Fast noncontact imaging of material microstructure using local surface acoustic wave velocity mapping

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***Abstract*— The make-up of the material microstructure of multi-grained materials such as titanium alloys and aluminum is of great interest to many in industries such as aerospace. The ability to map the material microstructure - in effect to image the grains - quickly and in a nondestructive manner would be useful from both a process control perspective and in the area of nondestructive evaluation. There are several techniques in the field that are capable of imaging grain structure, including simple etching, orientation imaging microscopy and scanning acoustic microscopy; all have their strengths and weaknesses. We present a new ultrasonic technique that can directly and quantitatively image the local surface acoustic wave (SAW) velocity over the surface of a material. Material microstructure can be determined if the phase velocity of the grains varies with grain orientation. The acoustic waves are generated and detected by lasers and as well as being noncontact, the technique is relatively fast, can cope with large samples, and is totally nondestructive.**

The new technique involves varying the spatial parameters of the excitation pattern in real time to maximize the generation efficiency of the surface acoustic waves at the phase velocity of the material, in the region of excitation. By repeating this over the sample surface, a surface wave phase velocity map can be produced.

As well as describing the velocity mapping technique in detail, several example results of industrially-relevant materials acquired using our new instrument are presented. The limit to the quantitative lateral resolution of the instrument is discussed, and how this relates to the qualitative lateral resolution. Results indicating the practical limit of the accuracy of velocity measurements are also presented.

We demonstrate imaging on several samples (40mm^2) and different materials. This shows that the the instrument can reveal the underlying microstructure and image areas of anomalous grain structure that may be significant for the performance of the material. The instrument currently works on smooth samples but can be extended to work on rough surfaces and components with unprepared surfaces and consequently this has high industrial relevance.

I. Introduction

Ultrasonic techniques have for some time contributed greatly to the methods used to investigate material microstructure. The principal contrast mechanism is the change in ultrasonic velocity, due to grain orientation. This change in velocity—usually 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] can produce excellent images of surface and subsurface features [2]. 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 excellent 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 author's 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.*[3], [4] has shown that it is possible to use a SAM to produce quantitative velocity maps of grain structures using Rayleigh waves [3], and velocity maps relating to residual surface stress using surface skimming longitudinal waves [4], by using a method based on the difference of arrival times of the direct reflected signal and the surface wave.

In this paper 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 and aluminum. The method uses lasers to generate and detect the surface acoustic waves and so is completely noncontact and, most importantly, completely damage free.

The theory of the technique is described in detail in the next section. Section III deals with instrumentation; a brief overview of the Optical Scanning Acoustic Microscope (O-SAM) is given, and how it has been adapted to perform velocity measurements. Velocity images taken using the SRAS technique are presented in section IV, including results showing the current practical velocity resolution. Finally, discussions concerning the results, and the lateral resolution of the technique, are contained within section V.

II. Spatially resolved acoustic spectroscopy

The technique is based on an acoustic version of a common optical measurement technique, namely spectroscopy. 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 line spacing of the grating is swept over a certain range, corresponding to the likely range of SAW wavelengths at the fixed frequency f. The SAWs are detected using a broadband detector. 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.

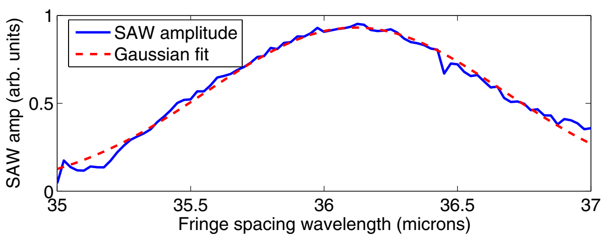

Fig. 1. The graph shows how the amplitude of the detected surface acoustic waves varies with respect to the fringe spacing of the pattern used to generate the SAWs. The greatest amplitude occurs—unsurprisingly—when the fringe spacing matches the wavelength of the acoustic waves. The solid blue line represents experimental data, and the dashed red line represents a Gaussian curve fitted to the data. By finding the location of the peak of the curve, and with knowledge of the excitation frequency, the SAW phase velocity can be determined.

1 is produced. This is because the efficiency with which the SAWs are generated in the region of the grating depends on the line spacing. The grating produces the largest amplitude acoustic waves when the grating line spacing matches the SAW wavelength, λ. Hence, by finding the line spacing that produces the largest waves, the phase velocity v can be determined by the relationship $v = f\lambda$.

