2. LASER HEATING APPLICATION FOR HEAT TREATMENT

Classification of chapter:

Time necessary for study: 220 minutes

Aim: After study of this capture

- **You give information about main principles of LASERs and their properties;**
- **You will be able to orientate in different types of LASERs and their possible application;**
- **You get a knowledge about steels and cast irons properties after laser**

exposition;

- **You will be able to understand physical-metallurgical principles of laser ray with metal surface interaction;**
- **You will be able to consider and review the microstructure and strength properties of metal materials after laser exposition**

Lecture

2.1. Laser

The word Laser is deduced from the name "Light Amplification by Stimulated Emission of Radiation" – a quantum generator of light beams, which served for amplification of light waves with the aid of stimulated radiation emission. Extremely hard materials can be cut using this technology, whereas the quality of cutting edges and the used cutting speed do not depend on hardness of material processed (machined) this way. The very cut is very narrow and very small holes can also be bored into highly hard materials using this technology. Newly formed surfaces (i.e. places of the laser beam interaction with a metallic matrix) feature high mechanical (strength) properties. More detailed analyses of physical-metallurgical characteristics have enabled to define in this quite thin surface layer the basic structural phase conditions of its formation and it has been possible to work up fundamentals for the technology of heat treatment of metal surfaces using laser. Each laser has three basic parts:

Laser active environment – amplification of radiation occurs here
Excitation source – for excitation of the active environment
Resonator – creates a feedback between the radiation and the active environment leading to origination of laser oscillations

Selected summary data for utilization of extreme concentrations of laser energy are set in **Table 2.1.**

Table 2.1 Selected data – extreme concentrations of laser energy

Energy source	Density of energy [J.cm^{-3}]	Density of power [W.cm^{-3}]
Electrical condenser	10^{-2}	-
discharge	10^{-4}	$10 - 10^{9}$
Chemical explosive	10^{-4}	10^{9}
Heavy current electronic beam	10^{6}	$10^{13} - 10^{14}$
Atomic explosive	$10^{10} - 10^{11}$	$10^{16} - 10^{18}$
Intensive LASER beam	$10^{10} - 10^{12}$	$10^{20} - 10^{22}$
Mass annihilation [10g-cm^{-3}]	10^{15}	-

2.2. Basic technical principles of lasers

In principle, lasers transform lower quality energy (thermal, chemical, electrical etc.) to higher quality energy – coherent radiation energy. Generally, it can be stated (from the thermomechanical point of view) that a laser is a device that decreases entropy of a system, while absorbing a certain amount of energy. To describe a laser activity a simplified case of a “three-level” atom is considered; a basic energy state E_0, an excited state E_2 and a metastable state E_1 in between. For excitation, radiation of **ν** frequency determined by the following relation is needed:

$$\nu = (E_2 - E_0).h^{-1} \qquad \text{(h= Planck constant)} \qquad (1)$$

In spontaneous transformation, radiation of the following frequency is emitted:

$$\nu = (E_2 - E_1).h^{-1} \qquad (2)$$

whereas impletion of E_1 energetic state occurs. Now, if it is supplemented in a radiation system of frequency:

$$\nu = (E_1 - E_0).h^{-1} \qquad (3)$$

the so-called simulated emission occurs, i.e. the transition from E_1 state to E_0, whereas the emitted radiation is in a phase with the exciting radiation and thus a fully coherent beam originates. An excited atom (ion, molecule) is included in the active environment (e.g. CO_2 molecules in lasers based on CO_2 - N_2 –He, chromium atoms in a ruby laser etc.). Then, the stimulated emission process is the most significant for a laser function. It occurs at the interaction of an excited quantum system – an atom or a molecule – with electromagnetic radiation – a photon, a frequency ν of which is directly proportional to the energy difference between the excited one and some of the lower state of a quantum system. Concurrently a quantum system transition into this lower-energy state occurs and, at the same time, the excitation energy is released by emitting a photon with energy **$h.\nu$.** Properties of the emitted photon are the same as of the photon which has stimulated the emission. This is a principle of light amplification.

A principle of a laser is depicted schematically in **Fig. 2.1,** where 1 refers to the initial state, 2 – a quantum system in the excited state and 3 – a stimulated emission and energy levels of quantum systems E_1 and E_2.

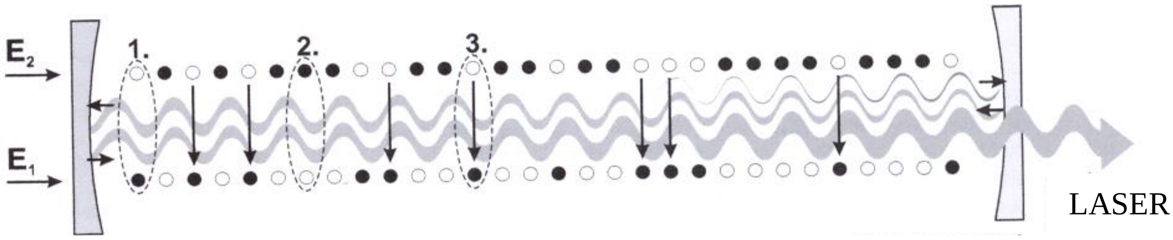


Fig. 2.1 Scheme of laser principle

2.2.1. Basic classification of different LASER types

According to the state of the active environment, lasers are divided to **solid-state, liquid, gas and plasma** types**.** Then, a special group covers **semiconductor lasers – laser diodes.** Ruby crystals are used as the active environment for solid-state lasers the most frequently. A ruby laser is a source of radiation impulses of different lengths and with a different distribution of energy in a pulse. Present-day lasers reach the pulse energy as high as about 10^4 J, which at a pulse length e.g. 10^{-3} corresponds to 10^7 W output. The most similar to crystal lasers are lasers with a glass matrix with the most often used admixture of neodymium (for instance Q-lasers – up to 10^{11} W). These laser types allow creating special pulses of high energy and a length of 10^{-8} – 10^{-9} s. Solid-state lasers are capable to work in all possible modes, they are stable, robust and maintenance-free.

