LASER ULTRASONICS FOR NON-DESTRUCTIVE EVALUATION OF METAL MATRIX COMPOSITES

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Abstract: Laser ultrasonics is based on the generation of elastic waves by transient surface heating or ablation with short laser pulses. These waves are traveling through the sample, are reflected and scattered at interfaces and the backside of the sample. To realize an ultrasound measurement device we have used either an interferometer coupled to a continuous wave laser (contact-free) or the sample was coupled to an optical prism for the detection of the elastic waves on the sample surface. In the prism we use the change of optical reflectance (acoustorefractive effect) at the interface between a glass prism and a liquid coupling layer near the critical angle of total internal reflection.

The run-time of these waves in various directions of the samples can be measured contactless with a Fabry-Perot interferometer(point-source-point-receiver technique). From these data the 5 independent components of the complete elastic elasticity tensor for the unidirectional fiber reinforced composites can be determined. These results agree with measurements by a resonant beam technique (RBT), acoustic resonance and 4-point bending tests. The laser pulse technique has several advantages: it is contactless, non-destructive and it can be used for online quality control in production processes.

Introduction: At low power levels the optical generation of ultrasound is based on the thermoelastic effect, which is the generation of elastic waves by transient surface heating with a laser pulse [1]. At high power level the laser source operates in the ablation regime by vaporizing a small amount of surface material. The radiated field of such a source resembles a monopole radiating strongly in all direction from the point source [2]. Laser ultrasonics uses one laser with a short pulse for the generation of elastic waves and another one, a long pulse or continuous laser, coupled to an optical interferometer for the detection of the ultrasound [3]. We have used for detection either a Fabry-Perot interferometer coupled to a continuous wave laser (contact-free) or the sample was coupled to an optical prism for the detection of the elastic waves on the sample surface (see Fig. 1). In the prism we use the change of optical reflectance (acoustorefractive effect) at the interface between a glass prism and a liquid coupling layer near the critical angle of total internal reflection [4].

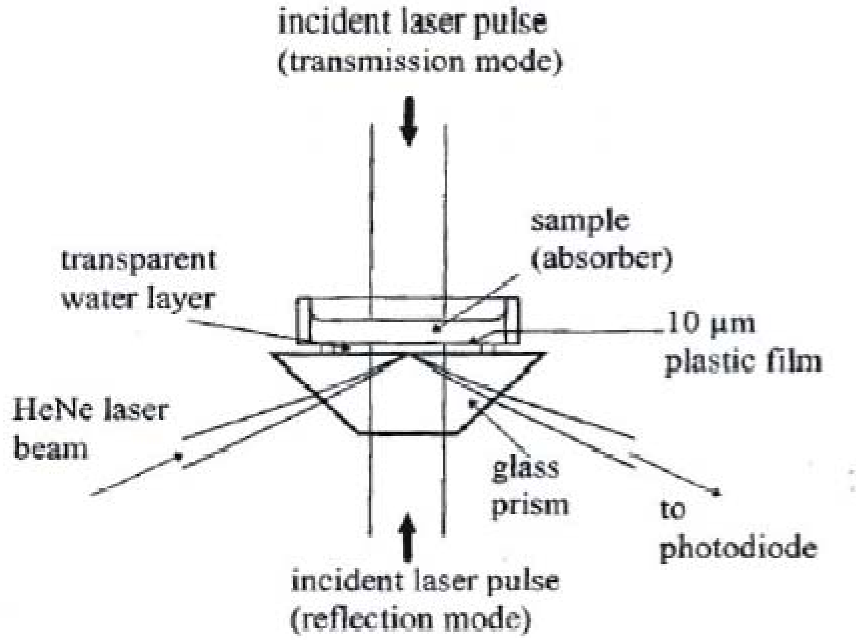

Fig. 1. Laser ultrasound with glass prism as detector [4].