In any practical instrument which is subject to noise in the measured acoustic amplitude, a small amount of processing would normally be applied to the measured signals. This could involve either smoothing the data with a low pass filter to produce a smooth peak, or curve-fitting with a Gaussian or polynomial.

The above description illustrates 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. 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.

III. Instrumentation

The instrument that we use to acquire the results shown in the next section is the Optical Scanning Acoustic Microscope (O-SAM), and has been described previously [5], [6]. The important aspects of the O-SAM are shown schematically in Fig. 2. This research instrument has been redesigned and modified over a number of years, and is capable of rapid, high resolution, nondestructive vector contrast imaging of SAWs without measurement perturbation, damage or contamination of the sample surface.

A. Optics

An important component of the system is the spatial light modulator (SLM), which is used to control the excitation source distribution. The use of 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 optical

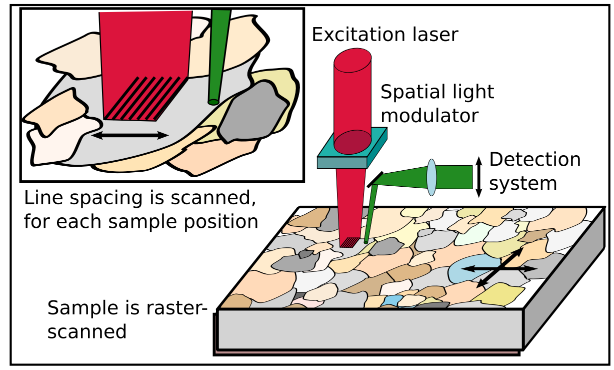

Fig. 2. This figure shows a schematic of the key aspects of the O-SAM system. A Q-switched mode locked laser, with a fundamental frequency of 82MHz, is used to excited the surface acoustic waves. The energy from this laser is applied to the material surface via a spatial light modulator (SLM). This device consists of an array of pixels that can be used to change the optical distribution of light, and is used to image a pattern of fringes onto the material surface. As the fringe spacing is adjusted, the generation efficiency varies. The waves are detected using another laser, using the optical beam deflection technique.

energy from the pulsed laser is imaged to a 1.6mm square area on the sample surface using the SLM, and this image contains 512×512 programmable pixels. The SLM image can be reprogrammed at a rate of 1kHz—this is also the Q-switch repetition rate. The SAWs are detected a small distance away from the SLM image, using a slightly modified optical beam deflection technique.

B. Rapid data acquisition

Laser ultrasound techniques in general often suffer from poor signal to noise of the detected signals, and this is usually resolved by digital acquisition of waveforms, and digital signal averaging. We have previously demonstrated this acoustic spectroscopy technique for analysis of surface and pseudo-surface waves on single crystals [7], and digital acquisition and averaging was used. However the single crystal measurement technique was effectively a single point measurement repeated for different orientations of the crystal. For that experiment, measurement acquisition speed was not critical; 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. This is capable of measuring the amplitude (and phase) of every single laser 'event,' i.e. every single Q-switch pulse envelope. Since there are approximately 1000 events 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.

In order for the analogue detection technique to work, we must ensure that the signal to noise ratio is as good as possible. The fact that we are exciting the waves over a 1.6×1.6mm area works to our advantage, since the power density is very low and we can use reasonably high optical powers without fear of damaging the sample. In addition, we excite the SAWs using

