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SURFACE HARDENING OF STEEL AND CAST IRON TOOTHED GEARS BY PENCIL LASER

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***Summary**: The paper presents the general theory of the thermic treatment of hardening through surface quenching of the steel and cast iron toothed gears by a pencil laser, the possibility of renderring the entire process on the computer, the power and speed relations of the laser for a surface quenching of a given depth, the determination of the beam`s oscillation, the method`s advantages compared to classic proceedings of surface hardening and the sketch of the first romanian installation for surface quenching through laser beam.*

***Key words**: hardening, surface quenching by pencil laser, tooth flanck surface.*

Surface quenching by using laser beams is a modern method of fast hardening for metallic surfaces that represents numerous echonomic advantages compared to classic surface treatments (high coherence and mono-chromaticity, directivity and high intensity) have permitted its usage, ako in applying surface treatments the external surface of the flanck, under the action of the laser beam, in the solid phase. The suerfaces are hardened through quenching or cemented at a small depth, so that the base material would preserve its physical, mechanical properties (duchility, malleability, etc.). Laser installations are very efficient at a rapid increase of temperature on the radiated surfaces and if the power of the laser is high enough, after passing the beam over the metallic surface, its rapid cooling, through the absortion of heat by the toothed gear`s proper mass, it produces the quenching of the surface withant the need for an exterior cooling agent.

Two simplifying hypothesis are made when calculating the radied surface temperature increase: 1 – the termic properties of the absorbing metal are independent from the temperature; 2 – the loss of thermic energy on the surface through radiation and convection are negligible, as the absorbed laser power by the unity area (over 10^{10} W/m^2) is a lot bigger tham the power lost through thermic radiation (aprox. 10^7 W/m^2), even for the high temperatures of the heated surface. Thus, the equation of the heat flux on the radiated surface considered in plan xOy ($z = 0$), is:

$$\nabla^2 T(x,y,z,t) - \frac{1}{\delta}\cdot\frac{\partial T(x,y,z,t)}{\partial t} - \frac{1}{\lambda}\cdot A(x,y,z,t) = 0 \qquad (1)$$

where: ∇ - Nabla operator; T - temperature; δ - thermic diffusion coefficient; λ - thermic conductivity; A - the heat produced by the laser beam on volume unit and time unit; t - time.

We add to equation (1) the initial condition (for $t = 0$): $T(x,y,z,0) = T_0$, and the limit condition, that is this case, imposes that $T \to T_0$ for $z \to \infty$ and for $z = 0$, in the absence of the incidental laser radiation. Equation (1) is solved by assuming that the heat flux propagates uni-dimenssionally on the direction z, fact that imposes the transversal dimenssion of the laser beam that constitute the heat source, should be bigger than the depth to which the heat gets into the flanck of the tooth during a laser impulse. Equation (1) in an uni-dimenssional form is:

$$\frac{\partial^2 T(z,t)}{\partial z^2} - \frac{1}{\delta} \cdot \frac{\partial T(z,t)}{\partial t} + \frac{1}{\lambda} \cdot A(z,t) = 0 \qquad (2)$$

The heat source term is:

$$A(z,t) = F \cdot F(t) \cdot e^{-\alpha z} \qquad (3)$$

where: α - absortion coefficient of the luminous radiation near the tooth flanck surface; $F(t)$ - a factor of $(1-R)$ bigger than the incident laser flux F_0 at $z=0$, R - being the reflection coefficient of the considered surface, that is: $F(t) = (1-R) \cdot F_0$. It is assumed that the laser flux is uniformally distributed in plane xOy, having on infinite extent.

