Ultrasonic Non-destructive Prediction of Spot Welding Shear Strength

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Abstract. To enhance a corrosion resistant of ferritic steel in reactor pressure vessel, stainless steel was used as a cladding. Bonding process between these two steels may result a inhomogenity either sub-clad crack or un-joined part. To ensure the integrity, effective inspection method is needed for this purpose. Therefore, in this study, an experiment of ultrasonic test for inspection of two bonding plate was performed. The objective of this study is to develop an effective method in predicting the shear fracture load of the join. For simplicity, these joined was modelled with two plate of stainless steel with spot welding. Ultrasonic tests were performed using contact method with 5 MHz in frequency and 10 mm in diameter of transducer. Amplitude of reflected wave from intermediate layer was used as a quantitative parameter. A set of experiment results show that shear fracture load has a linear correlation with amplitude of reflected wave. Besides, amplitude of reflected wave also has relation with nugget diameter. It could be concluded that ultrasonic contact method could be applied in predicting a shear fracture load.

Keywords: Non-destructive prediction, Ultrasonic test, Spot welding, Shear strength

Introduction

Ferritic steel has been used as reactor pressure vessel materials due to its superiority in ductility and neutron embrittlement resistance. But, in other hand, this material has a low corrosion resistance against primary cooling water in light water reactor. Thus, as a countermeasure, a high corrosion resistance material such as stainless steel 304 was used as cladding. In fabrication, overlay weld method was applied for joining ferritic steel and stainless steel. Since reactor pressure vessel is a non-replaceable component, pre-service and in-service inspection play an important role to ensure the reliability. The objectives of inspection are to find sub-clad crack, unjoined parts and other inhomogenity. Therefore, an effective inspection method is needed for this purpose.

To simplify the specimen, two pieces plate of stainless steel are joined by spot welding. As in reactor pressure vessel cladding, spot-welds must be carefully inspected, since the quality of the welds directly influences the strength and durability of the welded body. A various studies regarding to spot welding have been performed. Numerical simulations have been performed to improve the welding process [1-2]. Studies on mechanical and metallurgical of welding spot have been performed in order to qualify the results [3-5]. General practice in determining the quality of spot weld, destructive testing is applied. Due to the destructive character of these testing methods, many non-destructive testing methods were developed to increase the effectiveness and accuracy of testing, such as ultrasonic
method, infrared thermography method, and magnetic testing method [6-8]. In ultrasonic methods, various techniques have been studied for this purpose, such as a water immersion method, C-scan method, and the use of lamb wave [8-11]. Intensive studies were also been performed regarding to the signal analysis to quantify the ultrasonic wave parameters [12-14]. In previous studies, an ultrasonic techniques are succesfully applied to monitor fatigue damage process [15]. Unfortunately, most of these studies used a spesific ultrasonic equipment or a generic ultrasonic equipment, by means, it is difficult to be applied in manufacture lines. Thus, the objective of this study is to develop a new ultrasonic testing technique to inspect a spot welding result using a conventional ultrasonic flaw detector. This technique should be suitable for the quality assurance of spot welds in the series production line and it significantly reduces testing time and material cost.

1. Materials and Experiments
1.1. Specimen and material
The specimens were made from austenitic stainless steel 304 by resistance spot welding method. Materials chemical composition and specimen’s geometry are shown in table 1 and figure 1, respectively. Spot welding was performed in the centre of overlapping area between two sheets of stainless steel with 3 mm thick.

|      | C    | Si   | Mn  | P   | S   | Ni  | Cr  | Mo  | Al  | Cu  |
|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| weight (%) | 0.21 | 0.27 | 0.69 | 0.005 | 0.004 | 0.78 | 0.38 | 0.63 | 0.015 | 0.16 |

**Table 1. Chemical composition of SS 304 material.**

Spot welding process were performed using a single-phase alternating current (AC) 50 Hz equipment. This machine has two electrodes with 25 mm body diameter and 9 mm face diameter. The controlled welding parameters were welding current, electrode force, and force holding time. In order to obtain a variation in quality of spot welding, specimens were welded by various parameters, whilst the electrode force was kept in a constant value, 1.000 N. Five specimens were obtained from each welding parameter. Figure 2 shows an example of a set specimen obtained.
1.2. Ultrasonic testing of welded joint

