Automated non-linear acoustic NDT of Friction Stir Welds

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Abstract

This paper reports further work on non-linear acoustic NDT of Friction Stir Welds, following on from the European Framework 7 project "StirScan". New developments include real-time automated scanning and enhanced Technology Readiness Level.

Introduction

The European Framework 7 funded project "StirScan" sought to investigate and identify possible Friction Stir Weld (FSW) defects, such as kissing bonds, through the application of non-linear acoustic inspection techniques (StirScan, 2015). Part of the work developed a test apparatus, including a contact based pitch-catch head assembly and a manually driven X-Y scanner enabling flat friction stir welded plates to be scanned. The head comprised a transmitter and a receiver, mounted on Rexolite wedges such that an emitted signal would interface with the welded section of the plate and return to the receiver. Figure 1 shows the arrangement.

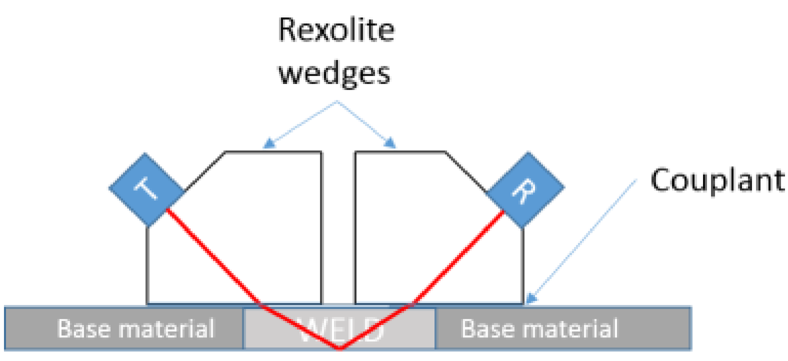

Figure 1 - Pitch-catch head assembly schematic. T is the transmitter, R is the receiver

The manually driven X-Y scanner mounted the head assembly so that scanning could be undertaken.

Software tools developed in LabVIEW and MATLAB were created to control hardware for generation of the driving waveforms, collection of the responses, and subsequent post-processed analysis.

The equipment was designed to perform experiments to identify potential defects in aluminium alloy friction stir welded plates. Of particular interest were kissing bonds, a type of defect that can significantly reduce the strength and fatigue life of a FSW part (Oosterkamp, 2004), (Kadlec, et al., 2014). TWI invented FSW and as part of the StirScan project manufactured both good welds and welds containing kissing bonds.

The work carried out by the StirScan project showed an apparent kissing bond detection in a 7000 series aluminium FSW but did not show it with reference to either the base material or a known good weld (Tabatabeipour, et al., 2015).

Theta Technologies has built upon the initial work carried out in the StirScan collaboration, have improved and automated the hardware to enable repeatable experimentation, and have produced software to enabled real-time, repeatable data visualisation, analysis and post-scan scrutiny. This paper presents the current state of the art.

Non-linear NDT using Pulse Inversion

The non-linear technique used in this process is that of 'Pulse Inversion' whereby two discrete ultrasonic pulses, the second phase-inverted with respect to the first, are injected into a test sample and the responses captured and then summed. If the test sample exhibits no non-linear behaviour, the summed response (the 'residual') will be zero. If the test sample exhibits some non-linearity the residual will contain even harmonics (Ma, et al., 2005). The principle is explained in greater detail elsewhere (Wright, et al., 2013).

Hardware and Software Development

Theta have experience in producing hardware and software for the inspection and analysis of different types of material using both linear and non-linear NDT. The StirScan project collaboration developed a scanning head and software such that it was able to perform promising inspection under careful laboratory conditions. However, both the hardware and software needed further improvement to enable repeatable, robust examination of FSW.

We have raised the Technology Readiness Level (TRL) of the system by improving the hardware, creating new analysis algorithms and implementing them in new software. The hardware required improvement to increase reliability and repeatability of scanning, specifically in the way the head arrangement functioned and in the way the test sample was mounted. Additionally it required a level of automation such that continuous operator intervention was no longer necessary. The improvements to the software involved integration of a number of pieces of code, the inclusion of a real-time update system to enable the operator to assess scanning progress and the development of a new post-processing suite.

