Ultrasonic Non-Destructive Evaluation for Spot Welding in the Automotive Industry

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Abstract—The pulse echo non-destructive evaluation (NDE) technique has been used within the automotive industry for many years, but this is an offline approach, where tests are carried out after welding. Recent research has been carried out to monitor spot welding online. This paper proposes a portable online, real time, through-transmission, continuous wave ultrasonic non-destructive evaluation system for the monitoring of spot weld quality. The ultrasonic transducers are mounted on the top and bottom electrode arms of the spot welding machine. Results have been achieved that show an increase in received signal amplitude upon formation of the spot weld, but a reduction with the occurrence of splash, indicating a poor weld, when compared to results taken from destructive tests.

I. INTRODUCTION

Spot welding had been used for decades within the automotive industry as the preferred method to join the body-in-white structure of a car, which usually has thicknesses between 0.5mm and 3mm. One sheet of metal is placed on top of another and a current is passed through them using copper alloy electrodes which are located above and below the two metal sheets, as shown in Fig. 1 [1].

Heat for resistance spot welding is generated by the resistance to the flow of current between the steel sheets, and can be calculated using (1). This contact resistance is not only dependent upon the surface condition of the steel sheets but also on the profile of the electrode caps which change as they begin to wear [2].

\[ H = I^2RT \]  

(1)

where \( H \) is the heat generated in joules,

\( I \) is the current in amperes,

\( R \) is the resistance in ohms,

and \( T \) is the time the current flows in seconds.

Figure 1. : Resistance Spot Welding (Inset: Spot Welding Machine)

The force provided by the electrodes improves electrical contact between the sheets and also helps to contain the molten metal within the joint. The two metal sheets are then fused together at the point and this area is known as a weld nugget.

Weld quality is an important aspect in the automotive industry where the durability of a car is very much dependent upon the integrity of the body-in-white structure. Poor quality welds occur for example when the parts being welded do not fuse completely as shown in Fig. 2, or when the area of the nugget may be smaller than required for a strong joint, as shown in Figure 3. A weld’s quality can be determined by its geometric or physical features, its strength or performance or by inspection of the process during welding.

Figure 2. : Undersized Weld

Figure 3. : Stuck Weld
The lifetime of the electrode caps are reduced by the use of zinc coatings on the steel to inhibit corrosion [3]. In addition to electrode cap wear indicating poor welds, expulsion during the welding cycle, more commonly known as splash, is a key sign that the welds being produced are of an inadequate quality [4], and also promotes electrode cap wear.

II. INFLUENCES ON SPOT WELD QUALITY

A weld’s attributes are usually visible after a weld is created or can be made visible by performing destructive tests on the welded joint by using the peel test, the chisel test or even by cross sectioning the weld. Non-destructive methods, for example ultrasonic inspection can also be used. Factors such as the microstructure of the base metal and the weld, electrode cap type and integrity, expulsion, surface impurities and steel grades all that have an effect on spot weld quality.

A. Microstructure

During welding, the microstructure of the steel in and surrounding the weld alters due to the rapid annealing and cooling derived from the electrodes [5]. The metallurgy of the welded joint can be categorized into two major regions, the fusion zone and the Heat Affected Zone (HAZ). The fusion zone is the parts of the steel that have melted together, where the solidification completely changes the microstructure. The HAZ, however, represents the regions that are in close proximity to the weld, where the heat input is insufficient to melt the steel but still changes the microstructure [6]. This area is also frequently susceptible to the development of micro-structural defects due to the often weakened mechanical properties and metallurgical processes involved during welding. If the HAZ spreads to the electrodes the probability of electrode failure becomes greatly increased.

The microstructure of a weld is revealed by taking a cross section of the weld nugget, polishing it to a mirror finish and then using Nital, which is a solution of nitric acid and alcohol, to chemically etch it. Fig. 4 and Fig. 5 show microscopic images captured of the microstructure of the base metal (mild steel), and the welded area respectively.

Before welding, the grains of this grade of steel are large and coarse. After a weld has been carried out this grain structure is altered, and due to the presence of martensite which can cause embrittlement of the weld, the grains become anisotropic and needle shaped as they grow along the direction of heat flow.

B. Electrode Cap Wear

Zinc coatings which are used to inhibit corrosion, significantly reduce the lifetime of electrode caps, compared with uncoated steels [2]. During the welding cycle the zinc on the steel surface melts first due to its lower melting point. The electrode force then pushes some of this molten zinc, which has a higher conductivity than steel, to the edge of the mechanical contact area until solid-solid contact is reestablished at the sheets. This displaced zinc effectively increases the electrical contact area resulting in a lower contact resistance, which means that more heat is generated within the tip which leads to a decrease in the welding current density and subsequently, in substandard welds [7]. The zinc from the coating also alloys with the metal of the electrode caps which causes non-uniform pitting of the electrode tips [8]. This eventually degrades the edges of the tip face and a comparison between a new and a used electrode cap are shown in Fig. 6 and Fig. 7 [9]. Electrode caps can be redressed to re-establish the correct profile (until the cap needs replacing) but this requires the welding to cease while it is performed. This changing tip profile has a profound effect on weld integrity.

