Analytical Solution to Predict Transient Temperature Distributions during Laser Surface Hardening.

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Abstract: This paper introduces a new analytical solution to predict transient temperature distributions in a finite thickness plate during laser surface hardening. This analytical solution was obtained by solving a transient one-dimensional heat conduction equation with convection boundary conditions at the surfaces of the work piece. To calculate the temperature field analytically in laser surface hardening processes, laser beam absorptivity was evaluated as one of the most important parameters, the laser and materials parameres were determined. It was extremely difficult to find an accurate value for laser beam absorbtion rate. Therefore, in this paper, absorptivities were determined theoretically under various hardening conditions, including variations in hardened thickness beside variation in surface and subsurface temperature.Owing to the simplicity of the solution method, the analytical model developed may be easily implemented for simulation work for analysis and prediction of laser surface hardening processes under various hardening conditions.

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1. Introduction

Heat transfer is energy in transit, which occurs as a result of a temperature gradient or difference. This temperature difference is the driving force that causes heat to flow. Heat transfer occurs by conduction during laser irradiation of metals and alloys. Conduction of heat in solids is thought to be due to motion of free electrons[(1),(2)], lattice waves, magnetic excitations, and electromagnetic radiation. The motion of free electrons occurs only in substances that are considered to be good electrical conductors. The theory is that heat can be transported by electrons, which are free to move through the lattice structure of the conductor, in the same way that electricity is conducted [(3),(4)]. This is usually the case for metals. The molecular energy of vibration in a substance is transmitted between adjacent molecules or atoms from a region of high to low temperature[(5),(6)].

In 2000 the using of UV light in material processing is studies by H.Endert and others, the effect of new ultraviolet lasers upon the material surfaces produce color and properties change which may be explained in terms of microstructure changes[(7),(8)].

The ultra violet laser is a clean source of high energy density [(9)]. Surface irradiation processes involve non equilibrium phenomena due to high heating and cooling rates induced by the laser irradiation. The inherent rapid cooling due to high thermal conductivity of steel makes lasers very attractive since the irradiated parts contain various microstructures with metastable and stable phases, fine grain, minimum segregation, and extended solid solutions which improve the mechanical and metallurgical properties of the irradiated parts[(10):(14)].

The amount of heat used for irradiation along the depth is considered to be proportional to the input heat flux along the direction of that unit depth [(15)]. This assumption is based on the fact that in the absence of conduction loss, the amount of irradiated material, that is the amount of heat used for irradiation increases as the input heat flux increases and vice-verse. Therefore, the amount of heat used for irradiation can be expressed as function of temperature and physical parameters such as thermal conductivity, density and specific heat [(17):(19)].

2. Theoretical Investigation of the problem

Analytical model for the computation of temperature and heat flux distribution in a semi-infinite solid when subjected to spatially decaying, instantaneous laser source is investigated. The appropriate dimensionless parameters are identified. The reduced temperature and heat flux as a function of these parameters are presented in mathematical formula. Temperature and energy are presented as a function of different laser parameters[(20),(21)].

Mathematical model gives us description for the material behavior specifically the values that can not be measured. Stainless steel 304 has been chosen as an example for characterizing laser irradiation of the alloys[(22),(23),(24)]. The reflection was about 85%, and scattering was about 4% [(25)]. The reflectivity of stainless steel is nearly constant in the range from 300K to 1800K [(26), (27)]; which is the case in this investigation. Fig (1) shows Schematic representation of Steps of the analytical solution.

The analytical solution of the heat equation includes phases transition for pure metals in the solid state.

$$K(T)\left[\frac{\partial^2 T_s}{\partial z^2}\right]=\rho(T)C_p(T)\frac{dT}{dt}+\rho\left(\frac{d(z_m-s)}{dt}\right)H \quad (1)$$

The heat equation in one dimension includes phase transition

$$\rho(T)C_p\frac{dT}{dt}=k\left[\frac{\partial^2 T_s}{\partial z^2}\right]-\rho\left(\frac{d\Delta z}{dt}\right)aH \quad (2)$$

$$T(z,0)=T_s=2q_s\frac{(Dt)^{1/2}}{K(\pi)^{1/2}} \quad (3)$$

$$-k(dT/dz)=\frac{Q}{a\eta}=I\eta=\left(\frac{3P}{\pi r^2}\right)(\eta)\left(1-\frac{r}{R}\right) \quad (4)$$

where $z_m-s=\Delta z$

$$\frac{dT(z,t)}{dz}=0 \quad (5)$$

Differentiating equation was solved by laplace transform and inverse laplace transform techniques to give it is interest to Calculate the heat flux at any z