For this form of the flux, on metallic surfaces, the absortion coefficient is: $\alpha = 10^7 \div 10^8$ m^{-1}. In this case equation (2) leads to a relatively simple solution, and the temperature at depth z of the tooth flanck surface is:

$$T(z,t) = 2 \cdot F_0 \left(\sqrt{\frac{\delta \cdot t}{\lambda}} \right) \cdot ierfc\left(\frac{z}{2 \cdot \sqrt{\delta \cdot t}} \right) \qquad (4)$$

where: $ierfc\left(\frac{z}{2 \cdot \sqrt{\delta \cdot t}} \right)$ - is the integrad for the normal function of distribution of Gauss ` errors and for the flanck surface $(z=0)$ we have:

$$T(0,t) = \frac{2 \cdot F_0}{\lambda} \sqrt{\frac{\delta \cdot t}{\pi}} \qquad (5)$$

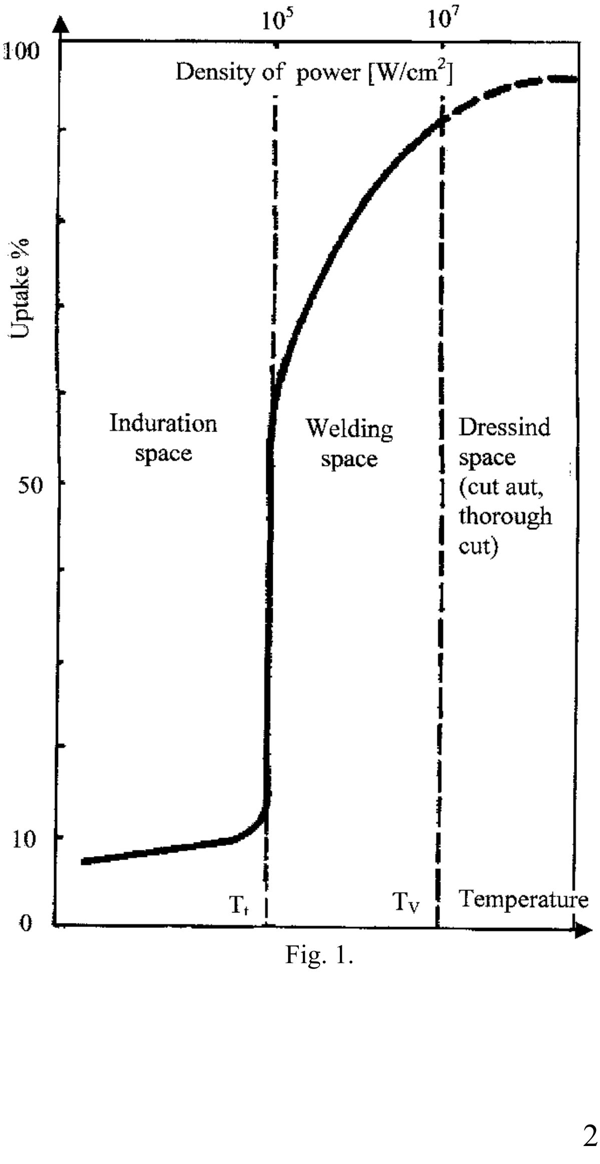

Fig. 1.

The determination of those temperature can be also done experimentally through measuring the electronic emission of the radiated surface, of the ionic emision or of the electro-magnetic radiation emission.

The thermic treatment of surface quenching of the tooth gear surface can be done by using CO$_2$ laser installations having the power P between 1÷2 kW (it is necessary that $P > 600$ W), considering that metals at a room`s temperature have a low coefficient of absorption, for the laser radiation with the wave – length $\lambda = 10{,}6$ µm, emitted by these installation (as the most intense line).

Fig. 1 presents the variation curve of laser absorption with the temperature of the carbon steel surface, positioned in infra-red, in the above mentioned condition, T_t - the melting temperature; T_v - the metal`s vaporizing temperature. Laser in-stallations YAG:Nd (continuos wave) with powers between 0,5÷5 kW are also used in order to focus the radiation, lenses with a focal length of $F = 25 \div 300$ mm, as well as mirrors, rotaring lenses are used, fabricated of NaCl, KCl, Ge, GaAs, fact that assures the obtaining in the focus of optical systems superficial power of $10^3 \div 10^8$ W/cm^2, the diameter of the focused beam being of 10÷10.000 µm.

