Application of laser for surface treatment

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Naslov rada na hrvatskom jeziku: **PRIMJENA LASERA ZA OBRADU POVRŠINE**

Naslov rada na engleskom jeziku: **APPLICATION OF LASER FOR SURFACE TREATMENT**

Opis zadatka:

In theoretical part it is required to describe possible application of lasers in surface treatment with goal to improve tribologic and exploitation properties of metallic materials. Furthermore, definition of laser working parameters in surface treatment is to be done from the aspect of their impact on properties of treated layer. Specifics of the laser types should be described together with detailed explanation of laser light physics.

Through experimental part applicable investigation methods should be described in order to define the properties of treated surfaces. Achieved results on selected practical examples should be analyzed in detail and adequate discussion is required.

Finally, conclusions should be made based on presented matter.

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I declare that I wrote this thesis independently, using the knowledge I gained through my studies and the cited references.

Hereby I would like to thank Prof. Dr. Carsten Gachot, being my mentor and friend, working with me all the way from the Vienna Universitiy of Technology. I would also like to thank Prof.dr.sc. Ivica Garašić for inspiring me with his teaching approach and his inspiring relationship with all of his students.

In the end, I would like to thank all my friends and colleagues who helped me, they made this journey fun. Aside from them, I would like to thank my family (Melita, Nenad and Mihael) and of course, my loving girlfriend Nika.

Mislav Ćuže

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SUMMARY

With a new and increasing technological demands come new solutions. This is how laser treatment found its way into material processing. As a main field in material processing, laser surface treatment is the main focus of this paper. As it involves laser, in the first, theoretical part, laser, their principle of working, types and their characteristics alongside with laser light and its physics are described. In the second part, basic categorization and description of laser surface treatment is given. The third part involves one of the processes described more thoroughly; laser cladding. It gives practical problems and examples regarding repairing technology in aerospace industry and sets up ground for a possible future experiment. At the end, tests, which are recommended to be utilized to check the results of the future experiment, are slightly described.

SAŽETAK

S novim i rastućim tehnološkim zahtjevima dolaze nova rješenja. Tako je laserska obrada pronašla svoj put u obradi materijala. Kao glavno polje u laserskoj obradi materijala, glavna tema ovog rada je laserska obrada površine. Kako ono uključuje laser, u prvom, teorijskom dijelu, opisan je upravo laser, njegovo načelo rada, tipovi lasera te karakteristike vezane za lasersko svjetlo i osnovnu fiziku iza nje. U drugom dijelu dana je osnovna kategorizacija i opis postupaka laserske obrade površine. Treći dio je fokusiran na jedan od bitnijih postupaka primjenjen u laserskoj obradi površine; lasersko oblaganje. Prikazani su praktični problemi i primjeri vezani s tehnološkim remontom u svemirskoj industriji te su postavljeni temelji za budući eksperiment. Na kraju se ukratko opisuju česta ispitivanja koja se mogu provesti kako bi se pomno provjerili i zabilježili rezultati budućeg eksperimenta.

1. Introduction

Laser light was not even thought to be possible, yet today, it is used practically everywhere around us and therefore digging into the science behind is very worthwhile. One of those applications of laser is also in material processing and surface treatment industry. It gives a lot of possibilities and there is still a huge gap for them to fulfill, so it is lately very common topic to be discussed. This paper is a result of such a high interest, but it is written with a little different approach.

It gives basic information starting from physics of light; stimulated emission phenomenon and basic laser beam characteristics such as its wavelength, coherence, mode and polarization. Also, basic linear beam effects such as absorption, reflection, scattering, diffraction and laser beam interreference are described. Then, explanation of basic laser working principle and its types (gas, solid state, diode, dye and free electron lasers) is given [1].

After that, this paper transfers to the laser material processing industry applications, describing basic processes involving only surface heating (e.g. transformation hardening), surface melting (e.g. cladding) or shock hardening of the surface layers [2].

At the end, this work consists of the hypothetical experiment yet to be made by laser cladding. It is containing explanation from selection of basic parameters to other important factors such as selection of the paired materials. It is based and will show the important parts of the real experiments made in [4] and [5], dealing with laser cladding of the turbine blades in the aerospace industry and of the milled parts, on different materials such as different types of high-quality stainless steel and Ti-6Al-4V. [4][5]

2. Laser

2.1 Introduction to a laser

2.1.1 What is light?

Many of scientists were "arguing" what is the correct explanation of the beam of light. There are three main theories which explain the concept of light beam. First, according to "particle theory", light is a stream of particles. On the other hand, light beam can be represented as a wave through the "wave theory". The representing problem of wave theory was that it was unable to explain the photoelectric effect; the ability of light to eject the electron from a surface which is independent of the light intensity, but dependent on the wavelength. On the other hand, the problem with particle theory was the explanation of the famous Thomas Young's (1773–1829) double-slit experiment. It couldn't explain the resulting pattern of light after letting the beam of light through the slits onto the screen, which gave totally different results than expected (today it is explained as a light diffraction). The third theory which connects those two theories is a "quantum theory of radiation." It gives explanation of light as a group of photons, particles with no mass, which travel at the speed of light ($3x10^8$m/s) in form of electromagnetic waves – a transverse wave with an oscillating electric and magnetic energy fields perpendicularly to its direction of traveling (see in Figure 2). The basic laws of electric and magnetic fields are described with four famous Maxwell's sets of equations, describing induction and capacitive energy storing principles, which is the basis for deduction of all the other equations concerning electric and magnetic fields. [1]

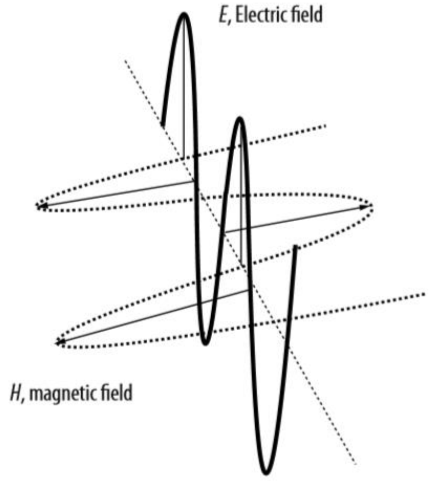

Figure 1 Electromagnetic transverse wave – light [1]

2.1.2 How is wave generated and how the beam interacts with matter?

Everything in nature moves and so all tiny particles move as well. Any energy disturbance can cause the generation of the electromagnetic radiation. Electric field disturbances, such as light beam impacting the surface, causes a vibration of electrons which means that they possess energy and that energy must be either emitted or absorbed. Also, by photons impacting the surface, they impact electrons sited in so-called “electron gas” zone. By vibrating freely, they generate electric field which produces electromagnetic waves 180° out of phase, but with the same angle of reflection as the angle of incidence. This is called re-radiation or reflection and it happens only in electron gas which means it doesn’t interrupt anything further than approximately 2 lengths of atoms from the surface. Beside re-radiation, there is also possibility of transmission, which is passing of the light through the material – but it does not mean absorption! Absorbing means vibration of the electron is constrained, so that vibration is then passed further onto the phonons (a bonding energy of solid or liquid structure). It causes movement of all linked molecules and atoms or better said, the vibration of the whole structure, that is, actually, a heating process. [1]

2.1.3 Stimulated emission phenomenon

The word “laser” is not word by itself, it is actually an acronym and it stands for “light amplification by stimulated emission of radiation”.

For a long time, it was a mystery on what is actually happening. It was considered as some kind of a weird noncommon occurrence, but in reality, it wasn’t and it is pretty common. Basically, the whole process is based on stimulated emission phenomenon. Einstein was first to postulate the basic principle of it through his analysis on hot object radiation. So, the basis is, in fact, radiation process as mentioned in acronym “laser”. What he found, and what is found to be true, is that a radiant species (a photon) causes, through the striking of the excited species, emission of more radiant photons thus amplifying the light. That is also the way, how the initial photon gets released, by change of the energy of the species. But, as suspected, there must be some preconditions in order for stimulated emission phenomenon to occur. Firstly, in order for atoms or molecules to emit rather than absorb energy, there must be more of them in excited state than in lower energy state. Secondly, the lifetime of the higher state also must be longer than of the lower energy state atoms or molecules.

It is interesting that almost all materials can have this phenomenon going, but what separates them is efficiency and their power capability, so there are only few of them which provide the desired results. Some of the most common laser used nowadays are carbon dioxide (CO_2), carbon monoxide (CO), neodymium-doped yttrium aluminium garnet (YAG; Nd:YAG), neodymium glass (Nd:glass), excimer and diode laser. [1]

2.1.4 Laser components

Laser design is simple and it can be separated into three major parts:

1. Active medium
2. Pumping source
3. Optical resonator

Active medium (1.)

Active medium consists of excited atoms or molecules which emit the desired photons, but in order to emit those photons, the medium must be “active”, or in other words, in higher energy state. All materials can lase if their substances get hit “hard enough”. It was proven that even edible laser could be created, but is not, of course, as efficient as others. Active medium can exist in all 4 states; solid, liquid, gas or plasma. The usual solid active medium is ruby, Nd:YAG and Nd:glass; liquids are usually organic dyes dissolved in alcohol or water and gases are He–Ne , CO_2, argon and nitrogen. For a medium to become active, here comes pumping source into the play. [1]

Pumping source (2.)

Pumping source is any energy source that results in active medium become active. What this means is that by providing energy to the medium it becomes excited and ready to emit photons. Some of the commonly used energy pumping sources are flash lamps, laser, electrons (DC, RF, e-beam), chemical reactions and others.[1]

Optical resonator (3.)

This is the main part of the laser; it is a cavity where active medium is present, powered by pumping source. In this cavity there are two parallel, relatively distanced mirrors, one is completely reflective whereas the other is partially reflective. What happens inside the cavity is by reflecting the light created by photon emission, the light reflects back and forth between the mirrors on the axis and during that time it is “fed” with other photons and thus getting amplified. Since one mirror is partially reflective it passes some of the created light through.

The light created this way is coherent, polarized and unidirectional. These characteristics will be better explained later in the text. [1]

The simple sketch of the basic laser components can be seen in Figure 2.

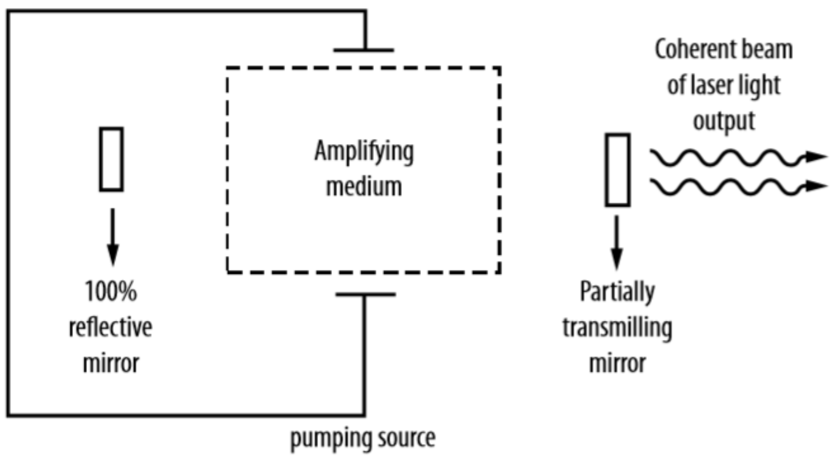

Figure 2 Basic laser components [1]

2.2 The physics behind the generation of laser light

This subtopic is a short overview of basic information connected to physics of the laser light. As already mentioned, the active media consists of the atoms or molecules which are in excited state due to impact of the electromagnetic field of the pumping source. To change the energy state, energy needs to either be absorbed or emitted. Einstein knew that and so he described the three major processes explaining these occurrences.

Those three possible processes are:

1. Spontaneous emission
2. Absorption
3. Stimulated emission

2.2.1 Spontaneous and stimulated emission

The major characteristic of this process is that by spontaneously emitting the photon, it travels in any direction, has various types of frequency, phase and sense of polarization. So, because laser light is a directed, coherent, unidirectional light, it must emit photons with the same direction, same phase, same frequency and same sense of polarization in order to be amplified in the first place. Is this possible? What are the chances of that occurrence? Well, what needs to be done is that only one photon needs to be spontaneously emitted in the "right" direction (it needs to be emitted onto the cavity axis) so the process starts to uncoil on its own. What happens with the stimulated emission is that when the atom is hit by a certain photon (which lays on the cavity axis, thus oscillating between cavity mirrors), it impacts other excited species what than causes the emission of the photon with the same properties further on (same direction, same frequency, same phase and same sense of polarization). This is the reason why the light can be amplified. [1]

2.2.2 Absorption

Absorption is basically the same process as the emission but the energy level rises instead of lowers. The photon is than absorbed rather than emitted.

2.3 Laser viability

What Einstein did with these three processes is that he introduced his coefficients for each of them to describe them. Those coefficients are characteristics of the atom and all three are correlated. What they do is they describe the energy transition rates (change in population density – let's say from higher to lower energy state). They show the need of population inversion in order for a laser to become viable. Having that inverted population, a certain energy gain is provided from the atomic system. Energy gain is usually described with an energy gain coefficient. Every laser has its own need for population inversion and therefore energy gain coefficient. By calculating the minimum energy gain coefficient based on some basic parameters of the laser; such as reflectivity of both mirrors and the length of the laser cavity, using equations that all come from the use of Einstein coefficients, the viability of the laser can be determined. [1]

2.4 Laser beam characteristics (basic terms)

In order to better understand laser light and further see what are its applications, one has to first get to know basic terms which are interrelated with the laser beam and optics.

These terms will be slightly touched and described

- wavelength
- coherence
- mode
- polarization

- linear beam effects
    - absorption and reflection
    - refraction
    - scattering
    - diffraction
    - interference
- non-linear beam effects

2.4.1 Wavelength

One of the main aspects of light beam and very important in laser technology is its wavelength. This is what separates a commercial significance in choosing the proper suitable laser for its application. Most commonly used wavelengths of laser are shown in table 1.

