Ultrasonic thickness measurement of the aluminum plate with wavy surface

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1. Introduction

Ultrasonic thickness measurements are used for quality control of products in various areas of industry. The most common is bulk wave pulse echo technique, because it is relatively sensible and enables one side access measurements [2, 3, 10]. In the case of multilayered structures the signals reflected by internal interfaces in the object may be exploited for thickness measurement of each layer separately.

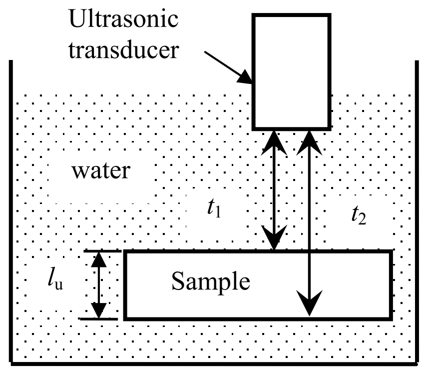
This technique is sufficiently fast to enable thickness monitoring in industrial conditions, for example, when aluminum plate goes out through the rolling mils [4, 10]. The calculation of thickness is based on measurement of the time of flight of ultrasonic signal in the plate. The accuracy of this thickness measurement technique depends mainly on time of flight measurement [5]. One of disadvantages of the pulse echo measurement technique is that ultrasound velocity should be known in advance [5]. Nevertheless, there are many other factors which can influence measurement accuracy essentially, such as measurement conditions, surface conditions, type of the material and etc. For metals with thickness ranges from 0.1mm up to 10cm approximate minimum uncertainty limit is ±0.002mm [9].

The time of flight measurement error depends on a selected signal detection technique, such as maximum amplitude, zero-crossing or cross-correlation techniques [6, 7, 9]. In some cases for the thin plates (0.13mm-0.06mm) the advanced wavelet analysis was used [1]. For precise thickness measurements using pulse echo technique, the incidence angle of an ultrasonic beam must be perpendicular to the surface of the test sample. Therefore, the measurement errors due to the curvature of the surface and positioning of the transducer have to be taken into account. If the surface of the sample under a test is wavy, the reflected signal can be distorted in comparison with the reflection from a planar surface [9, 11]. The curved surface can give some focusing effects also [11], which can cause additional measurement errors.

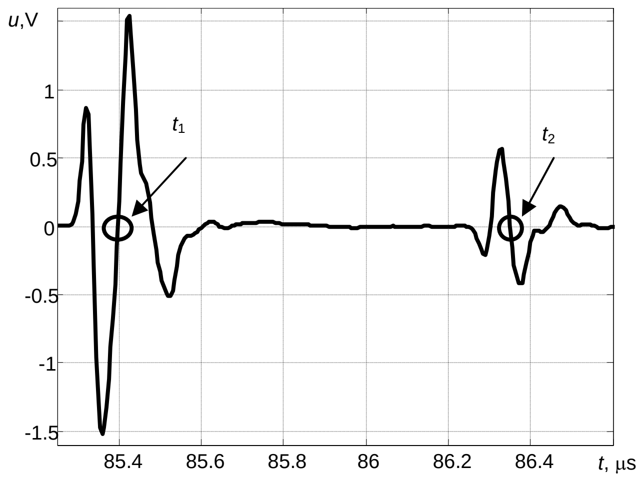
The objective of this work was to investigate the influence of the non-perpendicularity of transducer and curvature of the surface to the errors of thickness measurement of metallic plates.

