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Ultrasonic Examination of Thick Austenitic Stainless Steel Welds and Factors Influence the Sensitivity

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Abstract The problems encountered by ultrasonic testing of austenitic stainless steel weld joints are discussed in the paper. Due to low thermal conductivity and the occurrence of single phase between the melting point and the room temperature, coarse and oriented grains are formed in such weld metals - more in thick sections. This leads to higher scattering at the grain boundaries and low signal to noise ratio, and extensive beam skewing. Experimental results to understand these problem are explained.

Keywords: austenitic stainless steel, weld metal, repair welding, ultrasonic testing, beam skewing, scattering

1. Introduction

Austenitic stainless steel (Aus. SS) is used in many industries, like chemical, nuclear, space etc., for its high corrosive resistance, excellent fracture toughness and creep properties over a range of temperature. It also possesses good mechanical formability. Normally, its weldability is ensured by a judicious choice of welding electrodes, weld joint design and proper joint fit up scheme. However, all the good properties of the steel are offset by a problem encountered by ultrasonic testing while it is used in a weld joint - particularly in thick sections. The problem is due to the occurrence of coarse and oriented grains in the weld metal. This occurs due to two reasons. First, there is only one phase that occurs between the melting point and the room temperature. Therefore, contrary to a ferrtic steel weld metal in which there are three phase fields, there is no chance for restructuring when the weld metal is cooling down. Secondly, since the steel has a low thermal conductivity, only a thin layer gets molten in a previously deposited weld metal, when the succeeding weld pass is given. By this, epitaxial growth takes place leading to coarse grains with oriented fibre axes. During ultrasonic testing, the coarse grains then lead to scattering at the grain boundaries, lower signal to noise ratio, and beam skewing. A similar situation occurs during weld repair when repeated heating and cooling takes place.

2. Ultrasonic Examination of Austenitic Stainless Steel

2.1. Ultrasonic Beam Propagation in Austenitic Stainless Steel Weld Metal

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2.1.1. Attenuation and Velocity

In Aus. SS weld metals, the ultrasonic beam undergoes higher attenuation than in the parent metal. Tomlinson, Wagg and Whittle[1] studied the ultrasonic wave propagation and concluded that the orientation of ultrasonic beam relative to the fiber axis is the major cause for attenuation. They further concluded that the dependence of the transmitted signal on beam orientation arises as a result of the macroscopic anisotropy of the assembly of grains, and is not related to the composition of the weld metal.

Measurements of compression wave velocity as determined by Tomlinson et al(1) are shown in Fig.1. These curves are constructed using the theory that the velocity is a function of direction in a medium of the relevant crystallographic symmetry. In other words, the velocity of compression (longitudinal) wave is a function of direction of its propagation relative to columnar grain axis. It is established that at 45° to 50° incident angle of the beam with respect to the columnar grain axis the ultrasonic wave propagates with the maximum velocity. The velocity of the beam decreases if any angular deviation from the above. The variation in velocity leads to variation in resolution and sensitivity as the wave length varies for a particular frequency. The curves represent the computations made from elastic constants derived by both Salmutter & Bradfield and experimental results[1].

It can be seen that the sound velocity is high when the direction of propagation is about 45° to 50° to the columnar grain axis[1] as explained.

2.1.2 Beam Scattering and Skewing

An important feature of wave or energy propagation in any anisotropic medium is that it will not be perpendicular to the wave front. This phenomenon gives rise to skewing of the beam off the axis of transducer. The largest angle of skew observed by Tomlinson et. Al[1] for compression wave is about 15° as indicated in Fig. 2, but for shear waves the calculation showed that beam may deviate by up to 50° from the expected direction of propagation. It is clear that with deviations of this order of magnitude a shear wave examination would be extremely difficult to carry out and even a compression wave examination will need extra care in interpretation of the position of indications. Further it is necessary to account for mode conversion of the compression waves if we use over half skip distance. As a rule, in any material with pronounced anisotropy, scattering of sound will be quite appreciable, increasing with the grain size. There is a limit of grain size for given frequency of ultrasound up to which flaw detection is possible. In general, the grain size in any austenitic stainless steel weld will be ranging from 0.5 mm to 2.00 mm and the allowable average grain size for good defect detectability with shear wave is established as 0.2 λ, where λ is wave length of ultrasound in the material in mm[2].

