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Ultrasonic testing method for quality control of mold castings

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Abstract. The paper presents the review of one of the promising testing methods for quality control of mold castings that is ultrasonic inspection. Pulse-echo method, through transmission method and phased array technique are considered. The advantages and limitations for the analyzed methods are discussed. The produced by foreign and national companies aperture is reviewed.

1. Introduction

The share of acoustic methods in the volume of nondestructive testing comprises more than 60% in relation to other testing techniques [1]. This is conditioned by a number of advantages pertaining to these methods such as: high speed, accuracy of measurement, high sensitivity, inspection with one side access to the object, safety for the operator's health, option to use portable ultrasonic testing equipment, in-service testing during technological processes, capacity to transmit ultrasonic waves into moving objects avoiding their direct contact with transducer.

The analysis of research published [2-4] demonstrates that the systems based on application of ultrasonic testing method are more promising among the nondestructive testing systems for mold castings as these systems possess the highest sensitivity and are highly self-descriptive when it comes to characteristic technological and operational defects in metal. The obtained using this testing method data about the defect's size, square and spacing enables quality visualization for subsequent assessment of capability and service life of a metal part. The obvious advantage of ultrasonic testing application is the potential to build automated systems applying quite acknowledged in practice solutions [5-7]. In this respect it is possible to state that acoustic methods and systems are the most promising for nondestructive inspection of metal parts quality.

However, in spite of sufficiently wide application of acoustic methods for nondestructive testing, they possess limitations such as low detectability of single volume defects, low efficiency of testing materials with great oscillation damping.

From a wide range of acoustic methods available, pulse-echo method, through transmission method and phased array technique are chosen for testing metal parts.

2. Pulse-echo method

The principle of the pulse-echo method is that during electric pulse generation the ultrasonic transducer generates oscillations transmitted to the object under control. The same transducer receives echo-signals reflected from defects [8]. This method is widely used in industry due to its simplicity as only one transducer is needed to perform testing of an object. In this case there is no necessity to use specific



constructions for location and alignment of acoustic axes which is required if two transducers are to be used [9]. The ultrasonic nondestructive method also allows quite accurate detection of location, depth of occurrence and spacing of the defect in the object under control in relation to the transducer. The method can be used with one side access to the object under control.

To the main characteristics of pulse-echo method pertain the following: the maximum penetration depth, the minimal dead zone, high sensitivity, resolution, location accuracy and productivity.

In addition to the advantage of one side access, the pulse-echo method possesses the highest sensitivity to detect internal defects as well as reliable accuracy for defects' spacing detection. Judging by the amplitude value of the signal reflected it is possible to detect the defect size, while judging by the spectral composition of the impulse reflected it is possible to detect the defect type and shape.

The diagram of ultrasonic wave front passing along the depth of the object under control is given in Figure.1. Figure. 1, a demonstrates the zone without the defect, while Figure 1,b demonstrates the zone with the defect which re-echoes the signal.

The ultrasonic impulse path occurs from the source to the reflector and backwards and constitutes:

$$2D = C * t_3, \quad (1)$$

where t_3 – the delay time of the echo pulse arrival in relation to the initial one; D – the distance from the defect to the source; C – the ultrasonic wave speed in the object under control.

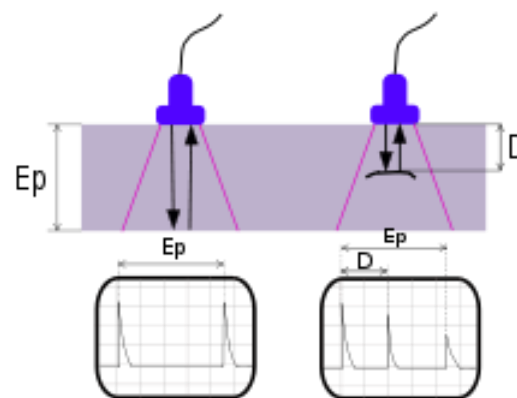


Figure 1. The diagram of the ultrasonic wave passing through the object under control, pulse-echo method used: a) without the defect; b) with the defect.

Pulse-echo method equipment enables to determine the defect behavior, classify defects according to their size, shape and spacing.

The leading world manufacturers of ultrasonic equipment produce instruments for metal parts testing within their product range. *Sonotron NDT* produces ultrasonic defectoscope *ISonic AUT 16* which allows for metal parts testing (Figure 2) [10].

