CHARACTERIZATION OF CAST IRON USING ULTRASONIC TESTING

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ABSTRACT *- This paper presents an overview of possibility of the cast iron characterization using ultrasonic testing that could eliminate most of the disadvantages of the metallographic method, but its usage is limited by the fact that velocity and attenuation of ultrasonic wave depend on technological singularities of cast iron production. Characterization of microstructural features and mechanical properties of cast iron is based on the ultrasonic testing parameters, primarily on ultrasonic wave velocity, which depends on the elastic modulus and density of the cast iron.*

Keywords: *non-destructive testing, ultrasonic testing, cast iron, characterization*

KARAKTERIZACIJA ŽELJEZNIH LIJEVOVA ULTRAZVUČNIM ISPITIVANJEM

SAŽETAK *– Ovaj rad prikazuje pregled mogućnosti karakterizacije željeznih lijevova ultrazvučnim ispitivanjem koje bi moglo otkloniti većinu nedostataka metalografske metode, no njegovo korištenje ograničava činjenica da brzina i prigušenje ultrazvučnih valova ovise o tehnološkim posebnostima proizvodnje željeznih lijevova. Karakterizacija mikrostrukture i mehaničkih svojstava željeznih lijevova temelji se na parametrima ultrazvučnog ispitivanja, prije svega na brzini ultrazvučnih valova, koja ovisi o modulu elastičnosti te o gustoći željeznog lijeva.*

Ključne riječi: *nerazorna ispitivanja, ultrazvučno ispitivanje, željezni lijev, karakterizacija*

1. INTRODUCTION

Ultrasonic testing is widely used method of non-destructive testing in which beam of high frequency sound waves is introduced into material. An ultrasonic beam will propagate through a material with some attenuation, until it reflects on an interface or discontinuity. Energy reflected from interfaces or defects can be used to define the size and location of defects or the thickness of the material. Much less often, ultrasonic testing is used for material characterization: to define bond characteristics or to determine physical properties, structure, grain size and elastic constants [1].

Ultrasonic testing has some disadvantages. Rough material surface, size and complexity of material geometry, as well as unfavorable discontinuity orientation parallel to the sound beam can hinder interpretation of the echo pattern. Also, internal structure, such as grain size, inclusions, fine dispersed precipitates or graphite structure in cast iron can even cause problems during testing due to low sound transmission and high noise signal.

Therefore, in industrial and laboratory practice the cast iron microstructure is usually analyzed using destructive metallographic method. Ultrasonic testing of the cast iron could eliminate most of the disadvantages of the metallographic method, but its usage is limited by the fact that velocity and attenuation depend on technological singularities of cast iron production. That is why it is necessary to develop its own method for specific type of cast iron produced at the specific foundry [2].

Cast iron is an alloy of iron with carbon as the main alloying element, containing more than 2.03 %C. In addition to carbon, cast irons contain silicon and manganese. Silicon has the greatest influence on the microstructure of gray and nodular (ductile) iron enhancing graphite formation. Moreover, the microstructure also depends on the cooling rate of castings in molds. Mechanisms of austenite decomposition on perlite, bainite or martensite are identical to those of steel.

Figure 1 shows the microstructure of gray and nodular cast iron.

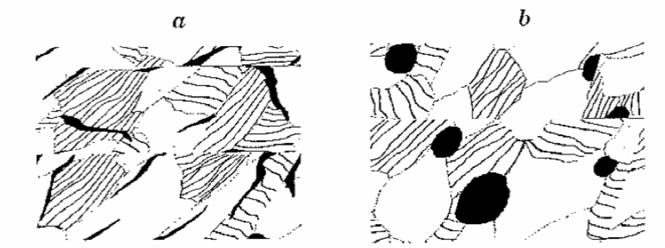

Figure 1 *The microstructure of gray iron (left) and nodular iron (right) [3]*

The gray iron microstructure consists of a ferrite-perlite matrix and the graphite in the form of flakes. The properties of gray iron are influenced by the size, amount and distribution of the graphite flakes, and by the relative hardness of the matrix. In the nodular iron the graphite occurs as spheroids which have less influence on the mechanical properties of the material. Nodular iron exhibits a linear stress-strain relation, a considerable yield strength and ductility. Nodular iron castings are made in a wide range of sizes with sections that can be either very thin or thick.

2. PARAMETERS FOR MATERIAL CHARACTERIZATION

In the past two decades, researches have been carried out to characterize microstructural features and mechanical properties of materials using ultrasonic testing [4-8]. Changes in microstructural features and mechanical properties significantly affect the ultrasonic testing parameters. Some of the commonly measured parameters for material characterization are ultrasonic velocity, attenuation, noise amplitude and critical angles [4].

