Optimization of Laser Beam Transformation Hardening by One Single Parameter

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Received on January 9, 1991

SUMMARY

The process of laser beam transformation hardening is principally controlled by two independent parameters, the absorbed laser power on a given area and the interaction time. These parameters can be transformed into two functional parameters: the maximum surface temperature and the hardening depth.
It has been proved that with a constant hardening depth the results (hardness, residual stress, etc.) can be optimized easily with respect to only one independent parameter, the maximum surface temperature, which is applied directly in adaptive control strategies.

KEYWORDS: Laser, hardening, optimization, residual stress

LIST OF SYMBOLS

A	absorptivity	-
H	hardness	HV
I	laser power density	W/m^2
P	laser power	W
R	laser spot radius	m
T	temperature	°C
t	time	s
t_i	interaction time	s
Z	hardening depth	m
a	thermal diffusivity	m^2/s
λ	thermal conductivity	W/m.K
σ	residual stress	MPa

INTRODUCTION

Lasers are successfully used to improve the surface properties of metal products. The different processes are shown in the I-t diagram (Figure 1). The results of the different processes can be controlled by varying the power density and the interaction time. In case of transformation hardening the resulting surface properties as hardness, hardening depth, residual stress and fatigue strength depend on these two independent process parameters.
It is shown that each point in the I-t diagram corresponds with a unique combination of maximum surface temperature T and hardening depth Z. Instead of the I-t diagram thus also a T-Z diagram might be used. When the depth is not a free parameter but prescribed beforehand, the hardening results can be expressed as a function of just one free parameter, the surface temperature. As a second advantage the surface temperature can be controlled directly by a closed loop laser power control, eliminating uncertainties caused by unknown or varying surface absorptivity and optical losses in the beam delivery system.

THEORY

Transformation hardening is a well known process which is applied on a wide range of carbon steels. When the steel is heated above the Ac_3 temperature (Figure 2) the carbon is solved completely in the 14-points austenitic γ-structure. The austenite can contain 2% carbon as a maximum against 0.025% for the ferrite. When cooling down, a 9-points ferritic α-structure is formed and the remaining carbon is excreted as cementite (Fe_3C) forming perlite. This is a fine mixture of α-iron and cementite.
At high cooling rates there is not enough time available for the austenite-ferrite transformation. Below the M_s temperature at about 250 °C the austenite transforms almost instantaneously into martensite. The carbon is not excreted and remains in the crystal structure.
In the case of conventional hardening the temperature is long enough above the Ac_3 line to obtain a homogeneous γ-structure. Laserbeam hardening, however, is a fast process. This requires higher temperatures to obtain a sufficient high diffusion rate for the required homogeneous austenitic structure within a short time. A second reason for a high surface temperature is that we need a high temperature gradient to get the heat deep enough into the material within that time.
In a simplified model, in which the heat flow is considered to be one dimensional, the temperature on a depth z and on the surface where z=0 are given by Carslaw & Jeager (1978) as:

$$T_{z,t} = \frac{AI}{\lambda}\sqrt{4at}\ \mathrm{ierfc}\sqrt{\frac{z^2}{4at}} \qquad (1)$$

The surface temperature is given in Eq 2. For a given maximum surface temperature T_s and a hardening depth Z (where the temperature is just the Ac_3 temperature) the interaction time t_i can be solved from Eq 3.

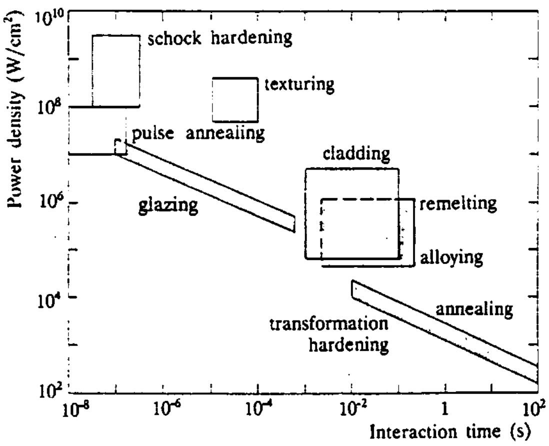

Figure 1. Power density and interaction time are used to distinguish the different surface treatment processes (Meijer,1988).