Scanning Head Improvement

The original scanning head developed was suitable for mounting on the test rig such that it could be driven in two orthogonal axes, X and Y to enable a 2D scan of a plate containing a weld. The mounting method needed improvement as it was not suitable to provide consistent force against the sample; therefore it was easy to experience a considerable change in contact conditions between the sample and the head, thus significantly changing the scan result. We have designed and constructed an adjustable, spring mounted slide system that holds the contact face of the head firmly in the X-Y plane but which allows it to be sprung against the sample being inspected.

A pair of slides with rear-mounted springs allows force to be applied to the rear of the head such that the head is pushed against the sample. This helps to maintain a consistent level of contact between the head and the sample.

Sample Support Platform

Originally, the X-Y scanner was developed with wheels to make it easy to move over different samples, but any sample being analysed was only supported by the substrate below, often a table or work bench. There was an assumption made that the support was planar, level and acoustically insignificant, but often this is not the case and so the equipment was amended to include a sample support platform and a polycarbonate sheet. Maintaining good contact between the head and the sample whilst scanning relied on the XY plane in which the scanning head moved being parallel with the plane of the sample; therefore creating a controlled mounting surface was vital. The support platform was aligned with the planar motion of the X-Y scanner such that a constant distance was maintained between the scanning head and the support platform.

Both these modifications were essential to allow repeatability and reliability in measurement.

Automation

Scanning had previously been undertaken by the operator winding a handle slowly to cause the head to traverse the sample in a particular axis. Encoders mounted on each axis counted how far the head had moved and triggered the generation and collection of signals. The winding of the handle was both laborious and increased the possibility of error because the operator could wind at difference speeds, thus changing an experimental variable, and could inadvertently introduce some backlash into the system by stopping and restarting. We have automated the control and actuation of the axes by adding a geared electric motor to the winding system and integrating the control of the motor to the testing software.

Software Modifications

The software used in the StirScan apparatus was a combination of LabVIEW code, MATLAB code and some proprietary code developed by Theta. During the project different algorithms were developed to help the inspection of samples, but in all cases these algorithms were applied as a post-processing operation.

Theta have subsequently developed a real-time data processing and analysis tool. This software package implements a number of new algorithms, gives real-time visual feedback and removes the requirement for MATLAB to perform the post-scan analysis. The output of the algorithms is a special form of 2D spectrogram showing the level of residual at different frequencies vs the distance along the scan. We refer to these maps as *Thetagrams*. The Thetagram is built up in real-time as scanning is taking place giving the user invaluable feedback and insight into their scan. It has a dynamic colour scale which varies from blue, through greens, yellows, oranges and up to red, where blue is the lowest response and red is the highest response. Parameters can be configured for different materials to allow for different features to be displayed, i.e. a good weld or a bad weld. When used as a post-processor, any scan displayed can be examined in further detail by plotting it against a number of other spectra from the scan on a line chart. The 2D colour visualisation and the line chart inspections allow for rapid sweep analysis and close inspection if required. A number of scans may also be opened and compared against one another to create a composite Thetagram, making it easy for the operator to identify differences between individual scans. The figures shown in this paper were created by the new software.

Experimentation and Results

The hardware and software developments were assessed using samples prepared by and employed during the StirScan project. Previous work has focused on the examination of 7000 series aluminium alloy samples; this work investigates 2000 series aluminium samples. A known good weld sample and a sample designed to be of variable FSW quality were examined in this work. They are hereafter referred to as the “control sample” and the “suspect sample” respectively. In both cases, the samples are fabricated by friction stir welding two plates together. The plate thickness is 6.35mm, the width of each sample is approximately 300mm.

Validation of Experimental Technique

It can be seen from Figure 2 that the control sample is much shorter along the axis of the weld than the suspect sample, and therefore a series of experiments were undertaken to confirm that the length of the material would not affect the results of any subsequent experiment. The length of the control sample was so short that there was insufficient room for it to be scanned in the direction aligned with the weld. Instead the sample was scanned from the base material, across the weld, and onto the base material again as shown in Figure 2, line 1. A similar scan was performed on the on the suspect sample, as shown in Figure 2, line 2.