The flaw detector is the portable multichannel instrument intended for high speed automated ultrasonic testing machines and monitoring systems. The instrument contains 16 independent channels, each channel comprising its own pulser-receiver, and 100 MHz sampling rate signal digitizer. Each channel may drive either single element probe or probe pair of phased array.

The scanning zone visualization can be formed in A-, B-, C- and D-Scan, 3D-View modes, etc. Significant increase of scanning speed may be achieved due to various specific probe pairs of phased arrays; each of these is toggled via its separate gate to one control module (Figure 3).



Figure 2. Ultrasonic defectoscope *Sonotron ISonic AUT 16*.



Figure 3. Ultrasonic defectoscope *Sonotron ISonic AUT 16* in service.



Figure 4. Ultrasonic defectoscope *DIO 1000 PA*.

STARMANS electronics, s.r.o. produces ultrasonic defectoscope *DIO 1000 PA* (figure 4). Image visualization is formed in various scan modes (A, B, C, S and W - scans) in this defectoscope. Scanning speed increases significantly when using phased array. Phased arrays may be used in manual as well as automated mode (data array storage output in the editing C-scan mode) using the scanners. The application for this instrument is testing products of metals, composites and plastic.

3. Through transmission method

Through transmission method of nondestructive testing is the method where two ultrasonic transducers 2 and 3 are used (Figure 5). The transducers are located on both sides of the object under control 1 along the same axis. Transducer 2 excites ultrasonic waves while transducer 3 receives them. If the defect 4 is present, the amplitude of the ultrasonic signal received reduces significantly or the ultrasonic signal is completely lost due to the defect casting acoustic shade.

Through transmission method for testing metal materials enables detecting more fine defects throughout great thickness of parts in comparison to pulse-echo method. It is based on caused by defects attenuation of elastic oscillations of ultrasonic frequency [11]. Through transmission method is applied to determine layering, foreign inclusions, holes and other defects.

For through transmission method to function efficiently there has to be two side access provided to the object under control. The method limitation is its complexity. First of all, it is related to the problem of two transducers orientation in relation to their central beams of the directional pattern, impossibility for accurate assessment of defects location and low sensitivity (up to 20 times) in comparison with echo methods.

To the advantages of the through transmission method pertain the following: minor dependence of signal amplitude on the material discontinuity location, high noise immunity and absence of dead zone.

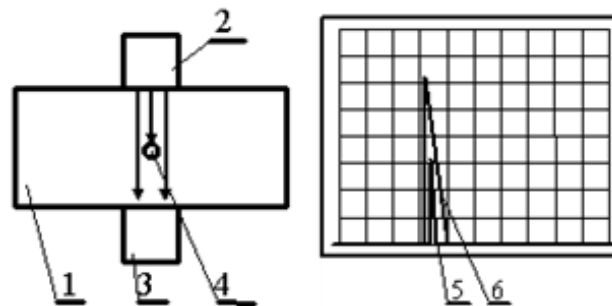


Figure 5. The diagram of ultrasonic wave passing along the thickness of the object under control when using through transmission method:

1 – the object under control; 2, 3 – transducers: the source and receiver
4 – the defect; 5, 6 – bed signals with and without the defect.

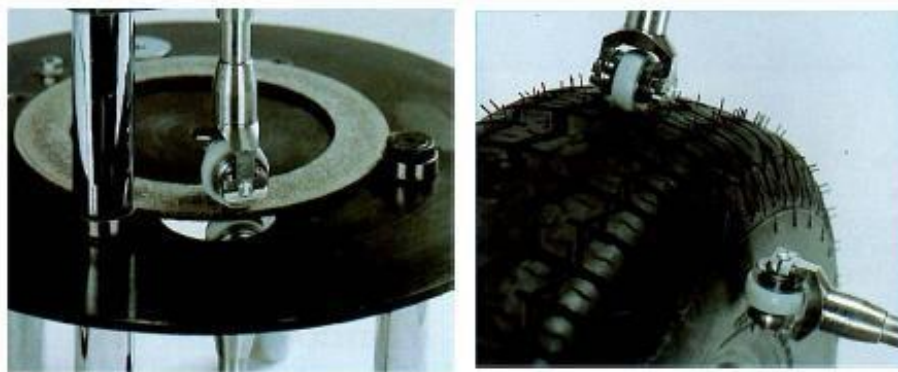


Figure 6. Ultrasonic defectoscope *DryScan 410* in service, through transmission method is used for carbon products inspection.

