Evaluation of Anisotropy in Additively Manufactured Materials Using Resonant Ultrasound Spectroscopy

Introduction: Resonant measurement, or using sound to provide insight into a material's condition, has been used for 100s of years. Very simply, this would take the form of listening to the "ring" of an object when struck sharply. Such approaches have been historically employed in casting, for example in the manufacture of clock tower bells, or for rudimentary non-destructive testing (NDT), for example wheel tapping in the rail industry. Acoustic methods have since progressed to become more quantitative than qualitative and there are now several different instrumented methods and analyses available.

NPL CASE STUDY Quick Facts

- There are several acoustic measurement techniques available for materials characterisation.
- RUS offers a means to generate anisotropic elastic property data for materials quickly and with few samples.
- The technique is sensitive to the shape, dimensions and density of the test piece.
- RUS measurement compares well with mechanical measurements for conventionally manufactured materials.
- A preliminary comparison of additively manufactured AlSi10Mg alloy has shown that RUS can provide comparable results to conventional mechanical testing.

- Impact excitation (IE) is a technique which is based on impulse tapping a freely suspended sample with a small projectile (can be a ceramic bead attached to a flexible cable tie to act as a precision hammer or an electromagnetic striker). The induced vibration signal is recorded with a microphone (or laser vibrometer) in the time domain and converted to the frequency domain by fast Fourier transform. The characteristic vibration modes (longitudinal, flexure and torsion) and measured natural frequencies, along with geometry, dimensions and density can be converted into elastic properties using analytical equations (support locations and impact location/direction are also important). This technique may require multiple samples cut at different orientations or different impact/support combinations to generate all modes of vibration. It is not ideal for non-isotropic materials and requires specific dimensional ratios in application.

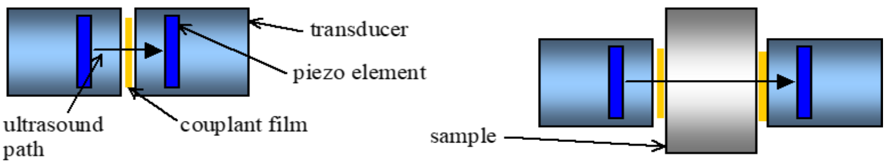

Figure 1: Example of ToF test setup showing transducers and couplant layer.

- Ultrasonic time of flight (ToF) is based on measuring the velocities of several wave modes across known symmetry directions and then calculating the corresponding stiffness components. The specific velocity of interest (propagation/polarization and wave type) is calculated from propagation distance, sample/transducer orientation and measured transit time. By knowing the symmetry, dimensions and density of the sample, the velocities can be converted into elastic properties. This technique usually requires the use of a couplant and the precise dimensions of the sample must be known (Figure 1). Considerations include plane wave propagation assumptions which limit the wavelength, sample extent and transducer size. In addition, precise off-axis samples are required for complex symmetries as well as mathematical optimisation of the refracted wave mode speeds.

- The resonant ultrasound spectroscopy (RUS) technique is based on the measurement of all vibrational eigenmodes of well-defined geometries (spheres, cylinders, parallelopipeds) in one test, such that all elastic properties are determined from one spectrum and one sample. The sample is held lightly at diametrically opposing points between two transducers (Figure 2), leaving the samples free to vibrate in any mode. The driving transducer sweeps over a large frequency range, exciting forced vibrations in the sample with the amplitude response detected by the other transducer. A large resonant response is usually observed at the vibration eigenfrequencies depending on the sample shape, orientation of axes of symmetry, density and elastic constants. The elastic properties can be determined from inverse modelling, an iterative process matching calculations to the test spectrum. For best results, low noise amplifiers and care with input impedances is needed. The measurement can be affected by transducer resonances (minimised by optimum transducer design) and also clamping force.