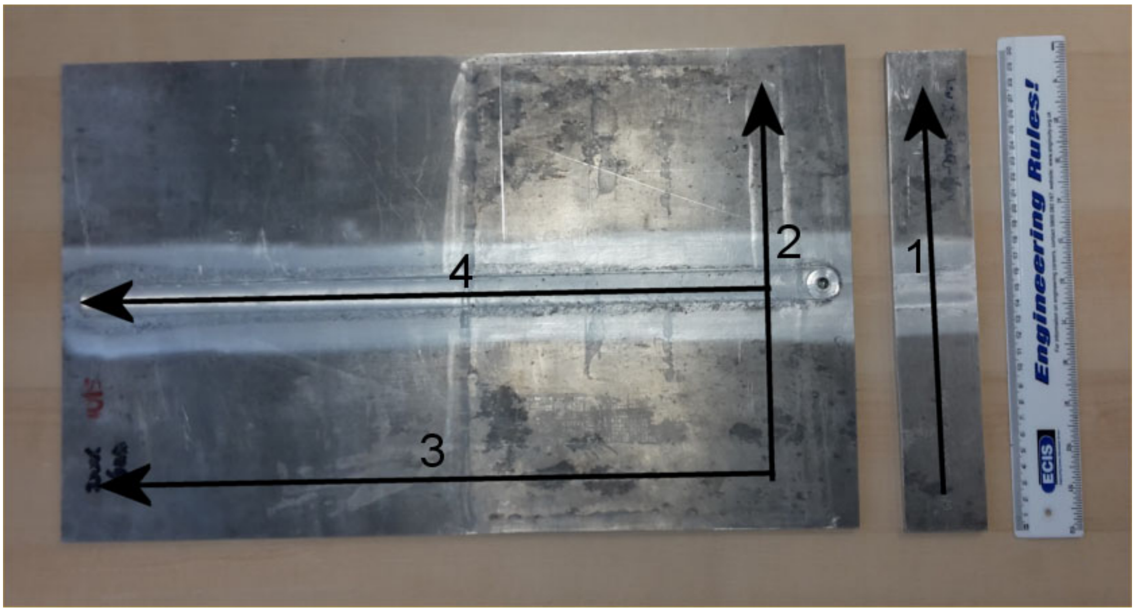

Figure 2 - Sample materials and scan positions referred to in this paper

To allow comparison of just the base materials, the results obtained prior to the head passing the weld were examined. Figure 3 shows the Thetagram of the combined results. The first 28 results shown on the axis marked "Scan distance (mm)" show the control sample base material spectra for each mm of the scan. The next 28 results show the spectra for the base material of the suspect sample. It can be seen that all colours shown are blues and greens – the software is configured to show these colours as "low response", indicating base material.

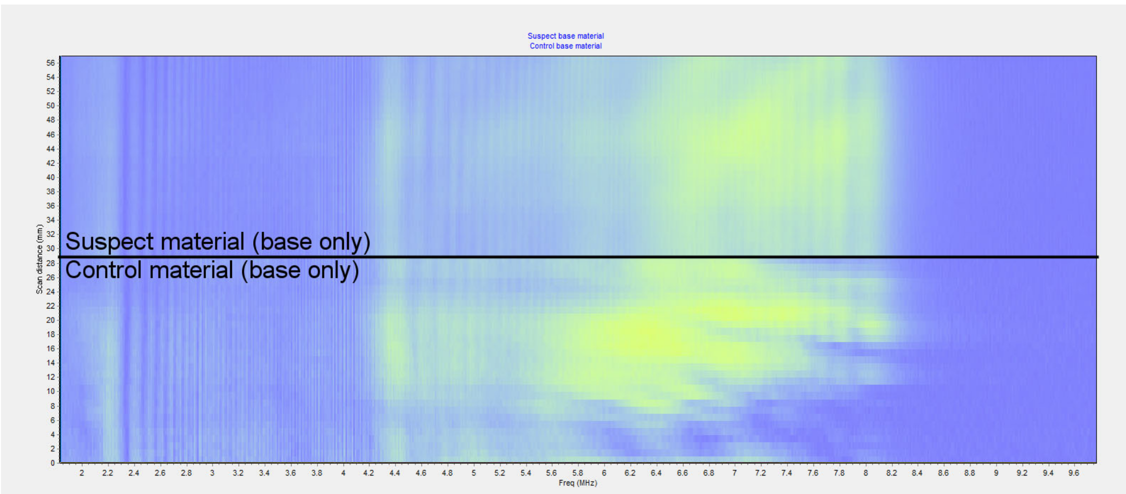

Figure 3 - Examination of base material characteristics of two different sized samples