$$-q=-k\frac{\partial T}{\partial x}=\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)e^{[3P\eta(1-r/R)/\pi r2(T-Ts)]}\frac{z}{k}+\left[\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)(T-T_s)\right]\frac{2Dt}{k^2}\mathrm{erf}\left[\frac{z}{2\sqrt{Dt}}+\left[\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)(T-T_s)\right](Dt)^{1/2}-\right.$$
$$-\frac{\mu k}{2}\left(\frac{d\Delta z}{dt}\right)H\, e^{(-\mu z+D\mu 2t)}\mathrm{erf}\left[\frac{z}{2\sqrt{Dt}}-\mu(Dt)^{1/2}\right)-\frac{\mu k}{2}\left(\frac{d\Delta z}{dt}\right)H[[\mu+\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)\frac{1}{k}[(T-T_s)]/[\mu-\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)(T-T_s)]\; e^{(\mu z+D\mu 2t)}\mathrm{erf}\left[\frac{z}{2\sqrt{Dt}}+\mu(Dt)^{1/2}\right)]$$
$$+\left(\left[\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)\frac{1}{k}(T-T_s)\right]\frac{2Dt}{k^2}\right)\mathrm{erf}\left[\frac{z}{2\sqrt{Dt}}+\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)\frac{1}{k}(T-T_s)\sqrt{Dt}\right]+\frac{\mu k}{C_p}\left(\frac{d\Delta z}{dt}\right)H\, e^{(-\mu z+D\mu 2t)}+\frac{k}{2C_p}\frac{d\Delta z}{dt}H\left[2\left[\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)\frac{1}{k}(T-T_s)\right]\right]^2$$
$$\left[\mu-\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)\frac{1}{k}\;(T-T_s)\right]e^{[z\frac{3P\eta}{\pi r^2}\left(1-\frac{r}{R}\right)\frac{1}{k}(T-Ts)}$$

(6)

List of symbols

Symbol	Unit		Definition
Q	joule	J	Energy
I		W/m^2	irradiance
Z	mm		Distance
P	watt	W	Laser power
T	kelvin	K	Temperature
t	Sec	s	Time
ρ	Kg/m3		Density
A			Absorptivity
a	cm^2		Area
ρ	g/m^3		Density
η			Efficiency
C_p	J/kg.K		Heat capacity
D	cm^2/sec		Thermal diffusivity
I_o	J/cm^2		Energy released by laser source
K	W/cm.K		Thermal conductivity
P	watt		Laser power
q	J/cm^3		rate of heat generated per unit volume
r	cm		The beam radius
s			Laplace transform variable
T			Temperature
t	sec		Time
x	cm		Spatial variable
Z	mm		Distance
μ			Absorption coefficient

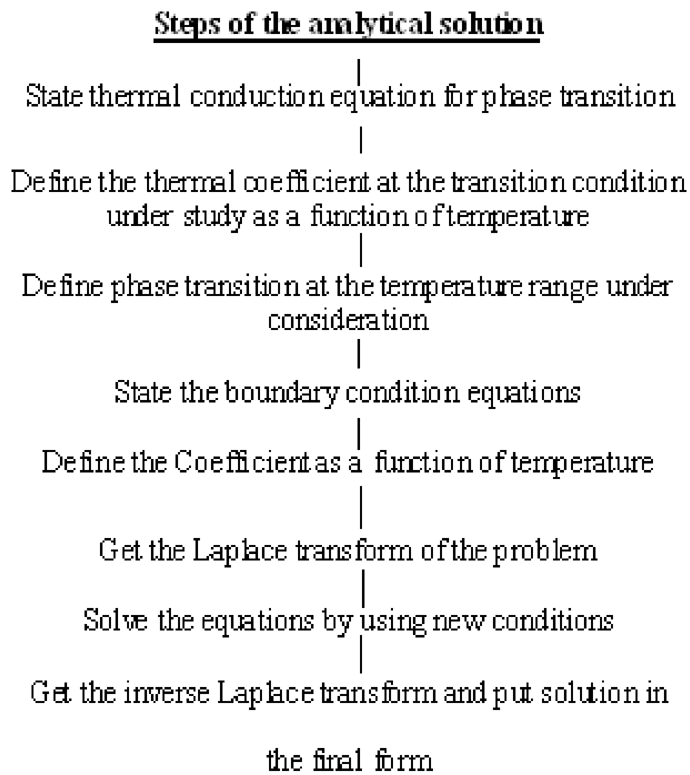


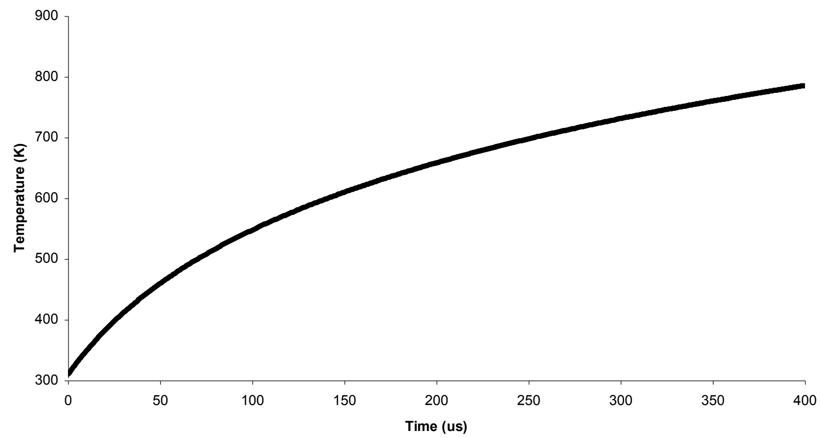
Fig (1) **Schematic representation of Steps of the analytical solution**