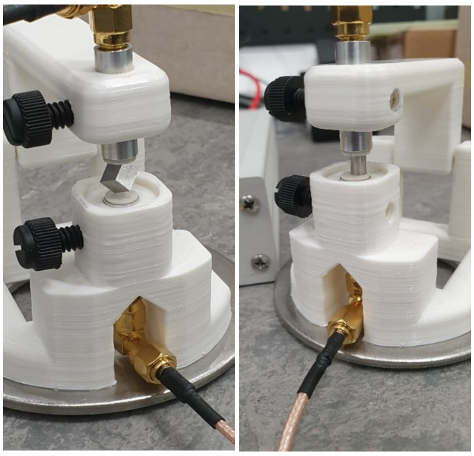

Figure 2: Samples setup for RUS sweep.

Resonant Ultrasound Spectroscopy: For additively manufactured (AM) materials there are some key points that need to be taken into consideration. AM builds tend towards anisotropy and part complexity so are not ideally suited to industrial NDT, but RUS provides a complementary route to elastic property measurement and anomaly detection, including defects, throughout the part. It is suited to inspecting mass produced parts, and is reportedly easily able to detect 'outliers' or components that differ from 'normal' production (comparative method) and so can be integrated into automated processes for quality assurance checks. The method is suitable for anisotropic materials (up to 21 independent elastic constants in the stiffness tensor compared to 2 for isotropic) and has a reduced material requirement with low sample volume, simple preparation and rapid test time thus readily lends itself to AM application.

Validation: To validate the RUS method, tests were conducted on several reference materials. Examples of measurements on Pyroceram are presented in this document. Cuboid samples 6 x 5.5 x 5 mm were machined from bulk material and RUS measurements conducted. An example of the RUS data obtained for the Pyroceram samples is shown in Figure 3. A comparison of the bulk, Young's and shear modulus measured by the OEM and NPL are shown in Table 1 along with a comparison with literature values.

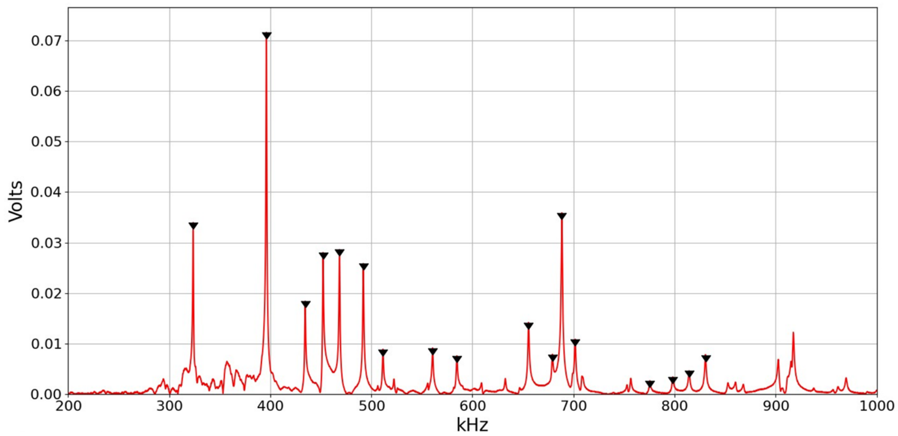

Figure 3: RUS data for the 6 x 5.5 x 5 mm Pyroceram cuboid sample.

This shows that there is good repeatability and reproducibility between the two different laboratories and that the values agree well with mechanical data from literature.

Sensitivity to Specimen Geometry: The following section details preliminary data to evaluate the sensitivity of the RUS measurement to different specimen geometries and aspect ratios. At the time of writing a full quantitative analysis has yet to be performed. A qualitative comparison of the RUS spectra has been generated for cylindrical specimens with different diameters and aspect ratios manufactured from IN718. Table 2 details the different samples used for this purpose and examples of the RUS spectra are shown in Figure 4.

Table 1: Comparison of RUS modulus values, wave velocity and stiffness constants for Pyroceram measured by the original equipment manufacturer (#1&2), NPL and literature values, where available.

