

Laser Based Manufacturing

Prof. Shrikrishna N. Joshi

Department of Mechanical Engineering

Indian Institute of Technology – Guwahati

Module # 03

Lecture # 08

Mechanisms of Laser Welding Part 2

Hello everyone. I welcome you all in the third week of NPTEL online course on Laser Based Manufacturing. Let us study what are the various modes of laser welding.

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MODES OF LASER WELDING

Conduction mode joining

- laser beam is focused to give a power density on the order of 0.5 MW/cm^2
- Fusion of material to create a joint without significant vaporization.
- Conduction welding may be performed in two modes: direct heating; and energy transmission

During direct heating

- Heat flow is governed by classical thermal conduction from a surface heat source and the weld is made by melting portions of the base material.

Transmission welding

- It is an efficient means of joining polymers that transmit the near infrared radiation of Nd:YAG and diode lasers
- energy is absorbed through novel interfacial absorption methods.

Conduction welds can now be made in a wide range of metals and alloys in the form of wires and thin sheets in various configurations using CO_2 , Nd:YAG and diode lasers with power levels on the order of tens of watts.

isotherms

- Laser Power
- Low density
- shallow \rightarrow bowl shaped
- depth/width < 1
- aspect ratio < 1

Figure 1. Conduction Mode

The first mode of laser welding is conduction mode: it is a conduction mode of joining. As the name suggest we are using laser beam, we are focusing the laser beam on the work part generating the power density and that power density is up to 0.5 megawatts per centimeter square. In general when we generate a power density of about 0.5 megawatt per centimeter square we are generating conduction mode of joining.

What is the meaning of conduction mode? Here we are applying the laser beam energy and we are generating melting significantly without having vaporization of the work parts. We deliberately applying controlled laser beam heat energy to get the melting only and by using this melting and re-deposition we are getting shallow type of weld joints. Conduction welding again may be performed into two modes that is: direct heating and energy transmission. This conduction mode further can be applied by using these two modes that is direct heating and energy transmission.

Now, let us see what is the meaning of direct heating? In direct heating case, we are trying or we are using the classical thermal conduction from a surface heat source and we are generating the weldment. Simply you apply the heat energy on the surface, get it conducted by the materials natural thermal conductivity and then generate the weldment that is the direct heating.

However, in transmission welding we are using some other materials, some innovative way to transmit the heat energy inside the work material. Some sort of ink that we are using to get the laser power to absorb the laser power, get it heated and that heated ink will transmit or will dissipate the heat energy inside the work material that we call the transmission welding.

During laser heating heat flow is governed by the classical thermal conduction while in transmission welding we are using some sort of novel interfacial absorption methods such as inks and transmission welding is basically being used for polymers. Some of the polymers maybe transparent material and that transparent material can be processed by using this transmission welding operation.