Based on the through transmission method a number of low frequency ultrasonic defectoscopes produced in Russia are available: UD4-76 [12], UD-22 UM [13], UD2H-PM [14], as well as defectoscopes produced abroad are available: USN-60 [15], RapidScan2 [16], DryScan 410 (Figure 6) [17], and MasterScan 380M [18]. These defectoscopes use special probes: low frequency direct single probes, dual-mode probes, inclined single, single-dual and immersion probes.



Figure 7. Ultrasonic defectoscope *UD4-76*.

National industry also produces a range of ultrasonic defectoscopes of UD series. For instance, the main purpose of ultrasonic defectoscope UD4-76 (Figure 7) is to detect failures in uniformity and continuity of materials in end products, green parts and welded (soldered) joints.

UD4-76 enables visualizing and storage of testing results in B-scans mode in relation to the transducer location during scanning.

In spite of through transmission method` theoretical studies and practical applications in ultrasonic testing being known for quite a while [19], its application was limited by only single acoustic path – single source and single receiver.

4. Phased array technique

The main advantage of this technique is high productivity of testing in comparison to single element transducer. The ultrasonic tomography image reconstruction is based on imaging due to reflection of elastic waves from material discontinuity which is equivalent to obtaining C-scan. Application of tomographic reconstruction using equally spaced linear phased arrays allows to determine spacing of several defects located in the inspection zone, with sufficiently high resolution.

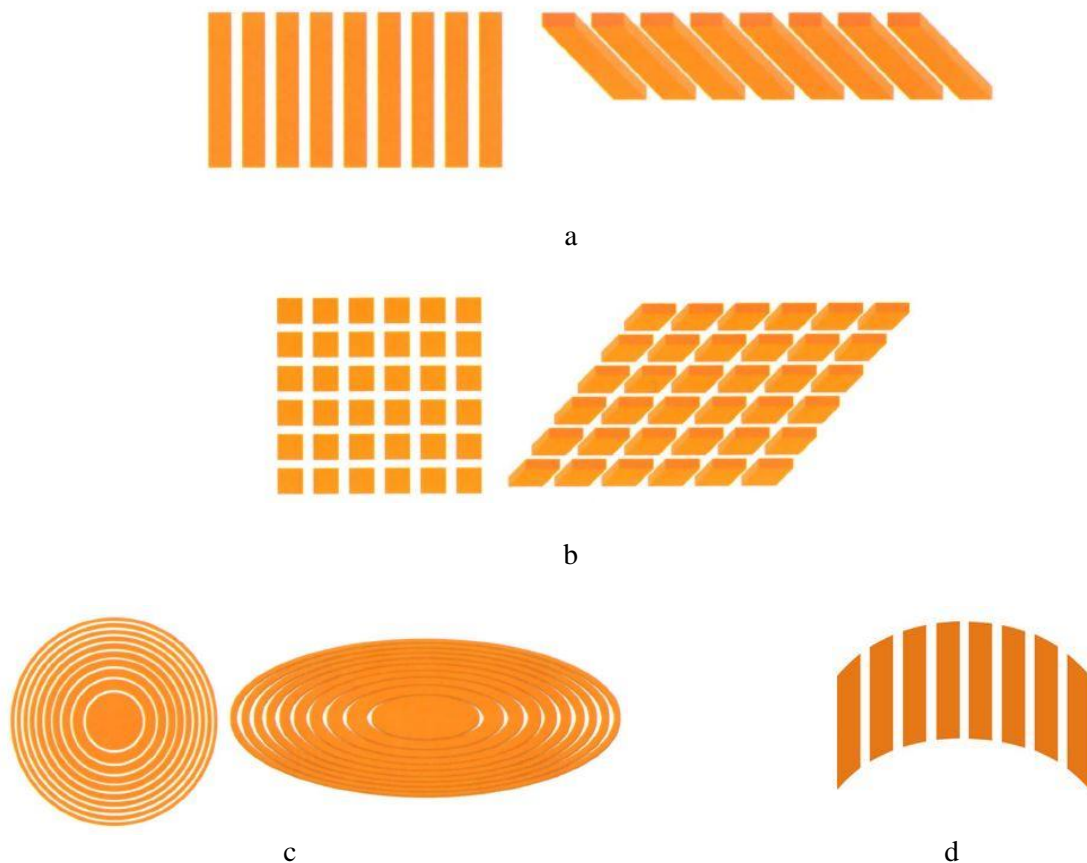


Figure 8. Types of phased array transducers.

Application of phased arrays allows to determine material discontinuity variously oriented to the acoustic axis. Single element transducer is highly likely to miss defects which are located aside of the acoustic beam under great angle to the acoustic axis of the transducer [20].

