A INVERSE PROBLEM IN ULTRASONIC TESTING AND MECHANICAL PROPERTIES OF POLYCRYSTALLINE MATERIALS

ОБРАТНАЯ ЗАДАЧА В УЛЬТРАЗВУКОВОМ ТЕСТИРОВАНИИ И МЕХАНИЧЕСКИЕ СВОЙСТВА ПОЛИКРИСТАЛЛИЧЕСКИХ МАТЕРИАЛОВ

Assoc. Prof, PhD. Alexander Popov[1] , MSc Eng. Georgy Dobrev[2],
[1]Institute of Mechanics - BAS, Sofia, Bulgaria, [2]Institute of Metal Science - BAS, Sofia, Bulgaria,
E-mail: alpopov@abv.bg ; dobrevbg@mail.bg

KEYWORDS: INVERSE PROBLEM, ULTRASONIC TESTING, MECHANICAL PROPERTIES, POLYCRYSTALLINE MATERIALS

Abstract: *The direct problem in ultrasonic testing (UT) is: "Evaluation of attenuation coefficient by means velocity of ultrasonic wave propagation, frequency and grain size in polycrystalline materials". The inverse problem in UT is formulate as "Non-destructive evaluation of grain size by measurement of acoustical characteristics". The values of acoustical characteristics* $(V_L;V_T;\alpha_L;f)$ *are measured, according ASTM E 494:2015. In this article a equation for grain size* $(\overline{D})$ *is derived.*

Key words:, *ultrasonic testing, acoustical characteristics, grain size, yield stress, ultimate tensile stress, fatigue limit.*

1.Introduction

In UT investigation of polycrystalline materials the relationship $\alpha_L = \alpha_L(V_L;V_T;f;\overline{D})$ is obtain. This is Lifshic-Parhomenko-Merkulov's formula [1]

(1) $$\alpha_L = \frac{8.\pi^3}{375}.\frac{\mu}{\rho^2}\left[\frac{4.\pi}{3}\left(\frac{\overline{D}}{2}\right)^3\right].f^4.W(V)$$

where ρ - density; $(\overline{D})$ - grain size; f – frequency; $(V_L;V_T;\alpha_L;f)$ - velocity of longitudinal -V_L and transversal V_T - ultrasonic waves, α_L - attenuation in ultrasonic wave propagation, $\mu = \rho.(V_T)^2$,

$W(V) = \left(\frac{1}{V_L^3}\right)\left(\frac{2}{V_L^5}+\frac{3}{V_T^5}\right)$.

This is direct problem in ultrasonic testing (UT).

2. Inverse problem in ultrasonic testing

The inverse problem in UT is formulate as "Non -destructive evaluation (NDE) of grain size $(\overline{D})$ by measurement of acoustical characteristics $(V_L;V_T;\alpha_L;f)$ of the material".

After reversing the direct problem (1), a cubic equation (with a single real root) to determine the grain size is obtained [2]

(2) $$\left[\frac{4.\pi^4}{1125}\left(\frac{V_T^4}{V_L^3}\right)\left(\frac{2}{V_L^5}+\frac{3}{V_T^5}\right)f^4\right].(\overline{D})^3 - \alpha_L = 0$$

This is equation for evaluation of the grain size $(\overline{D})$ by means measured acoustical characteristics $(V_L;V_T;\alpha_L;f)$, according ASTM E 494:2015.

3. Mechanical properties

3.1. Yield stress - σ_S

This value is evaluated by means Hall-Petch's relationship [3]

(3) $$\sigma_S = \sigma_0 + K_y(\overline{D})^{-1/2}$$

It is accepted that the constant is called "Pierre-Nabaro's tension" [3]. It takes into account the frictional tension - which compensates for the forces overcome by the dislocations when they move into the grain, [3]:

(4) $$\tau_{PN} = \frac{2G}{1-\nu}exp\left[-\frac{2\pi}{(1-\nu)}\left(\frac{c}{a}\right)\right]$$

where ν - Poisson coefficient, G - sliding module, *a* and *c* - crystalline grid parameters in a plane {100}. For *c* ~ 0.2% i.e. low - carbon steels. The approximation of parameter σ_0 is

(5) $$\sigma_0 \approx \frac{2}{3}.\frac{G}{1-\nu}$$

where $[\sigma_0] = MPa$; [G] = *GPa*.