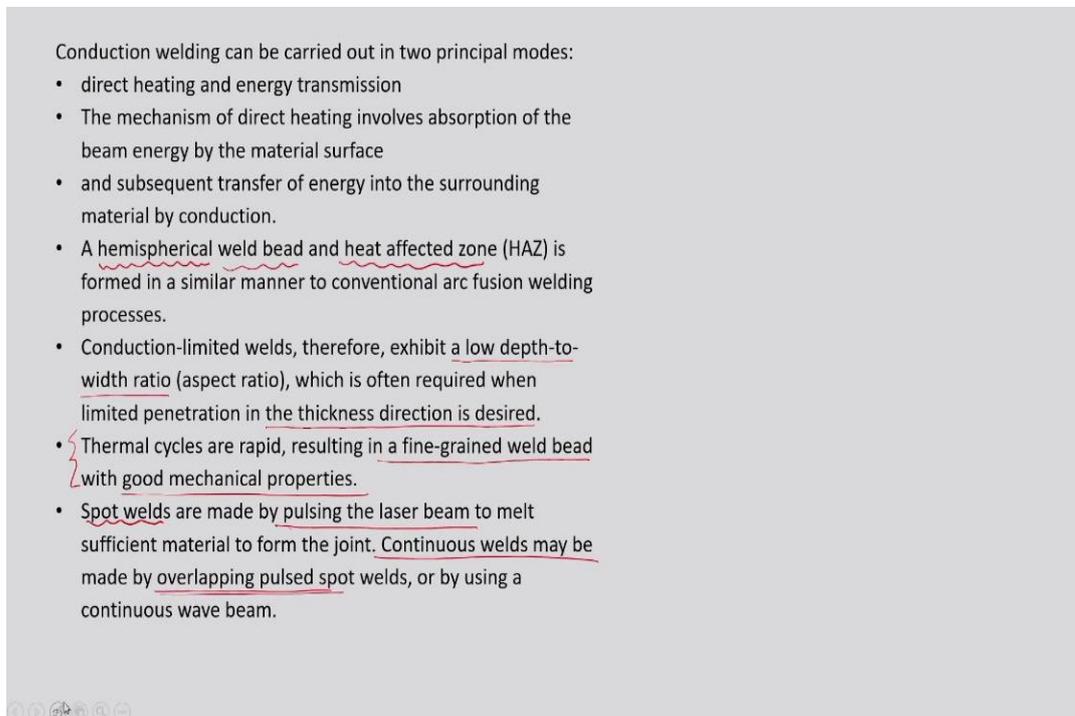
Now, let us see how exactly this conduction mode is getting occurred. Here, to get the conduction mode possible we are applying simply the laser beam energy. This is the laser head and this is the base material 1 which is thicker and let us consider that we are having another base material 2 (thin BM2), this is BM1. Now, we want to weld BM2 with BM1 by using a spot welding using lasers. What we do we apply the laser beam on the surface by using pair of lenses, the laser is focused on the surface and due to the laser material interaction we are generating the thermal energy. These thermal energy is getting dissipated inside the work material. Based upon the thermal conductivity of BM2 and BM1 we are getting the isotherms. These are the isotherms. Needless to say that the heat energy should generate the melt isotherms, the energy should be quite enough to melt the material, but it should not vaporize the materials, it should not be more than the sufficient level so that the material will get vaporized.

When we get the melting due to conduction and deposition that is nothing, but the conduction mode of welding. Now, let us consider that in case of butt welding suppose we want to join two parts by using this butt mode of welding. Let us consider two parts are here: this is Part 1 and Part 2. The laser will be applied, there would be generation of weldment and then we just keep on traversing the laser beam, we will just scan the laser beam either in pulsed mode or in continuous mode along the path where we need to join these two materials. This is the path along which we can just simply move it to get the required welding done.

What are the various major parameters as far as the conduction mode. In conduction mode, the major parameter is laser power itself and the spot diameter. By using the laser power and spot diameter we can control the power density. We need to generate low density in comparison with the other process that is keyhole based laser drilling or keyhole based laser welding. We required to have low power density.

On your screen you can see an optical micro graphs of the laser welded parts which are in conduction mode. This is part 1 and this is part 1. Part 1 is put on the part 2 and these two parts are laser welded. Ultimately whatever the bead that we are getting is of this shape. You can see over here, this is the shape of the bead that we are getting. We can notice that the beads are shallow, their aspect ratio is less than 1. Depth-to-width ratio is less than 1 that we call the aspect ratio. In conduction mode in particular we are getting lower aspect ratios. These are shallow and bowl-shaped beads are getting generated during the conduction mode.

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Conduction welding can be carried out in two principal modes:

- direct heating and energy transmission
- The mechanism of direct heating involves absorption of the beam energy by the material surface
- and subsequent transfer of energy into the surrounding material by conduction.
- A hemispherical weld bead and heat affected zone (HAZ) is formed in a similar manner to conventional arc fusion welding processes.
- Conduction-limited welds, therefore, exhibit a low depth-to-width ratio (aspect ratio), which is often required when limited penetration in the thickness direction is desired.
- Thermal cycles are rapid, resulting in a fine-grained weld bead with good mechanical properties.
- Spot welds are made by pulsing the laser beam to melt sufficient material to form the joint. Continuous welds may be made by overlapping pulsed spot welds, or by using a continuous wave beam.

