Non Destructive Characterization Of Resistance Spot Welded Joints By Ultrasonic Technique

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ABSTRACT

Spot weld quality in terms of soundness of joint and nugget penetrations have been evaluated by ultrasonic technique. Furthermore, the variations in ultrasonic attenuation characteristics caused by grain boundary scattering have been utilized to assess grain coarsening at weld metal due to spot welding heat. The interpretations of ultrasonic signals are found to correspond with the results obtained from peel off and shear tensile test and are at par with the optical and TEM observations.

Keywords: ultrasonic technique; spot weld; grain size; dislocation density; attenuation

INTRODUCTION

In any manufacturing industry joining plays an important role to improve its product and productivity. Among the different joining processes used in sheet metal fabrication, Resistance spot welding (RSW) is still maintaining its position since 1930s as the primary joining method for automotive structure due to its high productivity and consistent weld quality. In RSW, quality evaluation is an important issue for reliability and satisfactory performance of an automobile structure having several thousands of spot welds. Recently, attempts are being made to increase productivity by reducing the number of spot welds in automotive structure and this approach has demanded stringent quality control requirement even for each spot weld. The spot weld quality is usually measured by peel off test, tensile shear strength and cross tensile strength, which are time consuming processes and fail to apply on finished structure. In this regard, for the quality assurance of spot welds, particularly in industry, researchers have been trying to develop a suitable non-destructive test (NDT) method.

Although NDT methods such as radiography or acoustic microscopy are being applied to evaluate quality of spot welded joint [1], both the techniques have their inherent limitations. For example, smaller nugget size of spot weld imposes difficulty in estimating weld quality by radiography and it also affects health factor due to harmful radiations. Again, acoustic microscope is expensive and time consuming as well as unsuitable to be used in industrial environment [1]. On the contrary, ultrasonic test (UT) method, which gives better accuracy, fastness and reliability as well as facilities for recording data, finds potential in evaluating the quality of spot weld [1-5].

Ultrasonic testing, which involves reflection of high frequency sound wave back and forth between material interfaces, is being used as an established method for detection of weld flaw and discontinuities in conventional arc welding processes. Furthermore, the technique has also been employed for evaluating the quality of RSW. A. B. Doyum et al [5] predicted spot weld quality and nugget penetration with multiple pulse echo technique by evaluating the positions of reflected echo on the time scale and their attenuation characteristics. However, the work was mainly restricted to predict soundness of weld joint through nugget size measurement and to identify undersized or stick weld situations. Similar attempt was also made by

Donald et al [6] to characterize spot weld quality in case of aluminium alloys. Furthermore, UT signals were utilized to implement neural network systems in order to assess spot weld quality based on nugget size measurement by Mansur et al [7] and Martin et al [8]. However, apart from nugget size, weld metal strength is another essential criteria for spot weld performance characterization. Very limited publications have enlightened nugget size-mechanical property correlation detected by UT [9-10]. Although the strength of a spot welded joint is often related to its physical attribute such as nugget size, it is primarily controlled by the metallurgical characteristics of the weldment such as microstructure and deformation status. In this respect, microstructural details like grain size or dislocation structure of weldments will provide better insight into the RSW process, which will ultimately assure about the desired mechanical properties at a predicted weld sequence for any grade of steel.

The change of ultrasonic attenuation coefficient due to dislocation mobility and interaction of dislocations with precipitates etc was first detected by Truell et al [11] and later was mathematically formulated by Granato and Lucke [12]. Utilising the string model developed by Granato and Lucke, attenuation characteristics were correlated with dislocation density during fatigue and creep deformation [12-15]. Fei [13] observed variation of attenuation characteristics due to dislocation - impurity interaction for 99.999 wt% Al under tensile and compressive stress. Similarly, Johnson [14] verified dislocation damping after plastic deformation through UT in interstitial free and carbon steel. Moreover, attenuation coefficient was correlated with grain size for plain carbon steel by Klinman [15] and austentic sheet by Hecht et al [16]. Although ultrasonic method has already been employed to reveal dislocation nature and grain size of metals and alloys to predict microstructural changes during fatigue or creep deformation of steel, there is scarcity of published literature on similar microstructural prediction in RSW weldments.

In the present investigation, spot welded joints of 1 mm thick galvannealed interstitial free steel sheet, spot welded with different parameters of increasing heat input, were tested using high frequency ultrasonic technique in order to assess the spot weld quality. Attempts have also been made to reveal microstructural details of spot welds, such as grain size, dislocation density etc with the help of optical and transmission electron microscopy and the observations were correlated with ultrasonic signals obtained from different weld metal. The quality of the spot welded joints was also checked by peel off test followed by nugget diameter measurement and shear tensile test.

