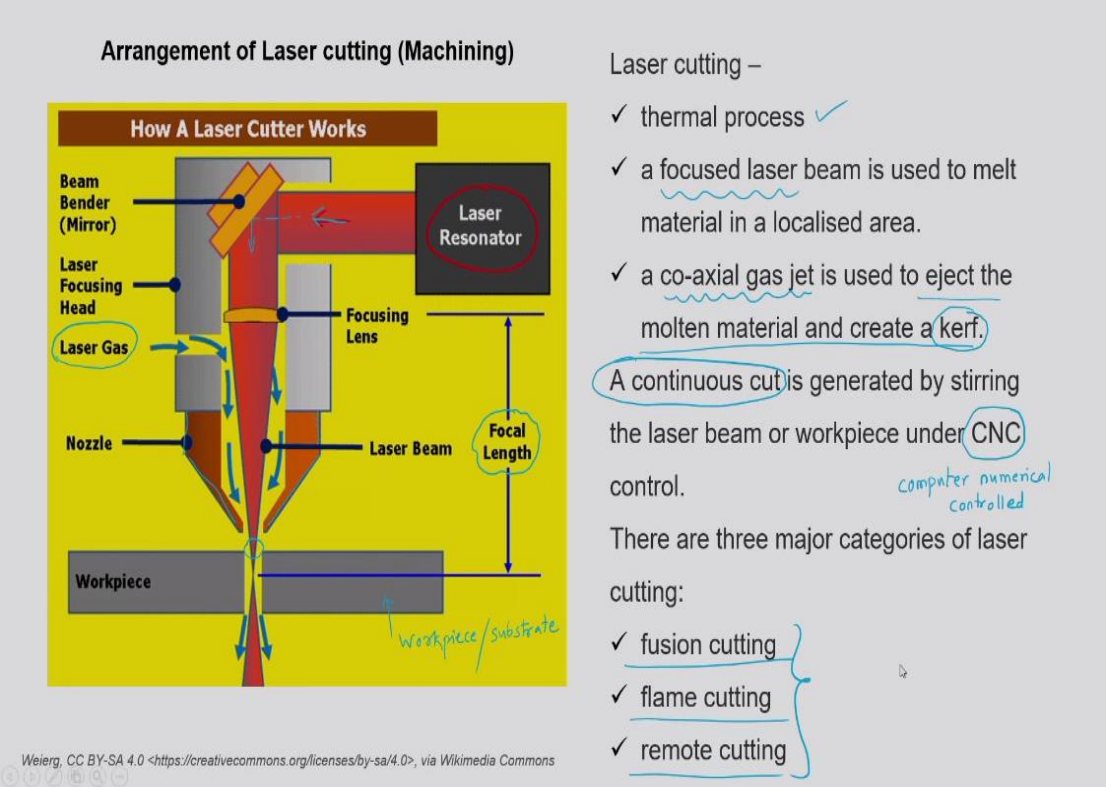

On your screen you can see a detailed schematic of the laser cutting arrangement. We have seen that we required laser resonator which is generating the laser beam, that laser beam is being applied, but to focus the laser beam at the substrate we are using beam benders or pair of reflecting mirror, so that this efficient application of laser can be applied. When we are getting the bend beam of laser that to be focused on the substrate material. This is substrate, this is work piece or the substrate and through focusing lens we are focusing the laser beam on the substrate materials. As we have seen that for pyrolytic process there is a need to have laser gas or assist gas which is helping for protecting the surface after the heating operation, melting operation and to carry away the dross or the molten material. This is the nozzle through which we are applying the assist gas.

We have seen that the laser is a thermal process and we need a focused beam always to be applied on the substrate. We have to have conscious decision what should be the focal length and this is all depends upon the type of laser that you are using and the size of focus or the diameter of focus that you want on the work piece surface.

We are having a coaxial gas jet which is used to eject the molten material and create a kerf. Kerf is nothing, but the width of the cut that is being generated during this laser based operation.

Now, how we get the continuous cut? To get the continuous cut you have to have the relative motion between the laser beam with respect to the work piece. Either you move the work piece in XY plane or you move the laser beam in XY plane. For this purpose we need the computer numerical controlled machine tools which are now commonly being used in the industry - computer numerical control machine tools.