Figure 4 shows two of the results from Figure 3 plotted against each other to show how similar the two samples are. The grey line is 14mm along the scan from the control base material, the purple line is 14mm along the scan from the suspect base material. It can be seen that in the difference between the two lines in the 5MHz to 10MHz range is usually around 3dB or less. This suggests that the two scans are very similar.

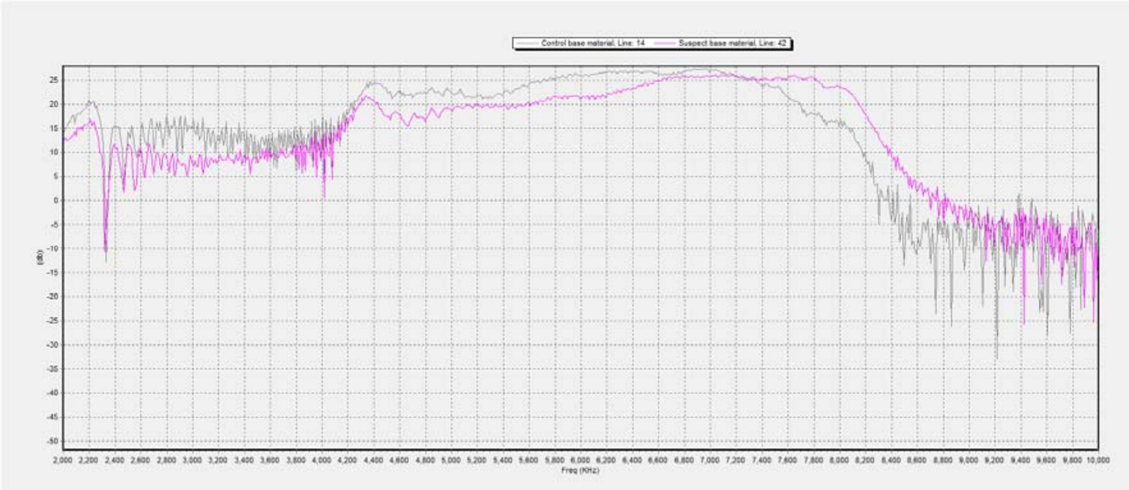

Figure 4 - Inspection of spectra taken from centre of base material scans on control and suspect samples

This experiment showed that scanning the base material of two different sized samples produced similar results, but the scan direction used here was the same in each case. To confirm that the scan direction itself did not change the results, and so that the control sample could be used to compare with results gained from scanning orthogonally to the control sample scan, the suspect sample was scanned again along its long axis, the line of scan being shown as line 3 in Figure 2.

Figure 5 shows the result of adding the scan of 300mm of the suspect sample base material. It can be seen that the colours in the 5MHz to 10MHz region are very similar, particularly for the first part of the scan where the suspect material was scanned previously in the other direction, thus accounting for the similarity between the "Suspect material (base only)" result and the "Suspect material (base, long axis)" result.