Table 1 Most common laser and their characteristics [1]

Laser type	Lasing species	Principle wavelength (μm)	Region	Date invented/commercialised
Excimer	F_2	0.157	UV	1975/1976
	ArF	0.193	UV	
	KrF	0.248	UV	
Nd:YAG frequency-quadrupled	$Nd^{3+} \times 4$	0.266	UV	
	XeCl	0.308	UV	
	XeF	0.351	UV	
Nitrogen	N_2	0.337	UV	1966/1969
AlGaN diode	Band gap	0.38–0.45 (tunable)	Blue	
Helium–cadmium	Cd^+	0.4416	Blue	1968/1970
Argon	Ar^+	0.4880	Blue	1964/1966
	Ar^+	0.5145	Green	
Copper vapour	Cu^*	0.5106	Blue-green	1966/1981
	Cu^*	0.5782	Yellow	
Nd:YAG frequency-doubled	$Nd^{3+} \times 2$	0.532	Green	
Helium–neon	Ne^*	0.6328	Red	1962
Ruby	Cr^{3+}	0.6943	Red	1960/1963
Alexandrite	Cr^{3+}	0.700–0.820 (tunable)	IR	1977/1981
Ti:sapphire	Ti^{3+}	0.670–1.100 (tunable)	IR	
AlGaAs diode	Band gap	0.7–0.9 (tunable)	IR	1962/1965
Nd:YAG or Nd:glass	Nd^{3+}	1.064	IR	1964/1966
Yb:YAG or Yb:glass	Yb^{3+}	1.030	IR	1990s
Chemical oxygen–iodine	Chemical ($O_2 + I_2$)	1.3	IR	1964/1983
Er:YAG	Er^{3+}	1.5	IR	
Hydrogen fluoride	Chemical ($H_2 + F_2$)	2.6–3.0	IR	1967/1977
Helium–neon	Ne^*	3.39	IR	
Carbon monoxide	CO vibration	5.4	IR	
Carbon dioxide	CO_2	9.4	IR	
	vibration	10.64	IR	1964/1966
Dye	Fluorescence	1.1–0.3 (tunable)	IR–UV	1962/1965
Free electron	Electron vibration	12.0–0.1 (tunable)	IR–UV	1963/1969

Radiation coming from a laser beam is one of the purest forms of radiation known. It can be manipulated so there is almost only one wavelength present within the process (thus being monochromatic – of one color), so being very pure, but it is often not worth the effort for material processing. What is actually used are beam wavebands, i.e. the band of wavelengths which can be more or less broad. For short pulses of laser to be formed, what is first needed is a broadening of the waveband of the beam so it can be manipulated and lumped into a short powerful pulse. But, on the other hand what is interesting for material processing are wavebands that are not either too broad (as for pulses), nor too narrow (not being so pure). [1]

2.4.2 Coherence

Two beams of light are coherent when the phase difference (temporal and spatial) between their waves is fixed (constant). Laser, because of stimulated emission phenomenon, produces a beam with fixed components (frequency, phase difference), so this means it is coherent source of light.

Coherence of laser light, when combined with a low order beam mode contains the ability to produce continuous, even few meters long waves. The comparison between beams of a non-coherent and coherent light source can be seen in the Figure 3. Basic, everyday light is not coherent, whereas laser light is. Often, in material processing there is no need of the coherency of the light, it still has not found its purpose there, but is used in other areas of laser application. However, the laser still produces coherent light as a result of stimulated emission phenomenon. [1]

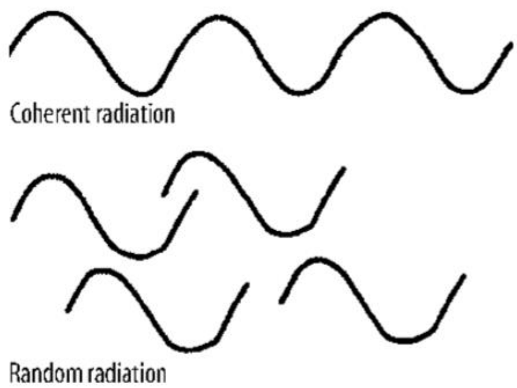

Figure 3 Non-coherent and coherent light

2.4.3 Mode

The mode property of laser is very important. It shows how well the laser beam can be focused to a spot. So, the lower the mode order, the easier it is to focus a laser beam. In the laser cavity, due to oscillation of the beam the interaction of the waves takes place and a transverse standing wave is created. However, not only one transverse standing wave is created, but more of them, running at angles slightly off the axis (defined by so-called Fresnel number). So, by laser beam emerging from the cavity, it creates a pattern withing its impact area (spot), which is called mode structure of the beam. Through that spot there is a distribution of the energy, the distribution of beams’ spatial intensity and amplitude. These mode structures are often generally divided into low-ordered or high-ordered, but they are also classified according to (TEM_{xyz}) classification (based on a number of radial - x, angular -y and longitudinal - z zero fields) – see its amplitude distribution in figure 4. and a its various patterns in figure 5. [1]

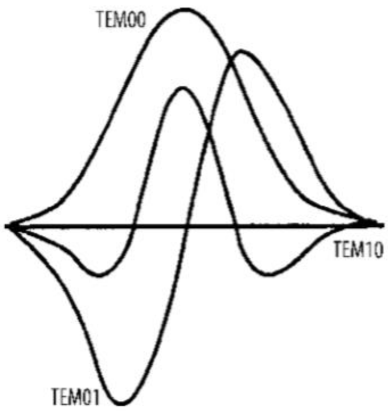

Figure 4 Amplitude variation for various modes [1]

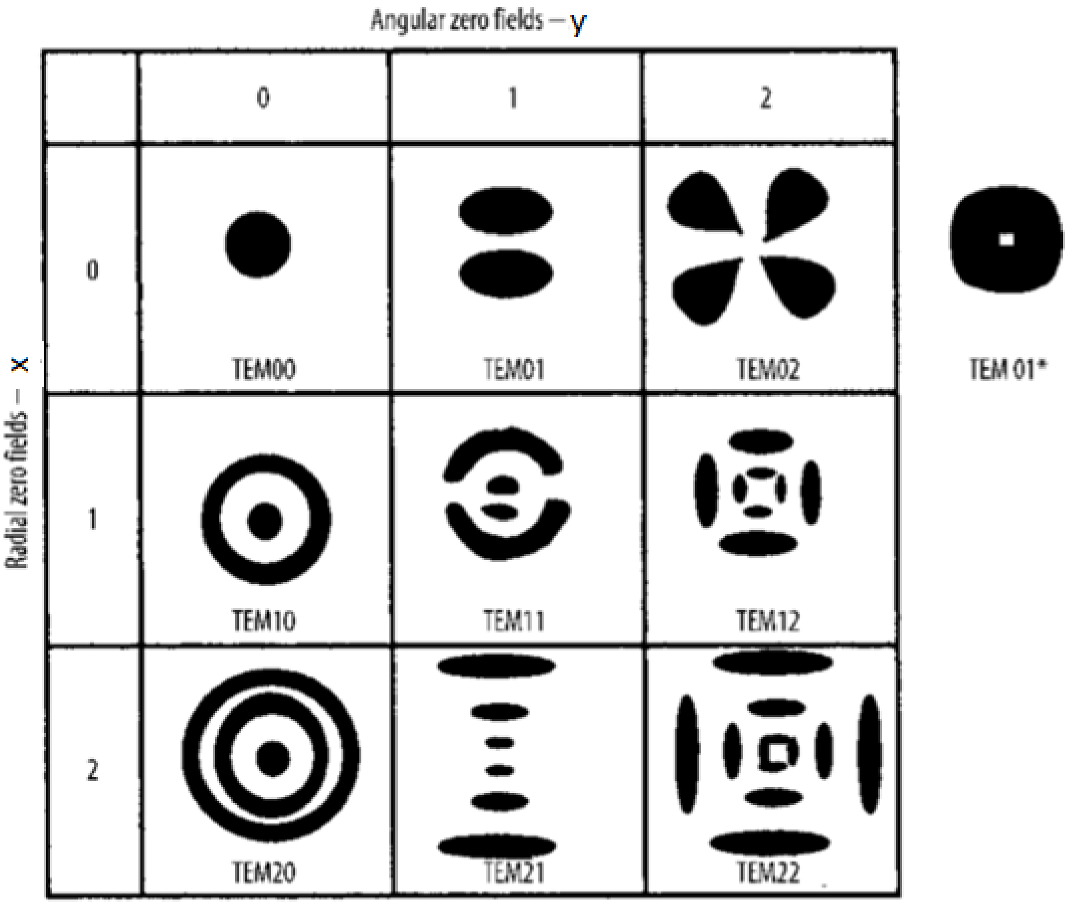

Figure 5 Various mode patterns [1]

Looking at these mode patterns of laser beams, it is hard to establish the beam diameter. And this exactly is a problem in material processing. The solution is often based on an agreement that a laser beam diameter is a distance within which exists the total power greater than $1/e^2$. [1]

2.4.4 Polarization

The electromagnetic radiation is a transverse wave, which means that electric and magnetic fields oscillate perpendicularly to the direction of travelling.

What does it have to do with polarization?

Basically, if those oscillations happen in a particular electric vector plane, not changing with time, it means that the light is polarized. If the electric vector plane (within which the light oscillates) is random, i.e. light is randomly changing its planes of oscillation, it means that the light is not polarized. Light can be linearly or circularly polarized. Linearly polarized means that the oscillation happens only in one electric plane. If, however, the field rotates (clockwise or counterclockwise), there are two vector directions and the polarization is circular (or could be elliptical). Polarization is important because it effects reflectivity and scattering of the light – for example, cutting the material with polarized and non-polarized laser light exhibits different cut qualities. Laser become polarized within the cavities using folding mirrors. Now as the light oscillates, nearly all its waves become completely polarized (it is never perfect). The representation of linear polarization of light is shown in figure 6. [1]

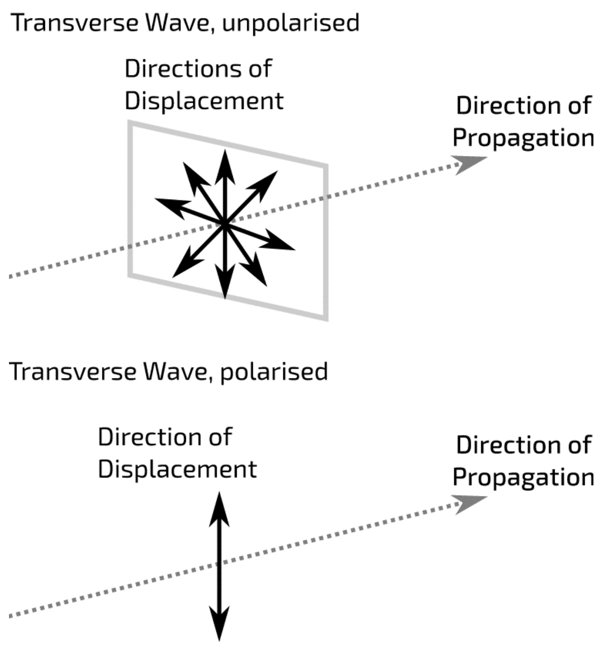

Figure 6 Linear polarization of light

2.5 Linear beam effects

2.5.1 Absorption and reflection

Absorption and reflection coefficients are correlated and dependent. It shows the percentage of light being reflected or absorbed.

For opaque materials the reflection coefficient is

Reflectivity = 1 – absorptivity

But for transparent materials, here comes transmittivity into play:

Reflectivity = 1 – absorptivity – transmissivity

There are many factors which impact the reflectivity of the light and here are mentioned some of them;

- wavelength
  - The shorter the wavelength of incident beam, the more likely is for a photon to be absorbed. This happens because the shorter the wavelengths are the greater number of electrons can absorb greater energy coming from those photons. This can be seen in figure 7. [1]

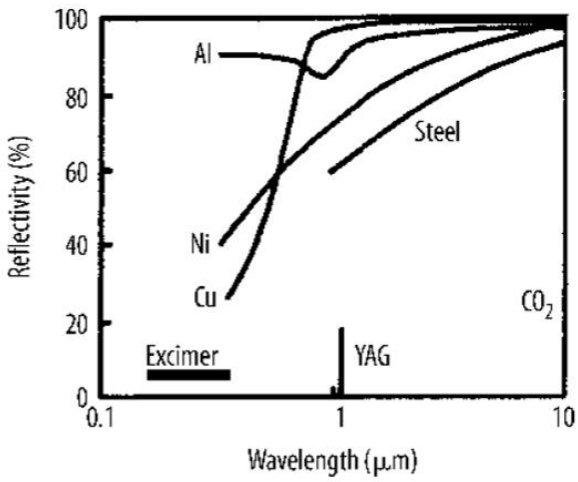

Figure 7 Reflectivity-wavelength dependence [1]

- temperature
  - As the temperature rises, the number of phonons also rises which are than impacted by the vibrating electrons, subsequently absorbing their energy. Shown in figure 8. [1]

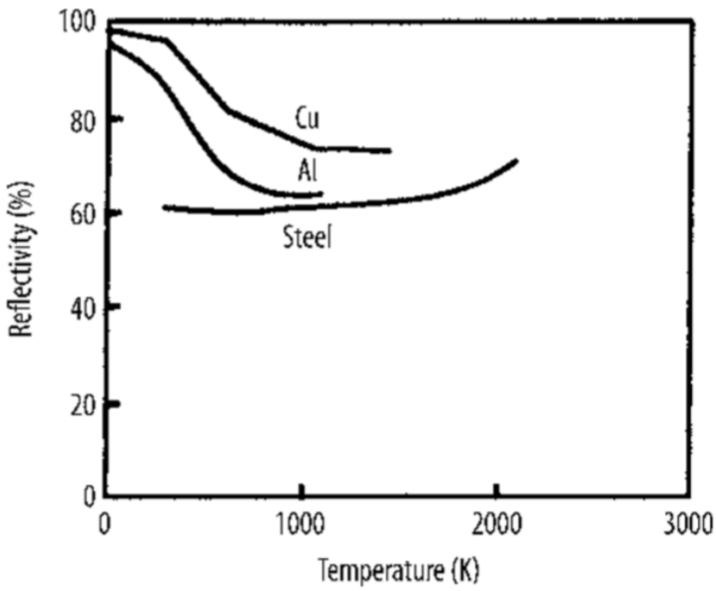

Figure 8 Reflectivity-temperature dependence of a 1,06 μm radiation [1]

- angle of incidence
  - This effect also depends on polarization planes. Based on that, there are two main groups of rays/beams: p-ray and s-ray. P-ray has its polarization plane

parallel to the plane of incidence, whereas s-ray has polarization plane perpendicular to the plane of incidence. Each ray acts in terms of reflection and absorption differently according to angle of incidence. It is shown in figure 9.