Hardening treatments of the tooth flanck surface are performed under temperature T_t, when over 90% of the incidental beam`s energy is reflected on the surface of the flanck, while al T_t, the absorption coefficient increases shorthy to values of over 50% and even over 90% al the vaporizing temperature T_v. For this, a thin layer of strong absorbant radiation $\lambda = 10{,}6$ µm, fabricated of: wolfram or cooper oxides; Mg, Mn or Zn phosphates; paints; black pigment; etc. Is applied on the surface to be thermically treated. The usage of Mg phosphates is cheaper and easier to apply at industrial scale.

For the thermic treatment of hardening the toothed gear`s flanck it is recomended as a method of controli of the laser beam „*the oscillatory methodh of the pencil laser*”, as it has a high productivity and allows obtaining a superior quality of the quenched surface. It is presented in fig. 2.*a*, and the oscillatory pencil laser scavenges the treated are with a frequence that ean be of hundreds of hertzs, while the tooth moves with a certain speed, perpendiculary the direction of oscillation of the beam, dependent on the height or widht of the tooth. Thus, the homogeneity in depht of the hardened layer increases (fig. 2.*b*). The process takes place with densities of the laser beam of at least 10^5 W/cm^2, in order to reach the optimum temperature of the thermic treatment.

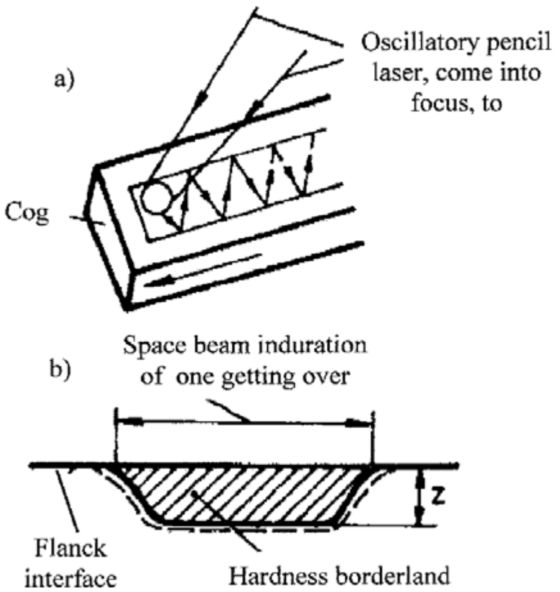

Fig. 2.

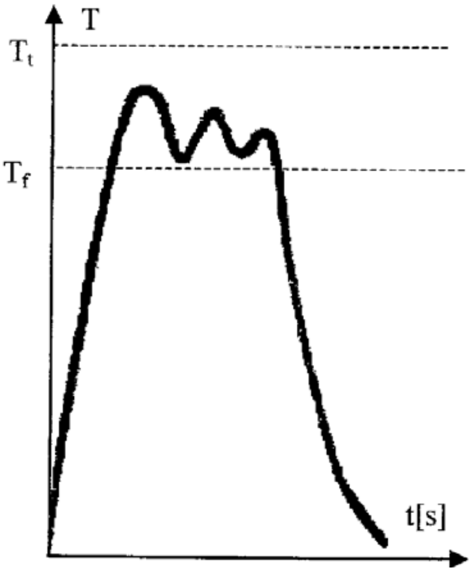

Fig. 3.

The chart temperature – time (T,t) of a thermic treatment of hardening the flanck surface of a toothed gear is rendered in fig. 3. It presents the cooling – heating cycle of the thermically treated surface layer by a pencil laser, over the treated surface, and the passing speed must be chosen so that the tempersture of the flanck interface, at the moment of the impact with the laser beam, would be under T_t, but superior to the transformation T_f (austenitization) at which the hardening of the surface is realized, and where when cooling the carbon steels, the transformation of austenite in a rough mixture of pearlite and martensite takes place.

