INVESTIGATION OF SPOT WELDING ELECTRODE TIP WEAR AND A NON-DESTRUCTIVE TEST OF PLASTIC JOINING IN THE AUTOMOTIVE INDUSTRY

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Abstract

The automotive industry is reliant on resistance spot-welding just as the sandwich making industry is reliant on bread. An automobile contains an average of 5000 welds. The quality of these welds is inspected and governed by certain standards. In order to maintain these standards there are different approaches to quality control. There are many factors that are accountable to a successful weld. The main factors are the voltage across the electrodes, the pressure applied by the electrodes at the interface of the metal sheets, the current applied, the surface condition and the composition of the sheets. The main problem in determining whether a weld complies with the standard is that the most reliable test is a destructive test, which not only destroys a potentially good weld, but it stalls the entire production line in order to perform the test. This is a process where the weld is taken apart sometimes with a chisel. Once the weld is dismantled the quality can be analysed. During the course of this thesis the chisel test, and other comparable tests were carried out. The following thesis presents 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. Data from the practical tests is analysed using SORPAS Software Package in order to compare between real life practical tests, and theoretical simulations preformed in SORPAS. Reducing sparks caused during each weld is another requirement to prevent bumps on the bodywork that may cause further complications at later stages, this project will greatly improve productivity in the production line, since damaged tips can be identified and changed during the manufacturing process. The results show that at a pressure of 4.0bar productivity of welds that conform with the necessary British standards was increased three fold. A new type of non-invasive plastic bond testing is also investigated. This bond testing research was driven by the industrial need for a novel real-time non-destructive method of measuring both the quantity and type of material. Microwave sensors which monitor the change in permittivity of PF glue were developed for this purpose and successfully tested. These sensors have also been used to differentiate between different plastics.

TABLE OF CONTENTS

List of Figures

Chapter 1

Introduction

1.1 Project overview

As a modern vehicle contains 2000 to 5000 spot welds, the strength of the weld under different load conditions and fatigue is very important for ensuring safety. Accurate failure strength criteria for spot welds does not exist due to the wide range of variables involved such as sheet thickness, weld nugget size, metal type and the variety of stress loads that the weld has to sustain. The industry generally carries out extensive testing for defining the welding criteria prior to production runs and accordingly, manufacturers invest in capital intensive studies to come up with the correct parameters for the weld. The dilemma is that these parameters are not 100% accurate because of the complex combination of tension, shear, torsion and bending stresses acting on automotive spot welds. Defining a practical standard for lap shear, impact and cross tension have been continuously investigated by researchers [1].

The common understanding of coalescence is the fusion of two materials as their grain structures merge into one another. The American Welding Society (AWS) defines a weld as “a localised coalescence of metals or non-metals produced by either heating the materials to the required welding temperatures, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler materials.” This means a weld is a joint formed when two materials soften and flow into each other and become one piece [2]. Application of pressure may or may not be necessary; as pressure may be sufficient and cause the materials to join together and form a single piece. This is to say that welding is not confined to metals alone and welds are also performed on plastic, composite and ceramic materials today [2]. For example, in the automotive industry, resistance spot welding (RSW) is an extensively used sheet joining procedure. It has been proven that RSW is preferred because it is both simple and cost effective. There are thousands of spot-welded joints in a car which makes RSW the single most predominant metal sheet joining process in the automotive industry [3]. Therefore, small improvements in making the spot welding process more efficient and/or eco-sustainable can result in the following: Firstly, substantial energy saving and a sizeable reduction of the automotive industry's carbon footprint. Secondly, the industry saves on heavy costs of switching over to new technologies. And last but not least, more efficient spot welding processes will provide competitive advantage to companies.

Spot welding is a type of resistance welding that uses the heat generated by resistance to electric current passing between two electrodes through the work pieces. A low voltage high density electric current is applied while the metallic sheets (or work pieces) are pressed together at the spot to be welded. Heat is produced because of the resistance of metals to the flow of current and is given by the formula "Heat = I^2RTK", where I^2 is the square of welding current, R is the resistance of the work pieces [2], T is the weld time, and K is the heat losses during the weld. The heat softens the metallic work pieces at the location of the spot weld and produces a weld nugget as the pressure is removed. The pressure and the current are usually applied via the same electrodes as shown in Figure 1

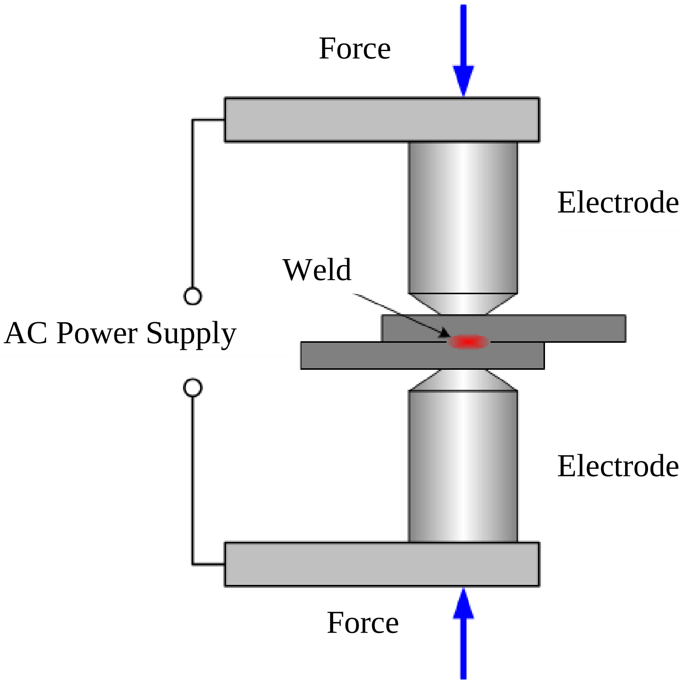

Figure 1: The pressure and the current are usually applied via the same electrodes

1.2 Aims and Objectives

The aim of this project is to increase the spot welding process efficiency by minimizing the disruption of the production line. The process measures each spot as it is welded and identifies faults in the welding tips. This process also aims to reduce greenhouse gas emissions and energy wastage in the widespread spot welding industrial process by suggesting a simple and cost effective mechanism for its control. This thesis presents an overview of electrode current selection and its variance over the lifetime of the electrode tip. It proposes an analysis system for the selection of welding parameters for the spot welding process as the electrode tip wears. This process will show a considerable improvement in the productivity of the production line by making it possible to identify and change damaged tips at an early stage of the manufacturing process. This is because the quality of the weld is monitored through its electrical properties as the weld is performed.

In a nutshell, the main objectives are:

- To find the optimum condition for the spot welding nugget to achieve good welds/nugget.
- To increase the life of the electrode and decrease the power usage.
- To design, construct and implement a real time monitoring system for spot welding technology utilizing an electromagnetic wave sensor and a standalone software package to display the integrity of the spot weld.
- To customise SORPAS software for simulations and optimizations of resistance welding processes.
- To analyse data from practical tests in SORPAS in order to correlate real life practical tests and theoretical simulations performed in SORPAS.
- To investigate energy usage in all spot welding processes.
- To eliminate 'Splash' in order to save energy and the environment.

1.3 Thesis Structure Description

Chapter one introduces the reader to the project, outlines the project's aims and objectives and the need for such research to minimise industrial, financial as well as economical loses. Chapter two describes in brief the history of resistance spot welding, its evolution over time, and provides a literature review of current technologies and common understandings of spot welding theory.

Chapter three identifies spot welding monitoring techniques and explains them in relation to the weld growth curve and the effects on electrode tips. This chapter also highlights the benefits of non-destructive test methods. One of the benefits of this process is that each and every point, as it is welded, is checked and tested, i.e. the weld with different tip life and electric and force parameters. Faults in the tips are also identified by image processing software, and various simulations using SORPAS calculated measurements of the force exerted by the tips on the metal.

Chapter four is based on the analysis obtained from the spot welding processes simulated using SORPAS, a tested and reliable welding software. These processes determine the life of electrode tips, temperature distribution and other parameters. Data from the practical tests were analysed in SORPAS software package in order to correlate real life practical tests and theoretical simulations preformed in SORPAS. The process itself began with using a TECNA 4621 pedestal welder which was fitted with a current meter, a voltmeter and cameras, infrared and ultrasonic sensors.

In chapter five, various types of welds were performed and their parameters were studied using the data from the sensors. Weld growth curves were studied in this chapter with a new electrode tip and with increments of 75 till 1575/welds. By doing so, it was possible to examine the effect of weld parameters on electrode tip wear. And in studying the curves, the optimum pressure setting for the weld nugget was determined. At the end of chapter five, the data capturing techniques are fed into a combination of LabView software in order to calculate the relevant forces from the current, voltage and resistivity of the materials involved.

Chapter six, therefore, presents and introduces a new technology of plastic joining: microwave sensing. This is a rapidly developing technology used as a sensing method for various industrial applications.

And to conclude, Chapter seven presents the end results of the research and identifies the future work that is still needed in the field of spot welding.

1.4 Research Methodology

Multiple methodologies were used in this study. After introducing and describing the aims and objectives of the project and what benefits the study will have in order to make a positive contribution to the field, the history of spot welding is outlined in brief and how it evolved over time within various industries. In order to identify spot welding monitoring techniques, several practical tests had to be carried out at different currents and pressures at various stages of production to achieve the optimum quality of spot welding nugget. Data from these tests were correlated in order to check that they conform with the minimum limits (formula: $4\sqrt{t}$ where t=thickness of the sheets) this is set by the (BSI) British Standards Institute welding standards and specifications, which is put in place to aid welders and manufacturers in their quality control process. Also, in determining the weld growth and the effects on the electrode tips, practical tests had to be carried out and results analysed producing 600 BSI conforming welds instead of 300. In doing so, faults will be identified early enough and less time will be consumed redressing the tips. The practical tests' results were compared with results obtained from using SORPAS simulation.

The use of the methodologies mentioned above has aided the research in achieving the following results: (a) prolonged tip life, (b) reduction of splash, and (c) promoting energy saving techniques. The contribution of this research to the field of spot welding is evident in the methods used and identified to show welders and industries how to control costs entailed in the process and the process' effectiveness, as well as ways of online monitoring. Besides, the research also contributes to the industry by introducing and presenting the implementation of a new technology, i.e. plastic joining using an electromagnetic microwave sensor, and the benefits of using it as an alternative to spot welding.