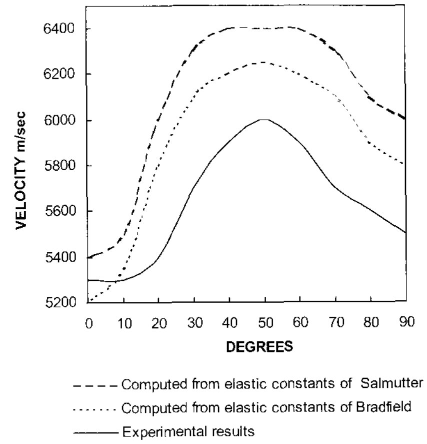

Fig. 1 Compression wave velocity as a function of direction of propagation relative to columnar grain axis[1]

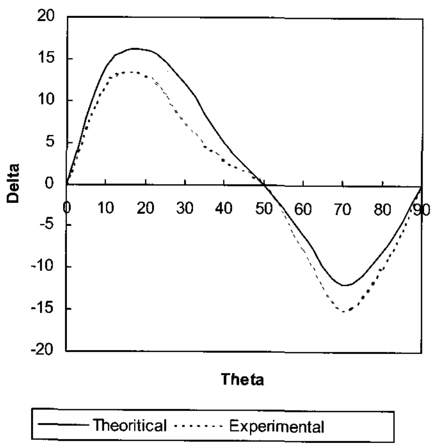

Fig. 2 Skewing angle Δ (Delta) as the function of angle Θ (Theta) between the normal to the wave front and columnar grain axis[1]

Generally, shear wave is preferred for the examination of ferritic steel welds. However, it is not quite effective for Aus. SS welds due to low signal to noise ratio and extensive beam skewing. For shear wave probes of frequencies 1, 2 and 4 MHz, the acceptable average grain size that can guarantee assured flaw detectability without sound scatter, is approximately 0.6, 0.4 and 0.2 mm respectively. Thus, the weld comprising of 2 mm average grain size will no longer be conducive for examination employing transverse sound wave, due to excess sound scattering. Whereas, for longitudinal wave with 2 & 4 MHz. frequencies, the wavelength works out to be 3.0 mm and 1.5 mm respectively, which is well suited for Aus. SS welds (with average grain size 0.5 to 2 mm) for satisfactory flaw detectability. Also, if the longitudinal wave transducer picks up the compression mode converted shear waves, it will get displayed far away from the longitudinal wave signal in the CRT time scale, due to low velocity (approx. half). The noise expected from longitudinal and mode converted shear will be much less in amplitude compared to direct shear wave. It is further advisable to adopt scanning from '0' to '1/2' skip distance while using longitudinal angle beam probe to avoid the mode conversion and related reflections and noise.

3. Experimental

An experimental study was undertaken to analyze the problems as discussed above on thicknesses ranging from 15 mm to 75 mm of Aus. SS welds. It was found that for the lower thickness up to 15 mm the effects were not significant. Over 15 mm, the noise (grass) was found very much and hence the use of shear wave is not suitable. Only longitudinal wave angle beam can be used for this. To establish and quantify the effects further, two weld mockups, one with 45 mm thick and the other with 75 mm thick of AISI 316 Aus. S.S were prepared with double V butt joint employing shielded metal arc welding (SMAW) process. Three side drilled holes at the gap of 1/4 T on parent metal and weld and notches with 3% and 5% depth on weld were made to serve as reference reflectors, for both the samples. The details of holes and notches are given in Fig. 3.

3.1. Effect of Attenuation

The welds were scanned with 45° - 2 and 1 MHz. shear wave transducers and longitudinal angle beam transducers, both single and twin crystal types to record the results and further analysis. It may be noted that single crystal probe is better suited to cover the entire weld thickness in single scanning. However, double crystal requires number of scans to cover the entire weld metal cross section, particularly for thicker sections, owing to the focal distance of a particular probe. The data obtained from different trials with 45 mm and 75 mm weld pads are presented in the Tables 1 and 2. It was noted, in the case of 45 mm thick weld, that an extensive noise has been picked-up by the shear wave probes (MWB45 N2 & MWB45N1), as indicated in Table 1. It was also noted in the case of 75mm weld, that the shear wave probes indicated above could not bring out any meaningful defect signal, as the noise was very high. It indicates that the shear wave probes are not suitable for examination of SS weld metal thickness above 40 mm, whereas the longitudinal angle beam probes (WSY45-4, VRY45-4 & VSY45-4) are better suited with good signal-to-noise ratio. Further, various types of single and double crystal longitudinal angle beam probes were tried on various thicknesses ranging from 15 mm to 75 mm. It was noted that single crystal longitudinal angle beam probes provided better results even with higher thickness of 75 mm as compared to twin crystal probes (VSY 45 - 4 & RTD 45 - 2) as it could be seen that twin crystal ones need high gain, with relatively increased noise. The signal amplitudes obtained from the side drilled holes and notches (reference reflectors) on the parent metal and the weld metal varied quite

