ADVANCED ULTRASOUND WAVEFORM ANALYSIS PACKAGE FOR MANUFACTURING AND IN-SERVICE USE

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Abstract: Users of ultrasonic NDT are fundamentally limited by the scarcity of low-cost advanced ultrasonic methods. But the resultant lack of procedures requiring such methods is often stated as the reason that they are not readily available in the NDT marketplace! Consequently many users are unaware of the potential benefits of advanced ultrasonic analysis. By using standard file formats with the new rapid full-waveform capture scanning capabilities, these advanced processing methods will become cost-effective. And, through versatile Windows-based software packages, analysis techniques can be customised to provide the exact material or structural parameters required, without needing to understand the underlying Physics. The NDT user could benefit from scans of, for example, hidden surface roughness due to corrosion, or of fibre-volume fraction or percentage porosity in composites. Such parameters can be calculated by the software using the full spectral data available in a stored ultrasonic waveform. This paper gives examples of rapid full-waveform acquisition methods, currently-available advanced analysis methods, as well as the potential for future advances.

Introduction: Low-cost high-volume computer memory and data storage has made full-waveform capture and storage of ultrasonic data both inexpensive and readily available. However, the emphasis in the NDT market is still firmly focused on conventional flaw-detector capabilities. This paper explores the potential for introducing advanced ultrasonic analysis techniques once full-waveform data has been stored. Both manufacturing and in-service environments will benefit from the storage of the full-waveform data-set, although this paper uses an in-service corrosion application as an example.

The poor ability of ultrasound to penetrate into the second layer of multi-layer structures will always limit its usefulness for detecting and characterising defects such as cracks and corrosion. However, for corrosion in the first layer, ultrasonic methods offer far greater resolution and information about the surfaces, and any corrosion, than eddy-current methods. In places where coupling into the second layer can be expected to be good, then it is possible to develop reliable ultrasound techniques for crack detection.

Multiple time-gates on the waveform can be used to determine thicknesses of layers and bond state, whilst ratios of reflection amplitudes can eliminate some of the effects of surface undulations around fasteners. Ultrasonic spectroscopy applied to each time-gate offers the potential for isolating and mapping various different material properties, ultimately producing maps of relevant parameters such as fibre-volume fraction or surface roughness.

The ANDSCAN® Waveform software contains a multitude of waveform analysis functions. These are packaged in a way that allows technique developers to develop and store a technique using just the capabilities required for the job. The aim is to enhance the limited toolset available on conventional ultrasound flaw detectors by building the know-how and methodologies developed at QinetiQ into this waveform analysis package.

For example, the most complex analysis used for this paper involves assessing the frequency-dependence of the reflection coefficient of a hidden surface to determine root-mean-square (rms) roughness [1,2]. This technique has recently been optimised to include adaptive gating and other methods to improve the reliability of the measurements [3] and it is now thought to be at a stage where it can be applied routinely.

Finally, a demonstration is illustrated of the synergy obtained by using data fusion methods to combine three different ultrasonic analysis methods, which are good examples of the problem of signal classification.

Ultrasonic Full-Waveform Capture For Corrosion: Whilst frequencies up to 80 MHz have been used by QinetiQ Ltd to accurately measure the corrosion profiles in specimens such as these, scanning with such high frequencies involves many practical problems on real aircraft structures. For this reason, a lower frequency of 22 MHz was used with a focused transducer to avoid some of the severe normalisation problems experienced at these frequencies.

In order to illustrate some of the possible benefits of advanced ultrasonic analysis, scans of a corrosion specimen from a KC135 aircraft are shown below. The structure of the specimen was quite complex in places with up to five dry-assembled layers of different thicknesses, some being spot-welded together prior to assembly (see Figure1).

Amplitude ratio (Figure 2), roughness (Figure 3) and thickness (Figure 4) scans were performed on the complex region of multi-layered structure shown in Figure 1.

