Spatially resolved acoustic spectroscopy for fast noncontact imaging of material microstructure

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Abstract: We have developed a noncontact and nondestructive technique that uses laser-generated and detected surface acoustic waves to rapidly determine the local acoustic velocity, in order to map the microstructure of multi-grained materials. Optical fringes excite surface waves at a fixed frequency, and the generation efficiency is determined by how closely the fringe spacing matches the acoustic wavelength in the excitation region. Images of titanium alloys are presented, acquired using the technique. Methods to improve the current lateral resolution of 0.8mm are discussed, and the ability to measure velocity change to an accuracy of one part in 3300 is experimentally demonstrated.

OCIS codes: (110.7170) Ultrasound; (350.3850) Materials processing; (300.0300) Spectroscopy; (110.5120) Photoacoustic imaging.

References and links

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1. Introduction

Ultrasonic techniques have in recent years complemented other methods—including orientation imaging microscopy and simple etching—used to investigate material microstructure. The

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principal contrast mechanism is the change in ultrasonic velocity, due to grain orientation. This change in the velocity of Rayleigh or surface skimming longitudinal waves can be measured in a number of ways, and amongst the methods used the scanning acoustic microscope (SAM) [1, 2] can produce excellent images of surface and subsurface features [3]. The contrast is due to the interference between the leaky surface wave and the directly reflected wave, and thus the amplitude of the received signal varies with surface wave velocity. Although the technique can produce valuable qualitative results—for instance showing good contrast between grains of a metal—it is difficult to get a quantitative map of surface wave velocity. It is possible to quantitatively determine the surface wave velocity using the $V(z)$ method, but to the authors' knowledge imaging using this method has not been attempted, due to the amount of time it would take to acquire an image. Work published in recent years by Sathish, Martin *et al.*[4, 5] has shown that it is possible to use a SAM to produce quantitative velocity maps of grain structures using Rayleigh waves [4], and velocity maps relating to residual surface stress using surface skimming longitudinal waves [5], by using a method based on the difference of arrival times of the direct reflected signal and the surface wave.

In this letter we present a new technique, which we have termed spatially resolved acoustic spectroscopy (SRAS) for directly and quantitatively imaging the local surface acoustic wave velocity over the surface of industrially relevant materials such as titanium alloys. The method uses lasers to generate and detect the surface acoustic waves and so is completely noncontact and, most importantly, completely damage free.

SAWs are excited from a fixed frequency source—in the case of our own instrument this is a pulsed laser—using a grating of regularly spaced lines. The fringe spacing of the grating is swept over a certain range, corresponding to the likely range of SAW wavelengths at the fixed frequency. The SAWs are detected and analyzed. If the amplitude of the detected acoustic waves are plotted with respect to the grating line spacing, then a graph such as that shown in Fig. 1 is produced.

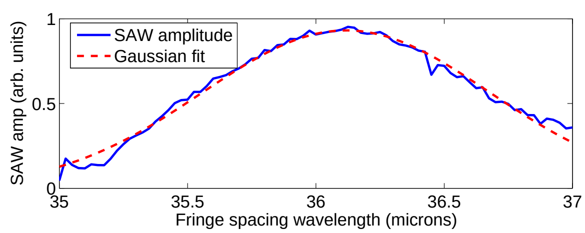

Fig. 1. The graph shows how the amplitude of the detected surface acoustic waves varies with respect to the fringe spacing of the pattern used to generate the SAWs. The solid line represents experimental data, and the dashed line represents a Gaussian curve fitted to the data.

