INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING Vol. 16, No. 5, pp. 905-909

DOI: 10.1007/s12541-015-0118-x

ISSN 2234-7593 (Print) / ISSN 2005-4602 (Online)

Non-contact Measurement of Elastic Modulus by using Laser Ultrasound

Jongbeom Kim[1] and **Kyoung-Young Jhang**[2,#]

1 Department of Mechanical convergence Engineering, Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul, 133-791, South Korea
2 School of Mechanical Engineering, Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul, 133-791, South Korea
Corresponding Author / E-mail: kyjhang@hanyang.ac.kr, TEL: +82-2-2220-0434, FAX: +82-2-2299-7207

KEYWORDS: Elastic modulus, Laser ultrasound, Non-contact, Non-destructive

Non-contact measurement of elastic modulus is necessary for the in-line assessment of material in harsh environments such as high temperature. In this paper, a fully non-contact method to measure elastic modulus is proposed based on the laser ultrasonic technique (LUT) that uses a short-pulsed laser to generate ultrasound and the other laser coupled to an interferometer using a photorefractive crystal to detect the ultrasonic wave displacement. Basically, this method measures velocities of shear wave and longitudinal wave to obtain the elastic modulus. The uniqueness is that the velocity of shear wave is measured in the thermo-elastic regime first and then the velocity of longitudinal wave is measured in the ablation regime. This is because the strong mode of generated ultrasound is the shear wave in the thermo-elastic regime while the longitudinal wave in the ablation regime. Regime change can be achieved simply by switching the laser power, with no change in the measurement setup. In order to demonstrate the usefulness of the proposed method, the elastic modulus of aluminum casting alloy has been measured and the results were compared with a conventional contact method and a destructive tensile test. They showed good agreement with each other, which verified the usefulness of the proposed non-contact elastic modulus measurement method.

Manuscript received: October 14, 2014 / Revised: February 9, 2015 / Accepted: February 9, 2015

1. Introduction

In order to evaluate the elastic modulus of material, the tensile test is normally conducted. However, the tensile test is destructive, so that specimen should be separately prepared and they cannot be reused after the test; thus, it has disadvantages in cost and time compared to the nondestructive method.

Ultrasonic method has been considered as a promising nondestructive method to evaluate the elastic properties of material, because the propagation characteristics of ultrasonic wave in the material are very closely associated with the elastic properties of material. Especially, ultrasonic wave velocity is directly dependent on the elastic modulus of material, so the measurements of longitudinal wave velocity and shear wave velocity can be reduced to the elastic modulus.[1]

Meanwhile, conventional ultrasonic methods have been developed in the scheme of contact method using contact transducers to transmit and receive the ultrasonic wave, in which both of the longitudinal transducer and the shear transducer are required. Moreover, in order to measure the local elastic modulus, those two transducers should be located at the same position. That is, one of the transducers is contacted to the test material to measure the wave velocity, and thereafter, this transducer is detached and another transducer is contacted to measure another wave velocity. In addition, the couplants are generally different for the longitudinal transducer and for the shear transducer. These processes make the automization difficult. Of course, a packaged set including both of longitudinal and shear transducers may be used with a special couplant in order to avoid such inconvenience of switching the transducers.[2] Nevertheless, the application of the contact method to high temperature material is essentially difficult. To overcome these limitations of contact method, non-contact ultrasonic measurement technique based on the laser-ultrasonic technique (LUT) has been studied.