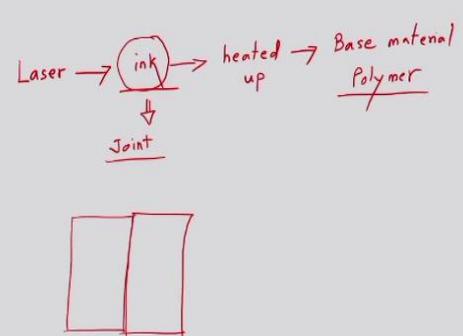
Fine, we have already seen about the direct heating and the energy transmission, the mechanism as well. Now, in particular as I mentioned we are getting a hemispherical weld bead and there is a HAZ as well (heat affected zone), which is very similar to the conventional arc fusion welding process. As I mentioned we are getting low depth-to-width ratio which is often when the penetration in the thickness direction is desired. What maybe a limitation to this process that is a conduction mode of laser welding. When we carry out multiple number of thermal cycles we can get a fine grained weld bead with good mechanical properties because mechanical properties of the weld beads are very essential when we use the welded joints or welded parts for the multiple cycles of loadings for dynamic loading.

The mechanical properties of the welds should be very good, they should be sufficiently high enough to get the required operation done. We can generate spot welds by using pulsing laser beam and the continuous welds can be carried out by using overlapping pulse spot welds.

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Some Remarks

- The energy transmission mode of conduction welding is used with materials that transmit near infrared radiation, notably polymers.
- An absorbing ink is placed at the interface of a lap joint.
- The ink absorbs the laser beam energy, which is conducted into a limited thickness of surrounding material to form a molten interfacial film that solidifies as the welded joint.
- Thick section lap joints can thus be made without melting the outer surfaces of the joint.
- Butt welds can be made by directing the energy towards the joint line at an angle through material at one side of the joint



The diagram shows a laser beam entering from the left, hitting a circular area labeled 'ink'. An arrow points from the ink to the right, labeled 'heated up', which then points to 'Base material Polymer'. A downward arrow from the ink points to a vertical line labeled 'Joint'. Below this, a simple sketch shows two overlapping rectangular blocks representing a lap joint.

About the energy transmission mode some remarks are there. Some remarks about the energy transmission mode. These mode of welding is used when we are processing the materials which transmit the near infrared radiation. Some polymers which are transmitting the radiation, in that case it is not possible for them to absorb the laser energy and conduct the laser energy or use the thermal energy generated by the laser beam energy for the welding operation. In that case we are using an absorbing ink. These absorbing ink at the interface of the lap joint is applied and this ink is absorbing the laser beam energy and as the ink is getting heated up, that heated ink is further dissipating the energy to the polymeric material at the interfacial joint. This is interface, the ink will transmit the heat energy to the base material that is the polymers. The polymers will get melted and on solidification of these melted polymers we are getting the welded joint.

The process is that the laser is heating up the ink which is at the joint and that ink is getting heated up and that heat which is at the ink will be transmitted to the base material. The base material is polymer and in this way the ink is playing an important role in the transmission type of welding and which is making easy for using a lasers to process the transmittive materials such as polycarbonates.

As far as the butt welds are consider we can use these processes as well, for example, the butt welds are to be processed. Either you can apply the laser beam energy at the top surface of the

butt joint or at the rear surface of the butt joint, at the top end of the butt joint or at the rear end of the butt joint.