3. Results & discussions

Heating & phase transformation stages

The process of heating begins by absorbing the laser energy and converted it into heat. This heat source is considered as laser beam irradiation. The absorbed energy heats up the surface layer and the heat propagates into the metal by conduction. The heating of a semi-infinite insulated rod of Steel sample was done by laser radiation of intensity 150 W/cm^2.Energy per pulse was 6mJ and the total energy was 30J at 5000 pulses and Fluence 0.75J/cm^2. The problem is analyzed in one dimension using the heat transfer differential equation. The boundary conditions include the heat flux at one end and room temperature of 300K at the other end. The initial condition of the sample is the room temperature at 300K. The sample is semi-infinite. There is a sensible temperature variation at the interaction zone.

The problem is solved by the analytical solution method described before by Laplace transformation method. Figure (2) shows the variation of temperature with time at position (50µm) in the metal sample during laser irradiation. The temperature increases with increasing time and the rate of increase depends on the distance from the surface. The steps of temperature rise at different times (5 µs, 10 µs, and 15µs) with laser irradiation are shown in Figure (3). At all times during the laser irradiation process the surface temperature is higher than the substructure temperature and the temperature gradient is continuous until inside of the samples reach room temperature. The curves show the different stages of the heating process. Figure (4) shows the temperature distribution versus depth inside the metal after phase transition. The temperature at the surface reaches the phase transition 1183K (910°C –γ formation) after 20µs. Phase transformation process is a function of temperature, so all corresponding processes such as hardening and softening is a function of temperature. Every phase has formation energy. The energy of formation is a function of temperature. Temperature rises due to laser irradiation. The alloy absorbs photons of light at specified power and number of pulses, then the alloy reaches the energy of phase transition at critical temperature of phase transformation. Theoretical model explains the physical phenomena of phase transition which is considered as the main reason for hardening or softening resulting from laser interaction with the surface of the alloys [19].



Fig(2)The Variation of Temperature of Steel with time at the surface point z4=50um During The First Pulse

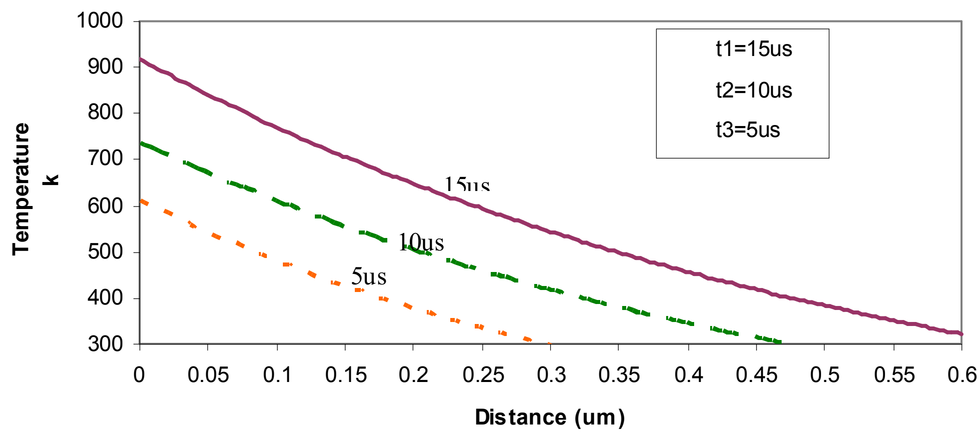
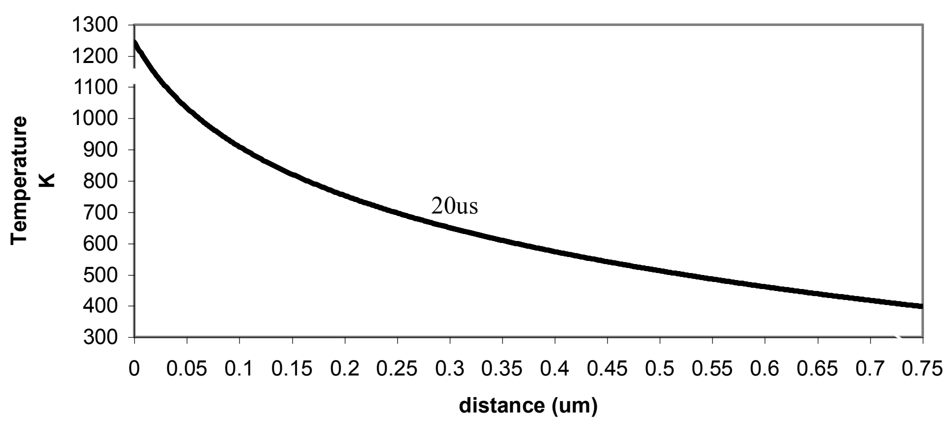