The constant K_y is called Petch's coefficient. It takes into account the passage of dislocations from one grain to another [4]:

(6) $$\frac{K_y}{G} = \frac{2}{\cos\vartheta}\left\{\frac{|b|}{25\pi(1-\nu)}\right\}^{1/2}$$

where ϑ - angle of maximum deviation of the slip directions, $|b|$ - module of the Burger,s vector [3].

After regrouping the values in (6), for the Petch's coefficient K_y is obtain

(7) $$K_y \approx \frac{1}{4}.\frac{G}{\sqrt{1-\nu}}$$

where $[K_y] = MPa/mm^{1/2}$, [G] = *GPa* .As

(8) $$G = \rho.(V_T)^2 \ ; \ \nu = \frac{0.5-(V_T/V_L)^2}{1-(V_T/V_L)^2} ,$$

then from relationships (5) and (7) are obtain

(9) $$\sigma_0 \approx \frac{2}{3}.\frac{G(V_L;V_T)}{1-\nu(V_L;V_T)};$$

(10) $$K_y \approx \frac{1}{4}.\frac{G(V_L;V_T)}{\sqrt{1-\nu(V_L;V_T)}}.$$

This is the obvious look of coefficients $\left(\sigma_0 ; K_y\right)$ in Hall-Petch's relationship (3).

NDE of yield stress - σ_S is by (9), (10) and the solution $\overline{D} = \overline{D}(V_L ; V_T ; \alpha_L ; f)$ of equation (2).

3.2. Ultimate tensile stress - σ_B

Is being considered the Busibesq's solution [6,7]

(11) $\sigma_S = \varphi(\nu).HB$

where *HB*– Brinel's hardness, ν -Poison ratio,

$$\varphi(\nu) = \left\{\frac{1}{2}(1-2.\nu) + \frac{2}{9}(1+\nu).[2.(1+\nu)]^{1/2}\right\};$$

$$\nu = \frac{0.5-(V_T/V_L)^2}{1-(V_T/V_L)^2}.$$

Putting (11) in Hall-Petch's relationship (3) we have

(12) $\sigma_S = \sigma_0 + K_y\left(\overline{D}\right)^{-1/2} = \varphi(\nu).HB$

This is Stroh's relationship [5] in type

(13) $HB = \sigma_0^{(HB)} + K_y^{(HB)}\left(\overline{D}\right)^{-1/2}$

where

(14) $\sigma_0^{(HB)} = \dfrac{\sigma_0}{\varphi(\nu)}$;

(15) $K_y^{(HB)} = \dfrac{K_y}{\varphi(\nu)}$.

If $\varphi(\nu) \equiv \varphi(V_L ; V_T)$, then according (5) , (7), and (8), the relationships (14) and (15) are recorded in the form

(16) $\sigma_0^{(HB)} = \dfrac{2}{3}.\dfrac{G(V_L ; V_T)}{1-\nu(V_L ; V_T)}.\dfrac{1}{\varphi(V_L ; V_T)}$;

(17) $K_y^{(HB)} = \dfrac{1}{4}.\dfrac{G(V_L ; V_T)}{\sqrt{1-\nu(V_L ; V_T)}}.\dfrac{1}{\varphi(V_L ; V_T)}$

The value of σ_B, by Markovic's relationship, $\sigma_B \approx 0.34HB^{0.989}$ [7] , is obtain.

NDE of ultimate tensile stress - σ_B is by (16), (17) ,the solution $\overline{D} = \overline{D}(V_L ; V_T ; \alpha_L ; f)$ of equation (2) and Markovic's relationship.