- This happens because at certain angles of incidence, the electron oscillation is more constrained – especially at higher angles of incidence with p-ray, so there occurs an increase in absorption.[1]

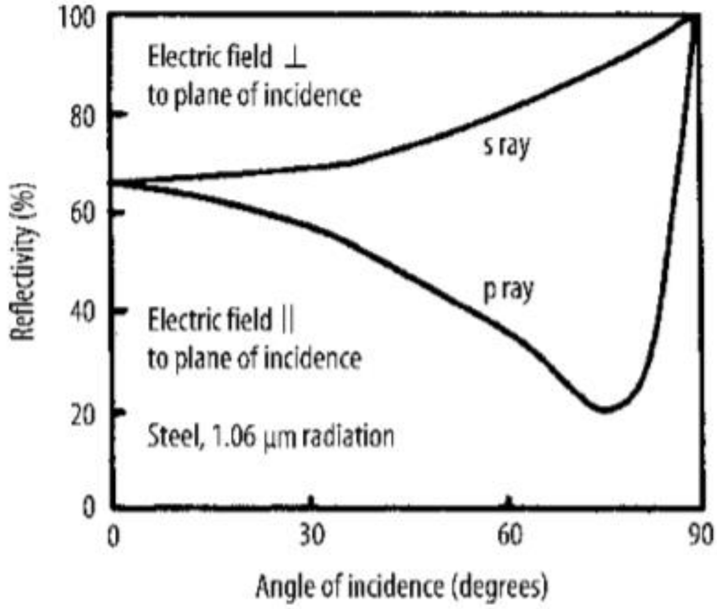

Figure 9 Reflectivity - angle of incidence dependence of a 1,06 μm radiation [1]

- surface films
  - surface films and its thickness have a great effect on reflection and absorption (see figure 10)

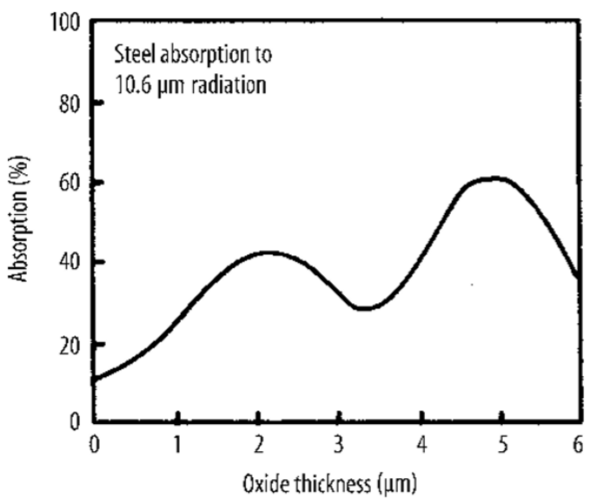

Figure 10 Absorption - oxide thickness dependence of a 10,6 μm radiation [1[

- surface roughness
  - changes in roughness can also cause great changes in reflectivity; e.g. point of incidence of He-Ne ray on the perfect mirror should not be seen because wavelength is lesser than roughness, and in that case, surface acts as being perfectly flat
  - if the roughness is greater than the wavelength, phenomena, such as “stimulated absorption” can occur due to interaction with asperities and also “diffuse reflection” which means spreading of incident beam in different directions [1]

2.5.2 Refraction

Refraction is phenomenon which occurs through the transmission of the light. It is first described by Willebrord Snell (1591–1626, Professor of Mathematics at Leiden University, Holland) by the Snell’s law:

$$\sin\Phi / \sin\Psi = n = v_1 / v_2$$

Where φ is incidence angle, ψ is angle of refraction, n is refractive index and v_1 is seeming speed of ray travel through medium 1 and v_2 for medium 2.

Having “two different velocities of light”, one could think, could it be that a light particle travels slower than with a speed of light? That was thought previously in wave theory, but the answer is actually no. Light beams always travel by the speed of light, but during refraction and transmission what happens is that light is being scattered by interfering with different molecules and atoms – e.g. re-radiation and absorption. The cause of different velocities of light in different media is the retardation of the phase of the light wave. That is why velocities are notated as “seeming velocities”. [1]

2.5.3 Scattering

Because of imperfections and inhomogeneities of the medium through which the light is travelling, so occurs the effect of scattering. Those inhomogeneities become a small re-radiating and absorbing centers of the light, resulting in light propagation which is no longer uniform, but in moves in various directions.

The scattering depends on the particle sizes and their number (density of the medium) as well as the wavelength of the light passing through.

Scattering is often divided into three major scattering types:

- Rayleigh scattering
    - for particles much smaller than a wavelength of the incident beam, the radiation centers are created within a number of materials' imperfections which than produce a spherical electromagnetic wave
    - the reason why the light appears blue
- Mie scattering
    - for particles sizes about the size of wavelength, especially relevant for material processing, within the interaction zone that produces boiling or ablation, e.g. laser welding, the air bubble is produced; an aerosol which than scatters the light beam
- Bulk scattering
    - for particle sizes larger than the wavelength, scattering is independent of the wavelength of the incident beam
    - the reason why the snow and fog appear white [1]

2.5.4 Diffraction

This light phenomenon occurs when the light ray strikes a sharp edge. What happens next is that it divides itself and is no longer a collimated stream. Divergence angle depends on the wavelength, the larger the wavelength the larger the divergence angle, i.e. spreading more.

After spreading, rays can have two types of fronts. The plane front and the curved front. Each can then be calculated accordingly to their equations (after Fresnel – curved front, or Fraunhofer – plane front). [1]

2.5.5 Interference

Adding and subtracting different waves is called interference.

The electromagnetic waves, which are energy disturbances traveling with a speed of light in a form of waves oscillating transversely to its direction, are called transverse waves.

By their interference, there occur tons of other forms of waves, for example in laser cavity, the interference of the same wave travelling in opposite directions creates a standing wave. [1]

2.6 Nonlinear effects

All of the mentioned effect above are a part of linear effects. Usually, the majority of the things we experience with light are linear light effects. However, in recent years scientists discovered that not all light effects happen in such, proportional, ways; and it opened a gate for a many new applications of the light. With non-linear effects, the incident beam changes its frequency within the process.

Basic example of non-linear effect is fluorescence. When a surface is hit by the light beam, to lose the excess energy it either absorbs it and turns it to heat, re-radiates it with the same frequency or fluorescence occurs; irradiated particles re-radiate at lower frequencies. Different materials re-radiate at different rates. Glowing hand watches are an example of “phosphorescence”, which re-radiate very slowly after being exposed to the light radiation which can then be perceived a glowing effect. [1]

Now, getting to know the physics and basic optic knowledge about the laser light and the light in general, it is time to see the real laser, their design, what powers them, how they work and their application in material processing.

2.7 Laser construction concepts and design

The basic laser consists of two parallel mirrors which are placed at some distance within the chamber, the optical oscillator of the laser. Also what is there is an active medium which amplifies the oscillating light by the stimulated emission phenomenon and the pumping source (usually RF od DC power input for gas laser such as CO_2 laser or other laser, such as semiconductor laser, diode laser, used as a power source for solid state laser; e.g. ND;YAG laser) which keeps the active medium “active”. If both of those two mirrors would be totally reflective, what would happen is that the light would oscillate within the cavity forever (if it wasn’t for absorption or other losses), therefore one mirror is semi-transparent, which enables for some of the amplified light to emerge from the cavity. Also, as a solution to alignment problem, the back, totally reflective mirror is usually bent. So, materials, shape, transparency of the mirrors are important (also folding mirrors), but what is also important is a cavity design (measurements, shape) and a cooling system. [1]

2.7.1 Cavity mirror design

The curvature of the mirrors, however, must be up to a certain value because it then becomes unstable and starts to lose a lot of its power around the edge of the mirror. Also based on the output power of the laser, there are two major mirror designs being used. For laser of a power up to 2kW, the “stable” cavity mirror design is used (figure 11 a). This means that the laser light converges inside the cavity and passes through the partially transparent output mirror (for CO_2 laser the reflectivity of the output window is 35%). Also, special materials, e.g. for CO_2 laser, such as zinc selenide (ZnSe) or gallium arsenide (GaAs) are used and are coated very precisely in order to achieve the desirable reflectivity. The “unstable” cavity mirror design (figure 11 b) is, on the other hand, used for laser of a power greater than 2kW, where the beam is being spread inside the cavity. The spread beam doesn’t pass through the partially transparent mirror, but the output part of the cavity consists of the totally reflective metallic optics surrounded and sealed by the window, so the beam than passes through that window and creates a ring-shaped beam. The reason why a high-power laser doesn’t have partially reflective window is because the risk of the breakage of the mirror. For CO_2 laser, it could cause implosion (the pressure inside its cavity is around 54 Torr) and for excimer laser it can cause explosion (pressure inside cavity is around 4 atm). Most common shapes of beams are round or ring shaped, but could also be square. [1]

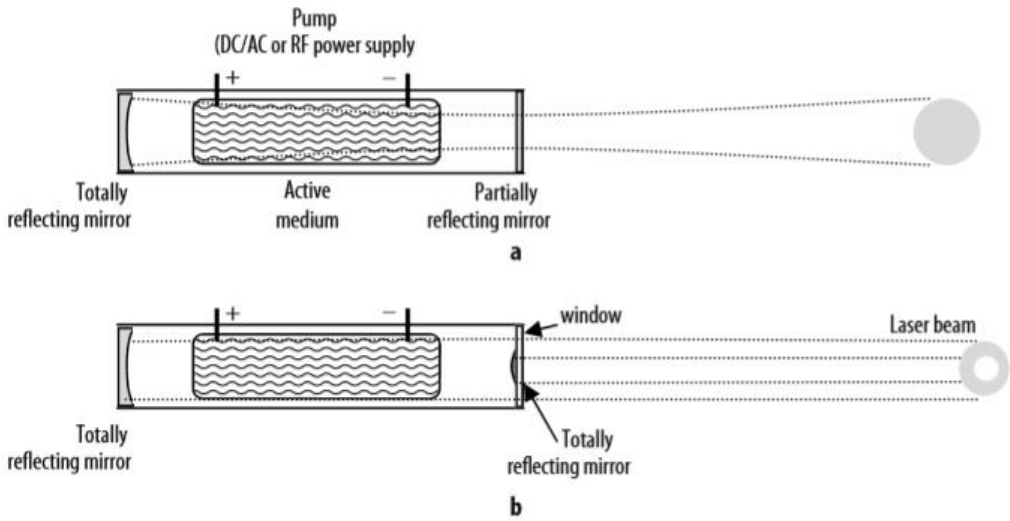

Figure 11 Stable (a) and unstable (b) mirror cavity design [1]

2.7.2 Cavity design – dimensions

The cavity dimensions are all about the Fresnel number, $N = a^2 / \lambda L$. The Fresnel number represents the mode order of the beam. A small Fresnel number indicates a low order beam, which is easy to focus to a spot. Fresnel number represents the ratio of the cavity length (L), aperture radius (a) and the integer number of the half wavelengths of the beam. The greater the length of the cavity and smaller the aperture radius, the lower the Fresnel number. The Fresnel number can also be seen on the output screen as the number of "fringes"; the bright spots occurring due to the constructive interference of the of axis standing waves. Fresnel number can be controlled either by modifying the mirror curvature (the flatter, the smaller Fresnel number), or by inserting apertures into the cavity, but on the cost of some power loss.[1]

2.7.3 Cooling system

The cooling system impacts the design of the laser in a big way. The output power is constrained by the ability of the laser to be cooled. The unwanted heat is generated as a lot of the pumping source power doesn't get used, so it builds up. The laser must not exceed the critical temperature (depends upon the type of laser), because than the lasing action wouldn't occur (the excited species' energy can't be lowered fast enough to the ground state – see Figure 12) and it wouldn't be able to operate - There are two major types of cooling; the convective and conductive cooling. Below can be seen division of some of the laser based on cooling systems.

- Gas laser:
  - slow flow laser – conductive cooling
  - fast axial flow laser and transverse flow laser – convective cooling
- Solid state laser
  - conduction cooling by active media supports such as rods, fibers or discs

Different cooling methods exhibit different properties; e.g. slow flow laser with the conductive cooling don't give much power per unit length, but because it only depends on the length the laser cavities are made long so it gains power that way and with that comes a low Fresnel number and therefore makes their beam easily focused. This property is often used for material cutting.

Fast axial-flow laser have a better cooling efficiency and exhibit around 10 times better power per unit length than slow flow laser, but the Fresnel number is not as good as with the slow flow laser.

Transverse flow is very efficient cooling method and exhibits a great power and low Fresnel number, but the ray is not symmetric due to the cooling design and this could cause problems. [1]

2.8 Basic types of laser

The basic classification of the laser is based on the active media present. More roughly, the aggregate state of it. So, the laser is divided into gas, liquid (dye) and solid-state laser, and last, but not least, free electron laser. The most commercially used laser types based on that division are:

- Gas laser: CO_2 laser, CO laser, excimer laser
- Solid-state laser: Nd;YAG, Nd;Glass, diode/semiconductor laser (disc, fiber)
- Dye laser
- Free electron laser

In material processing, gas, Nd;YAG and fiber laser types are the most commonly used.[1]

Now, here will be briefly described most common laser types used nowadays.

