An online real time ultrasonic NDT system for the quality control of spot welding in the automotive industry

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Abstract. Resistance spot welding is the main joining technique used for the fabrication of body-in-white structures in the automotive industry. The quality of the welds depends on the profile of the spot welding electrode cap. The increased use of zinc coated steel in the industry increases wear rate of the caps, making quality control more difficult. This paper presents a novel online real time ultrasonic NDE system for resistance spot welding which evaluates every weld as it is formed. SEM results are presented to show the alloying of the electrode caps.

1. Introduction
Spot welds are used to join sheets of metal which typically have thicknesses between 0.5mm and 3mm. One sheet of metal is placed on top of another and a current is passed through them using electrodes which are located above and below the two metal sheets [1]. The heat for resistance spot welding is generated by the resistance to the flow of current between the steel sheets, as shown in Equation (1). This contact resistance is dependent upon the surface condition of both the electrode caps and the steel [2]

\[ H = I^2RT \]  

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.

The force provided by the electrodes improves the electrical contact and 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, as shown in Figure 1. Weld quality is an important aspect in the automotive industry where the durability of a car is very much dependent upon the weld quality within the body-in-white structure. It is possible that the parts being welded may not fuse completely, or that the area of the nugget may be smaller than required for a strong joint. 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.

The life time 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 produced are of an inadequate quality [4]. The presence of splash during welding also promotes electrode cap wear.

![Figure 1: Resistance Spot Welding (Inset: Pedestal Spot Welding Machine)](image)

2. Spot weld quality

2.1. Influences on weld quality

2.1.1. Micro-structure of a weld. During welding, the micro-structure of the steel in and surrounding the weld becomes altered due to the rapid annealing from the electrodes. As a result of the vast change in heat penetration throughout the welding cycle, the grain structure of steel becomes altered, which can quickly change the strength and reliability of the material. The micro-structure of this steel before and after welding therefore plays an important part in spot weld quality [5].

The metallurgy of the welded joint can be categorized into two major regions, the fusion zone and the heat affected zone (HAZ). In the fusion zone the solidification completely changes the micro-structure of the steel. 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 sufficient to alter the micro-structure [6]. This area is also frequently susceptible to the development of micro-structural defects due to the often weakened mechanical properties and metallurgic processes involved during welding. If the HAZ spreads to the electrodes the probability of electrode failure becomes greatly increased.

![Figure 2: The Micro-Structure of a Weld](image)

The micro-structure of a weld is revealed by taking a cross-section of the weld nugget, polishing it to a mirror finish and using Nital (a chemical solution of alcohol and nitric acid) to chemically etch the polished weld nugget. This chemical etching of the weld reveals, amongst other things, the
constituent zones of the weld which appear by the intensity of the etching or different colorations. These differences show the structure generated by the welding operation [7].

Here the weld nugget width can be established along with the HAZ, the indentation from the electrodes, and the penetration, as shown in Figure 2. This micro-structure is used to help determine weld quality.

2.1.2. 

**Expulsion.** Splash, also known as expulsion is the unwanted formation of small metal particles that are expelled from the welding area during the welding process. These small particles, that are visible as hot sparks or splash, are usually thrown into the air, which then solidify to form small balls or filaments but can also remain loosely attached to the weld area, as shown in Figure 3.

![Figure 3: Filaments of Splash on the Surface of a Weld.](image)

At a particular current level the weld diameter will reach what is regarded as the minimum acceptable size (according to the British Standard) [8]. If the current is increased beyond this critical level, the size of the nugget will increase until a point is reached when the electrodes can no longer contain the molten metal. This is when splash occurs. The expulsion causes the electrodes to collapse further into the metal which results in a thinner weld, potentially containing discontinuities, which can spread with vibration and lead to weld failure. Part of the expelled metal is often from the electrode itself, which results in a reduced electrode life. Sheet surface contamination can also lead to splash due to the dissimilar thermal conductivities of the steel and the surface contamination. The zinc coating used for galvanisation has a lower melting point (419°C) than steel (1370°C), so this is expelled from the surface before the steel begins to melt.

2.1.3. 

**Electrode cap wear.** As the zinc begins to melt, the electrode force pushes some of this molten zinc to the edge of the mechanical contact area until solid-solid contact is re-established 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 [9]. The current level is increased accordingly in order to help counteract this problem. The zinc from the coating also alloys with the metal of the electrode caps which causes non-uniform pitting of the electrode tip. Figures 4 and 5 show a comparison between a new electrode tips and used ones, which shows the degraded edges of the tip faces [10].

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.

The effect of alloying in used electrode tips makes it slightly harder than the copper of the new tip. This may seem like an improvement, however, the resistance of the electrode caps also increases leading to more heat being generated at the tips [11]. This effectively causes annealing of the electrodes making the resulting brass softer. Brass is made softer by annealing and becomes harder when it is being worked, making it eventually become brittle. Heated brass crumbles easily if it is bent while it is hot, and this occurs due to the high pressures being used and the repeated mechanical impacting at the interface [12].
3. Current NDT techniques

Ultrasonic pulse-echo NDT 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. This type of weld testing has been made compulsory in many welding standards and procedures. It is also the most widely used method within the automotive industry due to the recent advances in ultrasonic equipment and transducer design allowing spot weld testing to be performed quickly and with greater accuracy. It is a method of characterizing the thickness or internal structure of a test piece through the use of high frequency sound waves. The frequencies used for testing using ultrasonics are typically in the range of 0.5MHz to 20MHz which would mean that the resulting wavelength, in steel, would be in mm [13]. The use of frequencies below this range would mean that the interaction of the waves with internal flaws would become uncertain.

The transmit and 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 NDT inspection is rarely used within the automotive industry as access to both sides of the body-in-white structure is often impossible. However, as this paper proposes an online ultrasonic testing system where inspection is carried out simultaneous to welding, the ultrasonic transmitter and receiver can be located on the electrode arms of the spot welding machine.

4. Results

SORPAS© was used to simulate welds in order to find the correct welding parameters prior to real welding, to reduce steel waste [14]. IF180 steel was then used to carry out a set of welds using the parameters chosen from simulations. A current of 7kA and a pressure setting of 3.5bar were the chosen settings.

An experiment was performed offline as proof of principle, using the setup shown in Figures 6 and 7, 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. 50 spot welds were carried out with increasing weld times measured in cycles of 20ms to resemble the forming weld. The produced welds were opened using the peel test and the resultant weld nuggets were measured.

The average nugget diameters for each cycle 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.

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 Figure 8, 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.

### 5. Conclusion and future work

The various influences on spot weld quality have been discussed. A novel non-destructive ultrasonic method has also been investigated. This transmits ultrasonic waves through the spot welding electrode arms. Results from an experimental setup showed that as the weld forms, the received signal will increase in amplitude. Upon the production of discontinuities, the signal strength will then begin to decrease due to the change in acoustic impedance between the steel and the discontinuity from which the transmitted signal will be reflected.

Two ultrasonic transducers are being developed that will have a lower resonant frequency than the transducers used to achieve the results presented. There is no necessity to have high frequency transducers when using the transmit receive technique as overlapping of the transmitted signal and the
subsequent echoes does not occur. An amplifier is also under construction to amplify the received signal. The final system also needs to be tested on an industrial spot weld machine to see whether these results can be replicated.

Figure 8: Ultrasonic Results for IF180, Welded with 7kA and 3.5bar References

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