2. Measurement technique

Pulse echo measurements usually exploit multiple reflections of ultrasonic waves between internal and external interfaces of the object under investigation. In a simplest case an object consisting of a single planar layer is immersed in water. For measurements only the signals, reflected by the front and back walls of the object, are used (Fig. 1).



a



b

Fig. 1. **The ultrasonic pulse echo thickness measurement technique: a- measurement set-up; b- the waveform of the reflected signal**

The time of flight (TOF) of ultrasonic wave in the test sample at the normal incidence is calculated as:

$$t_f = t_2 - t_1, \qquad (1)$$

where t_2 is the TOF of the signal reflected from the back surface of the sample, t_1 is the TOF of the signal reflected from the front surface. The measured time of flight is dependent on various factors which cause errors in measurement results:

$$\Delta t_n = \Delta t_r + \Delta t_m + \Delta t_\alpha + \Delta t_d, \qquad (2)$$

where Δt_r is measurement error of the TOF value of the ultrasonic wave in the test sample (reference), Δt_m are the TOF measurement error caused by the selected signal detection technique (i.e. zero-crossing or cross-correlation), Δt_α is the error caused by the non-perpendicularity of the incident ultrasonic wave with respect to the surface of the sample, Δt_d is additional error of the TOF caused by diffraction effects.

2.1. Zero-crossing technique

The measurement of the TOF using zero-crossing technique is performed as follows. First, the reflected signal from the front surface using negative threshold level is detected. In the case of reflection from the back surface, the positive threshold level is used. Then it is searched from that point in forward direction for the time instance $\hat{t}_{1,zc}$ or $\hat{t}_{2,zc}$, when the signal crosses the zero level.

In the case of the positive and negative peaks the delay time can be expressed as:

$$\hat{t}_{zc} = \hat{t}_{2,zc} - \hat{t}_{1,zc}, \tag{3}$$

where $\hat{t}_{1,zc} = \arg\{u_1(t) = 0\}, t \in \left[t_{01} : t_{01} + \frac{T_{01}}{2} \right]$,

$$t_{01} = \arg\{\min[u_1(t)]\};$$

$$\hat{t}_{2,zc} = \arg\{u_2(t) = 0\}, t \in \left[t_{02} : t_{02} + \frac{T_{02}}{2} \right],$$

$$t_{02} = \arg\{\max[u_2(t)]\};$$

$u_1(t)$ is the front surface signal, $u_2(t)$ is the back surface signal, $\hat{t}_{zc}$ is the estimated delay time between the corresponding reflections measured by the zero-crossing technique, T_{01} is the period of the $u_1(t)$, T_{02} is the period of the $u_2(t)$.

This approach possesses methodical error proportional to the sampling interval $\pm \frac{dt_s}{2}$, therefore for more precise calculation of the zero-crossing time the 3rd degree polynomial approximation of 5 samples was used to calculate $\hat{t}_{zc}$.

The zero-crossing technique is relatively fast, but works reliable only when the reflections are completely separated in the time domain.

2.2. Cross-correlation technique

The most reliable and accurate are methods based on calculation of a cross-correlation function between reflections from the object boundaries. The signal reflected by the front surface of the object usually is used as a reference signal in the cross-correlation analysis.

Using the cross-correlation technique the TOF was calculated in the following steps. The cross-correlation function $y_{cc}(t)$ between the front surface signal $u_1(t)$ and back surface signal $u_2(t)$ is given by:

$$y_{cc}(t) = \frac{1}{T} \int_0^T u_2(t) \cdot u_1(t - \tau) d\tau, \tag{4}$$

where τ is the integration variable, T is the duration of the signal used for calculations.

Determination of the maximum of the cross-correlation function $\hat{t}_{cc}$ corresponding to the time delay between the signals $u_1(t)$ and $u_2(t)$ is performed in the following way:

$$\hat{t}_{cc} = \arg\{\max[y_{cc}(t)]\}. \tag{5}$$

Maximum position of the cross-correlation function was calculated of the derivative of the cross-correlation function additionally using 3rd degree polynomial approximation through 5 neighbor points [6, 7, 8].

3. Experimental setup

Test object with curved boundaries complicates pulse-echo measurements, because the ultrasonic beam can be incident not at the normal angle to the surface of the sample. Therefore, the first task of investigations was to evaluate the influence of the ultrasonic beam angle deviation from the normal incidence. For that a flat plate was rotated around its symmetry axis, ultrasonic transducer was positioned at a fixed position and signals, reflected by the plate immersed in water were acquisited (Fig. 2).

