# Laser surface hardening of thin steel slabs

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The transformation hardening of steels by surface heating by a c.w. laser beam has been studied. We examined the surface treatment of thin steel slabs by a suitable mathematical model of the thermal transient induced by laser beam heating. The laser parameters for surface hardening of such samples and the resulting microstructures are discussed. Hardening depths calculated from the mathematical model fit well with experimental results.

## 1. Introduction

The laser can be used in many different ways at high power density as a heating source for the treatment of metal and alloy surfaces. The laser presents many advantages in localized surface hardening because its beam can be directed and focused accurately [1]. This minimizes the thermal effect and consequently any deformation in the piece being treated.

The laser's uses in the surface hardening of various steels have been examined showing its practability and possible application in industry [2–4].

Most of the previous studies have been carried out on thick sample pieces, which means that the heated surface cools down quickly leaving a hardened surface layer, because the heat transmitted by the laser passes into the bulk of the piece, and therefore no external cooling device is needed.

The aim of this work was to ascertain which parameters to use on thin sample pieces in order to obtain the same good surface hardening coupled with self-cooling in the absence of external cooling devices.

## 2. Experimental procedures

The following types of steel were used for testing, as slabs 2 to 10 mm thick:

(a) SAE 1040 after normalizing treatment (structure composed of ferrite and fine perlite), and quenched and tempered (sorbitic structure);

(b) AISI 410 steel quenched and tempered (with a structure composed of tempered martensite and about 15% ferrite).

The two steels chosen have many different properties such as hardenability and austenitizing and martensite start temperatures. An examination of laser applications to surface hardening on these two steels will thus provide useful information for a wide range of steels with different compositions.

The laser treatments were carried out at the RTM Institute with an AVCO CO2 15 kW continuous wave laser. By means of a beam integrator, the beam was distributed evenly over a spot of 10 mm × 10 mm. A cone calorimeter was used to test the effective beam power before the actual testing. The interaction time, defined as the time taken for the spot to cover a distance equal to its dimension, was varied by moving the sample piece under the stationary laser at different speeds. The treatment parameters used were: incident power 2 to 4 kW and interaction time 0.2 to 1 sec; the surface of the sample piece was flattened, and was covered with a graphite–alcohol suspension in order to increase the absorption of laser radiation.

The laser-treated samples were then tested for the eventual presence of cracks, and they underwent the usual metallographic tests using light and SEM microscope and microhardness measurements.

## 3. Analysis of the thermal transient

As is well known, in order to obtain transformation hardening the steels must be exposed to a thermal cycle as follows:

(a) Heating above a minimum temperature (transformation from ferrite to austenite) which depends on the composition of the steel.

(b) This temperature must be maintained long enough to almost partially dissolve the carbides and allow a sufficient carbon diffusion in the austenite.

(c) Cooling with a rate not lower than the critical value necessary to obtain the martensitic transformation.

For a correct choice of the hardening parameters it is necessary to consider the thermal transients induced in the surface layer by laser beam heating, in terms of mathematical models. The analytical equation which describes the heating of a flat slab with a semi-infinite thickness moving uniformly under a stationary source of heat was developed by Jaeger [5]. In order to integrate this equation, several solutions were proposed [6], based on numerical methods. The solution