LUT can be classified into the thermo-elastic regime and the ablation regime. In the thermo-elastic regime, the induced by the thermo-elastic expansion irradiated laser contributes to generation of ultrasonic waves. In the ablation regime, the irradiated laser on the surface of material induces the material removal, which contributes to generation of ultrasonic waves.[3-5] In general, LUT generates both of longitudinal and shear waves at the same time, regardless of generation regime. However, those two regimes have different propagation

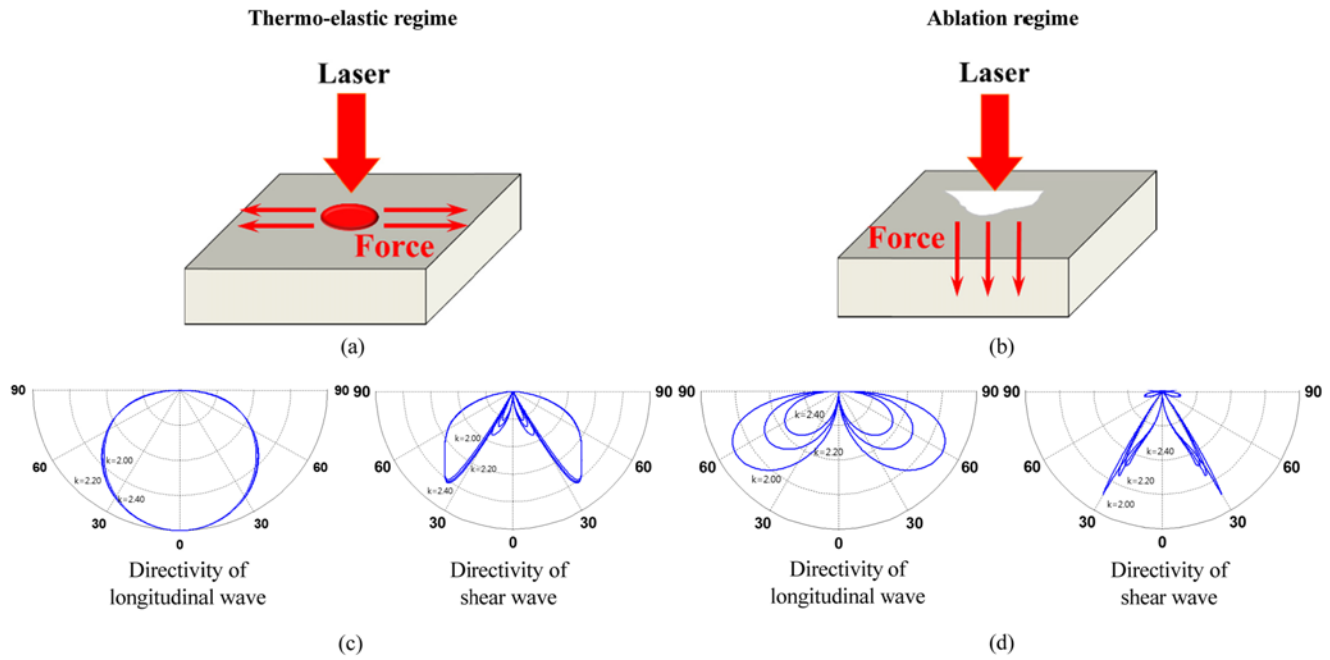


Fig. 1 Laser ultrasonic wave generation mechanisms and the directivities of the generated ultrasonic waves in each regime: (a) thermo-elastic regime, (b) ablation regime, (c) directivities of the ultrasonic waves generated in the thermo-elastic regime, and (d) directivities of the ultrasonic waves generated in the ablation regime

characteristics of generated ultrasonic waves, such as amplitude and directivity. In the thermo-elastic regime, the shear wave is stronger than the longitudinal wave and the main propagation direction of shear wave is closer to the normal direction, so when we received the ultrasonic wave transmitted through the material on the opposite side of material the shear wave is more intensely received. In the ablation regime, however, the longitudinal wave is much stronger than the shear wave and its propagation direction is the normal direction, so the longitudinal wave will be more intensely received.[3]

Therefore, in this paper, we propose a unique method that measures the shear wave velocity in the thermo-elastic regime first and then the longitudinal wave velocity is measured in the ablation regime. The alternation of the thermo-elastic regime and the ablation regime can be achieved simply by switching the laser power with no change in the measurement setup. In addition, this method allows to guarantee the measurement of longitudinal and shear wave velocities at the same position.

