Surface Engineering for Corrosion and Wear Resistance Application
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Lecture-53
Laser Materials Processing: Introduction

Welcome to the 53rd lecture of Surface Engineering, we have earlier talked about two specific directed energy beams namely ion beam and electron beam and seen how they can be utilized for various surface engineering applications including welding.

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Today we are going to start a series of discussion on Laser assisted Material Processing and in particular laser surface engineering. This entire series may be about I think some somewhere around 4 to 6 lectures we will cover a wide range of applications including some of the materials processing leading to I mean layer by layer synthesis of bulk and so on.

So, without much ado let us get started. So, first part we need to understand the application of laser even before that application we will talk about laser generation of laser the various characteristics of laser which suits us for various kinds of surface heating and materials processing.

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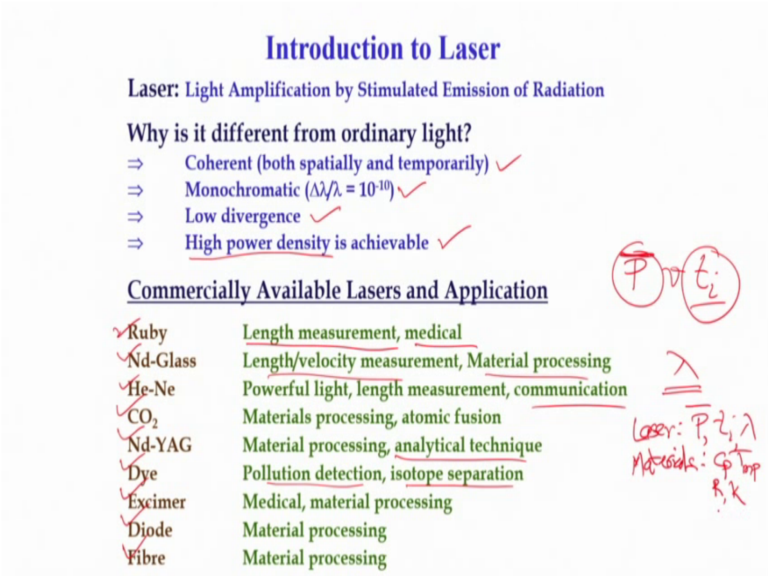

So, if you look at this view graph you immediately understand that we are talking about laser is the acronym which comes from light amplification by stimulated emission of radiation. So, we are talking about electromagnetic radiation of a particular wavelength typically in the visible range, there are a few features which actually make laser so useful for material processing.

So, there are four specific characteristics we should talk about for example, we are talking about both specially in space and in time temporarily coherent beam comprising multiple rays and all these basically are completely coherent with each other both in space and time.

Number 2: we are talking about monochromatic with very little spectral width practically we can in all practical purposes we can say that essentially the divergence is delta lambda over lambda wavelength wise is less than 10 raised to 10. So, essentially we are talking about a single wavelength. We also are talking about very low divergence; that means, the beam will follow a straight line absolutely a straight line path. So, that from where it is launched to where it is incident there will be no divergence.

And the most important thing as far as material processing is concerned is a high power density. So, essentially not energy; energy into time power over the irradiation area the power density is so high that actually you can treat any kind of solid and cause anything from heating to melting to vaporization and so on and so forth.

So, we are not talking about characteristics of laser what exactly why laser is monochromatic, what is the spectral width possible, how we can vary, how we generate laser and so on, but we are essentially looking at laser as a source of contactless heating which can cause various kinds of thermal activation to solids leading to various possibilities of processing. There are host of lasers before we go into actually their generation part and application there are host of lasers traditionally which can be used for various kinds of processing, starting from ruby laser to Nd glass.

So, basically the species which produces laser is the neodymium ion in glass or non-crystalline matrix. Helium neon laser, CO 2 laser at times also there were certain applications using carbon monoxide laser, then Nd YAG laser. So, here the neodymium ion is dispersed in each ml aluminium garnet crystal, solid state laser various dye laser where actually the wavelength can be very conveniently varied over a wide range.

Excimer laser more recently the most of the applications are concerning or make use of diode laser or fiber laser. So, we will we will discuss some of the characteristic features that are very important for laser. So, all these lasers basically vary from each other in terms of wavelength, in terms of the amount of energy that it can deliver and; obviously, that defines what is the various types of scopes of application.

So, it can be metrological applications, medical applications where as they can metallurgical applications various kinds of materials processing for which can be used for communication or for path guidance also for analytical purpose, for spectroscopic purpose, pollution detection, isotopic separations and various kinds of materials processing.

So, one chooses the utility of a particular laser will depend upon the application we have in mind and there are two key parameters which actually determine the scope of application will be the so called power density and the other one is the velocity or essentially interaction time.