3.3. Fatigue limit - σ_{-1}

This value is evaluated by Terentiev's relationship [9]

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

To derivate the coefficients $\left(\sigma_0^{(-1)} ; K_y^{(-1)}\right)$ in (18) is being considered the ratio [8]

$$\frac{\sigma_{-1}}{\sigma_S} = \frac{0.165HB}{\varphi(\nu)HB} = 0.165\varphi^{-1}(\nu)$$

We have the recording

(19) $\dfrac{\sigma_{-1}}{0.165\varphi^{-1}(\nu)} = \sigma_0 + K_y\left(\overline{D}\right)^{-1/2}$.

Therefore

(20) $\sigma_0^{(-1)} = \dfrac{0.165}{\varphi(\nu)}\sigma_0$;

(21) $K_y^{(-1)} = \dfrac{0.165}{\varphi(\nu)}K_y$.

According (5) and (7) for the coefficients (20) and (21) are obtain

(22) $\sigma_0^{(-1)} \approx \dfrac{1}{10}.\dfrac{G}{\varphi(\nu)(1-\nu)}$;

(23) $K_y^{(-1)} \approx \dfrac{2}{5}.\dfrac{G}{\varphi(\nu)\sqrt{1-\nu}}$.

According (8) the coefficients $\left(\sigma_0^{(-1)} ; K_y^{(-1)}\right)$ are

(24) $\sigma_0^{(-1)} \approx \dfrac{1}{10}.\dfrac{G(V_L ; V_T)}{(1-\nu(V_L ; V_T))}.\dfrac{1}{\varphi(V_L ; V_T)}$;

(25) $K_y^{(-1)} \approx \dfrac{2}{5}.\dfrac{G(V_L ; V_T)}{\sqrt{1-\nu(V_L ; V_T)}}.\dfrac{1}{\varphi(V_L ; V_T)}$.

This is the obvious look of coefficients $\left(\sigma_0^{(-1)} ; K_y^{(-1)}\right)$ in Terentiev's relationship (18).

NDE of Fatigue limit - σ_{-1} is by (24), (25) and the solution $\overline{D} = \overline{D}(V_L ; V_T ; \alpha_L ; f)$ of equation (2) .

4. Conclusion

It's resolved the inverse problem: Non destructive evaluation of $\left(\overline{D}\right)$ by means measure of acoustical characteristics of the material i.e.

(26) $\overline{D} = \overline{D}(V_L ; V_T ; \alpha_L ; f)$.

The values measurement of $(V_L ; V_T ; \alpha_L)$ are according ASTM E 494:2015.

For the non-destructive evaluation of mechanical properties: σ_S , σ_B and σ_{-1} by means

(27) $\sigma_S = \sigma_S(V_L , V_T ; \alpha_L ; f)$;

(28) $\sigma_B = \sigma_B(V_L , V_T ; a_L ; f)$;

(29) $\sigma_{-1} = \sigma_{-1}(V_L ; V_T ; \alpha_L ; f)$.

are could be used.

5. Reference

1. E.Papadakis, Ultrasonic attenuation and scattering in polycrystalline materials, Physical Acoustics, Vol.IV, B, edited by U.Mezon, Fizmatlit, Moscow. 1963.
2. Popov Al. , Mesomechanics of ferrous alloys, Series "Applied Mathematics and Mechanics", Vol. 8, Institute of mechanics - BAS, Sofia, 2017, (ISSN: 1314-3034).
3. Zolotorevskii V.S., Mechanical properties of metals, Misis, Moscow, 1998.
4. Meshkov Ju.Ia., The physical basis for the destruction of steel structures, Naukova dumka, Kiev, 1981.
5. Petch N., Metalographic Aspirations of Destruction, in Fracture Vol.1, edd.by H.Liebowitz, Mir, Moscow, 1973.
6. Timoshenko S.P., J.Gudier, Elasticity theory, Nauka, Moscow, 1979.
7. Markovic M.P., Un samples methods for determining the mechanical properties of metals, MEI, Moscow, 1983.
8. Kuzmov D., &, Calculation and testing of fatigue in mashinbuilding, Technika, Sofia, 1979.
9. Terentiev V.F., Fatigue of metal materials, Nauka, Moscow, 2003.