On the other hand, previously reported methods using LUT have been performed in thermo-elastic regime only or in the intermediate regime of thermo-elastic and ablation effects to measure shear wave and longitudinal wave simultaneously.[6,7] However, the signal detected in those methods was complicated, which makes it difficult to interpret the signal. Moreover, they have limit to be applied on thick material or high-attenuate material since the longitudinal wave may be too weak when only the thermo-elastic regime is used and both of shear wave and longitudinal wave may be too weak in the intermediate regime.

Note that the ablation regime needs comparatively higher laser power, so that the crater mark may be slightly left on the surface in the ablation regime measurement. However, it is no matter if the surface is cleaned by post-processing of LUT, such as in the process of slab manufacturing.

In order to verify the usefulness of the proposed method, the elastic modulus of aluminum casting alloy was measured, where a Nd:YAG pulse laser was used for generating ultrasonic wave and an interferometer using photorefractive crystal was used for the detection of ultrasonic wave. The measured results were compared with the results of the conventional contact method and the destructive tensile test.

2. Methods

2.1 Generation of ultrasonic wave by laser

When a laser pulse is irradiated on the surface of material, absorption of laser energy produces a local temperature elevation, which, in turn, creates a local thermal expansion. This sudden thermal expansion generates ultrasonic wave.[8]

In the thermo-elastic regime, the horizontal dipole force is acted at the center of laser beam irradiated on the surface of material as shown in Fig. 1(a), which contributes to the generation of ultrasonic wave, so the shear wave is generally stronger than the longitudinal wave. In the ablation regime, the reaction force of material removal in the vertical direction as shown in Fig. 1(b) contributes to the generation of ultrasonic wave, so the longitudinal wave is much stronger than the shear wave.[3,9] Also, these two regimes have different propagation directivities for longitudinal and shear waves.

Figs. 1(c) and 1(d) show the ultrasonic wave directivities theoretically calculated for three different wave numbers in the thermo-elastic regime and in the ablation regime, respectively, where the material is aluminum alloy and k is the wave number.[3] In the thermo-elastic regime, the propagation direction of the shear wave is much closer to

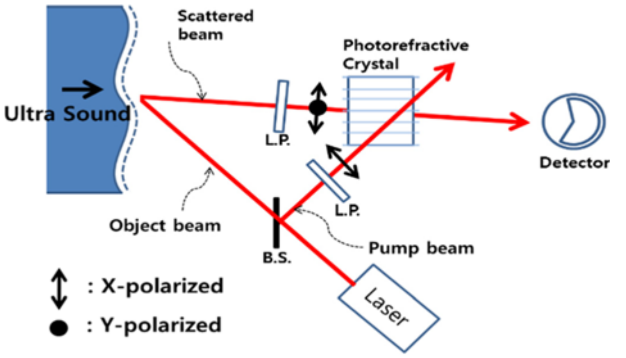


Fig. 2 Principle of the ultrasonic wave detection using holographic interference in a photorefractive crystal

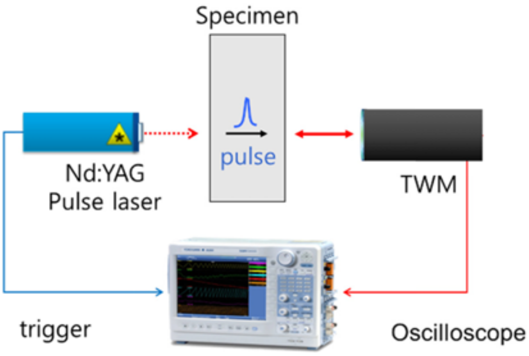


Fig. 3 Experimental setup of non-contact ultrasonic test

the normal direction (vertical direction in the figure) than the longitudinal wave. Therefore, the shear wave will be much stronger than the longitudinal wave when received at the opposite position of the laser shot. However, in the ablation regime, the longitudinal wave propagates along the normal direction, while the propagation direction of the shear wave is quite far from the normal direction. Therefore, the longitudinal wave will be more intensively received than the shear wave when received at the opposite position of the laser shot.

Consequently, in this study, the shear wave in the thermo-elastic regime and the longitudinal wave in the ablation regime are used.

