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Spatially Resolved Acoustic Spectroscopy for Material Characterisation: White Paper

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Richard Smith, Wenqi Li, Steve Sharples, Matt Clark, Mike Somekh

Applied Optics Group, Electrical Systems & Optics Research Division

University of Nottingham

Richard.J.Smith@nottingham.ac.uk

Introduction

Spatially Resolved Acoustic Spectroscopy (SRAS) is a technique for mapping the surface acoustic wave (SAW) velocity of a material. The technique is analogous to optical spectroscopy techniques where analysis of the optical spectrum and the wavelengths that are most readily transmitted or absorbed tells us some properties of the sample being examined. In the acoustic sense we monitor the spectrum of sound waves emitted from a grating source. The instrument produces images of the grain structure of the material which is very useful for inferring properties of the sample (grain size, orientation, texture, strength etc.)

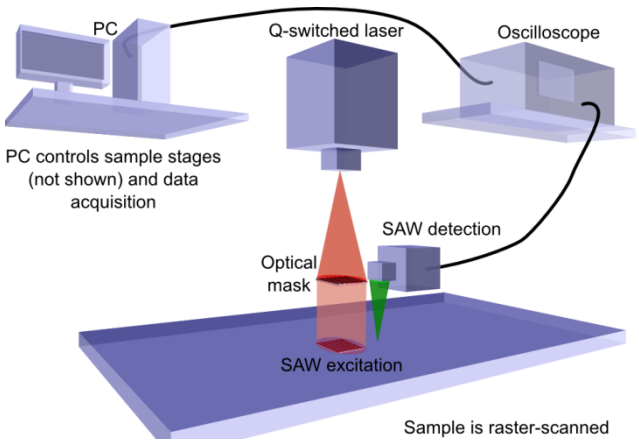

Figure 1 Cartoon of SRAS system

The SRAS instrument is capable of imaging a large range of important material parameters. The surface acoustic waves that form the basis of the measurement are directly sensitive to the elastic properties of the material on a very local scale - tens or hundreds of microns - and this sensitivity at this scale has not been achieved previously. The most obvious parameters that can be measured are the grain size (and variations in this), without the need of etching; this influences the mechanical strength of the component. Furthermore, grains of similar orientation are readily apparent, removing the ambiguity of optical inspection; these effective structural units - clusters of similarly-oriented grains - are highlighted by the technique, this is important for determining the likelihood of component failure due to local strain accumulation. “Anomalous grain growth” or “irregular grain boundaries” have been cited in incidents as diverse as premature failure of aluminium axle bosses used in climbing gear, to uncontained separation of high pressure Ti-6242 compressor discs in aeroengines. The ability to image texture and crystallographic orientation over large areas (hundreds of millimetres, limited only by scanning stages) removes the uncertainty of not knowing whether your inspected area is typical of the whole sample, a problem with scanning electron microscope based techniques (such as electron

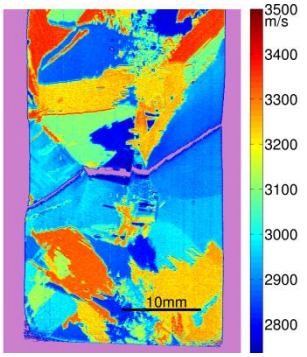

Figure 2a Example SRAS scan on Ti-LG685

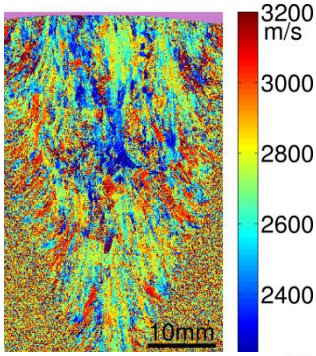

Figure 2b Example SRAS scan on austenitic stainless steel weld

backscattered diffraction, EBSD) which are highly restrictive in the sample size that can be imaged.

