Converging Laser Generated Ultrasonic Waves using Annular Patterns Irradiation

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Abstract: We report on a contactless method to focus laser generated bulk and surface ultrasound waves in the thermo-elastic coupling mode by annular shaped illumination. By using a spatial light modulator (SLM) the beam profile of a pulsed picoseconds laser was shaped to annular forms flexibly and further rings with a thickness of 50 μm and a generation energy as low as 2 mJ were generated on the surface of aluminum plates. The annular shapes have been used to focus acoustic waves toward the center. In this work, a photorefractive adaptive interferometer set up based on Two-Wave Mixing in a fast BSO crystal was used to probe and detect the converging acoustic pulses at the center of the laser generated rings. By moving the detection point about 1 mm out of the ring epicenter, the amplitude of bulk and surface waves drop quickly which shows the converging evidence of the acoustic waves in the ring center. For a 3 mm thick aluminum plate, the ring size from 1 mm to 10 mm was scanned. The optimum ring diameter and the focal length of the acoustic waves along the central axis were found. Applications of this technique in subsurface defects detection as well as sample thickness measurement are investigated.

1. Introduction

Generation and detection of ultrasound pulses by using lasers is a valuable method for non-destructive testing of materials[1]. In this technique optically a pulsed laser with a short pulse length of picoseconds or even shorter is focused in a point on a material and due to local heating, ultrasonic waves with amplitude in order of nanometer are generated and propagated in all directions in the material[1,2]. By increasing the intensity of generation laser in one point on the sample surface, one can reach to the ablation mode. In this regime, a very thin layer of the surface is melted and the ultrasonic pulses with sufficient amplitude are generated in the material. For many industrial applications, detection of acoustic wave in the thermo-elastic generation region at very low incident energy and low amplitude is required which can be performed without destruction and melting the surface of sample.

One method to enhance the acoustic pulses amplitude at thermo-elastic mode is focusing the generated ultrasonic waves[3]. By changing the beam profile of a pulsed generation laser to an annular shape, ultrasonic pulses with spatial distributions are converged in the main axis of the annular shape [3]. This simple converging method by combining all generated signals into a point provides acoustic waves with efficient amplitude and furthermore ultrasonic measurements are performed with very low generation energy density. In this method because of spreading the short pulses energy in the beam shaped area, no ablation effect occurs in material [1] and the ultrasonic waves are generated in photothermal coupling regime.

C. K. Jen and coworkers reported on focused surface acoustic waves utilizing an axicon lens to shape the beam profile of a Q-switched YAG pulsed laser with energy of 100 mJ and 10 ns pulse width
By changing the position of the axicon lens in respect to the sample surface, they generated annular forms on the surface a polished sample with diameter about 16 mm. They presented an amplification factor of 20 for surface waves detected in the center of a full ring generated in comparison to the line generation with the same laser fluency. A Michelson interferometer combined with a He-Ne laser was used to detect the generated surface waves in the center of the rings. X. Wang and coworkers used a mask to shaped the beam profile of a Q-switched Ti:Al$_2$O$_3$ pulsed laser with wavelength of 800 nm and pulse width of 50 ns [4]. They masked the laser output to a ring and by using a convex lens projected 0.5 mm thick rings on the surface of an aluminum plate. The rings radii were adjusted by changing the lens-sample distance. The generated bulk ultrasound waves were detected by contacting a piezoelectric transducer on the backside of the samples.

In the presented work here, we used a SLM which is a programmable electro optic device via a computer to flexibly shape and change the beam profile of a pulsed laser [5] to any arbitrary form such as point, line, elliptic as well as ring on the surface of an aluminum plate. By generation of rings with thickness of about 50 μm and programmable diameters, we were able to generate and focus the high frequency ultrasonic longitudinal pulses and surface acoustic waves.

2. Experiments and results

For detection of ultrasonic waves in the center of generated rings, a high sensitive photoelectroactive (PR) receiver set up with a BSO crystal based on two wave mixing method (TWM) in the crystal was used. In this ultrasound detector, a reference beam with a plane wave front and a reflected objective beam from the sample surface with a distorted wave front interfere in the BSO crystal [6]. Because of the PR effect, the refractive index of the crystal is modulated and due to generation a grating hologram in the PR material, two beams are coupled and diffracted. The wave front of the diffracted reference beam is adapted to the wave front of the transmitted signal beam. A fast photodiode is used to detect the modulated intensity of the diffracted and transmitted beams after the PR crystal. We applied this combined ring shaped illumination-PR detector set up for the sample thickness evaluation and subsurface defects inspection in a 3 mm aluminum plate.

A CW Nd: YAG KlasTech laser with power of 300 mW and wavelength of 532 nm was used to detect the ultrasonic displacements on the sample surface. To increase the overlap distance between the reference and the signal beam inside the crystal, the reference beam by using a Galilean telescope was expanded to cover the BSO crystal. The polarizing beam splitters (PBS) and wave plates (HWP, QWP) were used to adjust the signal - reference beam intensity ratio. The spot size of the detection beam on the sample surface was about 200 μm. The interfered beams after the crystal are focused by means of a lens on the 125 MHz Photo-receiver.

