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Numerical Investigation of Influence of Temperature on Propagation of Ultrasonic Waves in Waveguides with Mode Conversion

E. Jasiuniene[1], E. Zukauskas[1], R. Kazys[1]
[1]*Ultrasound Institute, Kaunas University of Technology, Studentu St. 50, LT-51368 Kaunas, Lithuania*
elena.jasiuniene@ktu.lt

***Abstract*—In the case of the objects with a high temperature the measurements are often performed using waveguides in order to protect the ultrasonic piezoelectric transducers from a high temperature. In some cases, for measurement of specific properties of materials, shear waves are used. Shear waves can be generated exploiting mode conversion phenomenon using a longitudinal wave transducer and a waveguide with deflected front surface. However, the deflection angle has to be carefully selected, when it is required that the shear waves would propagate parallel to the waveguide axis. The proper deflection angle depends on material used for the waveguide properties. When the temperature changes, the properties of the material (as ultrasonic velocity) change as well, causing the change of the reflection angle and the propagation path. A numerical investigation was performed in order to evaluate how the change of the temperature will influence the reflection angle of the ultrasonic waves and the propagation path. It is shown that the change of the temperature influences the reflection angle and propagation path of ultrasonic waves and should be taken into account.**

***Index Terms*—Mode conversion, numerical simulation, temperature gradient, ultrasonic waves, waveguides.**

I. Introduction

When the objects to be inspected possess high temperature, measurements are often performed using waveguides in order to protect the most often used piezoelectric transducers from high temperatures. Waveguides are used to transfer the ultrasonic waves from the transducer to the object efficiently and at the same time they have to be of low thermal conductivity in order the temperature is decreased along the length of the waveguide.

To use the waveguide as a thermal buffer is not a new idea [1]–[7]. Usually waveguides are used to transfer longitudinal waves. But in some cases measurements have to be performed using shear ultrasonic waves, because measurement using ultrasonic shear waves gives more information about the properties of the object under the test. As shear wave transducers are more expensive, it was proposed, that shear waves can be generated by mode conversion using conventional longitudinal wave transducers. Shear waves are generated by mode conversion when longitudinal wave is reflected from the boundary with acoustic impedance discontinuity, when appropriate angle is chosen carefully [1], [2], [8], [9].

The problem can arise if temperature will change, because ultrasonic velocity in the material depends from the temperature and if the temperature will change, the propagation angle of the mode converted shear wave will change, and that can influence the measurements considerably.

Therefore the objective of this research was to investigate the influence of the temperature on the characteristics of the propagation of shear ultrasonic waves after mode conversion in the waveguide. Numerical investigations were performed using CIVA software and finite element method.

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II. Generation of Shear Waves using Mode Conversion

The ultrasonic shear wave can be generated by a mode conversion, when a longitudinal wave is incident on a boundary with an impedance discontinuity (Fig. 1).

Fig. 1. Schematic diagram of the waveguide with mode conversion.

If the longitudinal wave L_{inc} is incident with appropriate angle, then not only longitudinal L_{ref} wave is reflected, but also the shear wave S_{ref}. The angle of the reflection of the shear wave can be found using Snell's law

$$\frac{c_s}{c_l} = \frac{\sin\ \varphi}{\sin\ \theta}, \qquad (1)$$

where θ is the incidence and the reflection angles of the longitudinal wave, φ is the reflection angle of the shear wave, c_l is the velocity of longitudinal ultrasonic wave and c_s is the velocity of shear ultrasonic wave.

Measurements with waveguide can be carried out only when reflected shear wave propagates in parallel direction with an axis of the waveguide. This can be achieved only when the sum of the reflection angles of the longitudinal and shear ultrasonic waves is equal to 90°. In such a case the incidence and the reflection angles of the longitudinal wave θ will be equal to the deflection angle of the waveguide front surface and can be obtained using this equation

$$\theta = \mathrm{arctg}\left(\frac{c_l}{c_s}\right). \quad (2)$$

In order to find necessary deflection angle of the waveguide front surface, the material properties of the waveguide have to be known. For waveguides, used as thermal buffers, different materials are used: aluminium [3], [9], stainless steel [4], titanium [5], [8]. In our work ASTM Grade 4 Titanium was chosen. Ultrasonic velocity of ultrasonic longitudinal waves in it at 20°C is 5762 m/s, the velocity of shear waves is 3007 m/s. Taking into account these values it was estimated, that the deflection angle of the waveguide front surface has to be 62.45°. If waveguide front surface is deflected by such angle the ultrasonic shear wave would propagate along the waveguide axis and can be used in pulse echo mode – i.e. after reflection from the back wall of the waveguide it will propagate back to the inclined surface of the waveguide, will be mode converted again to the longitudinal wave and will be acquired by the longitudinal wave transducer.