The most frequently laser types used in industry are gas lasers. They enable to achieve high outputs (above 100 kW) at relatively small dimensions. For heat treatment purposes, lasers of output 5 ± 3 kW are optimal. There are also semiconductor type lasers. A principle is an electroluminescent diode allowing current to pass through in the permeable direction. In this case the active area is of a miniature capacity. **According to the operation mode,** lasers can be divided into two groups. **Continuous wave lasers** (CW) with continuous-wave radiation, and **impulse (pulsed) lasers** radiating light energy in pulses. They are more advantageous for the "strictly local" use of the thermal effect. For surface heating purposes in heat treatment of metal surfaces, lasers with a continuous wave mode are usually more applicable. Solid-state lasers are not advisable for continuous operation at laser higher output owing to low thermal conductivity and thus also problems of ensuring active environment of cooling. So the most suitable laser type for heat treatment is a continuous CO_2 laser.

2.2.2. Laser devices for heat treatment of metal materials

CO_2 laser uses a mixture of CO_2, N_2 and He gasses, ensures a reliable operation, stable output and a high quality of the laser beam profile. Using high voltage, gaseous nitrogen molecules get to the "high energy" state, where they vibrate rapidly. This energy is transferred to CO_2 molecules, which get to "vibrate" as well. During transition of CO_2 molecules to a lower energy state, radiation in the infrared region with a characteristic wavelength of 10.6 μm is released. The very laser has an output power ranging between 600 – 2500 W. The output power stability is max. up to 5 %. Parameters of a laser are: wavelength: 10.6 μm, a diameter of the outgoing beam – 30 nm and a beam divergence is 1.2 mRad (along 8 m length). The described device is highly advisable for the use in heat treatment because this way more homogenous and deeper surface heat treated layers can be achieved.

An integral part of a "hardening laser device" is also an equipped worktable including a move of heat treated parts along x and y axes. A diagnostic modulus is a part of laser devices as well.

2.3. Basic properties of laser radiation

Spatial coherence is an important property of laser radiation. Laser radiation can be spread practically in a shape of a plane wave, divergence of which exceeds only a little the minimal divergence determined by diffraction of light waves.

$$\phi = \lambda/a \qquad (4)$$

where λ is the laser beam wavelength. This coherent radiation can be focused through an appropriate optical system to a very small spot, dimensions of which are comparable to the laser wavelength. Further, laser radiation features high **mono chromaticity** determined by the laser principle, which generates coherent light waves with maximum amplification frequency and at minimum light loss in a resonator. High **output** of laser radiation, **spatial coherence** and **mono chromaticity** are the basic physical characteristics. Lasers can work (according to the active environment) in a region of wavelengths from ultraviolet up to infrared. The basic laser parameters are **power density I** and **interaction time τ** and also **penetration depth υ** depending on energy density level (see **Fig. 2.2**). Parameters (**I and τ**) define spheres for application of lasers – see **Fig. 2. 3.**

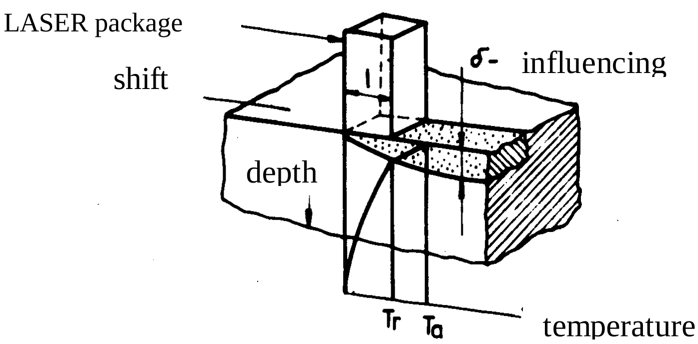


Fig. 2.2 LASER exposition

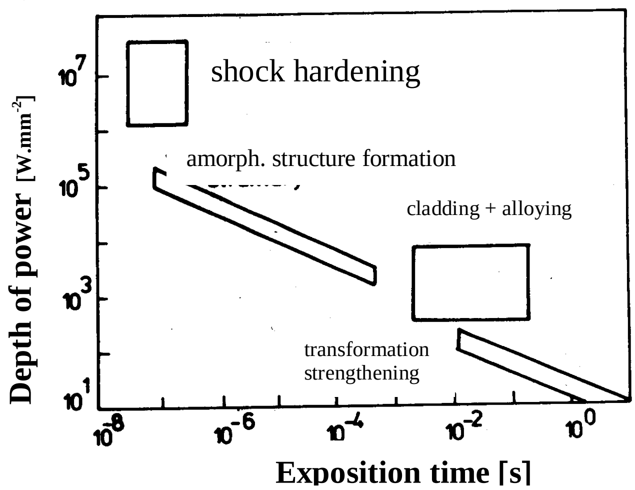
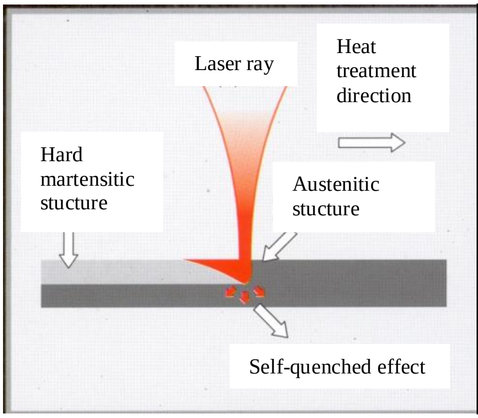


