Energy reduction for the spot welding process in the automotive industry

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Abstract. When performing spot welding on galvanised metals, higher welding force and current are required than on uncoated steels. This has implications for the energy usage when creating each spot weld, of which there are approximately 4300 in each passenger car. The paper presented is an overview of electrode current selection and its variance over the lifetime of the electrode tip. This also describes the proposed analysis system for the selection of welding parameters for the spot welding process, as the electrode tip wears.

1. Introduction
Spot welding is an important welding technique that has been long established and extensively used in industry, especially the automotive industry [1]. The main quality control tests are the destructive chisel test and peel test, which are carried out on welds obtained from the production line of the product [2,3]. These have been supplemented by non-destructive methods [4], where measurement of a representative sample is undertaken, examined and evaluated and if there is a substantial increase in failure, then the whole batch of the products is rejected as faulty. Traditionally, resistance welding process control has been based upon monitoring the voltage and current, or their derivatives, power and resistance [5,6]. While these sensors work well under model conditions, surface contaminants and/or metal impurities can cause under strength or under sized welds to be formed despite the voltage and current values conforming to the ideal standards [7]. Recently, work has been in progress for analysis of every spot weld, as simply having the right conditions for weld formation does not mean that the desired weld has been formed. Therefore, other parameters must be examined as well in order to give a complete picture of the quality of weld formation [8-10]. Recently however, a different concern has come to light, namely that of energy consumption within industry, both financially and environmentally [11].

In practice, the manufacture of welds of acceptable quality depends on the definition of optimum welding parameters and the implementation of suitable controls to ensure constant weld quality over a production run. These methods to optimize the spot welding process can be formalised as Weld Growth Curves and Weldability Lobes [12], which are the industrial accepted methods. The ability to make a weld is best defined by a weldability lobe, which outlines the available manufacturing tolerances between minimum and maximum limits. Both two and three-dimensional weldability lobes exist, which are defined in terms of welding time, electrical current and electrode force.
The weldability lobe can only provide a snapshot of the welding current range, because as the electrode tips wear, the weldability lobe can drift. These two factors are controlled by the interaction between various parameters, which control the temperature distribution in the metal parts during the welding thermal cycle. Galvanised steel typically has narrower lobes and greater electrode wear when compared with uncoated steel. [13]

2. Experimental Setup

Figure 1 shows the spot welding machine used for the experimental trial, which is a TECNA 4621 Pedestal Welder [14]. The top arm is hinged to move down in an arc. On the bottom arm, which is fixed, are several sensors to monitor in real time the weld as it takes place [10]. Sensors used on the machine include current, voltage, cameras, infrared and ultrasonic sensors, as shown in figure 2.

The sensors are placed in positions that give the most effective detection. All these sensors have their readings captured using data acquisition boards and recorded using a personal computer. The data-acquisition program is specifically written for this project in the Pascal based Delphi environment. All the data is captured continuously, and when a weld takes place, the data from 0.5s before a weld to 0.5s after a weld is saved for analysis.

3. Optimal Weld Selection

The process of selecting a suitable current for performing a weld is based upon the parameters within the British standard [7]. This standard carries a guideline set of tables for the selection of welding current and welding time, extracts of which are reproduced in tables 1 and 2. Table 1 and table 2 show the requirement for uncoated mild steel and electroplated mild steel respectively. As can be seen, the force and current requirements are greater for coated steel than uncoated steel because the process has to melt the coating before the actual spot welding can take place.

| Material Thickness (mm) | Force Setting (kN) | Weld Time (50Hz Cycles) | Weld Current (kA) |
|------------------------|--------------------|-------------------------|-------------------|
| 0.4 to 0.6             | 0.9 to 1.1         | 5 to 7                  | 4 to 6            |
| 0.6 to 0.8             | 1.2 to 1.3         | 7 to 10                 | 5 to 7            |
| 0.8 to 1.0             | 1.4 to 1.5         | 9 to 12                 | 6 to 8            |
| 1.0 to 1.2             | 1.6 to 1.8         | 11 to 15                | 7 to 9            |
| 1.2 to 1.6             | 1.9 to 2.1         | 14 to 18                | 8 to 11           |
Table 2: Spot welding conditions for electrolytically deposited zinc coated mild steel

| Material Thickness (mm) | Force Setting (kN) | Weld Time (50Hz Cycles) | Weld Current (kA) |
|-------------------------|---------------------|-------------------------|-------------------|
| 0.4 to 0.6              | 1.5 to 2.0          | 6 to 7                  | 6.5 to 8.5        |
| 0.6 to 0.8              | 1.9 to 2.2          | 8 to 10                 | 7.5 to 9.5        |
| 0.8 to 1.0              | 2.2 to 2.9          | 9 to 12                 | 8.5 to 10.0       |
| 1.0 to 1.2              | 2.8 to 3.6          | 10 to 13                | 9.5 to 12.5       |
| 1.2 to 1.6              | 3.4 to 4.5          | 11 to 15                | 12.0 to 14.5      |

Looking at the tables, there is a range of parameters available for a given metal thickness. These data have been determined by the use of weld growth curves, and weldability lobes. A weld growth curve, as shown in figure 3, is constructed by the method of performing several welds at different power settings, and taking the average size of the resultant nuggets, such that you have a range of input powers covering settings that produce no welds through to power settings that cause ‘splash’. The range of weld types performed covers the following criteria:

- **No weld**: This occurs when there is insufficient current to melt the parent metal
- **Stuck weld**: This strictly refers to the case where, when spot welding galvanised metal, the coating metal having a lower melting point melts, but the parent metal does not. This results in the metals being stuck together, but with minimal mechanical strength, see figure 3.
- **Undersized weld**: This is where a weld is created, but upon destructive testing the nugget is smaller than the required size, which is, according to the BS1140 standard [7], 3.5 times the square root of the thinner parent metal (in mm). This minimum requirement can be overridden by a particular requirement from the manufacturer, such as 4 times the square root of the thickness.
- **Acceptable weld**: This is the condition where the weld nugget is above the minimum size and below any maximum size (if specified) and does not result in splash (expelled metal), see figure 3.
- **Oversized weld (if specified)**: This is the upper size for the weld nugget. If not specified, the acceptable range extends to the current where splash starts.
- **Splash weld**: This is where some of the molten metal is expelled from the molten nugget, causing the electrodes to collapse into the metal further, resulting in a thinner weld.

