Investigation of surface acoustic waves in laser shock peened metals

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Laser shock peening is a well-known method for extending the fatigue life of metal components by introducing near-surface compressive residual stress. The surface acoustic waves (SAWs) are dispersive when the near-surface properties of materials are changed. So the near-surface properties (such as the thickness of hardened layers, elastic properties, residual stresses, etc.) can be analyzed by the phase velocity dispersion. To study the propagation of SAWs in metal samples after peening, a more reasonable experimental method of broadband excitation and reception is introduced. The ultrasonic signals are excited by laser and received by polyvinylindene fluoride (PVDF) transducer. The SAW signals in aluminum alloy materials with different impact times by laser shock peening are detected. Signal spectrum and phase velocity dispersion curves of SAWs are analyzed. Moreover, reasons for dispersion are discussed.

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Laser shock peening[1,2] is a new technology for material surface modification, which uses high-pressure stress waves, produced in the process of interaction between high-power laser pulses and materials, to enable the materials to have residual compressive stress and high dislocation density on their near surface after peening. This technology can change the physical and mechanical properties of metal materials, and improve the surface hardness and anti-fatigue life a lot. Compared with the traditional shot peening, laser shock peening shows advantages of deeper affected layers, smaller surface roughness, and easier automatization, especially for some parts and irregular surface that the conventional shot peening cannot process, such as corners and welding lines. Consequently, laser shock peening is used more and more widely in aerial materials. Therefore, it is very important to do non-destructive testing about the change of the hardened layer properties after peening. So far, many researches have been done by several groups. X-ray stress analysis of laser peened aerial aluminum alloy has been made by Fan *et al.*, and residual stress distributions of the aluminum alloy peened by laser under different peening intensities obtained[3]. Ruiz *et al.* discussed the effect of peening intensity and surface roughness on surface wave velocity for shot peened materials[4]. Using transducer excitation and optical receiver to test surface acoustic waves (SAWs), Chenni *et al.* evaluated the elastic properties of the hardened steel which was regarded as a two-medium system (two layers of materials)[5].

In the above studies, piezoelectric transducers and optical detection technology were usually used to excite and probe SAWs. However, piezoelectric transducer excitation is narrowband and only single-frequency waves can be obtained at a time. Many transducers are needed to obtain the velocity-frequency curves. Furthermore, the optical detection technology is of low sensitivity, especially to the rough surfaces. In this letter, an experimental method is presented to excite ultrasonic waves with lasers and detect SAWs with polyvinylindene fluoride (PVDF) transducer. In this way, the broadband excitation and reception of signals are achieved. Laser-based ultrasonic generation[6,7], in comparison with conventional methods, has the advantages of broad bandwidth, high spatial resolution, non-contact and obtaining various elastic waveforms, such as bulk waves, surface waves in bulk materials, and even Lamb waves in thin plates. So it is applied widely in non-destructive detection. Moreover, coupling fluid is not needed and rough surfaces are permitted by PVDF transducer detection. SAWs can penetrate the surface layer for about one wavelength and their amplitudes decay exponentially with the depth. These properties make it an ideal means to inspect the characteristics of the near-surface materials. Based on the researches on velocity, dispersion characteristics, scattering, and attenuation of ultrasonic signals, the characteristic changes of the near-surface materials can be evaluated. The SAW signals in aluminum alloy materials under different conditions by laser shock peening are detected. Furthermore, the phase velocity dispersion in aluminum alloy with various sequential repeated processing on one side is attained and analyzed. The thickness and the elastic properties of the near-surface layer could be determined by comparing the velocity dispersion curves with the theoretical results.