The ultrasonic velocity is a function of the elastic modulus, density of the material and porosity size and distribution due to porosity effects on density and modulus. Several techniques are available for precise measurement of ultrasonic velocity in materials. Most of them require specialized or auxiliary equipment. Ultrasonic velocity measurements are useful for calculation of elastic modulus, shear modulus, Poisson's ratio and acoustic impendence [9-10].

For a homogeneous material, the longitudinal ultrasonic wave velocity through a material depends on the elastic modulus, *E*, material density, *ρ*, as well as on Poisson's ratio, *v* [11]:

$$v_{\mathrm{L}} = \sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)}}\sqrt{\frac{E}{\rho}}. \tag{1}$$

Attenuation is the loss of sound energy during propagation of the ultrasonic beam through the material, caused by absorption and scattering. Energy loss due to absorption can be caused by dislocation damping, unlike scattering which in polycrystalline materials depends on their grain size and wavelength of ultrasounds. Therefore, attenuation measurements are used for analysis of grain size and distribution of second phase particles.

Noise signals caused by scattering carry information about the size and nature of scatter. Hence, determination of noise amplitude, together with attenuation measurement, can provide information about the material grain size and distribution of second phase particles. Besides, ultrasonic backscattering has been successfully used as a method for measuring the case depth of hardened components [12].

On the interface of the two media, the incident longitudinal wave undergoes refraction and mode conversion. The refracted angle of longitudinal and transverse (shear) wave in the other medium depends on the incident angle, on the ratio of sound velocities in the two media, as well as on surface properties of the material. With the purpose of assessing surface properties, the ultrasonic goniometer is used [13].

3. CHARACTERIZATION OF MICROSTRUCTURAL FEATURES OF CAST IRON

3.1. Grain size

Grain size is one of the most important microstructural features which affects mechanical properties, such as strength and fracture toughness which are increased by reducing the grain size. The grain size estimation could be based on measurement of scattering coefficient, α_s [5]:

$$\alpha_s = C_r D^3 f^4 \tag{2}$$

where C_r is the scattering parameter depending on the ultrasonic wave type and the material anisotropy, D is the mean grain size and f is the frequency. Equation 2 is valid in case where wavelength is greater than the grain size. For an unknown grain size, the scattering coefficient is obtained from the calibration curves of scattering coefficient dependence on grain size.

3.2. Graphite morphology

Graphite morphology in cast iron also affects their mechanical properties. It is known that the elastic modulus of nodular cast iron is about two times higher as compared to gray cast irons. A size and nodular graphite content could be estimated based on the value of ultrasonic velocity. The longitudinal ultrasonic wave velocity being a parameter depending on the elastic modulus, changes as well as the graphite form [14]. ***Figure 2*** shows the

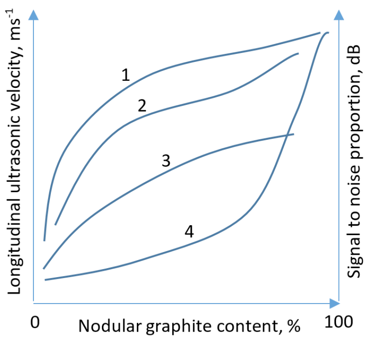

Figure 2 *Longitudinal ultrasonic velocity and signal to noise proportion versus size and content of nodular graphite, [2]*

influence of the graphite morphology in nodular iron castings on the longitudinal ultrasonic velocity, as well as the signal to noise proportion, for three cases: 1 – small, 2 – medium and 3 – big sized graphite. It is clear from the figure that the value of ultrasonic velocity increases with increasing nodular graphite content, while it decreases with increasing size of casting modules. For large castings, because of slow rate of cooling, the number of nodules is less and there is a chance for nodule to grow.

In many papers, correlation between nodularity and the ultrasonic velocity is represented, where nodularity is given as:

$$\text{nodularity} = \frac{\text{number of nodulus}}{\text{total number of particles of graphite}}. \tag{3}$$

The increase of ultrasonic velocity with nodularity could be attributed to the continuity of the alloy as the nodularity increase [4].

The variation of attenuation coefficient with nodularity shows that the attenuation decreases with increasing nodularity while increases with increasing size of casting module, which means increasing of attenuation with decreasing of nodule size. Decreasing of attenuation with increasing the nodularity could be explained in the way that the non-nodular graphite reflects and scatters ultrasonic waves much more than nodular graphite.