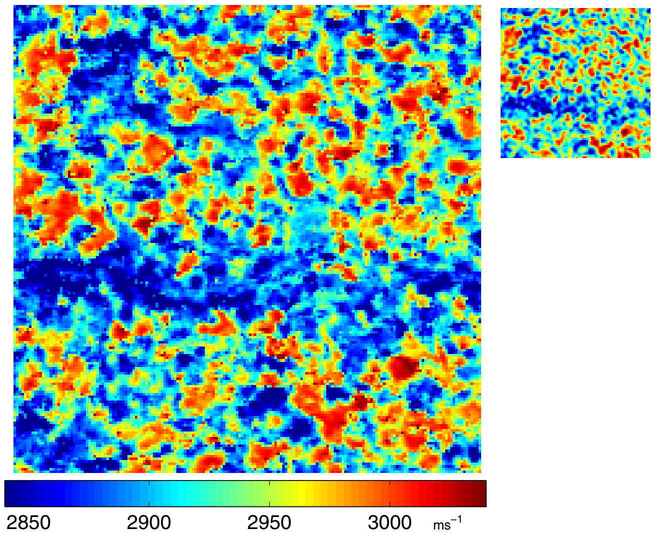

Fig. 3. The main image (to the left) is a velocity map of a 45×45mm area of a titanium alloy. As with all the images that follow, the colour indicates the phase velocity of the SAWs horizontally across the image. The main image was acquired in around 3 hours. The sub-image is of a similar area, but at a lower spatial and velocity resolution, and was acquired in around 10 minutes. It is shown to illustrate that scans performed very quickly can also reveal very useful information.

a pattern of geometric arc fringes, rather than a set of straight lines. This has the effect of focusing the waves to a point, where the amplitude is much greater, and it is at this point that the acoustic waves are detected.

IV. Results

In this section we present results of surface wave velocity images on a variety of industrially relevant materials. Not only do the results illustrate grain structure on metal alloys, but we show that it is also possible to use the measured velocity variations to determine coating thickness. A velocity map of the surface of an elastically isotropic piece of glass (an 'ideal sample') is presented to illustrate the current practical velocity resolution limit.

A. Grain structures in metals

Fig. 3 is a 45×45mm velocity map of a titanium alloy. In this figure and all that follow, the colours represent the surface wave phase velocity in the horizontal direction. The figure immediately illustrates one of the potentially important uses of the SRAS technique for metalurgists, in that it can show the degree of randomness (or uniformity) of the grain structure. There is clearly a large region—in dark blue—indicating a cluster of grains of the same orientation.

The small sub-image to the right of the figure has a lower spatial and velocity resolution than the main image, however it only took around 10 minutes to acquire, whereas the main image took around 3 hours. It is included to illustrate that the instrument can produce very useful results of sufficient quality to be genuinely useful in a very short timeframe.

Fig. 4 shows two velocity maps of two pieces of aluminum. It can be seen that the two pieces of metal used to be joined

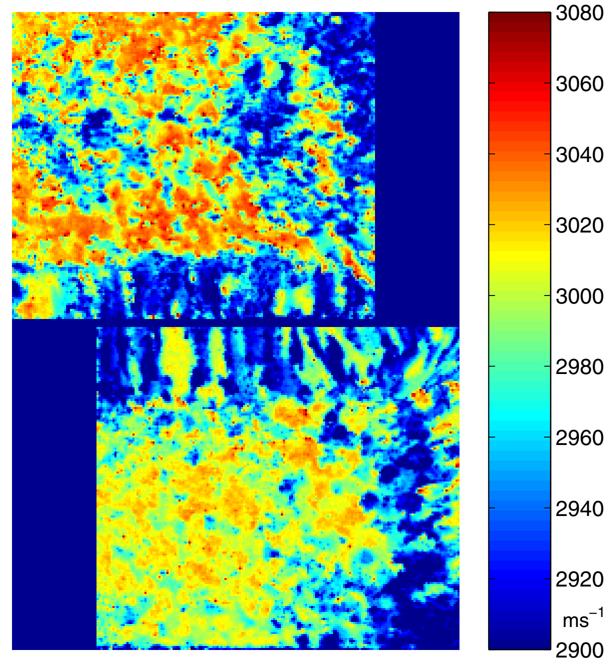

Fig. 4. The figure shows two velocity maps of two pieces of aluminum. The size of each piece is approximately 45×40mm. The two pieces of aluminum used to be joined together. Each of the two halves of the image were acquired in half an hour, and the pixel size is 250μm.

together. The distribution of velocities—much lower at the right hand edge and around the cut between the two sections of the block—is interesting. In fact, the two blocks combined are only one half of a larger block which was joined on the right. The dark blue regions where the velocity is slower marks out the areas where a metal rod was used to stir the molten aluminum before it set.