There are basic three categories of the laser cutting. We can have a fusion cutting mode or a flame cutting mode and the remote cutting mode that we will see in our coming slides.

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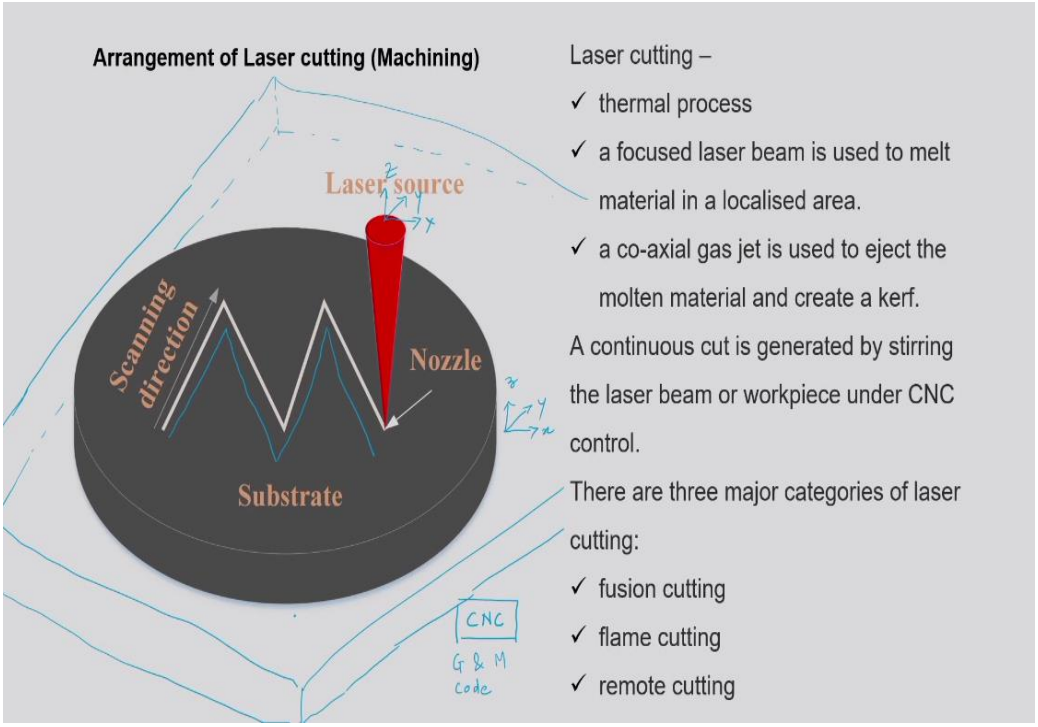

Now as I have mentioned that we have to employ the CNC technology to have the relative motion between the laser source and the substrate to get the required shape. Now, here we consider we want to scan or we want to manufacture a slot in this shape, that is a zig-zag shape. To get this particular slot as I mentioned either you move the laser source in the plane that is XY or you can move the substrate in a plane XY.

You can have a table here and this table can be moved in XY plane. This is a table - this is the CNC table that we do have. We can move the CNC table by using the programming, that is the G and M code. This G and M code has to be written to move the substrate with respect to the nozzle.