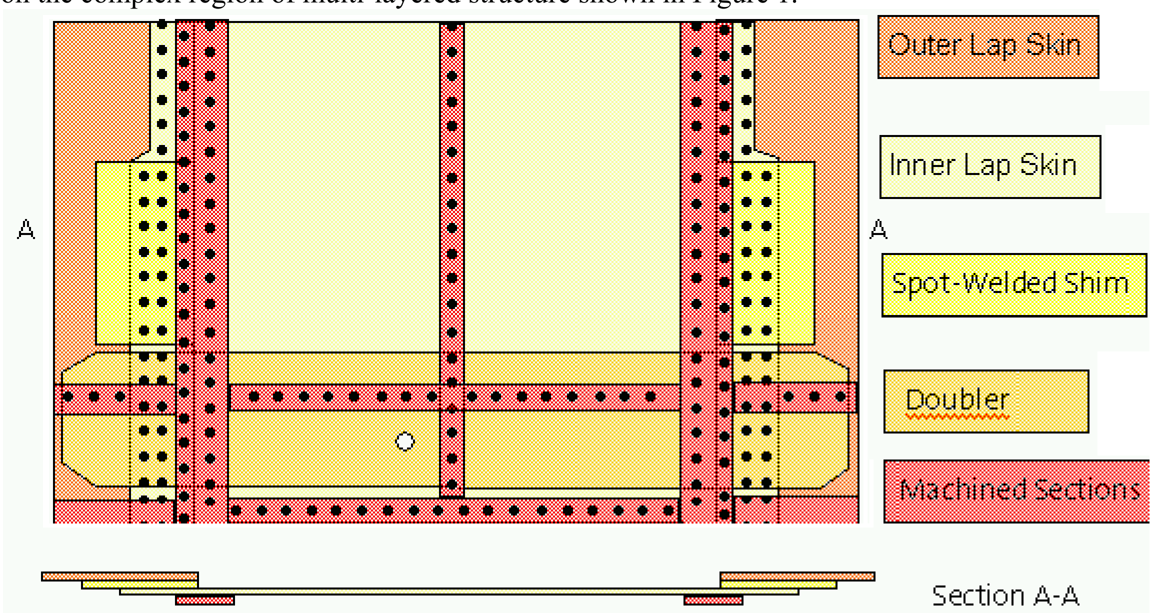

Figure 1. Schematic diagrams of the structure scanned during this corrosion characterisation programme as if viewed from inside the fuselage. The dashed blue box shows the region scanned in the following ultrasound images.

There are some very interesting features of these scans. The black regions in the amplitude-ratio scan (Figure 2) are either single layer or double layer where there is no corrosion. The lighter region near the top-right is where the paint layer has reduced the reflection amplitude, probably by being a thinner layer of paint there and causing a reduced reflection coefficient due to interference between the reflections from the two paint interfaces. Reflection coefficients from thin layers are highly dependent on layer thickness, and not just on impedance mis-matches.