So, essentially the power density and the interaction time these are the two most important parameters. And, this will determine ha what kind of laser we choose for the given application we have in mind. We also will certainly worry about the wavelength because this wavelength determines what level of absorption can happen, then in addition to this. So, these are from the laser side from the material that is going to get processed there are two or three things which are very important.

So, I would say overall one is laser related parameters and there all these power density, the interaction time, wavelength these are the laser related parameters would be important. The other part that will determine or will actually govern the selection will be from the various material properties.

And in fact, these material properties will be starting from all the way from specific heat to melting temperature, then reflectivity, the thermal conductivity yeah and then so various kinds of physical and mechanical properties of the material.

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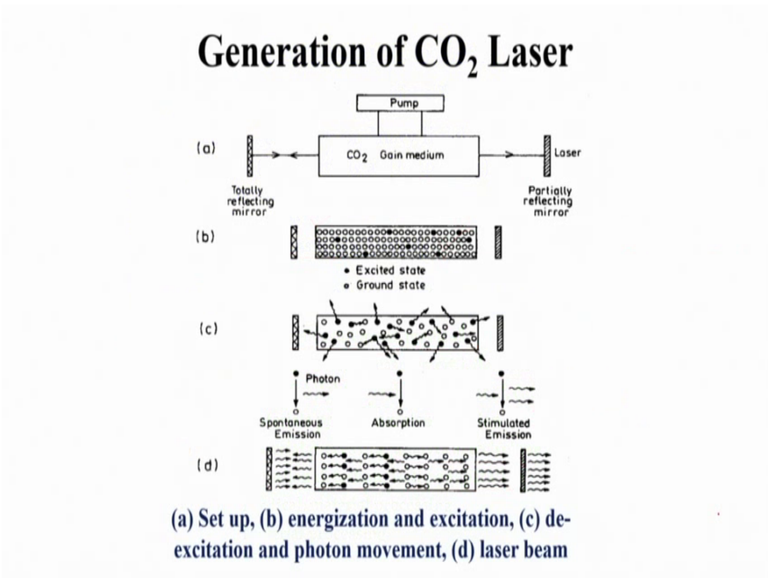

So, just a minute on the generation of laser in this case we are talking about CO 2 laser this was one of the foremost type of high power laser that was useful for material processing. So, essentially you will have a medium filled with various carrier gases and a part of that the active species of that will be CO 2 of very low volume fraction though. So, you will have on one side which is completely reflecting type of mirror. So, this is completely reflecting type, the other end will be partially reflecting; that means, it will allow partial transmission of rays through this side. So, you will have active species in it and then you either through pumping of rays optical rays or electrical pulses or electromagnetic pulses.

So, various kinds of sources of excitation one needs to excite some of the active species inside, most of the molecules or species inside will be at the ground state, but the one which will directly interact with the exciting medium will get excited. And, so once its excited, so there will be two types of emission possible following excitation, excited species that atom or molecule will fall back on to the ground state. So, in this transition from excited to ground state there will be emission of radiation and these emissions could either be spontaneous emission or stimulated emission.

So, laser basically will depend upon will largely depend upon the stimulated the volume or the population of stimulated emission which eventually will attain coherency and that is how there will be a synergy and so the excitation process will happen in coherence and as a result there will a be multiple events happening. And, because of which the eventually through the semi transparent window, the laser of certain wavelength and intensity or energy will be allowed to leave the chamber.

So, this process of the entire process will require excitation taking the species to higher energy state energization and then de excitation falling back on to the ground state and in the process emission of photons and these photons initially would be random and subsequently will attain certain coherence. And, once they are they can make constructive interference or they are coherent with each other, then there will be emission of laser initially and the total intensity of the laser will depend upon the population that will undergo excitation subsequently inversion and also which will be able to maintain the coherence.

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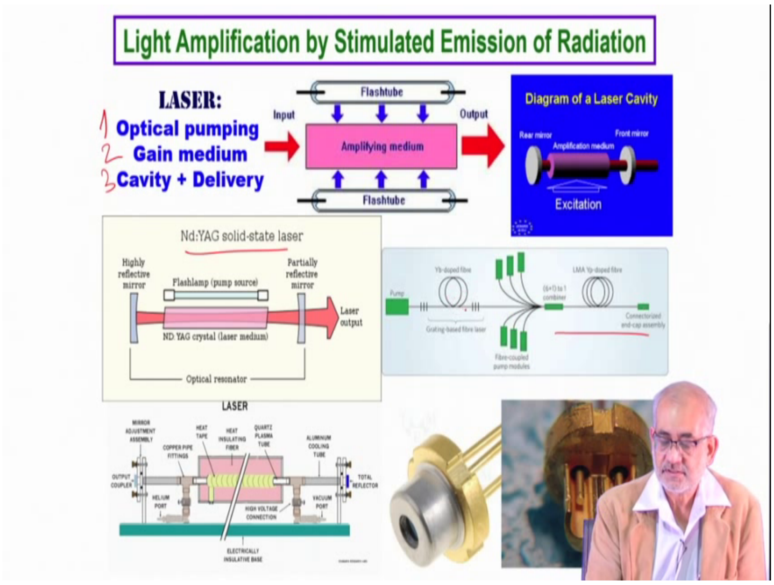

So, this is the process which is by and large true for all kinds of laser I mean be it CO 2 laser or solid state Nd YAG laser or a diode laser or say fiber laser this is one of the most common and the most widely used high power laser variety it could be.