Chapter 2

History of Welding

2.1 Welding History overview

The history of welding goes back to at least 3,000 years BC, as archaeological finds in Iraq and Egypt depict. It was the Sumerians in the Bronze Age who first made swords by hard soldering. Iron was smelted in around 1500 BC, but it was not common until 1200 BC. The iron and bronze items discovered at excavations near the Egyptian pyramids are from 1000 BC and were forge welded. Welding was mainly used in the Iron pillar in Delhi, India, about 310 AD, weighing 5.4 tonnes [4], as shown in Figure 2

Figure 2: Delhi Iron Pillar 310 AD [5]

Ancient methods of joining metals usually included making a sand mould and casting the desired shape directly on the base metal. Another procedure involved pouring molten metal between two work pieces [2]. Welding was reintroduced in Europe then the Middle East in the 8th century BC. Steel was not easy to produce with the methods available at the time, and other alloys were easier to make, such as wrought iron. The earliest history of forge welding, smelters and blacksmiths in Europe can be traced back to the age of the Vikings (AD 870 to 1000) and Early Medieval period (AD 1000 to 1264) in Iceland. However, the exact extent of the trade and its contribution to the society is hard to determine because of the lack of writings available on the subject. Historical evidence suggests that as the Norse spread in Europe and colonized, they lay special emphasis on finding new sources of raw iron and smelting it to form the tools necessary for their expansion, like agricultural implements [6, 7]. The Middle Ages brought forge welding as a method to improve the steel edges; at the time blacksmiths did this by pounding hot metal until it bonded. Vannoccio Biringuccio, an Italian metallurgist, released a paper account called, 'De la pirotechnia' in 1540. It is basically a detailed account of mining and how to extract metal, including descriptions of the forging operation. It was the most comprehensive document of metallurgical, casting and smelting techniques and comprised "ten books in which are fully treated not only every kind and sort of mineral but also all that is necessary for the practice of those things belonging to the arts of smelting or casting metals and all related subjects". It is the first printed book dealing with the applied metal arts and the processes of ore reduction [8]. Forge and hammer welding was the predominant method of welding in Europe during the industrial revolution between 1750 and 1850. Consequently, it remained the preferred technique of joining until Elihu Thomson patented the resistance welding technique in 1886 [2, 4].

As Renaissance craftsmen continued to gain mastery of the welding process, it continued to grow and improve during the centuries after the industrial revolution. In the 1800s Sir Humphrey Davy discovered the electric arc, which mainly remained a scientific curiosity until the last part of the nineteenth century, when electric power supplies became available. Vasily Petrov (1802), another Russian, is also known for his discovery of the electric arc and its possible use in welding metals. It was in 1885 that Nikolai Bernardos received a patent for working metals with electricity and used a carbon electrode arc to weld and coat metals and used a coloured glass screen to shield the eyes of the workers [9]. Welding continued to advance with the invention of the metal electrode by a Russian engineer Nikolai Slavyanov (1888) and an American scientist C.L. Coffin (1890). A. P. Strohmenger, a Briton, introduced coated metal electrodes in 1900, which gave a more stable electric arc. The first carbon arc torch had already been invented by the French inventor Auguste de Mertiens in 1881.

Russian scientist Vladmir Mitkevich proposed the use of a three-phase electric arc for welding, in 1905. In 1919, alternating current welding was invented by C.J. Holslag, but did not become popular for another decade. During the end of the 19th century resistance welding had been developed with the first patents going to Elihu Thompson in 1885. The process continued to progress further over the next 15 years. However rival welding processes like thermite welding and oxyfuel welding were developed around the same time. Thermite welding was invented in 1893. Oxyfuel welding also became well established and competed with resistance and arc welding. Edmund Davy had discovered acetylene in 1836, none the less it was not practical in welding until the 1900’s, when a suitable blowtorch was developed.

Oxyfuel welding initially became more popular because it was portable and relatively low cost. As the 20th century progressed, it was largely replaced with arc welding as shown in Figure 3, as metal coverings for the electrodes continued to improve and the arc became more and more stable. The two world wars spurred welding technology into a new era of rapid development. Welding technologies used for manufacturing and repairing ships and aircraft were sometimes highly secretive. And as a result, the 1920s saw the introduction of automatic welding in which the electrode wires were continuously fed. Scientists paid attention to the details of the welding process such as the atmospheric gases surrounding a weld and weld problems like porosity and brittleness. Solutions were developed for these problems by using helium, hydrogen and argon as gases for the weld atmosphere. New technologies were introduced for welding reactive metals like aluminium and magnesium.

Figure 3: Representation of Arc welding

The technologies that evolved during 1930s included automatic welding, alternating current, and fluxes. Arc welding continued to develop as submerged arc welding was invented in 1930 and the first underwater arc welding was successfully carried out in 1932. The 2^{nd} World War further fuelled the growth of welding process as Gas Tungsten arc welding was perfected in 1941 and Gas Metal arc welding was introduced in 1948, allowing for fast welding of non-ferrous materials. These processes required the use of expensive shielding gases, so in 1950s shielded metal arc welding was developed, followed by flux-cored arc welding, in which the self-shielded wire electrode could be used with automatic equipment. Both these technologies greatly improved welding speeds and rapidly gained popularity. Plasma welding was invented in 1957, followed by electroslag welding and electrogas welding in 1958 and 1961 respectively. More recent Welding Technologies include electron beam welding, laser beam welding, electromagnetic pulse welding and friction stir welding. These welding technologies are used in specialized applications and automated equipment and their higher costs of equipment preclude their widespread adoption by the industry.

2.2 Literature Review

In this section, the aim is to shed light on the current understandings and usages of spot welding and also to present some current technologies in the field.

Firstly, the current understanding of spot welding and its usages will be described here. Through extensive investigation and experimentations, it has been concluded that the common understanding of resistance welding is that it is a type of fusion welding that utilizes both heat and pressure to soundly join two materials. Spot welding, seam welding, projection welding and butt welding are the various forms of resistance welding. Spot welding is the simplest form of resistance welding, in which two or more sheets are clamped together under pressure and heat is generated by resistance to electric current passing through the work pieces that are to be joined. As any current, generally ranging from 1000 to 100,000 amperes [10] is passed between the electrodes, the resistance of the metal sheets produces enough heat to melt the pieces and fuse them together at the point where pressure is being applied, forming a weld nugget. The heat generated is a function of the current, the duration for which the current is passed and the resistance of the work pieces. The resistance depends on of the resistivity and the condition of the surface of the sheets that are to be welded. It is also a function of the size, shape and material of the electrodes and the force applied by the electrodes. For instance, aluminium is harder to resistance weld as compared to steel, because it has a higher electric conductivity and requires higher welding currents [11]. Moreover, the electrodes are made from copper which forms an alloy with aluminium when heated. This results in rapid wear of the electrode surface and a shorter electrode life. Spot welding is a cost effective, simple and economical technology especially when it comes to large scale production, as in the automotive industry, where RSW has been extensively used [12]. Therefore, spot welding methods are generally less polluting and more efficient, but their applications are somewhat limited and they are predominantly used to join metal sheets up to 3 mm thick [13].

The important characteristic of spot welding is that, a lot of energy can be delivered to the spot in a short time and the welding heat does not affect the rest of the sheet. As shown in Figure 4, spot welding requires a specific combination of pressure, current intensity and duration. It is a very fast process and can be repeated over and over with little interval, hence it is more suitable for repetitive sheet welding processes. There are three common stages for spot welding: Firstly, one that involves applying a small amount of pressure by using the electrodes on the metal. The second is welding two materials together to conduct electricity through the work pieces. And the third involves removing the current from the cold work piece which is cooled by the coolant flowing through the centre of the electrodes. In most of the spot welding mechanisms, water and brine solutions are used as coolant [14].

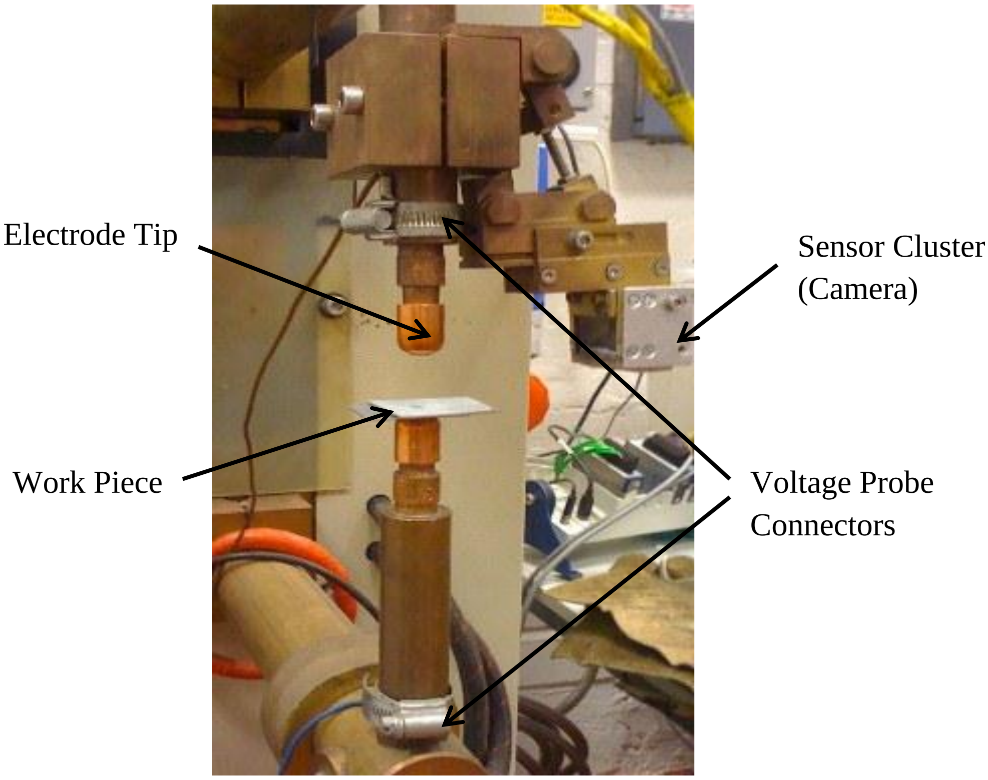

Figure 4: Electrode tip and Work piece

Secondly, it is important to know the current technologies in the field of spot welding. The highly competitive nature of the automotive industry makes it always in demand for improvements and precision engineering [15]. There are, thus, various current technologies in the field of spot welding. Errors and problems due to tip damage and wear can cause great losses due to halts in the production line. The current system used by automotive manufacturers is to check of the quality of nuggets cars, once every two weeks. The test method is offline, and it is done destructively; it is a 10 day process. If the sample is proven to not conform to the BSI standard, then the 10 cars prior to the sample car are scrapped and all cars after the sample are also scrapped. This causes a long delay in the production process. In order to determine the current efficiency of the existing technology, several experiments were set up to monitor the step-by-step degradation in weld quality. The experiments were performed initially on coated 0.8mm sheets, the variables were current, voltage, force, water coolant and pressure. To check the quality of the weld as shown in Figure 5, it must be checked by destructive testing.

