ABSTRACT

The inspection of welded austenitic stainless steel components commonly found in the nuclear industry can be challenging. Austenitic welds contain an anisotropic, inhomogeneous grain structure which causes attenuation, scattering and beam bending. These effects reduce the defect detection and sizing capability of any ultrasonic inspection technique. The inspection of components where the weld cap has not been removed is even more difficult due to the irregularity of the surface geometry. A membrane coupled conformable phased array device containing a linear array transducer has previously been produced. This device couples the ultrasonic energy into the component under test via a water path encapsulated by a low loss membrane. A twin crystal membrane coupled device has now been produced containing two linear phased arrays positioned adjacent to one another within the same housing. The delay laws for each array can be electronically controlled to steer and focus the ultrasonic energy. The arrays are angled relative to one another so that the transducer provides a pseudo-focusing effect at a depth corresponding to the beam crossing point. This type of design is used to improve the signal to noise ratio of the defect response and reduce noise in comparison to simple linear phased array transducer inspection. An enhanced inspection system has also been developed that allows the rapid acquisition and processing of scanned full matrix capture (FMC) inspection data using both the linear and twin crystal membrane coupled devices. Experimental results obtained from the through weld inspection of an austenitic stainless steel component with an undressed weld cap in place will be presented. These results demonstrate that small lack of side wall fusion defects can be reliably detected in large complex structures.

INTRODUCTION

Austenitic stainless steel is commonly used in the manufacture of pipe-work within the nuclear industry. Stainless steel is used because it has high strength and toughness; it is resistant to brittle fracture and demonstrates good resistance to corrosion and oxidation. Welding must then be carried out to join sections of pipe-work together to produce the final component. Although care is exercised during the welding process some small defects can be introduced into the structure. In operation the pipe-work will experience a range of loading conditioning, which may lead to the propagation and growth of any flaws that were introduced during manufacture.

Typically radiographic inspection techniques are used to detect defects during manufacture. In radiographic inspection, X-ray or gamma ray radiation passes through a component and differences in the amount of radiation absorbed/scattered by the component are monitored. Radiographic inspection is best suited to the detection of volumetric defects that cause an appreciable change in the level of attenuation of the radiation but are less appropriate for the detection of planar defects [1]. Volumetric flaws are less of a concern than planar defects in terms of the structural integrity of the component. Radiographic inspection is also expensive to carry out. In order to reduce the exposure of personnel to ionising radiation large exclusion zones are required around the site of the inspection. This prevents parallel manufacturing processes from being adopted, increasing cost and production timescales.

A non-destructive evaluation (NDE) technique is required that is capable of detecting small planar flaws through the entire thickness of the pipe-work. Ultrasonic inspection is well suited to the detection of this type of defect. However, the performance of this approach is limited due to the grain structure of the austenitic welds and the presence of surface irregularities due to the welding process.
Austenitic welds are anisotropic and inhomogeneous; large columnar grains are formed during the welding process which leads to scattering and beam steering of the ultrasound [2]. The scattering effects occur from the grain boundaries, whereas the beamsteering is due to locally varying material properties across the different grains within the weld, which in turn leads to changes in the acoustic velocity. Conventional ultrasonic inspection of this type of component is performed using rigid wedge transducers that are scanned in contact with the component under test. Inspection coverage is restricted due to the complex surface profile associated with the weld cap geometry which increases the level of difficulty associated with this type of inspection. The ultrasonic inspection of austenitic stainless steel pipe-work with an undressed weld-cap is an area of specific interest to Rolls-Royce Nuclear and an ultrasonic inspection capability to address this type of inspection is under development. A photograph of the cross-section of an example welded test-pieces produced to support this development activity is shown in Figure 1. This photograph indicates the weld region and the irregularity of the surface finish. Rolls-Royce Nuclear has been collaborating with researchers from a range of UK academic institutions to gain an improved understanding of the effects of the austenitic weld material and to develop a better the ultrasonic inspection of this type of component [3, 4].