2.8.1 CO_2 laser

This type of laser is very commercially dispersed and used in many applications.

As with every laser, the basis of it is stimulated emission phenomenon. Now, it shall be seen how this works with CO_2 laser.

The CO_2 can be only in several energy states, called quantized states, meaning it cannot appear somewhere in between, it either is in that state, or in another.

So, there are several major states in which CO_2 can appear. Firstly, it appears because of an electric discharge from the pumping source which makes a low-pressure plasma out of CO_2 gas with its molecules in various states. The asymmetric oscillating excited state which is suitable for spontaneous and stimulated emission and is labeled as 001 state. The symmetric oscillating state is called 100 state. There is also a bending state called 010 state. They can also have several quanta (more energy to it) in each state, e.g. for bending state with two quanta it would then be a double bending state, 020, and for asymmetric oscillating state (001) with a rotational spin it would be $00^{1}1$.

Being said that, while molecule being in 001 state it can lose its energy with spontaneously emitting the photon, by a chance, in the optical oscillator axial direction which can then cause a chain reaction of stimulated emission process. But there are several transitions of quanta states which can then emit different wavelengths. Most frequently there is transition between the 001 to 100 state which produces the wavelength of 10.6μm. The second most frequent is transition from 001 to 020 which then produces a photon of 9.6μm wavelength. This waveband can be anywhere between 9 and 11μm of radiation. Here, the selective frequency mechanism can be used to select the wanted wavelengths.

But this would be possible only if there is a population inversion; which means that there are more molecules in excited state than in lower states in order to achieve stimulated emission rather than absorption. The condition for this is, in comparison to the rate of stimulated emission process, to have a faster rate of “clearing” the lower energy states (by further losing its energy) to the lowest of them all, the ground state (from where it can be discharged again and made excited. This is very nicely shown in Figure 12.

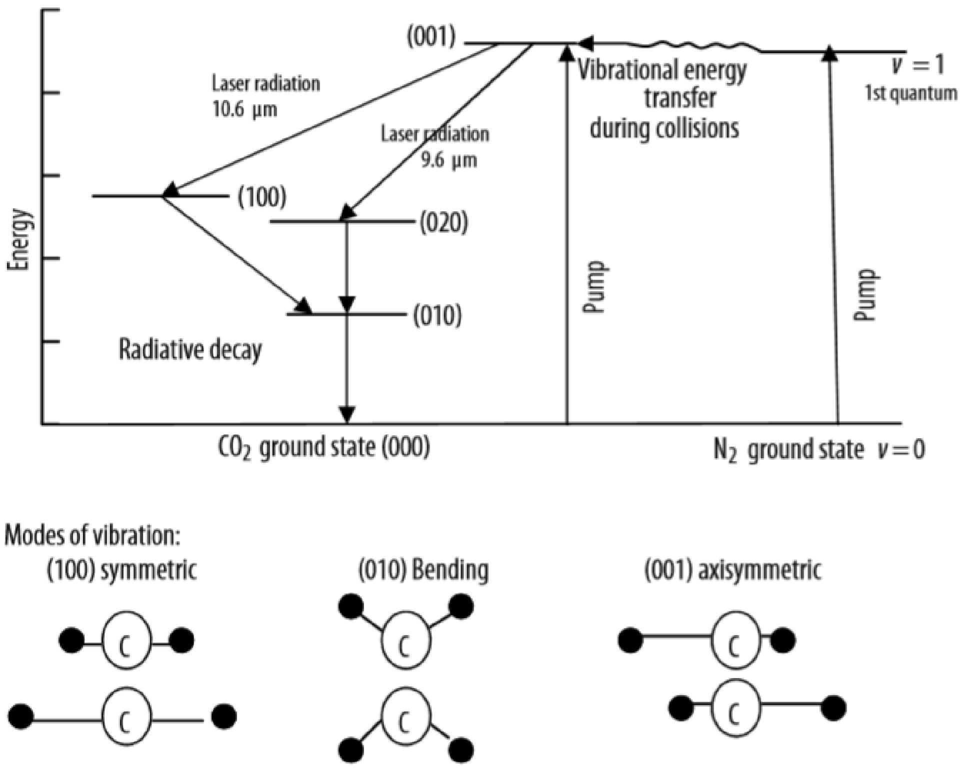

Figure 12 CO_2 laser stimulated emission process [1]

What is also shown in Figure 12 is the presence of nitrogen. Because of very specific coupling effect with CO_2, by stimulating nitrogen it can make CO_2 laser excited even when cold. This rises its efficiency by a big degree and that is what makes CO_2 laser so commercially available and good to use. But it can only be made when the CO_2 is in cold state so the cooling system is very important for CO_2 laser. [1]

2.8.2 CO laser

Very similar to the CO_2 laser, but the difference is with the wavelengths it produces, with its efficiency which is much better than with the CO_2 laser, but the big downfall for it is that it is severally reduced by the cooling requirements; it needs to be cooled at around 150K, so that energy is lost to the cooling requirements (the wall plug efficiency then falls form 19% down to 8%). Laser types and their energy efficiencies can be seen in table 2. [1]

Table 2 Efficiencies of different laser [1]

Type	Wavelength (μm)	Quantum efficiency (%)	Wall plug efficiency (%)
CO_2	10.6	45	12
CO	5.4	100	19
Nd:YAG	1.06	40	4
Nd:glass	1.06	40	2
Diode-pumped YAG	1.06	40	8–12
Diode GaAs	0.75–0.87	≈ 80	50
Diode GaP	0.54	≈ 80	50
Excimer KrF	0.248	≈ 80	0.5–2

2.8.3 Excimer laser

These types of laser produce high power, short pulses of beams within the UV specter wavelength. Its lasing species, the excited dimer molecules (complex molecules) is what the name is derived from. The energy of their photons (gain) is so strong that it doesn't need an optical oscillator. The gas mixture used consist of noble gas halides (table 3 shows which ones produce which wavelength**)**. The flaws of excimer laser are that the mode order is very high, so it can't be focused easily and the additional optical components are required. Also, the maintenance, equipment and running costs are high.

Table 3 Different gas mixtures (noble gas halides) used in excimer laser [1]

Gas mixture	Wavelength (nm)
F_2	158
ArF	193
KrCl	222
KrF	248
XeCl	308
XeF	354

2.8.4 Solid state laser

The active medium of solid-state laser is in form of insulating crystal or amorphous glass. The most common types are Nd;YAG (Neodymium–doped Yttrium Aluminium Garnet Laser), Nd-Glass. Basically, with the solid-state laser, there is a dopant (usually some rear earth element - e.g. Nd) which combines with the host (e.g. YAG or glass). Instead of Nd could also be used other elements, such as ytterbium (Yb) as an active medium and likewise the different host materials, for instance, yttrium lithium fluoride (YLF). The dopant combines with the host by host being pumped (discharged), most commonly by flash lamps or diode laser. The host exists usually in form of rods, but can also be in forms of disks and fibers, which can improve some of its properties.

The main advantage of solid-state laser over gas laser is that the excited state exists much longer. This characteristic can then be exploited by using a Q-switch. Q- switch (quality switch) is a mechanical device (for example mechanical choppers, optoelectric shutter or acousto-optic switch) which can, for a short time, prevent the lasing process and cause the accumulation of a certain amount of energy and then release it in forms of short, powerful pulses.

Pumping source heating is what causes problems with solid state laser. Originally used flash lamps emit a wide frequency specter from what only a small portion can be used and absorbed by the host. This goes to extent at around 2%. As could be assumed, this causes a lot of heat generation and with it a lot of problems, like distortion of elements (such as optics), non-uniformity of output power (varies 10-15% from pulse to pulse), potential breakage of the host (rod) etc. This requires a strong cooling, not only for the reason to not reach the limiting temperature, but also because of the need of the active medium to reach the ground state after lasing occurs, in order to be excited again. But most of those problems are generally solved using diode laser which emits only a specific wavelength that is suitable for absorption of it. Therefore, the efficiency highly increases, the cooling considerations are greatly lowered. The only problem of using diode laser as a pumping source is its price, but as it is becoming more commercially spread, it is dropping.

Also, there is one more capability of these kinds of laser. And that is the “frequency doubling” phenomenon. Basically, the wavelength is halved and the photon energy is doubled by letting the laser light pass through a certain nonlinear optical device (aligned crystals). If the wavelength emitted is 1,06μm, then by doubling the frequency, the laser emits green light, but after one more doubling effect it emits UV light which has a great per photon energy. This property makes a diode pumped solid-state laser a great competition for excimer laser in terms of UV light projecting laser. [1]

Regarding Nd;Glass laser, the difference between using the glass and crystal host is that a glass is being more energy efficient, but the downside is that it is bad conductively, so it needs better cooling of it.

Special mention deserve fiber diode pumped Yb:YAG laser which are often used in material processing because of its beam quality (great mode order), high power and long lasting of laser.[1]

2.8.5 Semiconductor laser

Semiconductor laser is another name for diode laser. They are the most commonly used types of laser in material processing, as a source of its own for material heating and welding, and as the pumping source. They have incredible capabilities; for a very compact design they can produce lots of power and are the most efficient laser available. Semiconductor laser have a wall plug efficiency up to 50%!

The most common materials used for diode laser are GaAs, GaAlAs and InGaAs. GaAs and GaAlAs produce light in specter from 750-850 nm and InGaAs from 900-1000nm. As the range is pretty wide, grating, as one of the cavity mirrors is used as the frequency selecting mechanism.

The problem is, however, with the increase of power there comes a greater light divergence, where the output light becomes more similar to a light from a torch than from a laser. Still, there are many mechanisms which can improve this, such as using master oscillator–power amplifier or feeding multiple beams into a fiber delivery system.

The majority of the diode laser application goes to the LED (light-emitting diode), as well as low-power diode laser applications such as bar code readers, CD and DVD players, lecturers' pointers…

In material processing, diode laser is mainly used as a pumping source for other solid-state laser, but there is a promising place for diode laser used for welding, soldering cutting, annealing, etc. [1]

2.8.6 Dye laser

Dye laser has a very low efficiency; however, it is one of the most quickly tunable laser in industry and that is the reason why it is used. Also, dye laser can produce beams with continuous wavelength to very short pulses (femtoseconds). The desired frequency can be selected by making different modifications of dye – changing its concentration and pressure and modifying cavity.[1]

2.8.7 Free-electron laser

This laser works differently than all the previous mentioned laser types. They do not emit photons which depend on excited states. The photons in free electron laser are emitted as a result of electrons, which are traveling in a ring-shaped circuit, changing its direction by the impact of the magnetic field. This type of radiation is called synchrotron radiation. The magnetic field is also called magnetic wiggler because it causes electrons to wiggle as a result of being short-wavelength magnetic field. Owing to the different velocities of the electrons throughout the circuit, this laser produces a wide waveband of light, thus it is also called "rainbow" laser. [1]

3. Laser surface treatment

Laser surface treatment is a main field in laser material processing. This is because laser characteristics are such that only a small area is treated with relatively high-power density and therefore reaching only surface levels. If wanting to reach deeper levels, the laser power should be much lesser in order to equally treat surface and layers underneath. This, however, enables to have different properties of the bulk material (which can therefore be tough and even cheap), compared with the high strength, fatigue, corrosion and wear resistant surface layers. Also, not even all surface area must be modified/coated with laser, but it offers to just treat a particular surface which needs enhanced properties. Most commonly used laser in surface treatment are CO_2, excimer and fiber laser. [2][1]

Why are laser being used for surface treatment?

Here are some advantages in using laser as a tool for material processing.

- small energy input, clean process -no chemicals, no gas jets, no spillage of the energy, small heat affected zone, small base material distortions due to small heat input
- reliable (quality, long lasting equipment), flexible (many processes which are listed below and many materials can be treated), precisely controlled process
- automation of processes

But there are plenty of disadvantages which makes laser not suitable for most applications.