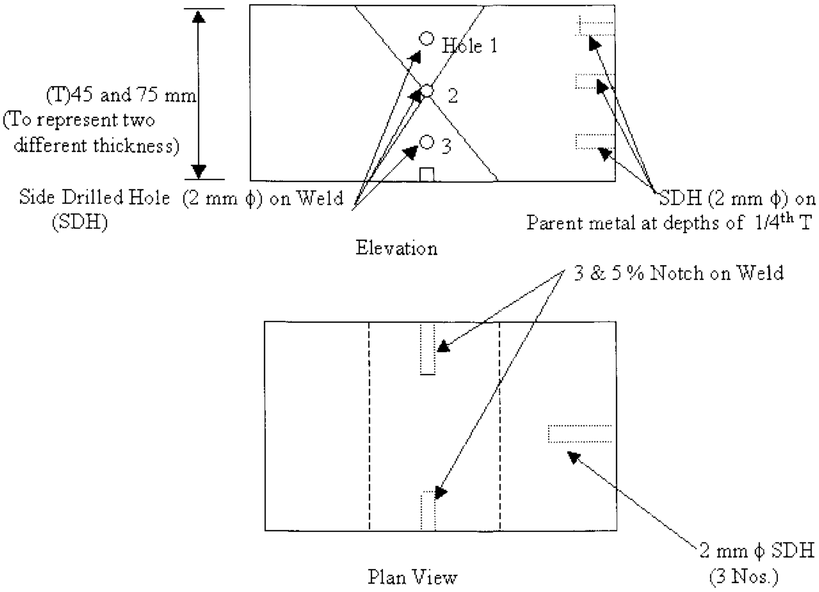

Fig. 3 Mock-up weld pad with reference reflectors

Table 1 Gain (dB) requirements for 80% reference signal in 45 mm thick SS weld for different probes

Reference Hole	MWB45 N2 (dB)	MWB45 N1 (dB)	WSY45 - 4 (dB)	WRY45 - 4 (dB)	VSY45 - 4 (dB)
Hole 1	44 (with noise)	42 (with noise)	52	58	52
Hole 2	40 (with noise)	40 (with noise)	50	56	52
Hole 3	42 (with noise)	40 (with noise)	52	54	52

Table 2 Gain (dB) requirements for 80% reference signal in 75 mm thick SS weld for different probes

Reference Hole	RTD 45 - 2(dB)	WSY - 2(dB)	VSY - 2 (dB)
Hole 1	71	75	75
Hole 2	80	80	85
Hole 3	86	84	88

extensively as the thickness increases, thereby indicating that the sensitivity level set on parent metal reflectors will no longer be valid for weld metal, if the thickness crosses 15 mm.

3.2. Extent and effect of Beam Skewing

Another problem encountered during the examination of higher thickness is the ultrasonic beam skewing during the propagation (3). This will lead to the wrong assessment of the defects, both in size and position. This will be more pronounced when the examination is carried out over the weld. The experimental study explained earlier was used to evaluate the extent of beam skewing on the 75-mm thick weld sample. Through transmission technique was employed to quantify the beam skewing as described in Fig. 4. The weld was scanned by keeping the transmitter at regular intervals of 8 mm (1/3rd of weld face width) on both sides of the face with respect to the centerline of the weld and the receiver was moved to obtain the maximum signal. This was repeated for 2 MHz transmitter and 4 and 6 MHz receiver combinations. It was noted that best result was achieved by the combination of 2 MHz transmitter and 2 MHz receiver. This could be attributed to the fact that the higher the frequency the more in attenuation in the weld with increase in noise due to scatter and grain boundary reflections in the case of austenitic stainless steel. The amount of beam skewing with respect to transmitter's position is given in Table 3 and the scheme is shown in Fig. 4.