Depending on the number and location of piezoceramic elements, phased arrays fall into the following types:

1. Linear arrays – a single sequence of elements, usually formed by cutting a large cuboid piezoceramic plate. The beam is steered in single dimension (Figure 8,a).
2. Matrix arrays – the elements are placed as lattice which also can be curved. The beam is steered in three dimensions (Figure 8,b).

3. Circular arrays – the elements represent circles typically formed by cutting from piezoceramic plate (Figure 8,c).
4. Sector (convex, concave) arrays – a single sequence of elements which is curved to form the required beam shape or in compliance with the geometry of the object under control. The beam is steered in single dimension (Figure 8,d).

There are three main methods to steer the phased array beam:

- Electron scanning: single focal law is switching within the group of elements. Scanning is performed under the constant angle and along the phased array larger lobe. This process is equivalent to mechanical movement of traditional single element transducer.
- Dynamic focusing along the depth (along the acoustic axis): scanning is performed by changing the focal length. When applied the same impulse is used for irradiation while the array is refocusing subsequently to various depth sizes in the receiving mode.
- Sector scanning (also called azimuth scanning or angular scanning): irradiation is performed by the same group of elements keeping the same focal length, however subsequently under various angles.

The instruments of Acoustic Control Systems – ACS Group (Moscow) can be named to illustrate this method application, the company produces a range of ultrasonic tomographs for various applications:

- ✓ *A1040 MIRA* low frequency ultrasonic tomograph [21];
- ✓ *A1050 PlaneScan* low frequency ultrasonic scanner-topographer [22];
- ✓ *A1550 IntroVisor* high frequency ultrasonic flaw detector-tomograph [23].

For instance, *A1550 IntroVisor* is ultrasonic flaw detector-tomograph with digital phased array focusing and tomographic reconstruction of the visualized zone. It is designed for defects detection in metals and plastic. The instrument provides real-time section imaging.

To the advantages of ultrasonic tomography pertain the following:

- Real-time flaw detection in material discontinuity in metals, plastic and composite objects with efficient visualization of the received data;
 - Velocity and efficiency;
 - Real-time imaging in tomograph mode with high information refresh rate;
 - Greater phased array aperture enabling weld control without shear scanning;
 - High frame rate, at that high scanning speed along welded joint up to 50 mm/sec is enabled.
- A1550 IntroVisor* ultrasonic flaw detector-tomograph parameters are given in table 1 below.

Table 1. The main *A1550 IntroVisor* ultrasonic flaw detector-tomograph parameters.

Parameter Name	Value
Permissible number of phased array elements	16 ÷ 64
Curvature	transversal, longitudinal
Image reconstruction rate	15 ÷ 35 frames per second
Tomograph size, pixels	256 × 256
Section reconstruction size, mm	±256 × 256 horizontally, in depth
Readings discreteness, mm	0,1 - 1
Operating frequency, MHz	1,0; 1,2; 1,5; 1,8; 2,0; 2,5; 3,0; 4,0; 5,0
Permissible ultrasonic sound velocity, m/s	from 300 to 15000
Display type	TFT SVGA 640x480
Operating temperatures	from –10°C to +45°C
Autonomous work duration	up to 8 hours

All acoustic tomographs of Acoustic Control Systems – ACS Group operate in pulse-echo mode only thus enabling tomograms based on echo signals only.

At present there is a range of produced abroad automated systems to perform ultrasonic testing of metal structures, namely, *Tecnatom* equipment (Spain) which uses echo method with ultrasonic wave input using coupling fluid (Figure 9).



Figure 9. *Tecnatom* equipment [24]: a –through transmission method; b – echo method

In spite of high accuracy and high quality control the equipment possesses some limitations:

- insufficient self-descriptiveness of the testing results to detect potential defect-related risks (during in-service inspection);
- applied, as a rule, with elastic vibrations input using coupling fluid.

5. Conclusion

The existing sufficient range of testing techniques for defects detection in metal parts allows to perform practically complete inspection of products. One of the most promising methods is ultrasonic testing method which possesses a number of advantages in comparison with other methods. However, a significant limitation of the available on the market equipment for ultrasonic testing is great labor costs due to low testing speed. Hence, development of the equipment which would integrate high resolution and high scanning speed to perform inspection is quite relevant nowadays.

It is expedient to use automated systems for acoustic testing method to perform testing of metal mold castings during production as well as at all stages of product life cycle. Application of phased array technique enables to ensure high detectability of defects, high self-descriptiveness of the testing results and identification of the visualized flaws topology.

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