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KEY HOLE BASED LASER WELDING

- A keyhole mode weld has a deep, narrow profile with an aspect ratio greater than 1.5. *depth/width > 1.5*
- The "keyhole" refers to a literal hole in the material, caused by its vaporization, which allows the energy beam to penetrate even more deeply.
- Energy is delivered very efficiently into the join, which maximizes weld depth and minimizes the heat affected zone, which in turn limits part distortion.
- The keyhole is surrounded by molten metal that flows and fills the void as the beam travels through the material, sealing up the weld.
- Many factors have to be controlled and balanced to keep the keyhole from collapsing; halting the welding process or cause porosity (which are gas pockets in the weld).
- Gas pockets weaken the weld.
- Keyhole mode welds are incredibly strong and are indicated for deep penetration and structural

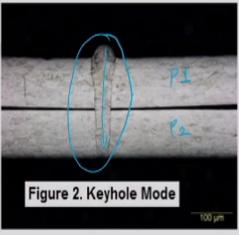
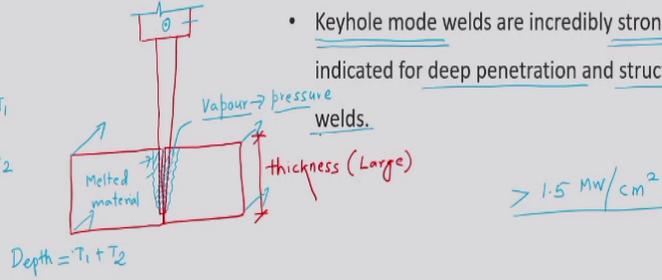


Figure 2. Keyhole Mode



Vapour → pressure welds.

thickness (Large)

Depth = $T_1 + T_2$

$> 1.5 \text{ MW/cm}^2$

Now, the next important mode of laser welding is keyhole based laser welding. Conduction mode is generally used to generate shallow type of weldments. Now, consider we want to process or we want to join two sheets or two parts which are having sufficient thickness, sufficient thickness means consider around 15 mm or around 20 mm thick sheets are to be joined together.

In that case it is essential for the laser to penetrate inside the work material, melt it and then redeposit and then resolidify the molten material to get it welded. For this purpose we are using intense energy generated by the laser beam. We are applying the intense heat by using laser beam at one spot continuously so that the temperature which is getting generated is more than the vaporization temperature. And when the temperature is more than the vaporization temperature there is a generation of plasma or vapours. Due to that vapours the walls which are melted, the walls which are in liquid zone will be there at its place. When the laser is passing when the laser pass through and then it will move to the next destination that melted or the molten sidewalls will deposit, they will get solidified and then two different materials will get joined. Here the keyhole is generated by vaporization of the laser beam which is very essential to join two different materials.

Keyhole mode is a deep narrow profile with aspect ratio more than 1.5. Here the depth-to-width ratio is more than 1.5. Keyhole literally is a hole which is getting generated by the vaporization process and it is allowing the energy beam to penetrate even more deeply.

Consider we are having a thick sheet and there is another thick sheet which we need to join by using butt joint only. This thickness is quite high. Now when we want to process these two materials, what we are doing? we are using a laser beam energy which will move inside these two materials. This is the laser beam which is moving inside and it is vaporizing.

During the process of vaporization some portion of the material will get vaporized and some portion will get melted. This is melted material and this portion some of the portion is getting vaporized, but these vaporized portion is generating a vapour and vapour is having pressure. Due to these vapour pressure these melted material will not fall down inside the cavity which is there.

However, the laser is not stationary it is moving to the plane of paper. It is moving perpendicular to the plane of paper in this direction. When it is moving to get the required welding done, what is happening? the temperature at the cavity is getting reduced, the vapour temperature will get reduce, pressure will get reduced and due to that melted material will fall down it will get mixed up and then it will get resolidified to have the required weldment done. There is another picture which is there in front of you. Here we are having two plates plate number 1 and plate number 2. These two plates are put over each other and then the laser beam is applied. You just look at the keyhole which is getting manufactured during this keyhole mode based laser drilling. The keyhole was almost equal to the addition of thickness of P1 and P2. This is T1 and T2 and the keyhole depth or the depth of the keyhole is more than or equal to $T1 + T2$. During this process of operation we have to ensure that the sufficient amount of energy is getting applied and it should be more than 1.5 megawatt per centimeter square. For this purpose we need to use some high energy laser beams.