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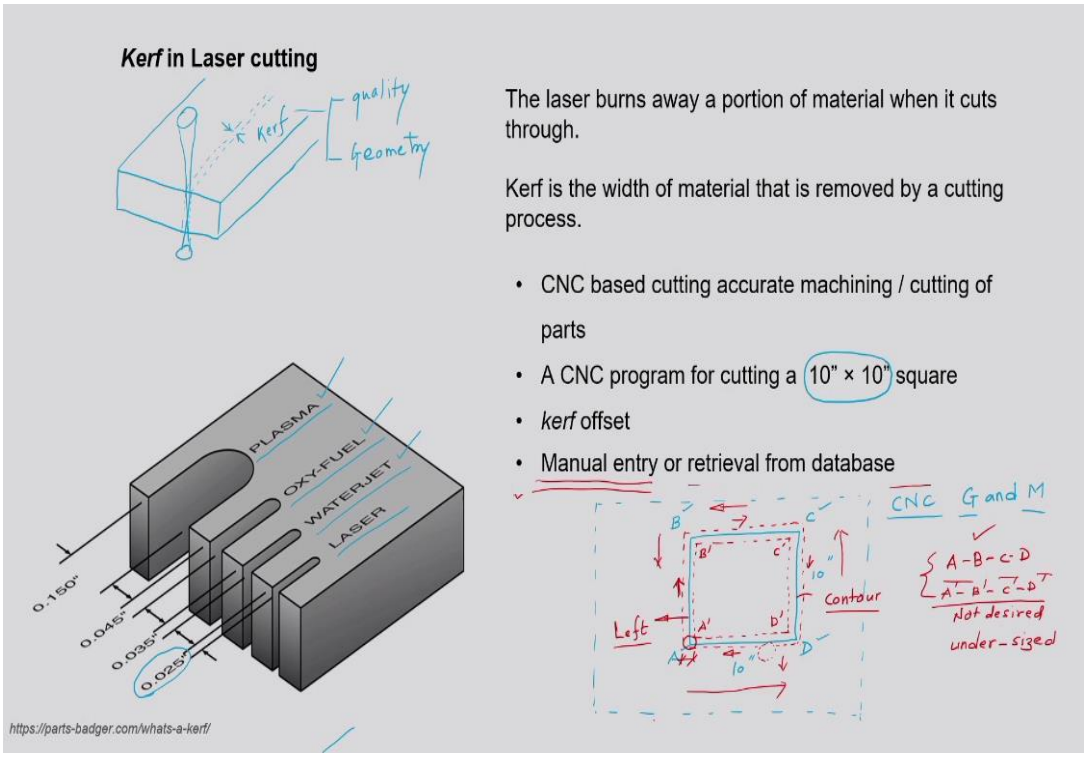

When we cut the material by using a laser beam, whatever the portion which is getting burnt away: the width of that portion is called as the kerf in laser cutting. Let us consider we are having a material and there is a laser beam which is focused on the material and we get the interaction of the material with the laser beam, some portion of the material is getting removed, it is getting vaporized. Width of that burnt away material is called as the kerf.

This kerf is very important element as per as the quality of the laser cutting is concerned: surface quality as well as the geometry of the features that we are generating by using the laser machining. We can apply variety of cutting modes in manufacturing. We can use plasma or oxy-fuel or water-jet operation of machining.

But here in comparison with this plasma, oxy-fuel or water-jet: laser is providing us very low kerf width. As the kerf width is low we can get the required cutting, very fine cutting, we can maintain the accuracy, we can get the precise components by using the cutting operation. The fine cutting or quality cutting is expected during these cutting operations. If you cut a material by using a scissor there is virtually no kerf in the scissor operation. But in laser there is little material which is getting burnt away that is called as the kerf, which we need to consider during our CNC operation. Why there is need to consider the kerf?

Let us consider that a square of about 10 inches by 10 inches is to be cut from a work part or a thin sheet that we do have. This is a work part a thin sheet, a large piece of thin sheet that we do have. And now let us consider that we have to cut a piece of 10 inches by 10 inches by using laser cutting. There is a square that we need to cut 10 inches by 10 inches. Let us consider its corners are A, B, C and D and we are using CNC technology to cut the piece.

Now to generate the part program, to generate the tool-path, we have to write G & M code that is preparatory and miscellaneous code. To generate G & M code we have to program the

corners of this square. The coordinates of A to be given, coordinates of B to be given, C and D. The CNC will generate the part program and it will use for further cutting.

Now, if we consider a laser which is having a certain kerf, now this is located at this point we are starting and we are moving along A to B, B to C, C to D and we will return to A from D. Now, when there is a kerf and we are programming with respect to the center point of the laser application, then what we get after cutting? We are getting the geometry something like this. This much portion will be moved, it will be removed and inside also there would be some portion that will get removed, it will get burnt away or it will get melted and then it will be flushed away. So, there is change in the geometry.

We were expecting exactly A, B, C, D, but ultimately we got A dash, B dash, C dash, D dash. This is A dash, B dash, C dash, D dash and it is not a desired geometry that we are getting because CNC is not considering the kerf width, this portion has not been considered during the programming. Ultimately the final work part that we get A dash, B dash, C dash, D dash, it is of under-sized, is not of true size or the size is reduced.

