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# Predictive modeling of laser hardening of AISI5150H steels

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**Abstract**

This paper presents accurate predictive modeling of the laser hardening process in terms of laser operating parameters and initial microstructure without the need of any experimental data. The model provides the diagrams that are useful for predicting hardness profiles, optimizing practical process parameters and assessing the potential of laser hardening for different steels. It is shown that the hardness and depth of the hardened layer in hypoeutectoid steels (carbon wt% $<1$) could be predicted from this model with good accuracy.

The model combines a three-dimensional transient numerical solution for a rotating cylinder undergoing laser heating by a translating laser beam with a kinetic model describing pearlite dissolution, carbon redistribution in austenite and subsequent transformation to martensite by utilizing the feedback from the CCT diagram. In order to validate the thermal model and assert the accuracy of temperature predictions the temperature was measured using an infrared camera and a good agreement between the predicted and measured temperatures is shown. Results are presented as processing maps, which show how the case depth and hardness depend on input operating parameters. The good agreement between the measured and predicted hardness profiles ascertains the accuracy of the thermal-kinetic model developed for AISI5150H steels.


*Keywords:* Laser treatment; Laser hardening; Phase transformation; Laser absorption

## 1. Introduction

In order to improve the wear resistance of parts without affecting the softer, tough interior of the part, a wide variety of surface hardening techniques have been used. This combination of hard surface and high resistance to breakage and cracks upon impact is useful in parts such as cams or ring gears that must have a very hard surface to resist wear. Further, the surface hardening of metals offers major advantages over other bulk hardening processes by eliminating or minimizing the problems of distortion and cracking. Surface hardening techniques include hardfacing, coating, diffusion methods and selective hardening processes. Selective hardening processes can be performed by a flame, induction heating, electron beams, and laser beams.

In laser hardening of steels, the workpiece surface is exposed to a laser beam, which heats up the workpiece locally, while the rest of workpiece acts as a heat sink. Movement of the laser across the surface produces hardened tracks. Laser transformation hardening of steels is a potentially good application of industrial lasers considering the broad employment of steels in a variety of applications.

Alloy steels like 5150H are chrominum, molybdenum, medium-carbon steels with high hardenability and good fatigue, abrasion and impact resistance. Their applications are varied and various hardening techniques have been employed. However, part distortion and long hardening time associated with traditional bulk hardening processes require a new efficient hardening technique. Laser hardening of steels offers significant benefits over conventional selective hardening processes. This study focuses on laser hardening of 5150H steels with the goal of overcoming these process drawbacks.

In the past, several researchers proposed theoretical models in an attempt to establish a relationship between laser processing parameters and temperature, which was

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## Nomenclature

| | |
|---|---|
| $A_1$ | eutectoid temperature (°C) |
| $A_3$ | austenization temperature (°C) |
| $c$ | carbon content of steel (wt%) |
| $c_c$ | critical value of carbon composition |
| $c_e$ | eutectoid carbon composition ~0.8%C |
| $c_f$ | amount of carbon in ferrite ~0.01%C |
| $c_m$ | mean carbon content (≈c/*f*) |
| $D_0$ | pre-exponential of diffusion of carbon |
| $D$ | diffusion coefficient ($m^2$/s) |
| $D_l$ | laser diameter, (mm) |
| $D_w$ | workpiece diameter (mm) |
| $f$ | volume fraction of martensite |
| $f_m$ | maximum volume fraction of martensite |
| $f_i$ | volume fraction occupied by the pearlite colonies (~c/0.8) |
| $g$ | average grain size (μm) |
| $H_m$ | hardness of the martensite (HV) |
| $H_f$ | hardness of the ferrite ( = 150 MPa) |
| $h$ | enthalpy (J/kg) |
| $k$ | thermal conductivity (W/mK) |
| $L$ | radius of the pearlite colony (μm) = $g/2\, f_i^{1/3}$ |
| $q''_{conv}$ | convective heat flux transfer (W/m2) |
| $q''_l$ | laser power (W) |
| $Q$ | activation energy of diffusion of carbon (J/mol) |
| $R$ | gas constant ( = 8.314) (J/mol K) |
| $r_b$ | laser beam radius (mm) |
| $r_w$ | workpiece radius (m) |
| $r,\phi,z$ | cylindrical coordinates (m) |
| $t$ | time (s) |
| $t_1,t_2$ | times taken to reach the critical temperature ($A_1$) during heating and cooling (s) |
| $T(t)$ | heat cycle |
| $T_{ref}$ | reference temperature (K) |
| $V_z,v$ | laser translational velocity, (mm/min) |
| $z_d$ | depth until which complete transformation of pearlite to austenite occurs (mm) |

*Greek symbols*

| | |
|---|---|
| $\lambda$ | interparticle spacing of the carbides (μm) |
| $\rho$ | density (kg/m3) |
| $\omega$ | rotational speed (rad/s) |
| $\varepsilon$ | emissivity |
| $\alpha_l$ | laser absorptivity |

then related to a corresponding hardness distribution. Based on Carslaw and Jaeger [1] semi-infinite analytical plate solution for a uniform heat source, Sandven [2] and Gregson [3] developed a one- dimensional (1-D) transient model for predicting the temperature distribution in the vicinity of a moving laser spot. For an approximate temperature distribution 1-D solution can be used, but a two- or three-dimensional analysis is required for improved accuracy. Cline and Anthony [4] and Sanders [5] presented a thermal model in 3-D form for a semi-infinite plate under a Gaussian laser beam. A 2-D heat flow model with the temperature dependence of surface absorptivity and the thermal properties of the material were presented for cylindrical bodies [6] and for a uniform strip heat source moving along the semi-infinite body for laser hardening of steels [7,8].

Ashby and Easterling [9] and Li et al. [10] developed an extensive modeling scheme for given steel and normalized microstructure. Their model assists in examining how changing process variables affects both the hardness and depth of the hardened zone in a single combined diagram called 'Laser processing diagram'. The idea behind using the simplified thermal analysis was to obtain a simple solution to thermal fields so that they could be combined with the equations describing the microstructure kinetics, which was otherwise difficult. Later, Shercliff and Ashby [11] extended this model and used the dimensional relationship between various process variables to arrive at master diagrams for determining case depth for Gaussian and uniform rectangular laser sources.

Davis et al. [12] included microstructure kinetics following the work of Ashby and Easterling [9] in their thermal model for a rectangular workpiece. They did not consider the cooling rate effects on their final hardness as they were convinced that the high cooling rates associated with self-quenching of the workpiece were sufficiently high for complete conversion to martensite, although they considered the time given for carbon diffusion above the transformation temperature in their model. Koai et al. [13] considered a 2-D finite element modeling technique for the laser hardening process of a cylindrical workpiece and compared temperature measurements with experimental results. Chen et al. [14] studied the detailed austenite transformation kinetics and developed a mathematical model based on phase transformation dynamics, which applied the atomic diffusion theory and thermal elasto-plastic theory throughout austenite transformation during laser heating.

Laser hardening research, in addition to pursuing more sophisticated thermal modeling techniques or kinetic modeling techniques, has explored other directions as well. The influence of initial structure on resulting martensite microstructure has been studied in this regard. During laser surface treatment, the prior state of the material has considerable repercussions on the results. Shiue and Chen [15] investigated the effects of initial tempering condition at different temperatures on the resulting microstructure of AISI 4340 steel. They developed a very simple mathematical model extended from the diffusion model of Ashby and Easterling [9], which was developed for normalized steel.