NDT&E International 88 (2017) 24–32

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Model based laser-ultrasound determination of hardness gradients of gas-carburized steel

F. Singer*, M. Kufner

Institute of Sensor and Actuator Technology Coburg, Am Hofbräuhaus 1b, 96450 Coburg, Germany

ARTICLE INFO

Keywords:
Surface acoustic waves
Laser-ultrasound
Case hardening
Gas carburizing

ABSTRACT

Gas carburizing is a common industrial process utilized for case hardening of low carbon steels. However, there is a lack of non-destructive evaluation systems for the measurement of hardness-depth profiles. We propose a novel measurement method for the determination of hardness-depth profiles of two-step gas carburized steel specimens. The method is based on the measurement of broadband laser excited Rayleigh waves. Rayleigh waves were generated by a pulsed Nd: YAG laser in the thermoelastic regime and measured with a heterodyne Mach-Zehnder interferometer in the near-field. From two measurements with different source to receiver distances the dispersion diagrams were calculated by means of the phase spectral analysis method. In order to simulate the observed dispersive behavior of the Rayleigh waves, first the two-step gas carburizing process was simulated using solutions of the diffusion equation. The resulting continuous hardness profile was then discretized into up to 100 layers. Thereafter the Rayleigh wave dispersion diagram was calculated from the discretized stack of layers using a delta-matrix formulation of the Thomson-Haskell transfer matrix method. In order to obtain best fitting hardness profiles, the simulated dispersion diagrams were fitted to measurements with a curve fitting algorithm. Comparison of the Rayleigh wave inversion method with destructively obtained Vickers hardness profiles shows good quantitative agreement.

1. Introduction

Laser-based ultrasound is a well established and widely used measurement method for non-destructive evaluation of technical components. A multitude of optical components and different types of lasers is available for excitation and detection of ultrasound waves. A common application is the Laser-Doppler-Vibrometer (LDV) measurement of ultrasound waves that were generated conventionally [1–5].

Beyond the mere detection of ultrasound waves by optical means, they can be excited optically by a pulsed laser. Usually pulse energies ranging from 1 to 1000 mJ and pulse durations in the range of 10 ns are used. Recently different approaches for the all-optical investigation of bulk wave propagation were studied. Strong pulsed laser excitation was used for bulk wave measurements in combination with LDV [6], a Sagnac interferometer [7] and in combination with a two wave mixing photorefractive interferometer (PRI) [8]. Surface wave excitation by pulsed lasers was recently studied in conjunction with LDV [9], in combination with PRI [10] and with a combined system consisting of a pulsed laser and an interferometer receiver head mounted on a robot arm [11].

Case-Hardening is a common industrial method used to obtain a hard surface while retaining a ductile core. There are several different case-hardening methods like gas carburizing, laser hardening or inductive hardening. The case-hardening process that is under consideration in this work is the gas carburizing process because of its great industrial significance. The resulting hardness-depth profile from such a process can be calculated using one-dimensional diffusion models [12].

The influences of gas-carburized case-hardened structures on the propagation of surface acoustic waves (SAW) were investigated before [13–16]. Gordon and Tittmann [13] first developed a theoretical model in which the gas-carburized case-hardened structure was simulated using Fick's 2nd law of diffusion. The dependency of longitudinal and shear velocities on the steel hardness was measured and used to connect the diffusion simulation with a simulation of the dispersion of Rayleigh waves. This was carried out using the Thomson-Haskell transfer matrix method. The dispersion of Rayleigh waves on case-hardened steel was found to be considerably high.

Later, measurements of the dispersion of Rayleigh waves on case-hardened steel with piezoelectric transducers and a dual beam Michelson interferometer were carried out [14]. Dispersion curves from simulated hardness profiles were then fitted to the measured

* Corresponding author.
E-mail addresses: f.singer@isat-coburg.de (F. Singer).

http://dx.doi.org/10.1016/j.ndteint.2017.02.006
Received 11 March 2016; Received in revised form 11 February 2017; Accepted 20 February 2017
Available online 22 February 2017

Rayleigh wave dispersion curves using the theoretical model described earlier. It was found that there is a good qualitative agreement between destructive mechanical hardness measurements and the Rayleigh wave inversion. However, there is a rather large disagreement between the Rayleigh wave measurement and the mechanical destructive measurement in a thickness range between 0.5 mm and 1.5 mm, which may be attributed to a lack of degrees of freedom of the theoretical model. First, the physical model of the gas carburizing process did not incorporate all process steps necessary for an accurate simulation of the hardness-depth profile. Second, the hardness-depth profile was discretized using only six layers which introduced considerable discretization errors. Measurements were conducted using eight ultrasound transducers with different center frequencies in order to obtain a broadband dispersion diagram. This is not only very cumbersome but may attribute to additional measurement errors as different transducers may have different characteristics. For example, especially the low frequency transducers excited additional wave modes that superimposed the Rayleigh waves.

A subsequent approach [15] already featured a non-contact all-optical setup comprised of a Q-switched Nd: YAG laser as optical pump and a spherical Fabry Pérot interferometer (SFPI) as optical probe. Induction hardened and gas carburized specimen were measured. The authors found a linear relationship between Rockwell hardness and phase velocity. In the measurements shown, they used a single-layer perturbation model to extract the case depth from SAW dispersion measurements. However, the physical principles of the gas carburizing process that lead to a slow decay of the hardness in thickness direction were mentioned but not incorporated in the analysis of the SAW dispersion data.