As well as microstructure, the technique can be used to examine layered structures, as the SAWs are sensitive to material properties up to a depth equivalent to their wavelength, which can be adjusted from around ten microns to over a millimetre. Changes in coating thickness, and delamination of protective coatings can be determined. There is potential for the technique to be used on composite materials, albeit at a much lower spatial resolution.

The SRAS instrument is based around the laser ultrasonic technique, where a pulsed laser is used to generate acoustic waves on the sample. Another laser is used to detect the waves after they have propagated/interacted with the sample.

To measure the acoustic spectrum at each point on the sample a grating is illuminated with a pulse of laser light, this generates the surface acoustic waves. We measure the waves that have been generated close to the excitation region with a continuous wave laser beam and optical detector (knife edge, Fabry-Pérot etc.) (see figure 1).

The detection laser is also used to take an optical image of the sample that is spatially correlated with the SAW velocity image, which is an extremely useful feature for relating ultrasonic measurements to registration marks etc.

We then calculate the acoustic frequencies generated and with the knowledge of the grating spacing we can obtain the acoustic velocity using $v = f\lambda$, where f is the frequency measured and λ is the grating spacing. If the sample is raster scanned we build up a detailed image of the sample velocity for that SAW propagation direction. The images in the figure 2 show the measured velocity for two different samples, Titanium LG685 (2a) and a slice through an austenitic steel weld (2b). The differences in acoustic wave velocity with grain orientation provides contrast to show the grain structure of the material.

Instrument Capabilities

The *emda* (East Midlands Development Agency) sponsored instrument, shown in figure 3, is the most advanced version of SRAS instrumentation we have at Nottingham. This instrument has been developed to provide rapid surface wave velocity imaging on a variety of surface finishes.

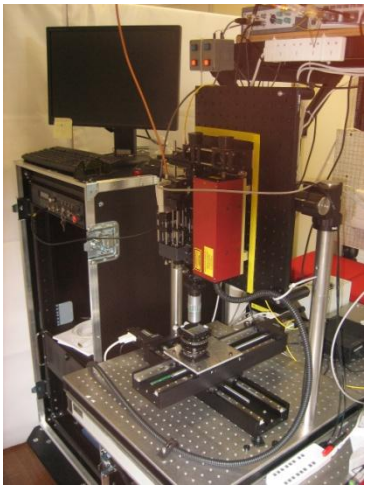

Figure 3 The SRAS instrument

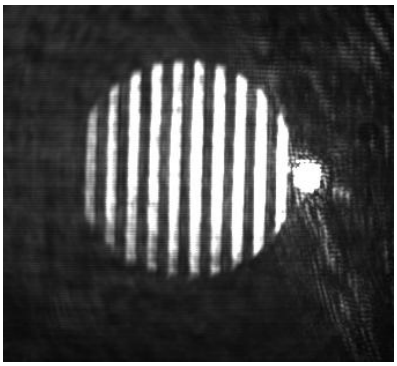

Figure 4 image of the grating pattern on the sample surface

The instrument can determine the surface wave velocity of a single point on the sample each time the laser fires a pulse. This makes the data acquisition very fast as the laser we use has a high repetition rate. The compact Q switched laser can be fired from 1000-12000 times a second, we typically perform 6000 velocity measurements per second. The final scanning rate, which includes the movement of the sample stages, downloading the data etc, is lower than this ~1000 points/second.

Spatial Resolution

The instrument has a variable spatial resolution and operating frequency range. This permits the measurement to be tailored for different sized samples and features of interest. Simple changes to the optics can change the generation patch size from ~0.75mm to 80 microns. Routine measurements are performed with spatial resolution ~100-50 microns.

The spatial resolution and velocity accuracy can in some cases be traded. If we increase the size of the generation patch but keep the pitch the same then we increase the number of lines in the generation pattern and therefore get a sharper peak in the measured spectrum allowing the velocity to be calculated more accurately.