The knowledge of the complete elastic tensor is essential for the design of components made of anisotropic materials [5]. The stiffness of specimens can be determined by destructive methods like bending tests and by resonance methods based on the characteristic sets of natural acoustical resonance frequencies as determined by the elastic moduli, the specific density, and the dimension of the body. For the measurement of the elastic moduli another possibility is the determination of the density and of the sound velocity in various directions. We have compared methods from all of these three categories in order to measure the elastic properties of fiber reinforced aluminum or magnesium. Laser ultrasonics is a contactless, non-destructive technique to characterize the elastic constants of materials locally via the ultrasonic waves induced by a pulsed laser [6]. This could be applied for quality control of fiber reinforced components.

The phase and group velocities are generally not equal in elastically anisotropic solids, even in the absence of dispersion and attenuation. Several inversion methods have been developed to measure the elasticity tensor components of composite materials from experimentally recorded signals [7] [8] [9]. The point-source-point-receiver (PS-PR) technique is illustrated in Fig. 2 and has shown promise as a method for measuring group velocities and determining of elastic constants[10].

The laser ultrasonic technique was used to determine the two elastic constants of planar isotropic short-fiber-reinforced metal -matrix composites [10]. These measurements were based on a conventional ultrasonic technique (pulse-echo-overlap method) [11].

In this paper the PS-PR technique is used to determine the elasticity tensor components of two examples of unidirectional continuous fiber reinforced metals (CFRM): aluminum matrix with alumina fibers and magnesium matrix with carbon fibers. The results are compared with measurements by resonant beam technique (RBT)[12], acoustic resonance [13] and destructive methods (4-point bending tests). The PS-PR technique has several advantages: it is contactless, non-destructive and it can be used for online quality control in production processes.

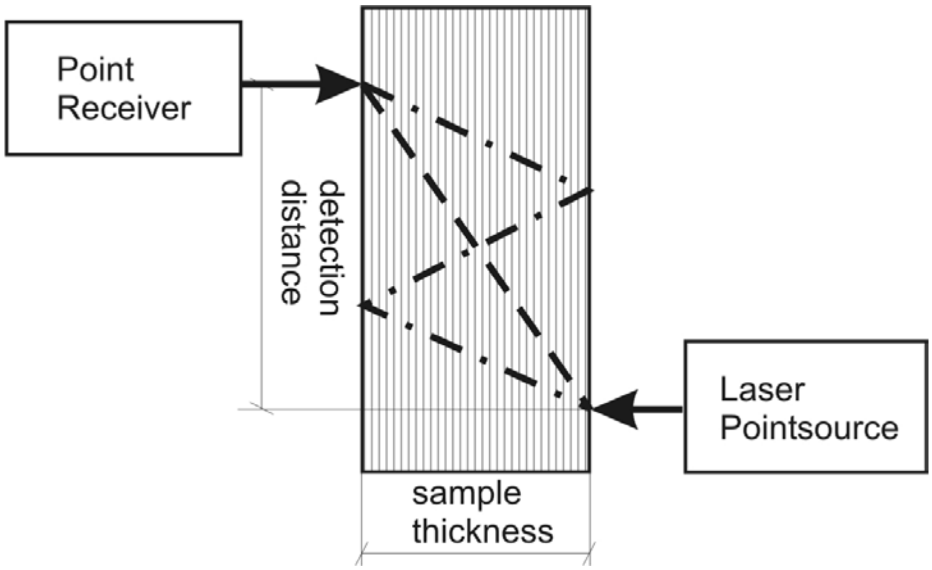

Fig. 2. Schematic diagram of the ultrasonic laser point-source-point-receiver method.

The continuous fibers used to reinforce the chosen light metals are described in Table1.

CFRM denomination	AlMg1/ Al2O3-N610/70f	MgAl0,6/ C-M40/70f
Matrix	Al 99,85 + 1wt.% h.p.Mg	h.p.Mg + 0,6 wt.% Al 99,85
Fibers	>99% α-Al2O3; Nextel N610, 3M	High modulus PAN C-fiber, M40B-6k-50B, Toray

Table 1. Ingredients, compositions and sample sizes of the investigated CFRM

Examples of fiber distributions are shown in Fig.3.