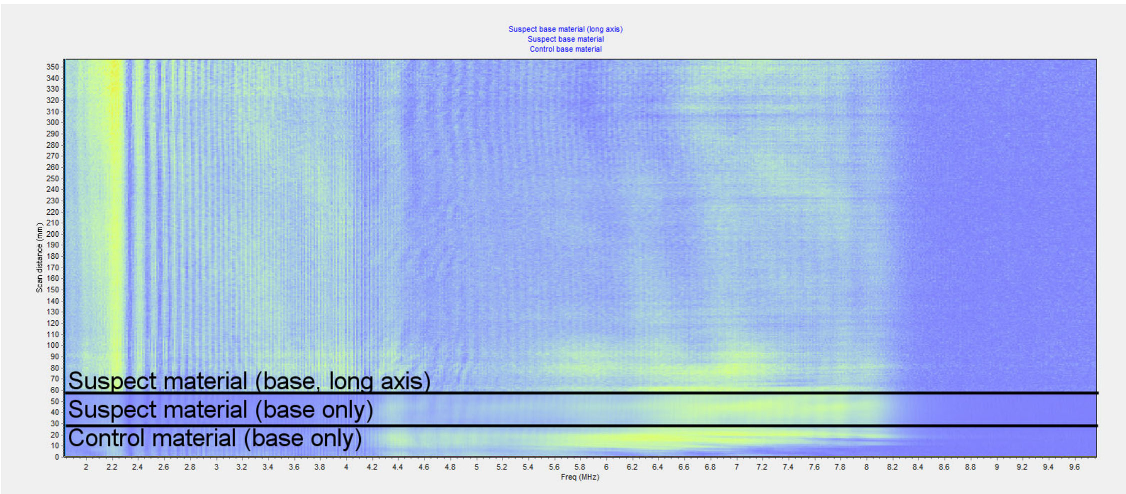

Figure 5 - Comparison of base scans

Closer examination of the individual spectra from the Thetagram shows corresponding similarities between the three scans.

Repeatability

The repeatability of scanning was confirmed through a series of tests where scans were performed in an identical manner. The 300mm suspect sample base material was used to test the repeatability. It was scanned, removed, repositioned, and rescanned having reconfigured the software. The scanning was again performed along line 3 in Figure 2. Figure 6 shows two of the scans. It can be seen that the patterns are similar.

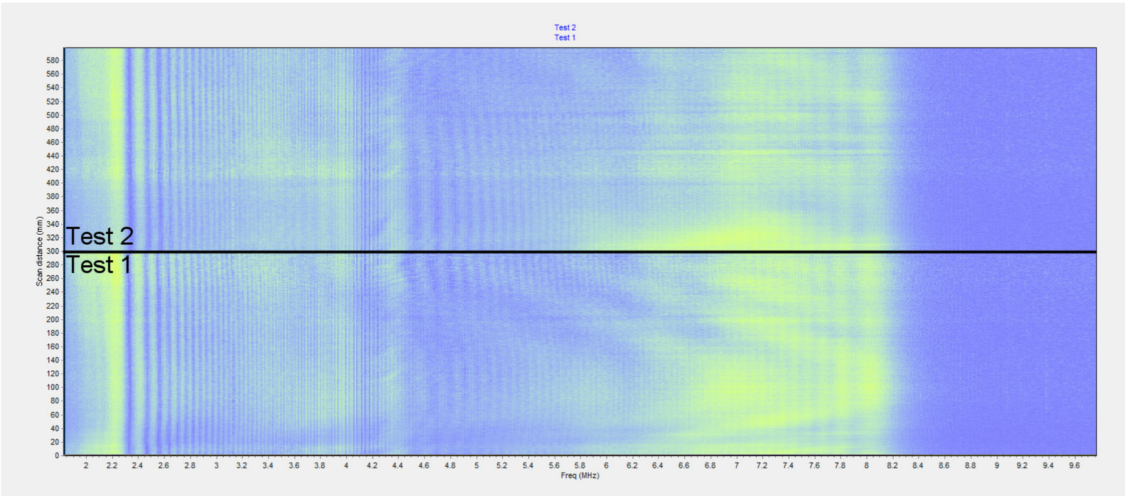

Figure 6 - Two scans of base material

A closer inspection of the midpoint of both sets of scans shows that the spectra produced are very similar indeed, with a 1-2dB difference across the range from 5MHz to 8MHz as can be seen in Figure 7.