To consider or to manufacture the accurate component we need to provide the kerf inside the programming. We need to consider the kerf inside the programming - we have to offset the laser along this direction, if we are moving from A to B, B to C, C to D and D to A. That means we have to offset the laser towards left, left to what? Left to the direction of movement. This is the direction of movement and we have to offset the laser towards the left when we approach this path.

Consider we are choosing the path A to D, D to C and C to B and from B to A. In that case we have to give the offset towards right. This is towards right of the contour. This is the contour that we want. If we are following A dash, B dash, C dash, D dash that is the route then we have to offset the laser along left side of the contour of the travelling direction. This value of kerf width, either you can enter manually or you have to retrieve from the database.

All the advanced CNC based laser machines they are having the data related to this kerf width. It is dependent upon the material and the thickness or the engineer or the process technician will compute, will get the data from the handbook and he or she will enter the data manually inside the CNC code. Once you apply this kerf width then you will get the accurate geometry that you want. Therefore the kerf width is a must to be considered during the part programming of the CNC based laser cutting.

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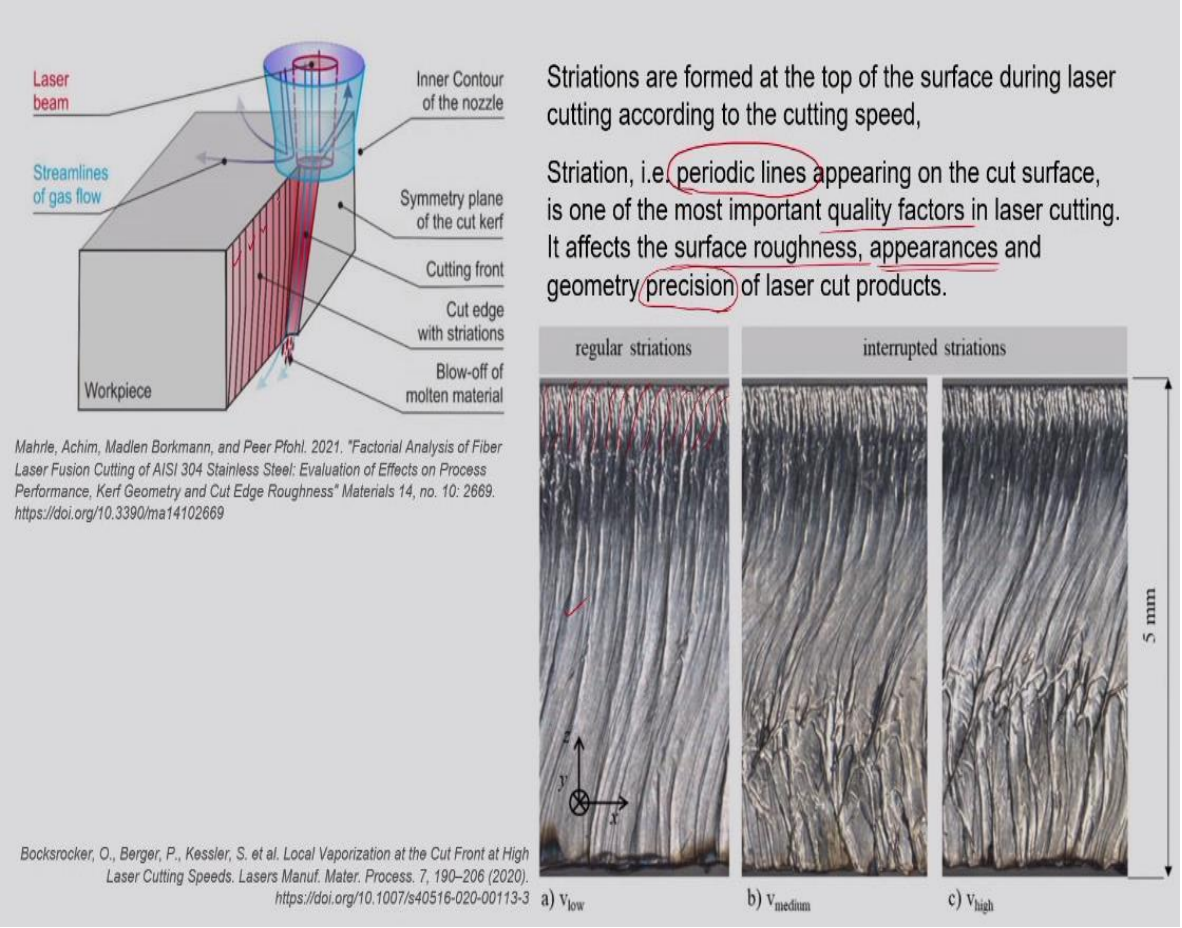