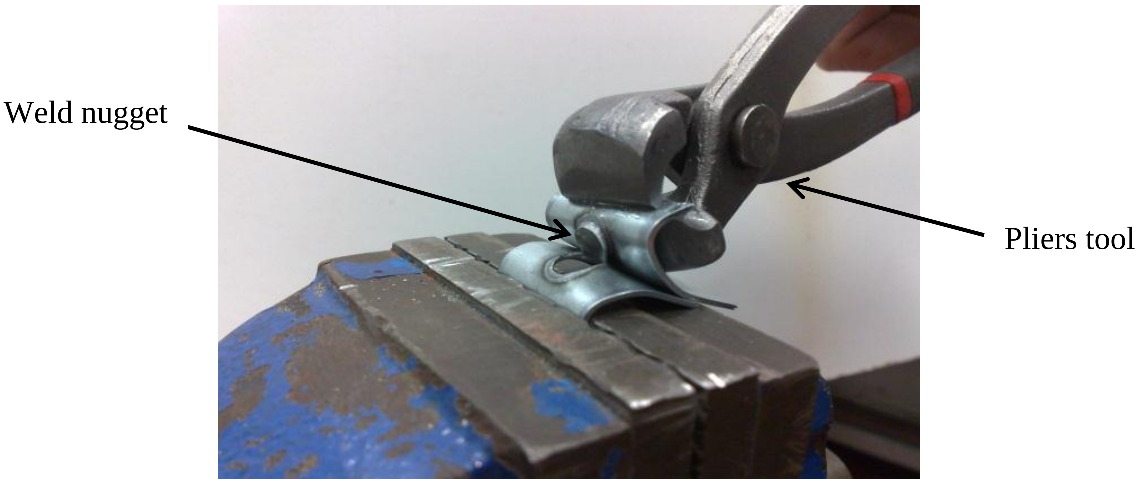

Figure 5: Destructive Spot Welding Offline

There are many types of spot welders available [16]. For this research study, the pedestal type spot welder is used. The pedestal type has a fixed vertical pedestal frame and integral transformer and control cabinet. The bottom arm is fixed to the frame that is stationary during welding, and takes the weight of the work piece. The top arm is hinged to move down in an arc. The pivoting arms are adjustable so as to have an adjustable gap between the electrodes, the arms are easily adjusted in the hubs and various length arms are able to be fitted giving access to difficult joints, Figure 6 shows the TECNA 4621 Spot Welding machine used for these trials as an example of current technology used in the field. This unit used has fully adjustable current levels suitable for light and medium industrial use.

Figure 6: TECNA 4621 Spot Welding Machine [16]

Additional sensors were added to the spot welding machine, as shown in Figure 7. The current sensor (not visible) is a Rogowski (air cored) coil [17]. This sensor gives a voltage output proportional to the current induced through the arms of the spot welder. The voltage sensor is, simply, two leads connected to each spot welder electrode. This signal is then passed through a buffer/ amplifier circuit and into a data logger within a PC. A through weld ultrasonic system is also used with the system, mounted at the top and bottom of the upper and lower electrode arms respectively, the collected data passes through a preconditioning circuit before being fed into the data logger. Typically for 0.8 mm galvanised steel, 0.2 sec (10 · 50 Hz mains cycles) is used for the weld time, the pre time of data capture is 0.3 sec (15 · 50 Hz mains cycles) and the post time is 0.5 sec (25 · 50 Hz mains cycles). This allows the data to be captured from before the electrodes are in contact with the metal, to after the electrodes are removed from the metal, which provides a full data set for the ultrasonic profile.

(1) Ultrasonic Transmitter

(2) Adjustable Cluster Bracket

(3) Monitoring cluster containing Camera

(4) Voltage Probe,

(5) Ultrasonic Receiver,

(6) Rogowski current sensor

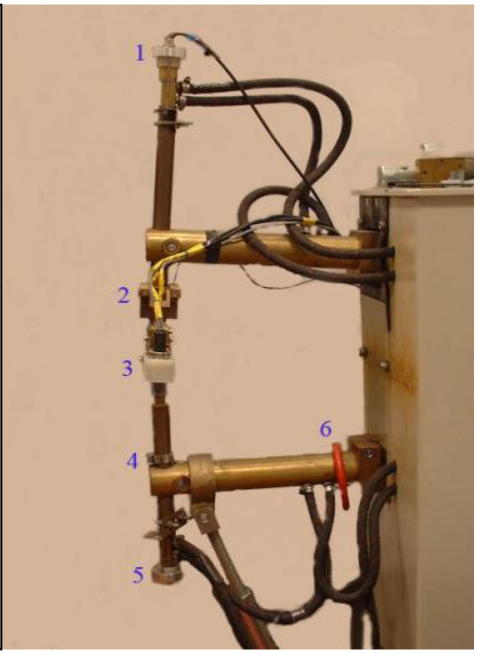

Figure 7: The Experimental sensors setup

The critical assessment of this literature review is that although the industry is in debt to these new technologies and to their usages, more research is required in order to further improve the use of these new technologies identified above and the overall efficiency of the process of spot welding. As is evident for some of these technologies, there are disadvantages for their usages whether in terms of costs, time spent, material waste, human effort, and energy consumed and more importantly, the overall safety of the user and the quality of the weld. In order to eliminate some, if not all, of these disadvantages, further tests are required and research into more energy efficient methods of spot welding without affecting the weld quality and ensuring that all safety measures are covered.

2.3 Current Research on Spot welding Quality

The ongoing research in the field of spot welding is largely concerned with ultrasonic testing. Takada et al [18] for example have used Lamb waves for non-destructive evaluation of spot welds, and Chena et al [19] have investigated pulse echo for non-destructive ultrasonic testing of spot welds. Some researchers are, however investigating spot weld quality. Lee et al [20] have used Neuro-Fuzzy inference system to control expulsion. Ozsarac [21] has investigated the properties of spot welds galvanized sheets in the automotive industry to find the optimum welding parameters for measuring joint strength. Ru-xiong [22] could determine the different weld properties through U-I curves by using a data acquisition at a frequency of 10kHz. This enables monitoring of the spot weld process of different materials that reflect different U-I curves.

2.4 Spot Welding Theory

Resistance spot welding requires the following basic equipment:

1. A mechanical system to hold the work-pieces together and apply pressure through the electrode.
2. An electric system that includes a transformer, a capacitor, a current regulator and a secondary coil to deliver the required amount of current to the electrodes.
3. A control system to regulate the time and pressure of the welding cycle [23].

There are generally three types of spot welding machines: rocker arm type, press type and portable type. The rocker arm type machines are used very commonly and utilize a foot pedal, air pressure or electric motor to apply pressure on the top electrode. These machines typically have a power supply between 10 and 20 kVA. Press type machines use hydraulic cylinders to press the upper electrodes; they are used for welding heavy sections. These have transformers up to 500 kVA. Portable welders are complete with hydraulic cylinders, transformers, electrode holders, electrodes and regulatory controls and are used when the work pieces are too heavy to be moved. Assembly lines generally use multiple spot welders to increase speed and conduct long welding runs. The distance between the electrodes on a multiple spot welder can be adjusted to suit the type of work [23]. Welding timers are built into the machines and control the time duration of the following four steps:

Squeeze Time: The time between the first application of electrode force and the application of electric current.

Weld Time: The actual time for which the current flows.

Hold Time: The time for which the electrode force is applied after the current is removed.

Off Period: The time for which the electrodes are not contacting the work pieces [23].

Different types of power sources can be used for spot welding depending on the nature of work and material. For instance, five different types of power supplies could be used for spot welding of aluminium. Other factors to be considered for the power supply include the primary current available, the output current required, the amount of space required between and around the electrodes and the portability of the equipment. Power supplies used for spot welding include single phase AC, 3 phase AC, and secondary rectified inverters. AC power supply is generally simpler, while secondary rectified three phase DC power supply is very efficient, light weight and can deliver a high current at low voltage [12]. By tradition, resistance welding process control has been based upon monitoring the voltage and current, or through observing their derivatives, power and resistance [24]. These control techniques work well under ideal conditions; however, surface contaminants and/or metal impurities can cause under strength or under sized welds to be formed, even with the voltage and current values meeting the requirements of the ideal standards [25]. Research work continues in which every spot weld is analysed to find out the right conditions for weld formation; however, this does not mean that the desired weld has been formed. Hence, physical post weld parameters have to be examined as well in order to give a thorough analysis of the quality of weld formation [26].

Time Control: Resistance spot welding uses resistance of the base metal to generate heat. Thousands of amperes are normally used in making good quality spot welds as shown in Figure 8. The other important factor is time. The time control in the four steps mentioned above must be precisely accurate in order to maintain weld quality [27].

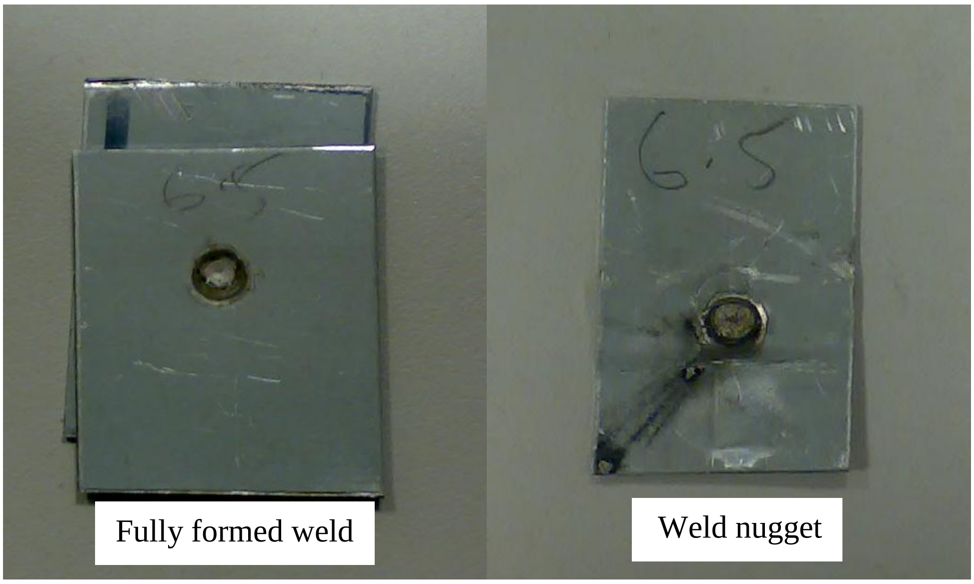

Figure 8: Good quality spot weld nugget at 6.5kA before and after the peel test

Force Control: Pressure is the force applied at the electrodes when the weld is taking place and holds the work pieces in tight contact. Its purpose is to push the pieces together, which must be clamped in skin to skin overlapping contact. Research has shown that when a certain pressure value is exceeded, the resistance at the weld location drops, necessitating higher current to generate the required heat. The effects of pressure should be carefully studied before making any changes to the force [27].

Electrode Tips: The shape, material and size of welding electrodes also play an important part in the spot welding process. For optimum performance, the welding electrode tips must maintain their shape and conductivity throughout the welding process. The Resistance Welders Manufacturing Association has categorized electrode tips into two classes based on the material composition: copper based alloys and refractory material tips. Copper based alloy electrode tips are commonly used in spot welding machines. Refractory material tips are a sintered mixture of copper and tungsten and have 40% or less conductivity of that of pure copper [27].