The keyhole is surrounded by molten metal that flows and fills the voids as the beam travels through the material sealing up the weld, that we have already seen. There are many factors which are controlling and balancing the keyhole. Particularly we have to be careful about the collapsing of the keyhole, the keyhole is getting collapsed during the application of laser beam energy itself, we may not get the good quality welding. The keyhole has to be filled up by the surrounding molten metal when the laser is passing through it and there has to be proper mixing of the molten material from both the parts to get uniform mixing and it also need to be ensured that there is minimum number of or less pores to be generated, the porosity of the material should be as much as less possible because of the bursting of the vapours during the operation may carried out.

These vapours are having very high temperature and high pressure. There are chances of having entrapment of the vapours inside the weldment and when they are getting cool down this vapours may generate various pores inside the weldment. This defect has to be controlled by controlling the process parameters very accurately during the process. In general the keyhole

mode is helping us to generate very strong weldments by providing deep penetration inside the work parts and they are widely used in structural welding applications.

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• Modes of Laser Welding Remarks

- Conduction Mode Welding
 - Power Density – 0.5 MW/cm²
 - Laser beam absorption only at the surface of the material and no penetration
 - High Width to Depth ratio Depth/width ↓
Aspect ratio ↓
- Keyhole Welding
 - Power Density - > 1.5 MW/cm²
 - Material in path does not only melt but vaporises as well
 - Cavity formation - “Keyhole”; Filled with metal vapor (in some case, it can be ionised forming plasma)

Figure 8. Schematics of pulsed-laser welding process

Jun Zhou, Hai-Lung Tsai, (2007), Porosity Formation and Prevention in Pulsed Laser Welding, Journal of Heat Transfer, Vol. 129, August 2007, Pg. 1014 – 1024, DOI: 10.1115/1.2724846

Fine, one more picture is there in front of you. Here you can see this is the metal zone, the solid zone and this portion during the application of the laser beam we are having solid and liquid interface and this is the plasma zone which I am talking about. Here the temperature is very high, here the pressure is also very high and during the application, it is holding this particular wall this molten wall. And when the plasma zone, temperature and pressure will reduce this wall will fall inside and it will get mixed to get required welding done.

These are the remarks basically about the modes of laser welding as we have already seen that the power density should be around 0.5 megawatt per centimeter square as far as the conduction mode is welding is concerned. However, we are getting high width in comparison with depth. The width-to-depth ratio is high, but depth-to-width ratio is low that we call the aspect ratio. Aspect ratio is low in case of conduction mode which we have already seen. In case of the keyhole welding the power density is quite high it is about 1.5 megawatt or more than that and whatever the cavity that we get that we call the keyhole and based on that we are joining the thicker materials.

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Figure 9. Laser Welding of a Pipeline

Barbara Nasilowska,
[https://commons.m.wikimedia.org/wiki/File:Laser_welding_of_the_pipeline.j](https://commons.m.wikimedia.org/wiki/File:Laser_welding_of_the_pipeline.jpg)
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- Expanding vapor or plasma contributes to the prevention of collapse of molten walls of the keyhole into the cavity
- Coupling of laser beam into workpiece improved by keyhole formation
- Deep penetration achievable through keyhole traversing
- High depth to width ratio

APPLICATIONS

Effective as an alternative to applications where Metal Inert Gas (MIG) welding is ineffective or Tungsten Inert Gas (TIG) welding is slow. Some of the applications are -

- Automobile Manufacturing ✓
- Shipbuilding ✓
- Bridge Construction ✓

Let us see what are the; various applications of the laser welding: here the laser welding as you can see on your screen there is a pipe and this pipe is getting welded by using the laser welding process. It is for the pipeline basically. Now, there are various other applications in automotive manufacturing, ship building and the bridge construction. The laser welding is very effective in comparison with MIG that is metal inert gas welding. And it is also very useful in comparison with the TIG that is the tungsten inert gas welding because TIG is found to be very slow in the industry and in some cases the MIG would be ineffective. Laser welding is solving some of the problems associated with MIG and the TIG type of welding.