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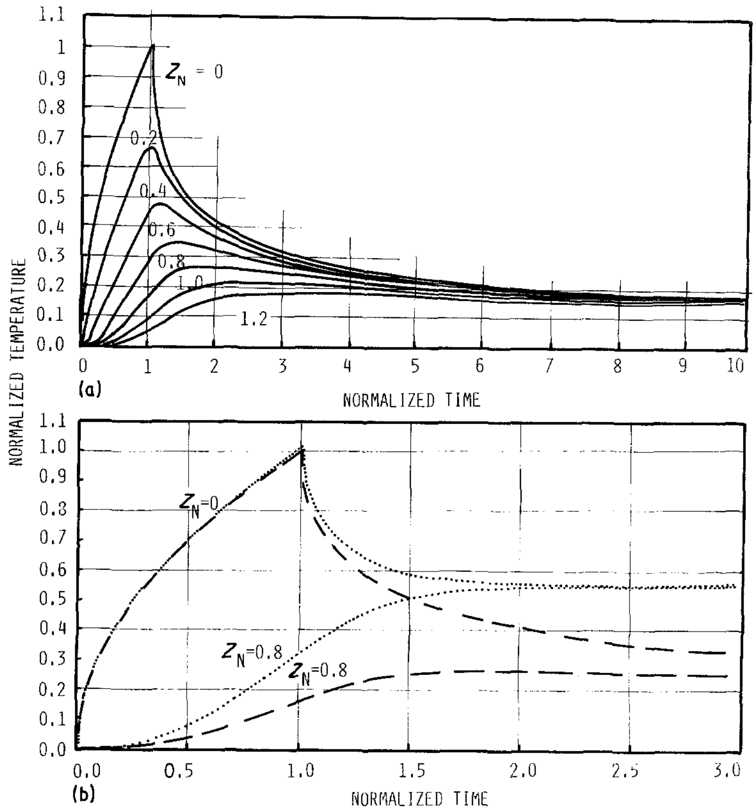



*Figure 1* Calculated temperature values, plotted against normalized interaction time with the laser beam, at various depths $z_N$ from the surface ($z_N = z/D_\tau$ is the normalized depth, where $D = (\alpha\tau)^{1/2}$ is the diffusion length at time $\tau$ and $\alpha$ the thermal diffusivity). (a) Semi-infinite slab; (b) (···) finite slab with $s$ = 8 mm at depth $z_N$ = 0 and 0.8 ($z_N = s/D_\tau$ is the normalized depth [8]), compared with (– – –) semi-infinite slab at the same $z_N$ depths.

is somewhat simpler if the heat transmission is assumed to be monodimensional [7].

An example of the results obtained by integrating Jaeger's equation is given in Fig. 1a. Here, the course of the temperature at various distances from the surface is reported as a function of time. It is both more convenient and more useful to express both variables with normalized values; the temperature in terms of the maximum temperature reached in the surface, and the time as a relation between current time and the value of interaction time.

Fig. 1a indicates an optimum interaction time of 0.5 to 2 sec and a power density (absorbed in the piece) of 1 to 2 kW cm$^{-2}$ in order to achieve surface hardening in most common medium-carbon steels. However, the aforementioned thermal model can give meaningful results and suggest correct treatment parameters only if the thickness of the slab is over about 10 mm, when the slab behaves and can be considered as having a semi-infinite thickness.

The surface hardening by laser of thinner slabs, which cannot be considered as having semi-infinite thicknesses, poses further problems in choosing the correct treatment parameters, because in this case it is necessary to reduce the overall thermal effect in order both to avoid overheating and to maintain the cooling rate high enough to obtain the martensitic transformation.

Jaeger's equation can be useful also to study the thermal transient in such thin slabs of finite thickness. However, a purely analytical solution of the simplified monodimensional case does not give a clear and immediate description of the physical phenomenon. It is therefore preferable to describe the heating of a steel slab of finite thickness not only in terms of the heat generated by the laser beam, but also in terms of the thermal reflections between the two surfaces of the slab. Therefore the thermal transient can be described by a new equation [8] obtained by adding a series of corrective terms to the basic Jaeger's equation for a semi-infinite slab.

Examples of some results obtained are shown in Fig. 1b, where are displayed the courses of the temperature at various distances from the surface, as a function of the time, for steel slabs of finite thickness. In this diagram, as in Fig. 1a, normalized parameters were used.

