THE ELASTIC MODULI MEASUREMENT OF HIGH-MELTING NANOPARTICLES MODIFIED METAL-MATRIX COMPOSITES WITH THE LASER OPTOACOUSTIC METHOD

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Main goals:

- Measurements of local Young’s and shear moduli and the Poisson’s ratio of particles reinforced isotropic composite materials with strong ultrasound attenuation with the laser optoacoustic method;

- Quantitative evaluation of the influence of technological features of material production, as well as the chemical composition and concentration of reinforced particles and porosity on elastic moduli of isotropic composites.
Elastic moduli determination

Young modulus \( E = \rho c_s^2 \left( \frac{3 c_L^2 - 4 c_s^2}{c_L^2 - c_s^2} \right) \)

Shear modulus \( G = \rho c_s^2 \)

Poisson’s ratio \( \nu = \frac{c_L^2 - 2 c_s^2}{2(c_L^2 - c_s^2)} \)

\( \rho \) – the actual density of an investigated sample,
\( c_L \) - phase velocity of longitudinal ultrasonic waves in the sample,
\( c_S \) - phase velocity of shear ultrasonic waves in the sample.

For strongly attenuating composite materials high-power probe ultrasonic pulses are needed
Properties of investigated composite samples

Matrix – 99,99% aluminum ($Al$).
The diameter of all samples is 25 mm, thickness $H = 5 \div 10$ mm.

<table>
<thead>
<tr>
<th>Melt dwell time, min</th>
<th>07 series modifier Ti</th>
<th>09 series modifiers: $Ti, D$ (50 nm)</th>
<th>010 series modifiers: $Ti, D$ (150 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rho$, g/cm$^3$</td>
<td>$P$, %</td>
<td>$\rho$, g/cm$^3$</td>
</tr>
<tr>
<td>2</td>
<td>071</td>
<td>2,702</td>
<td>1,8</td>
</tr>
<tr>
<td>20</td>
<td>072</td>
<td>2,657</td>
<td>3,5</td>
</tr>
<tr>
<td>60</td>
<td>073</td>
<td>2,694</td>
<td>2,4</td>
</tr>
<tr>
<td>90</td>
<td>074</td>
<td>2,754</td>
<td>0,3</td>
</tr>
</tbody>
</table>

The volume fraction of pores (porosity) arising during the reactive cast process:

$$P = (1 - \frac{\rho}{\rho_0}) \times 100\%$$

Calculated sample density:

$$\rho_0 = n_{Al_3Ti} \cdot \rho_{Al_3Ti} + n_{Ti} \cdot \rho_{Ti} + n_D \cdot \rho_D + n_{Al} \cdot \rho_{Al}$$

$Ti$ – titanium particles of the diameter of 100-1000 μm, $Al_3Ti$ – intermetallic phase originated as a result of the chemical reaction, $D$ – diamond nanoparticles, $n_i$ – the volume concentration of the corresponding component.
The intermetallic phase particles of Al₃Ti with higher elastic moduli are produced during the chemical reaction. So the obtained samples can be considered as particle reinforced composites.
Examples of metallographic pictures of 09 and 010 series samples
Principle of laser optoacoustic (OA) effect

Arrows indicate displacement directions of heated absorbing medium parts through its thermal expansion. This causes the origin of mechanical stresses and subsequent radiation of longitudinal acoustic wave pulses. The absorbing medium is termed as the OA source.
### Laser optoacoustic setup

- **Nd:YAG laser**
  - $\tau_L = 10$ ns
  - $\lambda = 1.064 \, \mu m$

- **Synchro-pulse**

- **Composite sample**

- **Piezoelectric detector**

- **Digital oscilloscope**
  - TDS 1200

- **Immersion liquid**

- **OA source of the probe**
- Ultrasonic pulses - optical filter
  - «blue-green glass»

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic frequency band</td>
<td>0.5÷50 MHz</td>
</tr>
<tr>
<td>Amplitude of ultrasonic pressure</td>
<td>0.01÷10 MPa</td>
</tr>
<tr>
<td>Sample thickness</td>
<td>0.1÷70 mm</td>
</tr>
<tr>
<td>Lateral locality of testing</td>
<td>1÷2 mm</td>
</tr>
</tbody>
</table>
Temporal profiles of the probe ultrasonic pulse and the ultrasonic pulse once passed through the aluminum-matrix composite sample.

The probe pulse and the pulse once passed through the sample.

Measured phase velocity of longitudinal ultrasonic waves in a composite sample:

\[ c_L = \frac{H}{\Delta T_L} \quad \text{and} \quad \frac{\delta(c_L)}{c_L} \approx 0.9 \div 1.0\% \]
Temporal profile of acoustic signal which caused by absorption of laser pulse in a aluminum-matrix composite sample

$L$ – longitudinal ultrasonic wave pulse,  
$s$ – shear ultrasonic wave pulse

Measured phase velocity of shear ultrasonic waves in a composite sample

\[
c_s = \frac{H}{\left( \Delta T_{sL} + H/c_L \right)} = \frac{H}{\left( \Delta T_{sL} + \Delta T_L \right)}, \quad \frac{\delta(c_s)}{c_s} \approx 1,5 \div 2\% 
\]
Maximum relative errors of elastic moduli measurements

\[ \frac{\delta(E)}{E} = 6\% \]

\[ \frac{\delta(G)}{G} = 4\% \]

\[ \frac{\delta(\nu)}{\nu} = 5\% \]
Young modulus of investigated composite samples

$E$, GPa

Series:
- 07
- 09
- 010

Melt dwell time, min
Shear modulus of investigated composite samples

$G$, GPa

Melt dwell time, min
Poisson’s ratio of investigated composite samples

Melt dwell time, min

Series:
- 07
- 09
- 010
Conclusions

• Local elastic moduli of high-melting particles reinforced isotropic composite samples were measured with the laser optoacoustic method with the high accuracy. The thickness and the diameter of samples can be in all proportions.

• Elastic moduli of aluminum-matrix composite material with intermetallic phase $\text{Al}_3\text{Ti}$ particles increase with the rise of melt dwell time, that is the strengthening of the material. However there is no strengthening by adding the diamond nanoparticles in melt, because they act as the local centers of pores formation, that in turn leads to decrease of elastic moduli values.

• The developed laser optoacoustic method enables one to analyze experimentally the influence of the chemical composition, sizes and the concentration of reinforced particles on elastic properties of isotropic composite materials.