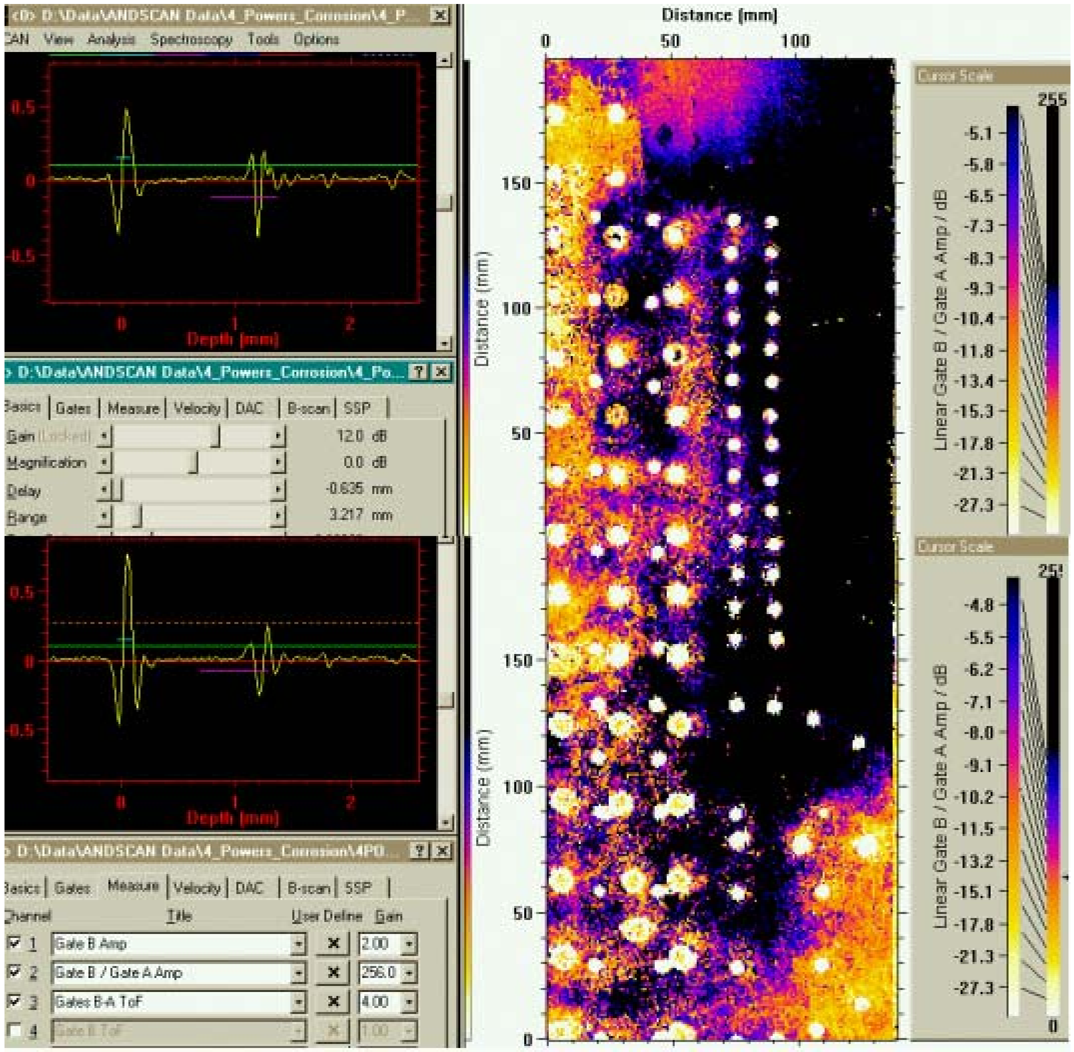

Figure 2. 22 MHz amplitude-ratio C-scan of the ratio of the reflections from the back surface to the front surface of the skin (first layer). The smaller white circles are spot welds, the larger ones are fasteners. Other lighter areas are reduced signals, thought to be due to either moisture ingress, scattering due to roughness, or trapped corrosion product reducing the reflection coefficient. The mottled effect could be caused by poor sealant bonding but it is unlikely that the doubler is sealed to the skin as well as spot-welded – most of these KC135 joints are thought to be dry-assembled. Note the region at the bottom-right where the scattering from corrosion appears to be a maximum.

The region to the bottom-right of each figure does not appear to have suffered much thinning due to corrosion (0.06 mm) (see Figure 4), but is one of the roughest areas (25 μm - see Figure 3). This shows the potential for roughness measurements to detect corrosion at its early stages. The roughness scan does not do well in the regions of maximum metal loss on the left near the top, but the roughness appears to be greater than 31 μm in places.

The most quantitative data is contained in the thickness scans of the outer lap skin (Figure 4) but it is interesting that some of the areas with little metal loss could easily be missed on these scans, whilst showing up very well on the roughness scan.