A comparison of the two diagrams in Figs 1a and b demonstrates the difference between the thermal transients in slabs of finite and semi-infinite thickness. If the power density is the same in both cases:

(i) the maximum surface temperature increases, and, in the last part, even the heating speed increases;

(ii) the final temperature of the steel slabs tends to be higher or different from its original temperature (considering the steel sheet to be adiabatic);

(iii) throughout the entire thickness of the steel slabs higher temperatures are reached; and

(iv) the cooling speed, in the temperature range of transformation, is slower.

The aforelisted qualitative differences do not have the same practical importance, if they are examined from a quantitative point of view. The following example refers to the surface hardening of SAE 1040 steel slabs with finite thicknesses of 2 to 7 mm.

Fig. 2 shows the temperatures reached on the front $T(0, \tau)_s$ and on the rear $T(1, \tau)_s$ surfaces at the end of the interaction time with the laser beam, plotted against the thickness of the treated slabs. The pairs of values of treatment parameters (interaction time and absorbed power density $F_0$) used in such calculations

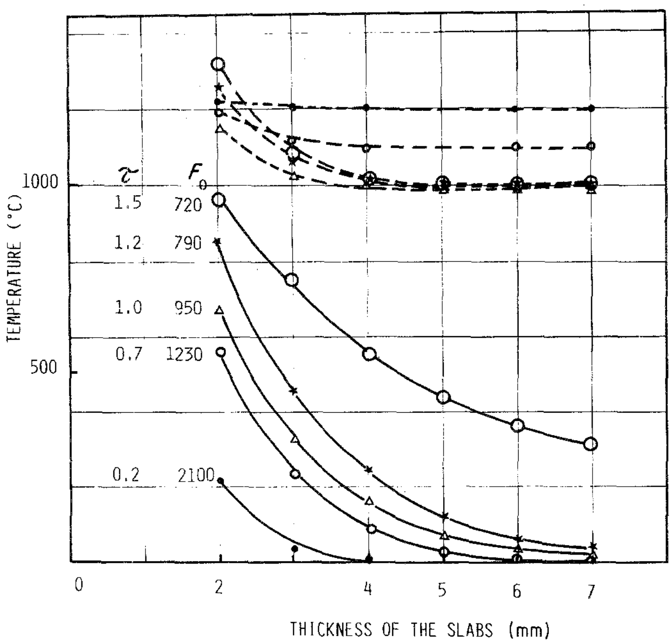



*Figure 2* Calculated temperature values (– – –) on the surface irradiated by laser $T(0, \tau)_s$ and (——) on the rear surface $T(1, \tau)_s$, plotted against the thickness of the slab. $F_0$ is the power density ($kW\,mm^{-2}$) and $\tau$ the interaction time.

are shown in the same figure. These pairs of values were conveniently chosen between that commonly used in laser surface hardening and generating maximum surface temperatures of about 1000° C on slabs of semi-infinite thickness. Fig. 2 shows that temperature values produced on the heated surface of finite-thickness slabs slightly exceeds those produced on semi-infinite slabs only if the interaction time is increased above 0.5 sec and the thickness is below 4 mm. However, the temperatures produced at the opposite surface are very different and higher in almost all cases considered. Only when the interaction time is reduced to below 0.2 sec does the rear surface temperature resemble that obtained, in the same conditions, on the semi-infinite slab.

Fig. 3 shows the final temperature reached throughout the entire sample, as a function of the interaction time, for all the cases considered in Fig. 2. This enables an important inference to be made: for interaction times above 0.7 sec and thicknesses below 8 mm, the piece (if considered adiabatic) reaches temperatures above 200 to 300° C, at the end of the thermal cycle which includes also the cooling phase. From this it can be shown that with interaction times over 0.5 sec in slabs of small thickness, the temperature remains high and somewhat higher than $M_s$, the starting temperature for the martensitic transformation. It can therefore be deduced, at least for the case under consideration, that it is possible to obtain surface hardening (without using external cooling) on steel sheets with thicknesses less than 8 mm, only if the interaction time does not exceed 0.5 sec.