The specially prepared aluminum plate with a flat (polished) surface was fixed perpendicularly to the axis of the ultrasonic transducer at the distance of 63mm from the transducer. For a pulse-echo immersion testing the PISL CX-166 transducer with the 15 MHz central frequency and 6mm diameter was used. Data acquisition was performed using the HP54645A digital oscilloscope. The data were transferred to a personal computer via IEEE488 interface for a further analysis. The plate was rotated around it symmetry axis in the range $\Theta=\pm 1°$ with the 0.1° step (Fig.2). It was assumed, that the transducer was positioned perpendicularly to the surface of the sample, when the amplitude of the reflected signal was maximal [11]. Waveforms of the reflected signals at the normal and oblique incidence are presented in Fig. 3.

At each rotation step the TOF were evaluated using the zero-crossing and the cross-correlation techniques, and then thickness of the sample was calculated.

The reference TOF (t_r) is calculated at the point of the normal incidence:

$$t_r = \frac{2 \cdot d_m}{c_u}, \tag{6}$$

where d_m is the reference thickness of the plate measured by a micrometer d_m=3.12mm±0.01mm; c_u is the ultrasound velocity in the plate c_u=6500m/s. At this point distortions of reflected signal waveform are minimal (Fig. 3).

At the normal incidence (Θ=0°) it was assumed that errors Δt_α, Δt_d, Δt_r could be neglected, so it was possible to evaluate TOF measurement errors (Δt_m), caused by the zero-crossing and cross-correlation techniques.

The TOF measurement error, caused by the zero-crossing technique is:

$$\Delta t_{m,zc} = \hat{t}_{zc} - t_r, \ \Delta t_{m,zc} = -7.1 \text{ ns}; \tag{7}$$

where $\hat{t}_{zc}$ is delay time estimated between signals $u_1(t)$ and $u_2(t)$ by the zero-crossing technique.

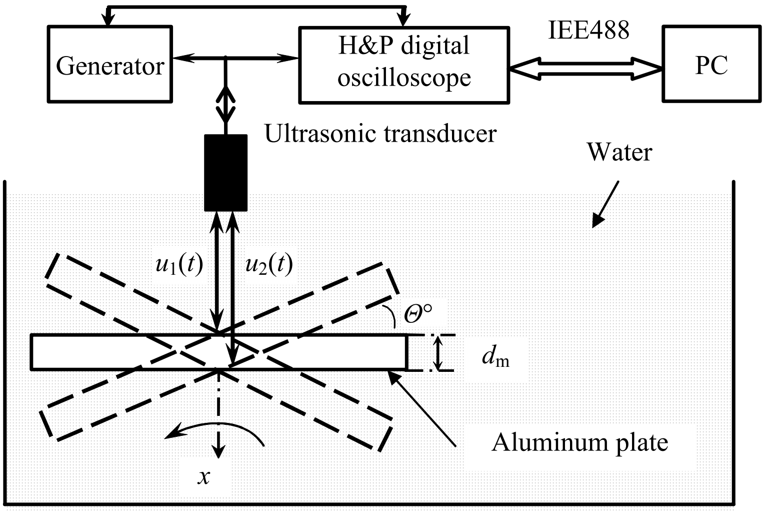


Fig. 2. **Experimental setup for investigation of the errors, caused by the non-perpendicular incidence**

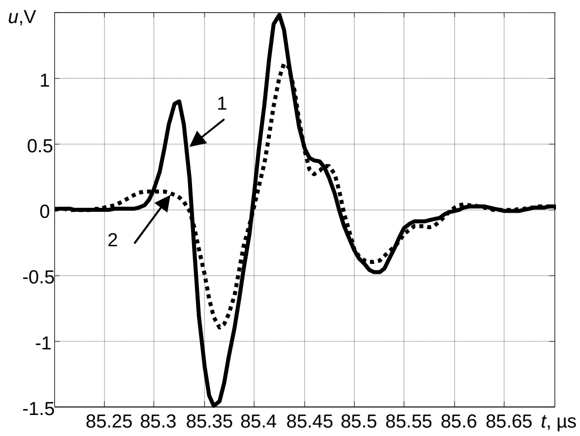


Fig. 3. **Waveform of the front surface reflection $u_1(t)$ at the normal and oblique incidence: 1-transducer perpendicular to the plate (deviation angle Θ=0°), 2-deviation angle Θ=0.5° from the perpendicular position between transducer and plate**