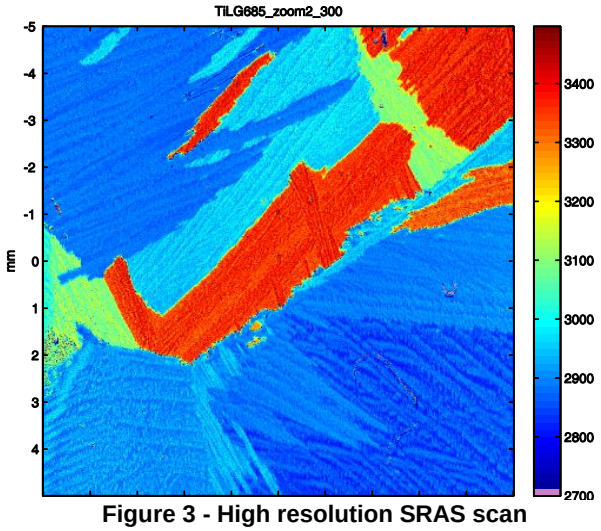

Figure 3 - High resolution SRAS scan

A high resolution SRAS image is shown in figure 5. Here the spatial resolution is ~40 microns and shows the very fine details of crystallites inside the large grains of this Ti-LG685 sample.

The spatial resolution is ultimately limited by the diffraction limit of the imaging optics and our requirement of projecting a minimum of ~5 fringes to obtain a good velocity measurement. With new detection electronics and higher numerical aperture imaging optics this could be as low as 5-10 microns.

Multiple Propagation Directions

The EMDA instrument can also generate waves in any arbitrary propagation direction as the optical mask can be rotated by a stepper motor. The detection spot can also be moved by use of a computer controlled piezoelectric mirror. This allows us to produce velocity surface maps or velocity vector maps without the need to rotate the sample. This produces robust data sets with changes in SAW propagation angle as the sample does not need reregistering between scans as the sample hasn't moved with respect to the optics.

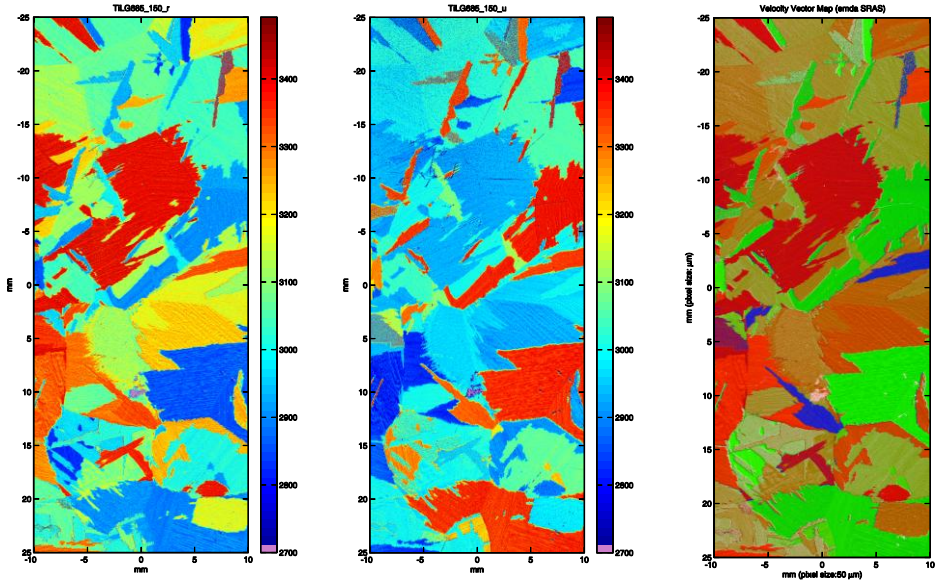

Figure 4 Saws propagating left/ right (left) up /down (centre) and a velocity vector map combining both (right)

Surface velocity maps are very useful for showing material microstructure but a single map cannot always identify all grains in a material as there may be different grain orientations that produce the same acoustic velocity value in one propagation direction. To obtain a more complete picture of the material structure the velocity can be measure in different directions and a composite image produced.