Mahrle, Achim, Madlen Borkmann, and Peer Pfohl. 2021. "Factorial Analysis of Fiber Laser Fusion Cutting of AISI 304 Stainless Steel: Evaluation of Effects on Process Performance, Kerf Geometry and Cut Edge Roughness" Materials 14, no. 10: 2669. https://doi.org/10.3390/ma14102669

Bocksrocker, O., Berger, P., Kessler, S. et al. Local Vaporization at the Cut Front at High Laser Cutting Speeds. Lasers Manuf. Mater. Process. 7, 190–206 (2020). https://doi.org/10.1007/s40516-020-00113-3

Now, in addition to the kerf width or kerf there is another byproduct which is coming during the laser cutting and that is called as striations. Striations are formed at the top surface during laser cutting, according to the cutting speed. Striation, what is the meaning of striations? Striations are nothing, but a periodic lines which are appearing on the cut surface. Here you can see a cut surface. This is the cut surface and you can notice that there are striations which are generated on the surface of the cut. These are in general getting manufactured or generated, the striations are generated due to the melting and flushing away of the molten material during the application of the inert gas. The striations are important quality factor and based on that the roughness of the cut surface is getting controlled. Moreover, the striations are also affecting the appearance of the laser cut surface, not only the surface quality and the appearances, the striations are also affecting the precision of the cut products. If you just look at a schematic of the laser cut surface then you can find that these are the striations which are generated on the cut surface.

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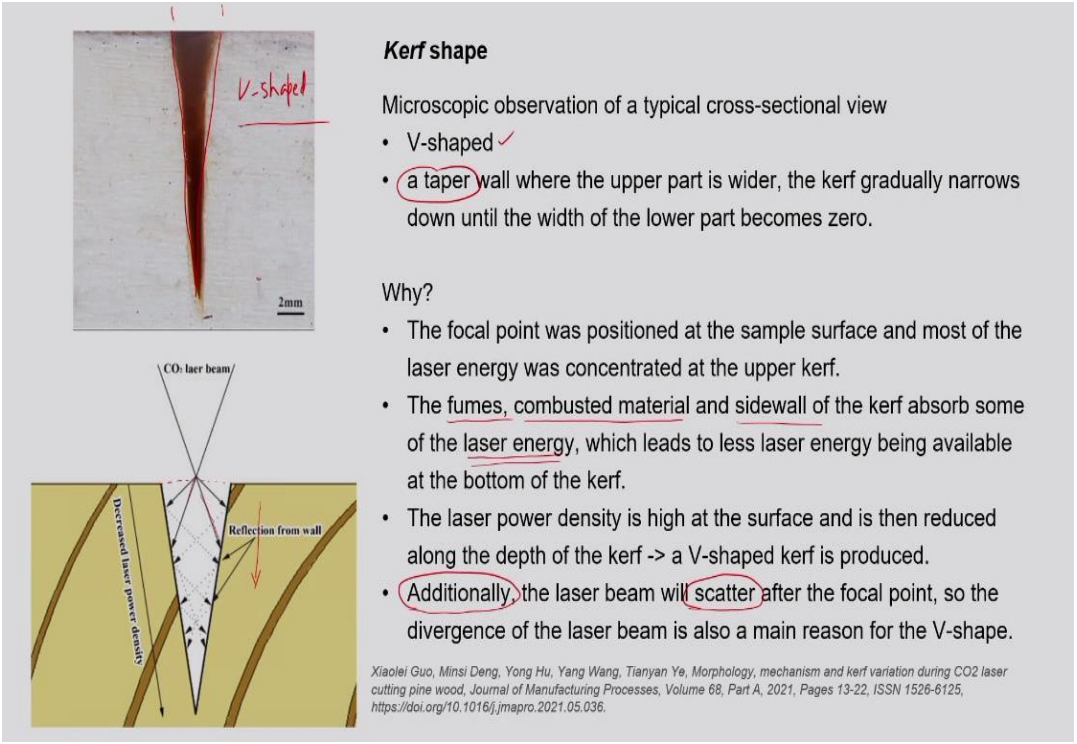

Now, let us see what is the shape of the kerf? In microscopic observation it has been found that in general the shape of the kerf is of V shaped. There is a taper. Here you consider this is the V shaped kerf that we got here; V shaped kerf. Here there is a taper, there is a wider portion at the opening and then this opening is getting reduced and it will become 0 at certain point.