In fig. 4 we presents the treatmen speed variation, depending on the depth of the hardened layer for two scavenging frequencies of the pencil laser with a power of $P = 1.500$ W. It is observed that for the beam $f_1 = 300$ Hz the flanck interface doesn`t melt, not even in reduced local areas, that is very narrow toothed gears, whileas at the frequency $f_2 = 200$ Hz some parts of the treated surface cand undergo local meltings, but a layer thickness of the hardened layer can be realized.

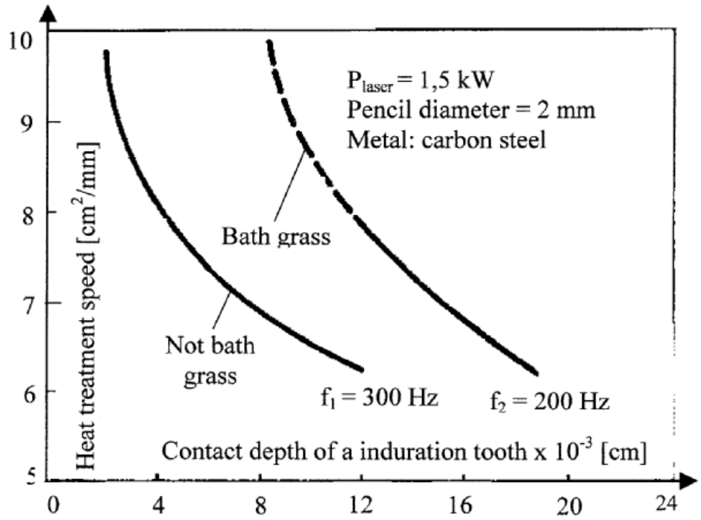

Fig. 4.

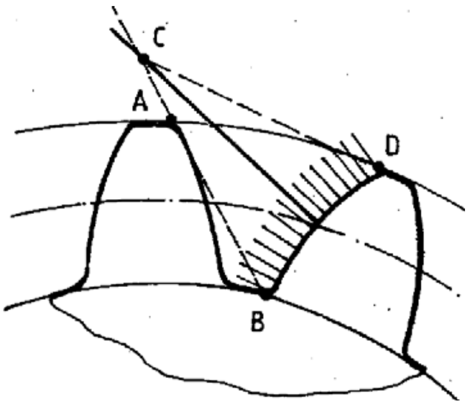

Fig.5.

Experimental results when hardening steel and cast iron surfaces, show that hardenesses of 70 HRC have beam obtained and depths of 0,27 mm, respectively 0,37 mm for the treatment with pencil laser, with CO_2, having the power of 600 W, respectively between 1÷2 kW. As the speed of surface hardening with pencil laser is of 10^6 ºC/s, the heating time is of microseconds, very thin layer can be austenited, of micro – metals, the cooling speed after radiation is extremely high, of $10^3 \div 10^4$ ºC/s, with a direct influence over structural transformation.

The hardening of the tooth flanck surfaces is realised through superficial quenching, in a solid phase, by pencil laser, when the austenitization is performed at higher temperatures than in the case of classic treatments: $T_f = A_{c3} + (200 \div 300)$ ºC, as point A_{c3} fluctuates at a lot higer temperatures, the heating not affecting the siye of the grain of austenite, bacause of the extremelly short period. The thichness of the quenched layer depends on the steel`s degree and property of being quenched and on the tehnological parameters.

The usage of the pencil laser allows the fast heating of very thin layers of 0,01÷0,4 mm, which after the radiation cod down extremely fast, with cooling speeds much higher than the critical ons, thanks to the contact to the cold metal mass of a tooth, which absorbs a high quantity from the heat produced by the laser in a very short time. A consequence of the local thermic balance is the metal graphic structure of the quenched layer, made of a sublayer of bainite, troostite and under 50% martensite, depending on the rate between the local cooling speed and the critical cooling speed, and a martensitic sublayer. The first sublayer, of 0,01÷0,05 mm, has therefore a decreased hardness.