A later approach [16] involved piezoelectric interdigital transducers (IDT) for the generation of SAW and a beam deflection optical measurement of the SAW. For each frequency one IDT was realized, similar to the measurements carried out by Gordon and Tittmann [14]. Despite the cumbersome procedure of using a special IDT for each frequency, measurement uncertainties were rather high and only a single-layer model was applied.

In this work theoretical dispersion curves of gas carburized case hardened steel specimens were simulated. The gas carburizing process was simulated using approximations of the solutions of the diffusion equations provided by Gegner [12]. The resulting hardness-depth gradient is then divided into a discrete stack of layers. Subsequently the dispersion of Rayleigh waves was calculated with a delta-matrix method. The delta-matrix method is a modified transfer-matrix method which does not suffer from the numerical problems of the transfer-matrix method which are encountered at large frequency-thickness products [17]. The proposed theoretical treatment of the problem and the inversion method employed in this work are based on the methods first suggested by Gordon and Tittmann [13,14] but were significantly enhanced. Measurements were carried out with a broadband, all-optical laser-ultrasound system. Care was taken to eliminate diffraction phase shifts and other unwanted contributions to Rayleigh wave dispersion.

2. Theory

2.1. Surface acoustic waves

Rayleigh waves are ultrasound waves that propagate on the free surface of an elastic half space. The Rayleigh wave amplitude decays exponentially in depth direction. It's penetration depth is about $d_{pd} \approx \lambda$, with λ=wavelength. Therefore the penetration depth is frequency dependent. Nevertheless, Rayleigh waves in an isotropic elastic half-space are not dispersive [18]. However, an isotropic layer on top of an isotropic half-space introduces dispersion. This dispersion can be calculated using the Thomson-Haskell transfer-matrix method [19,20].

In Fig. 1 the coordinate system of the problem is shown. The propagation direction of the surface acoustic waves is along the x_1 axis, the x_3 axis is normal to the surface of the specimen.

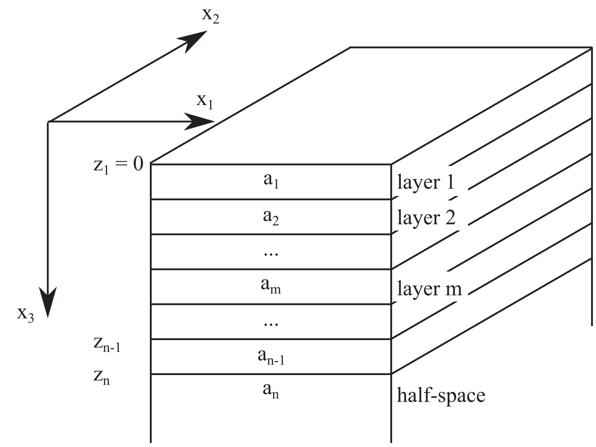

Fig. 1. Coordinate system and half-space with multiple layers.

In the transfer-matrix method the displacements and stresses at the top of a layer m can be related to the displacements and stresses at the bottom of this layer. The derivation presented here follows the free-plate problem derived from Thrower [17], but can similarly be adapted for the half-space problem. Let $W_{m,n}$ be a row vector of the m-th layer at the n-th interface that represents displacements and stresses, then

$$W_{m,m} = E_m \cdot W_{m,m-1} \tag{1}$$

connects the displacements and stresses on top of layer m to displacements and stresses at its bottom via the layer matrix E_m. Entries of the layer matrices can be found elsewhere [17].

Using the matrix product

$$F = E_1 \cdot E_2 \cdot \ldots \cdot E_n, \tag{2}$$

a connection between the displacements and stresses at the top of the half space and at the top of the multilayer system can be established:

$$W_{n,n} = F \cdot W_{1,0}. \tag{3}$$

After substituting the stress-free boundary conditions $\sigma_{33} = 0$, $\sigma_{31} = 0$ into Eq. (3), a set of four equations can be obtained. This set of equations is rearranged in terms of the unknown amplitude factors of the wave solutions. From the resulting coefficient matrix the characteristic determinant can be calculated. Roots of this determinant yield the Rayleigh wave velocity at a given frequency.

Unfortunately, the calculation of the coefficient determinant suffers from numerical instabilities at large frequency-thickness products. However, the numerical problems can be overcome almost completely if the matrix product is computed according

$$F^* = E_1^* \cdot E_2^* \cdot \ldots \cdot E_n^*, \tag{4}$$

where E_m^* is the second order δ-matrix of matrix E_m, and F^* results from the product of the δ-matrices of each layer. The δ-matrix E_m^* is constructed from subdeterminants of the layer matrix E_m and is now of the size 6×6. With help of the δ-matrices the coefficient determinant can be computed and the result will be free from numerical errors up to a very large frequency-thickness product.

Although the matrix F^* is now of size 6×6 instead of 4×4 as in the original transfer matrix formulation, the size of the matrix does not increase with increasing number of layers. Therefore the computation of multilayer systems is much faster compared to other methods like the global matrix formulation. Thrower [17] presented a computer program that was executed on a state of the art computer at that time. He reported on a computation speed of about 10 s per layer. The Matlab® program developed in this work takes about 5 ms per layer if executed on a consumer laptop.