The TOF measurement error, caused by the cross-correlation technique is:

$$\Delta t_{m,cc} = \hat{t}_{cc} - t_r \,,\ \Delta t_{m,cc} = 0.5\,\text{ns}; \tag{8}$$

where $\hat{t}_{cc}$ is estimated delay time between the corresponding reflections.

At each rotation point the corresponding thickness value was calculated from the TOF results with subtraction of the errors (Δt_m) for both techniques:

$$l_{n,zc} = \frac{c_u \cdot (\hat{t}_{zc} - \Delta t_{m,zc})}{2},$$

$$l_{n,cc} = \frac{c_u \cdot (\hat{t}_{cc} - \Delta t_{m,cc})}{2}, \tag{9}$$

where $l_{n,zc}$ is the thickness calculated from the zero-crossing results, $l_{n,cc}$ is the thickness calculated from the cross-correlation results, c_u is the ultrasound velocity in the plate c_u=6500m/s.

At the normal incidence (Δt_m was compensated using Eq.7-8, Δt_α ,Δt_r and Δt_d were neglected):

$$\Delta t_{n,zc} = 0\,. \tag{10}$$

At the oblique incidence measurement errors are caused by Δt_α and Δt_d (Δt_r neglected, Δt_m was compensated using Eq.7-8):

$$\Delta t_{n,zc} = \Delta t_\alpha + \Delta t_d\,. \tag{11}$$

The influence of Δt_α according to the geometrical increase of the propagation path deviation angle at the Θ=±1° is quite small Δt_α=±0.2ns. A significant error Δt_d is due to diffraction effects (Fig. 4).

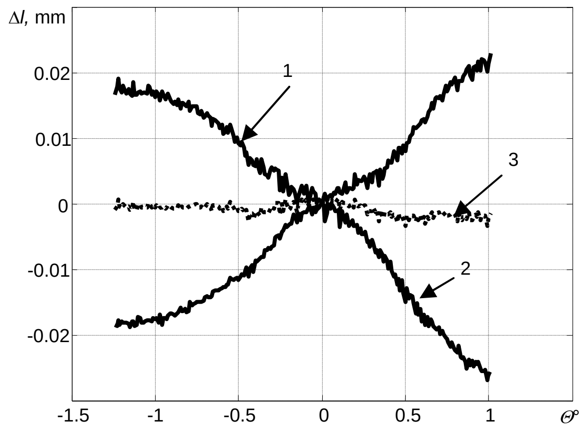


Fig. 4. **Thickness measurement errors with different techniques versus angle of the ultrasonic wave incidence: 1-zero-crossing, 2-cross-correlation, 3-average of the both techniques**

Both zero-crossing and cross correlation techniques are sensitive to the variation of the transducer angle and give almost contrary results with respect to deviation angle Θ (±1°) from the normal incidence 0° (Fig. 4). The maximum value of the cross-correlation results and the minimum value of zero-crossing results correspond to the point of the normal incidence. In literature no reference to such situation was found.