Sample	Bulk Modulus (GPa)	Youngs modulus (GPa)	Shear modulus (GPa)	Poissons ratio	C11 (GPa)	C44 (GPa)	Vcomp (m/s)	Vshear (m/s)
#1	78.52	120.64	48.49	0.244	143.173	48.490	7435.0	4326.9
#2	79.01	119.81	48.03	0.247	143.051	48.027	7462.8	4324.2
Lit	n/a	120	(45)	0.25 (0.29)	-	-	-	-
NPL	**76.90**	**120.07**	**48.43**	**0.240**	**141.471**	**48.425**	**7408.8**	**4334.6**

Comparison of RUS to Mechanical Testing: Tensile tests were conducted on AM AlSi10Mg using miniature dogbone (FTSB) samples and an Instron 5969 universal mechanical test machine fitted with a 50 kN load cell. The samples were gripped using a pair of wedge action grips fitted with serrated grip faces. The alignment of the test machine and grips was set prior to testing the samples by clamping a thick steel bar and pre-loading prior to locking the load train firmly. This pulls and locks the system into alignment with the loading axis. The test pieces were loaded at a crosshead speed of 0.5 mm/min until failure.

Prior to testing, the test pieces were speckled using white and black spray paints. Strain was subsequently measured optically on opposing faces of the test piece using a non-contact video extensometer (Imetrum®). The non-contact strain measurement method allows strain to be re-analysed in different ways using a single captured dataset. The user can use a full field approach and measure the strain over the whole gauge length, or multiple discrete areas can be selected allowing the user to simulate a standard strain gauge measurement. Scanning electron microscopy conducted on cross-sections of AlSi10Mg tensile test pieces sectioned in the X, Y and Z directions revealed crystallographic texture and elongated grains associated with the direction of laser travel (X/Y), shown in Figure 5. The tensile properties measured in the 3 orthogonal directions relative to the build (Z) direction are shown in Figure 6. The tensile results would indicate, that despite the differences in the microstructure, there was very little difference in the elastic modulus of the material~~,~~ with all three stress vs strain curves overlapping. However, differences were observed in the strain to failure with the Z direction samples exhibiting less ductility, as might be expected. The elastic modulus results for several repeat tests is shown in Figure 7.

Table 2: Summary of specimen sizes for IN718.