To conclude, it can be seen that the most important parameter under consideration, when carrying out surface hardening, is interaction time, not only because it determines the cooling speed, but above all because it determines the temperature of the treated workpiece at the end of the treatment. Moreover it seems that some practical indication can be deduced from the previous calculations performed using the thermal model, on the feasibility of laser surface hardening of thin steel slabs. Results are summarized in Fig. 4a, where the maximum allowed interaction time to obtain transformation hardening is plotted against the thickness of the treated slabs. In Fig. 4b the calculated maximum hardened depths (for steel SAE 1040) are indicated, corresponding to maximum values of interaction time.

## 4. Experimental results and discussion

The test results have demonstrated that using the laser with the conditions and limitations indicated by the aforementioned thermal model, surface hardening of surface layers up to 0.5 mm can be achieved on steel sheets of a thickness of 3 to 6 mm. Figs 5a and b show the profiles of microhardness obtained on samples of the two steels examined, corresponding to the indicated treatment parameters.

The laser heat affected layers have a hardness value similar to that obtained in the conventional hardening of steels examined. It is also interesting to note that the

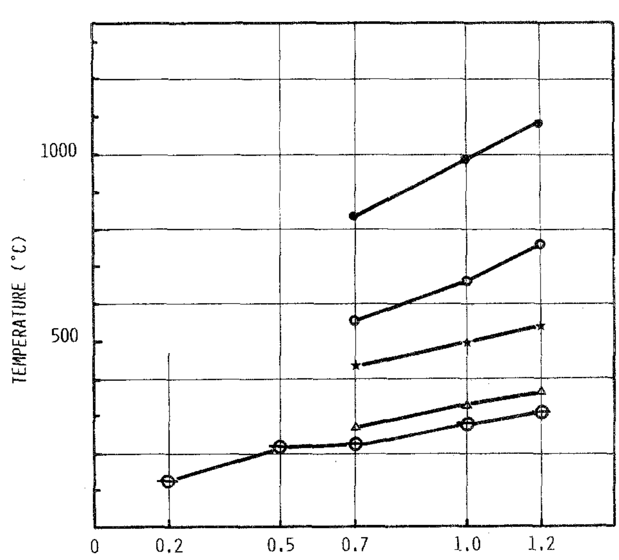



*Figure 3* Calculated final temperature reached throughout the entire sample (assumed adiabatic), plotted against the interaction time. Thickness (mm): (●) 2, (○) 3, (★) 4, (△) 6, (○) 7. $T(0, \tau)_\infty$ = 1000° C.

