

Spatially Resolved Acoustic Spectroscopy (SRAS) Microstructural Imaging

Matt Clark^{1,a)}, Adam Clare¹, Paul Dryburgh¹, Wenqi Li¹, Rikesh Patel¹, Don Pieris¹, Steve Sharples² and Richard Smith¹

¹*Optics and Photonics, Faculty of Engineering, University of Nottingham, UK*

²*Dovecote Electrical, Beeston, Nottingham, UK*

^{a)}matt.clark@nottingham.ac.uk

Abstract. Spatially resolved acoustic spectroscopy (SRAS) is an acoustic microscopy technique that can image the microstructure and measure the crystallographic orientation of grains or crystals in the material.

It works by measuring the velocity of surface acoustic waves (SAWs) via the acoustic spectrum. In the usual configuration, the SAWs are generated by laser using a pattern of lines and detected by laser at a point close to this grating-like source. The use of the acoustic spectrum as a means of measuring the velocity has a number of practical advantages which makes the technique robust and fast and gives good spatial resolution. This makes the measurement suitable for imaging and gives it many advantages over traditional laser UT and microstructural measurement techniques.

As SRAS is a laser ultrasound testing technique (LUT) which can be applied to a wide range of industrially relevant samples as a non-destructive evaluation technique. There are no size limitations on the samples that can be imaged and the surface preparation required is significantly more relaxed than many other techniques with the capability of operating on many as manufactured finishes. This permits the use of SRAS as an online inspection tool, for instance during additive or subtractive manufacturing, as a QA tool during manufacture or as an NDE/T tool in service.

INTRODUCTION

Spatially resolved acoustic spectroscopy (SRAS) is an acoustic microscopy technique that can image the microstructure and measure the crystallographic orientation of grains or crystals in the material.

The elastic properties of most microstructured materials vary with position in the sample and they also usually vary with orientation. In the case of polycrystalline materials, such as metals, the elastic properties vary with the orientation of the individual crystals and therefore vary with position across the sample. Since the elastic properties vary with position and orientation it is possible to image the microstructure by imaging the acoustic velocity. It is also possible to determine the orientation from the acoustic measurements[1].

There are many ways to determine acoustic velocity but the use of the acoustic spectrum has many advantages such as:

- It is robust and immune to the aberrating and scattering effects of the microstructure
- It can be performed in a very small area and therefore gives high spatial resolution
- It is simple to perform, especially with laser ultrasonic techniques
- It is simple to optimise the signal-to-noise ratio and exceed an SNR above 1 for a single shot measurement. This makes it very fast and suitable for imaging rather than single point measurement.

In this paper we will explain how SRAS works, explore some of the capabilities it offer and demonstrate some applications .

INSTRUMENTATION

Figure 1 shows a schematic of the instrumentation and a photograph of an industrial prototype SRAS system. A pulsed laser (Q-switch YAG, few ns pulse width, kHz repetition rate, few 100mW power, 1064nm optical wavelength) is used to generate the acoustic waves. The pulsed laser light is passed through a mask with a grating pattern which is then imaged onto the sample surface. This produces an regular array of lines, each of which generates an acoustic wave, because of constructive interference between the regular array of sources the wavelength of the generated wave is equal to the line spacing. This wave propagates across the sample and is detected by a laser ultrasound receiver and the signal is captured on a high speed digital oscilloscope and downloaded into a computer. The acoustic spectrum is then computed and the frequency of the peak amplitude is determined from the signal. This is then converted into the acoustic velocity using the equation, $C = f\lambda$, where C is the velocity, f is the frequency measured from the acoustic spectrum and λ is the wavelength determined by the line spacing.

It is worth noting that the velocity measurement corresponds to the area under the generation patch. As long as the acoustic wave reaches the detector, the area of the sample between the generation patch and the detector makes no difference to the measurement and is not probed. This is important because it means that the measurement is unaffected by the microstructure or surface condition between the generation and detection so long as the signal to noise ratio is sufficient to permit detection of the acoustic wave. This makes for a very robust measurement system where the signal amplitude, generation and detection efficiency and acoustic aberrations do not affect the measurement and a high quality velocity measurement can be obtain even when images of the amplitude resemble noise or acoustic speckle[2, 3].