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ADVANTAGES

- Capable of welding dissimilar materials with different properties.
- Capable of welding inaccessible areas
- High Production ✓
- High Speed automotive processing ✓
- High quality weld yield with increased structural strength
- Small HAZ
- Higher depth of penetration ✓
- Requirement of only single sided access to workpiece
- Non-contact processes
- No requirement of electrode ✓
- No requirement of X-rays ✓
- Reduced time consumption ✓

DISADVANTAGES

- High initial cost
- High maintenance cost
- Rapid rate of cooling due to which cracks may be produced in some metals
- Requirement of high-skilled labour
- Very low energy conversion efficiency usually below 10%

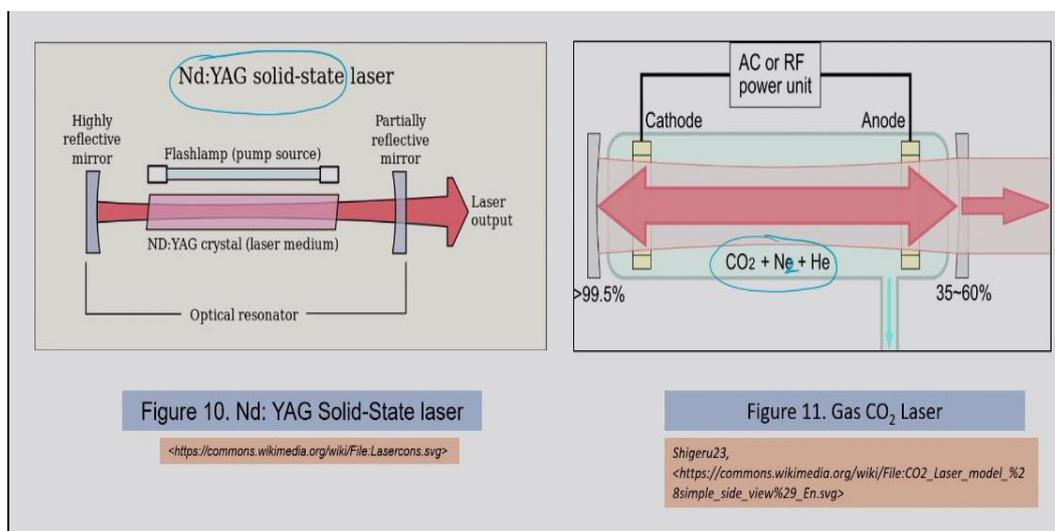
What are the various advantages of laser welding? Laser welding can weld dissimilar materials with different material properties that is its biggest advantage. As laser can move to inaccessible areas we can weld the parts where in general we cannot reach by using arc welding or some other mode of or some other type of welding operation. Here the inaccessible areas can be easily handled by using laser welding operation.

Production capacity is very high by using robots and CNC machines. Now, we can weld the materials at a very faster rate. Automotive processing as I mentioned, high speed automotive processing or automation is possible using the lasers. The heat affected zone is less in comparison with gas welding or arc welding because we are applying the heat energy at a very small portion. Therefore the heat affected zone would be less. We can achieve high depth of penetration during laser welding operation.

Here we need to have just only one sided access to the work piece. There is no need to go for the other side by applying the laser energy in most of the cases at one side would be sufficient. It is a non-contact process, no mechanical tool is essential. There is no requirement of electrode which is getting consumed and we have to maintain the gap between electrode and the work part continuously, we have to monitor the gap and accordingly we have to give feed to the electrode. There is no requirement of harmful radiation such as x-rays and there is a reduction in the time consumption as well

But there are certain limitations or disadvantages the cost or the initial cost is high. Maintenance cost is also high if we are using inert gases or the instrumentation associated with laser welding, the cost is the parameter as far as the maintenance is concerned. There is a rapid cooling of the process material weldments and due to the rapid cooling there are chances of having cracks in some of the materials. It is required to have high skilled labors to operate the laser welding process. And the is energy consumption is very high, the efficiency of the lasers are low, that is why we have to optimize its process parameters to find out the optimal levels of process parameters during laser welding as well.