III. Influence of Temperature to Propagation Angles of Ultrasonic Waves

In the case if the temperature of the waveguide will change the ultrasonic velocities of both - longitudinal and shear waves will change as well. Due to this reason the reflection angle of the waves can change as well.

The objective of this work was to investigate numerically, if the change of the temperature of the waveguide will influence the propagation angle of the ultrasonic waves. The main question was if the ultrasonic wave, mode converted from the longitudinal to the shear wave, and then propagating along the waveguide, reflected back from the back wall of the waveguide then mode converted again at the front surface will propagate back to the longitudinal wave transducer.

The spatial temperature distribution in the titanium waveguide under investigation was modelled using the ANSYS finite element software. Temperature distribution was modelled under assumption of free convection. The modelled temperature distribution is presented in Fig. 2. Modelling results show, that when temperature on the far end on the waveguide is 200°C, the temperature on the centre of the deflected front surface is 144°C. Such rise of the temperature should have strong influence to the shear wave propagation path.

In order to take into account the ultrasonic velocity dependence on the temperature, the elastic properties of titanium at different temperatures were used [10]. The angle of the deflection of the waveguide front surface was calculated for the temperatures from 10°C to 200°C degrees (Fig. 3). The calculation results show, that deflection angle of the waveguide front surface at which shear wave propagates in the direction parallel to the waveguide axis changes up to 2° in the given temperature range. But, the exact temperature of the waveguide can be not known in advance, so the question is, how much the change of the temperature will influence the propagation path of the ultrasonic waves, if the waveguide, fabricated with the front surface deflected by the angle optimal for 20°C, will be used.

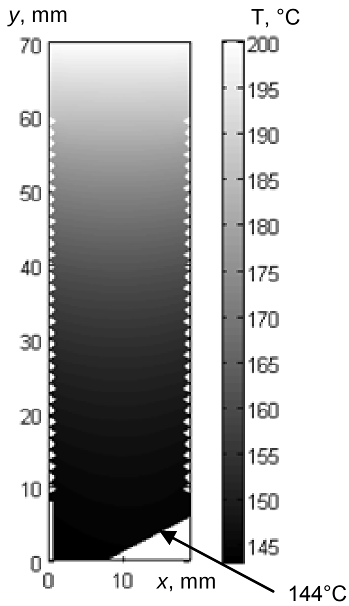


Fig. 2. Temperature distribution in the titanium waveguide.

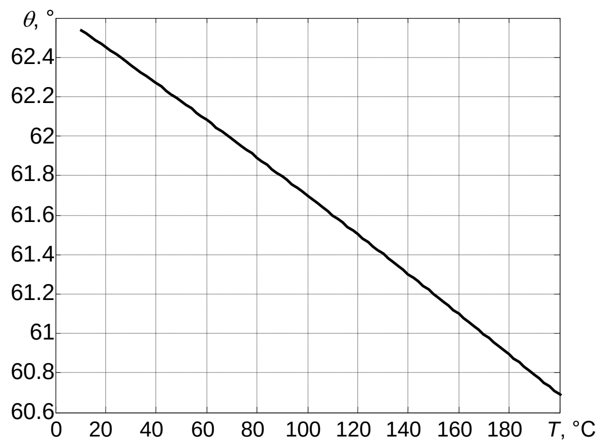
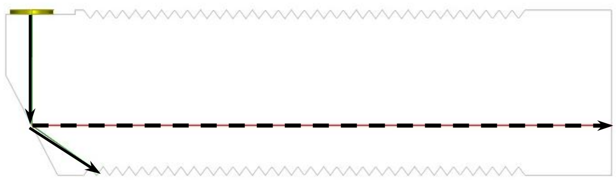


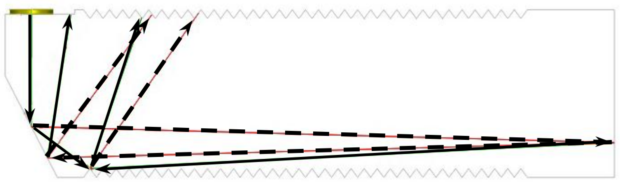
Fig. 3. Angle of the deflection of the waveguide at different temperatures.