Figure 3 shows an ultrasonic testing equipment set-up. The equipment consists of ultrasonic transducer, ultrasonic pulser-receiver, digital oscilloscopes and computer for data acquisition. The pulse-echo method was applied in this testing and A-scan data type were obtained. The ultrasonic wave was generated by ultrasonic pulser-receiver and transmitted to specimen by ultrasonic probe. The longitudinal type ultrasonic probe with 5 MHz frequency was used in this testing. The ultrasonic transducer has 10 mm in diameter. Ultrasonic back-wall echo signal was received by the same probe and displayed by digital osciloscope. Signal data were digitized in 2 GHz sampling rate and recorded by computer. For analyze purpose, an acquired data could be used to reconstruct the ultrasonic signal using software.

The ultrasonic testing was performed by placing the transducer in two positions as shown in figure 4. Position A is a position which the transducer is above the welding nugget, whilst position B is a position which the transducer was put on surface outside of overlapping area. Ultrasonic testing results were characterized using reflected wave from interface between two samples, and amplitude was used as parameter.

1.3. Tensile testing

After performing ultrasonic testing, tensile testing was subjected to the spot welded specimens. This test was performed to obtain a real shear fracture load of the welded joint. The test was performed using universal tensile machine with 1 mm/min elongation rate. The tensile machine was equipped with digital control which allows acquiring digital data of load and elongation. After performing tensile testing, observations of fracture surfaces were performed to measure the actual nugget size.
2. Results and discussion

Figure 5 shows a typical ultrasonic reflected signal from position A dan B, respectively. After emanating from transducer and entering sample, ultrasonic wave propagates through the thickness, and when encounters interface, the wave will be reflected. In case of position A, ultrasonic wave will encounter bonding area (nugget) between two sample, therefore, partially will be reflected and another part will be transmitted into the second sample. The intensity of reflected wave depends on how wide the nugget area is. The wider nugget area, the lower ultrasonic intensity is.

In case of position B, there is no bonding area along wave propagation path. Therefore, in this position, almost all of ultrasonic wave is reflected. In this condition, the reflected wave should be the maximum intensity compare to that one from position A. In order to obviate the uncertainty of intensity of reflected wave due to surface condition of each sample and electronic circuit of ultrasonic equipment, to quantify the intensity, then the amplitude of reflected wave from nugget area ($A_w$) was normalized by amplitude of reflected wave from back wall of sample I ($A_n$).

Figure 6 and 7 shows the relationship between ultrasonic reflected wave’s amplitude and shear strength. In figure 6, a vertical axis shows an original amplitude, whilst in figure 7, a vertical axis shows a normalized amplitude indicates by $A_w/A_n$. In figure 6, the data are widely scattered. It indicates, the amplitude of reflected wave ($A_w$) has no obvious correlation to shear strength. Whereas, in figure 7, there is an obvious correlation between normalized amplitude of reflected wave ($A_w/A_n$) and shear strength. The difference trend between an original reflected wave $A_w$ and normalized reflected wave $A_w/A_n$ indicates an effective treatment (normalization treatment) of ultrasonic signal. The deviation result in figure 6 may be caused by surface condition. Thus, the normalization process resulted in omission of surface condition effect.

![Figure 5](image1.png)

(a) Reflected wave

![Figure 5](image2.png)

(b) Reflected wave

**Figure 5.** Typical ultrasonic reflected signal (a) From Position B; (b) From Position A

![Figure 6](image3.png)

**Figure 6.** Reflected wave’s amplitude from nugget area versus shear strength.

![Figure 7](image4.png)

**Figure 7.** Normalized reflected wave’s amplitude from nugget area versus shear strength.
Figure 7 clearly shows that reflected wave decreases as increasing of shear strength. This relationship could be explained as follows. Shear strength of spot welding depends on bonding condition, which is nugget’s geometry and metallurgical fusion between two metal sheets. Larger geometry and more perfect fusion provide a high strength. Increasing in nugget geometry and quality of bonding increases portion of transmission wave. Contrarily, the portion of reflected wave decreases. According to figure 7, reflected wave amplitude and shear strength has a linear relationship.