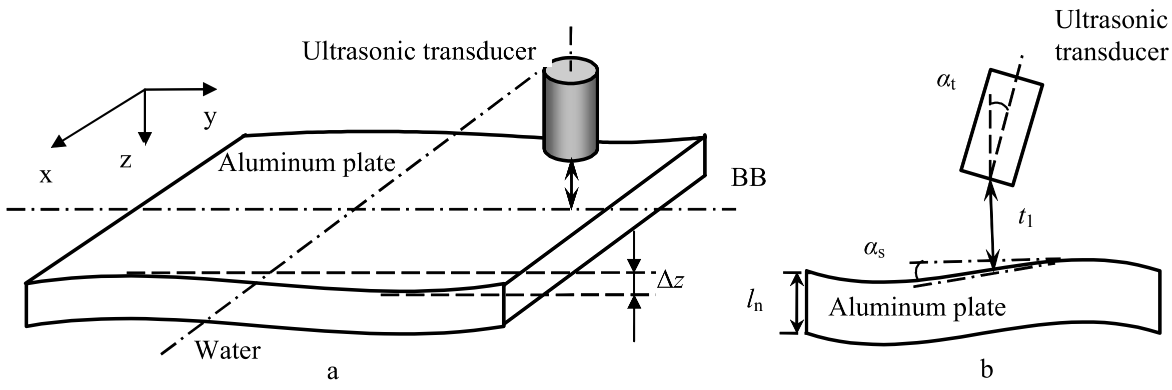


Fig. 5. **Investigation of the plate with a curved surface: a-wavy surface of the plate, b-curvature of the plate along BB cross-section, α_s is the angle of the surface curvature, α_t is the angle of the transducer orientation**

Because both techniques give similar deviations of opposite sign with respect to the point at which Δl=0mm (Fig. 4), the measurement errors (Δt_α and Δt_d) may be reduced using the averaging of the thickness calculated using cross-correlation and zero-crossing techniques (Fig. 4):

$$\bar{l}_n = \frac{l_{n,zc} + l_{n,cc}}{2}, \quad (12)$$

where $l_{n,zc}$ is the thickness calculated from the zero-crossing results, $l_{n,cc}$ is the thickness calculated from the cross-correlation results. The standard deviation of average $\bar{l}_n$ of both techniques is only ±1 μm (Fig. 4).

There is another way to increase accuracy of the thickness measurement of each technique separately. Thickness of the plate versus incidence angle estimated by the zero-crossing and the cross-correlation techniques (Fig. 4) can be approximated by the polynomial of *n*-th degree. The similar quadratic approximation, but for the reflection amplitude versus incidence angle was found in literature [11]. The following approximations can be used as the compensation curves to reduce the influence of the errors (Δt_α and Δt_d) for further thickness measurements of the plates with surface waviness.

4. Thickness measurement of the plate having a wavy surface

The hardware of the experimental setup was described in the previous part (Fig. 1). The acoustical properties of the plate were the same. The distance between transducer and aluminum plate was 63mm (Fig. 5, a). During the alignment of the transducer to the sample surface it was assumed that maximum amplitude corresponds to the normal incidence angle to the surface of the sample [11].

It was estimated from the mechanical measurements using a micrometer, that curvature of the surface along the BB cross-section is approximately Δz=0.3mm deep and has a wavy shape (Fig. 5, b), but the total thickness is constant d_m=3.45mm±0.01mm. The wavy shape of the plate surface may be due to transportation of the sheet through rolling mills during the manufacturing process. The angle of the incident ultrasonic wave with respect to the surface of the sample is found as:

$$\alpha_\Sigma = \alpha_s + \alpha_t, \quad (13)$$

where α_s is the angle of the surface curvature, α_t is the angle of the transducer orientation. In the case of the normal incidence α_Σ=0°. During scanning along wavy cross-section of the plate α_Σ is caused by transducer deviation angle α_t and surface curvature α_s, therefore $\alpha_\Sigma \neq 0°$ (Fig. 5, b).

To estimate the influence of the surface waviness to the measurement results, the transducer was scanned along the BB cross-section (y=1:97 mm) of the plate with the scanning step dy=1 mm.

The results of the thickness measurements obtained, when signal TOF is measured using the zero-crossing and the cross-correlation techniques, are also of opposite character (Fig. 6) as presented in Fig. 4. As it was mentioned in the previous part of this paper, the maximum value of the cross-correlation results and the minimum value of the zero-crossing results correspond to the normal incidence point, when the errors Δt_α, Δt_d, Δt_m are neglected (Fig. 6, point B'). Results obtained using two different zero-crossing and cross-correlation techniques are of opposite sign, because the distortions of the waveforms are caused by the diffraction error Δt_d.