3.3. Ferrite-perlite matrix

At a constant graphite volume fraction, in a gray iron higher perlite contents resulted in lower ultrasonic velocity. Perlite was found to produce slightly lower values of modulus and ultrasonic velocity due to less density than that of ferrite. However, higher perlite content usually reduces the graphite volume fraction when the carbon equivalent is constant. This explains that pearlitic irons have the higher ultrasonic velocity than ferritic irons. Consequently, an increase in ferrite produced by heat treatment of a gray iron at a constant carbon equivalent decreases the modulus and the ultrasonic velocity [6].

3.4. Heat treatment

Under the assumption of validity of equation 1, the longitudinal ultrasonic wave velocity through a material with a heterogeneous structure, as the cast iron, depends on volume fraction of microstructure components, according to the mixing law:

$$v_L = v_{LM} V_M + v_{LG} V_G, \quad (4)$$

where v_{LM} and v_{LG} are longitudinal ultrasonic wave velocities in matrix and graphite, while V_M and V_G are volume fractions of matrix and graphite respectively [15].

Since the cast iron microstructure depends on subsequent heat treatment, the heat treatment parameters greatly affect the propagation of ultrasonic waves through the material. Therefore, the ultrasonic testing can be applied in the analysis of the results of heat treatment of cast iron.

4. CHARACTERIZATION OF MECHANICAL PROPERTIES OF CAST IRON

4.1. Elastic modulus

The elastic modulus could be estimated based on velocity of longitudinal, v_L and transverse waves, v_T, as suggested in [16]:

$$\boldsymbol{E} = \frac{\rho\, v_T\left(4\, v_T^2 - 3 v_L^2\right)}{v_T^2 - v_L^2} \quad (5)$$

where ρ is the density of cast iron. In this case, the estimation error varies from 4 up to 10 %. The reliable ultrasonic testing of other mechanical properties of cast iron is possible in cases when mechanical properties are dependent on elastic modulus, such as hardness and ultimate tensile strength.

4.2. Hardness and strength

Hardness is not a fundamental property of material, nevertheless many properties are predicted from hardness values when combined with additional information such as alloy composition [17]. For example: resistance to abrasives or wear, resistance to plastic deformation, elastic modulus, yield strength, ductility and fracture toughness. Some of these properties, such as yield strength, have numerical relationships with hardness value [2].

In cast irons, hardness is affected primarily by the volume fraction of graphite and ferrite in the microstructure. The hardness decreased as the graphite volume increased, as well when castings are heat treated to reduce the perlite content in the matrix.

A multiple regression analysis was conducted to relate the effects of ultrasonic velocity, graphite and ferrite content on hardness [6,18]. Furthermore, a correlation between ultrasonic velocity and strength of cast iron has been investigated [2,4,6]. Higher ultrasonic velocities are associated with higher yield strength and higher ultimate tensile strength.

In general, correlation between ultrasonic longitudinal velocity and mechanical properties could be given by the regressive linear equation:

$$\boldsymbol{MP} = \boldsymbol{a}\, \boldsymbol{v_L} - \boldsymbol{b} \quad (6)$$

where MP is mechanical property such as hardness, yield strength, ultimate tensile strength and elongation, a and b are constants depending on mechanical property and material features.

5. CONCLUSION

Many researches have been carried out to characterize microstructural features and mechanical properties of materials using ultrasonic testing, where they were based on the assumption that the change in microstructural features and mechanical properties causes changes in the value of ultrasound parameters. Some of the commonly measured parameters for material characterization are ultrasonic velocity, attenuation, noise amplitude and critical angles.

Grain size of ferrite-perlite matrix, graphite morphology and volume fraction of microstructure components are the most important microstructural features which affects mechanical properties. In polycrystalline materials, scattering depends on their grain size and wavelength of ultrasounds. Therefore, the grain size estimation could be based on measurement of scattering coefficient. A size and nodular graphite content could be estimated based on the ultrasonic velocity, which increases with increasing nodular graphite content, while it decreases with increasing nodule size. Since the cast iron microstructure depends on subsequent heat treatment, the ultrasonic testing can be applied in the analysis of the results of heat treatment of cast iron.

The elastic modulus could be estimated based on velocity of longitudinal and transverse waves. The reliable ultrasonic testing of other mechanical properties of cast iron is possible in cases when mechanical properties are dependent on elastic modulus, such as hardness, yield strength, ultimate tensile strength and elongation.

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