So, in all these cases there are three things which are important one is the optical or some way of pumping of exciting the species to higher energy state you need a gain medium and you need a cavity for delivery. So, initially there will be excitation through these light flashes here or electrical pulses in some other cases leading to this kind of excitation population excitation and de excitation.

And because of which there will be random radiation generation and then subsequently there will be certain population which will be attaining the coherence and because of this synergy the excited the intensity of the emitted rays will be significantly higher. So, amplitudes will add and then intensity being square of amplitude the overall intensity of the coherent beam will be many times higher, than the initial random intensity of the random radiations.

Anyway, so these are various possibilities since I mentioned about of the fiber laser being one of the most widely used one these days, that happens because actually it’s very convenient the delivery the active medium and the delivery medium is the same.

So, essentially long optical fibers and you actually some of them they come with certain pumping devices which could be a certain diode coupled with diodes which will actually pump energy into them and so all of them will create a bundle and that is where they get combined.

So, multiple wavelengths coming from individual fibers will get will get to interact with each other and then that is where the laser is emitted from and the emitted laser is now taken through the same fiber laser leading to large distances wherever we want them to be doing the job.

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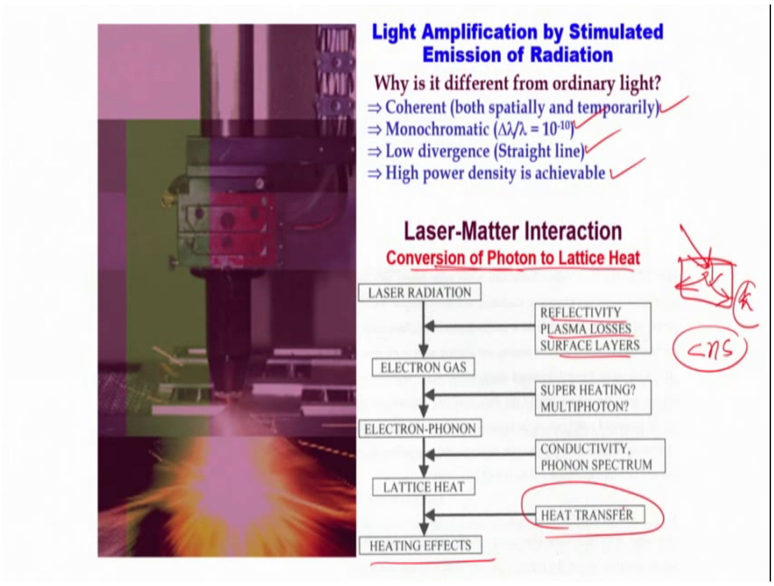

So, as I said there are four things which are important coherence, the monochromaticity, the divergence, low divergence and high power density. So, all these four characteristics together make laser a most suitable source of heating for various kinds of materials processing.

The conversion of incident photon, the packet of light of incident radiations falling onto solid matter this conversion actually goes through certain stages. Now, if we for the time being imagine the entire range of solids into two baskets into two compartments one with direct band gap namely the insulating or semiconducting materials and the other one being the overlapping band materials.

So, metallic and nonmetallic to be more you know make it much simpler. So, metallic materials will have free electron cloud available on to the surface. So, incident electromagnetic radiation or laser will have always an opportunity to interact with the free electron cloud and the majority of the incident wave length will actually have the possibility of getting reflected back.

So, you couple only a few percent of the incident energy onto a solid metal. So, metals have the capacity of or the property of always reflecting much of the incident wavelength particularly in the optical range to be reflected back. So, coupling laser onto metal, that to polished surface of a metal is a big challenge. On the other hand if you are dealing with the semiconductor or oxides or ceramics or compounds or particularly even covalently bonded polymers and so on, then coupling is much easier.

Now, one way of actually overcoming this problem would be either you raise the temperature where the coupling efficiency increases or you go for lower wavelength materials lower wavelength lasers. So, that the coupling efficiency increases and for that reason you would rather prefer Nd YAG laser or solid state laser or even short for shorter wavelength one goes to excimer lasers or diode lasers and so on and so forth.