Fundamentally, obtaining quenched bands can be realized shrongh many variants. The triatable flancks of toothed gears represent very big surfaces compared to the diameter of the pencil laser, so the most indicated method is that of oscillating the spot in a perpendicular plane on the gear`s direction of movement, on a given frequency, movement that can be realised on the width of gear (for narrow gears) or on the height of the teeth. The oscillation of the spot on the heigth of the gear is more advantageaus (as the amplitude of the scavenging movement will be considerably smaller, the turning points of the spot, being closer).

The best case in for the incident beams to foll perpendicularly on the tooth`s profille in every point of it, the charge of heat would be maximum and a quenched layer of a constant widht would be obtained on the entire hught of the tooth. The movement of the fixing point at as hig distances as possible from the surface, is therefore imposed. The determination of the laser`s head fixing point is obtained by uniting ful tap of the tooth (point A) with point B situated at the base of the tooth flanck that is under the process of hardening, obtaining a straight line that defines the area in which the oscillating point can move, so that to awoid „*shading*” (fig. 5). We take the normal to the evolventic profile of the tooth, that passes through the middle of its height, and which will intersect the line AB in point C if the beam will oscillate around point C, the quenching of the entire flanck BD will be performed, from top to base, as well as a convenient distribution of the quendind depth. The position of point C depends therefore on the gear`s module and on the its number of teeth. Toothed gears that can be successfully hardened by pencil laser are the ones with a big module and a small number of teeth.

From the equation of heat change the folloving relations derive for power P and speed V, requested be obtain a quenched layer of a given depth z_k [cm]:

$$P = \frac{\lambda \cdot r^2 \cdot \pi}{C \cdot z_k}\left(T_a - T_f\right) \tag{6}$$

$$V = \frac{8 \cdot \delta \cdot C^2 \cdot P^2}{\pi^3 \cdot r^3 \cdot \lambda^2 \cdot T_s^2} \tag{7}$$

where: r - the spot beam in cm; C - the absortion coefficient; T_s - the spot temperature at the surface $\left(T_s < T_t\right)$ in ºC; T_a - the maxim allowed temperature and the radiated surface, in ºC.

In table 1 the characteristies are rendered, along with their measurement units from the relation (6) and (7) for two steels used in fabricating toothed gears:

Table 1. The variation of power P and speed V for two steels.

Steels	λ W/cm ºC	δ cm^2/s	r cm	z_k cm	T_s º C	T_f º C	C	P W	V m/s
T30SiMn12	0,195	0,045	0,1	0,04	1250	1000	0,3	128	0,286
41MoCr11	0,557	0,127	0,1	0,04	1250	1000	0,3	365	0,8

The results show that in order to obtain the same depths in quenching a steel with a superior thermic conduction a higher speed and power are required.

The sketch of the first romanian installation of surface quenching by laser for toothed gears is presented in fig. 6. The radiation is induced in a CO_2 generator of 1,2 kW, conducted through optical cable to the laser head, in which the radiation, expanded by a lens, will be focused with the help of a second lens made of GaAs, with a large focal distance (8 inches). Between the laser head and the toothed gear on oscillatory mirror is interposed, achioned by a spacial mechanism RSSR crank – balancer, with a variable angle of oscillation of the final element. Through the oscillatory movement of the mirror the scavenging of the spot obtaine tooth flanck is realised. The scavenging speed is adjusted by varying the speed of the oscillating mechanism of the actioning servomotor. The aperture of the angle of oscillation is adjusted by manually modifying the angle of inclination of the crank axis rated be the shoft axis (fig. 7). The toothed gear is fixed on a rotating table, that can perform a vertically advancing movement, being actioned by a ball screw – nut mechanism (electric cylinder). The oscillating mechanism can rotate around the mirror`s vertical axis, being supported by an axial bearing; its position on the plane, towards the table can be adjusted with the help of two screw – nut mechanisms, respectively with the help of two a sustaining waggon masing on two rails.