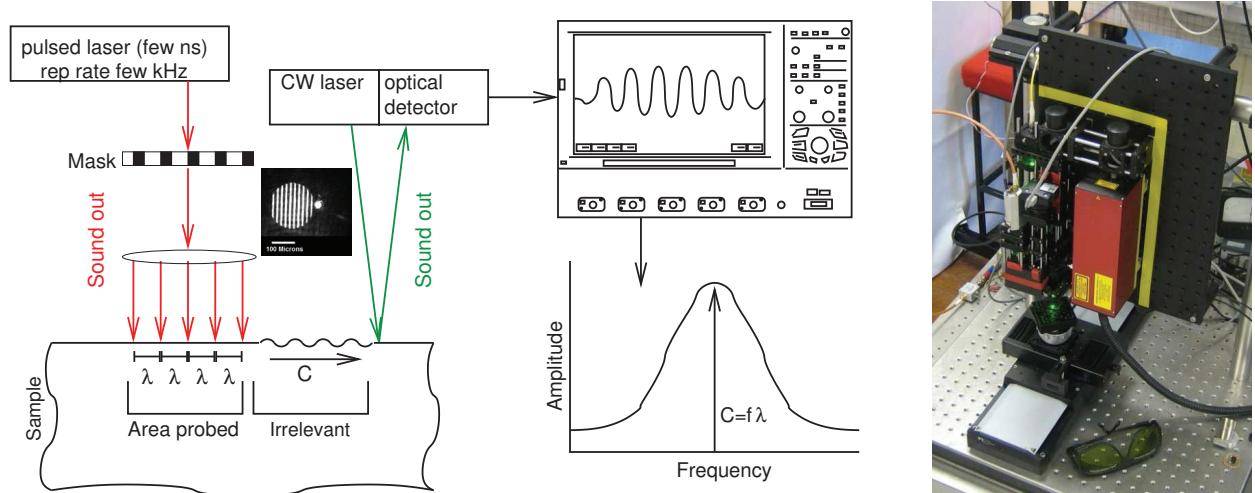


FIGURE 1. (left) Schematic diagram of a typical SRAS system. A pulsed laser is passed through a grating which is imaged on the sample surface producing a pattern of regularly space lines. The short laser pulses generate surface acoustic waves with a known wavelength equal to the line spacing. The SAWs propagate across the surface and are detected by a laser ultrasound receiver and the signals captured on a digital oscilloscope. From this signal an acoustic spectrum is computed and by determining the frequency of this peak amplitude the acoustic velocity, C can be determined. A microphotograph taken with a built in bore-sight camera of the generation patch and detection spot on the sample is show in the inset. (right) Photograph of a typical SRAS system showing the optics mounted on a compact breadboard above sample scanning stages.

In many LUT techniques the generation laser can cause damage through melting or ablation and high generation powers are often required to overcome the poor signal to noise ratio of optical detection (compared with piezo-electric systems). SRAS uses multiple line sources allowing the generation power to be spread over a comparatively wide area which reduces the power density to sub-damage levels. This arrangement also defines the acoustic wavelength used and narrows the bandwidth of the signal making it easier to electronically filter the received signal and allowing it to be amplified without saturation caused by other out of band noise sources.

The SAWs are detected by a LUT receiver. The type of receiver used depends on the surface finish of the component. For polished samples we use a simple knife-edge detector[4] and for (optically) rough surfaces we use a speckle-knife-edge detector (SKED)[5, 6] but have also used commercial detectors, however the high scanning speed

of SRAS systems means that detector must be capable of adapting rapidly to changing speckle and changing light levels. In order not to slow the data acquisition speed.

At each point on the sample the generation laser is fired and the signal is collected on a digital oscilloscope. The signals are down loaded to a computer and the frequency spectrum is computed using a fast Fourier transform. The frequency of the peak amplitude is computed from each spectrum and converted to velocity using the fixed wavelength determined by the lines spacing on the sample surface.

If a simple map of the grain structure is required then this process is repeated for all the pixels on the sample and a velocity image is produced (figure 2) by plotting the acoustic velocity as a function of position. As each grain's crystallographic orientation differs from its neighbours, its elastic constants with respect to the direction of sound propagation differ so the measured velocity of each grain differs resulting in clear contrast.