- non equal laser beam intensity distribution
- poor absorptivity for some materials, needed use of extra absorptivity coatings
- not suitable for treating large areas or slower heat input required processes
- very sensitive to change of parameters (can easily go from heating into melting if not well calculated)

As for any other process, there are certain parameters which are very important. For laser surface treatment they can be divided into 2 categories;

Laser beam parameters

- laser output power
- laser intensity (power density) distribution within the beam
- beam geometry (size and pattern)

- wavelength
- dwelling time (interaction time) – travelling speed

Treated material parameters

- thermal conductivity, specific heat coefficient
- microstructure
- phase transformation properties (latent heat amount, critical temperatures)
- material density
- absorptivity

These parameters can all be finely tuned in order to achieve desired results with treated materials. Laser is being computer controlled, handled and automated –this all depends on the precision required, weight of the equipment etc. Beam is controlled and directed via optical transmission systems, such as mirrors or fiber systems and beam shaping optics. For all these processes, shielding/active gases or vacuum during radiation process are usually applied in order to obtain desired results. [2]

The surface treatment, based on the power input and the result of it, can be divided into three major groups:

- surface heating
- surface melting
- shock hardening

Also, it can be further divided, as can be seen in Figure 13. [2]

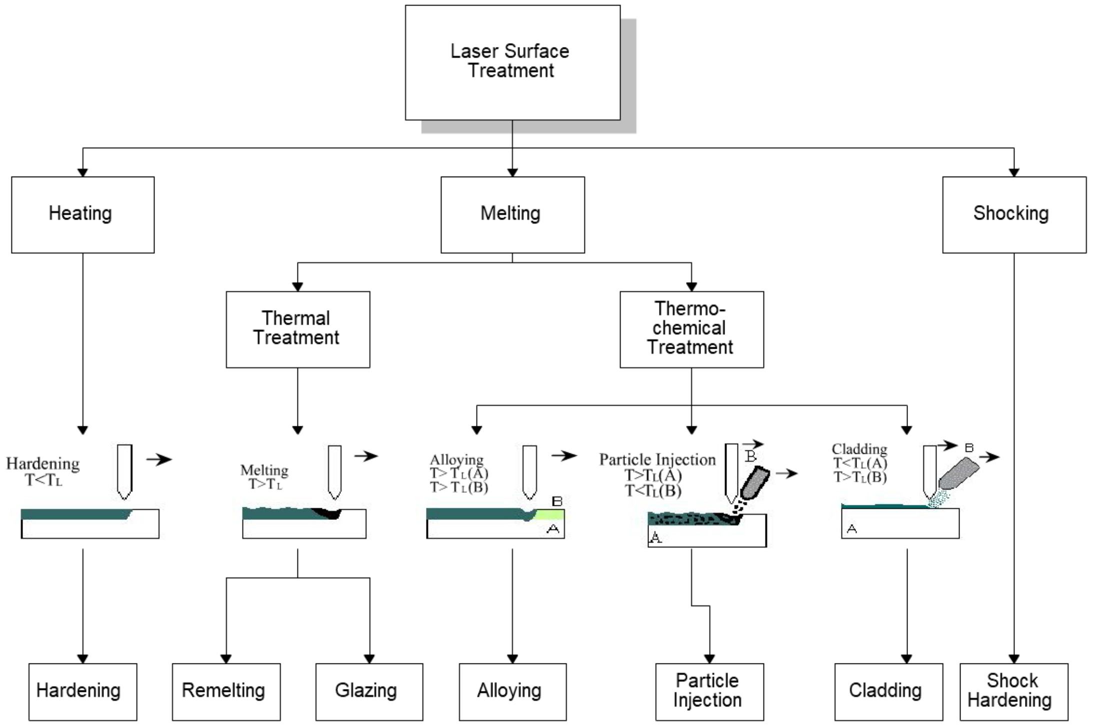

Figure 13 Division of the laser surface treatment processes [2]

Each of them has a several processes which are often used in today's industry.

3.1 Laser surface heating processes

The main process involved with laser heating of the surface is transformation hardening. The important note here is that melting of material never occurs. Therefore, there is only a very short interaction time of laser beam and treated surface. What happens is the transition between the transformation phases – heating of the material (most often steel) to the austenitic temperature and then letting it cool down on its own. Due to the high cooling rates of the surface layers, i.e. very fast conduction cooling (heat drains fast down through the cold base material), there comes the process of self-quenching and hard and strong martensitic microstructure is obtained.

In comparison to the similar surface heat-treating processes, one can see the power density difference between laser heating processes and other heating processes in table 4. Seeing that, laser surface heating differs from the other methods in that it only affects very shallow surface layers. Still, this technology has not reached a breakthrough due to the high costs.

Table 4 Different heating methods' power densities [2]

Heating method	Power density W/cm^2
Convection	0.5
Radiation	10
Conduction	20
Flame	1000
Induction	15000
Laser	10^3-10^7

It is also possible to anneal the material, but it is used very rarely due to the nature of the laser; which is very fast heating and high cooling rates, affecting small areas, which is not suitable for annealing the material. [2]

3.2 Surface melting

3.2.1 Laser surface remelting

This process is usually used for improvement of microstructure by making the grains much smaller, increasing hardness, wear and corrosion resistance of the treated surface area. This is achieved by the rapid solidification process. Things like phase nonequilibrium can also have a positive impact on the surface mechanical properties. Also, this process is used for refinement of any micro and macrostructural defects on the surface. The inevitable problem, however, lays within the residual stresses after the fast cooling of the substrate which can cause plastic defects or lower strength of surface layer.

Yet, it used for improvement (very often just particular areas of components) of the materials such as cast iron, tool steels, aluminum alloys, titanium alloys and stainless steel or even to improve properties of already coated materials (obtained with e.g. electrochemical process), such as their adhesion or homogeneity.[2]

3.2.2 Cladding

This process is not about the surface modification, as opposed to the other mentioned in this chapter, but a coating process. This means that it involves minimal interaction of the added layer with the substrate, therefore not impacting the properties of both of them. Especially laser coating process involves much less coating-substrate interaction compared to the other techniques and that is possible because of tuning of the laser parameters, such as beam power, angle of incidence, beam size, time of interaction and the characteristics of the added material, for instance powder grain size and its feed rate. It is extremely used process for this purpose.

The mentioned cladding material, can be added in two ways; simultaneously with the irradiation process or separately (preplacing of the added material).

If the cladding material is added simultaneously with the irradiation process, it is called one-step cladding (cladding material fed in forms of powder, wire). For the other method, its name is two step-cladding (cladding material in form of powder sheet, but can also be coated with other coating processes, like electroplating). [3]

The main advantages of laser cladding are cladding of the complex parts and specified areas, small distortion of the material due to low heat input, large extent of the materials which can be cladded forming a strong bond and minimal dilution i.e. interaction of substrate and coating. The downsize, again, is the price of the process, built up by the price of extra material which can sometimes be hard to produce in the desired form. [2]

3.2.3 Glazing

Using the property of high cooling rates after laser melting of the surface, the normal nucleation and crystallization is prevented, thus creating an amorphous (glass) surface layer. Representative parameters for this process are; power densities reach 10^5 to 10^7 W/ cm^2 with interaction time of 10^{-4} to 10^{-7} seconds. [2]

3.2.4 Particle injection

This process involves melting of the material with laser irradiation and then injecting the particles to the melted pool to combine with the base material. The protection with He is often used to protect the melted material from oxidation, and the added particles are usually of metallic-ceramic character. [2]

3.2.5 Alloying

Very similar to the cladding, laser alloying can also be separated into two groups; one-step and two-step alloying. The principle stays the same. The difference, however, is that this process involves modification of the surface, where cladding is only coating process.[2]

3.3 Shock hardening

For these processes, high power intensities are required which are obtained by using the very short laser pulses as opposed to continuous beam used in previous processes. Those pulses, whose length can vary from pico seconds to a few hundred nano seconds have power densities (power per unit area) reach 10^8 to 10^9 W/cm^2. This induces high stresses, a shock, which causes plastic deformations which then improves physical and mechanical properties of the material (dislocations of the material build up and any movement inside the material is severally constrained). The result could be compared with the shot peening process.

Also, with even higher power densities and shorter pulses, the cleaning process is possible - the removal of the layers by the vaporization of the surface layers.

Beside all this processes, there are many others yet to be mentioned, like surface texturing, LCVD or LPVD (laser chemical/physical deposition), laser marking, laser micromachining etc. [2]

4. Experiment

In this part, the focus will be on the cladding process as very common technique of the laser surface treatment. The goal of it, as of any other laser surface treatment technology, is to increase overall properties of the surface level layers, while keeping the properties of the bulk material in deeper layers. This enables a great combination of two different, often irreconcilable properties to blend together, as well as great savings in material costs. However, as this is the deposition process, its goal is to have minimal dilution levels with the substrate in order to retain their individual properties. Hardness, dilution levels, porosity, microstructure of the cladded material are all very important measurable characteristics which can determine the efficiency of this technique and show advantages over several other competitive processes in this field, if there are any. Having said that, here will be discussed those important properties and common cladding materials and material pairings, later some experimental examples of cladding processes will be shown and a base for the future experiment will be made. Beside that, at the end will be described tests which can be conducted in order to see the efficiency of the cladding process.

4.1 Dilution

The important aspect of cladding is level of dilution. With laser cladding, level of dilution from the substrate to the alloy is minimal and much better in comparison with using e.g. TIG for cladding. Dilution level depends on many factors such as: the initial substrate temperature, reflectivity of the material (needs to be checked for different wavelengths; for example, CO_2 laser emit 10,6 μm light wavelength), thermal conductivity, size of the component (heat sensitivity), laser power, beam interaction time, powder flow rate. Despite the low dilution levels, sound fusion bonds between those two layers can be achieved, but this depends on the power of the laser. For low powers, no fusion and no bonding between substrate and cladding material occurs, for high powers, on the other hand, melting is highly increased so is dilution. The main principle is to find an optimal power input. With that optimal power level, only the small, superficial melting of the substrate occurs, thus creating sound fusion and good adherence, while keeping dilution on very low levels. Sometimes, in the process the temperature of the melt pool rises so the power of the laser needs to be lowered for it to be kept roughly constant. Preheating the substrate is also a possibility, in order to lower the subsequent residual stresses. [4]

The dilution level is often checked by examining the cross-section of the cladded material. In microstructure assessment, porosity, as one of the most deteriorating issues, can easily be spotted. Due to the low heat input of the laser, very low distortion levels and small heat affected zone (HAZ) occur. This can be usually seen by etching the sectioned surface and noticing the discoloring. With higher distortion and dilution levels, the clad properties become deteriorated. [4]

4.2 Hardness

In most cases, increase in hardness also means increase in wear resistance. This connection makes wear resistance roughly easy to estimate, as hardness tests are generally easy to conduct. However, as the hardness and wear resistance increase, fatigue resistance, corrosion resistance and toughness rapidly decrease. Because of irreconcilability of these properties, one often has to look for the optimal in-between solution. On the other hand, by modifying surface levels of material by either only modifying microstructure or both microstructure and chemical composition (cladding), this problem can be partially avoided. Generally, hardness is counter proportional to the level of dilution. What that means is with lower level of dilution, the hardness becomes greater. This is one of the reasons for dilution to be as minimal as possible. [4]

Normally, while conducting hardness tests for examining the laser cladding materials, hardness is measured on the surface levels as well as transversely – on the different levels of materials depth. Also, what often needs to be noticed is uniformity of the results along and within the material. The more uniform the surface hardness, the better. If, however, there are great differences between the hardness test results it can mean local change in microstructure and therefore possible distortions and residual stresses, because of higher heat input and/or higher cooling rates. As an example of this, the melt-pool region records increase in hardness because of great convection currents leading to faster cooling. In the example given in [4], laser cladding, in comparison with the TIG welding, gives more consistent results along the surface. However, looking transversely through a dilution zone, because it is thinner, the differences are more abrupt than with the TIG welding.

4.3 Selection of the clad material

There are many tests that needs to be done in order to get more familiar with laser cladding and its benefits and to dissolve some of the existing problems. One of those problems of laser cladding, despite being superior to other surface modification treatments in some applications, are cracks, pores and other defects and large residual stresses. This happens due to high heating and cooling rates. In order to partially avoid these problems, the proper, compatible materials and proper process parameters should be employed. [5]

That being said, the material compatibility in choosing the cladding materials is one of the most important steps in defining the laser cladding process. Here can be distinguished two types of compatibilities; mechanical compatibility and compatibility of crystal structure and chemical properties. Important mechanical material properties are melting point of the material (Tm), coefficient of thermal expansion (γ) and modulus of elasticity (E). The more similar of those three properties between the substrate and clad, the better. If, however, there are great differences in those properties, it can cause problems like high residual stresses, cracking, peeling off of the clad etc. Matching of the crystal structure and chemical properties is closely related to the important principle of the cladding; wettability. Wettability shows the level of the tendency of the fluids to stick to the surface and it can be determined by looking at the surface structure. If the wettability is better, the metallurgical bonding is better as well. An example of this is; if the surface tension of the coating is lower than of the critical surface tension of the substrate, then the wettability is sufficient. One of the examples of coating materials with low surface tension are Co and Ni (with low melting point) and Ti and Al (as reactive metals). Relevant alloys of this materials are also employed. [6]

4.4 Experiment example 1

Some important points described in this chapter relevant for the possible future experiment are deducted from [4].

In today's industries, laser cladding is mostly used for hard facing high demanding components or repairing them. The typical instance of this is repairing of the turbine blades in aerospace industry, as well as in other aspects of power generation industries (casings, compressor blades…). [4]

4.4.1 One step cladding process

The deposition of the cladded material can be achieved in two ways; as a one step process or two step process. In the two-step process, the cladding material is preplaced onto the substrate in form of powder sheet or bed, plasma sprayed or electroplated. The more frequently employed is a one-step process, where the cladding material is added simultaneously with laser irradiation to the molten pool in the form of powder or a wire. [4] Powder is more often used due to its better flexibility regarding its chemical composition as well as accessibility. [5]

With that being said, one-step powder feeding laser cladding will be in focus.

The schematic representation of (one step) laser cladding process is shown in the figure 14.

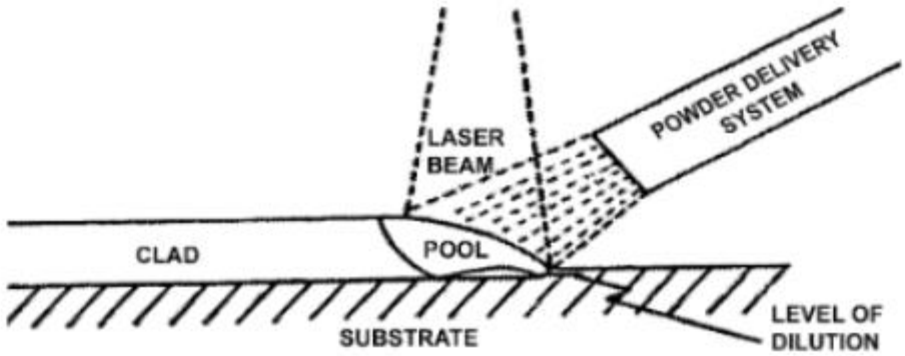

Figure 14 Laser cladding process [4]

4.4.2 Powder delivery system

Laser beam is modified and focused at the substrate using some form of beam manipulation and precision delivery system, creating a molten pool, where independently with the powder delivery system, powder is being fed into the molten pool and therefore also being melted and fused with the substrate. Very important is to say that powder is not fed on its own, but with an inert gas. It is done so that the molten pool does not interact undesirably with the gases (primarily oxygen) from the surrounding atmosphere and the second purpose is to carry the powder to the desired spot. It also makes powder more homogenous by improving its uniform flow. Typically, this protective gas, called also carrier or shroud gas, is Ar. The powder delivery system contains powder nozzle where Ar and powder combine. Sometimes, the hopper that contains powder is heated to prevent moisture in the powder. Delivery of the powder from the hopper to the nozzle is also regulated by the so-called hopper gas flow. Moreover, important parameter regarding powder is the size of the powder particles. Aside from Ar being incorporated with the powder delivery system, it also shrouds the laser beam itself so there is another gas flow, called axial gas flow, thus protecting the irradiated area additionally. The laser beam and powder delivery system are moving simultaneously based on given working parameters, such as laser velocity i.e. travelling speed by using control and instrumentation system. [4]

Also, a few things to have in mind before jumping into experiments are the following issues of laser cladding;

- laser beam, as it strikes surface becomes out of focus - meaning the quality of the laser beam or its mode order becomes relatively irrelevant
- the powder delivery system has a big impact on the results – making it almost the “heart” of the process – controls the form of the molten pool and impacts level of dilution

4.4.3 Process parameters and materials

Typical process basics used for laser cladding are shown in the table 5.