Fig. 2.3 Areas of some LASER applications

When using low power densities (around 10^3 - 10^4 W.cm^{-2}) and relatively longer interaction times (0.01 to 1s), in the thin surface layer heating to temperatures leading to austenite formation occurs, but without melting the entire material. However, the given heating is short and heat has not sufficient time to diffuse into the processing material volume. After finishing the laser beam acting, the metal surface cools-down rapidly due to intense heat removal. The temperature drop speed can be up to 10^4 °C.s^{-1}. A result is a formation of "quenching" structures in the surface layer and related surface (transformation) hardening known as **laser surface hardening** (**Fig. 2.4).** When increasing I value (even at a shorter interaction time), a thin surface layer (about 100 up to 300 μm) gets melted, which can be used for a possible modification of chemical composition of metal surfaces.

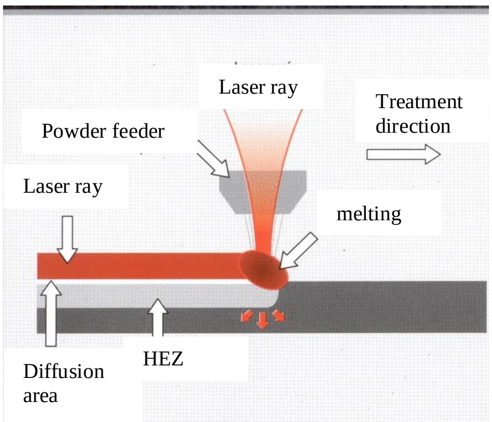
When a deposited material (e.g. in a form of powder) is melted simultaneously with the base material surface layer, diffusion into the base material occurs, while changing the surface chemical composition (**surface alloying**). At **coating,** an applied layer of a different material ensures new surface properties completely. In this case an applied material in a form of powder in a gas stream is fed into a laser beam and melted at the same time. A narrow alloy interlayer is then formed between the base and the added material – **Fig. 2. 5**.



- Local treatment of demanded areas
- Elimination of cracks and deformations
- Treatment of arbitrary geometry
- Controlled process according actual temperature
- High rate, reproducibility and reliability

Application
Shafts, pulleys, bearing sleeves, drive gears, components for energetic, tool of cast, compacting pressing forms etc.

Fig. 2.4 Application of LASER quenching

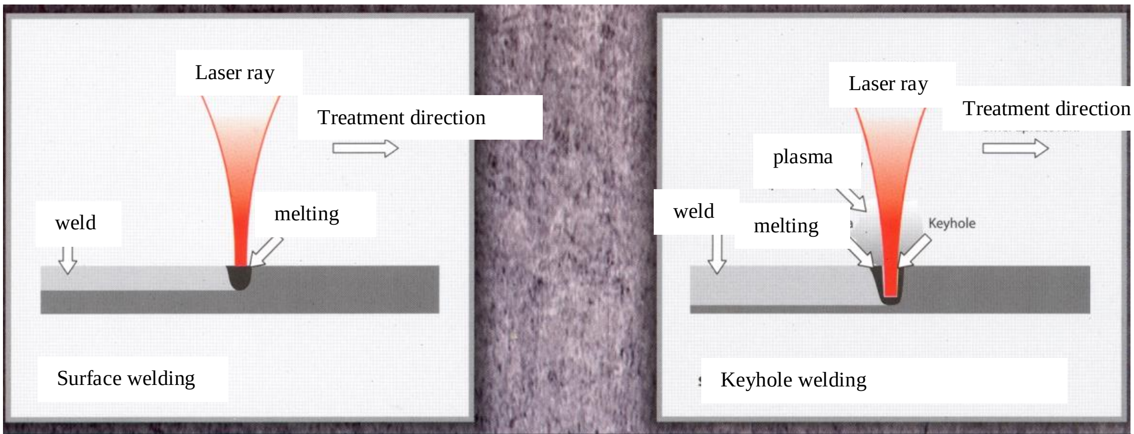


- Weld deposit with metallurgical bond on basic material
- Low added heat into deposited component
- Excellent adhesion and coherence of coat, without porosity
- Possibility of arbitrary thicknesses weld, as well as in 3D forms
- High efficiency and reproducibility
- Formed materials showing high abrasion, corrosion and oxidation resistance (at 1000 °C)

Application
Manufacturing, renovation, reparation of different shafts, spindles, flanges, journals, adjustable blades, forms, tools etc.