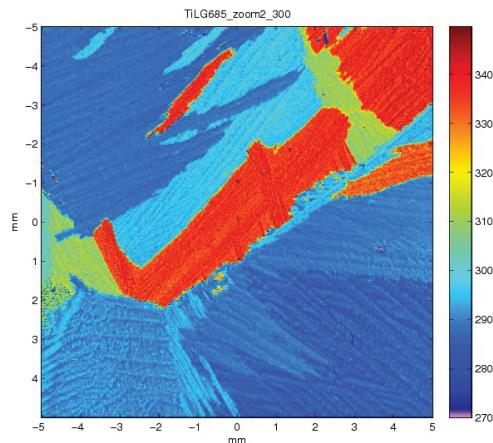


FIGURE 2. Velocity SRAS scan image of a titanium sample. This shows the velocity as a function of scan position in the sample. In this material the velocity ranges $> \pm 10\%$ across the material resulting in strong contrast between the grains.

If the crystallographic orientation of a single grain is required then the velocity at multiple acoustic wave propagation angles must be taken. If a map of the crystallographic orientation is required then the sample is simply imaged using multiple acoustic wave propagation angles.

As SRAS can usually produce signals with an SNR>1 it can acquire the signals with no averaging and take data “on the fly” while the stages are moving. As a consequence the imaging speed is limited by the generation laser repetition rate and the scanning stage speed and is typically 1000-2000 points per second allowing it to rapidly produce high resolution images of the microstructure.

Finding the orientation

In order to determine the crystallographic orientation we take multiple measurements at each point propagating the SAWs in different directions on the sample, from this we can build up a radial acoustic spectrum (figure 3 left). If an image of orientation is required then we scan the sample multiple times with the direction of propagation rotated each time (figure 3 middle) which results in images showing the same grain structure but different velocities at each grain.

However, the process of determining the orientation from the velocity is not straight forward. If two of the *orientation, velocity or elastic constants* are known then, in principle, the third can be computed. While determining the elastic constants from a known orientation and velocity or determining the SAW velocity from the elastic constant and the orientation are both relatively simple, determining the orientation from the velocity and elastic constants is an ill conditioned problem that does not lend itself to analytical solution.

In order to solve this problem we have developed a fitting procedure whereby we solve the forward problem (determining the velocity for angle orientation angles using known elasticity data)[7, 8, 9] and the fit this to the measured data[10, 7]. This is illustrated in figure 4 where the figure on the left shows a fitting figure of merit as a function of the orientation angles and the figure on the right shows the radial acoustic velocity spectra at one point on the sample with the best fit forward problem super-imposed on top.

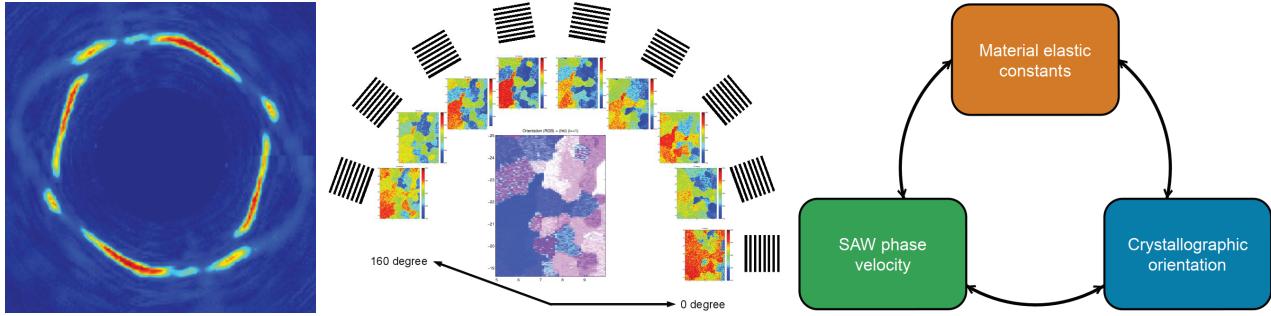


FIGURE 3. The acoustic velocity varies as a function of propagation angle on the surface of the material, the crystallographic orientation and the elastic constants. (left) acoustic spectra plotted radially as a function of propagation angle (middle) SRAS scans taken at a variety of propagation angles on the sample sample. The grain structure is always the same but the velocities of each grain vary with angle. (right) The elastic constants, the acoustic velocity and the crystallographic orientation are all related. In principle knowing any two allows the third to be computed, however going from velocity measurement and elasticity to orientation is very ill-conditioned.