B. Differences in coating thicknesses

A mask was made by milling three capital letters in a thin piece of brass, using a 1mm diameter milling bit. A large block of silicon nitride was then coated through the mask, with approximately 30nm of high purity gold. The mask was then removed, and the whole area was overcoated with approximately 500nm of aluminum, which completely obscured the gold pattern, so that it could no longer be seen. A velocity map of the area concerned was then acquired with the O-SAM instrument. Figure 5 shows both the optical image—essentially blank—and the velocity image. The mask itself was optically imaged separately, and the dashed lines in the figure show the mask edges. The area of gold can clearly be seen and, moreover, using a simple linear relationship (valid for very thin coatings) originally described by Bromwich [8], we can calculate the coating thickness from the given velocity change. Note that the velocity image has been smoothed, using a low pass filter, to reflect the spatial resolution of the system.

C. Current practical velocity resolution limit

An area of glass, coated with a thin uniform layer of aluminum to aid generation and detection of the surface waves,

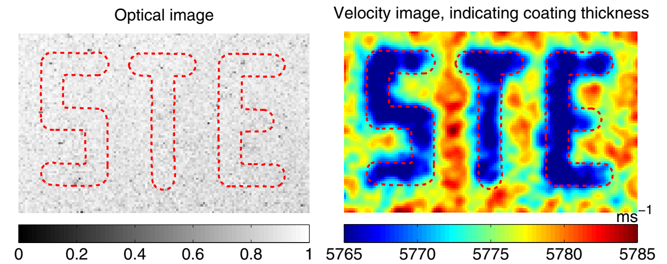

Fig. 5. Optical image and velocity map of an area of silicon nitride that had been overcoated with approximately 30nm of gold through a mask. The whole area was then overcoated with approximately 500nm of aluminum, to completely obscure the gold pattern. The image area is 13×8mm, the pixel size is 100μm. The difference in velocity indicates the presence of the gold layer.

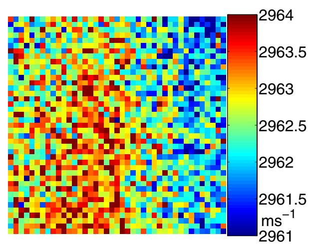

Fig. 6. Velocity map of a piece of elastically isotropic aluminum-coated glass. The image area is 10×10mm, the pixel size is 250μm. The standard deviation in velocity is 0.89ms^{-1}.

was used to ascertain the current practical limit of the SRAS measurement system, in terms of velocity accuracy; Fig. 6 shows the result. The sample is elastically isotropic, and so the velocity should be constant over the area scanned. The image is essentially noise, with a slight gradient across the image. Note the velocity range of the image is 2962.5$ms^{-1}$$\pm$1.5$ms^{-1}$. The measured standard deviation in velocity is 0.89ms^{-1}, this corresponds to 0.03%, or one part in 3.3×10^3.

V. Discussion

The spatially resolved acoustic spectroscopy technique described in this paper is an exciting new technique for the investigation of material microstructure. The current *practical* limit of velocity resolution in the instrument's current configuration is less than 0.05%. As with all systems there are trade-offs as far as speed, accuracy and resolution are concerned. Factors that influence the resolution include signal to noise ratio of the detected SAW amplitude, the number of fringes (the more fringes the better), the number of pixels in the SLM image, the excitation frequency, and the efficiency of the detection system. The signal to noise can be improved by using greater optical powers to generate the SAWs. More optical power means a bigger laser, and the limit may well be the damage threshold of the SLM. The footprint of the image of the fringes on the sample could be made smaller without increasing the optical power onto the SLM (although the optical design of the instrument gets trickier), but this reduces the number of fringes, making the peak of Fig. 1 broader and more difficult to locate. The frequency could be increased to increase the number of fringes but then the signal to noise tends to decrease due to other factors.

The *absolute* accuracy of the velocity measurements depends on different factors, and is predominently 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, as the instrument stands, it is rather sensitive to defocus and tilt of the sample, simply because any variation in focus also varies the size of the fringes, and hence the reported velocity.

The lateral resolution is determined by the SLM image size, and is of the order of half this. However it is further complicated by the fact that we use arcs to excite the ultrasound, and so factors such as the acoustic numerical aperture influence the lateral resolution. A footprint of 400×400μm is possible without damaging the sample at the current optical power level, giving a lateral resolution of approximately half that, although with reduced velocity resolution.

Finally, 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. The overall detected amplitude varies significantly as the sample is scanned; but since the excitation efficiency is not affected then—provided enough acoustic energy is received by the detector—the location of the peak, and hence the phase velocity, can be discerned.

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