III. EXPULSION

During welding at a specific current level the weld nugget diameter will reach what is regarded as the minimum acceptable size (according to the British Standard) [10]. As the current is increased beyond this critical level, the size of the forming weld nugget will increase until a point is reached when the electrodes can no longer contain the molten metal.
This is when splash occurs which is visible as hot sparks that are usually thrown into the air. Splash causes the electrodes to collapse into the metal which results in a thinner weld, potentially containing discontinuities. These discontinuities can spread and lead to weld failure due to the mechanical impact of the electrodes during adjacent welds. Part of the expelled metal is often from the electrode itself, which results in a reduced electrode life. Sheet surface contamination such as grit and grease can also lead to splash due to the dissimilar thermal conductivities. As the zinc coating has a lower melting point (419°C) than steel (1370°C), this is expelled from the sheet surface before the steel begins to melt. Fig. 8 shows a weld nugget revealed using the peel test, which shows the occurrence of splash.

![Figure 8. Splash Visible on Weld Nugget](image)

IV. THE ULTRASONIC NDT TECHNIQUE

Due to the extensive size of the automotive industry the benefits of non-destructive testing in terms of cost savings are substantial. An increased confidence in the quality of the welds using an accurate ultrasonic testing method would result in a decrease in the need to perform extra welds therefore a reduction in both process times and material costs. Ultrasonic inspection of welds is probably the most widely used non-destructive testing method in the automotive industry. Ultrasonic energy is transmitted via a transducer and is either reflected from the front and back walls of the test piece in a series of echoes, known as the pulse echo technique, or is received by another transducer that is located on the underside of the weld being inspected, known as the transmit-receive technique.

Ultrasonic pulse-echo NDE is a well established method for ensuring the integrity of welds as it can identify whether or not a weld contains cracks or voids. It can also check for incomplete penetration and other weld defects that are not noticeable upon visual inspection. The frequencies used for testing using the pulse-echo method are typically in the range of 0.5MHz to 20MHz. Frequencies below this range would mean that the interaction of the waves with internal flaws would become uncertain.

The transmit receive, or through transmission method, is an ultrasonic testing method where one transmitting transducer and one receiving transducer are placed on opposite sides of the object to be tested. An ultrasonic signal is then passed through the object. A reduction compared to the expected amplitude of the received signal would indicate the presence of a defect. As both a transmitter and receiver are required to perform the transmit receive testing method, this type of ultrasonic NDE inspection is rarely used within the automotive industry as access to both sides of the body-in-white structure is often impossible.

V. RESULTS

IF180 steel was used to carry out a set of welds using the parameters chosen from SORPAS® simulations [11]. A current of 7kA and a pressure setting of 3.5bar were the chosen settings. In order to produce a set of spot welds that resemble the forming weld nugget, 50 spot welds were carried out, with increasing weld times measured in cycles of 20ms. The 3 out of each set of 5 produced welds were opened using the peel test and the resultant weld nuggets were measured. The results from these welds are shown in Table 1, which shows that as the weld time increases, the size of the resulting weld nugget increases accordingly. 1 to 4 cycles were no welds, and although the nugget diameter is larger at 9 and 10 cycles, the weld will contain cracks and voids due to the presence of splash during welding.

An ultrasonic transmit receive experiment was performed offline as proof of principle, using the setup shown in Fig. 9 and Fig. 10, showing the actual electrode arms and spot welding electrode caps. A vice provided the force required to hold the electrode caps in close contact with the steel coupons.

<table>
<thead>
<tr>
<th>Weld Time (Cycles)</th>
<th>Average Nugget Diameter (mm)</th>
<th>Splash</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stuck</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Stuck</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Stuck</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Stuck</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Stuck</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>2.4</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>2.9</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>3.7</td>
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</tr>
<tr>
<td>9</td>
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</tr>
<tr>
<td>10</td>
<td>5.2</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Each of the welded steel coupons was placed in between the two electrode caps and held securely using the vice. A function generator (TTi TG2000 10MHz DDS) was used to send a sinusoidal voltage to the transmitting transducer. The resulting electrical signal was amplified using a Mini Circuits ZFL-500LN amplifier, the output of which was monitored using a spectrum analyser (Hewlett Packard 8594E, 9 kHz-2.9 GHz).

The results from this test, as shown in Fig. 11, reveal that, as predicted, the lower the welding time, the lower the amplitude of the received signal. This is because of the air gaps that are present between the steel coupons, and as the weld time increases these air gaps reduce in size as the metal begins to melt, resulting in a greater amplitude. However, as the weld time increases above 8 cycles, splash begins to occur and therefore the received signal amplitude decreases due to the discontinuities that are formed when the molten metal is expelled from the forming weld nugget.
VI. CONCLUSION AND FUTURE WORK

The various influences on spot weld quality have been discussed, and a novel non-destructive ultrasonic method has been investigated. In these tests, ultrasonic waves were transmitted through both the spot welding electrode arms and the welded sample. Results from the experimental setup showed that as the weld forms, the amplitude of the received signal increases. At the higher weld times, splash occurred, which is a sign of possible discontinuities and the signal strength began to decrease. This is consistent with the reflections that would occur between the steel and the discontinuities because of the change in acoustic impedance.

Further work has seen the construction of two 1 MHz transducers. These have been placed on the electrode arms of the industrial spot welding machine as shown in Fig. 12. In addition to monitoring the resulting received signal amplitude, the phase shift between the transmitted and received signal has also been observed. These tests have been repeated for different electrode cap diameters (4mm, 6mm and 8mm). The heights of these electrode caps also vary. It has become apparent that this phase shift can be used to help monitor electrode cap wear, as the phase shift changes as the electrode caps begin to wear.
REFERENCES