It can be observed in figures 3 and 4 that the radial acoustic velocity spectra are sometimes discontinuous and, at some angles, can contain multiple peaks. This results from the presence of multiple surface acoustic modes which can occur in some materials. These can be easily found using the method of [8, 9] and in some circumstances the system may generate more than one mode or may “hop” from one mode to another at certain angles[11] because of the changing efficiencies of generation and detection at the different angles[12]. Where present these addition modes and features in the spectra can be used to enhance the orientation fitting.

We have shown a good correspondence between SRAS measurements and electron beam backscatter diffraction (EBSD) in a variety of materials which is shown in figure 5.

Applications of SRAS

Unlike EBSD SRAS is not limited to small samples and does not require a very high standard of surface finish - in fact a SRAS system equipped with a suitable rough surface detector can operate on a wide range of as manufactured surfaces, including many which occur during manufacture. The non-destructive nature of the measurement, the ability to image without cutting up the sample or destructive surface preparation, the ability to operate on an arbitrary sample size, the compatibility with manufacturing processes and the speed of imaging means that microstructural imaging can be used in many applications where EBSD cannot (figures 6 and 7)).

Figure 6 shows a SRAS image of an Inconel sample. The inset shows an EBSD image of part of the same sample

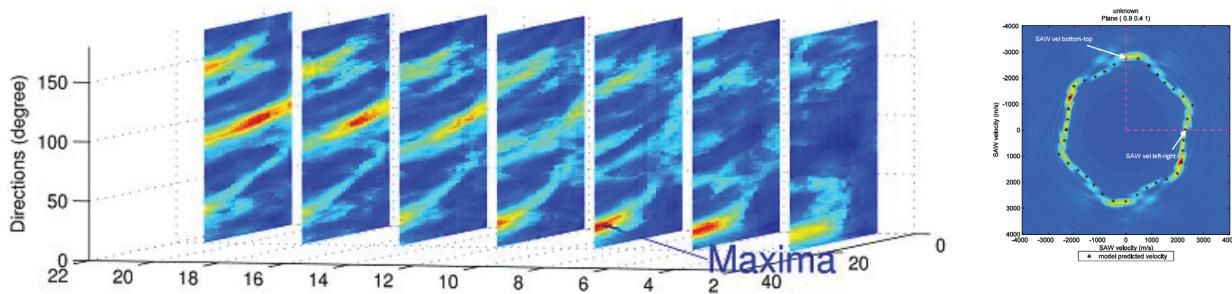


FIGURE 4. Finding the crystallographic orientation: (left) by fitting the solution to the velocity as a function of orientation angle to the measured data the orientation can be determined despite the ill-condition problem. Here the radial velocity spectra for one pixel has been compared with a range of orientation angles and a figure of merit for the fit plotted. The best fit (marked maxima) is plotted (right).

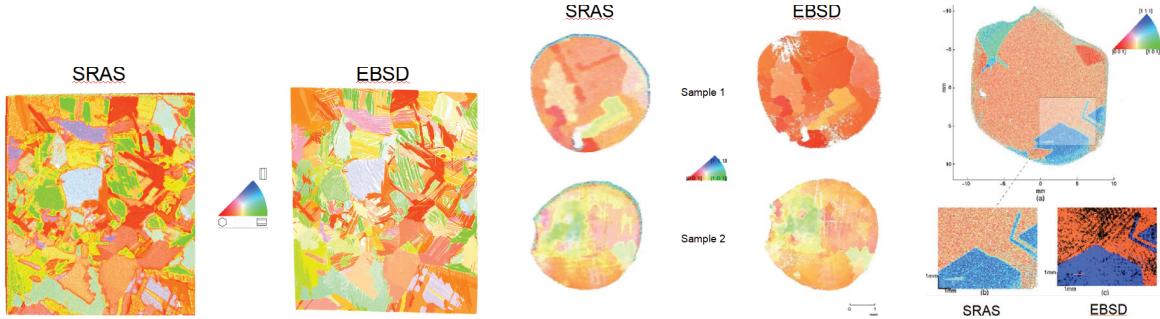


FIGURE 5. Comparison of SRAS and EBSD orientation imaging on: (left) titanium, (middle) nickel superalloy and (right) silicon. The orientation of the SRAS images agrees well with the EBSD measurements.

and, while the EBSD image demonstrates high resolution, the difficulty in scanning a large sample means that it is possible to miss large scale structure.