So, 10.6 micrometer would be the wavelength of CO 2 laser which is fairly on the higher side whereas, 1.06 micrometer would be from Nd YAG, but in case of excimer or diode it could be some micrometer. So, several hundreds of nanometer and one can actually vary by various kinds of frequency doubling mechanism and so on.

So, whatever is a wavelength when it is incident on a solid, so if this is a solid and the wavelength is incident on it; it goes through basically two kinds of interaction one is if you have free electron cloud. So, there will be immediate excitation and the de excitation and in the process the energy incident will be absorbed.

If you have valence band electrons meaning semiconductors and insulators, then the electrons will be excited from conduction to valence; valance to conduction and then excitation. So, the excitation process will be slightly relatively slower, but nevertheless whether its metal or non-metal the whole process is done very; very quickly.

So, incident radiation suffers reflection or creation of plasma or some interaction with the surface layer. So, some attenuation takes place, but then subsequently it creates an electron gas which is through the excitation process I mentioned and there will be super heating or multi photon activity during the irradiation. So, there will be electron phonon interaction and this electron photon interaction happens at very; very small time scale much less than even a nanosecond; so, typically of the order of a pico second.

So, that is the reason why the conversion of incident photon into lattice heat is very; very fast is typically less than a nanosecond. So, this conversion eventually will create heating of or create a situation for lattice heating and then the heat from the surface will gradually propagate down below and then also sideways.

So, that is essentially dictated by the conductivity of the material thermal conductivity of the material and so on. So, that is how basically we create a heating effect. So, conductivity or heat transfer coefficient will determine how soon that heating up actually occurs.

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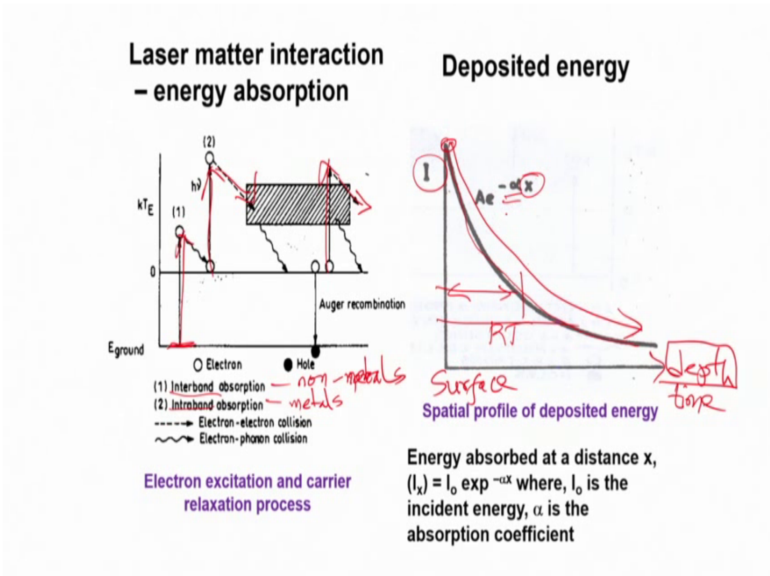

So, this is what I was mentioning a few minutes ago, that either you excite the electron from the from the valence band to the conduction band and then further excite to higher energy state or if it is a metal then you already have electrons in the conduction band. So, you excite them and then subsequently they get de excited.

So, no matter how it happens, so there will be excitation and de excitation process. So, whether it is inter band which is typically is a case for band gap material semiconductors and insulators or intra band transition which is typically the case of metals. So, this is what we expect in case of metals and this is what we expect in case of nonmetals.

So, once incident photon is absorbed and converted into lattice heat, then this is how the lattice heat flows into the bulk. So, this is depth and this is surface. So, what is significant here is that the peak absorbed absorption effect of the absorption or the peak of the absorption is felt right at the surface and not below.

So, this is how the deposition profile energy deposition profile decreases with depth and also with time. Now, what is important is that at the surface I have the highest heating effect and down below the heating effect decreases and below a certain temperature, the metal or the solid remains at room temperature. So, only a very shallow depth from the surface gets heated up to very high temperature this is intensity; obviously, the temperature will be proportional to the intensity of the energy coupling.

So, this decrease will be exponentially related to the depth and will also depend upon the absorption coefficient. So, this is the typical relationship that one needs to worry about and where this alpha the absorption coefficient varies from material to material and for direct band gap materials; obviously, this will be higher for metals this will be lower. So, as a result the coupling is more efficient in case of nonmetals than in case of metals.