EXPERIMENTAL

In the present experimentation, spot welding were performed on 1 mm thick galvannealed interstitial free steel sheet (Ys : 210 MPa, UTS : 340 MPa) with A.C type RSW machine (electrode pressure: 280 daN, electrode tip diameter: 6 mm). Peel off test was performed followed by nugget diameter measurement to assess the quality of spot welded joints. Weldability lobe (Fig.1) was generated on the basis of minimum and maximum acceptable nugget diameter complying with 3.5t and 5t, where t is the sheet thickness. Chemical composition of the steel, as determined by spectrographic analysis, is given in Table1.

In RSW, weldability lobe signifies a window of welding parameters such as current and time under fixed electrode pressure, which give rise to acceptable nugget size. Since heat input in RSW is calculated using the formula $H = I^2.R.t$ (i.e $H = I.V.t$), current (I)-voltage (V) data during the welding was recorded. The current-voltage characteristics under different welding conditions were subsequently plotted and weld heat generated under each welding conditions was calculated from these plots using data analysis software.

Five spot welded samples in increasing order of heat input were selected with reference to the weldability lobe (Fig.1) and ultrasonic technique in pulse echo mode was used to assess the quality of the spot weld. Ultrasonic measurements were carried out on the specimens using a 200 MHz Pulser-Receiver (model PR5900, Panametrics, RD Tech., USA). 20 MHz longitudinal probe was used for the ultrasonic study in contact mode. The received signal was digitized using NI PXI data acquisition card with sampling rate of 200MS/s. Signal acquisition, analysis and measurement of ultrasonic parameters; longitudinal velocity (Vl) and attenuation coefficient ( ) were made using indigenously developed software in the platform of LabView. Ultrasonic measurements were performed in the nugget locations to evaluate the quality of the welded region. Velocity of ultrasonic wave in the material was first determined at the base metal region and then the same was used to find the thickness of welded region. The experimental setup for ultrasonic measurement is shown in Fig.2.

The spot welded joints were then tested for shear tensile strength as per BS

1140:1993 test procedure. Micro-structural investigation was performed on metallographically polished weld nuggets under optical microscope. Thin foils of jet polished samples were examined under transmission electron microscope (TEM) at an operating voltage of 120 KV for the study of microstructure, distribution of precipitates and dislocation density.

RESULTS & DISCUSSION

The welding parameters, heat input along with nugget diameters and shear tensile strength of the weld nuggets are presented in Table 2. Weld metal microstructures and TEM photographs are shown in Fig.3 and Fig.4 respectively.

Table 2 indicates an increasing trend of both nugget diameter and shear tensile strength with increasing weld heat input. Again, with increasing weld heat input, grain coarsening takes place as observed under optical microscope (Fig.3) and dislocation density in weld metal also increases with heat input as shown in transmission electron micrographs (Fig.4). It is well known that grain size of weld metal will increase with increase in heat input. However, increase in dislocation density with higher weld heat input is probably due to enhanced thermal stress and higher deformation derived from increased volume of molten metal (weld nugget) under electrode pressure during RSW.

To analyse weld quality and micro-structural changes at the welded region using non-destructive ultrasonic technique, the measurement parameters were chosen as the amplitude of the 1st reflected echo and nugget penetration (indentation depth) and these parameters as determined for five welded samples are listed in Table 3. The ultrasonic signals of the samples are shown in Fig.5.

It can be assessed from Fig.5 that sample 2 corresponds to bad welding with multiple reflections of ultrasonic wave only from the interface of two sheets. Whereas, sample 1 corresponds to undersized weld with part of the incident energy reflecting back from the interface and rest from the back of the welded sheets. Although weld heat input of sample 2 (791.4 KJ) is slightly higher than that of sample 1 (775.7 KJ), the inferior weld quality of sample 2 is due to difference in weld current. Lower welding current involved with this sample attributes inferior weld quality in spite of higher heat input. This is not unexpected considering the principle of the RSW process ($H=I^2Rt$), which denotes higher contribution of current in weld heat due to square power of it. Further, with increasing heat input from sample 3 to sample 5, ultrasonic signals reflected only from the back wall of the two joined sheets at the weld region (Fig.5) which clearly indicate the improvement of weld quality with heat input. These ultrasonic observations are at par with the nugget diameter measurement results obtained from peel off test. Moreover, nugget penetration (indentation depth*) has also been determined from the thickness measurement in the welded region using ultrasonic technique as listed in table 3 and is also in agreement with the fact that indentation depth should increase with weld heat input.