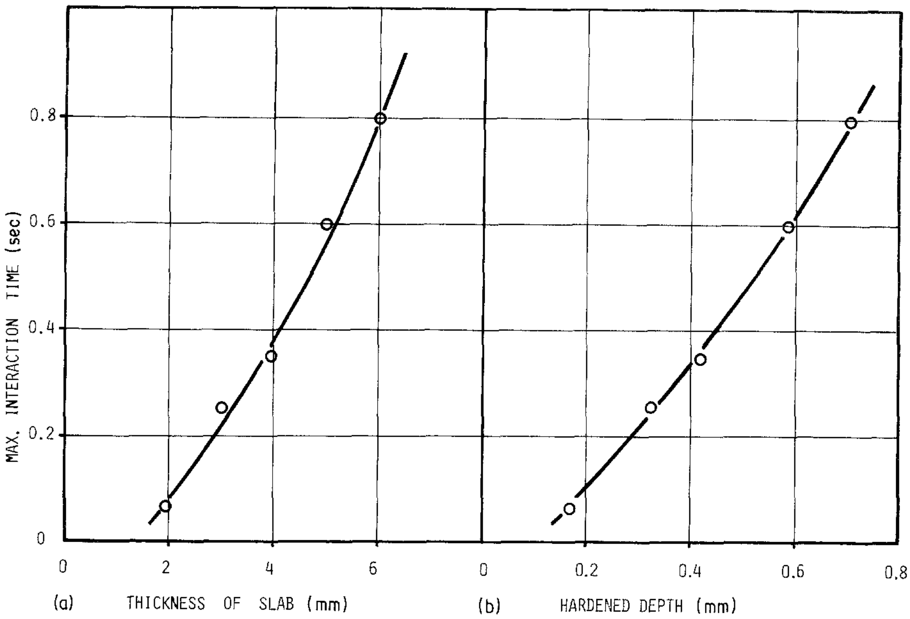



*Figure 4* (a) Calculated maximum allowed interaction time to obtain transformation hardening, plotted against thickness of slab, and (b) corresponding values of hardened depth.

sample with a homogeneous structure (quenched and tempered) has a hardness value which is almost constant throughout the hardened layer. The hardness value then decreases rapidly with decreasing depth, and soon reaches the value the steel had before treatment.

This result confirms that also in the surface hardening of low-thickness slabs by laser there is a sharp division between the treated and unaffected zones.

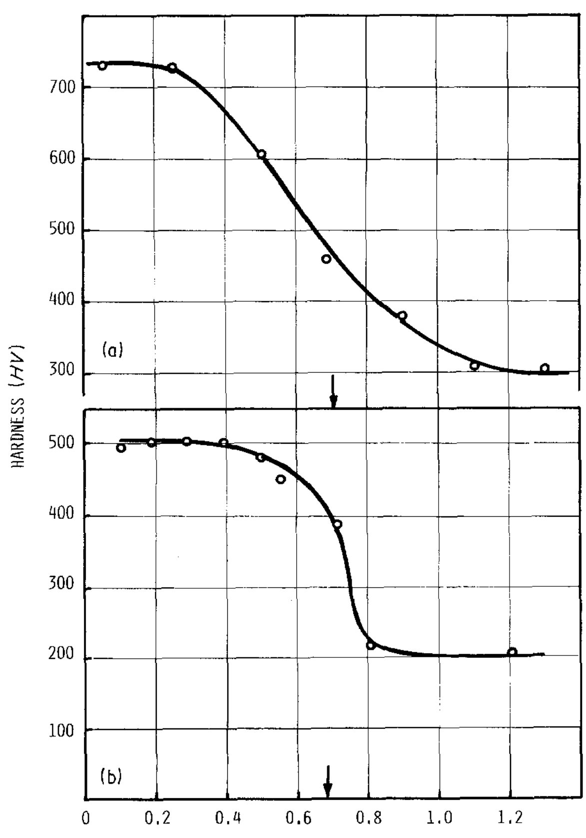



*Figure 5* Examples of hardness profiles of laser-treated samples for 2.4 kW power, $\tau = 0.8$ sec. Arrows indicate the calculated hardened depth. (a) SAE/1040, sample thickness 8 mm; (b) AISI/410 quenched and tempered, sample thickness 6 mm.

Indeed it is necessary to use only very short interaction times and the corresponding cooling rates are high and over the critical value. Therefore the martensitic transformation occurs in all the surface layer previously heated to the austenitic phase, whilst the inner zone remain unaffected. This feature produces the sharp difference between transformed and unaffected zones. On the other hand the same treatment conditions produce different hardness profiles in SAE 1040 steel, which has a structure of mixed pearlite and ferrite.

The microstructures of the laser-hardened zones are displayed in Figs 6 and 7. In all the tested samples, the zone immediately adjacent to the surface exhibits a structure typical of hardening, i.e. acicular martensite. In the samples with a homogeneous microstructure, all the rest of the hardened zone is composed of homogeneous martensite. However, in the normalized steel samples (ferrite and pearlite structure) the surface martensitic layer is followed by a succession of zones with a heterogeneous microstructure: first a zone of martensite with heterogeneous morphology of "lath" and "acicular" structure, then a zone mixed with acicular martensite and ferrite islands. In the border zone between the hardened and non-heat-affected zones, ferrite islands increase both in size and quantity, gradually replacing the "lath" martensite. This zone, composed of ferrite and acicular martensite, is derived from the transformation only of the pearlite present in the original structure of the steel.