So numerical investigation have been carried out in order to estimate the changes in the ultrasonic waves propagation paths and how it can influence the amplitude of the signal received by the transducer.

The calculations of the ultrasonic wave's propagation paths and possible mode conversions were performed using the CIVA software and are shown in Fig. 4. The waveguide, used for modelling, had the length of 70mm. In the case of 20°C degrees temperature (Fig. 4(a)) the longitudinal wave, propagating from the transducer is mode converted at the front surface of the waveguide to the shear wave and propagates further parallel to the waveguide axis. Therefore at the back surface of the waveguide it is reflected back with the same angle and propagates again parallel to the waveguide axis. At the front surface of the waveguide mode conversion takes place again and the longitudinal wave propagates back to the longitudinal wave transducer.



a)



b)

Fig. 4. Ultrasonic waves propagation paths in a titanium waveguide. a – 20°C; b 144°C. Solid line - longitudinal wave, dashed line - shear wave.

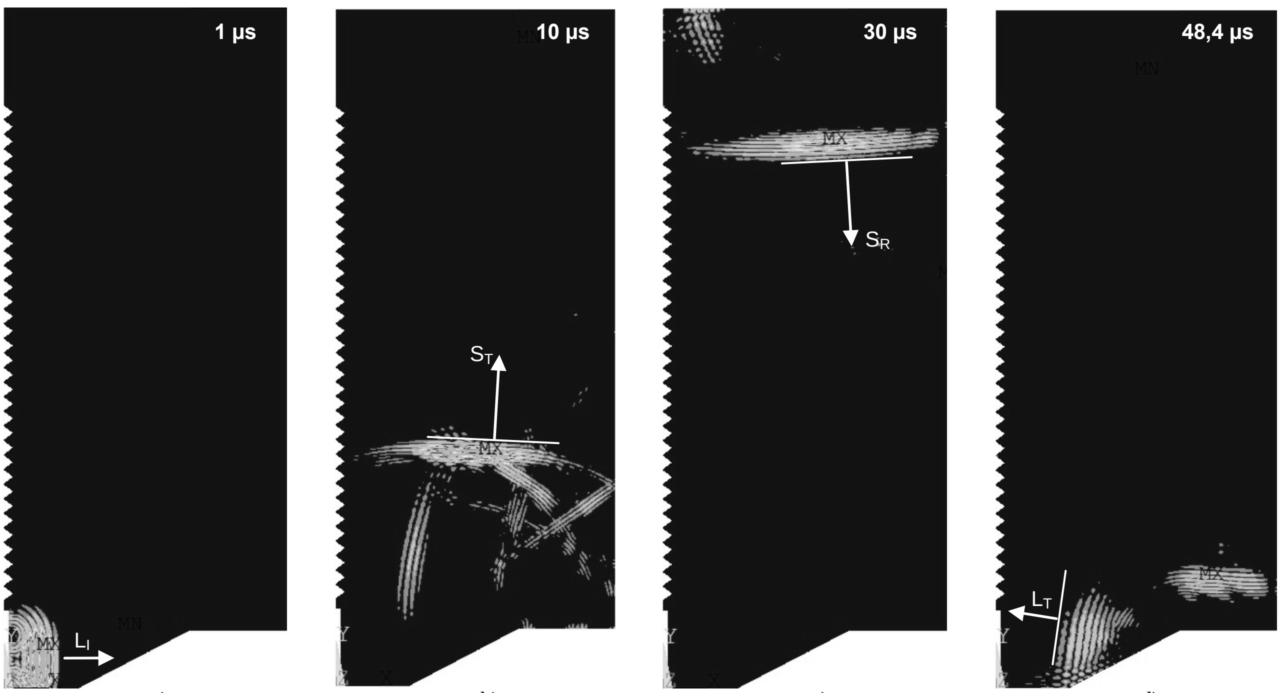
In the case of the 144°C degrees temperature, but when the waveguide with optimal deflection angle for 20°C degrees is used, the longitudinal wave, impinging on the deflected area of the waveguide is mode converted not at the optimal angle and propagates in the waveguide at some angle to the waveguide axis (Fig. 4(b)). At the back surface of the waveguide it is reflected back at some angle to the waveguide axis again. At the front surface of the waveguide, where the mode conversion takes place, the shear wave is converted to the longitudinal wave at not optimal angle anymore and therefore it even misses the ultrasonic transducer.