The response arises because the efficiency of generation in the region of the grating depends on the fringe spacing. The grating produces the largest amplitude acoustic waves when the individual line sources are in phase, which occurs when the grating period matches the SAW wavelength. The phase velocity, v, can be determined by the grating period that yields the largest acoustic wave amplitude using the relationship $v = f\lambda$, where f is the fixed SAW excitation frequency determined by the excitation laser, and λ is the SAW wavelength corresponding to the fringe spacing of peak excitation. In any practical instrument which is subject to noise in the measured acoustic amplitude, processing would normally be applied to the measured signals in order to determine the location of the peak accurately. In the images presented, we curve-fit with a Gaussian. Although this is not the exact form of curve, it works well because the limited

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scan range of the fringe spacing means that the ‘tails’ of the response are not present.

The above description, illustrated in Fig. 1, explains how the velocity for one ‘point’ is calculated (where a ‘point’ corresponds to the area under the grating). To build up a velocity map of the surface of the material, the material must be raster scanned with respect to the excitation grating and the detection point. This is illustrated in Fig. 2. The video shows the process of building up a velocity map by calculating the peak amplitude at different positions on the sample. The video is considerably slower than the actual acquisition time, and is for illustration only. It is important to note that the calculated velocity at each point in the raster scan corresponds to the SAW velocity of the *area under the grating*, not at the detection point.

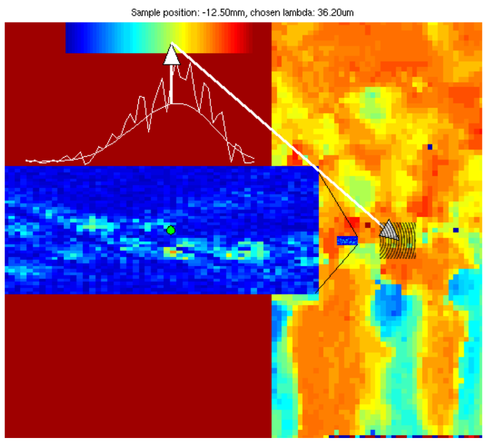

Fig. 2. (2.2 MB) This video shows the process of builing up a velocity map of a material by calculating the peak amplitude for each point on the material surface. The calculated SAW velocity corresponds to the area under the grating, rather than the point of detection. (9.7 MB version)

2. Instrumentation

The instrument that we use to acquire the results presented in this letter is the Optical Scanning Acoustic Microscope (O-SAM), and has been described previously [6, 7]. The important aspects of the O-SAM are shown schematically in Fig. 3.

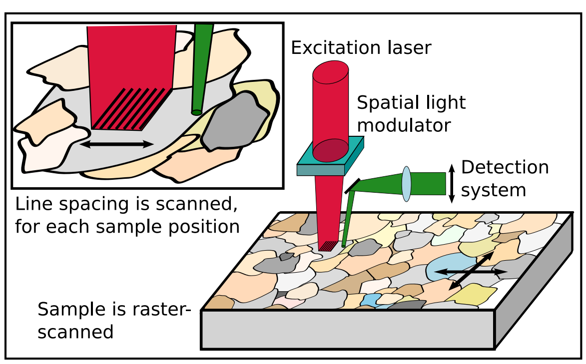

Fig. 3. Schematic of the experimental system.

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An important component of the system is the spatial light modulator (SLM), which is used to control the excitation source distribution. The SLM allows us to generate arbitrary optical distributions from the source laser. A Q-switched, mode locked Nd-YAG laser (82MHz fundamental frequency) is used as the SAW excitation source. The mean optical power used is approximately 300mW; the energy in each of the 200ps-long pulses in each 82MHz tone burst is of the order of 10μJ, giving a peak optical power of approximately 50kW. The optical energy from the pulsed laser is imaged to a 1.6mm square area on the sample surface using the SLM, and this image contains 512$\times$512 programmable pixels. An 82MHz tone burst is emitted by the laser at a repetition rate of 1kHz (determined by the Q-switcher), and the SLM can be reprogrammed sufficiently fast such that sequential tone bursts produce a different fringe spacing on the sample. The SAWs are detected at a distance of 1mm from the center of the SLM image, using an optical beam deflection technique. This particular method requires a reasonably polished finish; however other well-known techniques, such as Fabry-Pérot interferometry, would work just as well and would be able to cope with rough surfaces.