This well-defined succession of different layers, related to the original untreated microstructure, derives from the transformation during cooling of layers remaining heterogeneous even during the laser heating. The constitution of the heat-affected zone at the end of the treatment zone enables certain deductions to be made about the situation of the microstructure present in the surface layers after the short heating period.

1. The temperature reached and its duration in the

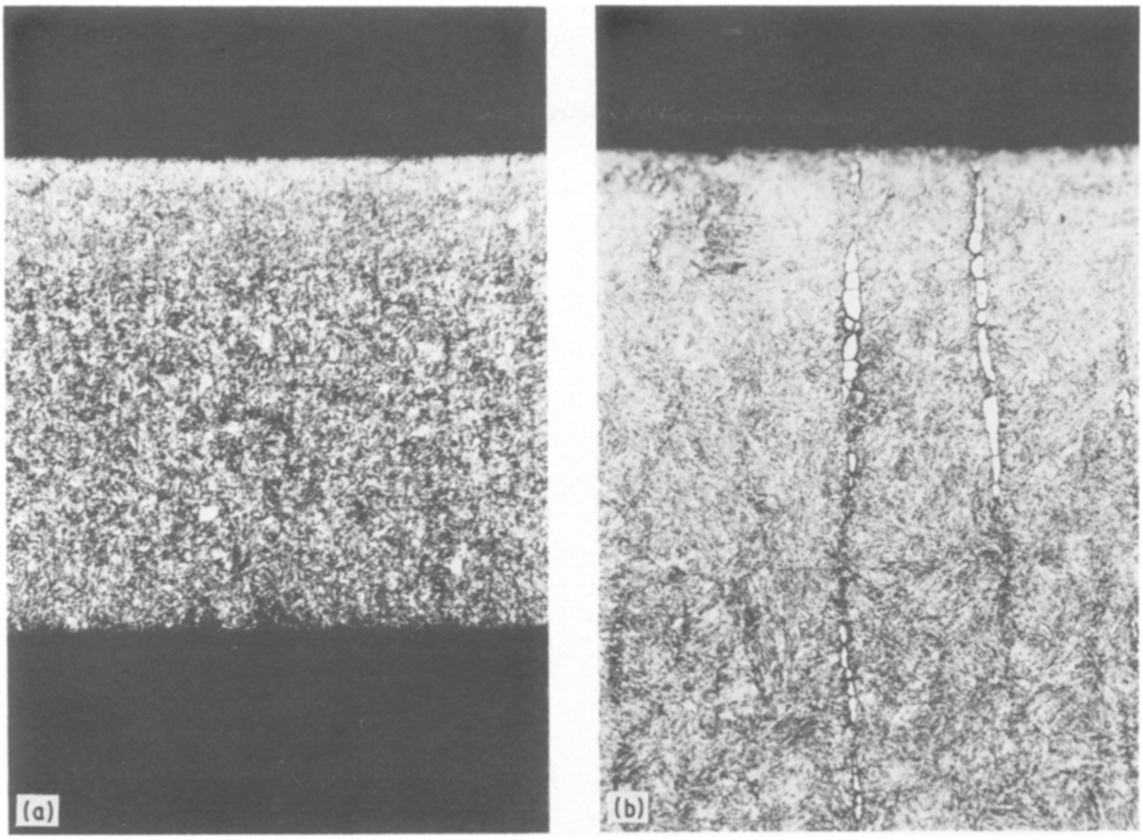



*Figure 6* Microstructure of hardened layer in AISI 410 steel: (a) × 25, (b) × 200.

first surface layer are sufficiently high to maintain the austenitic phase long enough for carbon diffusion to occur. This produces a homogeneous austenite and therefore also a homogeneous martensite.