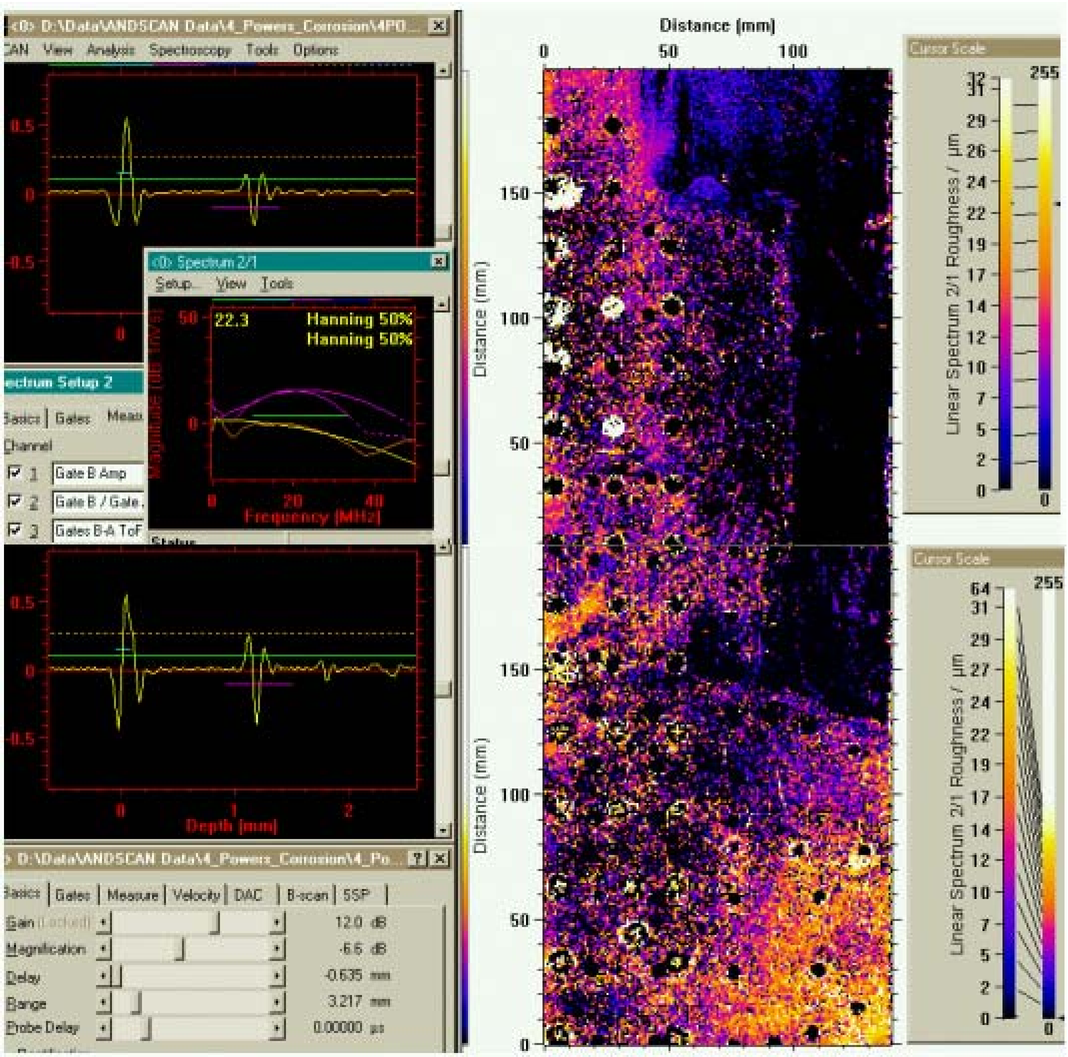

Figure3. Roughness scan for the back of the skin (first layer). Note that one of the areas of maximum roughness is in the bottom-right region where there is a doubler spot-welded on. The maximum metal loss is in a white region on the left near the top, next to one or two fasteners.

The spectroscopic measurement of roughness was originally developed at QinetiQ Ltd (then DERA) for two reasons:

- to distinguish between machined metal loss and corrosion,
- to detect early signs of corrosion, before significant metal loss had occurred and before corrosion products had caused visible ‘pillowing’ or ‘quilting’.

Hence the roughness technique appears to be achieving these original objectives.

In order to provide quantitative information about amounts of metal loss and to give profiles of the distribution of corrosion, line scans across the thickness-mode scan from Figure 4 can be plotted.