Table 5 Cladding process basic values [3]

Typical laser power	1 – 6 kW
Typical build up rate	0.1 to 12 kg
Typical coating thickness	0.2 to 4 mm (or more)
Coating materials	Weldable powders (metals, metallic alloys, carbide blends)

Also, here in the table 6. are some of the material combinations used in aerospace industry for turbine blades and their chemical composition in table 7.

Table 6 Material pairings of hard-faced turbine blades [4]

Sample No.	Substrate materials	Powder materials
1	C1023	Inconel 625
2	Inconel 792	Inconel 625
3	Rene 80	Inconel 625
4	Rene 125	Inconel 625
5	DS Rene 142	Inconel 625
6	C1023	Rene 142
7	Inconel 792	Rene 142
8	Rene 80	Rene 142
9	Rene 125	Rene 142
10	DS Rene 142	Rene 142

Table 7 Chemical composition of substrate material and alloy powders [4]

Typical composition (wt.%)	Ni	Cr	Co	Mo	Nb	Fe	C	Mn	Ti	Al	B	Zr	Hf	Si	Ta
Inconel 625, repair material	65	20–23	1 (max.)	8–10	3.1–4.1	5 (max.)	0.1 (max.)	0.5 (max.)	0.43	0.09					
DS Rene 142, repair and substrate material	60.4	13.96	9.5	3.8	0.03	0.01	0.17	0.01	5	3	0.02	0.06	0.01	0.01	0.01
DS Rene 80, repair and substrate material	59.7	14	9.5	4		0.2	0.17	0.2	5	3	0.015	0.03		0.2	
Rene 125, substrate material	58.8	9	10	2		0.32	0.1		2.8	4.8	0.015	0.05	1.6		3.8
Inconel 713, substrate material	72	13.5		4.5	2.1		0.14		0.9	6	0.01	0.08			
Inconel 738, substrate material	61.5	16	8.5	1.75					3.4	3.4					
Inconel 792, substrate material	60.9	12.2	9	1.9			0.12		4.1	3.5	0.015	0.1	0.5		3.9
C1023, substrate material	54.9	14.5–16.5	9–10.5	7.6–9	0.25	0.5	0.12–0.18	0.2	3.8	3.9–4.4				0.2	

Example of the experiment done in [4] contains parameters shown in table 8 and 9.

Table 8 Laser parameters used in [4] for cladding Rene 142 onto Inconel 713 [4]

Laser	Rofin Sinar 1 kW slab CO2 laser
Power used	550 W
Distance from nozzle to top of the clad	4 mm
Powder particle size	< 150 µm, spherical in nature
Powder hopper temperature	55°C

Table 9 Powder feed rate and different gas flow of laser cladding of Inconel 713 turbine blades [4]

Alloy powder material	Rene 142	Inconel 625
Powder feed rate	4,2 g/s	3,8 g/s
Hopper gas flow	3,6 l/min	3,6 l/min
Shroud gas flow	7,0 l/min	7,0 l/min
Axial gas flow	2,5 l/min	2,5 l/min

Experiment described in [4] with these parameters is done primarily to compare results from TIG and laser cladding, but here it is used as an example of which parameters are employed. In experiment of this thesis, materials used in [4] will be taken over and examined on the grooved parts, described in experiment example 2.

4.5 Experiment example 2

This example is described according to [5]. Later, more of its information and results will be employed throughout description of the possible future experiment.

Sometimes, in repairing the defect components, milling has to be done first. Therefore, milling grooves are made and according to [5], those are usually 3 different groove types, with dimensions shown in figure 15. [5]

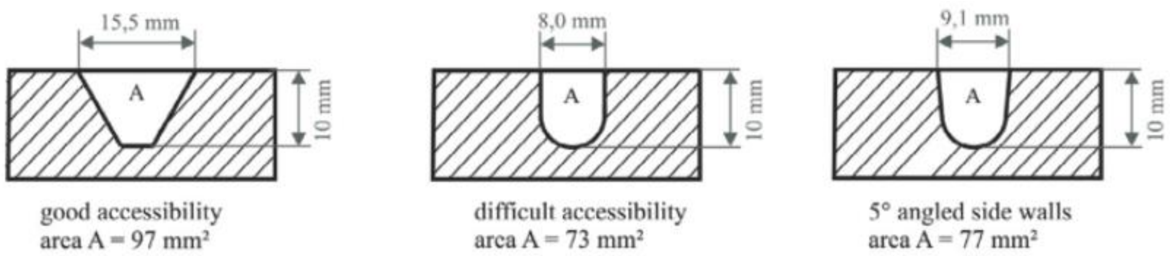

Figure 15 3 common groove types, a) V-groove, b) U-groove and c) U-groove with slightly angled side walls [5]

It was assumed that the defects on parts that need to be repaired do not exceed depth over 10 mm, therefore 10 mm groove depth was chosen to be tested. [5]

In order to correctly start an experiment, the specimen preparation is important. It is important to use some technology of surface cleaning, like the acetone for cleaning the milled grooves (or additionally sand paper for polishing the surface) as in [5].

As an example of this, the experiment conducted in [5] uses the following parameters shown in table 10.

Table 10 Parameters and equipment used in [5] for testing laser cladding of the milled grooves [5]

Laser	TRUMPF TruDisk 2.0 kW Yb:Yag laser
Carrier gas	Helium 5.0
Shielding gas (axial gas flow)	Argon 5.0
Powder grain size	45-125 µm
Powder alloy materials	Stainless steel and titanium alloy Ti-6Al-4V
Substrate materials	Stainless steel and titanium alloy Ti-6Al-4V

And welding parameters shown in figure 16;

Welding parameters	V-groove 1	V-groove 2	U-groove	a) Ti	b) Ti
Welding velocity	0.5 m/min	1.0 m/min	1.0 m/min	0.5 m/min	1.0 m/min
Laser power	1.0 kW	1.0 kW	1.0 kW	2.0 kW	1.0 kW
Laser spot diameter on surface	2.2 mm	2.2 mm	2.2 mm	2.2 mm	1.0 mm
Powder mass flow	4.0 g/min	8.0 g/min	8.0 g/min	9.4 g/min	3.8 g/min
Material	CrNi-Steel	CrNi-Steel	CrNi-Steel	Ti-6Al-4V	Ti-6Al-4V

Figure 16 Welding parameters of the 5 different processes done in [5]

The Ti in a) and b) case (according to the figure 16) is deposited onto the flat surface. The powder jet is controlled by the aid of 5-axis machine to reach difficult areas.

Aside from visual inspection, the results of these 5 examples were checked using x-ray testing, microscopy, cross section and hardness measurements. The main problem with the U-groove was accessibility of the powder jet resulting in porosity in the sidewall area. To avoid that, inclined and wider grooves are desirable. Also, using different technique, like welding the sidewalls parts first and then filling the middle of the groove track, was shown more successful.

The diameter or the spot size of the laser could be changed between 0,6 mm and 2,2 mm depending on the desired area to be covered. However, the important thing what was found is that with increasing the welding velocity, shorter total operation time emerged (even though greater number of tracks was needed) and lower heat input was put into element resulting in lower distortions. However, according to [7] the residual stresses are lowered with use of single-track over multiple overlapping tracks, showed by the use of x-ray diffraction test in remelted layers of Ti–6Al–4V. But in this case, overlapping is a “must”, so smaller heat input (increasing number of passes) wins the battle.

Also, Ti alloys, which are particularly sensitive to oxidation, nitridation or hydrogenation, show that with increasing velocity and lowering the power input (in a) Ti case), there was no need for trailing inert gas nozzle (as was needed with higher power and lower velocity speed), but gave similar results, in more passes. [5]

4.6 Future experiment

Following work and experiments done in [5] and materials used in [4] there comes a chance of testing repairing technology of laser cladding on turbine blades which have to be milled in order to be repaired.

As a one of mostly used compatible materials for hard faced turbine blades, shown in table 6 and its composition in table 7, Rene 142 will be chosen as a powder material which will be fed onto the Rene 125 (substrate).

Milling will be done so it results with a groove as described earlier, 10 mm deep V-groove as in figure 15. V-groove is chosen over other types simply because of better accessibility.

Grooved surfaces will be polished with sand paper and acetone will be used for cleaning them.

Similar to parameters described in [5], parameters shown in table 11 will be employed;

Table 11 Recommended parameters for future experiment

Laser	TRUMPF TruDisk 2.0 kW Yb:Yag laser
Carrier gas	Helium 5.0
Shielding gas	Argon 5.0
Powder grain size	45-125 μm
Powder alloy material	Rene 142
Substrate material	Rene 125
Welding velocity	1,0 m/min
Laser power	1,0 kW
Laser spot diameter on surface	2,2 mm
Powder mass flow	8,0 g/min

The welding velocity of 1 m/min over 0.5 m/min is used even though it results in higher number of passes (in [5] V-groove-1 results in 118 passes and V-groove-2 in 150 passes, but the heat input in first case is 50% higher, which results in higher distortion level). And as already mentioned, 150 tracks with welding velocity of 1,0 m/min result in shorter operation time than with welding velocity of 0,5 m/min with 118 tracks. As an example of this are results of cross section according to [5] which can be seen in figure 17., with parameters described in figure 16.

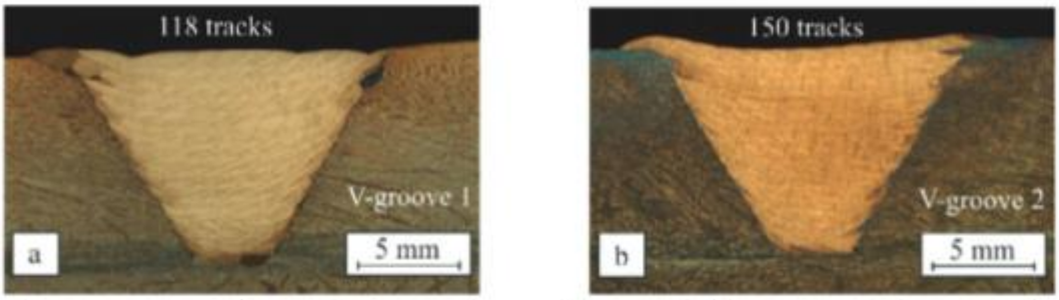

Figure 17 a) V-groove-1; b) V-groove-2 [5]

Also, higher welding velocity facilitates gas coverage so the danger of oxidation or any other unwanted process is significantly lowered. This is exceptionally convenient if there is no possibility of adding trailing gas nozzle which additionally protects cladded tracks. On top of that, smaller tracks have faster cooling rates resulting in smaller grain sizes. [5]

If possible, as shown in [5], a specific deposition strategy can be employed. It was shown that by firstly depositing tracks on the walls of the groove and then filling up the middle will give better results in terms of fusion. The results can be compared to the experiment in [5] (with the main focus being on side walls track), shown in figure 18.

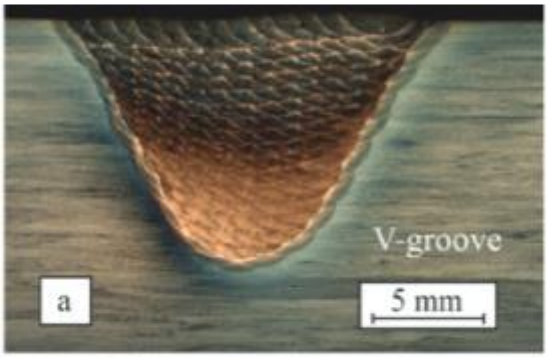

Figure 18 Result of different laser cladding technique employed in [5]

A laser spot of 2,2 mm is used (as used in [5] for stainless steel, see parameters in figure 16), simply because it covers the greatest area so the powder flow could be increased. If, however, precision is wanted, smaller spot size is therefore more optimal. On top of that, there was no difference in powder efficiency (but of course, the powder flow had to be lowered). In [5], when lowering the laser spot size, some powder was left behind unmelted, but that was not projecting any problems whatsoever (but could give problems if there is too much of it), because it was melted by the next pass.

Results of this process can be checked using cross section, SEM (scanning electron microscopy), x-ray testing, hardness measurements and other material characteristics (nanoindentation). On top of that, tribometer pin on disc can be employed to discover additional wear specifications of the repaired turbine blade.

In [5], x-ray testing looked like this (shown in figure 19). For V-groove-1 there was no cracks visible, but for V-groove 2 one void is visible. Overall, it shows good quality of the repair cladding process.