2. The temperatures reached in the following layers are high enough to induce a complete austenitic transformation, but their durations are too short to produce a homogeneous diffusion of carbon; therefore during the cooling period a heterogeneous martensite with an uneven distribution of carbon is formed.

3. In the next layer (further towards the interior) both because of decreased carbon diffusion and because of the lower temperature, only the pearlitic zones transform into austenite and ferritic zones remain almost unaltered. Therefore the final heterogeneous structure is composed of martensite, ferrite and undissolved carbides.

The same results are obtained when using high power density heating devices for surface hardening such as an electron beam, induction heating or a laser, because in all these situations the interaction time must be short.

Of course these heterogeneous microstructures can be avoided if steels of a homogeneous structure (obtained after quenching and tempering, for example), are submitted to laser surface hardening.

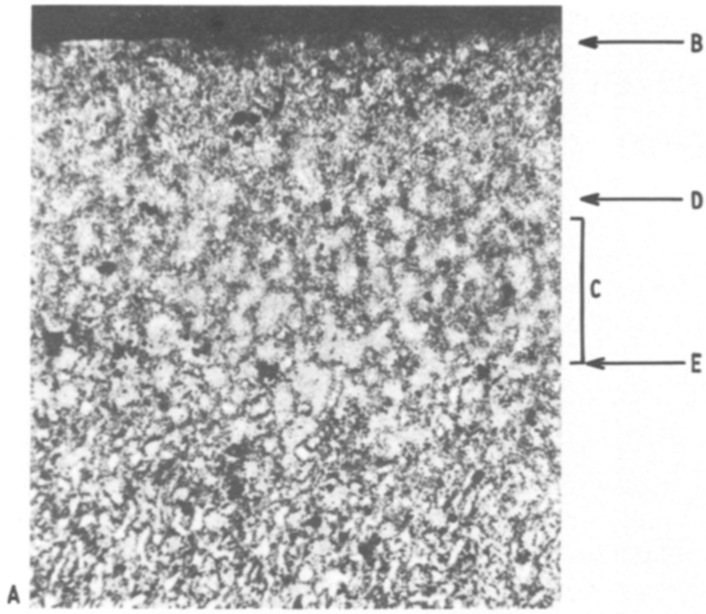
In order to verify the mathematical model used to describe the thermal transient induced by a laser in thin samples in terms of the maximum thickness hardened, a comparison between the calculations and the experimental data can be carried out. Generally the agreement between experimental and calculated data is satisfactory (see two examples in Fig. 5). However, this comparison is easy and meaningful only in the case of steels with homogeneous microstructure, where the experimental hardened depth appears well defined. Indeed in steels having heterogeneous microstructure, the experimental value of the hardened depth is quite difficult to quantify, because the heat-affected layer presents a series of heterogeneous zones that are only partially martensitic.

Moreover, in order to compare meaningfully the experimental data and mathematical calculations, it is necessary to know with sufficient accuracy the absorption coefficient of the laser radiation in the sample surface.

Unfortunately literature data are lacking in unambiguous experimental values of this coefficient. Very often this is calculated *a posteriori* assuming its values to be that which correlates the experimental data with theoretical calculations. The value generally accepted for the absorption coefficient of a steel surface coated by graphite dag is 65 to 70%. Assuming this value also for our samples, we can conclude that our model fit well with the experimental data, as shown in the example of Fig. 5.

Therefore the substantial validity of the proposed thermal model is confirmed, and its implications are valid for deciding upon the correct parameters to use in surface hardening practice.

Finally it has to be emphasized that deeper cases can be obtained by using a supplemental surface quench. Although this extra operation may make hardening operations more complex and reduce the economic effectiveness of the laser treating method, it is technically effective if a deeper transformed depth is needed.