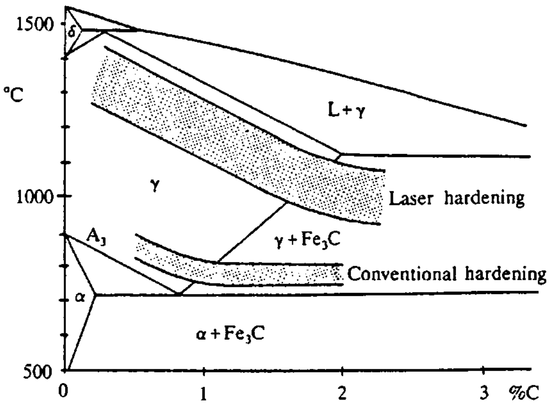

Figure 2. Temperature regions of conventional and laser beam hardening in the iron-carbon diagram.

$$T_s = \frac{AI}{\lambda}\sqrt{\frac{4at}{\pi}} \qquad (2)$$

$$\frac{T_{Ac3}}{T_s} = \sqrt{\pi}\ \mathrm{ierfc}\sqrt{\frac{Z^2}{4at_i}} \qquad (3)$$

Next the required (absorbed) power density can be solved from:

$$AI = T_s\lambda\sqrt{\frac{\pi}{4at_i}} \qquad (4)$$

Consider per example the hardening of a steel with a thermal diffusivity $a=10^{-5}$ m^2/s and an Ac_3 temperature of 890 °C. The desired maximum surface temperature T_s is 1200 °C and the required hardening depth Z is 1 mm. Then it is found from eq. 3 that the required interaction time $t_i=1$ s. With this result the required absorbed power density is obtained from eq. 4 (with $\lambda=35$ W/m.K) resulting in $AI=1180$ W/cm^2.

In this way lines of constant hardening depth are found to be nearly straight lines in the I-t diagram as shown later in figure 5.
For most practical applications, however, this theory needs some refinement since:

1. The heat flow is in 3 dimensions.
2. The laserbeam generally moves over the surface, introducing a convection term in the heat equations.
3. The Ac_3 temperature on the hardening depth Z reaches its maximum later compared to the maximum at the surface.
4. The Ac_3 temperature as given in figure 2 is the equilibrium temperature. Especially at high heating rates considerably higher values occur.

Ad 1: When the interaction time is of the same order or larger compared to the thermal time constant $R^2/4a$ a 3-dimensional solution is required. The temperature distribution caused by a stationary laser beam, with a uniform power density distribution on a circular spot with radius R, is given by:

$$T_{z,t} = \frac{AI}{\lambda}\sqrt{4at}\left\{\mathrm{ierfc}\sqrt{\frac{z^2}{4at}} - \mathrm{ierfc}\sqrt{\frac{z^2+R^2}{4at}}\right\} \quad (5)$$

where it is assumed that the workpiece dimensions are large enough for self quenching. The surface temperature at the end of the laserbeam interaction follows from:

$$T_s = \frac{AI}{\lambda}\sqrt{4at_i}\left\{\sqrt{\frac{1}{\pi}} - \mathrm{ierfc}\sqrt{\frac{R^2}{4at_i}}\right\} \quad (6)$$

With a hardening depth Z, where the maximum temperature equals Tac_3, the interaction time can be solved from Eq 7. This requires a numerical zero approximation method, in this case a bisection method.

$$\frac{T_{ac3}}{T_s} = \frac{\mathrm{ierfc}\left(Z/\sqrt{(4at_i)}\right) - \mathrm{ierfc}\left(\sqrt{(Z^2+R^2)/(4at_i)}\right)}{1/\sqrt{\pi} - \mathrm{ierfc}\left(R/\sqrt{4at_i}\right)} \quad (7)$$

With the interaction time known the required absorbed power density follows from equation 6. The results are given in the figures 5 and 6. For short interaction times e.g. for small depths the lines coincide with the results of the one-dimensional approach. In case of surface temperature control where the power density is adjusted automatically the figures are required as well to check wether the laser is capable to deliver that power.