We have previously demonstrated this acoustic spectroscopy technique for analysis of surface and pseudo-surface waves on single crystals [8]. There are two fundamental differences between the previously reported work and that which is presented here. Most importantly is that here the velocity information obtained by acoustic spectroscopy is spatially resolved; that is to say that the velocity over the surface of a material can be mapped, giving information about the microstructure. In the previous paper, no spatial information was available, and the technique was intended for single crystals. Secondly, we have improved the speed of the system by three orders of magnitude. In order to acquire images of the velocity over the surface of a material, acquisition speed is very important. For this reason, a high speed complex amplitude analogue acquisition system is used, capable of measuring the amplitude (and phase) of every Q-switch pulse envelope. Since there are 1000 of these per second, and the SLM is capable of displaying a different image for each event, it is possible to cycle through a range of fringe grating spacings—and measure the resulting amplitudes of the resulting SAWs—very rapidly indeed.

It is important to optimize the signal to noise ratio in order for the analogue detection technique to work. The fact that we are exciting the waves over a 1.6$\times$1.6mm area works to our advantage, since the power density is low and we can use reasonably high optical powers without fear of damaging the sample. In addition, we excite the SAWs using a pattern of concentric arc fringes, rather than a set of straight lines. This has the effect of focusing the waves to a point, where the amplitude is increased by focusing, and it is at this point that the acoustic waves are detected.

3. Results

Figure 4 is a 45$\times$45mm velocity map of a Ti-6246 alloy. The color scale represents the surface wave phase velocity in the left-to-right direction. The image immediately illustrates one of the potentially important uses of the SRAS technique, in that it can show the degree of randomness of the grain structure. There is clearly a large reasonably uniform horizontal region in the center that indicates a cluster of grains with similar phase velocity.

The small sub-image to the right of Fig. 4 has a lower spatial and velocity resolution than the main image, however it only took around 10 minutes to acquire—corresponding to greater than 12 points per second—whereas the main image took around 3 hours. The smaller image is included to illustrate that the instrument can produce very useful results of sufficient quality in a very short time frame.

Figure 5 is a velocity map of another piece of Ti-6246 alloy. The gray scale represents the surface wave phase velocity in the left-right directions. The grains of this material are relatively large, of the order of 5–10mm in diameter. These grains are clearly visible in the velocity map.

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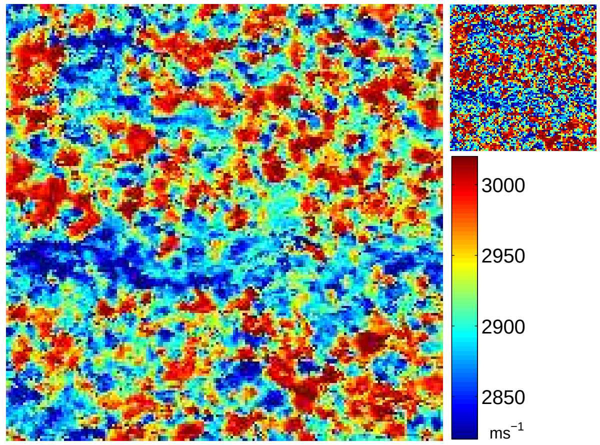

Fig. 4. The main image (to the left) is a velocity map of a 45×45mm area of a Ti-6246 alloy. The color scale indicates the phase velocity of the SAWs horizontally across the image. The sub-image is of a similar area, but at a lower spatial and velocity resolution, and was acquired in around 10 minutes.