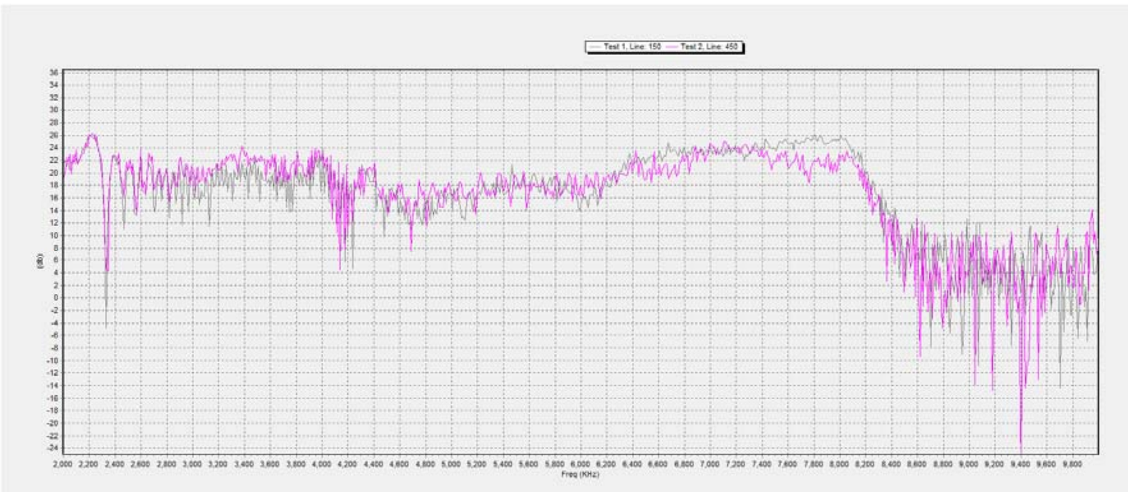

Figure 7 - Midpoints of 300mm long scans show spectra which are very similar

This confirmed that scanning was highly repeatable and that differences found when scanning welds would be attributable to the weld and not the methods used for scanning, data acquisition or processing.

Sample Inspection and Comparison

An experiment was devised to confirm the location of the most non-linear part of the weld to enable further investigation. Both the control sample and the suspect sample were scanned from base to base having crossed the weld, as in the first experiment described here. The two sets of results were then examined as illustrated in Figure 8. It can be seen that some degree of non-linear response is present in both scans, however, there is a zone near the centre of the suspect weld which exhibits considerably more response than the control weld.

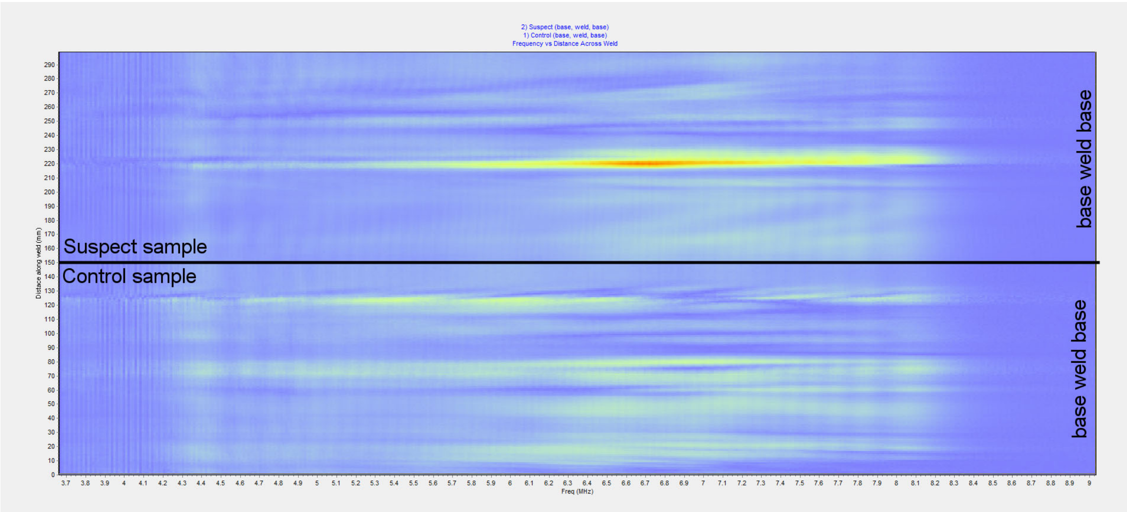

Figure 8 - Scan across the weld of the control and suspect samples

The peak of the “hot-spot” occurs at 220mm on the graph. This is approximately 70mm from the start of the scan across the suspect material. Comparison of the spectra at 70mm from the start of both scans shows that non-linearity in the suspect weld is up to 11dB higher than the control weld in the 5MHz to 8MHz range. Comparison of the suspect weld with respect to the base material shows that it is up to 19dB higher. Both these values are significantly greater than the 2-3dB variation found when inspecting the base material of both samples.