Fig. 2.5 Application of LASER cladding

If power densities reach values ranging between 10^6 up to 10^7 W.cm^{-2} and interaction times are very short (1 to 10^3 μs), the very thin surface layer is melted first and then solidified very quickly again (10^5 °C.s^{-1}). Under these conditions, an amorphous metal layer (metal glass) with noticeable abrasion resistance, fatigue properties, or possibly corrosion properties, is formed on the surface. This method is called **laser glazing**. Still higher power densities (10^8 to 10^9 W.cm^{-2}) and extremely short exposing times (10 to 100 ns) cause explosive deducting of the small layer (order-of-magnitude of several atomic spacing) from the material surface, while a shock wave originating at the same time leads to the material "densification" and its plastic deformation. Such induced strain (shear) processes and related formation of twins are the cause of an increase in hardness. This is **shock hardening by effect of laser heating.** Application of **transformation hardening** and **welding** has found the largest technical-technological use of the above mentioned laser processing methods so far. The laser welding technology principle is shown in **Fig. 2.6.**



- Low deformation temperatures of welded components
- Regular and smooth weld with low porosity
- High stability of process under high welding rates
- Optimised technology for automation
- A possibility to weld materials conventionally not weld-able

Application

Components welding, where high welding rates are demanded, as well as weld of high quality without cracks, impurities, porosity and thermal deformations in weld vicinity

Fig. 2.6 Application of LASER welding

2.3.1. Analysis of parameters of a laser beam interaction with a metal surface

Depending on intensity and time of a laser device interaction, the stages of laser radiation interaction with the processed material can be characterized as follows: a) **leading the laser beam** to the material, b) **its absorption** and **energy transfer** to the processed metal, c) **heating of the material** without its state change, **melting of the material, evaporation of the material,** d) **metal cooling-down** after finishing the laser exposure. The progression of these processes depends on physical properties of processed materials (surface reflectivity for the given radiation, thermal conductivity, latent heat of melting and boiling, melting and boiling point, material density etc.). Efficiency of heat treatment with the use of laser depends mainly on **absorption capacity** of the processed material. The reflected radiation proportion is the larger, the brighter the surface and the longer the used radiation wavelength is. Reflectivity of metal surfaces **decreases** slightly, while **temperature increases** and at temperatures near the **melting temperature** a sharp **reflectivity drop** occurs and the most of the radiation is absorbed. Rough surfaces (inadmissible in practice) absorb the laser radiation better, therefore the use of special absorption coatings is needed (e.g. colloid graphite, furnace black etc.). **Coating thickness, granularity, adherence to the surface, evenness, working temperature** and **heat transfer** play their part, too.

The simplest solution procedures for temperature distribution determination are based on known solutions proposed for one-dimensional heat conduction

:

$$\delta T/\delta t = \alpha \cdot \delta T^2/\delta z^2 \qquad (5)$$

where **T** stands for absolute temperature (K), **α** = K /(ε_p ρ) stands for temperature conductivity in $cm^2.s^{-1}$, **K** stands for thermal conductivity in $W.cm^{-1}.K^{-1}$, **ρ** stands for density in $kg.cm^{-3}$ and **z** represents a distance from the surface. An example of such a procedure is a solution for a semispace proposed by Mazumder, which is based on application of general solutions for heat conduction. For the case of heating:

$$T(z,t) = z\, F_0/K.\ (\alpha t)^{1/2}.\ \mathrm{ierf}\{z/(2.(\alpha t)^{1/2})\}$$
$$F(t) = \{\ F_0 \text{ pro } t>0,\ \ 0 \text{ pro } t<0\ \} \qquad (6)$$

for the case of cooling-down:

$$T(z,t) = (2\ F_0.\ \alpha^{1/2})/K\ \{t^{1\{2}\ .\ ierf(z/(2.(\alpha t)^{1/2})\ .\ ierf(z/2.(\alpha(t-t_L))^{1/2})\}$$

$$F(t) = \{F_0 \text{ pro } 0<t<t_L,\ \ 0 \text{ pro } t<0;\ t>t_L\} \qquad (7)$$

where **t** stands for time in seconds, **F_0** stands for mean power density $W.cm^{-2}$, **t_0** stands for time of the beginning of the exposure (s), **t_L** stands for time of the finishing of the exposure (s), **ierf** stands for a complementary value of the Gaussian error integral. The above mentioned equations are applicable in case that the thickness of a part was larger than $(4.\alpha.t)^{1/2}$. This model is advisable for laser heat treatment of cylindrical surface, perhaps even inner surfaces of a hollow cylinder with the aid of toric mirrors (**Fig. 2. 7 a, b**).

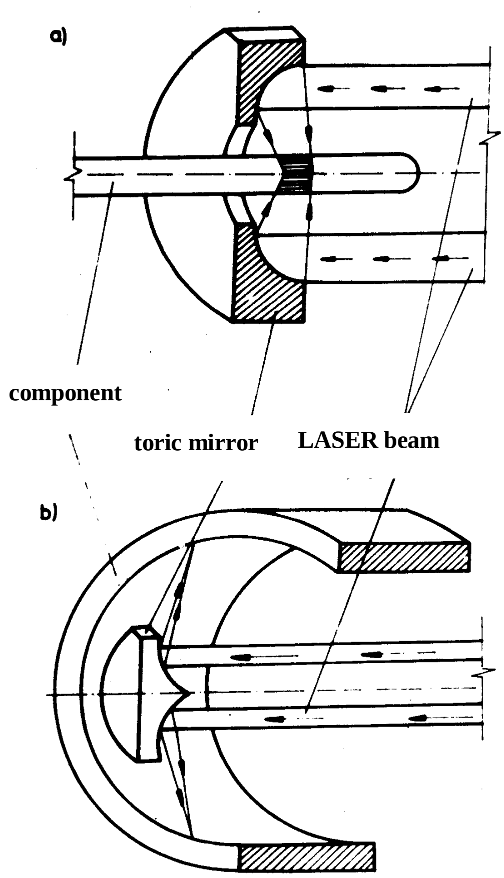


Fig. 2.7 LASER application for heat treatment of cylindrical form

2.3.2. Diffusion processes active during laser heat treatment

In steel with eutectoid composition, or similar to eutectoid, diffusion plays a big part (at inhomogeneity of carbon distribution in the initial condition). The carbon diffusion path can be expressed as follows:

$$X = (2Dt)^{1/2} \tag{8}$$

where **D** stands for a mean value of the carbon diffusion coefficient, **t** stands for laser heating time. However, for accurate determination of a diffusion distance it is necessary to solve a three-dimensional diffusion equation with a temperature independent diffusion coefficient. It is known that homogeneity of carbon distribution in austenite is a function of an initial microstructure and a temperature level and heating time. Aside from many technical-technological advantages, the use of very fast heating has also positive cost-saving effects. Only as much energy is fed into material, as much is needed for heating a thin surface layer. No special cooling medium is needed for quenching (a rapid heat transfer into the material "core").

Generally, the structural phase requirements can be summarized as follows:

a) **Austenitization of a very thin surface layer is necessary during a very short time using very high energy density;**

b) **Heat is "transferred" intensely into the material core by effect of very good steel thermal conductivity;**

c) **However, laser power density needs to be maintained on such a level, so that the melting point of the processed material is not exceeded during austenitization.**

Under optimal conditions, a microstructure of laser processed surface layers in steels is mostly very finely martensitic, however, it depends on heating time, temperature distribution in a moment of hardening and also on the initial microstructure. While heating time decreases and power density increases a danger of surface melting increases, which means e.g. an increased occurrence of residual austenite in the surface layer in steels with "higher" carbon content. In austenitization below 100 μs, hardening is not controlled by diffusion in the solid phase. Surface melting of carbides occurs here and under specified conditions even a formation of very fine (thin) purely austenitic surface layers occurs. This thin layer is a characteristic effect of an extreme rapid heating (at an exposure time shorter than 100 μs and power density higher than 100 $kW.cm^{-2}$), but it has no practical significance for technical applications of laser surface hardening. For surface fine martensitic microstructure, hardness higher by 50 to 100 HV30 is found after optimized heat treatment using laser exposure than after application of conventional methods of heat treatment. This microstructure is difficult to etch (sometimes called white layer – zone). However, the issue of carbon diffusion during laser processing has not been elaborated definitely yet, especially for a case of a pulsed laser effect. Carbon distribution for the model alloy Fe - 24%Ni – 0.3%C is described below.

a) **melting zone I –** immediately under the surface
b) **a zone of complete phase transformation of a matrix – II** (consisting of martensite for quenching in liquid nitrogen) – may reach to depth down to 100 μm
c) **a zone of partial phase transformation of a ferritic matrix to austenite – III - up to 150** μm
d) **a zone in which phase transformation has not occurred – IV- down to 350 μm** depth
Carbon content in zones **III**) and **IV**) (i.e. in depths from 100 μm to c. 350 μm) is lower than its mean content in the initial matrix, which implies a possibility of intensive "redistribution" of carbon content in the laser exposed matrix.

On the contrary, in zones marked as I) and II) the carbon content is significantly increased. These results imply a strong (cooperative) flow of carbon atoms from inside outwards to the surface (towards a "crater", or more precisely towards an area adjacent to the "crater" after the laser processing). Increased mobility of carbon atoms in the solid solution, detected at laser exposure of quenched steel (the microstructure in the model alloy Fe-N-C comprises approximately 90% of martensite and 10% of residual austenite), may relate to phase transformations at high heating rate and diffusion under conditions of high overheating, i.e. at very high momentum. Further it is necessary to take into consideration that these processes occur in increased density of structural defects, density of which increases extremely under laser heating conditions because newly formed defects cumulate to the existing defects by effect of laser exposure (increasing concentration of interstitial atoms, vacancies and simultaneously increasing dislocation density). However, these causes cannot fully clarify the effect of directed (controlled) "redistribution" of carbon. Probably an additional effect of gradient of pressure induced during the matrix phase transformation applies here. As it is known, not only material heating occurs by effect of laser exposure, but a zone of increased pressure reaching up to $10^6 – 10^7$ Pa forms for a short time. In the range of this zone (in its "high-temperature" part on the material surface), a matrix phase transformation to austenite occurs in a "martensitic" way (through shear), while specific volume decreases (around 1%). This process induces a rapid pressure change in the zone in which the phase transformation has occurred. A sharp pressure drop occurs here. Then, in a connection with other above mentioned factors, this can act as a momentum for "transfer" of carbon atoms from inside the material towards the surface of a "crater" originated as a result of the impulse laser acting.