Table 3 Extent of beam skewing

Position of Transmitter from center line of the weld	Position of Receiver from the Center line of the weld (X)
At Center Line (1)	45 - 50 mm
At 8 mm (2)	35 - 40 mm
At 15 mm (3)	10 - 15 mm

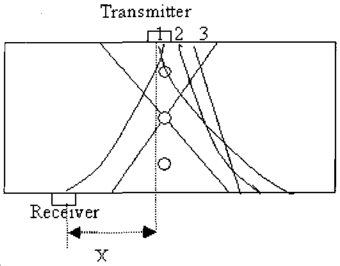

Fig. 4 Extent of beam Skewing in 75 mm thick Weld

4. Welding Processes and Its Effect on Sensitivity

In Aus. SS welding, the heat input affects the grain size of the weld metal. The heat input is a function of the welding process. An experiment was conducted to analyze the welding process variables on ultrasonic examination sensitivity, using SMAW and GTAW processes. The two processes were selected, as these are widely used in industries. A few numbers of weld pads of 15-mm thickness were welded using SMAW and GTAW processes. The weldments were examined using dye-penetrant examination and radiographic examination and cleared. In order to check the sensitivity of detection, 2-mm diameter side drilled holes have been drilled as shown in fig. 5.

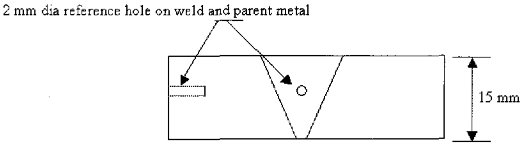

Fig. 5 Weld joint for assessing sensitivity due to welding Processes. The artificial defects are also shown

Ultrasonic examination was conducted from both the sides of the weld with 2 and 4 MHz shear wave. The gain required for keeping the reference hole signal at 80% of the full screen height was noted for both, the parent metal and on the weld. The values are given in Table 4.

Table 4 Gain (dB) required for 80% signal from reference reflectors provided in the parent metal and weld

Welding Process	Beam Path Distance (mm)	Parent Metal (dB)	Weld Metal (dB)
SMAW	40	65	67
	80	72	77
	100	74	82
GTAW	40	65	76
	80	72	81
	100	74	86

Also scanning was performed on the welds using 4 MHz normal beam probe to measure the gain required to obtain the back wall echo to 80% FSH. The gain requirements are given below.

Parent Metal (AISI 316): 52 dB. Weld (SMAW): 58 dB. Weld (GTAW): 61 dB

The data are presented in Fig. 6.

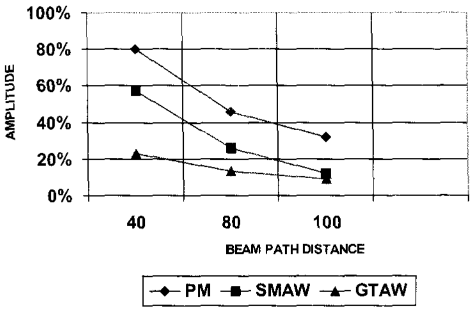

Fig. 6 Effect of welding process on ultrasonic examination sensitivity

From the above, it is evident that the weld metal deposited by GTAW process introduces greater attenuation as a result of coarser grain compared to the weld made by SMAW process. This feature could be attributed to the increased numbers of passes in GTAW process compared to SMAW process for the same thickness. This results in higher heat input and thereby grain growth in weld metal. Also, the arc in GTAW is more concentrated than in SMAW, which increases the severity of reheating of previously laid passes, thereby coarsening the grain. The micrographic examination of the two welds also confirmed the inference.

5. Repeated Repair of Austenitic Stainless Steel Welds and Its Effect on Ultrasonic Examination Sensitivity

It is inevitable that certain cases welds may have to be subjected to repair, occasionally repeated repairs, to remove unacceptable defects. It is essential that the effects of such repairs and the resultant micro-structural changes that will have influence on ultrasonic examination should be studied, analyzed and quantified. A study was conducted on 12-mm AISI 316 LN weld pads. Five numbers of weld pads were prepared using SMAW process. The configuration of the fit-up with backing strip is shown in the figure 7. After completion of the welding once, grooves were machined as shown in figure 8 in order to ensure that the weld metal, parent metal and the heat affected zone would suffer the influence of heat cycles involved during the weld repair. After machining the groove, weld repairs were taken up to four times. In this, the weld and the parent metal face heat cycles and the structural changes occur in the heat-affected zone and nearby areas, resulting in severe micro-structural changes which affects the examination and its sensitivity. Out of the five weld pads, pad 1 represents nil repair, pad 2 represents one weld repair and so on. After finishing the welds the backing was removed by machining.