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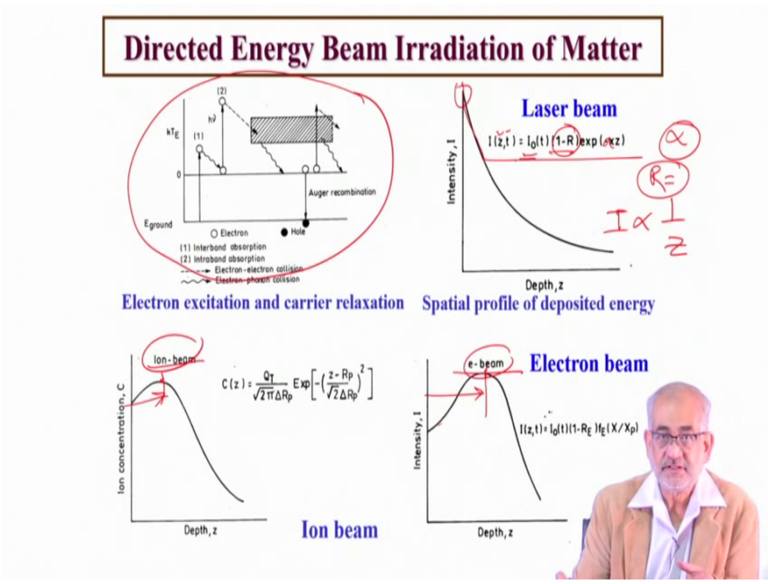

Now, So, this is the process of conversion of lattice incident photon into lattice heat and that is what we have just discussed. Now, if you compare the three main types of directed energy beams which means where the beam is convergent and the heating effect is it's a line of sight process and the heating effort is confined to the point of irradiation, compared to ion beam or electron beam in both the cases what we see is the peak is not at the surface, but below the surface.

So, if this is the peak this is not at the surface, but below the surface. In case of laser it is the other way round it is right at the surface when sides with the surface and then the intensity decreases as function of depth z and time. So, both time wise and depth wise it decreases, if I naught is the incident radiation then as a function of time it decreases in the following manner, 1 minus R where R is reflectivity.

And please remember the reflectivity is just the reciprocal of absorptivity, but absorptivity and absorption coefficient is not the same, absorptivity is a dimensionless quotient whereas, absorption absorptivity that is absorption coefficient this is actually alpha this has a certain unit.

So, nevertheless what it means is that intensity is decreases with z with the distance or depth from the surface. So, one would like to play with reflectivity one can use certain films or coatings or make the surface rougher, so that the coupling efficiency increases. So, reflectivity is simply whatever um, so if there are hundred radiations at a given point of time in a given area is incident.

How much of it is actually able to interact and couple and how much of it is actually getting reflected back? So, this whatever is not reflected, whatever is absorbed is expressed by this 1 minus R term. So, compared to electron beam and ion beam the biggest advantage of using laser beam is that, the absorption is maximum at the surface and it decreases exponentially with depth.

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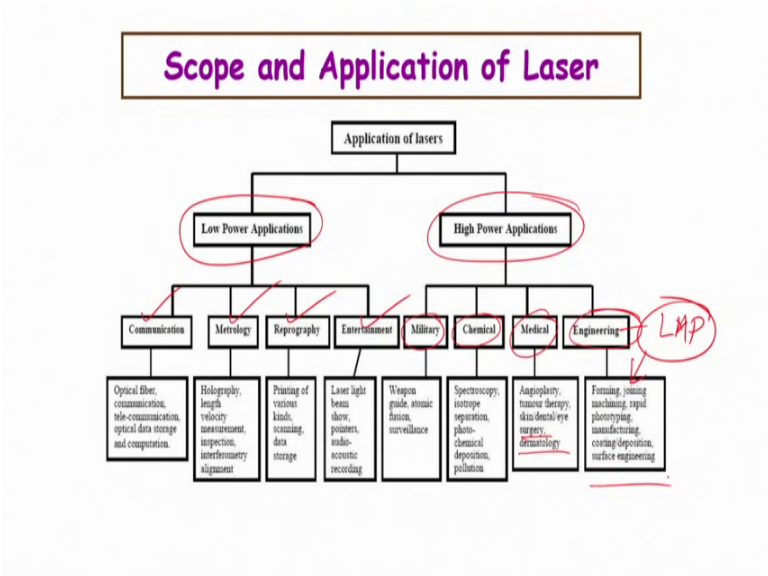

Now, the laser actually has multiple possibilities of application. So, there are two major scopes two major types of applications, typically in terms of the power. So, in case of low power applications we are talking about communications, metrology measurements, reprography, entertainment and various forms of them.

So, for communication through optical fiber, communication, telecommunication, storage, optical storage even computational activities. On the other hand using high power laser we actually can do various types of hardware applications involving hardware.

So, in extreme one can use for various one can think of various military applications including weapon guide or atomic fusion, surveillance and so on. In case of chemical sort of applications for various kinds of spectroscopy, isotrope separation, photo chemical deposition, pollution control, conversion and so on. Medical there are host of applications medical applications starting from various kinds of therapies or angioplasty or surgeries dermatology treating various forms of cancer cells and so on and so forth.

