Laser photothermal radiometric instrument for industrial steel hardness inspection

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Abstract. To meet the industrial demand for on-line steel hardness inspection and quality control, a non-contact, non-destructive laser photothermal radiometric instrument (HD-PTR) was developed. The instrument is equipped with a non-liquid-nitrogen-cooled HgCdZnTe (MCZT) detector, a National Instruments data acquisition card with a Dynamic System Analysis (DSA) module, and control software. A series of industrial steel samples which included automotive screws and aircraft gears (flat or curvilinear) were examined. The effective hardness case depths of these samples ranged from 0.21 mm to 1.78 mm. The results demonstrated that three measurement parameters (metrics) can be extracted when using a fast swept-sine photothermal method. These parameters include the phase minimum (or peak) frequency, \( f_{\text{min}} \), the half width, \( W \), and the area, \( S \). It was found that they are complementary for evaluating widely different ranges of hardness case depths. \( f_{\text{min}} \) is most suitable for large case depths, and \( W \) and \( S \) for shallower case depths.

1. Introduction

The performance of surface hardened steel parts is a major issue in automotive and aerospace industries. There is a strong need for hardening and heat treating companies to improve the quality control of their products by introducing new inspection systems which allow for non-destructive, non-contacting hardness profile measurements as an alternative to the presently used destructive indenter-based inspection methods [1-4]. The PTR phase frequency minimum is the result of thermal-wave interference [5] within the hardened layer, thus becoming a measure of effective hardness case depth. This determines the effectiveness of PTR technology in hardness inspection. It has been the aim of this work to develop a contact-free, calibrated non-destructive photothermal instrumentation and measurement principle, an important step toward achieving full on-line production control. In this paper we present the physical principles, instrumental implementation and characterization of a calibrated industrial hardness PTR system and report on its ability to measure case depth in hardened aerospace steels and gear teeth.

2. Three-dimensional PTR theoretical model

To properly describe photothermally the hardness depth profile of industrial steels, we have developed a 3-D model to study the thermal-wave interferometric effects of finite beam sizes in inhomogeneous materials [6]. With this model, a case hardened steel sample is treated as an axially inhomogeneous system which contains a thermophysically continuously inhomogeneous
hardened layer and a homogeneous substrate. The physical parameters in the inhomogeneous layer, such as microhardness, thermal conductivity, \(k\), and thermal diffusivity, \(\alpha\), are functions of depth as shown in Fig. 1. Fig. 1(a) shows a typical microhardness profile of a hardened steel sample measured with a mechanical indentation method (HV0.5). Hardness decreases with depth. Fig. 1(b) is a diagram of the inhomogeneous layer which is divided into \(n\) virtual layers thin enough so that each layer can be considered thermophysi cally homogeneous, that is, the thermal conductivity \(k_i\) and thermal diffusivity \(\alpha_i\) are constant within the layer of thickness \(L_i\). An intensity-modulated Gaussian laser beam at frequency \(f\), with radius \(a\) and power \(P\) impinges normally on the sample along the \(z\)-axis. A convenient ad hoc thermal conductivity depth profile is assumed [7]:

\[
k = k_0 \left(1 + \Delta e^{-qz}ight) / (1 + \Delta) \quad (1)
\]

where

\[
\Delta = \frac{1 - \sqrt{k_{L_0}/k_0}}{\sqrt{k_{L_0}/k_0} - e^{-qL_0}} \quad (2)
\]

Here, \(k_0\) and \(k_{L_0}\) represent the values of the thermal conductivity at two boundary surfaces \(z = 0\) and \(L_0\), respectively. \(L_0\) is the total thickness of the inhomogeneous layer. \(q\) is an inhomogeneity factor. It can be seen that Eq. (1) is adequate for expressing arbitrary monotonic profiles if parameters are properly chosen. The profile of the thermal conductivity is determined by the combination of \(k_0\), \(k_{L_0}\), \(q\) and \(L_0\).

Figure 1. (a) Typical microhardness profile of a hardened steel sample measured with the mechanical indentation method HV0.5. (b) A schematic diagram of a continuously inhomogeneous system including an inhomogeneous layer and a substrate \(M\).

Figure 2. Phase of a solid with inhomogeneous thermal conductivity simulating case-hardened AISI 9310 steel normalized by the corresponding homogeneous AISI 9310 semi-infinite steel sample using several beam sizes \(a\) (mm): (1) 0.01, (2) 0.02, (3) 0.05, (4) 0.5, (5) 1.0, (6) 2.0, (7) 5.0, (8) 10, (9) 20, (10) 40, (11) 100. \(k_0 = 20\) W/mK, \(k_{L_0} = 36.0489\) W/mK, \(q = 2529\) mm\(^{-1}\) and \(L_0 = 2.45\) mm.