In the laser shock peening experiment, aluminum alloy specimen 1060H24 with the density of 2705 kg/m^3, Young's modulus of 6.89×10^{10} Pa, and Poisson's ratio of 0.33 is used. The specimen is 19 cm in length, 1 cm in width, and 0.6 cm in depth. The aluminum alloy shocked by a high-power Nd:glass laser from Institute of High Power Laser of Jiangsu University of Science and Technology. The pulse energy of the laser is 50 J, pulse duration is 20 ns, and wavelength is 1.054 μm. In order to get different shocked results, three samples are

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impacted for different times successively. The first one, called sample A, is just shocked once. The second one, called sample B, suffers twice sequential repeated processing on one side. The third one, sample C, is shocked for three times. When the laser energy is not changed, the more the impact times are, the better shocked results we can get. Flat black paint is wiped on the metallic surface before the laser shock peening. On the one hand, ideal metals cannot easily absorb laser energy for its high reflectivity. With the coatings, it is easy to absorb laser energy and then the more powerful shock waves acting on the specimen surface are generated. On the other hand, absorbing most of the laser energy, the flat black paint can protect the specimen surface from laser ablation and melting after shocking.

Figure 1 shows a schematic diagram of the experimental arrangement in the surface wave dispersion measurement. SAWs are excited by a Q-switched Nd:YAG laser with 1064-nm wavelength, 10-ns pulse width, and 10-mJ single-pulse energy. The laser pulses go through the spectroscope first. Some reflected light, as a trigger light source, is absorbed by photo electricity diode (100-ps rise-time). The reflected light then travels to an electronic oscillograph as trigger signals. Then, the attenuation slice is added to reduce incident energy under the condition that the transmission light is still intense. Most of the laser energy is monitored by a prism and a cylindrical lens (focal length 100 mm) and then focused onto the sample surface. A line source is created by a cylindrical lens because the SAWs have a noticeable superiority in the propagation direction perpendicular to the line source. The excitation source and the distance of receiving points can be changed by an electrically controlled translational platform (repeated positioning precision 0.32 μm).

In the detection, a PVDF transducer[8,9] is utilized to measure the generated elastic wave signals from the laser sources. The PVDF transducer is placed in the SAWs propagation direction and adjusted precisely parallel to the laser line source. The wedge of the PVDF transducer contacts with the sample surface and is fixed. The acoustic disturbance caused by laser ultrasound will lead to small deformation on the material surfaces, produce mechanical stress on PVDF film, and then convert into electric signals. By a preamplifier (MITEQ, USA), the electric signals are converted into voltage signals and then travel into a 500-MHz digital oscilloscope (TDS3054B). When receiving laser ultrasonic signals, the PVDF transducer should be closely contacted with the specimen to get better detection sensitivity. Because the width of the wedge is in micron dimension and the SAWs are generated by laser line source, SAWs with broader bandwidth and larger amplitude can be detected. The apparatus is placed on a fixed experimental platform, the height of which can be adjusted precisely to ensure a better experiment condition.

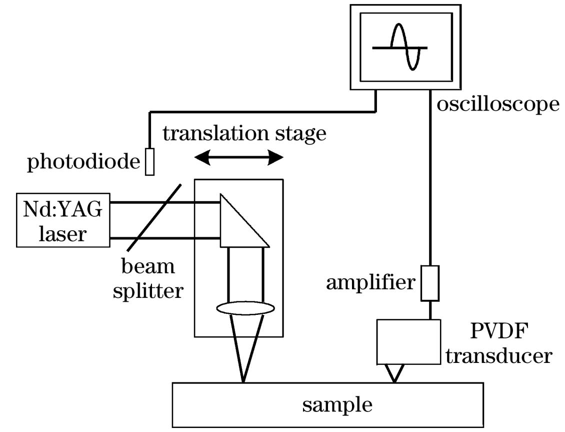

Fig. 1. Experimental scheme of laser induced SAWs.