But in engineering we have various possibilities and that is exactly all these applications typically what we do for engineering or manufacturing, we essentially call them laser material processing. So, this laser material processing essentially can be in the form of forming joining, machining, prototyping, manufacturing, coating, deposition, surface engineering so various forms of applications.

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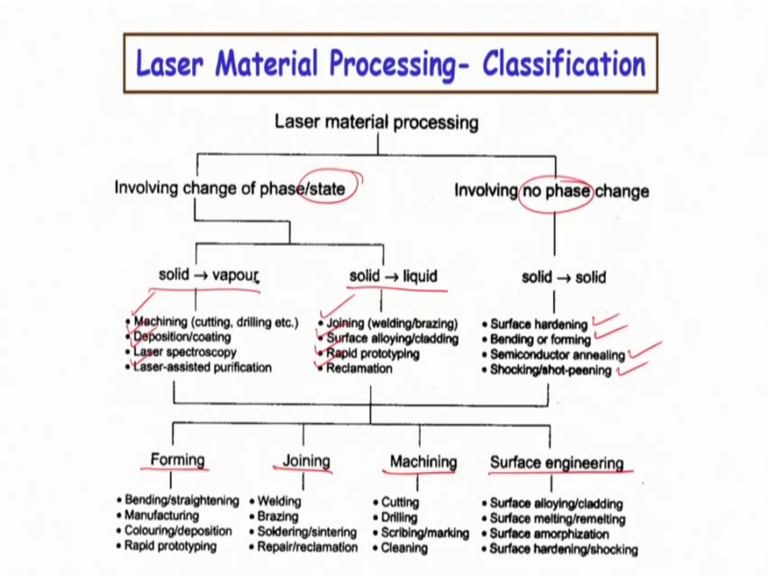

So, in terms of laser material processing we are talking about possibilities which would may involve change of state the physical state or involving no change of physical state. So, no change of physical state means we have a solid we simply are heating the solid to a higher temperature and then allowing it to cool by self. So, that application that kind of an application could be hardening surface hardening bending or forming or semiconductor annealing even laser pinning or laser shock pinning and so on.

Otherwise we may see a change of state and reverting back into the original state; so, solid to liquid then coming back to solid, so solid melting solidification vaporization condensation. So, if its vaporization, so; that means, we are heating the maximum for a certain period of time we are applying highest amount of power density. So, we can not only melt, but even vaporize. So, in the process we can do machining, we can do deposition or coating, we can do various spectroscopy's or even material purification by way of condensation.

If it is only heating up to the melting temperature not above melting temperature, but not crossing the boiling temperature, then we are talking about joining various types of joining, surface allowing cladding, rapid prototyping direct manufacturing, reclamation and so on. On the other hand as I already mentioned in case of solid; solid within the solid we can do hardening bending forming various applications. So, if you again mix them together and now do not worry about any change of state and say that whether it change of state occurs or not essentially, we are only worrying about the possibilities of engineering applications to be more precise various forms of manufacturing applications.

Then we should think of forming, joining, machining and surfacing as the four major classes of laser material processing that actually are very routinely exploited in engineering. By forming you mean a bending or straightening or manufacturing of components parts shapes, colouring deposition, rapid prototyping or direct manufacturing. You can in terms of joining you can think of welding, brazing, soldering or centering even various forms of reclamations refurbishment.

Machining is removable, so you can do cutting you can do drilling. So, cutting of a longer dimension or drilling with a much higher aspect ratio a small hole, but drilled through and through, you can do scribing or marking, you can do even cleaning removal from the surface very thin layer. On the other hand if you are doing surface engineering then you can do alloying or cladding you can do melting or remelting, you can do simply heating or hardening or shock pinning or shocking or you can even try an amorphize the surface by change of state by change of micro structural state.

So, all these possibilities in fact, one can always these are not exhaustive these are just representatives. So, one can come up with some other ideas other possibilities and certainly possible these are not the ultimate the final. So, whatever various forms of I mean changes one can bring in by way of heating leading to either just heating in the solid state or melting or vaporization, can all come under laser material processing. But then the question arises that if then what is a guiding principle I mean you are talking about more like a heuristic approach that whatever you do can be a processing, then what is a guiding principle, how do you classify them and how do you control them ? And that is fairly easy.