2.2 Detection of ultrasonic wave by laser

Generally, laser interferometers such as Fabry-Perot interferometer and Michelson interferometer[10] can be used to detect ultrasonic wave, however, their dynamic measurement ranges are usually lower than the commonly used ultrasonic wave frequency of MHz-order, and they use specularly reflected light so that it is difficult to detect stable signal if the surface of tested material is not mirror-like. In order to overcome these disadvantages, a laser ultrasonic detector using the scattered light was adopted in this study. Fig. 2 shows the principle of ultrasonic wave detection.

The detection laser source is divided into pump beam and object beam by a beam splitter. The pump beam is directly incident on the photorefractive crystal and the object beam scattered on the specimen is incident on the photorefractive crystal. Scattered beam which acquires phase shift is mixed in a photorefractive crystal with a pump beam to produce a speckle. The phase difference between the beams was recorded by the holographic effect in the photorefractive crystal, which becomes a reference of phase displacement measurement.

When the detection surface is displaced by ultrasonic wave, the phase of the scattered beam will be changed in accordance with the displacement of ultrasonic wave. Then, the difference from the phase recorded in the photorefractive crystal is measured by the interference effect.[11] Consequently, output signal is displayed in proportional to the displacement of the ultrasonic wave.

2.3 Measurement of elastic modulus

The elastic modulus of material can be obtained by measuring the shear wave velocity (C_S) and the longitudinal wave velocity (C_L), as shown in Eq. (1).[1]

$$E=\rho\left(\frac{4C_S^4-3C_L^2C_S^2}{C_S^2-C_L^2}\right) \quad (1)$$

Where, E is the elastic modulus and ρ is the density.

In this study, the shear wave velocity is measured in the thermo-elastic regime first and then the longitudinal wave velocity is measured in the ablation regime. Elastic modulus is then calculated from the measured wave velocities with the known density.

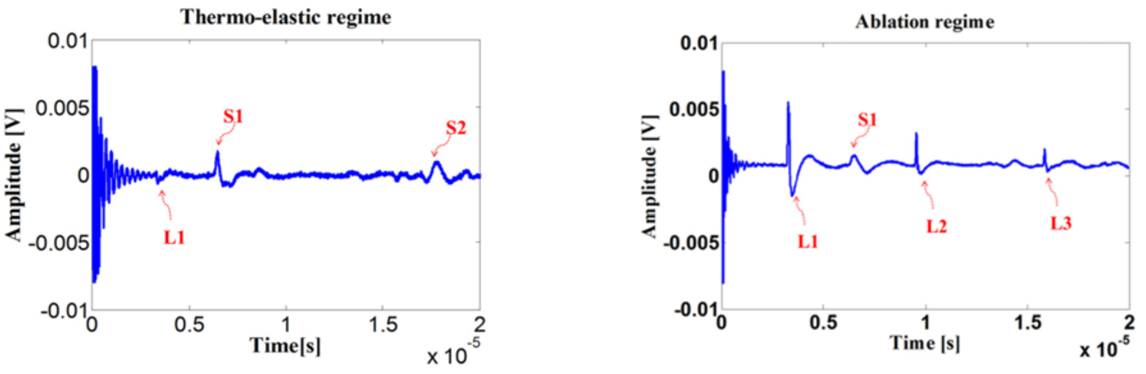
3. Experiments and Results

3.1 Experimental setup

The material of specimen is an aluminum casting alloy (Al-Mn-Cu-Si, density (ρ) is 2.4 g/cm^3) and the size of specimen is 100 mm × 100 mm × 20 mm. For the generation of ultrasonic wave a Nd:YAG pulse laser (wavelength of 1064 nm, time duration of 5 ns) was used as shown in Fig. 3. Also, the laser ultrasonic detector (TWM, TECNAR, Canada) whose dynamic measurement range is up to 30 MHz located at the opposite position of the laser pulse shot was used in order to detect the ultrasonic wave transmitted through the specimen. The shear wave and the longitudinal wave were received in the thermo-elastic regime and in the ablation regime, respectively, by adjusting the intensity of laser irradiated on the specimen. The wave signal detected by TWM is recorded in the digital oscilloscope (Lecroy, WS452).

