Frequency spectrum spatially resolved acoustic spectroscopy for microstructure imaging

# Frequency spectrum spatially resolved acoustic spectroscopy for microstructure imaging

**Wenqi Li, Steve D Sharples, Matt Clark, Michael G Somekh**

Applied Optics Group, Electrical Systems and Optics Research Division, Faculty of Engineering, University Park, University of Nottingham, NG7 2RD,UK.

E-mail: `steve.sharples@nottingham.ac.uk`

**Abstract.** The microstructure of a material influences the characteristics of a component such as its strength and stiffness. A previously described laser ultrasonic technique known as spatially resolved acoustic spectroscopy (SRAS) can image surface microstructure, using the local surface acoustic wave (SAW) velocity as a contrast mechanism. The technique is robust and tolerant of acoustic aberrations. Compared to other existing methods such as electron backscattered diffraction, SRAS is completely non-contact, non-destructive (as samples do not need to be polished and sectioned), fast, and is capable of inspecting very large components. The SAW velocity, propagating in multiple directions, can in theory be used to determine the crystallographic orientation of grains. SRAS can be implemented by using a fixed grating period with a broadband laser excitation source; the velocity is determined by analysing the measured frequency spectrum. Experimental results acquired using this "frequency spectrum SRAS" (f-SRAS) method are presented. The instrumentation has been improved such that velocity data can be acquired at 1000 points per second. The results are illustrated as velocity maps of material microstructure in two orthogonal directions. We compare velocities measured in multiple propagation direction with those predicted by the numerical model, for several cubic crystals of known orientations.

## 1. Introduction

SRAS—spatially resolved acoustic spectroscopy—is a nondestructive testing method which maps surface acoustic wave (SAW) velocity on a material surface. A velocity measurement taken using the SRAS technique is local to the area where the waves are being generated. As the measurement is relatively fast the sample may be scanned and an image built up of the velocity over the sample. The velocity at any point is determined by the material elastic parameters at that point and the resulting images clearly reveal the grain structure. This method is used to measure the velocity of the SAW over individual grains on industrial materials such as aluminium and titanium alloys. The variations of velocities, which indicate the orientations of grains, are presented as a colour map.

Microstructure imaging can also be accomplished by other methods such as electron backscatter diffraction (EBSD), which gains crystallographic information by impinging electrons on to the sample and analysing diffraction patterns [1]. Alternatively, the scanning acoustic microscope (SAM)—a contact technique—analyses the phase shift of a narrow band SAW signal. Both these methods have disadvantages such as restriction on sample size, or (in the case of the SAM) ambiguity caused by a periodic phase function. SRAS eliminates those concerns.

Experimental data are compared with theoretical results to determine the direction of single crystals on specific cuts. An advanced fast f-SRAS technique, where the scanning speed is maximised by utilising segmental memory acquisition on the oscilloscope, is also presented.

## 2. Theory

Figure 1 shows a schematic of the system setup. In the figure the pulsed laser is indicated as the excitation source. The pulsed laser beam passes through a mask consisting of a set of stripes. The unblocked light produces SAWs when it is imaged onto the sample surface. In our instrument there are twenty masks which have different curvatures and fringe spacings, to cover a range of different materials and conditions. A smaller distance between the fringes generates SAWs with a shorter wavelength and higher frequency. The results presented here use a straight (rather than focused) grating with an effective period of 45 $\mu$m on the sample.
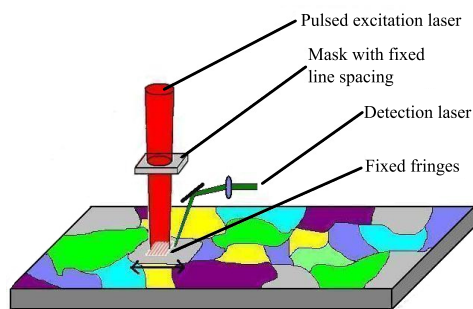