When two orthogonal directions are scanned a velocity vector map can be produced as shown in figure 6. This is achieved by combining the two velocity maps into a single map with a new colour map, colouring points that are fast and fast in both maps blue, fast and slow green and slow and fast red.

From Velocity to Orientation

To provide orientation measurements we need to convert from velocity contrast maps to true orientation information. The acoustic velocity of a known material in a known orientation can be calculated analytically. Starting with the materials elastic constants we perform an iterative search procedure to find which SAW and pseudo SAW velocities satisfy the boundary conditions. This method produces a velocity surface containing many wave modes for the chosen plane, not all of these wave modes will be detectable by our experiment. For example our current detector is sensitive only to the out of plane motion of the waves, so we calculate the out of plane motion for all of the modes found during the search and choose the dominant mode. This then gives us an indication of the expected velocity surface for that crystallographic orientation that will be measured with our experiment, some example velocity surfaces for Nickel on different planes are shown in figure 7.

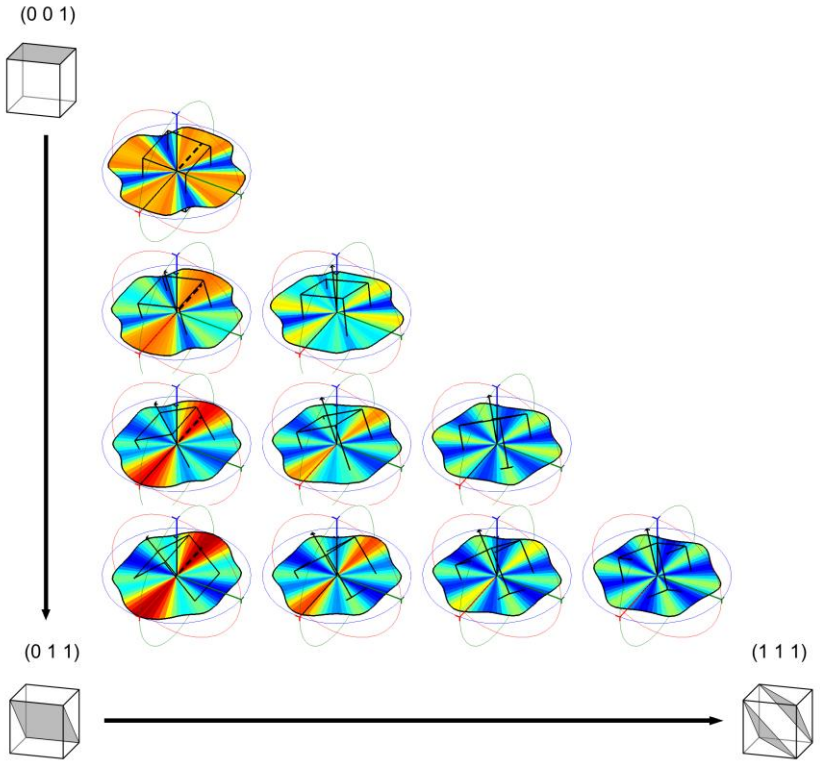

Figure 5 - Calculated velocity surfaces for Nickel

To find an orientation from experimental data we fit our experimentally obtained velocity surface to a database of velocity surfaces in all possible orientations until we get a good match. Figure 8 shows the SAW velocity measurements over 360 degree of three single crystal nickel samples, The radial distance from the centre of the square represents the SAW velocity in the direction of

the radius. The colour indicates the intensity level of the received signal, where red is the strongest and blue represents the weakest; the scale of the images represents velocities varying from 0m/s in the centre of the square to 4000m/s in the centre of each edge. The crystallographic orientation is determined by choosing the best fit and the results are plotted as black asterisks in the bottom of figure 8. An orientation map of a large grain Aluminium sample is shown in figure 9.