Deterioration of Electrode Tips: The automotive industry is increasingly using aluminium alloys to reduce the weight of the vehicles while retaining or improving safety and strength. Aluminium and magnesium alloys have better strength and lower weight as compared to mild steel, which makes them suitable for manufacturing modern automobiles. Aluminium presents particular problems in welding because it has low resistance and welding time, whilst having higher thermal conductivity. This necessitates a higher current for less time, which means that the voltage and the current have to be controlled more precisely in a shorter period of time [28]. Besides, the relatively shorter life of the electrode tips can become a major hindrance in mass production of spot weld joints. The rapid deterioration of welding tips is the result of high temperature, high pressure and alloying of copper with aluminium [29]. As the electrode tip wears as shown in Figure 9, the quality of the weld is immediately affected giving rise to phenomena like Cavitation, Pick up and Pitting. Different ways are adopted to increase tip life and reduce these problems. Some welding lubricants have been proven to reduce tip wear and the alloying effect. Resistance Welders Manufacturers Association recommends group A class 1 copper alloy welding tips for spot welding of aluminium -because the weld requires a higher current and that leads to better electrode tip conductivity [28]. Electrode tip wear and the variation of spot welding quality remains a major problem in large scale spot welding processes associated with the automotive industry. Thermal conditions at the faying surface (work-piece-work-piece interface) and the work-piece-electrode interface are critically important. While adequate temperature at the faying surface is essential for quality of the weld, excessive heat at the work-piece-electrode interface will shorten the life of the electrode. Knowledge of temperature distribution in the electrode cap is important for improving electrode cap life, power consumption, quality and economy of the spot welding process. To prevent melting at the work-piece-electrode interface, water is circulated inside the cooling chambers of the electrodes. Studies have revealed that temperature develops very rapidly at the electrode tip surface, which highlights the difficulties expected for designing tips for spot welding materials with a low melting point [30]. Worn electrodes can be redressed by removing the tip surface deteriorations in the automotive industry robotic welding arms will move to a park position after around 300 welds in order for the electrode tips to be redressed.

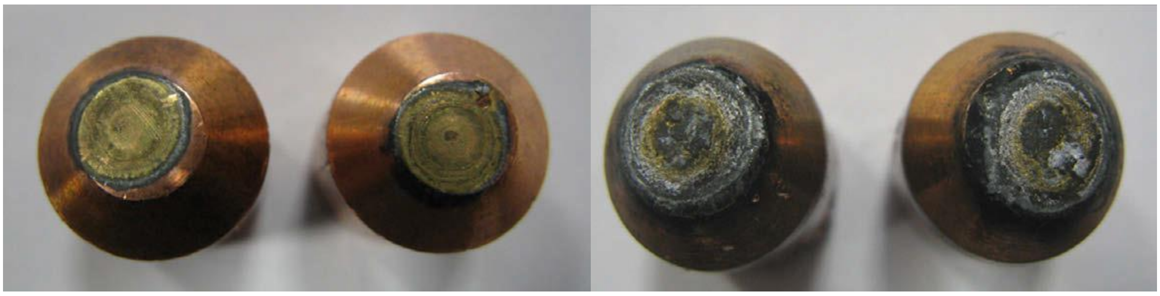

Figure 9: Deterioration of Electrode Tips

Electrode Geometry: Electrode geometry greatly influences current distribution around the electrode tip and the life of the electrode tip. Higher work-piece-electrode interface angles provide a more even current distribution. This results in uniform heating of the electrode surface around the tip. The peripheral area of the tip acts like a heat sink and reduces irregular electrode wear, giving better weld quality over long term use. However, because of heat absorption in the area adjacent to the tip, higher work-piece-electrode interface angles gives rise to the Mushrooming effect at the tip. Nied [31] has concurred with Greenwood [32] that the current concentration is maximum around the circumference of the tip in the initial stages. Once the current passes through the work-pieces, it does not flow straight but diverges. Therefore, a nugget weld is formed. If the current is strong enough to cause a weld in the initial stage, it would make a ring weld as noticed in the automotive spot welding. Weld quality and electrode life change as the angle at the tip-work-piece interface is varied.

Weak Weld and Expulsion:

An insufficient current, less welding time and excessive pressure during the spot welding results in a stuck weld. It is a weak weld and may fail under dynamic load conditions [33]. On the other hand, excessive current and/or welding time cause the phenomenon known as "expulsion" or "splash" and results in an oversized weld nugget; as shown in Figure 10 when more than a certain amount of current flows through the work-pieces under insufficient pressure, molten metals are expelled from the work-piece-electrode interface. Expulsion deteriorates weld quality and accelerates electrode wear; therefore, it must be controlled.

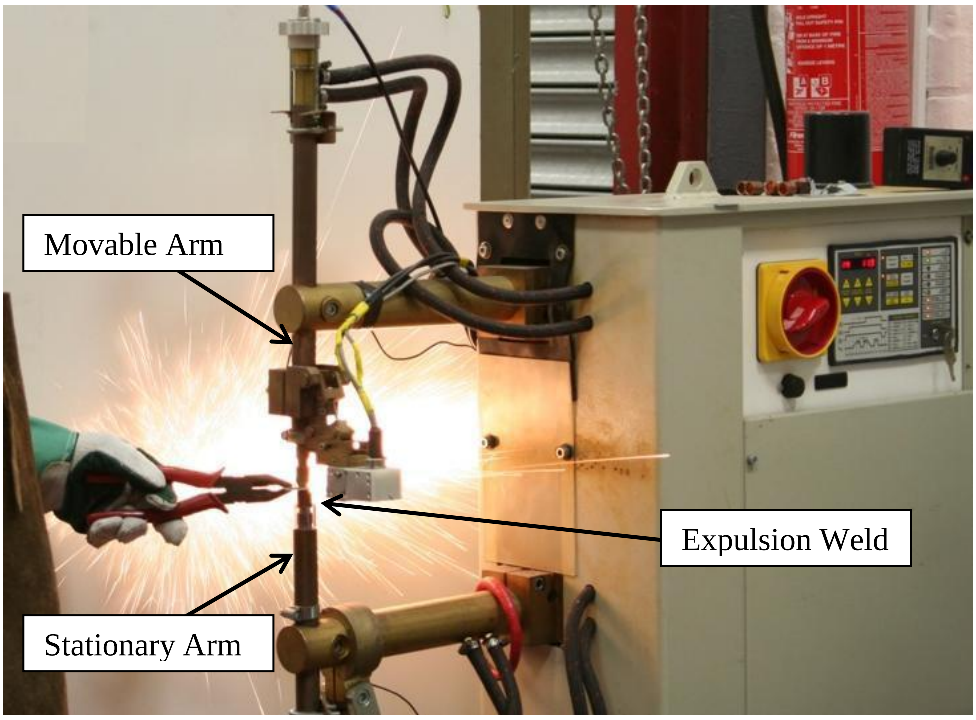

Figure 10: Practical representation of the Expulsion

2.5 Joining Types

The electrodes used can differ with different applications. They are used for high heat applications with a condensed tip for high pressure. For instance, in seam welding shown in Figure 11, which is a variant of resistance welding, disc or wheel shaped electrodes are used that roll along the work-pieces and create long seams of resistance welding. There are other variants of welding; namely: resistance welding, butt welding, projection welding, flash welding and upset welding.

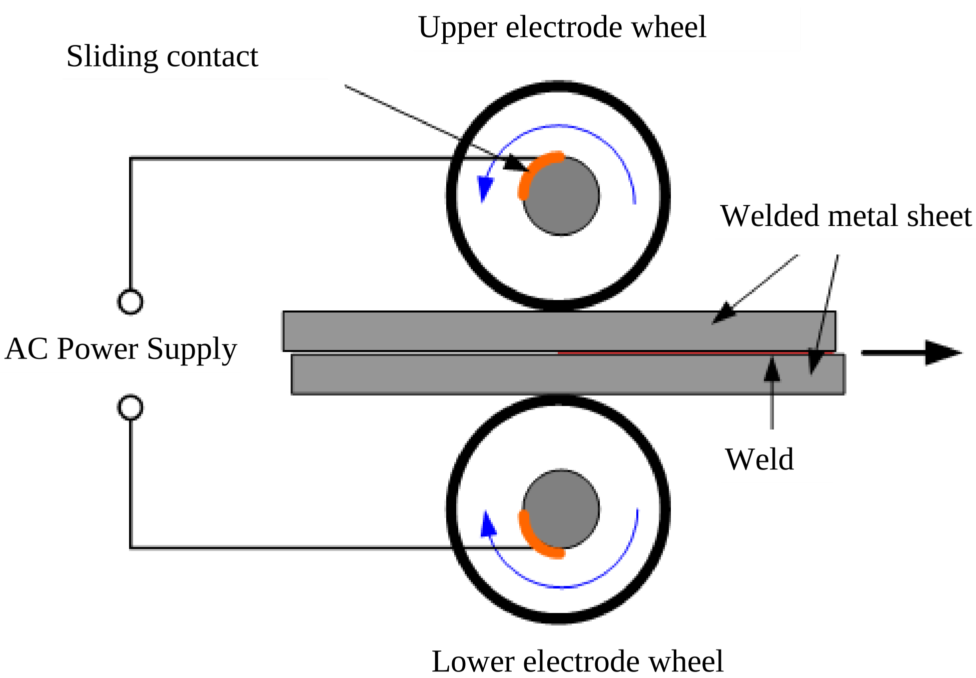

Figure 11: Resistance Seam Welding [34]

Shot welding, a specialized type of spot welding is carried out to join stainless steel [13]. Projection welding is used for joining captive nuts onto plates. Butt welding joins metal sheets from the inside and flash welding is a type of butt welding that uses resistance to heat the joining surfaces before forging them together under pressure as shown in Figure 12.

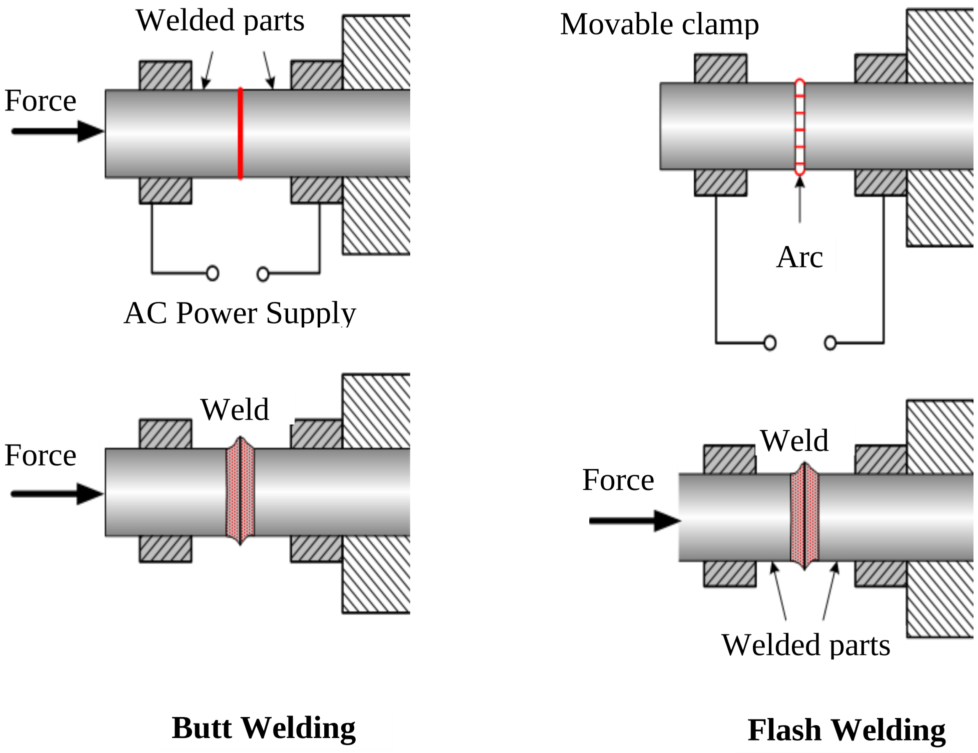

Figure 12: Resistance Butt welding and Flash welding [34]