Why this kind of shapes that we are getting? The answer is that when the focal point is positioned at the sample surface. We are focusing the laser over here. Naturally the more density of the laser beam would be at the top surface and due to that concentration of high laser beam we are getting more ablation, more melting and vaporization at the top surface.

During the process of melting and vaporization, fumes are generated, there is combustion of the material and there are side walls. These materials are absorbing the laser energy. The fumes, combusted material and sidewalls are also absorbing the energy which is left for the ablation or the melting or vaporization of the material would be reduced. Therefore there is reduction in the width of the kerf as we move in downward direction along the depth.

In addition to this there is a scattering of the laser beam. As we are focusing the laser beam over here then the beam is getting scattered. As the beam is getting scattered, naturally the density will get reduced and due to that as well there is reduction in the width of the kerf along the downward direction.

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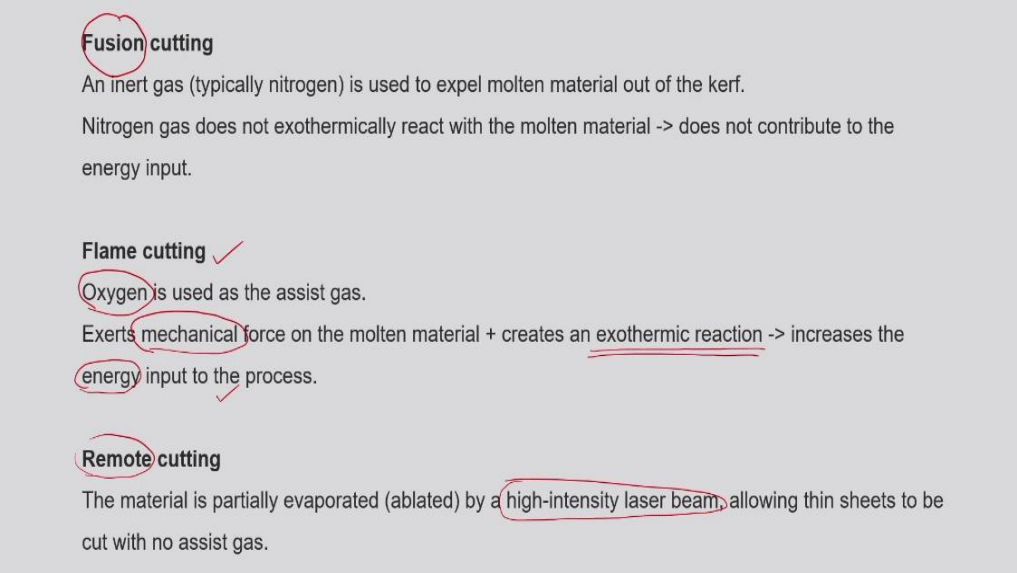

In our previous slides, we have seen that there are three ways of a cutting that is a fusion cutting, flame cutting and the remote cutting. When we are using inert gas, typically a nitrogen gas is used to expel the molten material out of the kerf. That is called as the fusion cutting. Nitrogen is non-exothermally react, it is not reacting with the molten material and it is not even contributing to the energy input. It is just an inert gas and it is just used to flush away the molten material, that is the fusion cutting.

As far as the flame cutting is concerned, we are using oxygen. Oxygen is not only expelling the molten material it is applying the mechanical force as well during the metal cutting and it is creating exothermic reaction during the application and due to this there is increase in the energy input as well. When we are using oxygen that oxygen is helping to enhance the cutting speed, cutting capability of the process. In certain applications we are not using any inert gas, we are not using any gas for any purpose, then how the expelling would be carried out? The expulsion of the material would be done by using the high intensity laser beam itself. The laser beam is coming striking at the surface of the work material. It is ablating, removing the material and it is carrying away the material by the laser itself. That is called as the remote cutting and based upon the application, based upon the requirement, the engineers or the process planners are choosing fusion cutting, flame cutting or remote cutting for their further utilization.