The amplitude of the first reflected echo from the back wall of the welded region (IR) and the thickness of the samples at the welded region as a function of input are plotted in Fig.6. It is observed that with increasing heat input, I_R decreases with the decrease in thickness of the material. Theoretically, when an ultrasonic wave of energy I_i propagates through a material of thickness x, the reflected energy from the back wall of the material is given by,

$$I_R = I_i e^{-\alpha x}$$

where, is the attenuation co-efficient. Hence, for a material with all other parameters constant, I_R increases with decrease in thickness. In this case, decrease in I_R with the reduction in thickness shows that there is an increase in attenuation co-efficient , since the incident energy of ultrasonic wave was kept constant during all the measurement. The attenuation coefficient ( ) consists of two parts, (1) attenuation due to absorption ($_a$) and attenuation due to scattering ($_s$). The attenuation due to scattering ($_s$) is related to the grain size (D) and frequency (f) of ultrasonic wave and is proportional to d^3f^4 when wavelength >>D. Hence the decrease in the amplitude of the first reflected echo with lesser thickness reflects the grain coarsening in the welded region with increase in heat input, which has also been observed in optical microscope (Fig.3).

For sample 5, sharp increase in I_R with the least thickness at the welded region was observed and is because of the combined effect of grain coarsening and high dislocation density at the welded region with the maximum of heat input as observed in TEM micrograph (Fig.4).

CONCLUSION

In this study, the quality of different spot

*2 X indentation depth =
2 X sheet thickness – nugget penetration

welded joints and nugget penetration is evaluated employing ultrasonic technique. The observations are compared with the results of conventional RSW quality estimation methods such as peel off test, shear tensile testing etc. The research conclusions are summarized as follows:

1. Although sample 1 and 2 correspond to the acceptability region of weldability lobe, ultrasonic evaluation shows that for good resistance spot welding of galvannealed interstitial free steel, heat input more than 791.4 KJ is required.
2. Reflection of ultrasonic signal from the back wall of the two welded sheets in sample 3 to sample 5 indicates the soundness of the spot weld with increasing heat input.
3. Scattering in UT signal is successively increased from sample 3 to sample 5 indicating grain coarsening in the weld.
4. Sharp decrease in the amplitude of the first reflected echo in sample 5 is attributed to the coarser grain and high dislocation density.
5. The interpretations of ultrasonic signals are found to correspond with results obtained from peel off, shear tensile test and are at par with the optical and TEM observations

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Table 1: Chemical composition of interstitial free steel										
%C	%Mn	%Si	%Al	%Nb	%Ti	%B	%S	%P	%N	%Fe
0.0035	0.36	0.0089	0.0299	0.005	0.0379	0.0013	0.019	0.046	0.0034	Rest

Table 2: Welding parameters, nugget diameter and shear tensile strength of different spot welded joints				
Sample No	Weld parameter	Weld Heat Input (kJ)	Nugget Diameter (mm)	Shear Strength (kN)
1	8 KA 6 cycles	775.7	4	4.423
2	7 KA 8 cycle	791.4	3.6	4.109
3	9 KA 6 cycle	981.7	4.7	5.889
4	7 KA 12 cycle	1187.8	5	5.598
5	9 KA 8 cycle	1309	5.9	6.502

Table 3: Measured parameters of ultrasonic technique of different spot welded joints			
Sample No	Amplitude of 1st reflected echo (V)	Nugget indentation (mm)	Nugget penetration (mm)
1	1.14	0.0575	1.885
2	1.25	0.035	1.93
3	1.1	0.0665	1.867
4	0.969	0.09	1.82
5	0.82	0.16	1.68