Figure 7 shows a large dog bone sample, part of a batch of similar samples under going fatigue testing and non-linear ultrasonic measurement[13, 14, 15]. The experiment required that each sample was repeatedly imaged between fatigue cycles something that would not be possible with any other technique.

Figure 8 shows SRAS scans of titanium forgings showing plastic flow and distortion of the grains resulting from the forging processes. Such large scale structure is hard to capture with other microstructural imaging techniques.

Figure 9 shows a steel weld and an aluminium casting both show the growth of large grains as a result of the cooling process as the sample was manufactured. The steel sample was previously diced for EBSD imaging but could have been scanned in one go using SRAS.

Figure 10 shows a wire and arc additively manufactured sample that has been SRAS scanned on its side and end to reveal the growth of large columnar grains. Figure 10 also shows a powder bed additively manufactured sample that has been SRAS scanned in its “as manufactured” surface condition. SRAS has also been shown to be sensitive to surface breaking cracks and voids and sub-surface defects in additively manufactured components, the latter are revealed by Lamb wave contrast as the surface acoustic waves travel over the voids[16].

CONCLUSIONS

SRAS is a promising alternative to existing microstructural imaging techniques with a number of distinct advantages. It uses surface acoustic waves to image the microstructure and measure the crystallographic orientation of the grains in the sample. It uses the acoustic spectrum of the generated SAWs to determine the velocity and this measurement

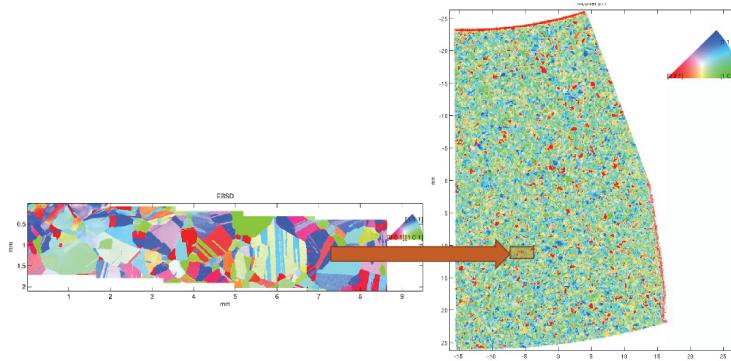


FIGURE 6. The arbitrary size handling of SRAS and its high speed means that it can be used to image much larger components and samples than EBSD. In this case the EBSD image (left) took significantly longer the SRAS image (right) and does not show significant large scale structure.

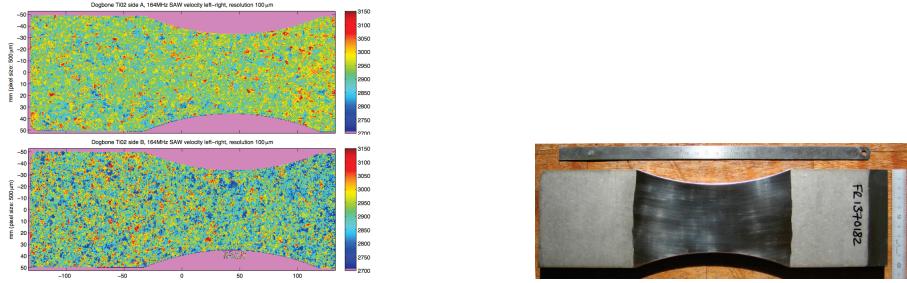


FIGURE 7. SRAS images of a large dogbone fatigue sample (left). (right) photograph of a sample for scale. The sample was repeatedly image on both sides between fatigue samples, a process that would have been impossible by any other method because of the size of the sample and the destructive preparation required.

technique has a number of advantages because it allows for single shot measurements (which allows rapid measurement and imaging) and is largely immune to the effects acoustic aberrations and scattering that can degrade many of the techniques.

Unlike EBSD, SRAS places no restriction on the size of the sample that can be imaged which is purely determined by the range of the scanning system used in the instrument. SRAS can operate on a wide variety of sample surfaces from polished to as manufactured depending on the laser UT receiver technology used. It has been demonstrated on rough, as manufactured and additive manufactured surfaces and on samples during the fabrication process and during on-going materials testing.