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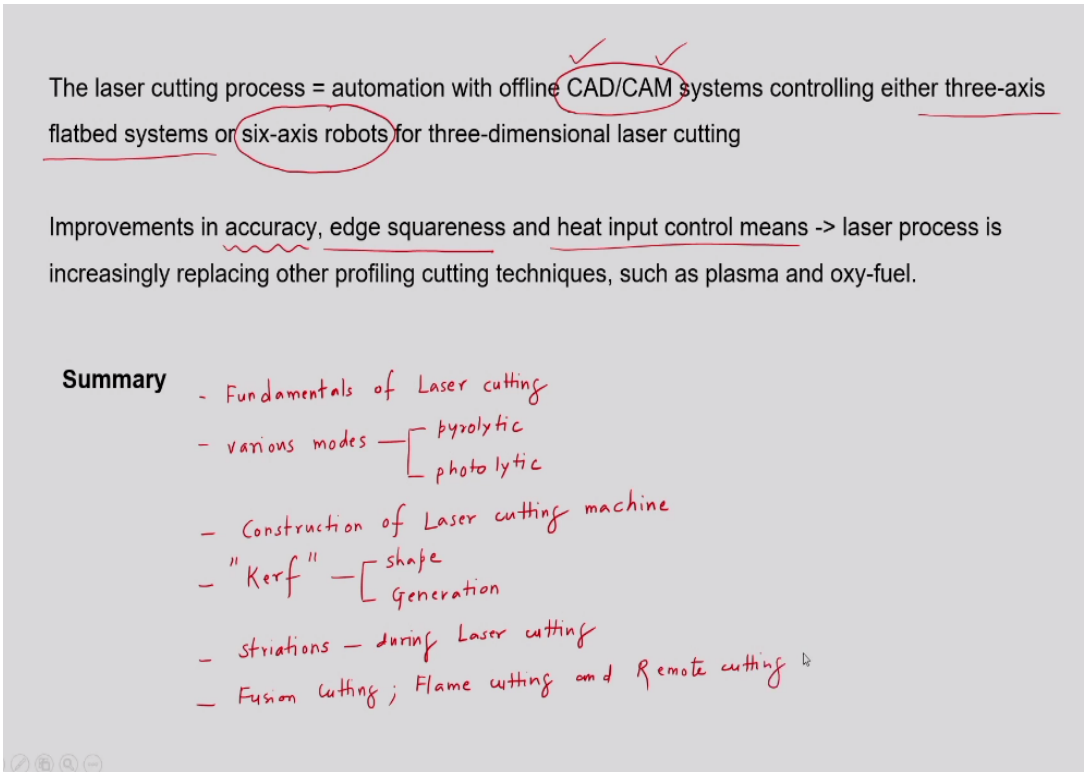

When we want to implement or when we want to employ the laser cutting process, we need to have a CAD CAM system as well. As we have seen that to generate the G & M codes, CNC part program, first of all we have to model the geometry. To have this we need to first make the geometry by using a CAD software and then generate the CNC part program using CAM software.

Then there are various CNC machine tools are available which are having the capability to move in XYZ direction, three axis movement or industrial robots - the 6 axis robots are employed in the industry along with the laser technology. That laser can be used for cutting or the welding purpose.

As far as the process performance is concerned the improvement in accuracy, edge, squareness and heat input control are very much essential to get the required performance during the laser cutting operation.

In our next lecture we will be studying what are the various process parameters related to the laser cutting and what are the various performance parameters need to be considered.

Let us summarize the Lecture 1 of Week 2. In this lecture, we have seen the fundamentals of laser cutting, various modes of laser cutting - that is pyrolytic process and photolytic process, then we have seen the construction of a typical laser cutting machine. Then we have seen the meaning of kerf which is a very important parameter during the laser cutting operation, the shape of the kerf, its generation. Then we have seen the concept of striations during laser cutting and at last we have seen that based on the application of the inert gas, there are again three modes of laser cutting that is: fusion cutting, flame cutting and remote cutting.

Fine, with this we stop for today's lecture: the Lecture 1 of Week 2. Thank you very much for watching the video and listening to the content of this video. Let us meet in the next lecture, lecture 2 of week 2. Thank you, bye.