Modelled propagation paths of the ultrasonic waves using CIVA software show the propagation path of the central ray of the plane wave. But real ultrasonic transducers with finite dimensions generate non plane wave. In order to understand regularities of the ultrasonic wave propagation and mode transformation in the waveguide 2D modelling using finite element method was carried out.

The dynamics of the wave propagation was modelled using finite element method. In order to save computation time the material properties in the whole waveguide were selected for 144°C, i.e. the temperature at the deflected surface of the waveguide with gradient (Fig. 2). In order to eliminate side effects the size of the waveguide was increased.

The snapshots of the particle velocity field at the different instances of time are presented in Fig. 5. Incident longitudinal wave L_I generated by ultrasonic transducer propagates to the deflected surface Fig. 5(a). It is clearly seen that the transformed shear wave S_T (Fig. 5(b)) and reflected from the end of the waveguide shear wave S_R (Fig. 5(c)) propagate in direction non parallel to the axis of the waveguide. Due to this phenomenon after shear - longitudinal wave transformation at the deflected front surface of the waveguide longitudinal wave L_T almost misses the ultrasonic transducer Fig. 5(d).

The modelling shows that the wave propagation paths of the ultrasonic longitudinal and shear waves are influenced by the temperature of the waveguide. If the special waveguide with the deflected front surface for shear wave generation is used the influence of the temperature has to be taken into account.



a) b) c) d)

Fig. 5. Snapshots of the particle velocity fields at the different instances of time: a – 1 µs, b – 10 µs, c – 30 µs, d - 48.8 µs.

IV. Influence of Temperature Gradient

In reality the one end of the waveguide will be exposed to the high temperature, and at the front part of the waveguide the temperature will be lower, as was shown in Fig. 2. Using the obtained temperature distribution the simplified model of the waveguide with regions of different temperatures and therefore with different ultrasonic velocities was created and used in the CIVA software to model the wave propagation paths in the waveguide with a temperature gradient.

The temperature at the back surface of the waveguide was 197°C, giving the longitudinal wave velocity of 5193m/s and the shear wave velocity of 2912m/s. At the front surface the temperature was 144°C, the longitudinal wave velocity - 5383m/s and the shear wave velocity 2952m/s. The changes in the wave propagation path in the case of the waveguide with the temperature gradient are similar as in the case with 144°C – after all the transformations, taking place along the ultrasonic wave path ultrasonic wave misses the transducer surface (Fig. 6).

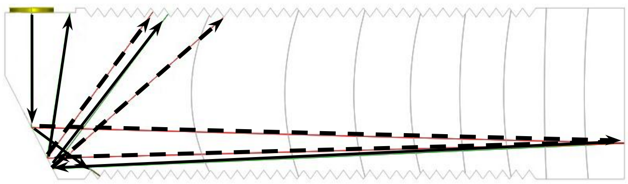


Fig. 6. Ultrasonic waves propagation paths in a waveguide with temperature gradient. Solid line - longitudinal wave, dashed line - shear wave.

V. CONCLUSIONS

It was shown that ultrasonic shear wave can be generated using ultrasonic longitudinal wave transducer and specially fabricated waveguide, which enables to use mode conversion phenomena. However, as the waveguides are most often used in order to protect the piezoelectric transducers from high temperatures, the temperature influence on the wave propagation path of the ultrasonic waves has to be taken into account. It was shown, that the temperature can have considerable influence on the wave propagation path and if the exact temperature is not known in advance and is not taken into account, in the worst case the ultrasonic wave can even miss the transducer because of changes in the wave propagation angles due to temperature variations.

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