Diameter, mm	Height, mm	Aspect Ratio
8	6	0.75
8	3	0.375
8	1	0.125
4	6	1.5
2	6	3

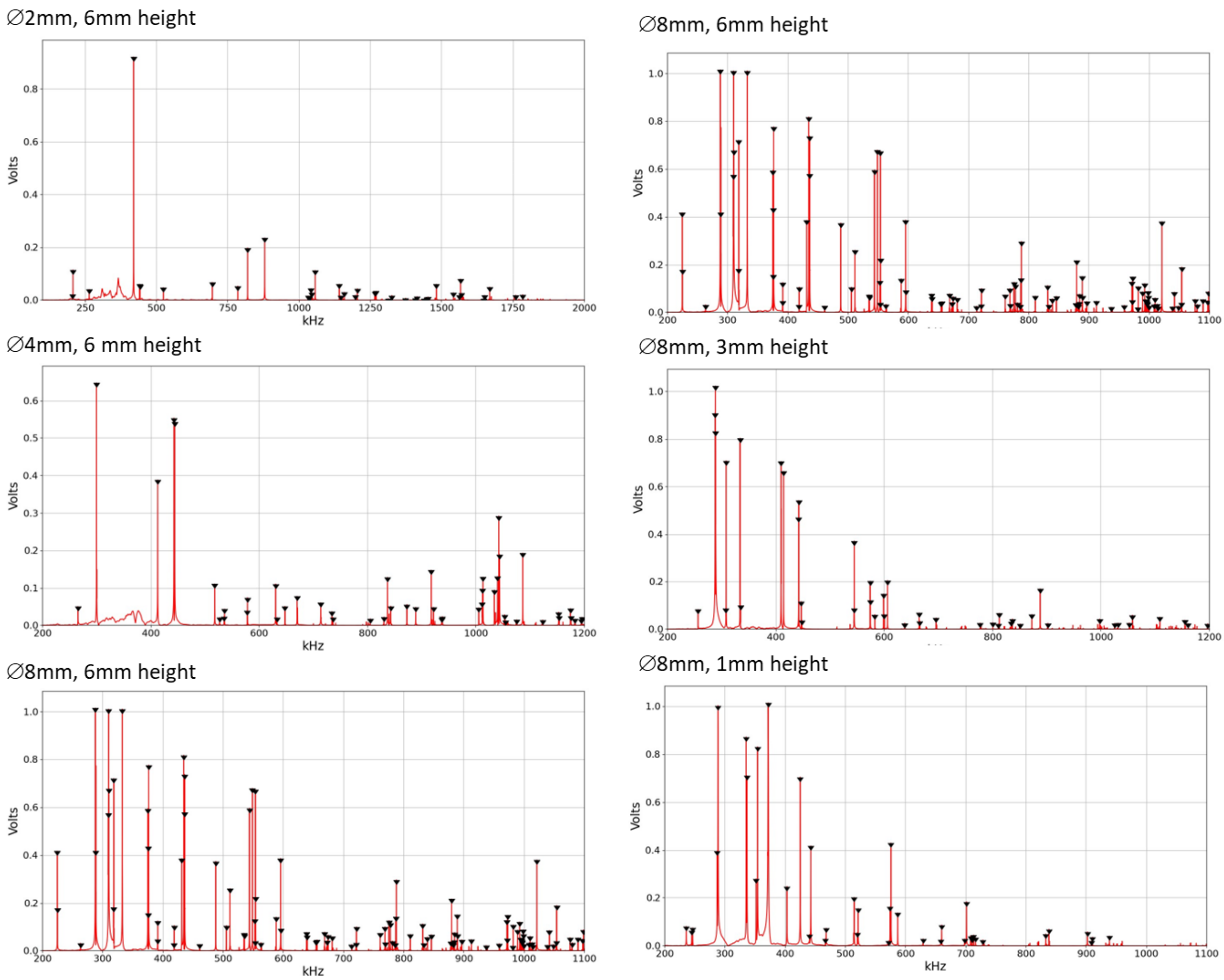

Figure 4: RUS spectra for measurements conducted on IN718 sample with aspect ratios.

RUS spectra were collected for the same material. Note that this requires samples to be accurately machined and measured for both dimensions and mass. The surface roughness will also affect the measurements as contact measurements will tend to overestimate as they contact the highest surface peaks. Some slight adjustment of the dimensions may be needed to optimise the frequency matches to compensate for this. To collect the RUS data the frequency sweep is set to start at a low frequency to ensure the lowest frequency (shear) mode is detected. A high signal to noise ratio is essential to ensure that even small resonances are accurately identified, missing frequencies complicate the subsequent analysis of the data.

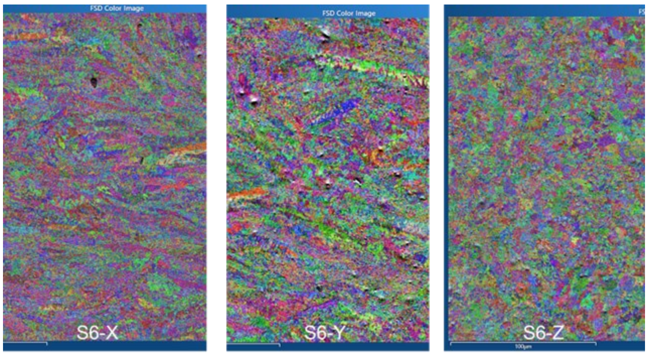

Figure 5: SEM images showing elongated grains.