**MEMBRANE COUPLED DEVICE DEVELOPMENT**

Conventional ultrasonic inspection of the target application component is performed using a large number of single element rigid wedge transducers that are scanned in contact with the component under test. The time associated with completing this inspection could be reduced by using a suitable rigid wedge phased array transducer. However, inspection coverage with all conventional rigid wedge transducers is restricted due to the complex surface profile associated with the weld region. Rolls-Royce Nuclear, in collaboration with Imperial College, London has developed a membrane coupled phased inspection capability. The standard membrane coupled device uses a conventional linear phased array, which is coupled to the surface of the component under test via a water path encapsulated by a low loss rubber membrane. Photographs of the 2nd and 3rd generation membrane coupled device are shown in Figure 2. The membrane coupled on a range of non-welded and welded test-pieces [5]. In comparison to conventional ultrasonic inspection techniques the membrane coupled device provides improved coverage and inspection speed, increased flexibility and better defect detection. However, performance is limited when the device is used to complete the through techniques and for near surface defect detection. These limitations are actually due to the fact that the membrane coupled device currently only uses a single linear phased array and are not specific to the membrane device design.
The first limitation in the membrane coupled device performance is due to the presence of an internal noise signal within the membrane device housing. The second area for potential improvement is to increase the defect signal to noise ratio (S/N) particularly when completing through austenitic weld inspection. An alternative approach to the linear membrane device design that is to use a twin crystal transmit receive longitudinal (TRL) transducer. In this type of device separate transmitter and receiver arrays are positioned side by side in a single housing. In order to reduce cross-talk between the arrays they are acoustically isolated from one another by an attenuative barrier material. Each individual array is tilted at the “roof angle” of the transducer, this controls where the energy from the transmit and receive elements intersect. This beam crossing point provides a pseudo-focusing effect and the maximum sensitivity can be achieved at this point. This improves the potential signal to noise ratio performance of the device and hence the inspection performance in noisy materials such as an austenitic weld. The use of a twin crystal transducer also eliminates the dead zone associated with linear phased array transducers thus allowing improved near surface inspection.

A twin crystal membrane device has been developed. The twin crystal device is designed to provide an improved direct specular inspection capability through the entire thickness of the target application component. The maximum sensitivity of the twin crystal device is achieved at the beam crossing point, which is controlled by the roof angle used within the transducer. The transducer performance decreases at depths less than and greater than the beam crossing point. The target application component has a wall thickness of greater than 50mm. It is therefore not possible to design a single, fixed roof angle, twin crystal array that provides satisfactory inspection performance. One approach to overcome this limitation is to use two, 1.5D arrays [6]. The element delay laws are then controlled to modify the beam crossing point and to change the refraction angle of the ultrasonic wave. However, the channel count of the phased array controller to be used is limited. A compromise must then be reached between increasing the element size to provide a better signal to noise ratio and a longer focal length and restricting the element size to maintain the required steering capability and to limit the production of secondary maxima. The ability to focus at long path lengths is essential to maximise the performance benefits of the membrane coupled device [5]. This cannot be achieved using a 1.5D twin crystal device and hence an alternative design has been adopted.

The twin crystal membrane coupled device used two linear phased array devices. The element size and pitch is identical to that used in the 3rd generation linear device. This has successfully been demonstrated to provide excellent beam steering and focusing and does not lead to excessive subsidiary maxima. This approach also provides a large footprint, which reduces the amount of mechanical scanning required and improved inspection speed. It also offers a long focal length, appropriate for thick walled structures. A mechanically variable roof angle design has been developed to provide control over the beam crossing depth. A photograph of the twin crystal membrane device, showing the variable roof angle is provided in Figure 3. The twin crystal membrane coupled device has a non-parallel top surface; the roof angle can be altered with the angle adjustment bolt, labelled in Figure 3.
Once a suitable roof angle has been selected the array is secured in place using the roof angle fixing bolt. This process is repeated for each of the two arrays independently, care must be taken to ensure that the final array configuration is symmetrical. The tilt angle of the device is fixed but the roof angle can be varied to control the actual beam angle produced. The design ensures that the emission point of the transmit array relative to the receiving array is fixed and that the roof angle can be varied to provide focusing at different depths within the component. When using the twin crystal membrane device over a component with complex surface geometry, such as a weld cap, the surface profile of the component must be measured to provide optimum inspection performance [7]. Ideally the surface profile is measured using the actual device being used in the inspection, this ensures that errors can be minimised in terms of locating the transducer. A schematic diagram of the twin crystal device with a 4º roof angle, which is appropriate for the detection of mid-wall defects, is provided in Figure 4. This diagram indicates that it is possible to complete surface profile measurement with the twin crystal device but only when the roof angle is small. The twin crystal membrane coupled device technology is complementary to the linear membrane coupled device and will be used in conjunction with the linear probe. When using step roof angles with the membrane device the surface profile previously measured using the linear device can be used.

Figure 3 - A photograph of the 4º roof angle configuration of the twin crystal membrane coupled device

Figure 4 - Schematic diagram of surface profile measurement using the twin crystal membrane coupled device
The schematic diagram in figure 4 also indicates that there is a potential crosstalk noise path within the twin crystal membrane coupled device. Ideally the acoustic barrier, which is used to isolate the transmit and receive arrays, would be in contact with the outer surface of the component under test. However, the diagram shows that this is not the case. The acoustic barrier material is relatively rigid and it is not possible to use this material as a barrier and maintain conformability. The experimental results provided below indicate that this does lead to the presence of some background noise. However, through suitable control of the set-up parameters used this noise can be kept to an acceptable level. It may also be possible to alter the acoustic barrier material in future design iterations to reduce the level of this noise still further.