Figure 8 shows the relation between shear strength and nugget size. Nugget size in horizontal axis represents a nugget diameter, since the nugget was assumed as a circle. The diameter was measured as shown in figure 9. It can be seen from the figure that shear strength of the sample increases linearly with the increasing diameter. The data scatter slightly wide. The cause in scattering data could be considered as follows. There is uncertainty in the measurement. As shown in figure 9, measurements were performed using a ruler which has a minimum scale of 1 mm. In this study, the measurements were rounded to millimetre; therefore, the measurement results include a deviation about 0.5 mm. Even the nugget shape is assumed as a circle, an actual shape of nugget is not a circle. Observation of the entire fracture surface, it could be clarified that the shape of nugget are irregular. The assumption affected to the nominal bonding area. The next factor on scattering data is internal discontinuity in the nugget. As shown in figure 9, fracture surface of nugget are not homogeneous. In this figure, in the centre of nugget, there is such a metallurgical discontinuity which could affect the welding strength. The last factor to be considered as reason on scattering data is the thickness of nugget. Nugget is a three dimensional geometry. A thickness increases linearly as diameter increases. Since a planar surface is irregular, the thickness also irregular. Thus, nugget diameter doesn’t represent actual nugget geometry.

![Figure 8. Shear strength versus nugget size.](image)

![Figure 9. Fracture surface.](image)

Figure 10 shows relation between ultrasonic reflected wave’s intensity and nugget size. An open diamond mark represents amplitude of reflected wave from nugget area (left side axis), whilst a closed triangle mark represents amplitude of reflected wave from nugget area normalized by reflected wave from sample’s back wall.

It can be seen from the figure that amplitude of reflected wave decreases linearly with nugget size. Both data (with and no normalization) are scatter, but normalized amplitude data gave a smaller scatter compare to without normalization. The reason was already explained in previous discussion for figure 7. If the scatter data in this figure were compared to figure 8, figure 10 has less scatter. In figure 8, a parameter related to nugget has a strong relationship to the shear strength. But, in figure 10, geometrically aspects in nugget have a few relations to reflected wave intensity. The effect of nugget area corresponds to the intensity of reflected and transmission of ultrasonic wave. Therefore, the uncertainty in diameter measurement affected in scattering data.

The main effect to be considered to the scattered data is position of transducer. In this study a circle shape transducer with 10 mm in diameter was used. To achieve a minimum scattered data, the
centre of transducer should coincide with the centre of welding nugget. But, it was hard to maintain this condition without special equipment. A shifting between centre of transducer and centre of welding nugget will affect in uncertainty to the result. It can be explained as follow.

Transducer with circle shape, the intensity of incidence wave within the circle is not homogeneous [16]. The intensity decreases in radial direction. From the centre to the half of radii, the intensity almost constant, after that decreases rapidly to almost 10 % compare to the intensity in the centre. Therefore, by considering the diameter of transducer and diameter of nugget, the shift between centre of nugget and centre of transducer will give uncertainty in measurement.

According to these results, the equation for predicting the shear fracture load for spot welding using ultrasonic testing, contact method was proposed as follow.

$$\tau_F = -17 \frac{A_w}{A_n} + 18.18$$  \hspace{1cm} (1)

where, $\tau_F$ is shear fracture load for spot welding and $A_w/A_n$ is ratio of amplitude of reflected wave from nugget area ($A_w$) and amplitude of reflected wave from back wall of sample. This equation is valid for spot welding to stainless steel and stainless steel.

![Figure 10. Reflected wave’s intensity versus nugget size](image)

3. Conclusion
Ultrasonic tests were performed to spot welded stainless steel plate for predicting shear fracture load. A contact ultrasonic method was applied for this purpose. Experimental results show that there is linear correlation between shear fracture load and ultrasonic reflected wave. The higher shear fracture load, the lower the ultrasonic reflected wave. A low reflected wave due to a wider nugget size constructed in the interface between two plates. A wider nugget size will transmits more ultrasonic energy. An empirical equation was derived from the experiments results to predict shear fracture load by using reflected wave amplitude. This equation can express a good relation between shear fracture load and ultrasonic reflected wave. This equation only valid for stainless steel and stainless steel under welding and testing method described in this paper.

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