Having confirmed that detection of differences between base material, good weld and suspect weld was possible, inspection of the suspect weld was carried out along a 300mm section as indicated by line 4 in Figure 2. A combined Thetagram is shown in Figure 9 which illustrates the differences between the suspect base material, scanned along the 300mm length, the suspect weld, again scanned for 300mm, and finally the control material scanned from base, across the weld and back onto the base material. The level of non-linearity in the first 300mm of the Thetagram is low. The next 300mm shows a rising level of non-linearity as the suspect weld is scanned suggesting an increased probability of defects towards the end of the scan. Finally, for comparison, the control sample scan shows the level of non-linearity present in a good weld. This is much lower than in the suspect weld.

The Thetagram will be used to guide the production of samples suitable for physical inspection and analysis.

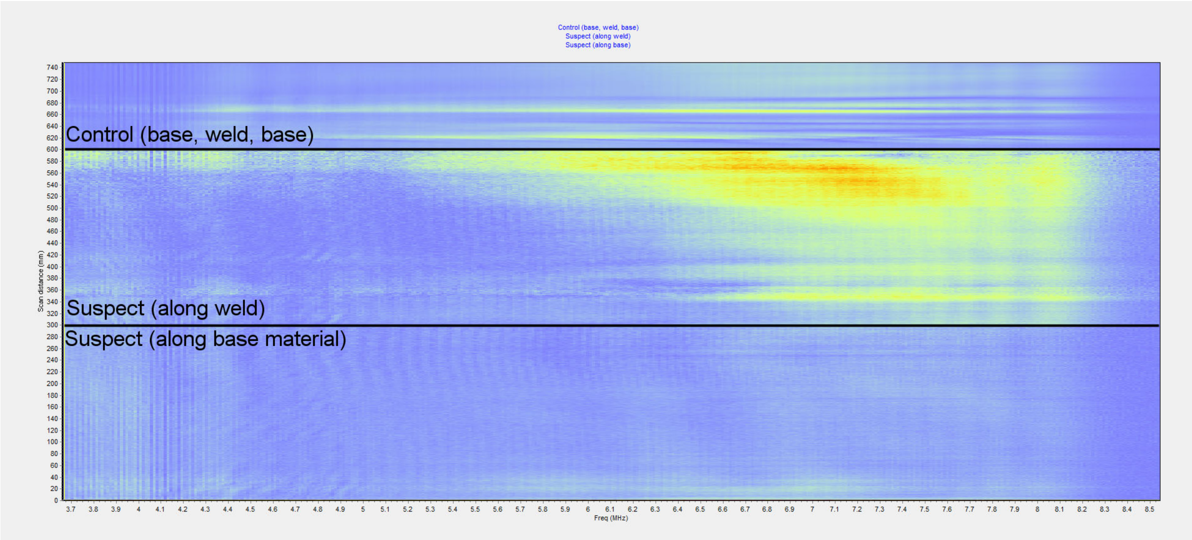

Figure 9 - Combined view of suspect base material, suspect weld and control scanned across weld

Conclusions and Further Work

This paper has described the improvements made to the hardware and software initially developed by the StirScan partnership. Analysis has taken place of two samples of friction stir welded 2000 series aluminium alloys. The analysis has shown that the suspect weld exhibits varying degrees of non-linear response. This suggests that the weld is not consistent. During the first part of the scan the weld seems low in defects as it responds similarly to the control weld and base materials. However, towards the end of the weld, the scan shows that the level of non-linearity increases which suggests the presence of defects.

These scan results will now be used to guide destructive analysis of the suspect weld such that the level and nature of defects can be assessed.

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