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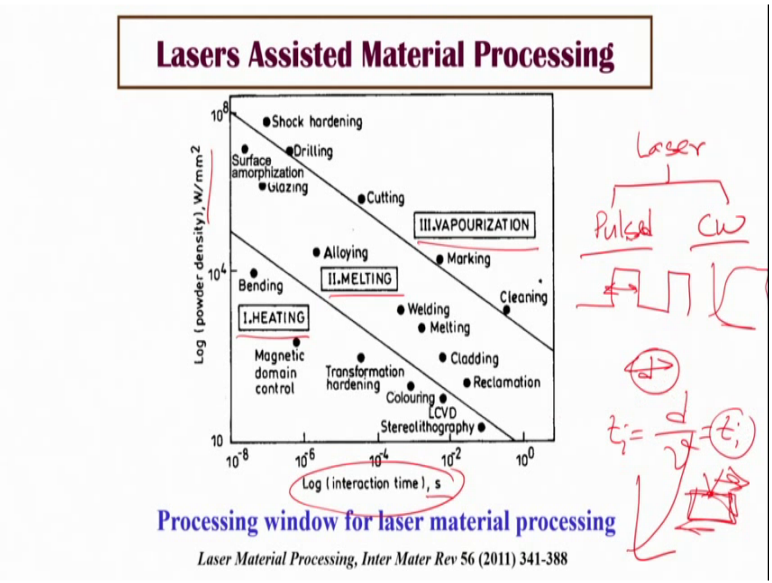

Processing window for laser material processing

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Surprisingly though the scope is very; very large, but it is fairly easy and you can as I said you can do three types of processing only heating within the solid state or melting, then solidification or vaporization condensation. So, these three caskets can all be controlled.

So, any type of laser assisted material processing one can think of can actually come in this x y space and on the y axis we have power density watt per millimeter square and in the x axis we simply have interaction time. Now, I think I should have mentioned that the way we generate laser and the way we extract laser and then make use of there are two possibilities. So, typically I would say that laser essentially is applied for material processing in either of the two form one is the so called pulse mode, the other was is called a continuous wave mode.

So, it essentially means that laser actually can be the intensity, so it in this case the intensity will go like this. So, there is a pulse on time and pulse off time right and so the frequency and the peak height or the intensity will determine what is the heating effect or what are the changes that you can bring in. On the other hand the continuous wave essentially would mean that once the beam is on, then it will remain on for the for a certain period of time.

And during this period there will be constantly the temperature will increase and heat will propagate and the material as a whole will see an extremely high rise of temperature and one needs to control, so that ultimately the solid is not destroyed.

So, the basic thing that I am trying to emphasize upon and this is what all of you will have to remember always while dealing with laser is that there are two only two major process parameters. The interaction time which in case of pulsed laser is simply the pulse on time and you can either go by cumulative time that you, that the laser beam is on or else simply the pulse width essentially this width is the so called time that we are talking about.

Or if it is a continuous wave laser and let us say this is the beam diameter of diameter d then essentially you are talking about the ratio of d upon velocity. So, continuous wave if this is the solid and this is where the beam is incident you cannot afford to have a beam stationary because the temperature will rise exponentially. So, whole material will immediately melt and drill a hole vaporize drill a hole and the hole will penetrate through and through the whole material will be destroyed.

So, you cannot afford the beam to let the beam stay where it is. So, you have to have a relative motion between the solid that you are directing and the laser incident beam. So, this relative motion can be either way either the beam moves or the solid moves either way. So, whatever is the direction of movement there will always be a velocity with which either the beam will move or the substrate will move.

So, and there is an area let us say it is a circular beam, so in that case there will be a finite diameter. So, the diameter over the velocity will essentially give you a time component and this time component will be another major parameter. So, the power density on one hand and interaction time on the other hand will create the space within which you can have all possible solids; all possible solid material processing using laser can be controlled.

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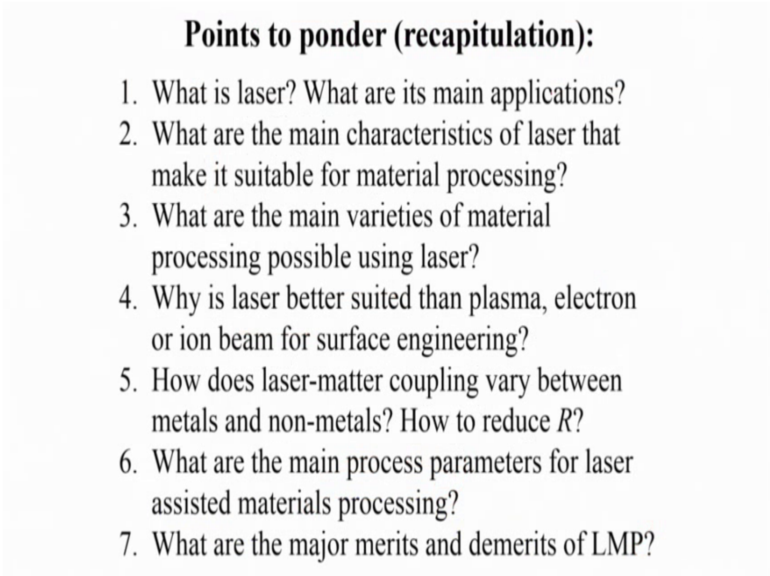

So, time to summarize, so we have understood what does laser mean light amplification how does it happen, so random how random emission gets into a state where they can synergize or be completely coherent or create constructive interference and then how the intensity builds up.

