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An Inverse Problem for Grain Size in Low Carbon Steels and Ultrasonic Measurements

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Abstract
Low carbon steels are considered in this article. It is often the case in practice to determine the average size of the grains $\overline{D}$ in them [1]. The non-destructive evaluation /NDE/ of $\overline{D}$ [2] is interest.

For a sample from normalized carbon steel, $\overline{D}, mm = 0.022 \pm 3\%$ by metallographic analysis is determined. For it, they are measured $(V_L; V_T)$ [2,4]. With the ZEROIN [5] program, the NDE of $\overline{D}, mm$ by measured $(V_L; V_T)$ is calculated.

Keywords: Inverse Problem, Grain Size, Low Carbon Steel, Ultrasonic Measurement

1. Introduction

The carbon steels in machine building are the most commonly. It is known [1,3,4] that the relationship $\sigma_{YS}(E)$ exists, where $(E; \sigma_{YS}; ...)$, where $E = E(V_L; V_T)$ – Young modulus $\sigma_{YS} = \sigma_{YS}(\overline{D})$ – yield stress. Here $(V_L; V_T)$ – velocities of longitudinal and transversal ultrasonic waves, $\overline{D}$ – average of ferrite grains. This is the direct problem.
An interest is the inverse problem, namely "Determining the average size of the grains $\overline{D}$ in carbon steels by measuring of $(V_L; V_T)$".

2. Theory

2.1. Relationship $\sigma_S(\overline{D})$

The semi-empirical relationship of Hall-Petch is considered [3]

$$\sigma_{YS} = \sigma_0 + K_y \left(\overline{D}\right)^{-1/2} \quad (1)$$

where σ_{YS} – low limit of yield stress ($\sigma_0 = 72MPa; K_y = 23.9MPa.mm^{1/2}$ [3] for low carbon steels).

2.2. Regression model $\sigma_{YS}(E)$

For carbon steel with a carbon content (0.10 to 0.35) % C, dependence $\sigma_{YS}(E)$ was obtained. The graphics is shown in Fig.1. It is shown 95% confidence intervals for the probability measurements.

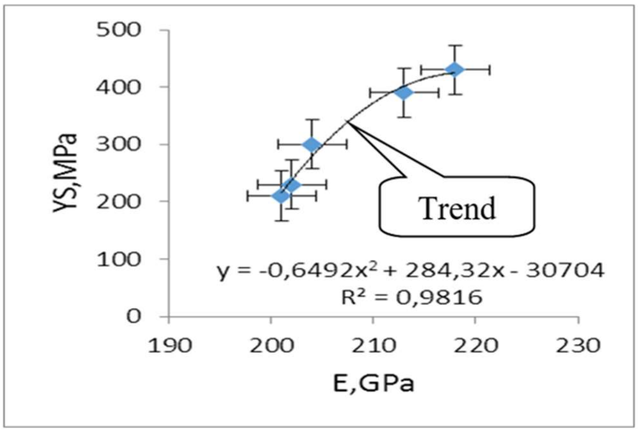

Fig.1. Polynomial regression for carbon steels, where $YS, MPa \equiv \sigma_{YS}, MPa$

It can be seen, that the trend of experimental data is approximated by polynomial regression (PR), (2).

$$\sigma_{YS} = \sum_{K=0}^{2} \beta_K E^K \qquad (2)$$

3. Inverse Problem for $\overline{D}, mm$

After equalizing (1) and (2), the equation $\overline{D}, mm$ is obtain

$$K_y.\left(\overline{D}\right)^n + \psi\left(V_L; V_T\right) = 0 \qquad (3)$$

where $n = -1/2$; $\psi(V_L; V_T) = \sigma_0 - \sum_{K=0}^{2} \beta_K E^K$; $\frac{E}{\rho.V_T^2} = \left[\frac{3-4(V_T/V_L)^2}{1-(V_T/V_L)^2}\right]$ [4].

The parameters in equation (3) are explained in dependence (1) and Fig.1. The parameters in (3) $\left(K_y; \sigma_0; \beta_0; \beta_1; \beta_2\right)$ are explained in dependence (1) and Fig.1. The equation (3) is non-linear. An effective method for its solution is the method of the bisection (Newton, 1669). The method is implemented with the algorithm ZEROIN (Brent, 1973) [5]. This algorithm combines the reliability of slotting with the asymptotic speed of the the souls method. The number of iterates for the implementation of the algorithm is $N \sim \log_2^2[(b-a)/TOL]$ where $TOL \sim 10^{-6}$ – uncertainty and *(a;b)* is the root search interval of the equation (3).

4. Equipment

For ultrasonic measurements the following equipment shall be used: Digital ultrasonic flaw detector SITESCAN 150S, Sonatest, England, transducers 5 MHz, with X-cut and Y-cut of piezo-plates, Panametrics, USA. Calibration block $(V_L = 5{,}93\, mm, \mu s)$, Sonatest, England, Digital micrometer Digimatic, Mitutoyo, Japan. With this micrometer, measurements are made with accuracy $\pm 0.5 \mu m$.

5. Experiment

A sample of steel grade 20, normalized, with dimensions h = 25 mm, a = 20mm, b = 150mm are measured. The velocities $(V_L ..;.. V_T)$ in the sample according to [4] are measured. The results are $(V_L = 5.92 \pm 0.03; V_T = 3.25 \pm 0.015)mm / \mu s$. Transducers with frequency 5MHz, X-cut and Y-cut of piezoplastins are used. The value $\overline{D}, mm$ is determined by the measured velocity $(V_L; V_T)$ and the solution of (3), received by the ZEROIN program, at a given root interval $(a = 10^{-6}; b = 0.05) mm$.

A metallographic shliph is made. The reference value $\overline{D}, mm$ for the metallographic microscope at 100x magnification is determined. The results of measured are given in Table 1.

Table 1.

The calculated value / NDT evaluation /	The reference value / Metallographic evaluation /
$\overline{D}, mm = 0.020218$	$\overline{D}, mm = 0.022 \pm 3\%$
The ZEROIN program is used The uncertainty is $TOL \sim 10^{-6}$	A metallographic shliph is used. Metallographic microscope at 100x

The calculated value for $\overline{D}, mm$, is by five real orders because in ZEROIN program the uncertainty is $TOL \sim 10^{-6}$. The number of iterations is ~ 117 (in this case the time of work of the program ZEROIN is ~ 5s). The error of NDE of $\overline{D}, mm$ is 0.68%.

6. Conclusion

The article formulated and solved the inverse problem of NDE the average of grain size – $\overline{D}, mm$ in a low carbon steel by using ultrasonic measurements – $(V_L; V_T)$. The solution for $\overline{D}, mm$ is obtain. It is decided by the ZEROIN algorithm. In this case $\overline{D}, mm = 0.020218$ is obtain. The error in NDE, by measuring velocities $(V_L; V_T)$, is less than 1%.

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