Fig (3) The variation of temperature with distance in analytical solution before phase transition of steel



Fig(4) Heating of steel along the distance when irradiated by lasers after phase transition and before melting at 20us

Comparing results with published

When comparing the experimental results with the mathematical model the increase in total laser energy leads to increase in the Gibbs's free energy absorbed and rise in the temperature of the alloys, this may produce suitable conditions for the formation of more energy phases. Figure (5) shows the variation of the irradiated depth with time when the sample irradiated by 308nm excimer laser. Irradiated depth increases exponentially with irradiation time. The increase in irradiation time increases the amount of absorbed energy, the energy absorbed can penetrate extra depth. Some literature (10), (13) observed several thermally induced effects when an intense laser radiation is incident upon a surface. A possible explanation for this phenomenon was given that the point of maximum temperature before the phase change occurs at the exposed surface lies inside the body because of the heat loss to the surroundings. The phenomena investigated analytically by calculating the temperature profile in a semi-infinite body with an exponentially decaying source and convective boundary condition. The position of the maximum temperature is a strong function of the physical parameters.

Fig (6) shows the variation of irradiated depth versus number of pulses. The irradiated depth increases linear as the number of pulses increase. At 50000 pulses the irradiated depth expected was 25µm. The irradiated depth at low number of pulses from 2000 to 15000 pulses was limited to less than 10µm. In the experimental results, the irradiated depth was less than the calculated depth. The irradiated depth measured in experimental work was limited to 200nm at all number of pulses. The deviation between experimental results and theoretical results was for the following reasons:

1-Error in experimental measurements

2- The mathematical model neglected the scattering of laser beam between atoms distribution inside the alloy (only consider surface scattering).

3-Degree of surface finish was calculated by theoretical model

4-Experimental method based on certain approximation to calculate irradiated depth.

The deviation between experimental work and the theoretical model was in the acceptable range recommended in the literature.

Fig (7) and Fig (8) show the variation of temperature versus energy in the range from 0 to 50000 pulses at the energy per pulse was 3.5mJ and 6mJ respectively. The amount of total energy at 50000 was 170000mJ when the energy per pulse was 3.5mJ and at 6mJ was 290000mJ. When the energy per pulse increased, the total energy absorbed also increased at the same number of pulses.

The effect of number of pulses

Fig (9) shows the variation of temperature with number of pulses. The temperature rises linear with increase in the number of pulses in the range from 0 to 15000 pulses. At a high number of pulses more than 20000 pulses, the temperature was changed exponentially with an increase in the number of pulses. According to the theoretical results the temperature reach to 1800K (melting point) when the number of pulses more than 50000pulses, which is the critical point in our study range that deal with transformation in solid state only.

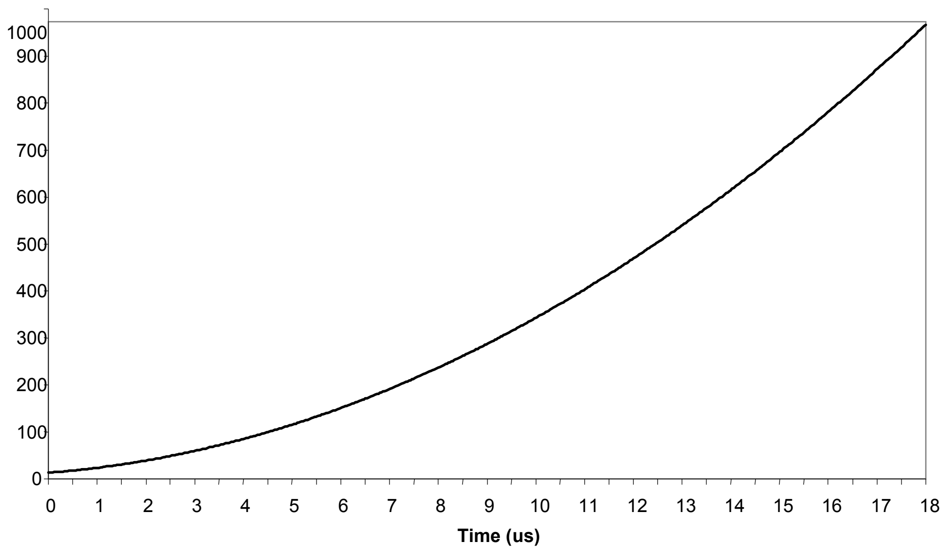


Fig (5) The Variation of The Irradiated Depth with Time for Steel irradiated by Excimer Laser at 308nm,200Hz,6mJ