In this sense, it differs from spot welding which only performs lap welding between overlapping metal sheets [29, 35]. A lap weld is defined as a weld where two metal sheet parts are overlapped adequately to give an ample area for the application of tile tips or electrodes used in making the weld. As shown in Figure 13

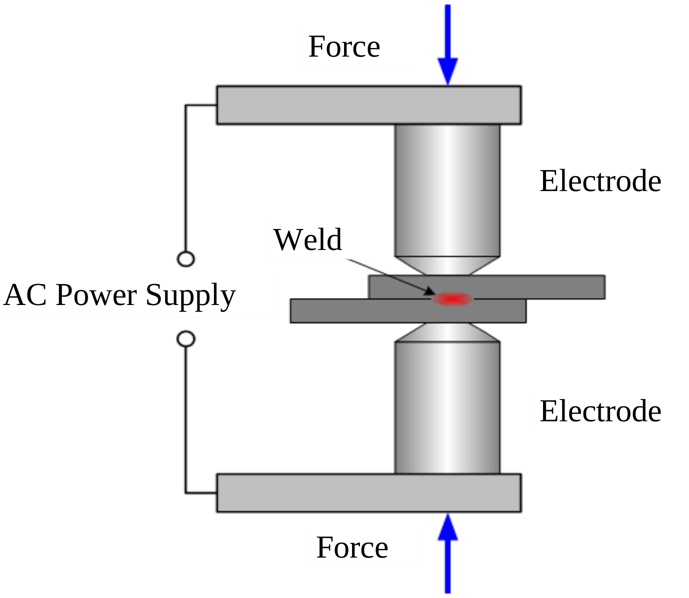

Figure 13: Resistance Spot welding [34]

2.6 Metal Joining Non-Destructive Test Techniques (NDT)

With over a hundred million spot welding joints being manufactured every day in Europe, spot welding quality is checked primarily by two methods: destructive and non-destructive testing.

2.6.1 Destructive Testing

Post weld destructive testing is necessitated in most industries and is the most common method of analyzing weld quality. In the destructive testing, the joint is torn apart by different methods and the diameter of the weld nugget is measured to deduce weld quality. The main quality control tests are the destructive chisel test and peel test (for thin sheets). As shown in Figure 14. Those tests are carried out on welds obtained from the production line of the product. These are simple tests carried out to take the weld apart by driving a chisel between two spot welds or by peeling away the sheets with the help of calipers or other mechanical means. Once the weld is disjointed, the nugget diameter is measured which must at least conform to the lower limit [36], which details minimum quality control requirements in relation to destructive testing of resistance spot welding and projection welds.

Other destructive testing methods include impact, cross tension testing, torsion, fatigue, metallurgical sectioning and examination, and hardness testing. All these tests are designed to measure weld parameters. Cross tension testing determines the ductility or the hardness of the spot weld joint [37].

Figure 14: Representation of destructive chisel test and peel test

2.6.2 Non-Destructive Testing:

Non-destructive methods include procedures such as ultra-sound testing, in which high frequency sound waves are transmitted into the weld joint and their reflection is measured to check the consistency of the weld joint. Ultra sound testing requires highly trained staff and a special testing facility [38].

Other common non-destructive methods include batch testing, in which weld nugget measurements of a representative sample are recorded, examined and evaluated. If the weld quality does not conform to the parameters as specified by the BSI, the whole product batch is labelled faulty and becomes rejected; because of the intense heat and displacement of sub-atomic particles caused by the passage of current, the micro structure of steel is altered and can affect the quality and strength of the weld. Thus, it is important to examine the granular microstructure of the steel before and after the weld in order to assess the weld quality [39].

The inner region of the weld nugget, where the structure of steel particles completely changes and the two work-pieces fuse together, is known as the Fusion Zone. In addition to the Fusion Zone, the surrounding metallic structure is also changed due to heat, but it is not melted and fused together like the Fusion Zone. This area where the microstructure changes but melting does not take place is adjacent to the Fusion Zone, and is known as Heat Affected Zone. Because of the change in structure, the Heat Affected Zone (HAZ), shown in Figure 15, becomes vulnerable to spot welding defects like fissures or failure under fatigue. If a higher current is passed through the electrodes, the HAZ extends to the electrode caps and rapidly accelerates electrode wear, causing them to fail [40]. In destructive testing, the microstructure of the spot weld joint is examined by dissecting the weld nugget and revealing its cross-section. The cross-section is polished to a mirror finish and a chemical solution of nitric acid and alcohol (Nital solution) is poured onto it to cause chemical etching of the weld joint. Etching highlights different portions of the joints in different shades, revealing the changes in structure caused by spot welding [41].

The weld quality is determined by observing factors such as the distance between the HAZ boundary and the centre of the Fusion Zone, the size of the Fusion Zone and the size of the HAZ.

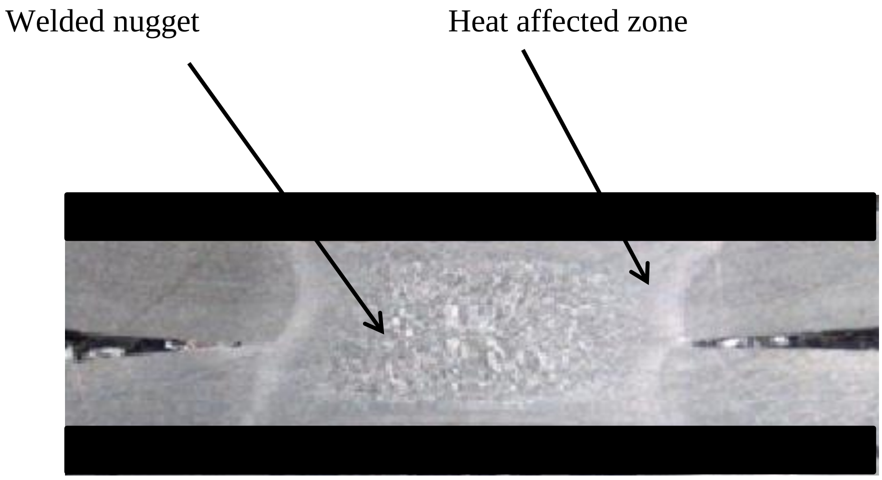

Figure 15: Examination of Spot Weld Nugget [42]

2.7 Current Industry Problems

This highly specialized and technically demanding industry requires extensive monitoring and testing at set production intervals as required by BSI standards. This takes the industry into numerous expenses and time-consuming processes which ultimately leads to production down-time which in itself translates into an expense.

To focus on just the issues within the industry that directly relates to spot welding, there are three main hurdles to overcome:

1. Delay in production: Current industrial monitoring procedures destructively check the quality of all the nuggets in a car once every two weeks. The nuggets are examined off line which takes approximately 10 days to complete. This can lead to significant financial losses which means that an on-line non-destructive would certainly reduce these losses.
2. Expulsion: A common phenomenon in resistance spot welding. It is the ejection of molten metal during welding. It occurs at the interface between the electrode tip and the work piece [43]. This can obviously affect the surface quality and electrode life. The expulsion is highly inconvenient since it involves loss of liquid metal from the nugget. There are also safety issues that can arise from expulsion of metal fragments at high speed. A metal particle travelling at such high speed can cause serious damage to the operator if proper protection is not used. The expelled particles can also embed in the body of the steel vehicle and this adds to the workload of the production line in order to remedy the irregularity of the vehicle surface.
3. Lost energy: Loss in energy means financial loss as well as an increase in carbon dioxide emissions which can have a detrimental effect on the environment. Other factors that can contribute to the loss of energy or over usage of it can be the wear of the electrode tip or alloying of the electrode tip with the workpeice. Alloying leads to an increased resistance to the current. To counteract this, the operator would have to increase the current flow through the electrodes to maintain the same weld quality and

nugget size and although the quality has been maintained, the cost can start to rise exponentially.

2.8 Proposed Solutions

From extensive research and the three identified problems mentioned above, the proposed solutions are:

1. A method for minimising, if not eliminating altogether, expulsion (splash) is by controlling the current cycles in order to reach optimum results and maintain a safe work environment.
2. By implementing non-destruction testing and eliminating expulsion altogether by 96% and above, energy loss will not be an issue. Taking all these factors in consideration, the production will be doubled and the wear of the electrode tip will be significantly reduced. Time will be conserved as a result of only having to redress the electrode tips every 600 welds instead of 300 welds.
3. The final proposal is to introduce to the industry a non-destructive test method of plastic joining which can be used in the car industry. Manufacturers have been replacing many metal parts with plastic materials, in order to reduce weight and increase economic performance. In this method, the research would be able to offer feasible solutions for environmental issues and sustainable energy.

2.9 Welding Techniques

The automotive industry uses spot welding for thin metal sheets. The thickness of the sheets is 0.8 millimetres. The sheets are placed one on top of the other between the welding electrodes and a current is passed through them as shown in Figure 16, which produces a localized melting of metals due to the heat produced by the resistance of the metals to the electric current. The resistance depends upon the condition of electrodes and steel sheets [44]. The heat produced is given by the formula

$H = I^2RT$

Or

Heat = Square of Current in Amperes * Resistance in Ohms * Weld Time in seconds [45]

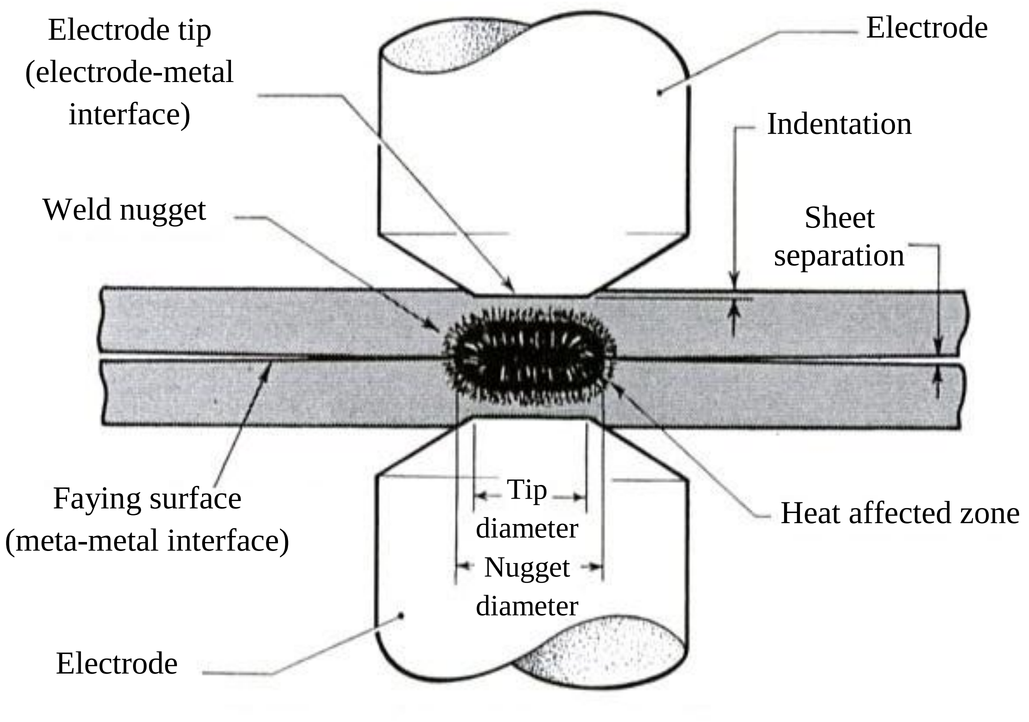

Figure 16: Formation of Weld Nugget

The electrodes are compressed by mechanical means to apply pressure on the metal sheets and press them firmly together to form a good quality weld. However, because of the deterioration of the electrode caps, the weld quality may not remain consistent. Electrodes are worn out as the number of spot welds they perform increases. As the resistance drops, the heat also drops, causing improper weld generation. Welding problems may include cold welds or welds with undersized nuggets. Electrode wear rate increases on galvanized steel sheet, as the zinc coating interacts with the electrode caps [46]. Expulsion and splash, which involves ejection of molten metal from the weld location, also indicates poor weld quality, apart from contributing to rapid electrode tip wear [15].