Based upon the weld growth curve, two acceptable weld points can be specified as being the minimum and maximum currents to produce an acceptable weld, for figure 3 these are 6.2kA and 6.7kA. These can then be plotted on a graph. If the weld growth curve is repeated for different settings for one of the parameters, when plotted, an envelope of points is created, that represent the acceptable values for the
welding current for that parameter. Figure 3 shows the growth curve produced for 2bar gas pressure on coated mild steel, resulting in an electrode force of 1.4kN. If this is repeated for the following pressures, 2.5bar (1.75kN), 3bar (2.1kN) and 3.5bar (2.45kN), which covers the range specified in the British Standard. The growth curves are shown in figure 4 (for uncoated steel) and figure 5 (for coated steel), and the resultant weldability lobe for coated steel is shown in figure 6.

**Figure 4.** Weld growth curves for different electrode forces for uncoated mild steel  
**Figure 5.** Weld growth curves for different electrode forces for coated mild steel

**Figure 6.** Resultant weld lobe for galvanised mild steel growth curves.

### 4. Electrode Tip Life and Weld Quality

To minimise energy usage for the spot welding process, it is desirable to perform the weld with the minimum current required for an acceptable weld, but this leads to a problem. As the number of welds performed using the same electrode tip increases, the tip becomes contaminated with the galvanising coating, effectively alloying the tip. This results in more heat generated at the tip, with a slight reduction in the heat generated in the metals. Thus, if the current is excessive, the tip profile can deform, causing a reduction in the welding current density. This results in a need to increase the weld current to maintain the same nugget size. Figure 7 shows the weldability lobes for electro-plated 0.8mm mild steel. For instance, the data for the gas pressure of 3bar (welding force of 2.1kN), when the electrode is new, the minimum current that can be used is approximately 7.3kA, but as the electrode ages, the minimum current increases, as shown in the table 3. In this case for example, after 1200 welds, the current required to create a minimum sized weld nugget also caused the weld to splash.

In industry, there are two common methods for setting up the welding current:

- Set the current at the maximum acceptable value, which results in excessive energy usage to guarantee the nugget size, and also shortens the tip life, typically to approximately 300 welds.
- Set the current to the mid point between minimum and maximum values, which gives a slightly better energy usage than setting the current to the maximum. The current is then
incremented in steps, e.g. every 100 welds. This strategy increases the tip life to approximately 450–500 welds.

However with an intelligent control algorithm it is then possible to set the current to the minimum value and increment it after every weld to give the minimum energy usage. Figure 8 shows the output of a curve-fitting algorithm to the data in table 3, which gives equation (1).

\[ \text{WeldingCurrent} = 7.3 + 3.1 \cdot 10^{-4} x - 1.1 \cdot 10^{7} x^2 + 9.2 \cdot 10^{-10} x^3 \]  

(1)

where \( x \) is the number of welds.

![Figure 7. Weldability lobes for the increasing number of welds](image)

![Figure 8. Curve fitting algorithm output for minimum current](image)

**Table 3:** Minimum current requirements as number of welds performed increases.

| Number of Welds | Minimum current (kA) |
|-----------------|----------------------|
| 0               | 7.3                  |
| 300             | 7.45                 |
| 600             | 7.6                  |
| 900             | 8.2                  |
| 1200            | 9.1\(^a\)            |

\(^a\) This setting produced nuggets of the minimum size, but they were splashing at the same time.

This rule based solution is acceptable where there is only one parameter to consider, namely the current used for the welding process. However there is no flexibility in the system to unravel the complexity of the spot welding parameters and factors. There are many factors, which affect the process in a factory, for example, fluctuations in gas pressure which affects electrode force, material contamination and variations in electrode cooling. An example of this can be seen in the weld lobe (figure 6), where the minimum current required changes as the pressure changes. Also as the tip wears, the minimum force that can be used changes as seen in figure 6. This illustrates the limitation of the rule-based approach of attaining the minimum current and force in the spot welding process.

5. **Artificial intelligence approach**

To unravel the above complexity, the use of different artificial intelligence (AI) approaches are currently being investigated, (adaptive rule systems, neural networks, genetic algorithms etc) [15] to allow the creation of a system that can take into account the fluctuations in a system by monitoring the process and feeding these parameters into an AI algorithm to generate a prediction of the minimum current required and of the resultant weld nugget quality. This is illustrated in figure 9.
6. Conclusions

It has been shown that an electrode tip can be used for more than the automotive industry recommended lifespan (approximately 500 welds) by reducing the current to the minimum value in order to produce an acceptable weld. This has the advantage of reducing the energy consumption for the welding process, which will have a positive impact both environmentally and financially. This enhancement is currently undergoing further development, which will enable the process to consume less energy by reducing the electrode force to a minimum. It is also envisaged that the artificial intelligence introduction will allow for a reduction in the time that a weld is performed, as well as adapting the system to be used on a different machine, which will give an improved deployment speed and hence reducing manufacturing downtime.

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