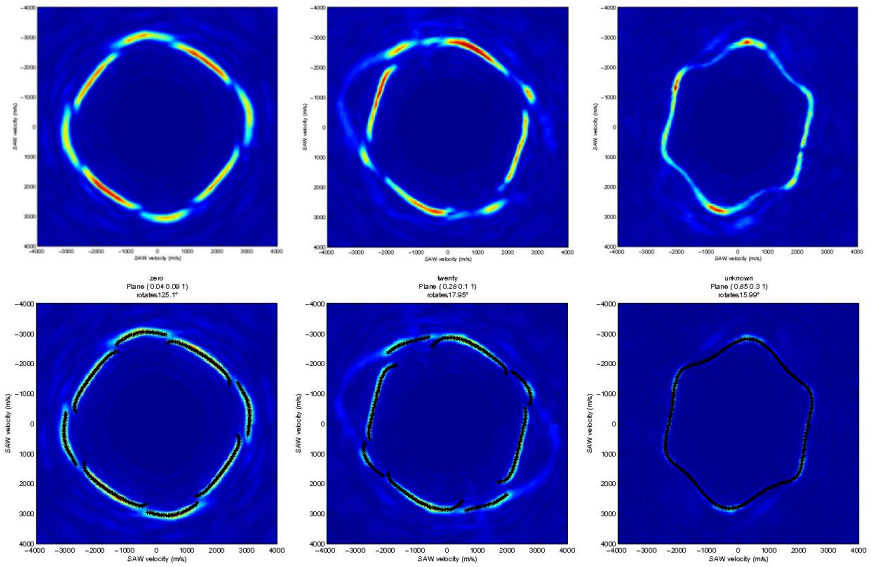

Figure 6 Top - experimental data on 3 single crystal nickel samples. Lower - data overlaid with the best fit modelled data.

Going Forward

All these capabilities have been constructed into a compact head that can be mounted above a scanning system, as pictured, or mounted directly to a scanning head. The current dimensions are approximately 350x200x150 mm with an umbilical connection to a rack containing the computer and other electronics. The next step is to reduce the size and weight of the head still further by fibre coupling the generation and detection lasers.

The instrument is currently being upgraded with a new detector that is capable of detecting acoustic waves on optically rough surfaces. Once installed, this will allow the instrument to perform scans on many more industrially relevant surface finishes, widening the applicability of the SRAS instrument.

We wish to continue to investigate the applicability of SRAS to a wider range of materials, such as silicon, composites, surface coatings and ceramics, and engage with industry to make sure that the instrument develops to meet any required specifications for key performance outcomes that different applications may have, such as spatial resolution, elastic property measurements, grain orientation accuracy, penetration depth sensitivity, measurement speed etc.

Could SRAS help your business? If you'd like us to scan one of your samples, or just to find out more about the technique, please contact Richard.J.Smith@nottingham.ac.uk or Steve.Sharples@nottingham.ac.uk

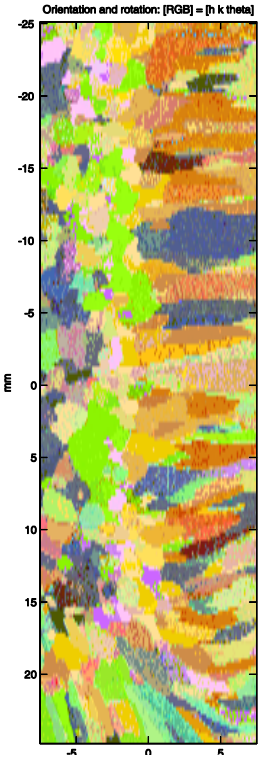

Figure 7- Orientation map of large grain aluminium sample