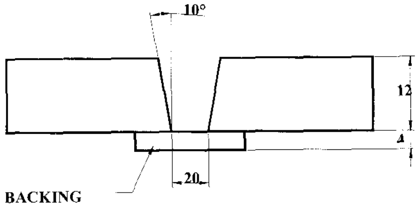

FIG.7

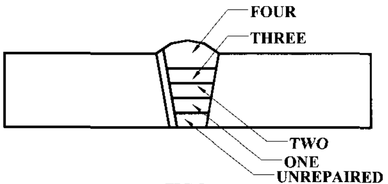

FIG.8

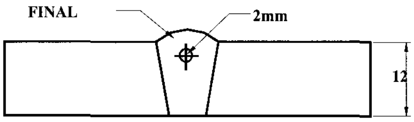

FIG. 9

Figs. 7, 8 & 9 Stages of Weld Sample Preparation along with reference reflector for Ultrasonic Examination

A 2-mm diameter side drilled hole was drilled on each weld as reference (Ref. Fig. 9). Each weld was examined ultrasonically on both sides and the gain required for getting 60% of FSH signal was noted. The weld was scanned with a variety of probes and the signal to noise ratio noted. The gain requirements and signal to noise ratio obtained for 45° shear wave transducer are given in Table. 5. Increase in gain requirement and reduction in signal to noise ratio was noticed with increase in number of repairs and this pattern was observed with different probes. The signal to noise ratio is high when low frequency and longitudinal probes are used.

From the above, it can be noted that the amplitude drops from the reference amplitude if the number of repairs increases [Fig. 10] Also it was noted that the signal to noise ratio decreased with the increase in the number of repairs.

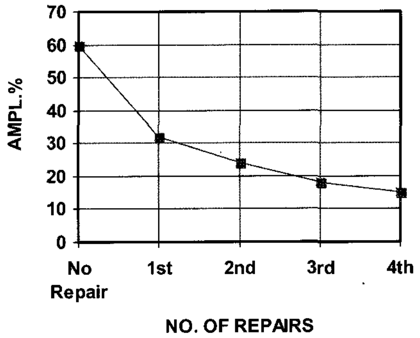

Fig. 10 Effect of Repeated Weld Repairs on Ultrasonic Examination Sensitivity

The amplitude drop noted was found to be pronounced if the number of repairs increased. The amplitude drop was more for the first weld repair compared to the un-repaired weld. This indicates that the reference taken for un-repaired weld will not serve as true reference to establish the sensitivity, even if the weld undergoes one repair. Separate reference blocks are required representing the same number of repairs, as that of the production weld. However, it may further be noted that there is a limit on number of welds which makes the weld fit for effective ultrasonic examination.

6. Conclusion

The above experimental studies have shown the difficulties experienced in ultrasonic examination of thick austenitic stainless steel welds, the effects of welding processes and repairs on ultrasonic wave propagation. Knowledge on

Table 5 Gain requirements and Signal to Noise Ratio for Repeated Weld Repairs

Sl No.	Plate Identification	Gain Requirement (dB)		Signal to Noise Ratio (dB)	
		A	B	A	B
1	Un-Repaired	80	80	21.6	21.6
2	First Repair	85	85	9.5	7.6
3	Second Repair	87	88	7.6	6.0
4	Third Repair	84	90	6.0	4.7
5	Fourth Repair	86	92	6.0	3.5

these aspects and use of appropriate techniques and transducers would help to reduce the difficulties. It is concluded with the following observations:

(a) The reference calibration holes/notches have to be necessarily provided on the weld metal instead of on the parent material, as is normally followed, to achieve a better defect detection sensitivity in the weld. This is more pronounced for sections above approx. 20 mm. As the thickness increases the beam skewing effect is more and proper estimation of it is important.

(b) Consideration and control of the weld structure must precede attempts to improve examination sensitivity by the use of special transducers or signal processing methods.

(c) The preparation of the reference specimen for standardization of the ultrasonic examination procedure must address the features like the type of welding process employed and that of the anticipated number of weld repairs as that of the component to achieve the required defect detection sensitivity.

(d) The design engineers should take account of the limitations of ultrasonic examination when applied to thick austenitic weld structures.

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