Real time monitoring is an important technology which is energy efficient for the spot welding process. It precludes the delays and wastage caused by Destructive Testing, which discovers the fault too late to be less wasteful. Ultrasonic monitoring is used in real time for monitoring the quality of the weld as it is made.

2.10 Weld Growth Curve

A certain minimum value of current is required to form an acceptable quality spot weld joint according to the specified weld nugget diameter standards [47]. As the current is increased beyond this critical value, the diameter of the weld nugget continues to increase, until a time when the molten metals cannot be controlled by the electrodes and are ejected out of the weld joint. This phenomenon is known as Splash. As pressure is applied on the electrodes, expulsion causes them to sink deeper into the molten work pieces and causes thinning of the weld joint. The splash can also contain molten metal from the electrode caps, which rapidly deteriorates electrode tips. Splash can also occur because of uneven conductivity if the surfaces of the work-pieces are contaminated or coated, as in the case of galvanized steel. The zinc coating has a melting point of 419°C, so it melts and splashes from the joint before the steel, which has a melting point of around 1370°C. Expulsion is a common phenomenon in resistance spot welding and is the ejection of molten metal during welding as shown in Figure 17. It occurs at the interface between the electrode tip and the work piece [43]. This can obviously affect the surface quality and electrode life, but not the strength of the weld if it is limited to the surface. In terms of weld quality, the expulsion is highly inconvenient since it involves loss of liquid metal from the nugget. There are several possible causes of expulsion including; an unexpected gap between the metals, dust particles between the metal surfaces, a greasy metal surface, a reactive chemical compound within the metal or coating, and an unnecessarily high current. Generally expulsion is increasingly expected when greater currents are applied; however, it is still possible to meet the weld nugget requirements in some circumstances.

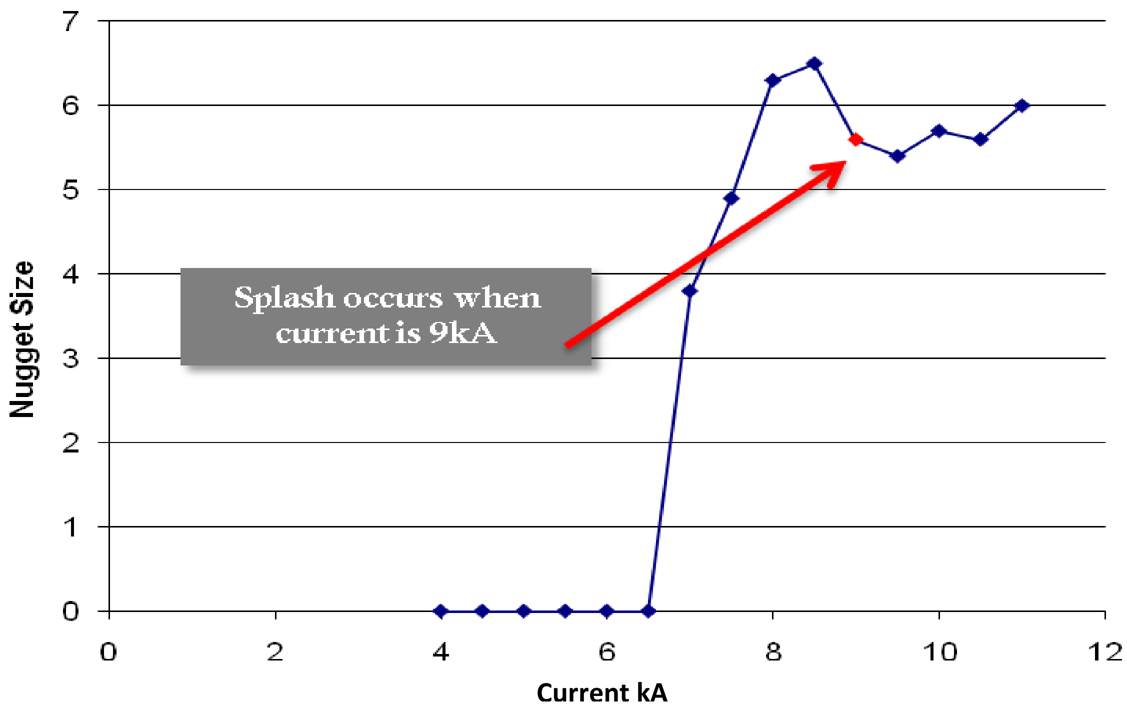

Figure 17: Representation of the weld growth curve and Splash occurrence

2.11 The Electrode Tips

Deterioration of the Electrode Cap: When joining galvanized steel sheets through spot welding the zinc melts before the steel. The liquefied zinc is displaced as pressure is applied on the electrodes and the electrodes push it towards the peripheries of the weld joint before they come in contact with the steel surface again. Because some of the current and heat is wasted in melting the zinc coating, the resulting weld quality drops because of insufficient heat and reduced current density [48]. In order to maintain the weld joint quality, the current has to be increased, but this leads to another problem. Molten zinc alloys with the electrode tips and renders them unusable by pitting their surface as shown in Figure 18 [49].

Figure 18: New Electrode Tips and Degraded Electrode Tips (after 2600 welds)

Alloying makes copper electrode tips slightly harder than new electrode tips; however, alloying also increases the resistance of the electrode caps, increasing heat generation at the tips [50]. This makes the brass material at the tips softer, causing annealing or mushrooming as the tips repeatedly strike the work pieces under high pressure [51]. Replacing electrode caps requires the production runs to be interrupted, causing losses and delays.

2.12 Weldability Lobe

When performing spot welding on galvanized metals, a higher welding force and current are required than for uncoated steels. This has implications for the energy usage when creating each spot weld. In actual fact, acceptable quality of the manufacture of welds depends on the definition of optimum welding parameters, and the functioning of suitable controls to ensure constant weld quality over a production run. As they are the industrially accepted methods, they are created to optimize the spot welding process, which can be formalised as Weld Growth Curves and Weldability Lobes [52]. The ability to make a weld is best defined by a weldability lobe. A weldability lobe 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. In turn these parameters 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 [53] as shown in Figure 19.

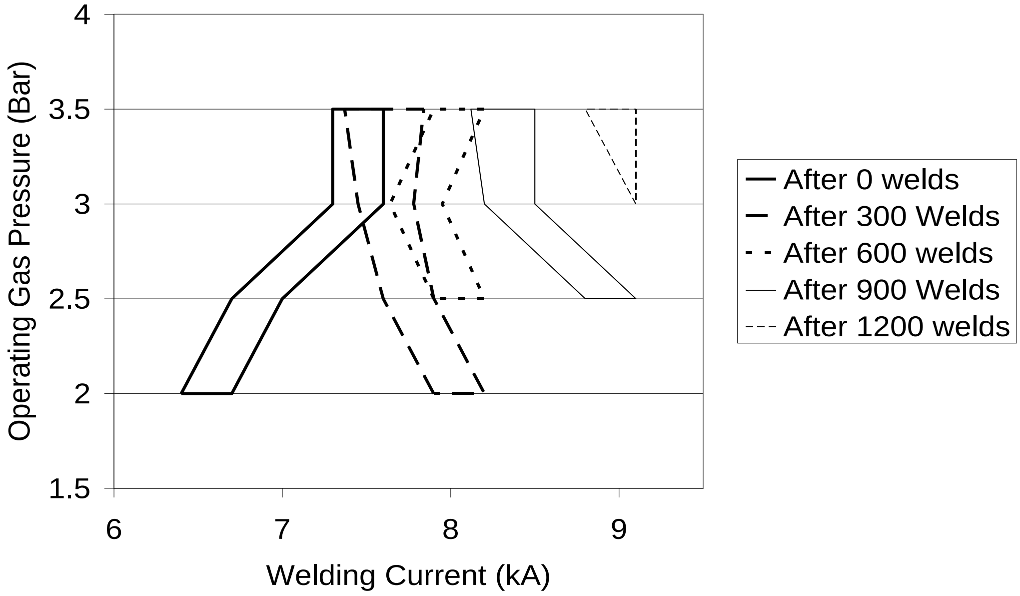

Figure 19: Representation of weldability Lobe for coated 0.8mm steel [54]

2.13 The Benefits of Non Destructive Test Methods

In this method, each weld is monitored as it is performed and its quality is evaluated by measuring the changes in the weld growth curve and current. SORPAS® is a simulation software based on a thermo numeric algorithm that will be used to compare actual experiment results with a pre-experiment SORPAS® simulation to determine the change in actual and simulated values of current and nugget size. This proposed technique can be used to eliminate production run interruptions by evaluating each weld through ultrasonic testing and comparing the results with BS standards. Consequently, current, voltage and weld nugget consistency can be used to calculate the optimum values for current and pressure, hence enabling better production planning.

Electrode force, amount and distribution of current, welding and cooling times, shape, size and condition of the electrodes, thickness and material of work-pieces are all variables that determine the type and quality of the spot weld joint. The complex correlation between these factors and the weld quality has always been the subject of research. The perfect parameters for producing high quality spot welds are hard to meet under practical circumstances, especially because of electrode wear. It means that apart from monitoring techniques, post weld testing has to be employed in the automotive (and other) industry to check the weld quality in production batches. NDT should be able to check the weld joint for fissures, bubbles and density. Ultrasonic NDT is a reliable and popular method, in which ultrasonic pulses are directed through a weld joint and their returns (or echoes) are measured to calculate its consistency. Ultrasonic NDT is a compulsory procedure in most spot welding operations. It can also discover weld quality problems that are not identifiable by visual inspections. The procedure has been widely adopted in the automotive industry because of its accuracy and speed, especially as the ultrasonic technology has progressed [55].

The recommended NDT method is known as the “transmit and receive” or “through transmission” method. As the name depicts, a transducer containing an ultrasonic transmitter is placed at one end of the object to be tested (a weld joint), with a receiving transducer at the other. HF and VHF sound waves are passed through the material of the weld nugget and are collected by the receiver. If the amplitude of the received pulses is less than a certain expected value, it means that there are defects in the weld joint. At present, a dual transducer ultrasonic NDT is seldom employed in the automotive industry, as it is often not possible to access both sides of a weld joint after the bodyworks have been completed. However, as this chapter proposes an online system for real time ultrasonic NDT, the transmitter and the receiver have been placed on the electrode arms of the spot welding machine. Ultrasonic NDT has thus been deployed in a real time environment to test the weld quality simultaneously during the welding process. The experiment uses SORPAS simulation prior to actual welding to determine the correct welding parameters [56]. More about SORPAS software will be discussed in the next chapter, when carrying out simulations for electrode tip analysis. For this experiment, a pressure setting of 3.5 bar and a current of 7kA is selected as experiment settings. The results of SORPAS simulation is tested on IF180 steel for evaluation.