So, how we control that what are the different medium used for laser and what is the active species accordingly we have series of types of lasers possible and what are the important characteristics of laser the energy the type of the laser whether it is pulsed or continuous wave and what is a wavelength what is a delivery system and so on and so forth.

Then on that is one side of the story, the other side of the story is the material properties which will involve the melting point, the density of the material, the specific heat, the thermal conductivity and in turn which will determine the heat transfer coefficient.

So, all these will determine: what is the thermal state what will be the level and mechanism of thermal activation. So, what is good about laser is that coupling efficiency is very fast, the way laser incident photon gets converted into lattice heat it takes less than a nanosecond, so extremely fast process.

The other good thing about laser is that heat deposition profile is exponentially decaying. So, maximum heating at the surface and only within a few micrometers from the surface temperature falls to room temperature. So, essentially you are at a time dealing with a very small volume of the solid and the rest of the bulk will all be at room temperature, so you are affecting very small volume. The, so there are the two main variables we are talking about one is the interaction time the other one is power density and by varying these two parameters we actually can cover a very wide range of materials processing.

We actually always consider laser to be a better suited agency for material processing particularly surface engineering, then plasma electron and ion beam because of the exponential nature of decay profile of the incident energy. The reflectivity is a very major impediment for metallic materials and there are reason means to reduce the reflectivity either apply coatings or absorbent coating and so on or make the surface rougher, but the most effective way is to go for a shorter wavelength laser.

The parameters already I have mentioned and in fact, by suitable choice of these parameters one can do only solid state heating or allow melting and solidification or alloying or one can do various kinds of machining micromachining and drilling and joining and so on. Everything is good about laser, but the capital cost is very; very high and you also need a fair amount of skill for making use of correct use of laser for various materials processing.

But on the other hand the biggest advantage is that it is an extremely fast process. Another barrier demerit is that the beam size is typically about in the order of millimeters or less than a millimeter. Whereas, a solid bulk solid that you are talking about in terms of volume or in terms of surface area is way too high is much higher than the size of the beam.

So, you require the beam to move fast which is possible independently one can change the speed or increase the speed, but you need a surface integration you need surface integration and you need also to allow sufficient interaction time for the heat to penetrate all the way to the to the other end.

So, if you want through and through it, so this is not an ideal tool for bulk heating you would rather use a furnace if you have let us say something like a few centimeter cube volume of material you cannot heat the whole material using laser, but laser is not meant for that laser is meant for doing or heating or affecting very small volume at a time not the entire volume. And bit by bit you actually can process the entire surface even the other surfaces, if you have good manipulation of the solid that you are irradiating.

So, the biggest advantage is that it is a non contact tool for heating and you can heat or in the process heat melt vaporize literally any solid. The independently you can vary the power density to such an extent and the interaction time such an extent that any solid any solid literally can be melted can be heated, can be melted, can be vaporized. And hence all kinds of materials processing are possible with laser in a irrespective of how hard or how high melting point or how difficult that material is. So, that opens up completely infinite possibility. So, only imagination is our limitation.

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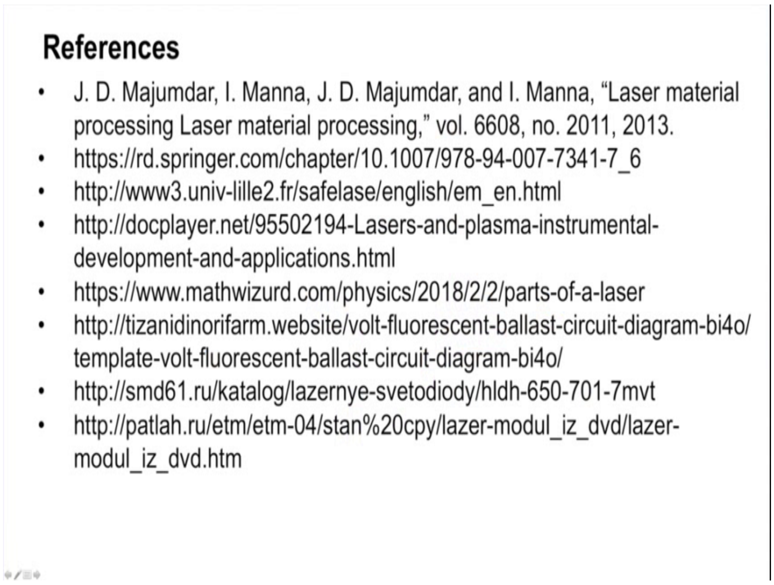

So; obviously, laser is an unique and an extremely exciting and a versatile tool and in the next few lectures we will discover as to what we can do with laser.

Thank you very much.