In Fig.1, the schematic of the SLM experimental set up for ring generation combined with the PR adaptive interferometer for detection of ultrasound pulses in the ring center is shown. As a sample, a 3 mm thick aluminum plate with a rough surface was used. In Fig.2A, typical received ultrasonic waves in the center and close to the center of a generated ring with diameter of 3 mm and generation energy of 2 mJ/pulse are shown. As clearly is seen, when detection point is moved about 0.5 mm out of the center, two small surface waves are detected (dashed line). While at the ring center, a surface wave with high amplitude and first reflected longitudinal wave from the backside of the sample are received (solid line). In Fig.2B, peak to peak amplitude of the detected bulk and surface acoustic waves (inset figure) in the center of a 3 mm diameter ring as a function of distance from the center are displayed. As is seen, the amplitude of both detected bulk and surface wave drop quickly when the detection point is moved away from the ring center with a same manner. This shows that by use of the annular shape generation, the ultrasonic waves are focused at the center.
In order to study focused bulk waves in the center of the rings, the SLM was programmed to generate 100 rings with diameters between 1 mm to 10 mm on the surface of the sample which is corresponding to focusing angle (the overlapping angle of longitudinal waves on the ring axis) range from 9° to 59°. The focused probe beam of the PR interferometer by means of focusing lenses was adjusted at the annular generation center accurately. To find the ring center, the focused probe beam on the specimen surface using a micrometer stage was scanned horizontally and vertically. As is seen in Fig.2, the Rayleigh wave with higher amplitude in the points very close to the center of the rings achieves. In Fig.3, the detected ultrasonic pulses as a function of ring diameter (1 mm to 9 mm) and time are
displayed. One can see clearly the Rayleigh waves (R) with high amplitude and other detected acoustic waves such as longitudinal and transversal waves.

The periodically reflected longitudinal bulk waves (L1, L2) from the backside of the sample with a time of flight of 940 ns are obviously observed and by knowing the ultrasound velocity, 6400 m/s, one can estimate the sample thickness. In Fig. 4A, the amplitudes of the detected longitudinal bulk waves (L1) in the rings center as a function of focusing angle of the bulk waves (α) inside the sample is displayed. As is seen, as the rings diameter (focusing angle) increases, the amplitude of the longitudinal waves reach to the maximum at the angle of about α_{max} = 50° which is due to convergence of the waves on the central axis points (focal depth) inside the material and near the surface. This angle is close to the directional calculated angle of α = 60° in directivity pattern of longitudinal waves for a thermo-elastic point like laser source in aluminum [1]. J. Guan et al. by using the finite element method in thermo-elastic coupling mode simulated the maximum amplitude of the longitudinal waves for ring-shaped laser illumination on aluminum plates [7]. They calculated that this appears at the angle 53.3° which is in good agreement with our experimental results.

Detection of subsurface defects and the flaws depth with a good resolution is an attractive industrial application of the non-contact ultrasound interferometers. Focusing the bulk waves inside a material in different focal depths by using the ring shape generation method is promising approach to detect and profile internal flaws and defects in materials. To perform such an experiment by use of our BSO PR ultrasonic detector, an artificial hole with 2 mm width in about 1 mm high (D = 2 mm from the surface) as a subsurface flaw on the backside of the aluminum plate was drilled. The optimum converging ring was calculated (D \tan(\alpha_{max})) and a ring with about 2 mm radius was generated on the sample surface. The sample was scanned horizontally by using a programmable stage. Fig. 4B shows the detected ultrasonic signals of the longitudinal bulk waves and reflected bulk waves from the subsurface defect on the backside of the sample which displays obviously the defect position and its profile.
We reported that the converging laser ultrasonic wave technique by using the ring-shape laser generation as a contactless and non-destructive method has some attractive approaches to evaluate the material with low generation energy in thermo elastic regime and high resolution. Using this technique, the laser generating rings with diameters between 1 to 10 mm and with a 50 μm thickness for full scanning of the aluminum plate surface were generated. Either the focused Rayleigh or bulk waves at the rings center were detected by use of a non-contact BSO PR adaptive interferometer. This promising thermo-elastic method with high resolution can be utilized to evaluate flaws and cracks in composite materials in airframes structure.

3. Conclusions

We reported that the converging laser ultrasonic wave technique by using the ring-shape laser generation as a contactless and non-destructive method has some attractive approaches to evaluate the material with low generation energy in thermo elastic regime and high resolution. Using this technique, the laser generating rings with diameters between 1 to 10 mm and with a 50 μm thickness for full scanning of the aluminum plate surface were generated. Either the focused Rayleigh or bulk waves at the rings center were detected by use of a non-contact BSO PR adaptive interferometer. This promising thermo-elastic method with high resolution can be utilized to evaluate flaws and cracks in composite materials in airframes structure.

References

[1] C. B. Scruby, L. E. Drain, Laser-Ultrasonics: Techniques and Applications (Adam Hilger, Bristol, UK, 1990).
[2] C. K. Jen, P. Cielo, J. Bussiere, F. Nadeau and G. W. Farnell, Appl. Phys. Lett. 46, 241(1985).
[3] P. Cielo, F. Nadeau and M. Lamontagne, Ultrasonics, 23, 55(1985).
[4] X. Wang, M. G. Littman, J. B. McManus, M. Tadi, Y. S. Kim, A. Askar, H. Rabitz, J. Appl. Phys. 80, 4274(1996).
[5] M. Clark, S. Sharples, M. Somekh, Meas. Sci. Technol. 11, 1792(2000).
[6] T. Honda, T. Yamashita, H. Matsumoto, Jpn. J. Appl. Phys. 34, 3737(1995).
[7] J. Guan, Z. Shen, X. Ni, J. Lu, J. Wang, B. Xu, Optics and Laser Technology, 39, 1281(2007).