Fig. 4 shows samples of the received signal. The received signal has been averaged over 200 repeated measurements to improve the signal-to-noise ratio. Fig. 4(a) was obtained at the laser pulse energy of 94 mJ in the thermo-elastic regime, which shows that the shear wave (S) is clearly detected but the longitudinal wave (L) is very weak. Fig. 4(b) was obtained at the laser pulse energy of 142 mJ in the ablation regime, which shows that the longitudinal wave is clearly detected but the shear wave is very weak.

In figures, S1 and L1 are the first arrivals and S2 and L2 are second arrivals. First arrival signal is the directly through transmitted wave, and the second arrival is the wave reflected by the back and front surfaces. There exists time difference between the first arrival and the second arrival, which is corresponding to the time-of-flight (TOF) for a round trip of the specimen thickness. Therefore, the velocity of wave can be measured from TOF between the first and the second signal with the known thickness of specimen. Finally, the elastic modulus is



(a) (b)

Fig. 4 Sample of signal received (a) in the thermo-elastic regime and (b) in the ablation regime

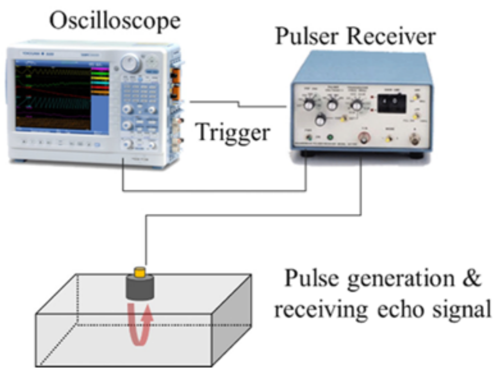


Fig. 5 Experimental setup of contact ultrasonic test

calculated according to Eq. (1).

Next, the conventional contact type experiment was conducted for the comparison. The ultrasonic wave was transmitted and received by a pulser-receiver (Panametrics, PR5500) as shown in Fig. 5. The pulser-receiver generates a spike pulse and receives the ultrasonic wave reflected from the back-surface of the specimen. A 5 MHz longitudinal broadband transducer was used to measure the longitudinal wave velocity and a 2.25 MHz shear transducer was used to measure the shear wave velocity.

After the ultrasonic experiment has been finished, the destructive tensile test was carried out for the comparison also. The tensile test specimen was taken from the original specimen with a size of 80 mm × 10 mm × 3 mm according to ASTM E8M standard. The tensile test was performed at the tensile speed of 2 mm/min at the room temperature by using MTS793 (Instron, USA).

3.2 Experimental results

Table 1 shows the result of velocities and elastic moduli measured by three tests; the laser ultrasonic test, the contact ultrasonic test, and the tensile test, in which the average and standard deviation of fifteen measurements were presented. We can see that the velocities of the longitudinal wave and the shear wave measured by the laser ultrasonic test are similar to those measured by the contact ultrasonic test. Their difference is only 0.3% in the longitudinal wave velocity and 4.3% in the shear wave velocity. Although the deviation in the laser ultrasonic test result is greater than that in the contact ultrasonic test, the absolute deviation is less than 1%, which is sufficiently acceptable. Note that the laser ultrasonic detector is more sensitive to the surface condition of the tested material than the contact transducer, so that the larger deviation in the laser ultrasonic detection is somewhat unavoidable.

Table 1 The results of ultrasonic velocity and elastic modulus measured by three tests; the laser ultrasonic test, the contact ultrasonic test and the tensile test

	C_L, Longitudinal wave velocity [m/s]	C_S, Shear wave velocity [m/s]	E, Elastic modulus [GPa]
Laser ultrasonic test	6574.9±37.4	3365.7±14.7	73.3±0.5
Contact ultrasonic test	6556.0±0.5	3227.3±1.4	68.3±0.05
Tensile test result	-	-	71.8±0.7

As for the elastic modulus, all three test results are similar to each other. When compared with the tensile test, the laser ultrasonic test showed a difference of 2.1%, while the contact ultrasonic test showed a difference of 5.1%. These results effectively verify the usefulness of the proposed laser ultrasonic technique.