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Now, let us see what are the various types of lasers used in welding operation in the industry. The first type of laser is Nd:YAG solid state laser. This is Nd:YAG solid state laser which is capable of generating 0.5 to 1.5 megawatt per centimeter square is able to help us to solve the industrial welding related problems or to generate the products or to weld the materials. The details about the Nd:YAG how it operates we have already seen our previous class.

Moreover, the CO₂ laser gas where we are using CO₂ as the lasing medium gas laser also generating the enough power which is required for the laser based welding. Here we are using the combination of three gases CO₂, nitrogen, N₂ and the helium. The details about the CO₂ lasers already we have discussed in our previous week.

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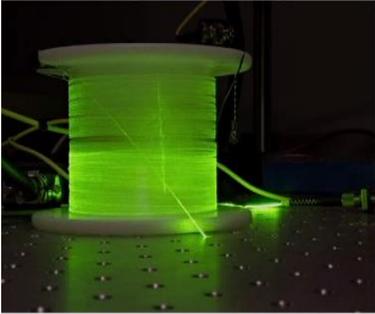


Figure 12. Erbium doped Fiber Laser

Commons.wikimedia.org. 2022. File:Erbiuim-doped fiber with green light.jpg - Wikimedia Commons. [online] Available at: <https://commons.wikimedia.org/wiki/File:Erbiuim-doped_fiber_with_green_light.jpg> [Accessed 28 August 2022].

- **Active Gain Medium** → Optical fiber doped with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, thulium, and holmium
- **Advantages**
 - Laser light generated and delivered by inherently flexible medium allowing easy delivery to focussing location and target
 - High output power ✓
 - High optical gain ✓
 - High surface area to volume ratio of fiber allowing efficient cooling
 - Produce diffraction-limited high quality optical beam
 - Compact in comparison to solid-state or gas lasers
 - Lower cost of ownership
 - Reliable and exhibit higher temperature and vibrational stability
 - Extended lifetime
 - Better for marking and engraving purposes



Figure 13. High Power Fiber Laser

Commons.wikimedia.org. 2022. File:1 fiber-laser.jpg - Wikimedia Commons. [online] Available at: <https://commons.wikimedia.org/wiki/File:1_fiber-laser.jpg> [Accessed 28 August 2022].

We can also use doped fiber lasers during the welding operation. Here the active gain medium is optical fibers which are doped with rare earth elements such as erbium, ytterbium, neodymium and many other materials which are mentioned on the slides.

What are the various advantages associated with this doped fiber laser? Laser light is generated and delivered by flexible medium and that is the advantage of fiber laser. The conveyance is very easy, output is very high and we can have a good optical gain as well, the enhancement or amplification is very high in fiber lasers. There is high surface to volume ratio of fiber that is allowing efficient cooling as well and we can generate very high quality optical beam by using these kind of lasers. The construction of the fiber laser is compact in comparison with the solid or the gases type of lasers that is why the cost of these kinds of machines is comparatively low.

And they are exhibiting very good temperature and vibrational stability during its operations. Therefore their lifetime is also extended and they can serve us for a longer period of time. These fiber lasers are not only used for welding they are also used for marking operation as well as the engraving purposes as well.

Fine, with this, I would like to stop for this lecture. In these two lectures we have seen the importance of welding, definitions of welding, various type of welding joints, types of welding and then we started discussing about how lasers are used for welding operation for joining operation. There are various modes of using lasers during the welding or joining operation, that we have seen that is a conduction mode. In conduction mode as well direct heating and transmission welding and there is important operation that is a keyhole based laser welding that also we have seen.

Various types of lasers are also used in the industry that is a solid state laser and a gases laser that also we have seen. With this we stop for today's class. Thank you.