**Figure 1.** Schematic of f-SRAS laser ultrasound system.
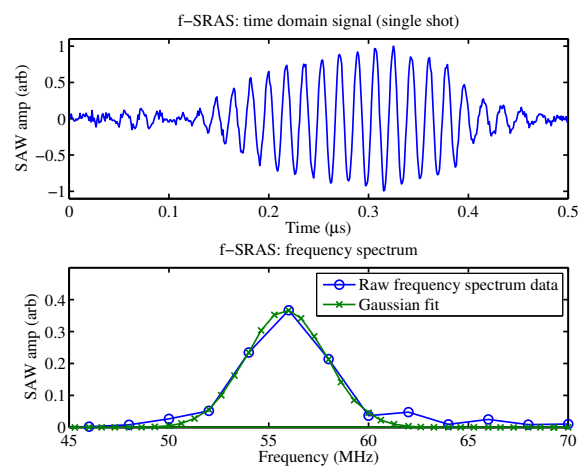


**Figure 2.** Raw data in the time domain (top) and frequency domain (bottom) with Gaussian fit.

The pulse from the Q-switched Nd:YAG laser ($\lambda = 1064$ nm) has a width of approximately 10ns, and has a wide bandwidth from DC to >100 MHz. The pulse repetition is 1 kHz, the energy per pulse onto the sample is 135 $\mu$J. The grating excitation pattern acts as a filter on the generation of the SAWs and is multiplied with the frequency content of the laser. The effective centre frequency of the grating is determined by the grating period and the local velocity ($c = f\lambda$). Since the effective bandwidth of the filtering action of the grating generation is much smaller than the bandwidth of the laser pulse, we can make the assumption that the frequency content of the laser is locally flat across the bandwidth of the grating and hence that the peak of the combined frequency response is at the same location as the peak of the grating filter; thus we can determine the local velocity. This method of determining the velocity—using the frequency spectrum of the SAWs excited using a fixed grating—is termed frequency spectrum SRAS (f-SRAS).

Figure 2 shows a typical SAW signal captured by the system. The spacing of the grating determines the wavelength of SAWs. The top graph is the waveform in the time domain; the amplitude FFT is on the bottom along with a Gaussian curve which has been fitted to the raw FFT data. The frequency where the amplitude is the largest indicates the closest value corresponding to the SAWs travelling on the grain. Note that the velocity measurement relates to the sample area under the generation patch, rather than at the detection point or in between the generation and detection.

## 3. Experimental Results

### 3.1. High Resolution of f-SRAS

Figure 3 shows f-SRAS experimental results where SAWs are propagating in orthogonal directions on Ti-685. The colour represents the velocity from 2700 m/s to 3500 m/s. Deep red means the surface waves propagate at a higher speed; deep blue shows the lowest velocity. The imaging speed of f-SRAS is restricted by several factors: oscilloscope acquisition speed, data processing time, scanning stage velocity, laser repetition rate, and potentially the number of averages required if the SNR (signal to noise ratio) is poor. Even though the Q-switched laser fires at a repetition rate of 1 kHz, previously [2] the data acquisition rate was limited—by the acquisition architecture—to a maximum of 60 points/sec. Taking advantage of segmented memory acquisition found on modern oscilloscopes, every single laser pulse is now utilised to take a velocity measurement. The SNR is sufficiently high enough to permit single shot measurement the acquisition rate is limited only by the laser repetition rate: 1000 points/sec. The images in Figure 3 were obtained in 40 minutes, approximately 76% of that time is spent on stage flyback and data transfer to the host PC; work is ongoing on to improve scanning efficiency.
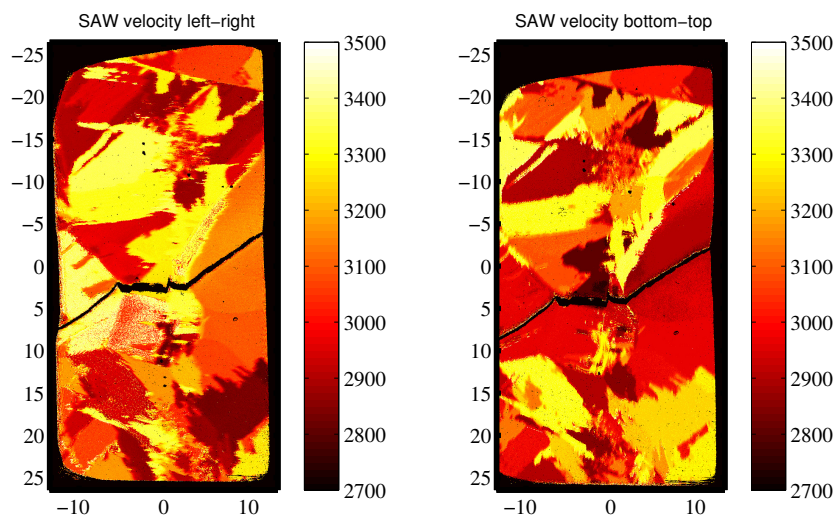


**Figure 3.** SAW velocity map of Ti-685 by fast f-SRAS: SAWs propagating left to right (left graph), top to bottom (right graph). Image size 27×52 mm, pixel size 50×50 $\mu$m.
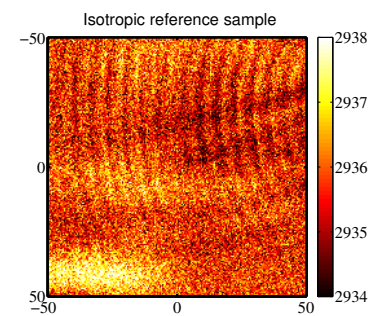
**Figure 4.** Standard deviation of f-SRAS. Image size 1×1 mm, pixel size 5×5 $\mu$m, velocity range 2934 m/s to 2938 m/s, 16 points average.