INSPECTION CAPABILITY

Inspections using all of the membrane coupled devices are completed using FMC data acquisition [8]. When operating in FMC mode the full matrix of time domain signals (A-Scans) from each transmitter-receiver pair within the array is captured and stored. All data processing can then be performed offline in post processing. By using this approach it is only necessary to capture a single set of data, thus reducing inspection time [5]. This allows different algorithms to then be applied to the data set in order to simulate each different test mode. Algorithms that can only be applied in post-processing such as the total focusing method (TFM/ATFM) [8, 9] can be used to improve the detection of small defects. This approach also future proofs the inspection; as more advanced algorithms are developed they can be applied to the same data set. However, FMC data acquisition and processing is not supported by currently available commercial phased array controller systems. Rolls-Royce has therefore developed a bespoke software suite that is capable of acquiring FMC inspection data “on-the-fly”, the data is stored in a binary file format and can then be subsequently processed using a wide variety of inspection algorithms. The software suite is designed to provide a high degree of flexibility and can be used with direct coupled, wedge mounted or immersion phased arrays. It has been written using a modular design, so that new processing functionality can be added as more advanced algorithms are developed.

EXPERIMENTAL RESULTS

The performance of the twin crystal membrane coupled device has been assessed by completing a through weld inspection of the flat plate test-piece shown in Figure 1. The test-piece has a wall thickness of greater than 50mm and contains an austenitic stainless steel weld. The test-piece contains a range of artificial planar defects; the specific flaw of interest in this work has been introduced to simulate a lack of sidewall fusion defect. The target defect occurs at 25º to the backwall normal with a through wall extent of less than 3\(\lambda\), it therefore represents a relatively challenging defect to detect in this type of component. A schematic diagram showing the inspection of this defect using the twin crystal membrane coupled device with the roof angle set at 4º is shown in Figure 5. The inspection of this type of defect has also been completed using the 3rd generation linear membrane coupled phased array. A comparison of the results obtained from the two different inspections is provided in Figure 5. In both cases the results have been generated from a single transducer position, with the centre of the array optimally positioned to detect the defect. Suitable delay laws have been generated to produce an unfocused 65º longitudinal wave with an aperture of 17 elements (12.5 mm). In the linear membrane coupled device inspection, shown in figure 6(a), the localised defect S/N is 10dB. However, the internal noise signal occurs at a higher amplitude than the defect signal, the data is therefore shown over a relatively large dynamic range. The twin crystal membrane coupled device result is provided in figure 6(b). In this inspection the localised defect S/N has been slightly improved to 11dB. Although only a small improvement in performance this demonstrates the benefits of pseudo-focusing effect of the membrane coupled device. The internal noise signal that is clearly observed in the linear membrane coupled device results is also eliminated.
A low amplitude cross-talk signal is observed in the twin crystal device result which is due to the cross-talk path labelled in figure 4. This signal does not significantly detract from the inspection performance and is removed from the region of interest. Work is ongoing to implement an improved acoustic barrier design to further reduce the effects of this cross-talk signal. In both of the results provided in figure 6 the defect signal is lower than expected and is slightly mis-located away from the known location of the actual defect. The low signal amplitude is due to attenuation and scattering of the ultrasonic energy as it passes through the austenitic weld. The mis-location of defect signal is due to the beam steering effects of the austenitic weld.

Figure 5. Schematic diagram of the through weld inspection of artificial lack of sidewall fusion defects within the flat plate welded test-piece using the twin crystal membrane coupled device

Figure 6 - Comparison of the 65º longitudinal wave B-Scan images obtained using a 17 elements aperture with unfocused delay laws for the inspection of the lack of side wall fusion defect through the weld using a.) the linear membrane coupled device and b.) the twin crystal membrane coupled device
CONCLUSION

The ultrasonic inspection of welded stainless steel components found within the nuclear industry can be extremely challenging. The austenitic weld material is anisotropic and inhomogeneous, which cause the ultrasonic waves to be scattered and steered as they propagate through the weld. The welding process also leads to a complex surface geometry due to the presence of a weld cap and distortion of the parent plate material.

A twin crystal membrane coupled phased array device has been developed. This device is capable of mechanically conforming to the complex surface of welded stainless steel pipe-work, thus improving the inspection coverage on this type of component. The twin crystal membrane device incorporates two linear phased arrays; both arrays are accommodated within the same housing and separated by an acoustic barrier. The transducer housing has been designed with a fixed tilt angle and a variable roof angle. The roof angle can then be optimised for defect detection at different depths within the component under test.

A bespoke software suite has been produced which is capable of acquiring, processing and storing FMC inspection data from a single user interface. This software suite has been used to control the twin crystal membrane coupled device and to complete the through weld inspection of small lack of sidewall fusion defects using direct specular inspection techniques. This inspection capability has been shown to provide superior inspection capability to the previously developed linear membrane coupled device.

ACKNOWLEDGEMENTS

This work is supported by Rolls-Royce Nuclear and the UK Ministry of Defence. The authors would like to thank Lionel Reyes and the Rolls-Royce NDE research team for their support.

REFERENCES