The subsystems are integrated in a commanding programming and controll system that includes a process compouter. After realizing the adjustement of the mirror`s position forwards the toothed gear, the laser emission is activated, the progress of the process being entirely controlled by computer.

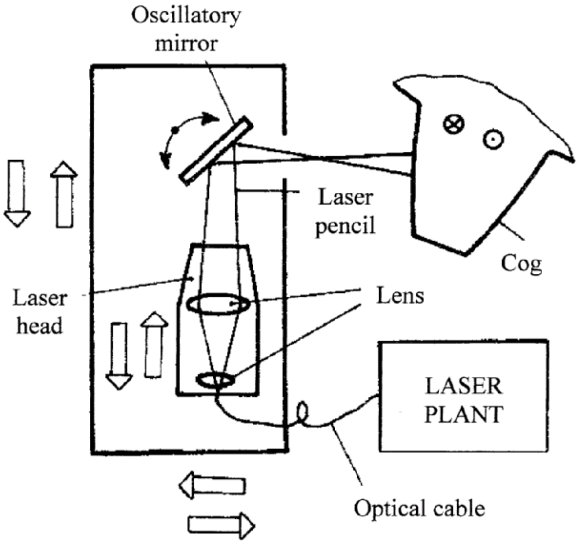

Fig. 6.

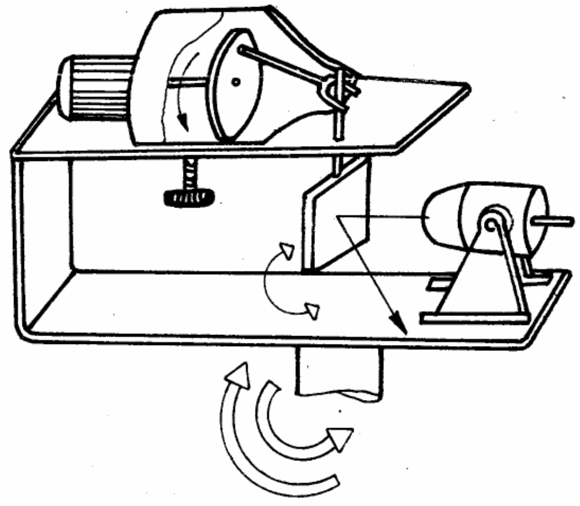

Fig.7.

This romanian installation of surface quenching by laser for toothen gears with a large module fits only to gears with straight teeth, buit with certain amendments of this prototyp, gear with angerlar or conic teeth can also be quenched.

Though the laser installation has a relatively high price, it is recommended for industrial application thanks be its advantages compared by after methods of surface quenching: the possibility of selective quenching of a toothed gears withant special devices, from moving from sides to sides a few simple adjustements are enough; it functions at a high speed, wirhant cooling source and it obtains structural transformation that bring akont a significant increase of the roughness, resistence for wearing and corrosion; thamks to high – speed cooling structures almost enthirely martensitic can be obtained to also in the case of steels poor in carbon; the quenched toothed gear doesn undergo deformation, so the surface quenching can be also used in the final processing of the gear; though the generation of the radiation is done with on efficiency of 15÷25%, from the heat exchange point of new, a superior efficiency is assured, compared to classic quenching by flame or induction it assures a rigurous control of the quenching process and high precission of processing, that is why the quenching depth and the hardness are reproducible; it easily fits to automation and doesn`t pollute the environment; after the possibility of introducing the process on computer, so that some mathematic modules can be used to fix hardening parameters, respectively the calculus of temperature T in connection with time t and depth of hardening according to the equations presented above mentioned.

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