Ad 2: The convection term due to the moving beam may be neglected when the time to heat a given point at the hardening depth is short compared to the cross over time, i.e. when $v < sa/Z^2$, with s the spot size in the direction of motion (Li, 1984). In practise this will usually be the case.

Ad 3: The temperature path of the surface layer and at the hardening depth Z is shown in Figure 3.

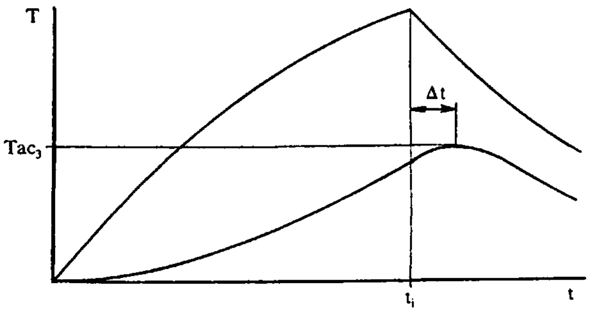

Figure 3. There is a time shift Δt between the maximum temperature at the surface and at the Ac_3 depth.

As a consequence of the time shift between both maxima, the value t_i in the numerator of eq. 7 has to be replaced by $t_i + \Delta t$. The time shift Δt shall be solved from the condition given in Eq 8. As shown in Table 1 the time shift can be neglected in most cases.

$$\frac{\partial Tac_3}{\partial t} = 0 \quad (8)$$

Ad 4: The Ac_3 temperature is not constant. Depending on the heating rate and the carbon content of the steel values between 723 °C and 910 °C will be found as shown by Figure 4. By laserhardening the heating time is very short. With more than 0.4 %C and heating times within 10 s a constant α-γ transformation temperature of 910 °C may be used. This covers almost all practical applications.

Table 1. Time shift between maximum temperature at the surface and at the hardening depth (spot diameter 5 mm, depth 1 mm).

T	t_i	Δt
°C	s	s
1250	6.070	0.009
1300	1.381	0.011
1350	0.934	0.012
1400	0.693	0.012

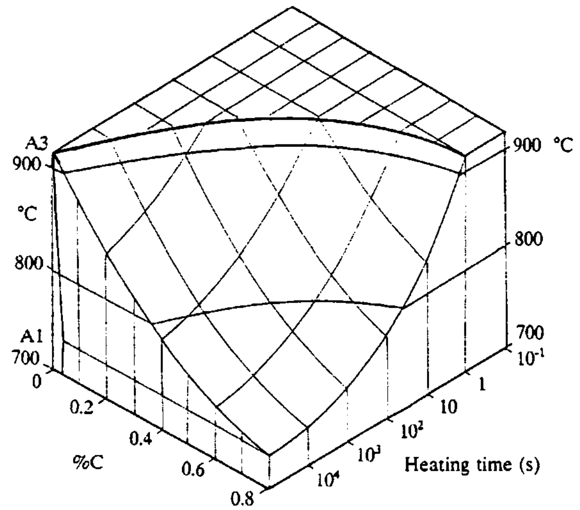

Figure 4. Shift of the α-γ transformation temperature as a function of the heating rate and carbon content, in an unalloyed carbon steel (Amende 1985)

The required power densities and interaction times have been calculated in accordance with the four former points for a range of hardening depths and surface temperatures. The results are given in Figure 5 and 6. They have been calculated for the given spot radius and the material properties of steel ($a = 9.5\ 10^{-6}\ m^2/s$, $\lambda = 35$ W/m.K). For practical applications where the laser power is controlled as a function of the measured surface temperature Figure 7 will be helpful. The relations can be generalized by converting the parameters into a dimensionless form with:

$\Phi = AI/(\lambda Tac_3/R)$	: power density
$\tau = t / (R^2/4a)$	: interaction time
$\xi = Z / R$	: hardening depth
$\Theta = T / Tac_3$	: temperature

The dimensionless results are given in Figure 8.