SRAS is a good candidate technology for integration into fabrication processes. It is capable of being built into fabrication and machining chambers and lends itself to on-line testing as a result. Since it requires no destructive preparation it is a good candidate for a production quality assurance tool or as a form of NDE/T.

SRAS can measure the texture of a wide range of different materials, it can image the individual grains and grain structure, and it can quantitatively determine the crystallographic orientation of grains with high accuracy. It can also detect and measure defects such as surface and subsurface cracks and subsurface voids.

This technique has the potential to be a useful tool for a wide range of applications in materials science, advanced manufacturing and industrial production.

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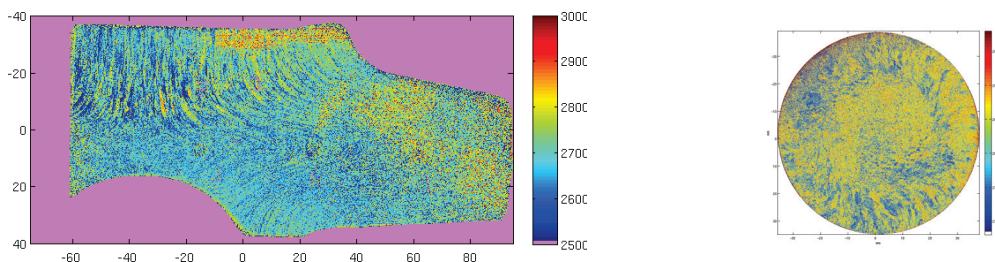


FIGURE 8. SRAS images of a titanium forgings showing evidence of plastic flow. Such large scale structure would be hard to capture with conventional microstructural imaging techniques.

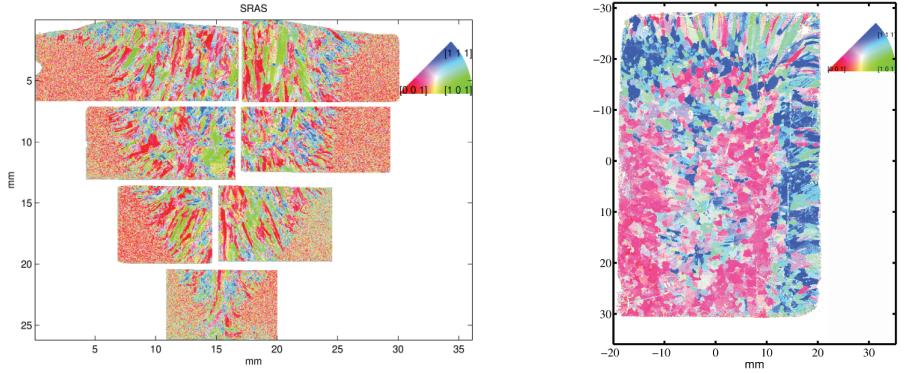


FIGURE 9. (left) SRAS image of a steel weld. The sample was previous cut up for EBSD imaging but could have been easily scanned in one go with SRAS. (right) SRAS image of a cast aluminium sample.

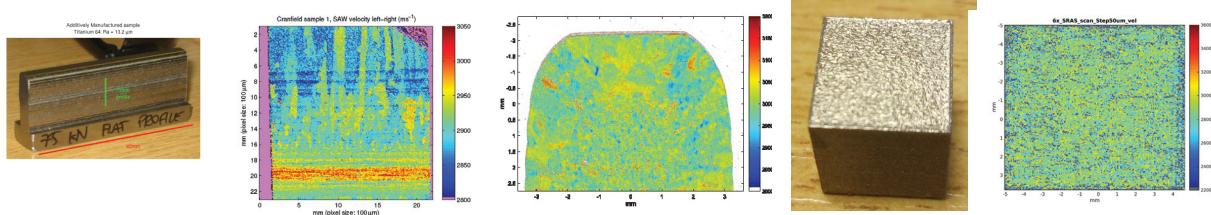


FIGURE 10. SRAS images of additively manufactured titanium samples. (left-right) photograph of sample made using wire and arc deposition, SRAS scan of the side of the sample, SRAS scan of the end of the sample, photograph of powder bed deposited sample with as manufactured finish, SRAS scans of powder bed sample using the as manufactured surface.

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