Further to these characteristics of the laser acting, physical-metallurgical causes of formation of above mentioned "white" layers will be analyzed in more detail in this part. This term generally covers structure zones formed in steels through various methods of rapid heating and subsequent quenching (self-quenching). White layers were found for example not only after induction surface hardening, electron beam heating, but also after friction impulse, for instance after grinding or hard braking of railway wheels, and aside from the above mentioned adiabatic (impact) effect in localized areas of high heating. The term "white" layers is used because these layers (zones) are difficult to etch in comparison with conventionally processed matrix. A condition for formation of these layers is usually very fast heating of a surface layer to the austenitic region, whereas melting of the surface with following very fast heat transfer into the material "core" can occur, through which the surface layer becomes hardened. When observing the microstructure using a light microscope, aside from difficult etch-ability, a noticeable property of "white" layers which can be found is a substantially higher hardness compared to a typically achieved level of the matrix hardness. There is a fine martensitic structure (with extremely fine plates), which has not been self-tempered. A structural phase analysis of individual areas forming a white layer on a laser processed material surface proved a complex layer consisting of a very thin amorphous layer (thickness approximately 0.2 μm) with an adjoining fine-grained austenite layer of c. 10 μm. Further, there is a martensitic-austenitic layer of approximately the same thickness here and then a fine-grained martensitic area underneath. In high-carbon steels at content about 1% C and when exceeding specified speeds of movement, i.e. below a certain time of thermal interaction, "light" etching zones with prevailing volume proportion of residual austenite are formed. However, their hardness is substantially lower than found in (martensitic) white layers as described above (it is around 100 HV30). A prove of a fact that in this layer austenite is a prevailing structure phase is a result of additional cooling-down to temperature -196 °C after which hardness of this layer increases as high as a level near to 800 HV30.

2.4. Structural phase analysis of various types of steels after heat treatment using laser exposure

Two basic types of thermal effect are typically observed at laser heat treatment (depending on movement speed and power density):

a) melted area does not occur at higher movement speed (usually higher than 15 $mm.s^{-1}$) and at proper energy density

b) melting of a surface layer occurs at lower movement speed and higher energy density

In a case ad a), in **pro-eutectoid** steels a surface layer comprises very fine martensite (of high hardness) – see the above mentioned discussion on structural phase composition of a "white" layer. Under this very hard surface layer a martensitic zone occurs with a "conventional" martensitic structure. A zone with incomplete transformation comprising mainly martensite and ferrite adjoins to this region. Generally, a region originating on a periphery of the heat affected area can be characterized as an area heated to temperatures ranging between A_1 and A_3. In pearlitic regions, austenite with a composition similar to eutectoid is formed. Ferritic regions transform to austenite with lower carbon content, while a part of it remains non-transformed. Upon rapid cooling the formed microstructure consists of high-carbon and low-carbon martensite and transformed ferrite. Hardness achieved in this microstructure is the lower the longer is the distance from the laser exposed surface.

Figure 2.8 shows a schematic depiction of the formed zones and a progression of hardness after the laser exposure in a case of normalized hypo-eutectoid steel and heat-treated hypo-eutectoid steel. In **hype-reutectoid** steels, in which the initial structure consists of pearlite and cementite, a martensitic-austenitic structure is formed on the area of the initial pearlite by effect of rapid laser heating and subsequent self-quenching. Cementite does not transform or partially transforms to high-carbon austenite, which transforms "back" again to martensite. **Fig. 2.9** shows a scheme of a change in a structure and hardness profile of hyper-eutectoid steel after soft annealing and the same steel heat treated after the laser exposure.

In a case ad b) mainly a structural phase character of the surface layer changes. Under these conditions, this comprises martensitic or martensitic-austenitic structure with a dendritic arrangement. Under this layer there is a structure of very fine martensite. Further succession of microstructures in a heat affected zone does not differ from those described above, where a surface layer has not been melted (see ad a)). In higher-carbon steels, melting of a surface layer leads to formation of martensitic-austenitic up to purely austenitic surface microstructure including austenite stabilization. In a surface layer in higher-carbon steels even heating near to the melting temperature can result in (even at relatively short-time exposure) grain coarsening and formation of residual austenite.