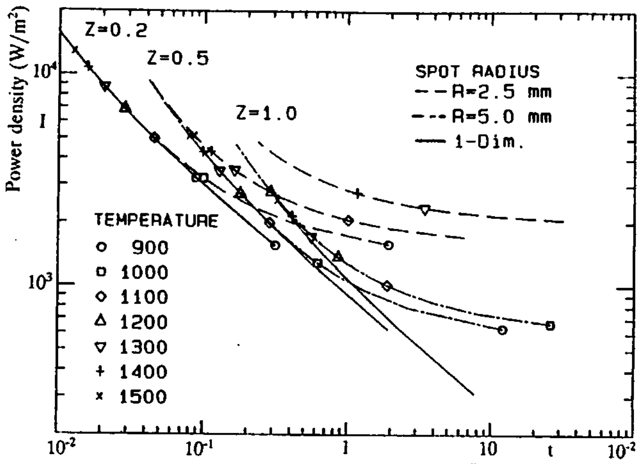

Figure 5. Lines of constant hardening depth in the I-t diagram.

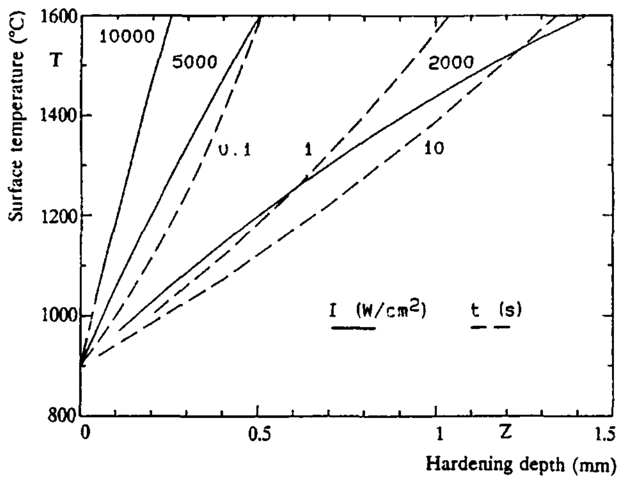

Figure 6. Lines of constant power density in the T-Z diagram.

EXPERIMENTAL METHOD

Hardening experiments were carried out on steel DIN 1.2311 (0.4%C, 1.4%Mn, 1,9%Cr, 0.2%Mo), a medium carbon mould steel and on 1.2379 (1.55%c, 12%Cr, 0.8%Mo, 0.8%V), a heavy duty blanking die steel. The objective was to increase the fatigue strength, by generating compressive stresses in the surface layer. The hardening result has been optimized for two hardening depths as a function of the maximum surface temperature.

The total coupling efficiency, from the laser into the sample, has been determined by calorimetric measurements. The coupling efficiency of the laser power into the sample has been found 56% (80% due to the optical system and 70% due to the absorptive coating). With this value the laser parameters could be obtained from the model. A validation check at the melting temperature showed a good agreement. For the optimization experiments the required laser power density and interaction time have been calculated for 5 mm spot diameter, hardening depths of 0.5 mm and 1.0 mm, and surface temperatures up to the melting point.

After machining the samples have been soft annealed in a vacuum furnace at 650 °C for 2 hours, to eliminate stresses. Graphite and Zinc-Phosphate coatings have been used to improve the absorptivity. Tracks of 80 mm length have been hardened, using a Rofin Sinar 1700 RF CO_2 laser. The beam was modified by a special developed beam integrator (Beckmann 1990) to an adjustable rectangular spot with uniform power density. The 5.3 x 3.6 mm spot could be approximated by a circular spot with 5 mm diameter. The track width was 5.3 mm. Nitrogen has been used as a shielding gas. The laser power ranged from 500 to 1800 W while the scanning velocities varied from 0.5 to 50 mm/s.

Cross sections of the hardened tracks have been cut to determine the hardness and hardening depth. With X-ray diffraction, the residual stresses and the diffraction profile width (FWHM) have been measured at the surface. FWHM values represent the lattice deformation, related to the surface hardness of the material.