In the experiment, the position of PVDF transducer is fixed and the relative position between the source and the receiver is changed by motorized translation stage. One shocked side is tested for all samples. The flat black paint is moved from the surface of shocked metal materials before experiment. Figure 2 shows the perpendicular displacement signals to the sample surface received on the aluminum alloy specimen. The distances between the laser point source and the receiver are 5, 8, and 11 cm, respectively. As shown in Fig. 2, the smaller the detection distance is, the later the waves arrive. With the wave propagation distance increasing, the amplitude of SAW is smaller and the characteristic dispersion becomes gradually obvious. The resulted dispersion leads to a characteristic oscillatory SAW pulse shape, which is obviously presented in the waveforms. These dispersion oscillating waveforms contain specific information of the mechanical and elastic properties of the specimen. Figure 2 shows that the lower frequency components arrive earlier. It is well known that, since SAWs penetrate into a solid by a few wavelength deep, the characteristics of the laser generated surface waves depend on the properties of near-surface materials and lower unaffected materials. The low-frequency part of the SAWs penetrates deeper, more easily being influenced by the substrate in propagation; while the high-frequency part is prone to be influenced by the near-surface materials. The elastic constant of the upper surface materials changes due to the residual stress, which causes the obvious dispersion of Rayleigh wave. Therefore, the property of sample A is not uniform any more after peening. To sum up, the laser shock peening inducing near-surface material property changes (Young's modulus, Poisson's ratio, and density) contributes to the velocity dispersion.

Utilizing the above experiment setup, the SAW signals are also detected on samples B and C. Figure 3 shows

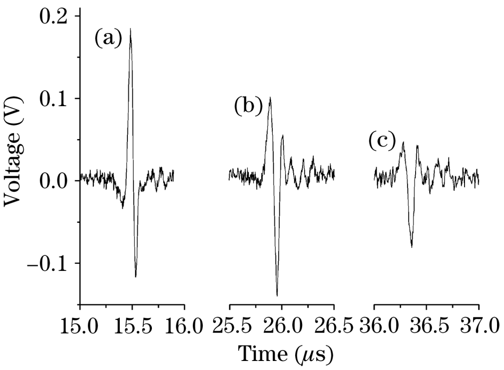

Fig. 2. Waveforms with different source-receiver distance in sample A. (a) 5 cm; (b) 8 cm; (c) 11 cm.

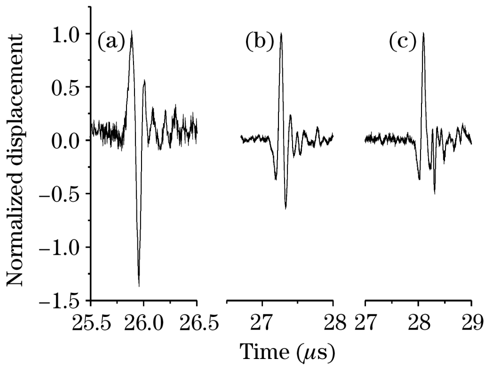

Fig. 3. Normalized waveforms of the three samples with the same source-receiver distance. (a) Sample A; (b) sample B; (c) sample C.

the normalized SAW displacement with the same distance between the source and the receiver for the three different samples. The waves' arriving time is sensitive to impact times. The changes of near-surface elastic properties caused by laser shock peening decrease the propagation velocity of SAW in materials. The more the impact times are, the later the arriving time of SAW is, because the SAW velocity is mainly influenced by the elastic properties. In addition, the more the impact times are, the more obvious the dispersion becomes. It is because that when laser energy is determinated, more impact times will lead to higher residual stress on the surface of samples, better results of laser shock peening, and greater changes of near-surface elastic properties.

A phase spectrum method[10] is used to obtain the wave velocity. The acoustic displacement signals for two different points on the shocked side of sample are obtained. The phase spectrum of each signal can be obtained by fast Fourier transform. The phase velocity of the SAWs can be calculated by

$$V(f) = 2\pi f \Delta d / \Delta\Phi(\omega), \tag{1}$$

where $\Delta\Phi(\omega)$ is the difference between the two phases, Δd is the distance between two different points, f is the frequency. Using the above mentioned method, a typical frequency spectrum is obtained, as shown in Fig. 4. The maximum frequency is about 16 MHz and the central frequency is about 8 MHz. And the phase velocities in the three samples are shown in Fig. 5.