This is followed by an off-line experiment, in which 50 spot welds are performed using the set up shown in Figures 20 and 21. The weld times are increased in cycles of 20ms and the resulting welds are examined through peel testing. Nugget diameters of the welds are measured and are as listed in Table 1. It is obvious that as the weld time increases, nugget diameter also increases. No welds are formed at 1 to 4 cycles of weld time. From 5 to 8 cycles, welds are formed with a corresponding increase in the nugget diameters. At 9 and 10 cycles, splash is observed, so the weld is likely to have defects.

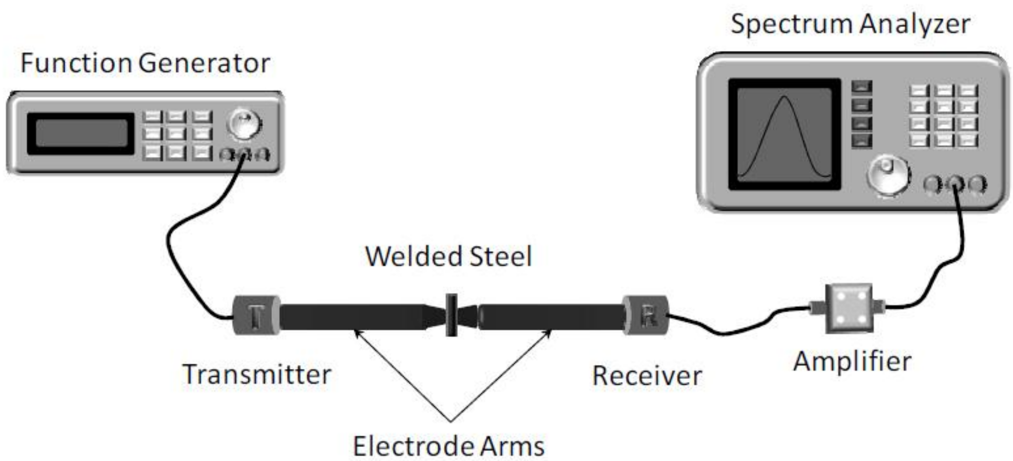

Figure 20: Experimental Set Up [57]

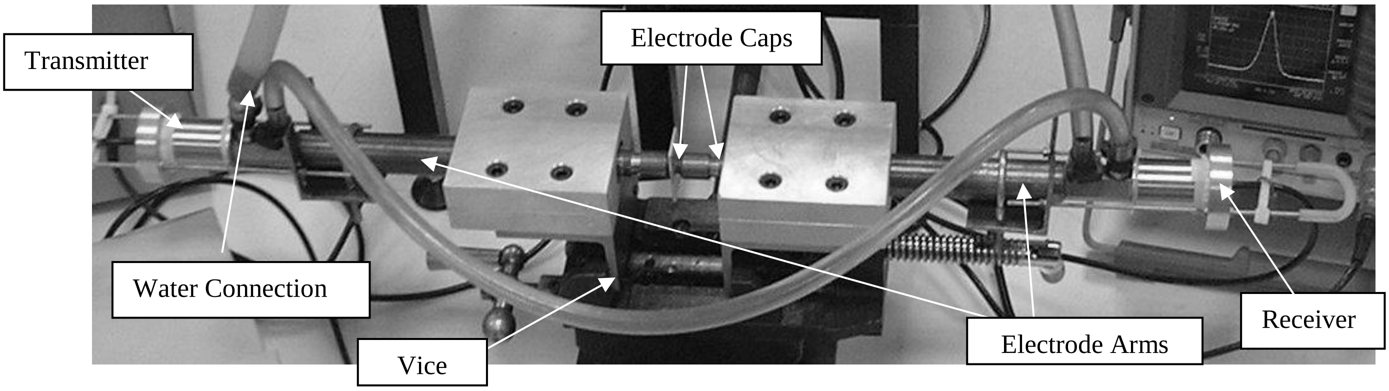

Figure 21: Electrode Arms and Sensors [57]

Table 1

Weld Time (Cycles)	Average Nugget Diameter (mm)	Splash
5	Stuck	No
6	2.4	No
7	2.9	No
8	3.7	No
9	4.9	Yes
10	5.2	Yes

In this process, the welded work pieces were held firmly between the electrodes caps using a vice. A sinusoidal voltage was sent to the transmitting transducer using a function generator type TTi TG2000 10 MHz DDS. The output signal was amplified through a ZFL-500LN amplifier and monitored by a spectrum analyser (HP 8594E, 9kHz-2.9GHz). The results of the above experiments are depicted in Figure 22. The amplitude of the received signals is lower when the welding time is low. This is because of the presence of gaps or voids in the weld joint. As the weld time increases, the melting is more pronounced and the gaps reduce in size, causing an increase in the amplitude of received signals. When the weld time is increased beyond 8 cycles, expulsion of metal causes inconsistencies in the joint, resulting in decreasing amplitude of the received signals.

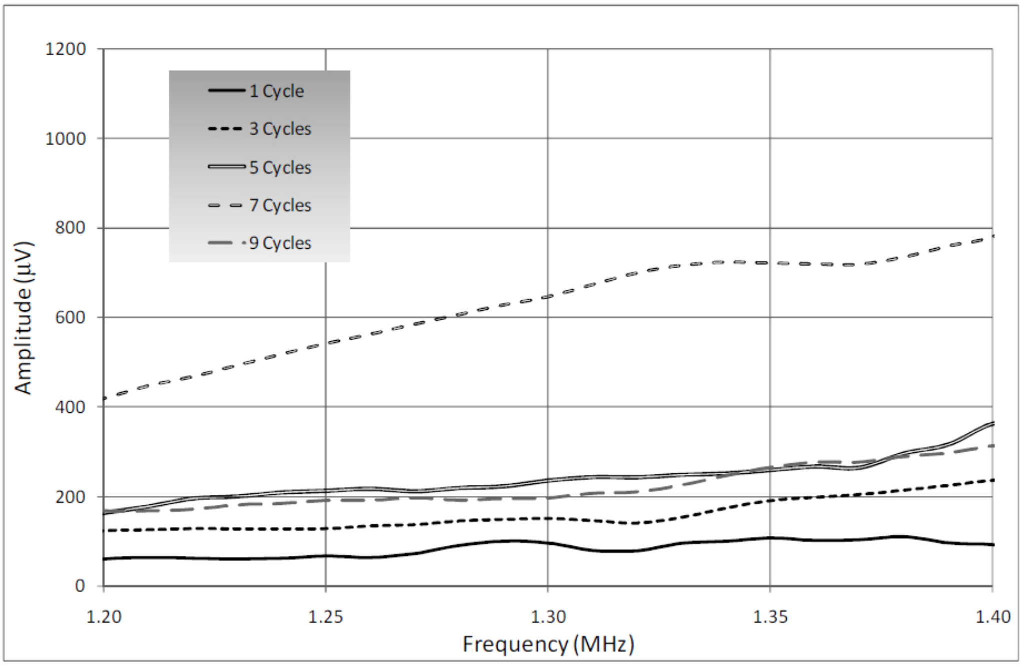

Figure 22: Ultrasonic NDT Results

The experiment has been used as the foundation for further work, which analyzes electrode tip life, pressure and energy savings. A NDT method is used in which the transmitting and the receiving transducers are placed on the electrode arms. The amplitude of the received signal increases as good quality welds are formed. The signal strength decreases as weld quality deteriorates and gaps or inconsistencies are introduced in the welding nugget [57]. Use of higher frequencies is precluded when both transmitting and receiving transducers are deployed, as overlapping or interference between transmitted and received signals does not take place. Work is underway on developing ultrasonic transducers with lower resonant frequencies to add accuracy to the proposed NDT method. An improved amplifier is also under study. There is need for testing the final system in actual industrial spot welding environment.

2.14 Summary

The resistant spot welding process in addition to the various joining types have been discussed and explained in detail. Different problems within the spot-welding process and its mechanical limitations, including but not limited to the weld integrity have been explained. The range of testing techniques that determine the quality of the spot-welds within the two categories of destructive and non-destructive analysis have been outlined. The various monitoring techniques have been discussed in detail; there are two main categories for testing which are; online testing and offline testing. Destructive testing was used to populate the weld growth curve and the weldability lobe analysis.

Chapter 3

SORPAS Simulations

3.1 SORPAS Software

Simulation and **O**ptimization of **R**esistance **P**rojection **A**nd **S**pot welding processes.

SORPAS [58] is a professional welding software, the acronym stands for simulation and optimization of resistance projection and spot welding processes. It is extensively used for spot welding simulation and analysis in the automotive and other industries. The software aids in defining welding parameters for different materials and helps select the optimum electrode design and welding parameters, the reason of using SORPAS is to determine the range of currents in the region of the values that would give a good weld, therefore saves time and material costs [56].

3.2 SORPAS Simulations

The procedure for creating simulation with SORPAS® is similar to the procedure for doing the practical welding process, which can be divided into the following three steps:

• **Data preparation** - the materials and geometries of the work pieces and electrodes are defined, the type of welding machine is selected and the process parameters are specified.

• **Running the simulation** - the parts are welded with the specified process parameter settings. The simulations can be carried out in three ways: single simulations, batch simulations and optimizations.

• **Evaluation of the results** - the results of welding and the quality of weld are evaluated thus the design and parameter settings are verified. With the optimization procedures the weld growth curve and the weldability lobes can be obtained.

The input data for preparation of simulation with SORPAS® can be summarized as below:

1) Geometry and materials:

- Define the geometry and select the material of the work pieces
- Define the thickness and select the coating material
- Define forms and select materials for the electrodes
- Define contact interfaces between materials

2) Machine settings:

- Define mounting of electrodes (or connection of electrode to machine)
- Select type of welding machine
- Set welding process parameters

3) Simulation control:

- Define time step and interval for saving result files
- Select numerical models and define accuracy of each model
- Set optimization procedures (weld growth curves, weldability lobes etc.)

3.3 Electrode Tip Life Analysis

In the simulation report, the initial conditions and the weld process parameter settings are shown together with the results of the simulation including a selected parameter curve and the final temperature distribution with weld nugget formation. The maximum power requirement and the total energy consumption of the welding process are also shown in the report, which are useful for the selection of welding equipment. An example simulation report is shown in Figure 23.