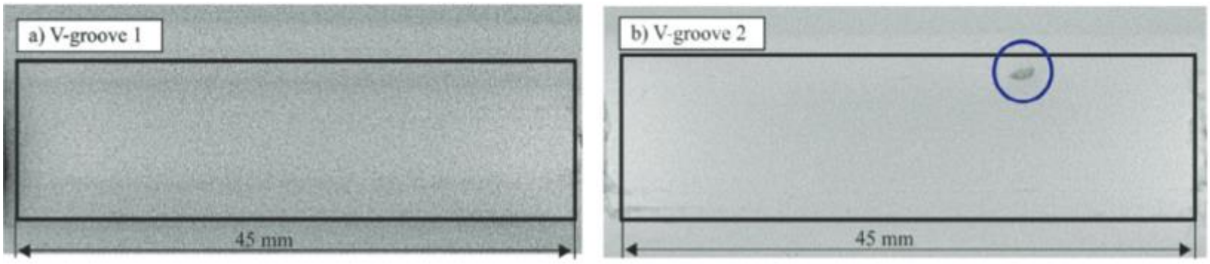

Figure 19 Results of x-ray linescan in [5]

Cross section can be made using line cutting machine – sectioned samples are then polished and etched with etchant (e.g. 10 ml HF, 30 ml HNO_3, and 90 ml HO_2)

All these tests are described in chapter 4.7.

4.6.1 Future trends of laser cladding

The ability of localization of the heat input makes the material less distorted, with smaller HAZ and smaller dilution levels and therefore not deteriorating clad properties of the nickel-based superalloys. This is exceptionally true for heat sensitive components. With lesser control over heat input (as with TIG welding), gamma prime phases (γ') partially dissolve which than causes the noticeable loss in properties. This shows a possibility of completely overpowering TIG processes in some fields of cladding.[4]

With high reproducibility and reliability of the laser beam comes a possibility of automatization of laser process.[5]

Other materials that are often tested with laser cladding technology, are titanium alloys (Ti-6Al-4V) and stainless steel. Also, the application of laser cladding is found in repairing sintering tools or depositing vanadium-carbide tool steels for die repair. [5]

One of the future trends is to develop laser cladding gradient coatings. This would be very beneficial for the reduction of residual stresses of the material, for a reason of gradually changing the microstructure, in contrast to the abrupt change. [6]

4.7 Tests

4.7.1 Tribometers

Tribometers is a name for all the devices used to measure friction force coming from two surfaces in contact in relative motion and based on that information giving access to wear evaluation. Pin on disk is one of the most commonly used tribometers because of its simplicity and variety of possible tests that can be made; unidirectional, rotational, fretting and other modes done in dry and lubricated conditions. Usually, these tests are made under conditions based on the following testing standards: ASTM G 99, DIN 50324, DIN ISO 7148-1, DIN ISO 7148-2 and others. Also, there are many important factors that can influence test results in a big way, so they must carefully be considered. For example, pin material (if it is softer than the disk material, usually wearing appears only on pin therefore changing the shape of it and conditions greatly) or pin location (if the pin is located from the bottom it enables the generated wear particle to fall down and don’t interrupt the process) and many others. [8]

The typical, schematic representation of pin on disk is shown in figure 20.

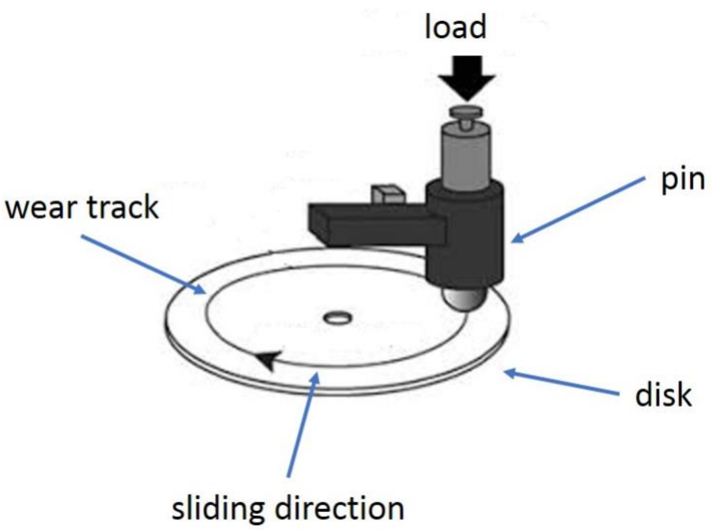

Figure 20 Schematic representation of pin on disk test [8]

Rotating disk and stationary, loaded pin are in contact. Pin can be made of different shapes, but most commonly used are ball and cylindrical shaped pins due to ease of alignment (as opposed to the flat pin, which is very sensitive to any misalignments). As the test is running, different data are measured. Usually, friction force, wear and temperature are being measured.

Typical diagram obtained showing relation of coefficient of friction with time is shown in the figure 21.

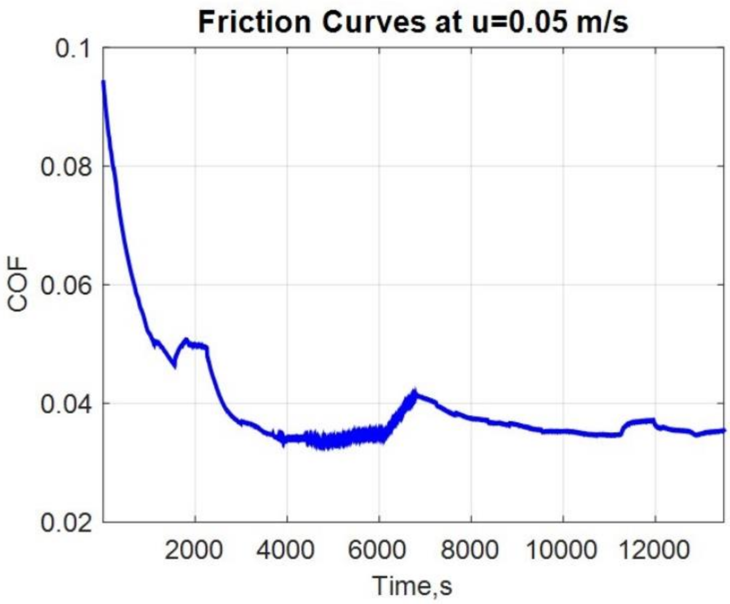

Figure 21 Diagram showing relation between COF and time [8]

After a certain amount of cycles, specimens are usually further investigated using scanning electron microscopy (SEM) or (energy dispersive) X-Ray analysis for a microstructural analysis, chemical analysis, tribofilms, surface roughness evolution, surface topography, wear volume and wear rate and others. Nowadays, modern tribometers have inline imaging systems which enable testing more easily and more frequently during the procedure. [8]

4.7.2 Scanning electron microscopy (SEM)

To be able to carefully see and inspect surface topography, scanning electron microscopy is therefore used. It is developed as a better solution than a light microscope, which is restricted in terms of resolution, not primarily because of limiting magnifications of the lens, but also because of the limit that using white light (detectable by the human eye) provides. Using the white light has a downside which lays in its wavelength (average is 550 nm) giving the theoretical limit of the microscope resolution of about 200-250nm, which is not sufficient enough for careful surface inspection. On the other side, electron beam provides much lesser wavelengths and therefore better resolution. It creates an image of the surface with a very high resolution. Very often that resolution equals 20 nm, but can also be in range of 1-20 nm with modern full-sized SEM-s.

A difference in results in scanning microfibers by using optical microscope and SEM is shown in figure 22.

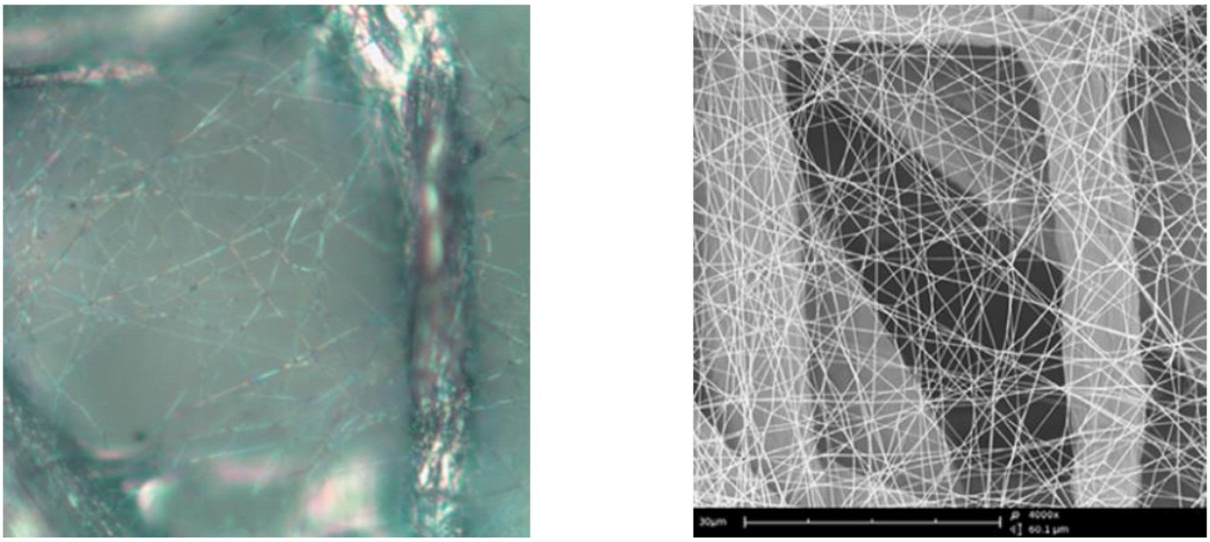

Figure 22 a) nanofibers detected by the optical microscope; b) same nanofibers detected by the SEM [9]

Scanning electron microscopy (SEM) creates an image by focusing an electron beam on the specimen surface and is detected by several detectors after its interaction with the sample surface. By connecting it with a computer, it gives a good insight into surface composition and topography. Aside from computer and display to see the gathered images, SEM consists of the electron source, column (where electrons travel and pass through electromagnetic lenses), electron detectors and sample chamber (vacuumed by the pumps). The scanning of the beam enables information of a defined specimen area to be collected. Schematic diagram of the SEM is shown in figure 23.

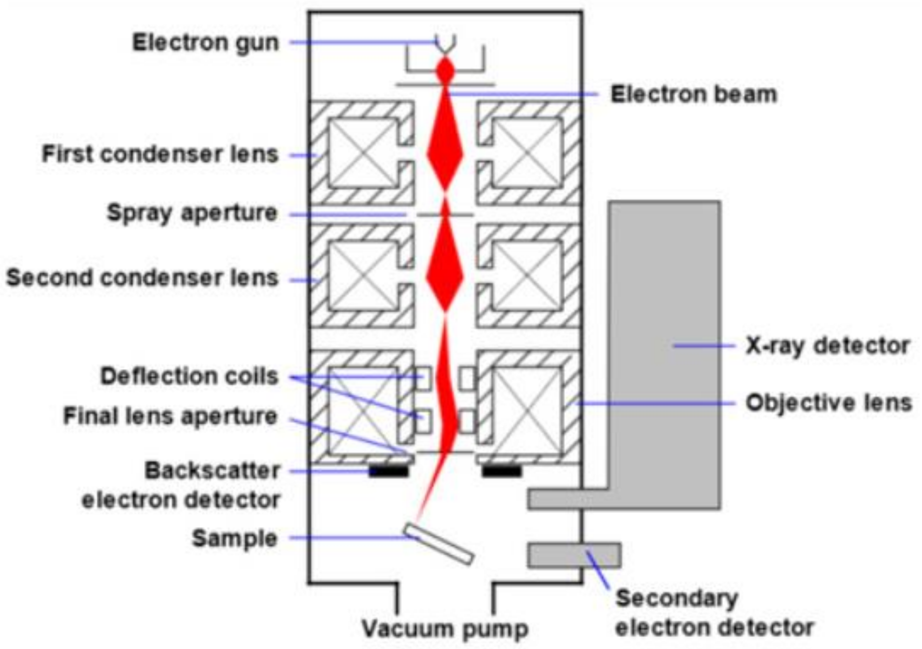

Figure 23 Schematic diagram of the SEM [9]

By the interaction of the high energy electron beam with the surface, a few characteristic signals are produced and then detected by the corresponding detectors. Electron beam penetrates only few micrometers in depth and produces secondary electrons, backscattered electrons, and characteristic X-rays. These signals and their location within the sample is represented in figure 24. [9]

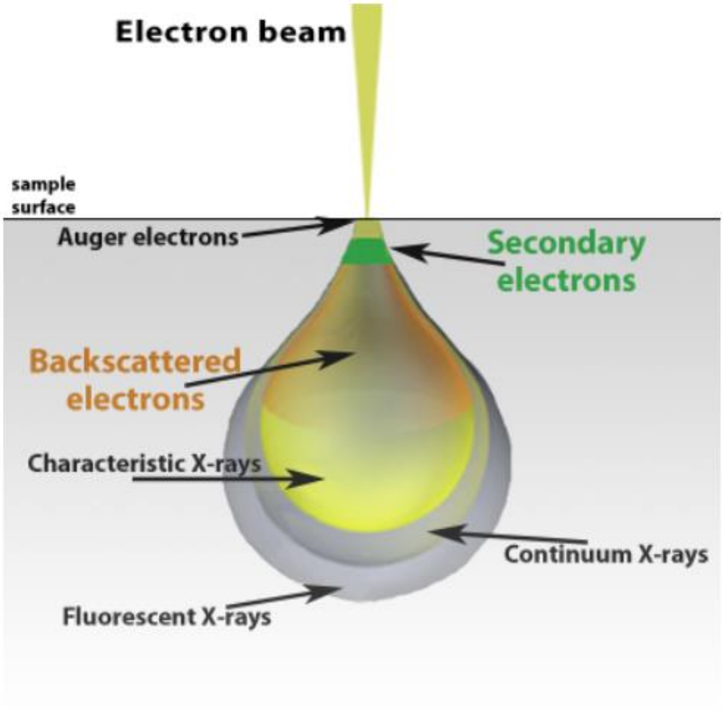

Figure 24 Schematic diagram of electron beam and surface interaction and their typically produced signals [9]

4.7.3 Energy Dispersive X-Ray Analysis (EDX)

Energy Dispersive X-Ray Analysis (EDX), also known as EDS or EDAX, is technique used to determine elemental compositions of materials using x-rays. Applications defer from product development to troubleshooting, deformulation and others.