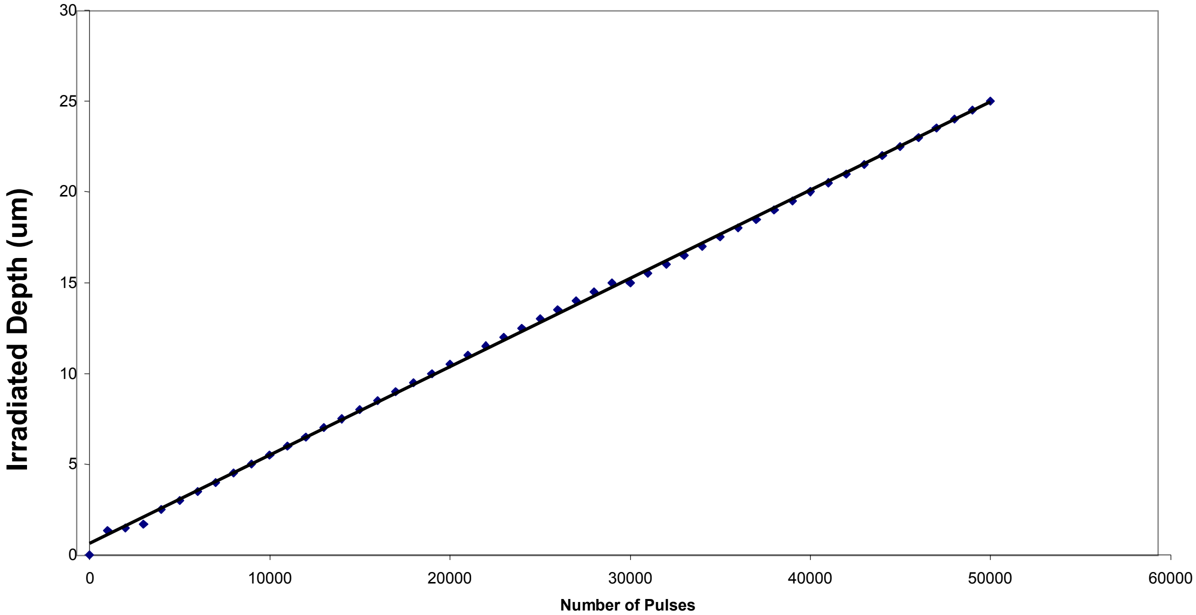


Fig (6) The Variation of irradiated Depth with Number of Laser Pulses For Steel Alloys Irradiated by Excimer Laser 308nm,200Hz,6mJ

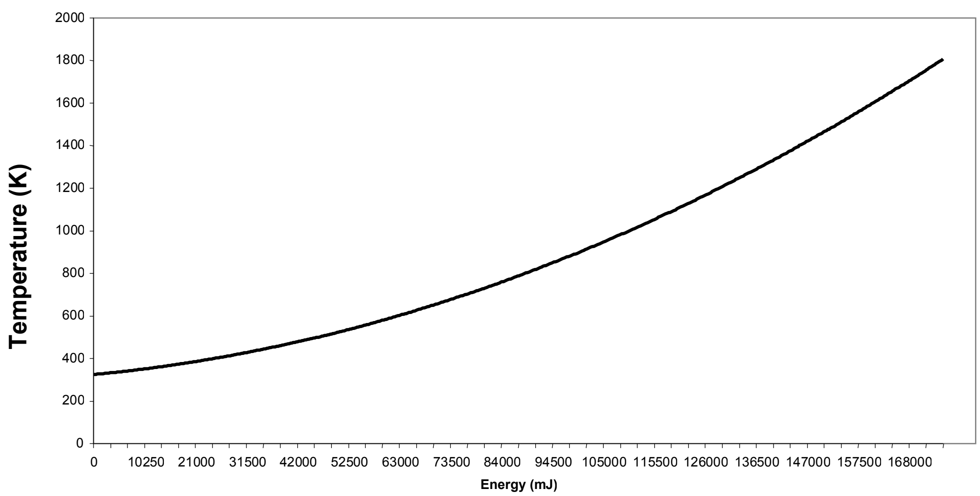


Fig (7) The variation of Temperature with Energy for Steel irradiated by Excimer Laser 200Hz when the energy per pulse 3.5mJ