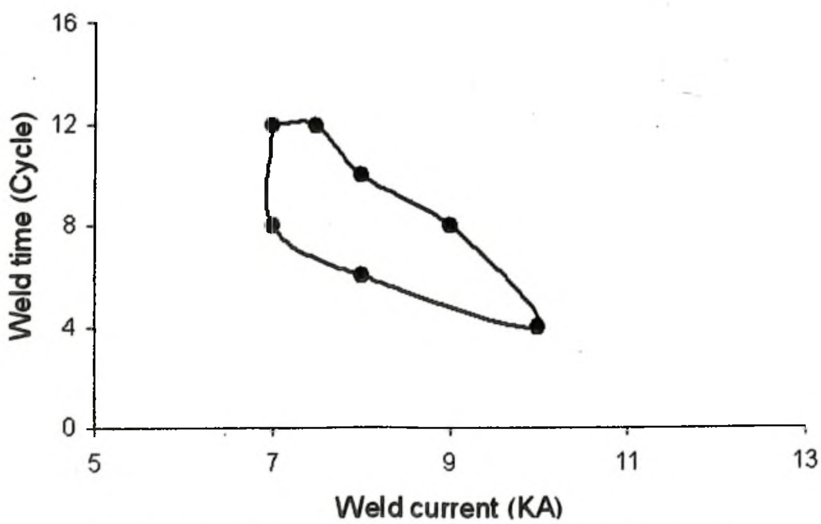


Fig. 1 : Weldability lobe of galvannealed interstitial free steel

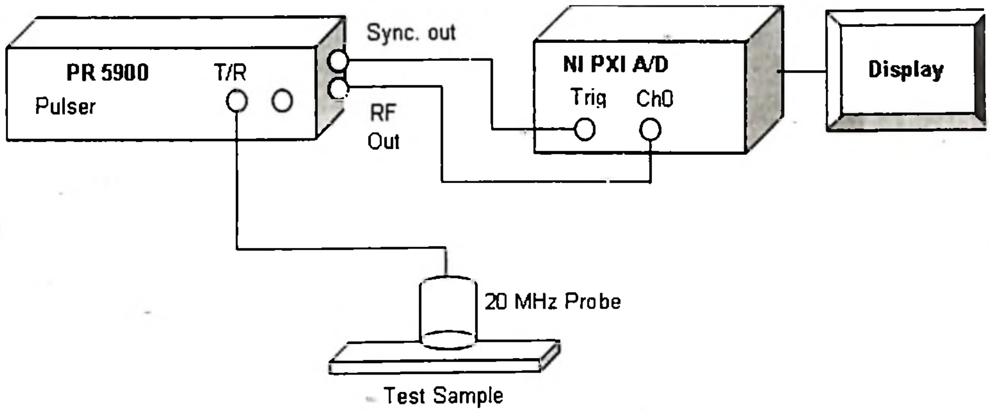
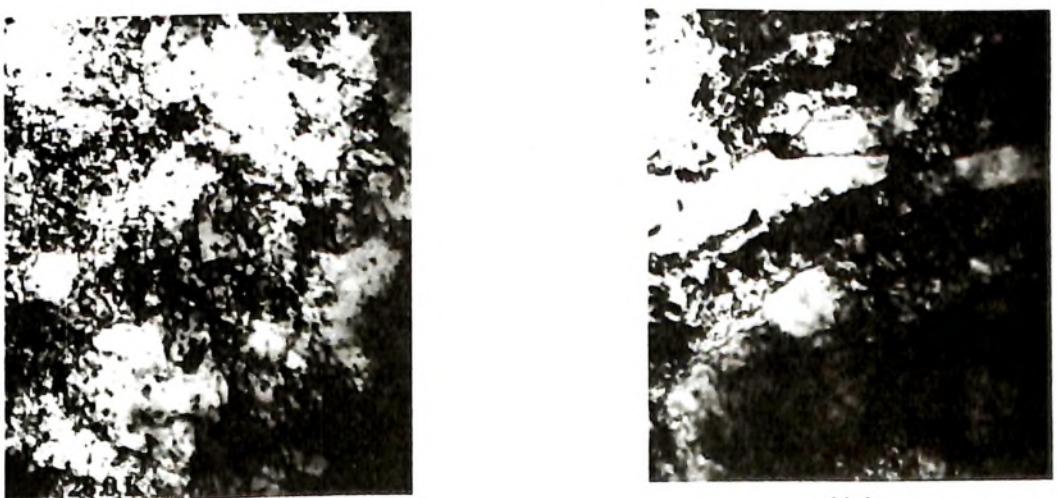


Fig. 2 : Experimental setup for Ultrasonic measurement

(a) (b) (c)

Fig. 3 : Microstructure of different spot welded joints at 500X magnification :
(a) 9 KA 6 cycle, (b) 7 KA 12 cycle, © 9 KA 8 cycle



(a) (b)

Fig. 4 : TEM photomicrographs of dislocation density at different weld metals :
(a) 7 kA 12 cycle (28000X magnification), (b) 9 KA 8 cycle (35000X magnification)