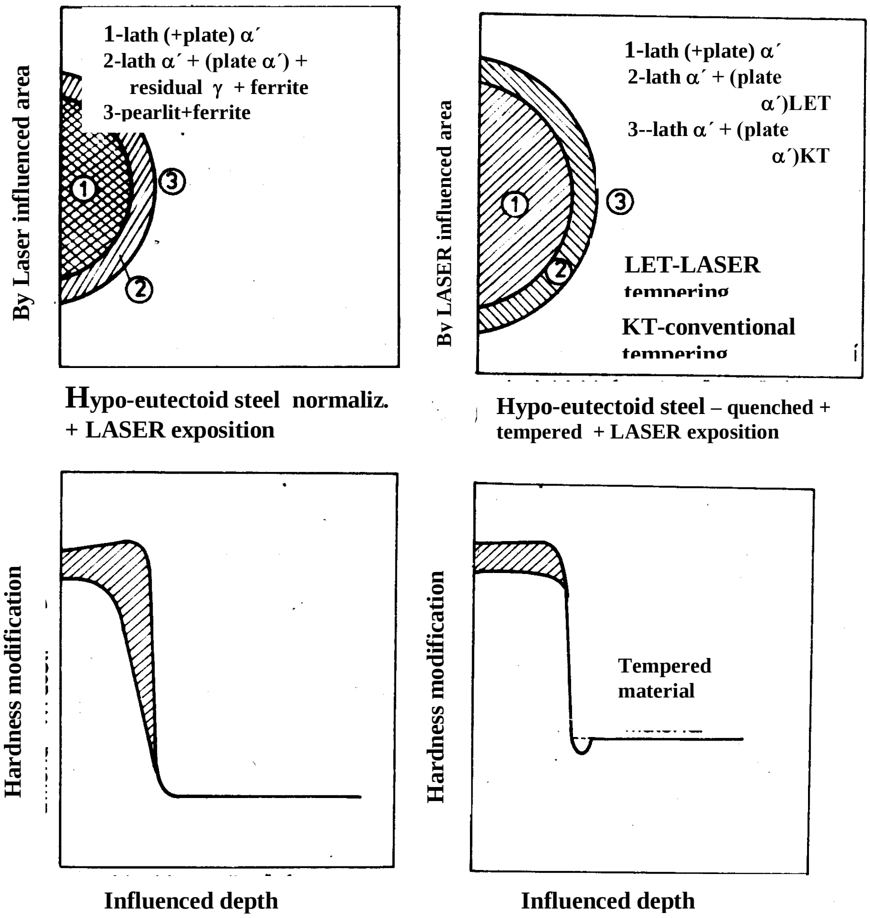


Fig. 2.8 LASER exposition of normalized hypo-eutectoid steel and impact on hardness modification

Laser heat treatment applied on various types of alloyed steels leads to formation of very complicated microstructure characteristics, which are also influenced to a great extent by the material initial state, mainly in connection with a presence of various types of carbidic phases and an entire complex of problems related to "redistribution" of alloying elements during the laser exposure. For laser heat treatment a fine-grained initial matrix with higher structural and chemical homogeneity is more favourable (with regard to shorter paths for diffusion and larger amount of potential nucleation sites for phase transformations at the laser exposure). In this context it can be stated that a degree of saturation of a solid solution and an achieved level of steel micro-hardness with an initial coarse structure can be also increased by decreasing the power density and by a laser beam movement speed. It is logical that an improper selection of these two main technological parameters of laser heat treatment leads to similar drawbacks known from conventional heat treatment methods.

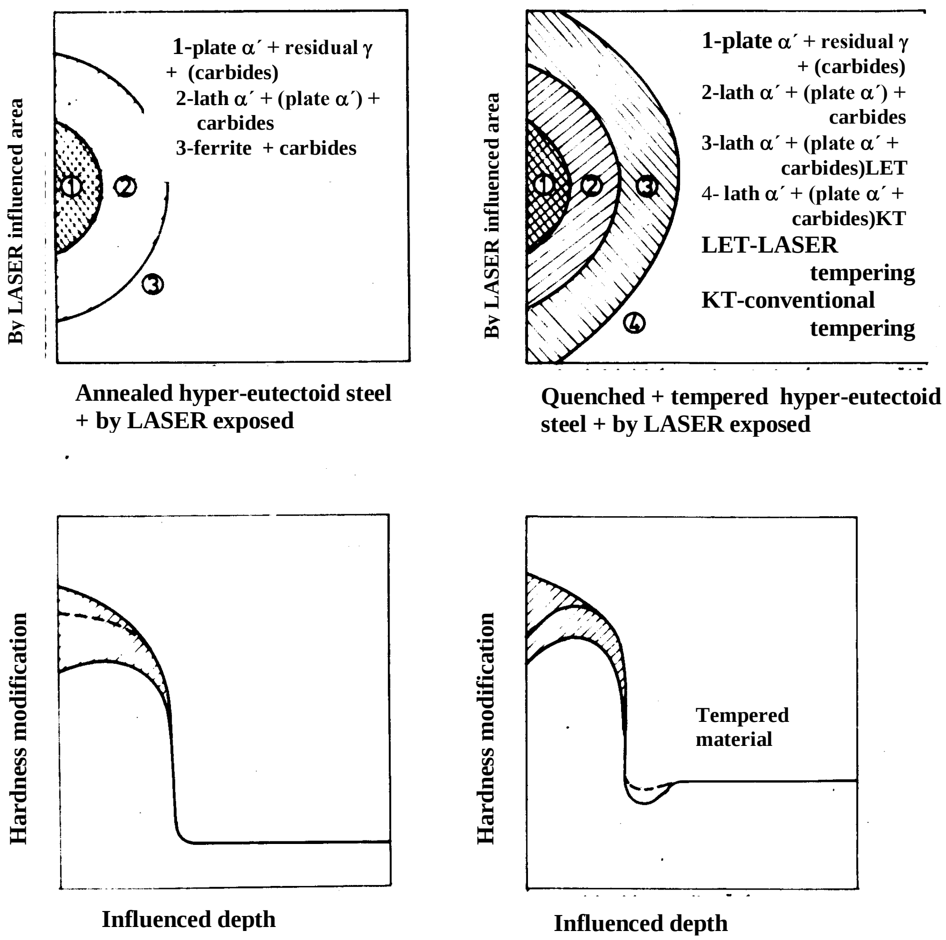


Fig. 2.9 LASER exposition of normalized hyper-eutectoid steel and impact on hardness modification

2.4.1. The use of laser heat treatment (HT) for other types of metal materials

The use of laser for surface heat treatment can be also applied for cast irons (e.g. grey cast iron, nodular cast iron etc.). For grey cast iron, the surface quenching mechanism can be described as follows:

a) phase transformation of pearlite to austenite during rapid heating and its retransformation back to martensite during the following rapid cooling,

b) diffusion of carbon from graphite to the surrounding ferrite (or pearlite), which leads to origination of conditions for formation of austenite during rapid heating.

Parameters of the following martensitic phase transformation (morphology and homogeneity) are determined to the great extent by the initial state of material (pearlite fineness, graphite morphology and distribution of free ferrite in a matrix). Cast irons with coarse graphite, or pro-eutectoid cementite, are not suitable for application of laser exposure. Besides, coarse graphite can “burn out” during laser heat treatment and thus to create conditions for formation of surface defects.