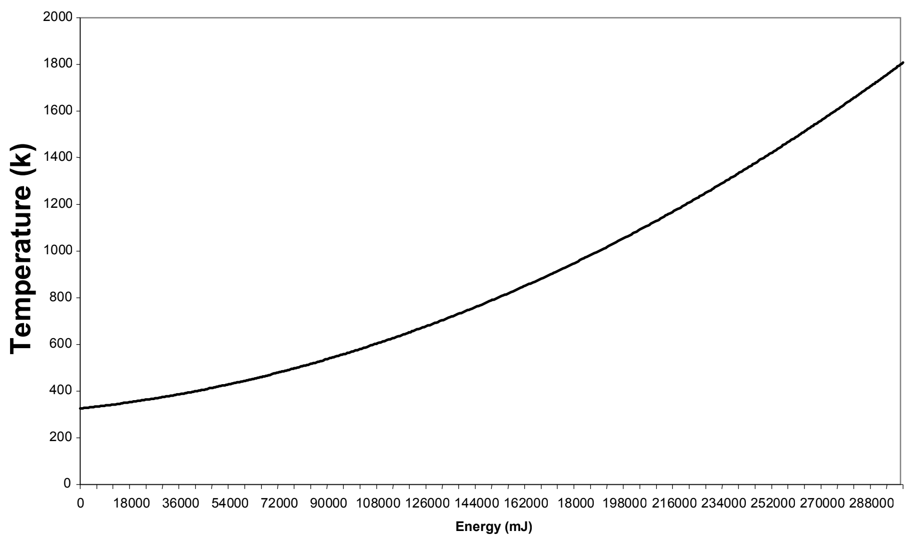


Fig (8) The variation of Temperature with Energy for Steel irradiated by' Excimer Laser 200Hz when the energy per pulse 6mJ

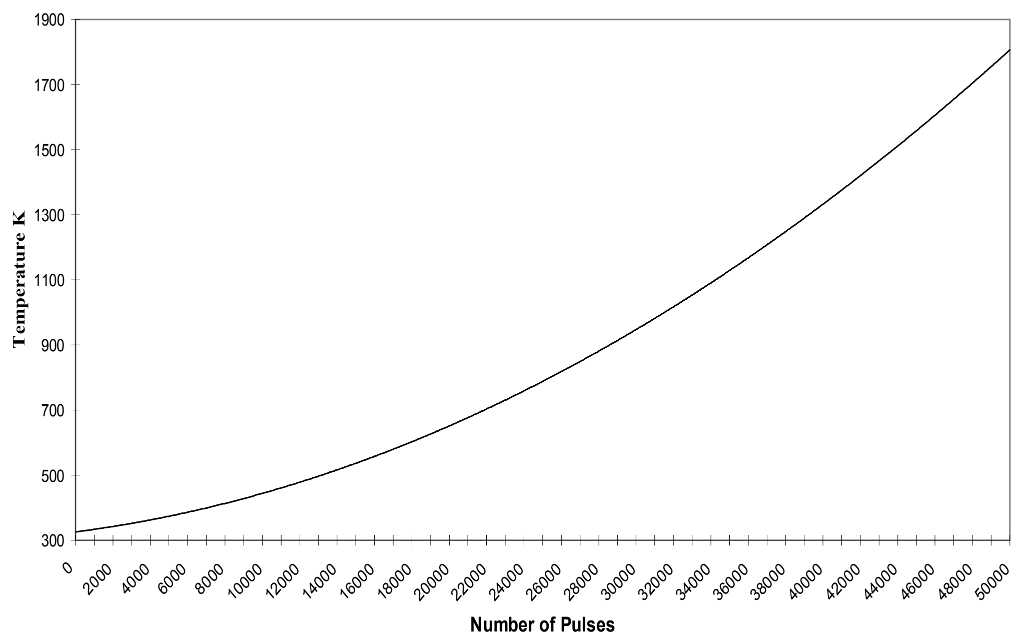


Fig (9 The Variation of Temperature with Number of Laser Pulses For Steel Alloys Irradiated by Excimer Laser 308nm,200Hz,6mJ

Fig (10) shows the variation of temperature versus irradiated depth. The increase in irradiated depth occurred as result of the increase in temperature of the sample surfaces. The increase in the surface temperature means the increase in the total amount of energy absorbed due to increase in number of pulses at constant repetition rate, wavelength and energy per pulse. Fig (11) shows the temperature variation with the rate of laser interaction with the alloy (velocity of interaction) as shown in the figure in solid state before melting point at 1800K. The rate of laser interaction was constant. When the temperature was more than 1800K (liquid state) the rate of interaction was linear and increased gradually with temperature rises.