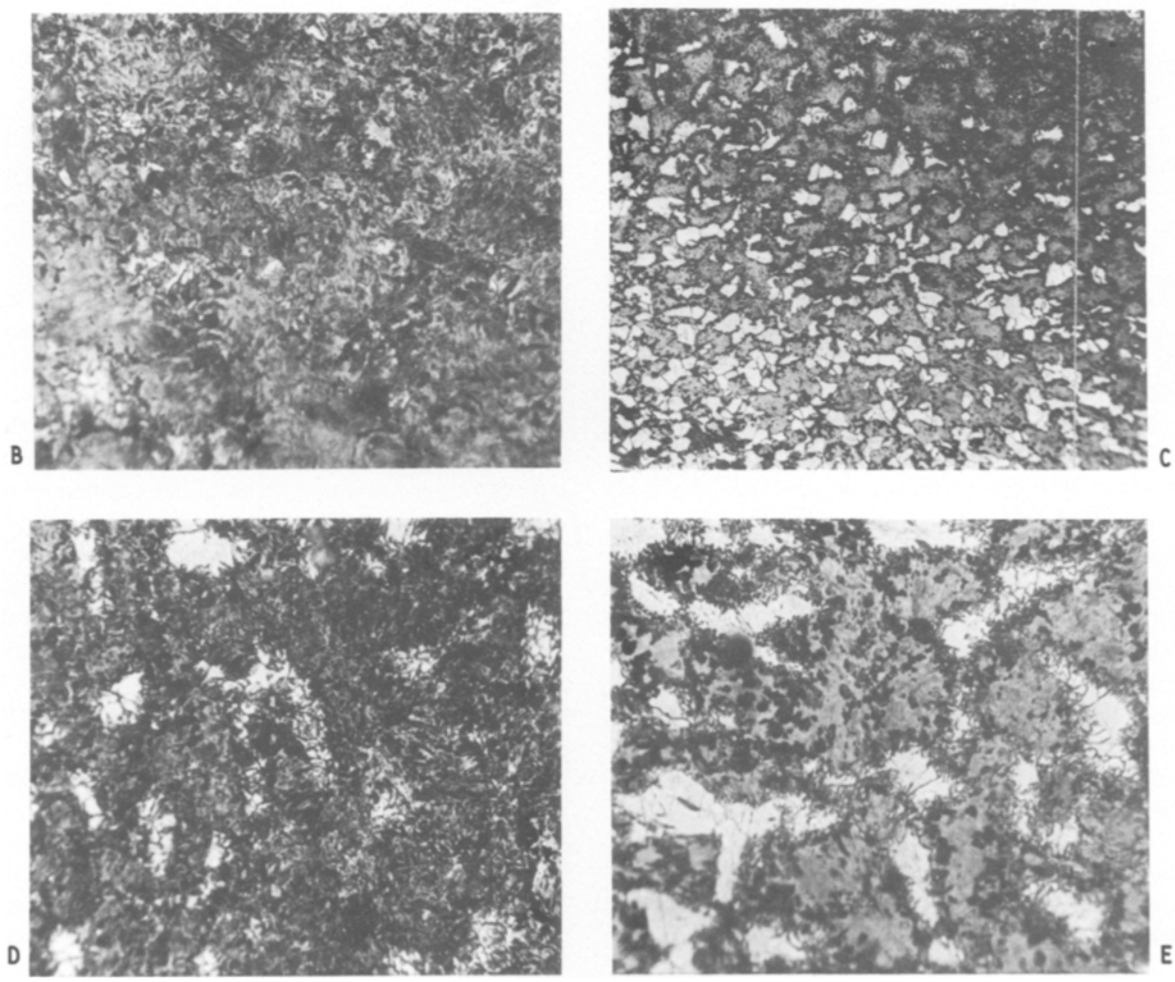




*Figure 7* Microstructure of hardened layer in SAE 1040 steel. A (× 100), B (× 500), C (× 200), D (× 1000), E (× 1000).

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