Very often, EDX systems are integrated with the SEM (Scanning Electron Microscopy) instruments. Data obtained with x-ray analysis contains spectra with different peaks corresponding to different elements thus making the true composition of the sample material (sometimes elemental mapping or line profile analysis are made afterwards, shown in figure 25 and 26). [10]

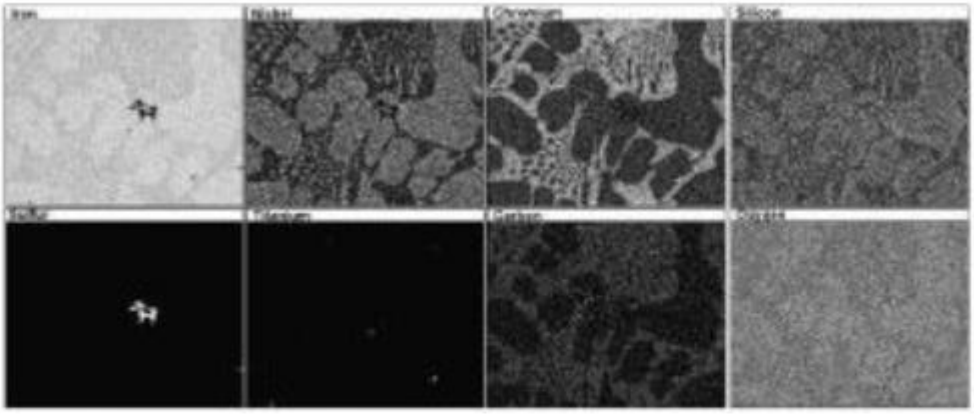

Figure 25 Elemental Map of a White Iron Casting [11]

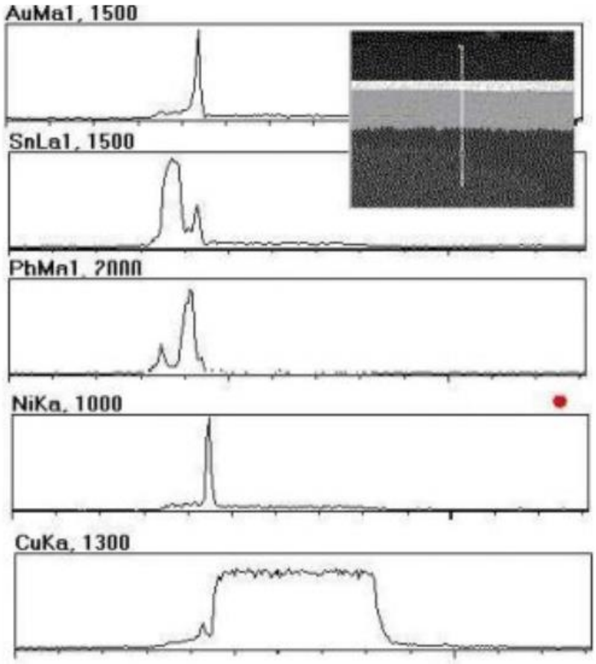

Figure 26 EDX linescan across plated PCB layers [11]

X-rays are being collected after bombardment of the SEM electron beams. Electron beam causes electrons being ejected, thus making vacancies which are then filled with higher energy electrons (being in higher state), thus causing energy disbalance. To counter that disbalance, characteristic x-rays are emitted being equal to the two electron states energy. This makes for every element a characteristic x-ray. [11]

With a multi technique approach, EDX can measure qualitatively, semi-qualitatively or quantitatively and with the already mentioned mapping, can provide spatial distribution of the elements. Features of the analyzed sample as small as 1 μm can be distinguished. EDX is very often used because it is completely nondestructive and can be made in situ. Samples could have little to no preparation. [10]

An example of EDX analysis result is shown in figure 27.

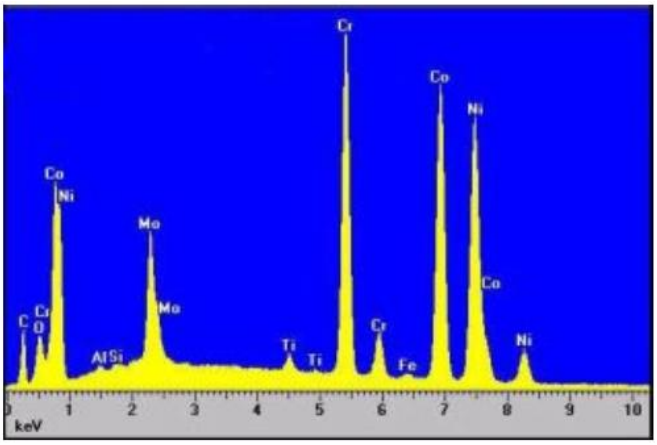

Figure 27 EDX spectrum of Alloy MP35N [11]

Typical applications of the EDX are:

- unknown material analysis
- material corrosion analysis
- coatings/thin film analysis
- phase detection and its spatial distribution

Not all sizes are favorable for EDX analysis. Typical measurements must not exceed 200 mm in diameter to be readily analyzed in SEM, if, however, larger samples are to be analyzed, limited stage movement is enabled and diameters then must not exceed 300 mm. Also, a maximum sample height is at around 50 mm. As it is performed in moderate vacuum atmosphere at around 2 Torr or less, samples must be compatible with it. [11]

4.7.4 Nanoindentation

Material testing and material development is one of the bases of mechanical engineering so many tests are designed in effort to measure different material properties as precisely, cost and time effectively as possible. In that respect, first need to be mentioned some of the traditional tests. Most commonly known are uniaxial tests used to measure tensile strength and elastic modulus, crack propagation tests for fracture toughness measurements and shear tests performed in order to obtain shear strength property. The main characteristic of these tests is that they need often complex sample preparation and are very time consuming. Sometimes it needs days to perform such a test. So, in effort to reduce costs, reduce time and enable simpler, all around test, nanoindentation was developed. Based on fundamental contact mechanic laws developed by Hertz, Sneddon and many others in 1800's, upgraded with a knowledge shared by Oliver and Pharr in 1990's, modulus and hardness of material was, for the first time, able to be measured only on its contact with another known material. Nowadays, nanoindentation became one of the most commonly used and versatile tests performed in material testing. It can measure properties for a variety of materials; from superalloys to polymers or biomaterials within few seconds.

Nanoindentation is used in many industries to measure and characterize thin films in electronics, coatings and base materials (for example in cutting tools), thermal barrier coatings, polymer's viscoelastic properties and even wear and scratch resistance of materials.

Two of the basic measurements needed for nanoindentation are load and displacement measurements. That being said, typical load-displacement curve is shown in figure 28.

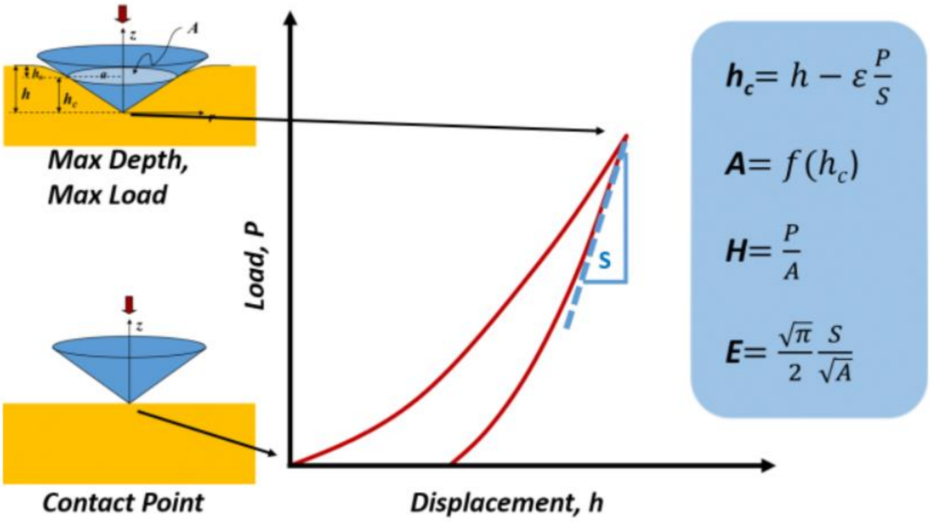

Figure 28 Load-displacement curve with equations needed to calculate modulus [12]

As shown in the picture, there must be a probe with a specified geometry. Therefore, based on its geometry, one can measure different material properties. For example, Berkovich probes are used for hardness and elastic modulus measurements, cube corner for fracture toughness, spherical for stress-strain. Material usually used is the diamond, with a tip as small as around 100 nm. As the load increases, indentation depth also increases. Thereby, using the indentation depth, area of the tip that was in contact with the material can also be measured which is later used to calculate the hardness of the material. On the other hand, what is as important as the loading portion of the plot is unloading portion. It is closely related to the to the stiffness of material, which then enables to calculate the reduced modulus of the system.

But, nanoindentation still needs a few extra points to be looked at. After applying the load, what must be looked at is the frame stiffness, for which the raw data given must be calibrated. When applying several indentations on the same specimen, there must be precisely measured and calculated spatial distributions at carefully picked sites. Those results are then categorized based on material properties into elastic, viscoelastic or soft material properties. Configuration properties of the materials containing coatings and thin films or having heat treated zones be calculated as well. What nanoindentation is also able to provide is measurements dependent on temperature, plasticity dependent etc. This is what makes nanoindentation such a versatile technique in material measurements.

Big step in nanoindentation technology was made by introducing continuous stiffness measurement technique.

An older, quasi-static indentation testing, gives information about the stiffness of material only for the certain indentation depth. If one wants to know what happens with higher or lesser indentation depths, he needs to do another measurement. In contrast to that, CSM technique gives that information in a single step by continuously providing dynamic load on top of the static load. This is how depth dependent properties can be easily obtained.

CSM method ejects the need for unloading cycles within the load-displacement history. It measures precisely the initial contact and continually measures contact stiffness as a function of depth or frequency. Also, CSM can be utilized by having a constant strain rate, which is a critical parameter in developing film/substrate systems.

Results of the elastic modulus as a function of indentation depth of the CSM nanoindentation method in a single step with a static indentation test result is shown in figure 29. [12]

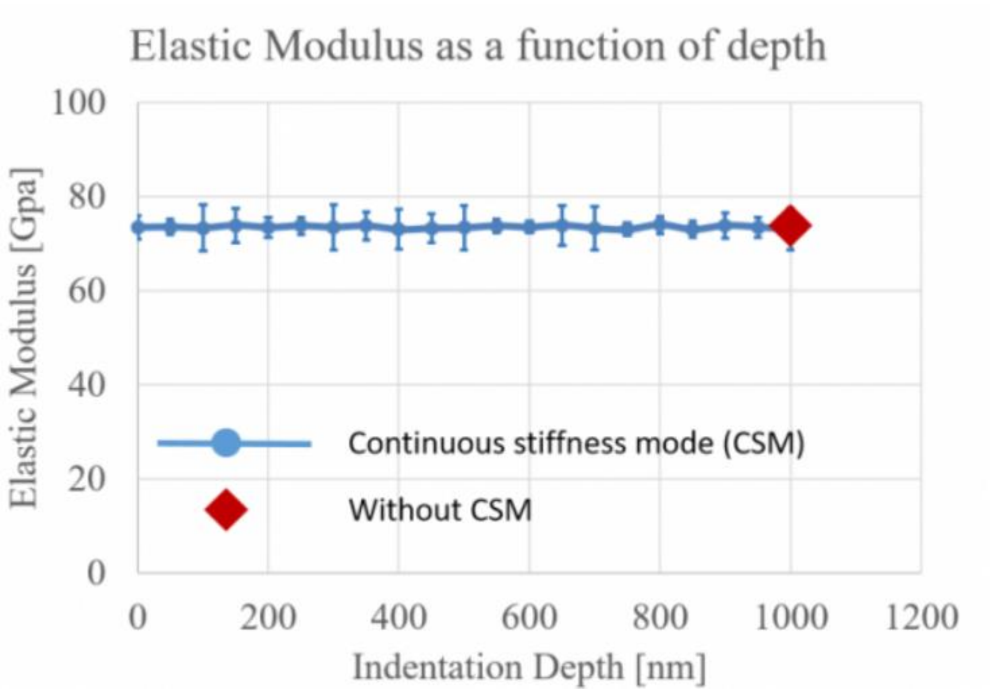

Figure 29 Results of the elastic modulus as a function of indentation depth of the CSM nanoindentation method in a single step with a static indentation test result [12]

5. Conclusion

The first, theoretical part deals more with the introduction to the physics of light and laser in general and gives a basic idea of a laser. On the other hand, laser technology found its way into material processing and second part gives a brief categorization and description of basic laser surface treatment technologies.

Finishing with a set-up of a future experiment in one of the main fields of laser surface treatment, this paper gives examples of researches done in laser cladding. More specifically, one-step cladding process is described based on the experiments done in [4]; where laser cladding technology is compared (microstructure, hardness, cracking, porosity and dilution levels) to the TIG technology for reparatory cladding of the turbine blades [4], and in [5]; where laser cladding technology is applied onto the reparatory process which involves milling first and then studying the effect of different parameters on the microstructure and heat affected zone of the stainless steel and Ti-6Al-4V [5]). Based on that, future experiment involves explanation of the choice of its laser cladding parameters, gives recommendation of laser cladding strategy which was proven to give good results in [5] and more. Furthermore, it involves milling of the turbine blades made of material Rene 125, with a clad material being Rene 142, as one of the most commonly used materials in aerospace industry for making of the turbine blades. At the end, tests, such as nanoindentation, scanning electron microscopy, energy dispersive x-ray microanalysis and tribometers (pin on disc) are slightly described which are recommended to be utilized to check the results of the future experiment.

Laser are really fascinating and going through this paper, it can encourage interest in further exploration of this topic, or give ideas for some future tests to be made.

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