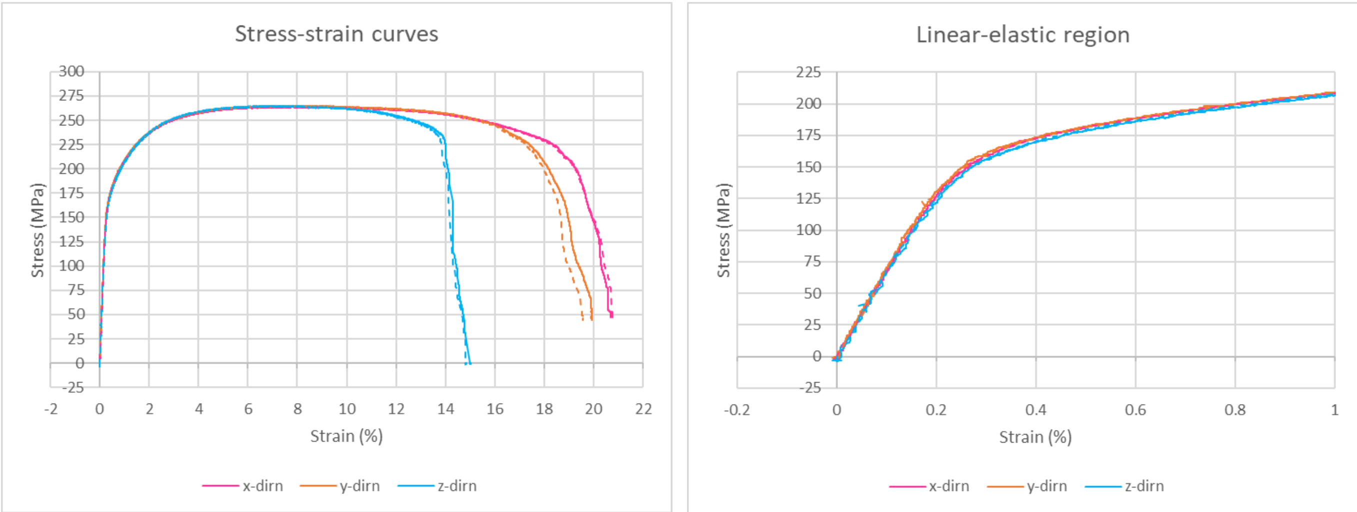

Figure 6: Example stress vs strain plots for tensile miniature FTSB samples tested in 3 orthogonal directions.

In the case of the AlSi10Mg additive manufactured RUS test pieces, a 5-parameter "transversely isotropic" symmetry model was fitted to assess the degree of anisotropy in the material properties. The fitting routine is also able to generate estimates of the confidence in the overall fit and the output stiffness parameters. When it came to fitting the RUS data for a heat treated Z-orientated sample it was found that the optimal fitting needed accurate dimensions which included accounting for slight non-circularity (assumed elliptical cross-section). Care was needed to align the measured and predicted peaks. The fitting resulted in elastic moduli in the Z and X/Y directions of 76.2 and 73.4 GPa respectively, and a Poisson's ratio of 0.33. This corresponds reasonably well with the mechanical test data which gave a mean elastic modulus of 72 GPa in the Z direction and 71 GPa in the X/Y direction. The RUS data is expected to be greater than the mechanical test data as the measurement is high frequency dynamic (adiabatic) and strain-free. Also given that the thermal history and defect structure are likely to be different between the specimen types, the agreement is most encouraging.

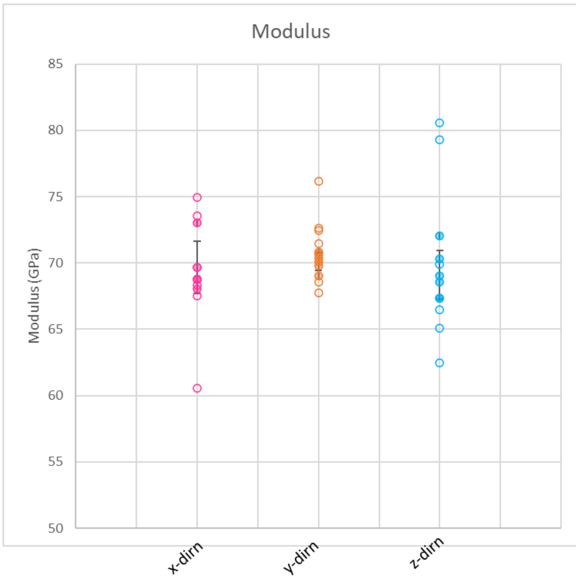

Figure 7: Summary of all measured tensile elastic modulus data.

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