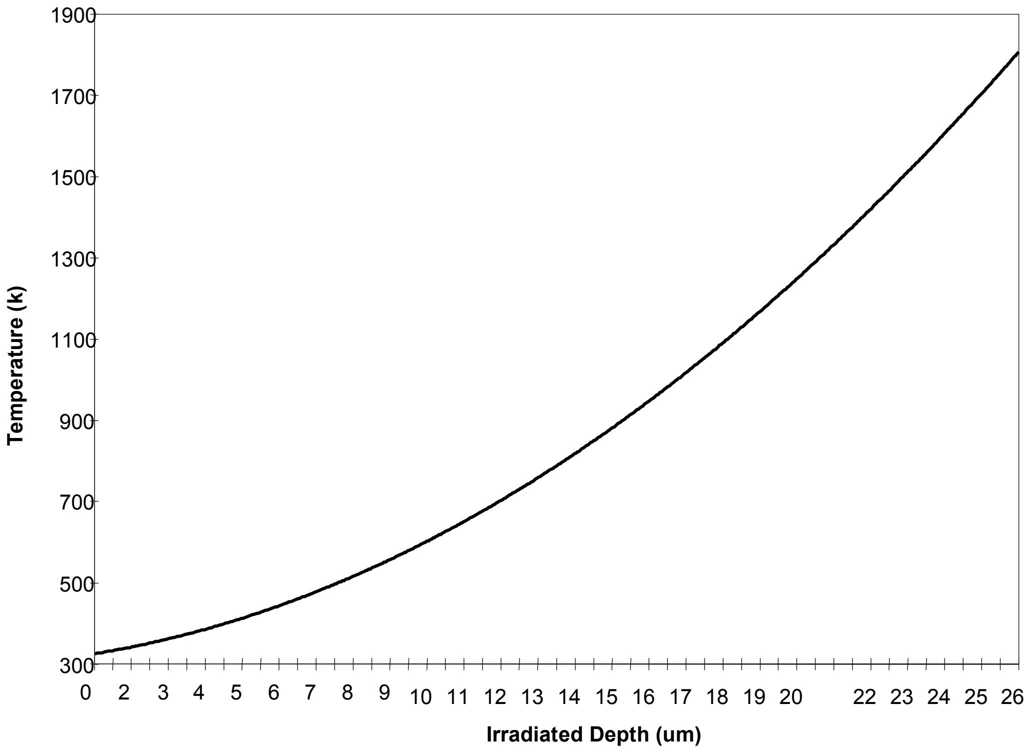


Fig (10) The Variation of Temperature with irradiated Depth for Steel irradiated by 308nm, 6mJ,200Hz

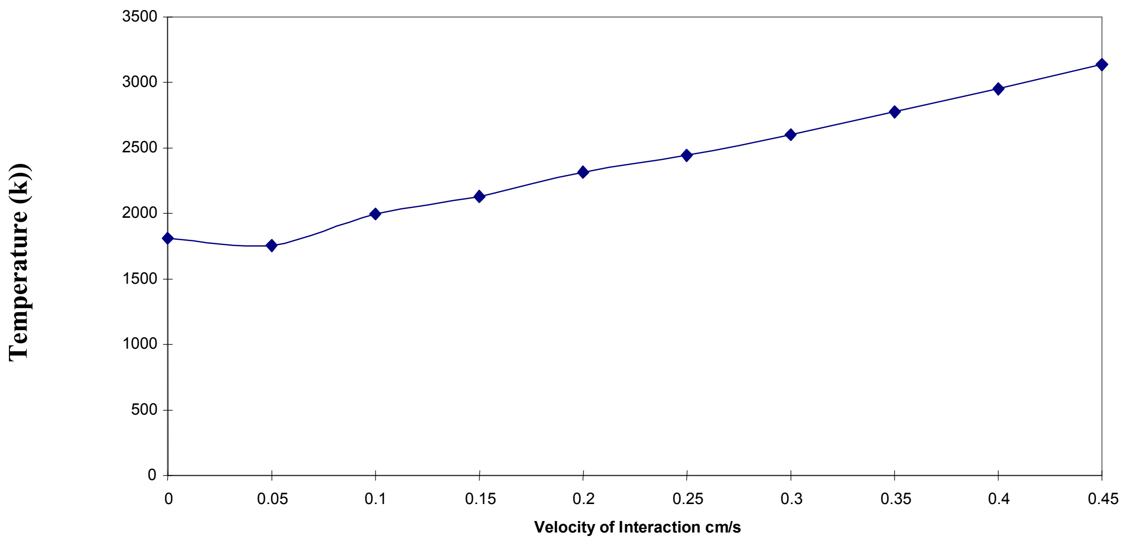


Fig (11) The Variation of Temperature with Interqaction Time for Steels when irradiated by Excimer Laser 308nm,200Hz,6mJ

Comparing theoretical & experimental results

Fig (12) shows the relation between temperature and measured depth for stainless steel 304. Comparing these curves with Figure (10), it shows that both theoretical and experimental results have the same trend.

There are some deviation in values between theoretical study and experimental work due to error in the experimental work and precaution of the model explained before. The results in literature concur with our results [13), (14]. The experiments in the literature use steel 45 and the relation between temperature and depth have the same trend. The deviation between experimental results and different methods of theoretical investigation was about ± 6% to ±20% [38), (39]. Our results were in the same range of deviation 17% approximately.