In nodular cast iron, occurrence of martensitic regions can be found around graphite nodules, which is “missing” in grey cast iron with lamellar graphite when surface quenched. This is related to a limited occurrence of free cementite in the given material, into which carbon could diffuse from graphite and would create conditions for transformation to martensite. If a surface was melted during HT, a thin layer with a fine cellular structure is formed, in which graphite has been solved, leading to formation of white cast iron.

In grey cast iron, disturbance of lamellar graphite in a transition area between a melted and non-melted region does not occur, however, in nodular cast iron, a gradual growth of dimensions of graphite nodules in a direction from inside the material towards the melted area can be noted.

Laser exposure can be also used for surface HT of duralumin-type alloys. In this case, hardening is a result of the solid solution oversaturation and general refinement of the forming microstructure. Aside from this, events of successful surface processing of Cu and Ti alloys have been known.

2.4.2. Other variants of technical applications using laser exposure

Except surface quenching, laser cladding can be considered the most promising of all other technical-technological procedures; this technology (6kW, CO_2 laser) is used e.g. for applying a thin layer of cobalt alloys (about 0.5 mm) on turbine blades, for example. This way a higher level of resistance is achieved than by arc welding deposition of the layer, and also higher material utilization and significant shortening of the entire technological operation from c. 14 min to 75s. Application of impulse laser hardening makes a real base for the use of this technology for an increase of resistance to fatigue failure in some aluminum alloys. An interesting and perspective sphere is also an application of laser exposure for the so-called surface glazing, which means formation of amorphous metal on an exposed surface.

The mentioned issues (glazing) have been discussed already before in context with an analysis of conditions for creation and stability of metallic glass (amorphous metal materials). Laser deposition of ceramic coatings on a surface of exposed parts and creation of e.g. TiN layers etc. is used, too. The use of laser for depositing special surface layers (coatings) brings-in higher functional levels of materials at high technical-technological parameters, leads to savings and higher utilization of material and to high productivity compared to conventional surfacing technologies.

2.4.3. Technical-technological applicability of laser processing of metal materials

For laser treatment, CO_2 – laser of a wavelength $\lambda = 10.6\ \mu m$ with absorption coefficient -A- (for steel) lower than 10% is usually used, whereas this value of A coefficient is relatively low even at temperatures just below melting temperature. An important issue within this heat treatment method is a question, in what atmosphere it is advisable to work, i.e. to characterize the oxidation procedure during the laser exposure. As far as the value of absorption coefficient A concerns, this does not vary too much during laser processing both in the inert atmosphere and in vacuum. Air exposure leads to a slight increase in A value at increased temperature (10%). Another important parameter is “coarseness” (roughness) of the exposed material surface. For sanded surfaces, the absorption coefficient value increases by 5 up to as extremely as 35%. From the point of view of effectiveness improvement and wider usage of laser heat treatment, it is necessary to increase the level of A absorption coefficient, i.e. to achieve higher energy utilization. In order to achieve the higher value A, various types of special surface absorption layers are used. These are graphite layers, phosphates (for example $Zn_3(PO_4)_2$), sulphides (Fe_2S_3), nitride layers and vapours deposited fine metal films. Under these conditions the absorption coefficient A increases to 80%, at maximum up to 97%. As far as this layer thickness concerns, except for optical parameters it must also meet a good thermal conductivity demand. A requirement for its uniform deposition and maintaining constant physical characteristics (reproducibility of properties) must be considered obvious. The laser radiation energy transfer to the material surface occurs in three stages:

a) **Primary energy transfer**
b) **Secondary energy transfer**
c) **Energy dissipation**

A primary effect lies in a mutual interaction between photons and quasi-free electrons. Electrons moving at supersonic speed transfer their energy in a lattice through a mutual interaction with other electrons (about 10^{-12} s) and as a result of electron-photon interaction (10^{-11} s). Through this secondary effect, the processed surface "gains" energy density around 10^5 W.cm^{-2}, leading to high heating rate from 10^3 to 10^4 K.s^{-1} in an order of magnitude. Energy dissipation is induced by material thermal conductivity.

The use of laser technology is cost-effective in case of localized processing of larger parts, typically difficult to perform using conventional technologies, even if their number is quite small. On the contrary, in a case of laser processing of smaller parts, heat treatment should be intended for relatively large production lots. In general, this concerns functional, heavy duty surface areas, for instance on bearings and parts related to rotary motion (shafts, axes). Another sphere covers guiding surfaces of machinery components in connection with a long operating life requirement, for example for translational motion, functional surfaces of special shapes (valves seat, gear wheels, clutches etc.). A sphere of application of laser heat treatment of cutting tools, saws, wire-drawing machines, etc. belongs to a separate group.

Σ Summarization of chapter terms

In the end of chapter main terms are recapitulated that you should master and understand their sense, resp. mutual connections

LASER exposition, stimulated emission, power density, exposition time, penetration depths, capacity of absorption

Questions:

1. Could you describe laser principle and its properties?
2. Divide laser types.
3. What power densities and times are necessary for different applications?
4. Describe laser welding, cladding, cutting, transformation hardening, drilling.
5. What the structural zones are formed in case of laser exposition of pro-eutectoid steel after normalization and/or quenching and tempering?
6. What the structural zones are formed after laser exposition of hyper-eutectoid steel dead annealed and/or quenched and tempered?
7. What structures are formed after laser exposition of quenched grey cast-iron?

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