(a) (b)

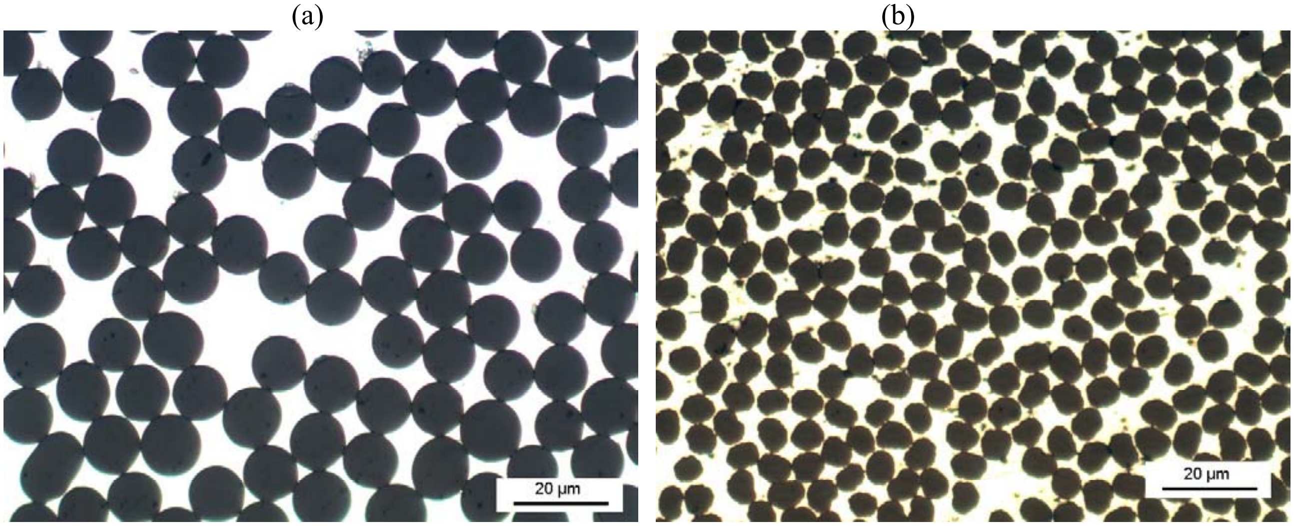

Fig. 3. Lightoptical micrographs of transverse sections of a) AlMg1/Al2O3-N610/70f, b) MgAl0,6/C-M40/70f.

Test conditions: The whole CFRM plate was supported in its nodal lines of its first free flexural vibration and excited by periodic magnetic fields [13]. The longitudinal and transverse elastic moduli are determined by the eigenfrequency of acoustic resonance measured in the two perpendicular directions.

Similarly the longitudinal sections cut from the plate given in Table 1 were measured by ultrasonic excitation RBT [12]. The longitudinal and the shear modulus are calculated from the characteristic ensemble of resonance frequencies and specimen parameters (dimension and density).

Further sections for 4-point bending tests were cut from the same plate in parallel and perpendicular directions to determine the bending stiffness in longitudinal and transverse direction for a support distance of 55 mm.

Sections from the same plate were examined by the PS-PR technique (see Fig.2). Taking into account the inclined wave propagation through the sample, the minimum region tested shall be wider than 2,5 times the specimen's thickness in all directions, where the receiver is placed. A detection distance of zero means that the source point and the receiving point are opposite with a distance equal to the sample thickness. For a varying detection distance, as shown in Fig.2, we get longitudinal and slower transverse waves and also multiple reflections for waves running 3 or 5 times through the sample thickness. The evaluation of the orientation dependence is described in the following.