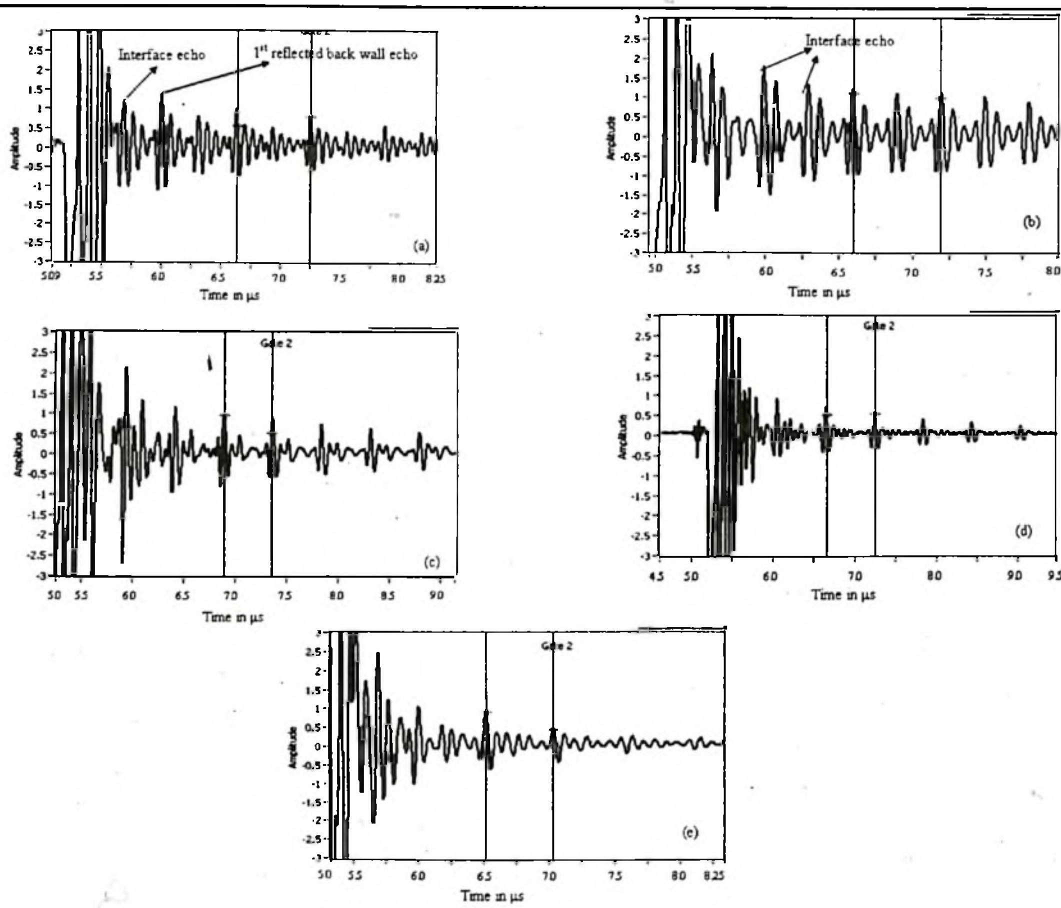


Fig. 5 : Ultrasonic signals received from different spot welded joints :
(a) 8 KA 6 cycle, (b) 7 KA 8 cycle, © 9 KA 6 cycle, (d) 7 KA 12 cycle, (e) 9 KA 8 cycle

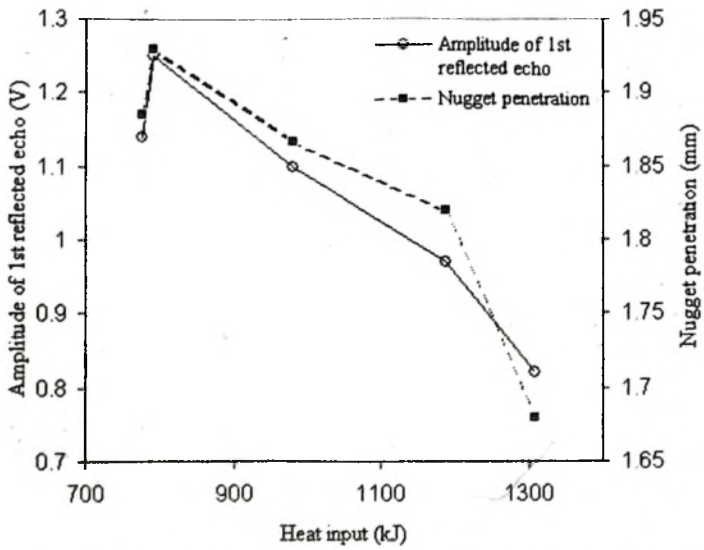


Fig. 6 : Variation of amplitude of first reflected echo and nugget penetration with spot welding heat input