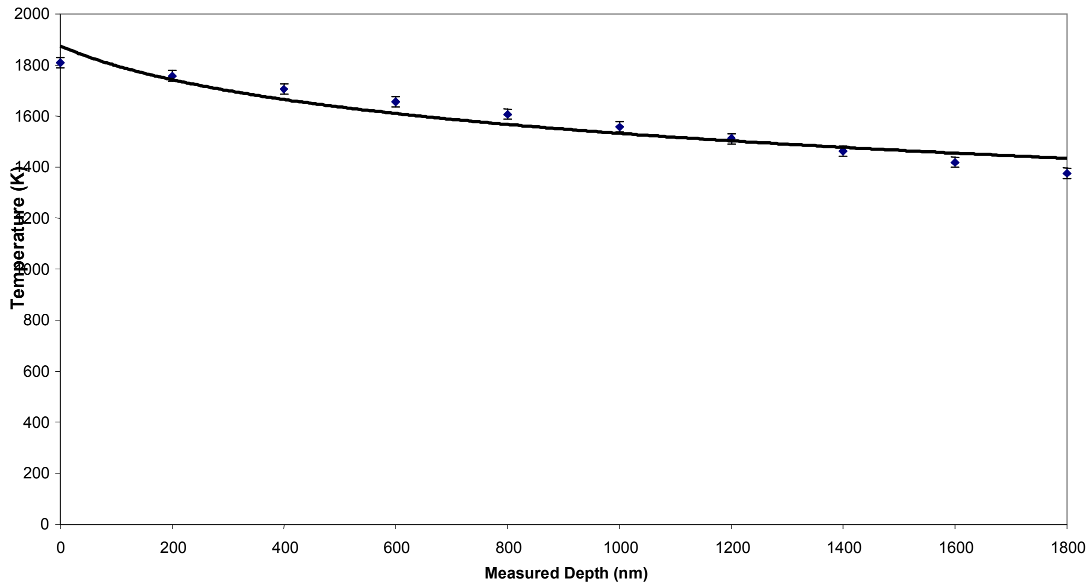


Fig (12) The variation of Temperature with Depth for Stainless Steel 304 irradiated by excimer Laser 308nm,6mJ,200Hz at Different Number of Pulses

The above theoretical results show those at all times during laser irradiation process the surface temperature is higher than the substructure temperature and the temperature gradient is continuous to the room temperature [5]. When comparing the experimental results with the published thermo-mechanical mathematical model, the increase in total laser energy leads to an increase in the Gibbs's free energy absorbed. The absorbed energy causes increasing in the temperature of the alloys; this may produce suitable conditions for the formation of high energy phases [17]. Under the action of external force resulting from the laser photon energy, the external force resulting from laser photons leads to the interaction of dislocations which form dislocation pile up of various degrees of stability and mobility. Frank –read source is also formed [15):(11]. The light photons of energy go through the surface and absorbed into the metal causing the atoms to move around their position and some atoms may be moved inside the structure[14]. The photon energy is transformed into kinetic energy and causes some change in the arrangement of atoms inside the structure; this disturbance causes the improvement in the properties due to redistribution of atoms and some hard phases may appear. The improvement in mechanical properties as a result of laser irradiation occurred [9),(11].

Pulse laser treatment in normal atmosphere is an attractive technique that differs from usual coating methods, is a new, very thin layer with different microstructure and different mechanical characteristics will be formed on the alloy surface[19),(17]. The laser interaction is the basis for an effective treatment. To induce the chemical-physical reaction with the atmospheric environment high power, short pulse lasers are used [18]. These results agree well with published results [10),(12]. In experiments study the laser processing of grey cast iron the longer the interaction time, the deeper is the melt zone. Current results agree well with published results [10) (12]. They prove that, the depth of the transformed zone increased with increasing interaction time at a laser power of 0.5KW [17].

Literatures recorded systematic discrepancies between the experimental results and the numerical computation [9]. The disagreement increases at high power, in other words, when the amount of absorbed energy increases. The surface absorptive varies with surface temperature thus; with laser beam power (the maximum surface temperature will be greater with a large laser beam power) [15),(18].

4. Conclusions

Phase transformation process is a function of temperature, so all corresponding processes such as hardening and softening is a function of temperature. Every phase has formation energy. The energy of formation is a function of temperature. Temperature rises due to laser irradiation. The alloy absorbs photons of light at specified power and number of pulses, and then the alloy reaches the energy of phase transition at critical temperature of phase transformation.

1. The temperature was changed exponentially with an increase in the number of pulses
2. The deviation between experimental results and different methods of theoretical investigation were about ± 6% to ±20% [(3), (13)]. Our results were in the same range of deviation 17% approximately
3. The thermal effect due to collision between lasers and atoms inside the structure; when taken into account in the total energy balance, it tends to reduce the efficiency of heating and phase transitions which mean transformation in solid state (i.e. the amount of heat able to form propagate microstructure changes) ; accordingly, it affect the amount of heat actually absorbed inside the material.
4. Disagreement between the current experimental work and some published theoretical studies [(9),(10)] have many reasons. The beam-metal interaction, and in the case where the fluence is high enough to rise the surface, temperature instantaneous and reflectivity changed, this effect is quite complex: the laser rays dissipated, thus reducing the effective energy really impinging on the target [(6)].

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