Fig. 2 shows simulated phases of a thermophysically inhomogeneous system, the frequency response of each quantity normalized by that generated with the same beam size from a semi-
infinite unhardened homogeneous AISI 9310 steel. It is seen from Fig. 2 that the phase is very sensitive to beam size. With increasing beam size from 0.01 mm (3-D limit) to 100 mm (1-D limit), the magnitude and frequency positions of the normalized phase minimum decrease and shift to lower frequencies. For practical hardness case depth measurements characteristic interferometric minima (or maxima) in the photothermal phase are obtained within the range of laser modulation frequencies such that the effective hardness layer thickness, $L$, is commensurate with the thermal-wave diffusion length, $\mu_H$:

$$\mu_H = (\alpha_H / \pi f)^{1/2},$$

where $\alpha_H$ is thermal diffusivity of the hardened layer and $f$ is the characteristic frequency. Eq. (3) shows that thermal-wave interference extrema occurring at smaller $f$ correspond to larger case depths. Since the characteristic frequency often indicates a phase minimum ("trough") rather than a peak, it is denoted as $f_{min}$ in this paper.

3. Instrumentation and materials

A PTR hardness inspection PTR instrument ("HD-PTR" system) was developed specifically for industrial on-line measurement purposes. The diagram of the HD-PTR system is shown in Fig. 3.

![Diagram of the HD-PTR system](image)

The system consists of laser source and control systems (I), optical box (II) and sample compartment (III). Part I provides the semiconductor laser source and current controls. The laser is 808-nm diode laser of 4.5 W dc output (VDM00018, JENOPTIK, Germany), a laser controller, a thermoelectric cooler (TEC) controller for the infrared detector and a computer for data acquisition and laser modulation. The laser is thermoelectrically cooled and its output is coupled to a 200-μm optical fiber of 0.22 NA. The laser has a coaxial 635-nm pilot visible beam of 1 mW for easy sample alignment. The computer is equipped with a data acquisition (DAQ) card with two sets of analog input/output ports (NI-PCI-4461, National Instruments, USA). It controls laser current modulation in a swept frequency model for frequency scan measurements, or at a constant frequency for beam focusing and sample alignment. Part II is a small box (19x19x10 cm dimension), containing a TEC-cooled 2-5-m mercury-cadmium-zinc-telluride (MCZT) detector (PVI-2TE-5, VIGO System, Poland), a collimator, a pair of steering mirrors, a lens, a pair of gold-coated high-reflectance parabolic mirrors and a CaF$_2$ window (99% transmission for both excitation and infrared emission spectral ranges). Part III is the sample compartment. The modulated laser beam is fiber-coupled into the collimator C and focused onto the sample S with a 0.7 mm diameter beam size and 16.4° angle relative to the normal of the window W. The emitted IR signal is collected and focused onto the detector D by a pair of parabolic mirror P1, P2, and then sent to the computer for processing. Compared with the conventional bench-top PTR systems reported in the literature, the present HD-PTR system is more stable (TEC-cooled MCZT detector), more flexible (compact optical box) and faster (software signal generation and detection.
Automotive screws and aircraft gears (flat or curvilinear) were examined using the H-D PTR system.

4. Results and discussion

Fig. 4(a) shows a typical phase minimum (“trough”) from a flat hardened sample (effective case depth $E = 1.78$ mm). A photothermal trough/peak extremum can be described by three parameters, minimum frequency, $f_{\text{min}}$, trough/peak width, $W$, and area, $S = \sum \Delta f_i P_i$.

Fig. 4(b) displays troughs from two root measurements of the N type gear tooth samples. It was found that not only $f_{\text{min}}$, but also $W$ and $S$ are correlated with sample hardness: smaller $f_{\text{min}}$, $W$ and $S$ indicate larger effective case depth. However, the three metrics are not interchangeable. They are complementary for hardness measurements in different ranges of case depth, with $f_{\text{min}}$ being most suitable for large case depths, and $W$ and $S$ for shallower case depths. Fig. 4(c) shows two troughs from screw samples. It is noticed that $f_{\text{min}}$ shifted to higher frequency due to different sample materials.

Figure 4. (a) a typical trough shape from the cylindrical hardened sample A1; (b) troughs from two root measurements of N type gear tooth samples. (c) troughs from two screw measurements.

5. Conclusions

The first industrial-level hardness HD-PTR instrumentation system has been developed and built. The system stability, signal quality for fast measurements, repeatability and reproducibility have been tested. A series of industrial steel samples, flat or curvilinear, with various effective case depths (0.21 mm - 1.78 mm) were measured. It has been found that $f_{\text{min}}$, $W$ and $S$ are complementary metrics to evaluate hardness case depth: $f_{\text{min}}$ performs optimally with large case depth profiles, whereas $W$ and $S$ are more suitable for shallow case depth measurements. With these three metrics, the HD-PTR system functionally spans very wide case depth ranges from ultra-shallow ($E = 0.2$ mm) to very deep ($E = 1.78$ mm).

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