The distance $l_w(y)$ between the transducer and the plate surface in water when the front surface is wavy is given by (Fig. 7):

$$l_w(y) = \frac{c_w \cdot \hat{t}_1(y)}{2}, \quad (14)$$

where c_w is the ultrasound velocity in water c_w=1470m/s, $\hat{t}_1(y)$ is TOF of the signal reflected by the front surface versus the scanning axis y (Fig. 5, a).

When front surface curvature is estimated from the arrival time t_1, the compensation curve of the thickness measurement, caused by the diffraction Δt_d and transducer positioning Δt_α errors, can be obtained.

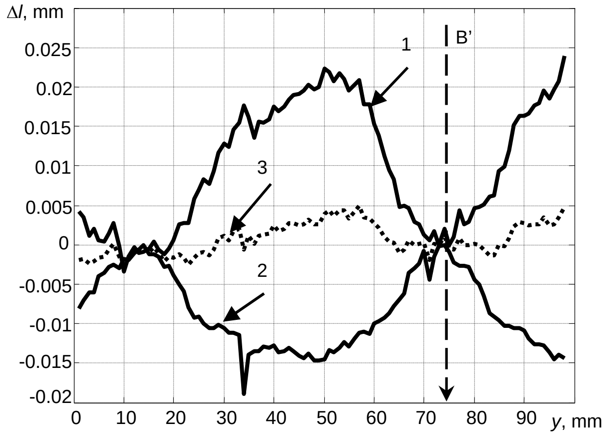


Fig. 6. **Thickness measurement with different techniques along the BB cross-section: 1-zero-crossing, 2-cross-correlation, 3-average of the both techniques**

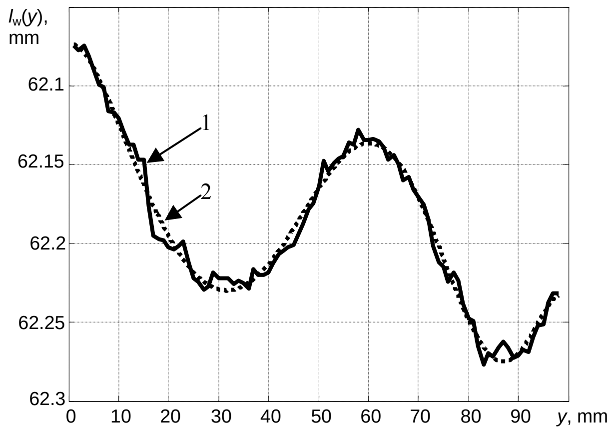


Fig. 7**. Distance to the front surface along the BB cross-section estimated by the zero-crossing technique: 1-measured distance *z*(*y*) from the transducer to the surface of the sample, 2-polynomial approximation $z_a(y)$ of the calculated distance *z*(*y*) with degree 8**

The 8th degree polynomial approximation $l_{wa}(y)$ of the calculated distance $l_w(y)$ between the transducer and the plate surface is given by:

$$l_{wa}(y) = p_1 \cdot (y)^n + p_2 \cdot (y)^{n-1} + .. + p_n \cdot (y) + p_{n+1}, \quad (15)$$

where p_1.. p_{n+1} are the polynomial coefficients, n is the degree of the approximation (n=8).

The gradient of the plate surface waviness in degrees was calculated in the following way (Fig. 8):

$$\alpha_\Sigma(y) = \arctan\left[\frac{dl_{wa}(y)}{dy}\right], \quad (16)$$

where $l_{wa}(y)$ was calculated using 8th degree polynomial approximation of $l_w(y)$ (Fig. 7).

The estimated deviation from the normal angle at the point B' is α_Σ= -0.47° (Fig. 8). In Fig. 8 compensation of the additive value of the positioning angle (α_Σ= -0.47°) to the zero is performed. The gradient of the plate front surface waviness causes corresponding TOF measurement errors (Δt_α and Δt_m). It was used as the compensation curve to reduce thickness measurement errors caused by the transducer positioning Δt_α and diffraction Δt_d errors. Thickness measurement results using the zero-crossing and cross-correlation techniques after subtraction of the compensation curves are presented in Fig. 9. This technique enables to compensate both zero-crossing and cross-correlation thickness measurement errors (Fig. 9) without self-aligning of the transducer during the scanning [11].