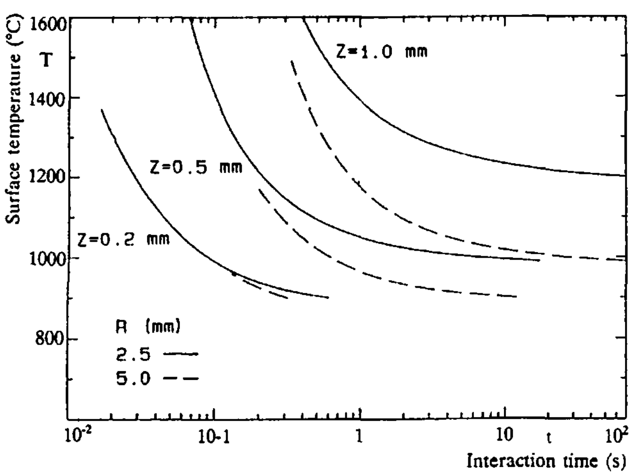

Figure 7. Lines of constant hardening depth in the T-t diagram.

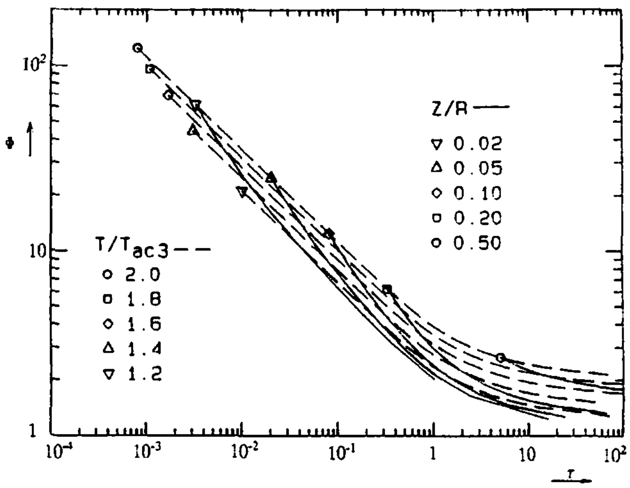

Figure 8. Dimensionless I-t diagram laserbeam hardening

RESULTS

An example of a hardening profile is given in Figure 9 with the laser parameters derived from a maximum surface temperature of 1400 °C and 1 mm hardening depth. The actual depth agrees with this value.
The results for other temperatures are given in Table 2 and 3. The residual stresses could be changed from tensile stresses by low temperatures into compressive stresses with high temperatures (Figure 10). The FWHM values increased with increasing temperature (Figure 11). With the graphite coatings on the material 1.2379 thin layers of retained austenite have been found. This can be avoided by choosing the right control temperature (Bergmann, 1990) or by deep quenching using LN_2 (Bach, 1990).
The depth of hardening was almost constant for 1.0 mm hardening depth, but decreasing from 0.7 to 0.45 mm. for 0.5 mm hardening depth. The variations are most probably caused by variations in the absorptivity by different power density and surface temperature. Note that the

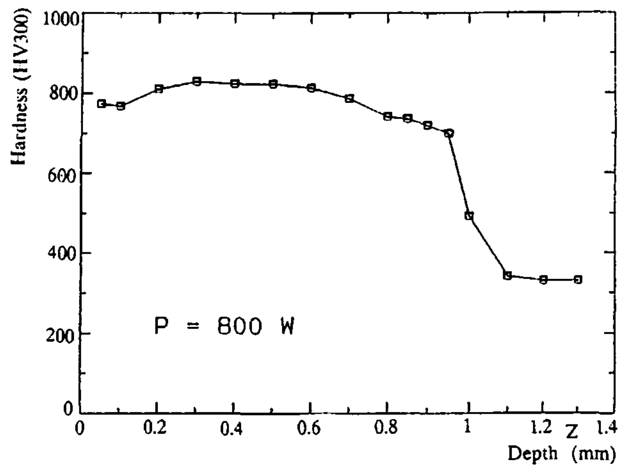

Figure 9. Hardness profile (steel 1.2311).

temperatures in the tables represent preliminary chosen values which are used to calculate the requested laser parameters. Later it was found that the absorptivity could not considered to be constant and a closed loop

Table 2. Results by a hardening depth of 0.5 mm.

T_s	t_i	AI	P	H	Z	σ	Fwhm
°C	s	W/cm²	W	Hv300	mm	MPa	°2θ
1000	6.50	1332	470	680	0.70	300	3.3
1100	0.47	2019	720	800	0.55	300	6.7
1200	0.22	2743	970	690	0.50	-45	7.8
1300	0.14	3503	1240	830	0.45	-340	7.9
1400	0.10	4293	1520	650	0.40	-400	7.6

Table 3. Results by a hardening depth of 1 mm.