4. Conclusions

A fully non-contact method using the laser ultrasonic technique was proposed for the measurement of elastic modulus. The uniqueness of the proposed method is that the velocity of shear wave is measured in the thermo-elastic regime first and then the velocity of longitudinal wave is measured in the ablation regime. The regime change can be achieved simply by switching the laser power. This method allows to measure the longitudinal and shear wave velocities at the same position without transducer alternation required in the general contact ultrasonic method. The usefulness of the proposed method was verified by comparing the measured elastic constant of aluminum casting alloy specimen with the results obtained by the contact ultrasonic test and the destructive tensile test. When compared to the tensile test, the laser ultrasonic test showed a difference of 2.1%, while the contact ultrasonic test showed a difference of 5.1%.

This method can be applied for measuring the elastic modulus of high temperature material in in-line and for the automatic scanning to measure the distribution of local elastic modulus.

ACKNOWLEDGEMENT

This research was supported by Nuclear Power Research and Development Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2013M2A2A9043241).

REFERENCES

1. Li, P., Hao, J., Zhao, J., and Duan, H., “The influence of Ageing Treatment on the Microstructure and the Elastic Modulus of Ti27Nb8Zr Alloy,” Materials Science and Engineering: A, Vol. 527, No. 29, pp. 7469-7474, 2010.
2. Olympus, “Ultrasonic Transducers,” http://www.olympus-ims.com/ko/ultrasonic-transducers/ (Accessed 23 MAR 2015)
3. Scruby, C. B. and Drain, L. E., “Laser Ultrasonics Techniques and Applications,” CRC Press, pp. 223-324, 1990.
4. Davies, S. J., Edwards, C., Taylor, G., S. and Palmer, S. B., “Laser-Generated Ultrasound: Its Properties, Mechanisms and Multifarious Applications,” Journal of Physics D: Applied Physics, Vol. 26, No. 3, pp. 329-348, 1993.
5. Lee, H., Chung, C., Kim, C. S., and Jhang, K. Y., “Fully Non-Contact Assessment of Acoustic Nonlinearity according to Plastic Deformation in Al6061 Alloy,” Journal of the Korean Society for Nondestructive Testing, Vol. 32, No. 4, pp. 388-392, 2012.
6. Aussel, J. D. and Monchalin, J. P., “Precision Laser-Ultrasonic Velocity Measurement and Elastic Constant Determination,” Ultrasonics, Vol. 27, No. 3, pp. 165-177, 1989.
7. Li, Z. Q., Zhang, X. R., Zhang, S. Y., and Shen, Z. H., “Determination of the Elastic Constants of Metal-Matrix Composites by a Laser Ultrasound Technique,” Composites Science and Technology, Vol. 61, No. 10, pp. 1457-1463, 2001.
8. Sun, G., Zhou, Z., Chen, X., and Wang, J., “Ultrasonic Characterization of Delamination in Aeronautical Composites using Noncontact Laser Generation and Detection,” Applied Optics, Vol. 52, No. 26, pp. 6481-6486, 2013.
9. Monchalin, J. P. and Aussel, J. D., “Ultrasonic Velocity and Attenuation Determination by Laser-Ultrasonics,” Journal of Nondestructive Evaluation, Vol. 9, No. 4, pp. 211-221, 1990.
10. Wild, G. and Hinckley, S., “Acousto-Ultrasonic Optical Fiber Sensors: Overview and State-of-the-Art,” Sensors, Vol. 8, No. 7, pp. 1184-1193, 2008.
11. Monchalin, J., “Non Contact Generation and Detection of Ultrasound with Lasers,” Proc. of the 16th World Conference on Nondestructive Testing, 2004.