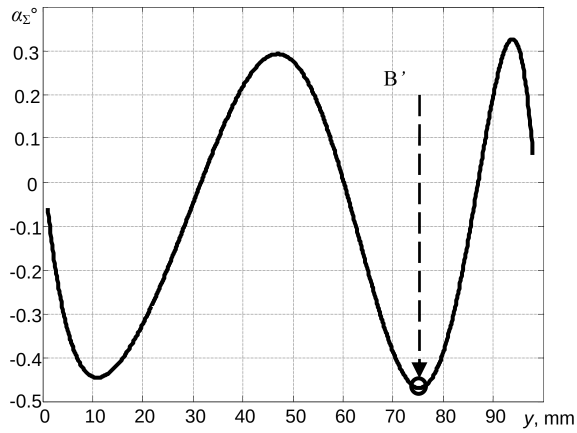


Fig. 8**. Gradient of the plate surface along BB cross-section**

Average of both techniques gives a standard deviation of thickness measurement ±0.002mm. Influence of the front surface curvature to the thickness measurements was reduced to the satisfactory limits after compensation of the positioning and diffraction errors to the both zero-crossing and cross-correlation techniques separately [10]. When average of the both techniques results is used, it is not necessary to use compensation.

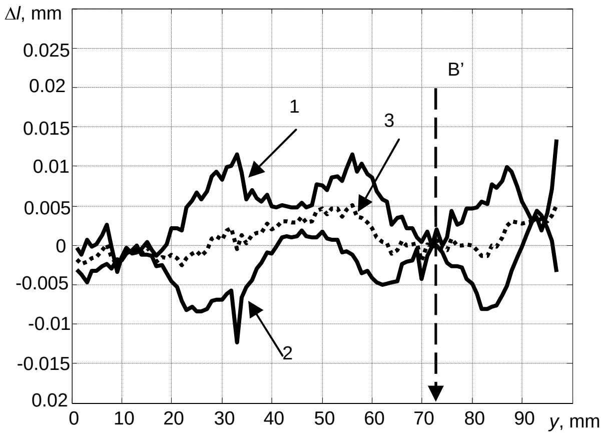


Fig. 9**. Thickness measurement along the BB cross-section with different techniques after compensation of the positioning and diffraction errors: 1-zero-crossing, 2-cross-correlation, 3-average of both techniques**

Conclusions

The results presented indicate that even small curvature of the front surface (±0.5°) significantly influences measurements of the plate thickness and gives an additional error of ±10μm.

The performed study shows that signal processing methods used to estimate the plate thickness are quite sensitive to the distortions of the reflected signal waveform. Distortions may be caused by different reasons, among them by diffraction effects of the transducer. Therefore, the time of flight measurement using the cross-correlation and the zero-crossing techniques give opposite results.

Two methods were used to reduce the influence of the surface waviness to accuracy of the thickness measurements: the compensation of the transducer positioning error and averaging of the measurement results obtained by the cross-correlation and the zero-crossing techniques.

Average of both techniques gives a standard deviation of thickness measurement ±0.002mm.

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Ultragarsinis aliuminio plokštelės su šiek tiek banguotu paviršiumi storio matavimas

Reziumė

Matuojant plonas plokšteles, svarbu įvertinti paviršiaus banguotumo įtaką storio matavimo tikslumui.

Straipsnyje pateikti aliuminio plokštelės su šiek tiek banguotu paviršiumi storio matavimo rezultatai. Tyrimais nustatyta, kad, esant nedideliam paviršiaus banguotumui (±0,5°), plokštelės storio matavimo paklaidos siekia ±10 μm. Šios paklaidos priklauso nuo vėlinimo laiko matavimo būdo. Taikant pasiūlytą paklaidų sumažinimo metodiką, pagerinamas storio matavimo, esant kreiviems paviršiams, tikslumas.

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