Figure 5 shows that the lower frequency components arrive earlier. The three dispersion curves start with the Rayleigh velocity of 2887.0 m/s in the substrate and decrease as the frequency increases. The typical thickness of the affected layer is about 1 mm in laser shock peened aluminum alloy and the total thickness of the aluminum alloy sample is 6 mm, so the lower layer of sample has not been affected by laser shock peening. The repeated impact times decide the trend of dispersion curves. At the same frequency, the minimum SAW phase velocity is that in sample C, while the maximum is in sample A. The velocities of samples A, B, C are respectively 2867.7, 2835.0, and 2805.0 m/s, and the frequency is 16 MHz. Therefore, the velocity changes caused by laser shock peening are 0.7%, 1.8%, and 2.8% in the samples, respectively.

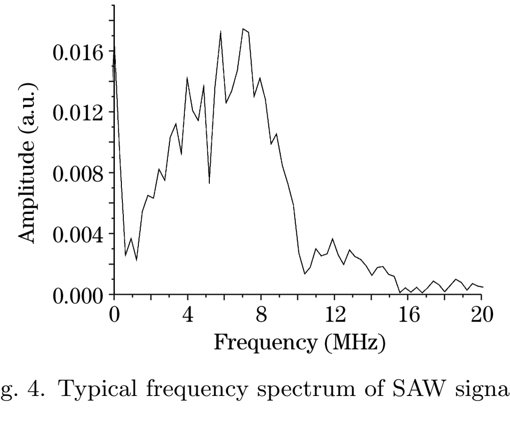

Fig. 4. Typical frequency spectrum of SAW signals.

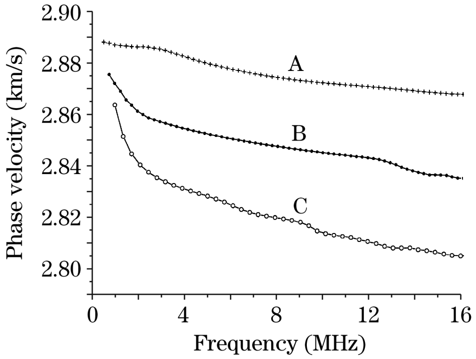

Fig. 5. Velocity dispersion in the three samples.

Generally, the dispersion of the surface waves is a superposition of different effects of shock peening, mainly including surface roughness, compressive residual stress, the increased dislocation density, and grain coarsening caused by surface deformation. For the traditional shot peening, the velocity dispersion of SAWs caused by surface roughness is about 0.2%, making the SAW velocity decrease with the increase of frequency[4]. But for traditional shot peening, metal balls with high speed are used to impact the sample surface, so that the samples can produce compressive residual stress which makes the surface very rough. In this letter, the samples are impacted by laser which is not contacted. Moreover, the surfaces of samples are covered with flat black paint which can protect the surface from damage after peening. So the surface becomes a little rough after laser shock peening and the influence of surface roughness on velocity changes of surface waves can be ignored. The velocity of SAWs caused by surface compressive residual stress increases as the frequency increases[11]. Accordingly, it can be thought that the dispersion in aluminum alloy treatment with laser shock peening is mainly caused by the increased dislocation density and grain coarsening. And the velocity change is higher than 0.7%, 1.8%, 2.8% in the samples. The affected layer decreases the SAW velocity and the change of impact times affects the results quite a lot.

In summary, a broadband excitation and reception experiment device is represented. Compared with other available techniques, this method is simple, effective, and easy to adjust. Laser is used to generate the ultrasonic signals and PVDF transducer is applied to detect the ultrasonic waves. By this device, the SAWs in aluminum alloy during laser shock peening are detected. With the source-receiver distance increasing, the characteristics of oscillation and dispersion become more obvious. Besides, the affected layer decreases the velocity of SAWs and the velocity changes of SAWs are different when the aluminum alloy suffers different impact times. Moreover, for the peened aluminum samples, it is believable that the velocity dispersion of SAW is mainly caused by the grain reorientation change and dislocation density increase.

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