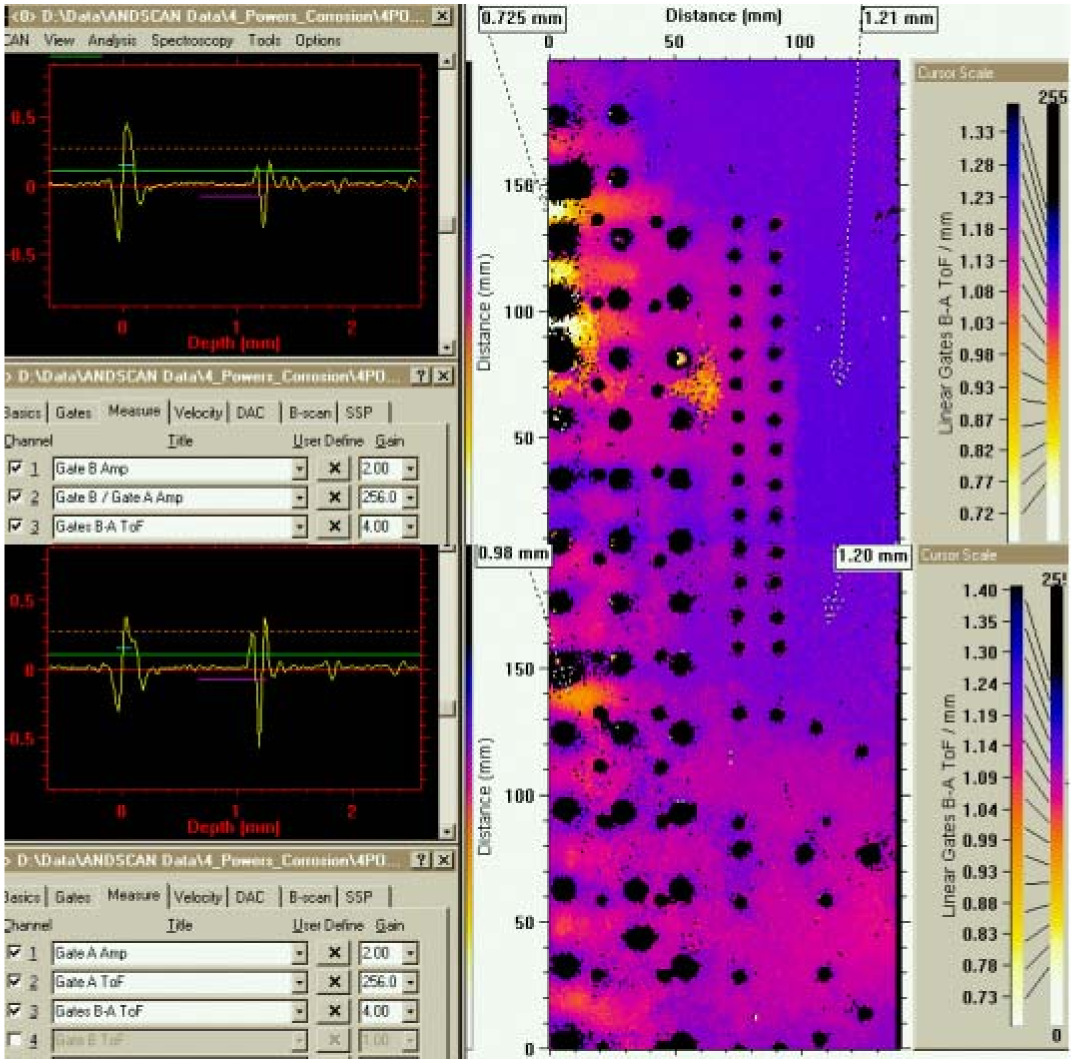

Figure 4. 22 MHz ultrasonic thickness scan for the skin (first layer). Note that one of the areas of maximum roughness, in the bottom-right region, does not actually have much metal loss due to corrosion. The maximum metal loss areas are white regions on the left near the top, between fasteners.