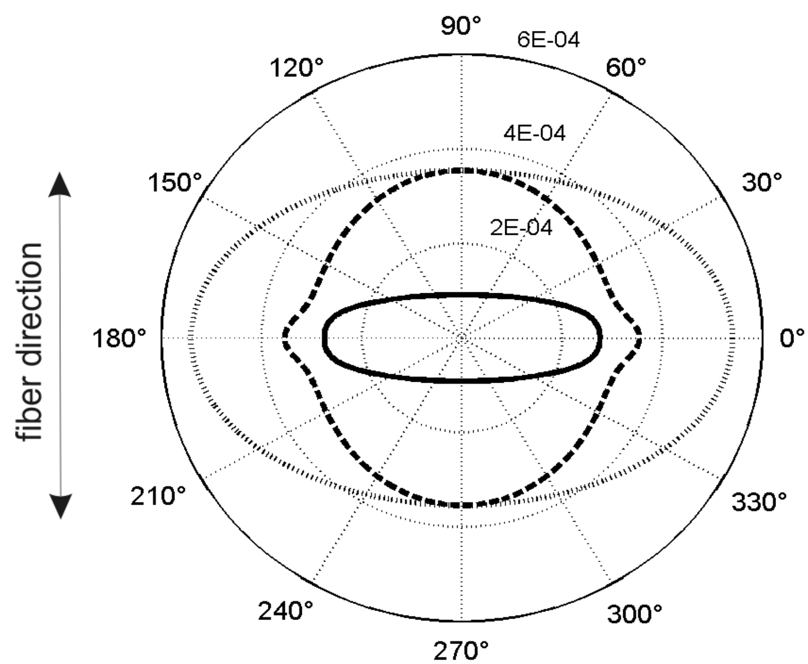

Fig. 4. Section of the slowness surfaces in a plane parallel to the fibers for the MgAl0,6/C-M40/70f sample for the longitudinal (solid) and the two transverse waves (dash, dot). The slowness (unit is s/m) is the reciprocal value of the phase velocity.

Elastic waves in unidirectional fiber reinforced composites:

The elasticity tensor c is invariant for all rotations about the fiber-axis. The planes perpendicular to this axis are elastically isotropic (see Fig. 3). For plane waves propagating in the direction n the

phase velocities and polarizations are given by the eigenvalues (ρV^2) and eigenvectors of the Christoffel tensor $\Gamma_{il}=c_{ijkl}n_j n_k$ [15].
If the fibers are in the z-direction we get e.g. with n in the [100] direction:

$$\Gamma = \begin{pmatrix} c_{11} & 0 & 0 \\ 0 & c_{66} & 0 \\ 0 & 0 & c_{44} \end{pmatrix} \qquad (1)$$

which gives one longitudinal and two transverse waves with the velocities:

$$V_L = \sqrt{\frac{c_{11}}{\rho}}, V_{T1} = \sqrt{\frac{c_{66}}{\rho}}, V_{T2} = \sqrt{\frac{c_{44}}{\rho}} \qquad (2)$$

Therefore we can determine these three elastic constants from a measurement perpendicular to the fiber direction. To get the other elastic constants we have to vary the detection distance parallel to the fibers. In the plane parallel to the fibers we have strong anisotropy, which can be shown by the slowness surface (Fig. 4). The slowness is the reciprocal value of the phase velocity or the time for the plane wave to propagate a distance of one meter.

As the pulse waves penetrate with a group velocity, which is different to the phase velocity even in the absence of dispersion in anisotropic materials, Every and Sachse showed how to determine the elastic constants from group velocities [7]. Additionally owing to the finite wavelength of the generated acoustic waves, diffraction occurs at the edges of this cusps. Therefore, ultrasonic waves can be detected in directions for which no acoustic ray can be calculated [16]. For the transverse wave with the displacement perpendicular to the fibers (dotted line in Fig. 3 and 4) and for the longitudinal wave (solid line in Fig. 3 and 4) such cusps do not occur.
If the slowness surface has an elliptical shape like the transverse wave in Fig. 3 (dotted) it can be easily shown that the wave surface of the group velocities has also an elliptical shape with the reciprocal value of the principal axis (dotted in Fig. 4). For other slowness surfaces the group velocities can be calculated numerically from the angle ψ between the phase velocity $\mathbf{V}(\theta)$ and the group velocity $\mathbf{G}(\theta-\psi)$, also called the power flow angle [17]:

$$\tan\psi = \frac{dV/d\theta}{V} \qquad (3)$$

The absolute value of the group velocity G is:

$$G = \sqrt{V^2 + (\frac{dV}{d\theta})^2} \qquad (4)$$

An increasing group velocity with increasing detection distance nearly compensates the increasing distance from the measurement geometry for the longitudinal wave. Consequently the run-time for the longitudinal waves in this material is approximately the same for a varying detection distance.

When the detection distance is perpendicular to the fibers we have isotropic wave propagation and with l as the detection distance divided by the sample thickness, i the number of runs of the pulse through the sample, the sample thickness d, and the sound velocity V, one gets for the run-time t of the pulse:

$$t = \frac{d}{V}\sqrt{i^2 + l^2} \; for\, i = 1,3,5,... \qquad (5)$$

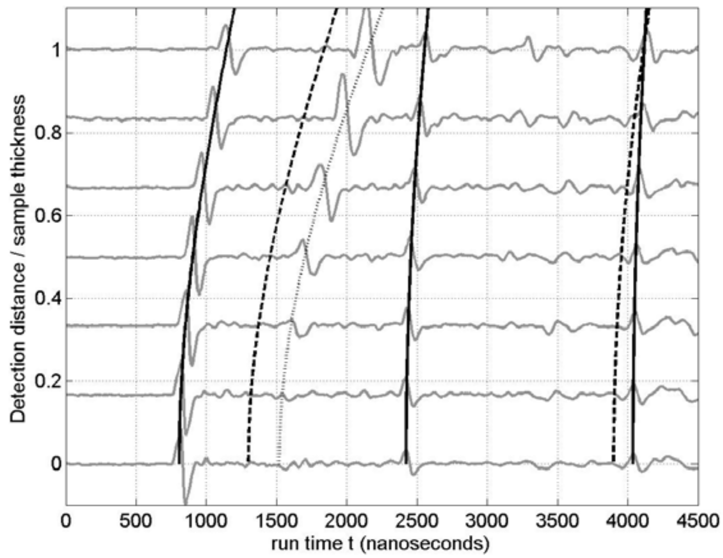

Fig. 5. Run time of waves in the aluminum matrix / alumina fiber CFRM with detection distance perpendicular to the fibers

Calculation of Young's modulus and Poisson's ratios from the elasticity tensor: The elasticity tensor relates stress and strain in Hooke's law:

$$\sigma_{ij} = c_{ijkl}\varepsilon_{kl} \quad with\ i,j,k,l = 1,2,3 \tag{6}$$

In matrix notation we can write:

$$T_\alpha = c_{\alpha\beta}S_\beta \quad with\ \alpha,\beta = 1,2,...,6 \tag{7}$$

where $T = (\sigma_1,\sigma_2,\sigma_3,\tau_{23},\tau_{31},\tau_{12})^t$ and $S = (\varepsilon_1,\varepsilon_2,\varepsilon_3,2\gamma_{23},2\gamma_{31},2\gamma_{12})^t$. Hooke's law can be inverted in order to express the strains in terms of the stresses, by:

$$S_\alpha = s_{\alpha\beta}T_\beta \quad with\ s_{\alpha\beta} = (c_{\alpha\beta})^{-1} \tag{8}$$

where s is the compliance matrix. The compliance matrix has the same symmetry properties as the elasticity matrix. For unidirectional fiber reinforced composites the elasticity tensor and therefore also the compliance tensor must be invariant for all rotations about the fiber axis (here the z-axis). For the hexagonal symmetry of the composites the elasticity tensor is described by 5 independent elastic constants c [15]. The inverse matrix is the compliance, and this gives theYoung's modulus:

$$E_T = c_{11} + \frac{2c_{12}c_{13}^2 - c_{33}c_{12}^2 - c_{11}c_{13}^2}{c_{11}c_{33} - c_{13}^2} \tag{9}$$

$$E_L = c_{33} - \frac{2c_{13}^2}{c_{11} + c_{12}} \tag{10}$$

which shows that the Young's modulus is different from c11 and c33. For the Poisson's ratios we get:

$$\nu_{TT} = \frac{c_{12}c_{33} - c_{13}^2}{c_{11}c_{33} - c_{13}^2} \tag{11}$$

$$\frac{\nu_{LT}}{E_L}=\frac{\nu_{TL}}{E_T}=\frac{c_{13}}{c_{33}(c_{11}+c_{12})-2c_{13}^2} \qquad (12)$$

CFRM	$AlMg1/Al_2O_3$-N610/70f	MgAl0,6/ C-M40/70f
Stiffness components determined by PS-PR [GPa]		
C_{11}	222±4	25.6±1
C_{12}	106±6	11.4±4
C_{13}	79±8	6.2±3
C_{33}	290±20	225±20
C_{44}	72±2	14.4±2
$C_{66}=(C_{11}-C_{12})/2$	58±2	7.1±2
Derived longitudinal and transverse constants		
E_L [GPa]	252±21	223±20
E_T [GPa]	165±7	20.5±4
ν_{TT}	0.42±0.03	0.44±0.16
ν_{LT}	0.24±0.04	0.17±0.09
ν_{TL}	0.16±0.03	0.015±0.008
RBT method [GPa]		
E_L	254±6	225±2
E_T	172±5	Not evaluated
Acoustic resonance [GPa]		
E_L	242±20	215±20
E_T	168±15	21.5±2
4 point bending test [GPa]		
E_L	262±8	232±3
E_T	180 ± 3	21±2
Linear and reciprocal rule of mixture for given vol% of fibers		
E_L [GPa]	282	288
E_T [GPa]	161	9

Table 2. Elastic constants [GPa] and Poisson's ratios of the unidirectional CFRM investigated by different methods.

Table 2 shows the elastic stiffness determined by the PS-PR technique, the calculated Young's moduli and Poisson's ratios (see equations 9 to 12), and measurement results by resonant beam technique (RBT), acoustic resonance and 4-point bending tests for the investigated CFRM. The results of the laser pulse method agree well with measurements from resonance methods. The results of the 4 point bending test of the transverse AlMg1/Al2O3-N610/70f samples are significantly higher than those of the other methods. This is attributed to an asymmetry of the elastic behavior of the samples when bent macroscopically, i.e. suffering significantly higher deformations than in the dynamic methods. The densely packed ceramic fibers produce a higher stiffness in transverse compression due to touching fibers. In tension the fibers do not touch, therefore the reciprocal rule of mixtures fits.

Conclusions and Outlook: Laser ultrasonics is a contactless technique to characterize the complete elastic tensor for continuous fiber reinforced metal matrix composites. The derived results agree well with measurements from resonant beam and acoustic resonance techniques. Laser ultrasonics has several advantages: it is contactless, non-destructive and it can be used for online quality control in production processes. For the 4-point bending test results it should be noted that the evaluation of Youngs modulus neglects effects which led up to the definition of Poisson's ratios. In a more realistic scenario the sample both stretches and thins out during bending. In the case of densely packed ceramic fibers, the stiffness in transverse compression is higher than that in tension causing an apparently higher bending modulus.

Especially for magnesium composites absorption and dispersion can be significant high and due to peak broadening and low signal to noise ratio we get a high standard deviation for some of the elastic constants. For future work absorption (e.g. via complex elastic constants) and dispersion should be taken into account to get smaller measurement errors.

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