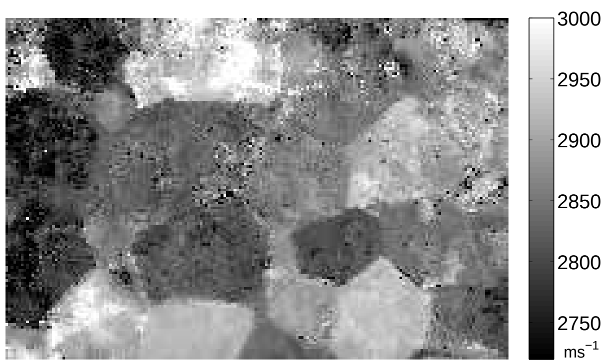

Fig. 5. A 48×33mm velocity map of Ti-6246. The contrast in the SAW velocity indicates large grains.

4. Discussion

In order to ascertain the current practical limit of the SRAS measurement system—in terms of relative velocity accuracy—the technique was used on an area of glass, coated with a thin uniform layer of aluminum to aid generation and detection of the surface waves. The sample is elastically isotropic, and so the velocity should be constant over the area scanned. The mean velocity was measured to be 2962.5ms^{-1}, and the measured standard deviation in measured velocity was 0.89ms^{-1}; this corresponds to 0.03%, or one part in 3.3×10^3. This represents the current *practical* limit of relative velocity resolution in the instrument's current configuration. Factors that influence this include signal to noise ratio (SNR) of the detected SAW amplitude, the number of fringes, and the number of pixels in the SLM image. The signal to noise can be improved by using greater optical powers to generate the SAWs. The current optical power density of around 12Wcm^{-2} is well below the level required to damage the sample, which in the authors' experience is in the region of 200 to 1000Wcm^{-2}. We note that the SNR of an all-optical system operating in the thermoelastic regime is proportional to the excitation laser power, and the square root of the detection laser power [7]. The number of fringes could be increased either by increasing the magnification of the SLM image—which will reduce the lateral resolution—or by increasing the frequency.

The *absolute* accuracy of the velocity measurements depends on different factors, and is predominantly determined by the accuracy with which the system is aligned. In order to determine the line spacing for peak generation efficiency, it is important to know the size of the SLM image; an error in this produces a corresponding error in the absolute velocity reported. In addition, in its current configuration, the instrument is rather sensitive to defocus and tilt of the sample, simply because any variation in focal length also varies the size of the fringes, and hence the reported velocity. This problem can be overcome by using telecentric optics for imaging the SLM to eliminate sensitivity to tilt. In the case of a non-planar surface, an active sample focusing system may be required. With a telecentric system the only requirement is that the sample is sufficiently flat over the area of excitation for the fringes to remain in focus. A simple geometric optics analysis suggests that our present instrument will operate without significant error for any surface with a radius of curvature greater than approximately 12mm.

The lateral resolution is determined by the SLM image size—currently 1.6mm square—and is of the order of half this (0.8mm). However it is further complicated by the fact that arcs are used to excite the ultrasound, and so factors such as the acoustic numerical aperture influence the lateral resolution. At current optical power levels (300mW), it is therefore possible to reduce the excitation source size to less than $400\times400\mu$m—giving a 200μm lateral resolution—without damaging the sample. In this case, the velocity resolution would be reduced, unless higher frequencies are used.

It is important to note that the technique is tolerant to acoustic aberrations, which affect the propagation of the SAWs from excitation region to detection point when propagating through random microstructure [7]. The overall detected amplitude varies significantly as the sample is scanned due to the effects of aberrations, however the propagation of SAWs between the edge of the excitation region and the detection point is not affected by a change in fringe spacing. If the excitation region is across two or more grains, then as the fringe spacing is adjusted the relative generation efficiency within each grain will change. This does affect the properties of the propagating wavefront, but it is a second order effect.

It is the authors' intention to develop the technique further, by propagating SAWs in more than one direction. Propagation in two orthogonal directions is a relatively simple improvement that should give significantly more information about the likely grain orientations. It may also be desirable to propagate in several directions to acquire the slowness surface of individual grains using the technique described previously [8], once the location of the grains has been determined.

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