As well as the need for quantitative information on parameters such as metal loss, it is very important to be able to classify indications in terms of their cause. A change in a single parameter may have several possible causes. However, there is potential with full-waveform data to 'fuse' scans of several parameters in order to aid the decision-making process by automatically classifying each point on the scan in terms of its most likely condition and the cause of any defect indication. This 'data fusion' process is illustrated in the next sections by application to the above scans.

Principle Of Data Fusion For Corrosion NDE: It has long been accepted that the NDE of corrosion will require a large 'tool-kit' of NDE techniques unambiguously to detect corrosion and then to go on and quantitatively characterise it. However, one of the issues is how to assimilate all this data in order to provide the user with a coherent picture of the cause of each indication and severity of any damage.

Data fusion is the synergistic combination of information from more than one NDE modality, or analysis method in order to enhance the information content and make it more accessible to the user.

Demonstration Of Data Fusion: The ultrasound technique shown above produced a large amount of data in several different scans. No single scan could simultaneously provide unambiguous information on the type of defect indication and also quantitative assessment of defect severity.

A data fusion method was developed using thresholds on each type of scan to categorise the signals from each point and then use a look-up table to determine what the likely state of the structure was at that point. This information was then colour-coded on a false-colour image.

As a demonstration, three different types of ultrasonic data were used: thickness, roughness of a hidden interface, and the ratio of back-surface to front-surface amplitudes. These are good examples of the problem. For instance, low amplitude signals from the back surface can be caused by increased scattering from a rough surface, trapped corrosion product, or a better transmission into the next layer such as through sealant, adhesive or water ingress in the joint. Thickness changes can be caused by blending repairs to past corrosion sites, machining at manufacture, or by actual corrosion. Roughness, on the other hand, should only increase when corrosion occurs, but some corrosion can be smooth and masquerade as machined metal loss!

Table 1 gives a guide to the methodology used for the classification of defects using this data fusion method. It is subjective in terms of the thresholds for 'deep', 'shallow', 'rough' etc. and should *not* be used as a means of *quantifying* corrosion, but merely as a method of classification of ultrasonic indications. Once a region has been identified as probably being corroded, then the quantitative information can be taken from the depth profile scan.

■ Deep Corrosion / Pitting	Either 'rough & deep', or 'low-amplitude & deep'
■ Light Corrosion	From 'rough & shallow' to 'smooth & very deep'
■ Corrosion Product / Good Bond	Lower amplitude, no thinning and smooth
■ Smooth Thinning / Blending	Some thinning but smooth
■ Disbond / Normal	Higher amplitude, no thinning and smooth
■ Welded / Hole	No signal, no thinning, no roughness

Table 1 . Guide to methodology for the data fusion classification of signals.

Finally, a data-fusion process has been applied to the ultrasonic thickness, roughness and amplitude-ratio scans, and has produced the false-colour images in Figure 5. There are areas of light-green indicating 'smooth thinning / blending' where the transient eddy-current scans have shown metal loss. This indicates that, although there is some thinning here, the roughness is insufficient to verify that it is rough corrosion. As some corrosion can result in a smooth surface, particularly the stripping of cladding layers, then this does not rule out the corrosion possibility in the light-green areas.

The regions of thinning in the bottom-right corner of Figure 5 have been classified as deep corrosion and, when the specimen is destructively examined, it will be interesting to see whether these are actually serious, despite only registering as less than 0.1 mm of metal loss.