T_s °C	t_i s	AI W/cm²	P W	H Hv300	Z mm	σ MPa	Fwhm °2θ
1250	5.98	1673	590	810	1.15	400	4.3
1300	2.39	1862	660	810	1.05	400	5.2
1350	1.38	2054	730	815	1.15	50	7.3
1400	0.94	2249	800	810	1.05	-30	7.0

laser control system was developed, based on on-line measurement of the surface (coating) temperature. This system is being implemented. Also the long term fatigue measurements are going on.

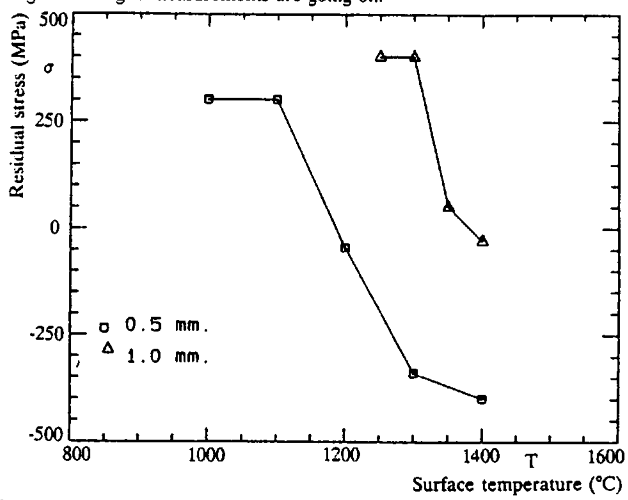

Figure 10. Residual stresses after laser treatment (steel 1.2311).

CONCLUSIONS

In most applications of laser hardening, process control is essential in order to obtain predictable results. It has been found that with a given hardening depth the maximum surface temperature is the only necessary control parameter to optimize the hardening result. Residual stresses for example could be changed from tensile into compressive by adapting the control temperature. Up to now a second machining parameter, for instance the feed rate, must be taken into account. The theory developed before, however, relates this parameter to the hardening depth which is for most applications constant, simplifying the optimization considerably.
The actual hardening depth as measured from the experiments has been achieved with laser machining parameters obtained from the given model. They proved to be well in accordance with the beforehand chosen depths of 0.5 and 1.0 mm.
The experiments have shown that the absorptivity of the coating changes with the surface temperature. This will not influence the results when the surface temperature is controlled directly. With a closed loop laser power control the surface temperature could be kept nearly constant.
Although we measured the coating temperature, instead of the metal surface itself, useful results have been obtained already. Further improvements might be expected when the temperature difference over

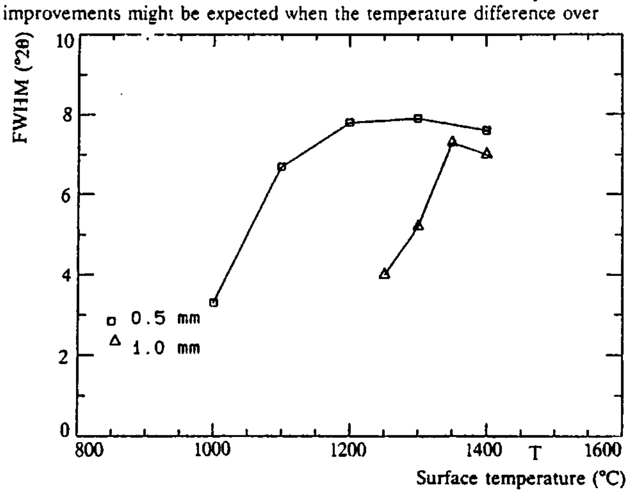

Figure 11. FWHM values after laser treatment (steel 1.2311).

the coating is taken into account. Therefor a least square based Kalman algorithm has been developed (Drenker 1990) which can keep the real surface temperature on a constant value, eliminating process uncertainties and allowing the development of fully automated hardening equipment.

ACKNOWLEDGEMENT

The project was sponsored by the Stipt/IOP-metals organisation, the X-ray and fatigue measurements were performed by mr.P.Teirlinck of the SGM Foundation for Advanced Metals Science.

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