### 3.2. Noise Analysis of System

Figure 4 shows the variation in SAW velocity on a nominally isotropic reference sample, consisting of BK7 glass coated with a thin layer of aluminium. The intention was to determine the system noise in terms of the standard deviation of the measured velocity, which is 0.87 m/s (0.03%). We note, however, that spatially coherent features—distinct areas where the velocity is faster or slower than the mean—implies that the noise is probably lower than this value.

### 3.3. Experimental vs. Theoretical: Results on Aluminium Crystals

Farnell [3] gave a detailed iterative search procedure of how to calculate the SAW velocity on a generic plane, along with the calculation results of a few crystals of different crystal structures in typical cuts. Based on this, the SAW velocity in any arbitrary direction on all the planes of a single crystal can be calculated if the elastic constants are known. Curve fitting could be

used to find out what plane of crystal's surface is, when the SAW velocities in a certain limited number of directions are known. Figure 5 illustrates how well the experimental results match the calculated results on three planes—(100), (110) and (111)—on single crystal aluminium. The mismatch on plane (100) is due to the wave mode at a certain angle transforming between a SAW and a pseudosurface wave, which degenerates into a bulk wave [3]. This occurs at 32 degrees from [100] to [110] on aluminium. The experimental results are approximately 100 m/s (3%) faster than the calculated velocities. This could either be due to an error in the size of the excitation grating, or to a small error in the elastic constants used in the theoretical calculations.
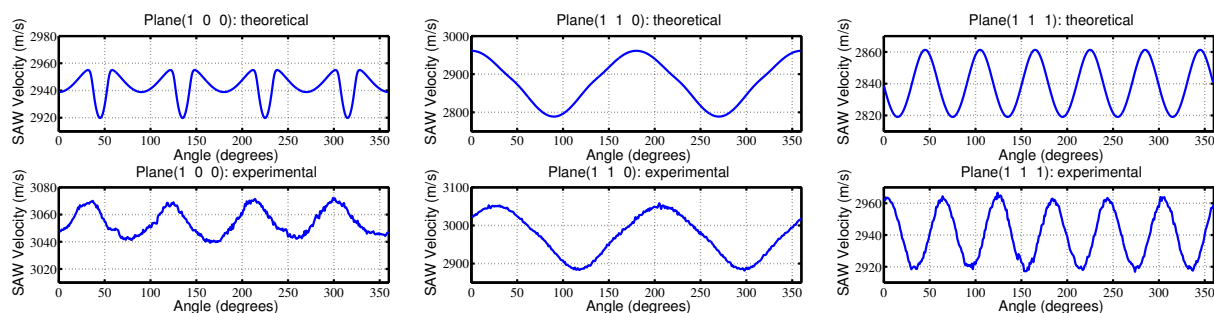


**Figure 5.** SAW velocity curves for all directions on three cuts of single crystal aluminium. The angular offset is due to the randomly selected starting propagation direction.

## 4. Discussion

An acoustic spectroscopy technique called frequency spectrum SRAS has been described in the paper. It is based on laser ultrasonics, and material microstructure can be imaged by determining the local SAW velocity on the sample surface. In the implementation described, the f-SRAS technique can acquire the local velocity of SAWs at 1000 points/sec by taking advantage of segmented memory acquisition, 17 times faster than previously described [2]. The spatial resolution is currently of the order of 400 $\mu$m, which is the size of the grating on the sample. This can be significantly reduced by using different masks with fewer lines at shorter wavelengths. Experimentally, the bandwidth of the excitation laser source used in our instrument limits the maximum frequency SAWs that can be excited (hence the minimum size of the grating). Ultimately—with a laser of sufficiently wide bandwidth— the resolving power of the optics used to produce the grating structure is the limiting factor on the resolution of SRAS. We have demonstrated velocity acquisition on three different planes of aluminium in all directions, and shown how this relates to theoretical calculations of the SAW velocity on these planes. The challenge now is to determine the optimum number of velocity measurements in a limited number of discrete propagation directions that is required to ascertain the crystallographic orientation at each point in multi-grained materials.

## References
[1] Randle V 2003 *Microtexture Determination and Its Applications* (London: Maney Publishing)
[2] Sharples S D, Li W, Clark M and Somekh M G 2009 *Rev. Prog. in QNDE* **29A**, 279–286
[3] Farnell G W 1970 *Properties of Elastic Surface Waves (Physical Acoustics* vol 6*)* ed W P Mason and R N Thurston (New York and London: Academic Press) chapter 3 pp 109–166