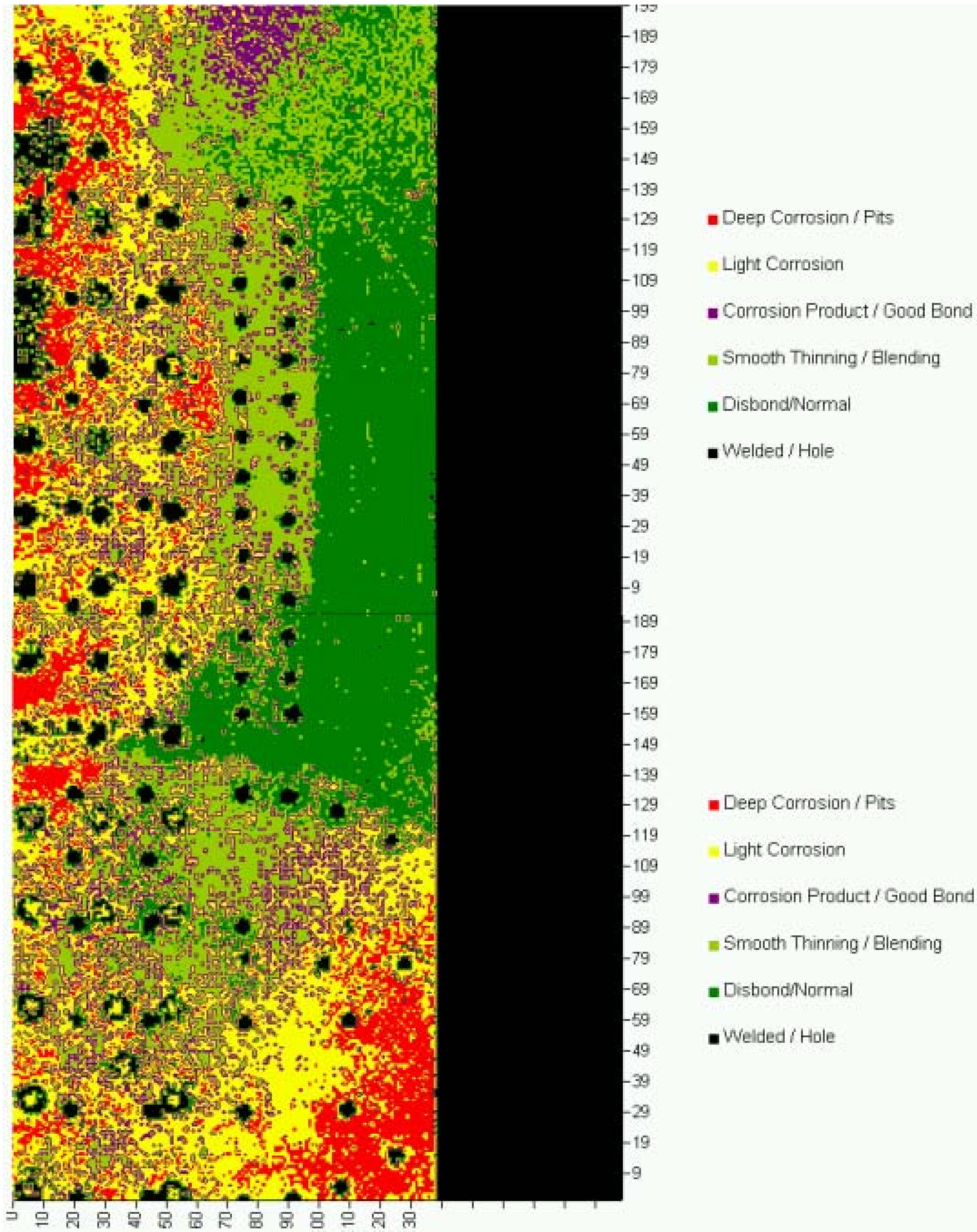

Figure 5. False-colour image showing classification of indications by data fusion of thickness, roughness and amplitude (back-wall divided by front-wall echo).

Conclusions: Through the use of a corrosion specimen, some of the potential advantages of full-waveform capture and advanced analysis methods have been demonstrated for an in-service environment.

These different images have been illustrated as examples of how the technique can be optimised to show the best information for the purpose. Effectively, the data has been decomposed into the parameters that best show the condition of the structure – amplitude ratio, thickness, and hidden surface roughness. These particular parameters involve combining data from multiple time gates whilst the roughness mode also requires spectral analysis to determine the frequency-dependence of the reflected signals in the gates.

Even more advanced techniques are possible with this software that decompose the spectral response into components from various different material properties. These offer potential for 'porosity' and 'fibre-volume fraction' scans of composite materials.

As well as decomposition methods, it is possible to use data fusion methods to recombine data into a form that helps the user to classify indications. Again, the example of a corrosion specimen has been used to demonstrate the possibilities for rapid characterisation of full-waveform scan indications.

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