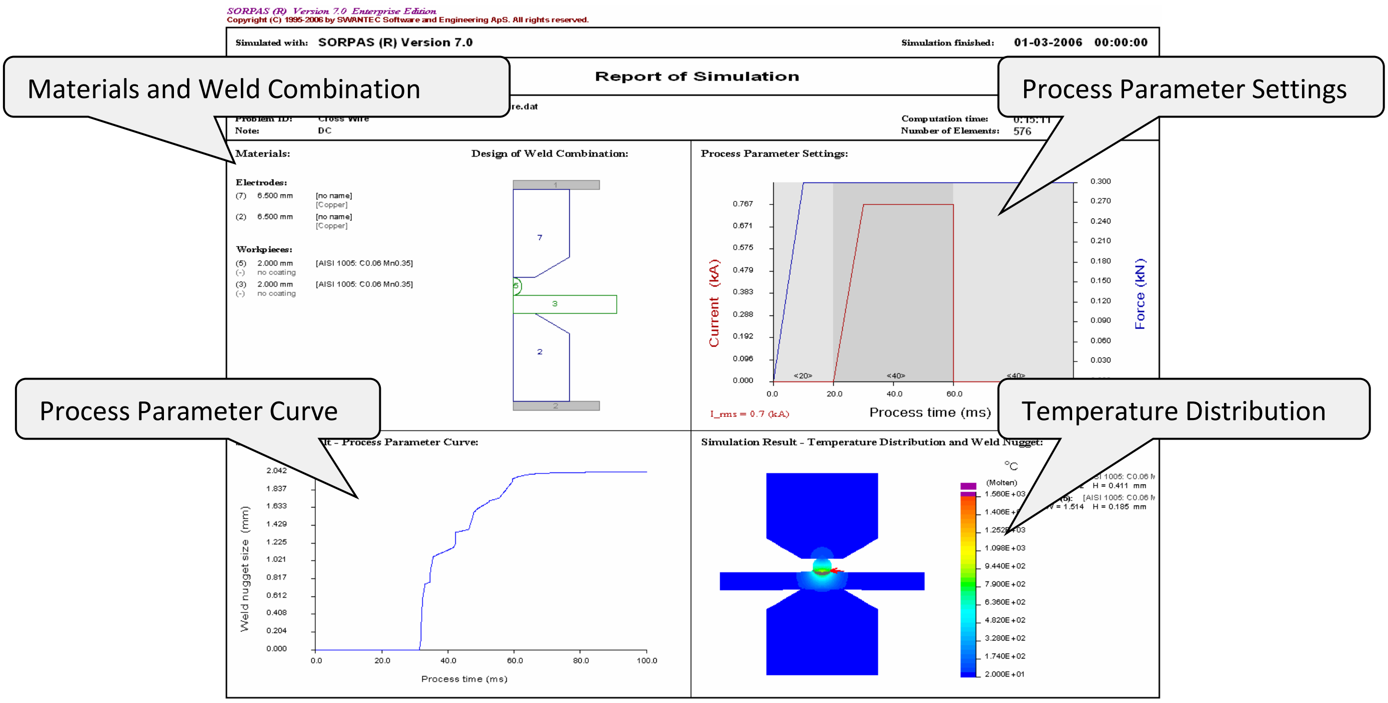

Figure 23: The simulation report generated by SORPAS®, the upper Part is the welding conditions and the lower part is the main simulation results.

3.4 Temperature Distribution

The final temperature distribution with the weld nugget formation is shown as the final result of the welding simulations. The weld nugget diameter is obtained and shown on the graph. If splash occurred, it is also shown with a graphical indication at the splash point (the red arrow). Figure 24 shows an example of the final temperature distribution.

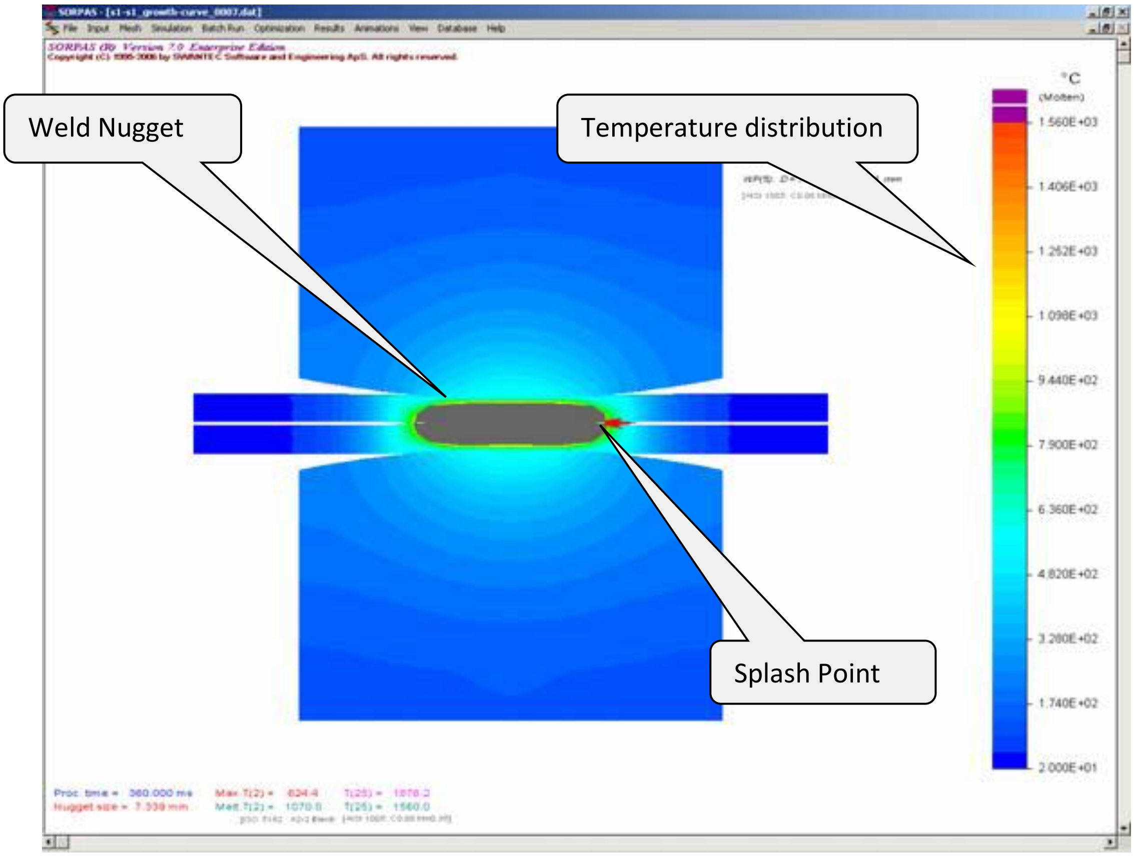

Figure 24: Final temperature distribution.

3.5 Theoretical Simulation of Spot Welding

3.5.1 Weldability Lobe

Weldability lobes provide an instantaneous view of the welding current and can drift because of electrode tip deterioration, like pitting or mushrooming.

Weldability lobes depict the tolerance of the spot welding process. In order to keep the weldability lobe stable throughout the spot welding manufacturing run, various parameters and their interaction are controlled to keep the temperature distribution within pre-defined limits. This research opens new possibilities for identifying and replacing faulty electrode caps without interrupting the production run, hence improving efficiency and savings

The Weldability Lobe Simulation for 0.8mm steel sheets, with 2l/min water flow rate, 2.5bar pressure, current ranging from 2.0 to 11.0kA, at 0.5kA increments, is shown in Figure 25

The red points indicate an oversized weld nugget or splashes at the interfaces between sheets, the red points indicate electrode melting, the black points indicate no weld, and the green points indicating welds with a nugget in between the maximum and minimum weld nugget diameters.

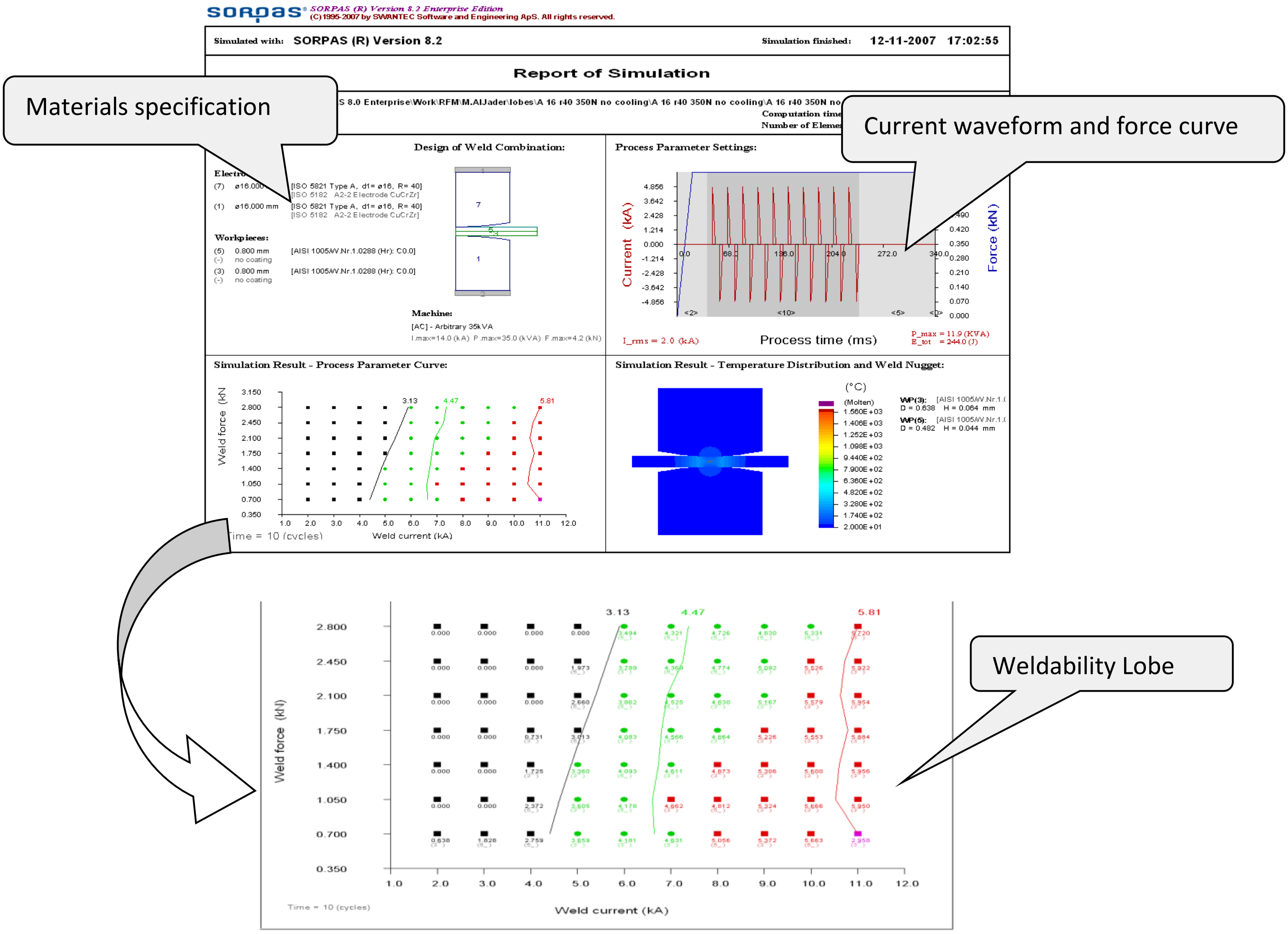

Figure 25: Representation of the welding profile, including materials specifications, current profile, and lobe welding temperature profile

3.5.2 Weld Growth Curve

The Weld Growth Curve Simulation for 0.8mm coated steel sheets, with 2l/min water flow rate, 2.5bar pressure, current ranging from 2.0 to 11.0kA, with 0.5kA increments is shown in Figure 26. The red points indicate splashes at the interfaces between the sheets, the black points indicate no weld and the green points indicate the welds with a nugget.

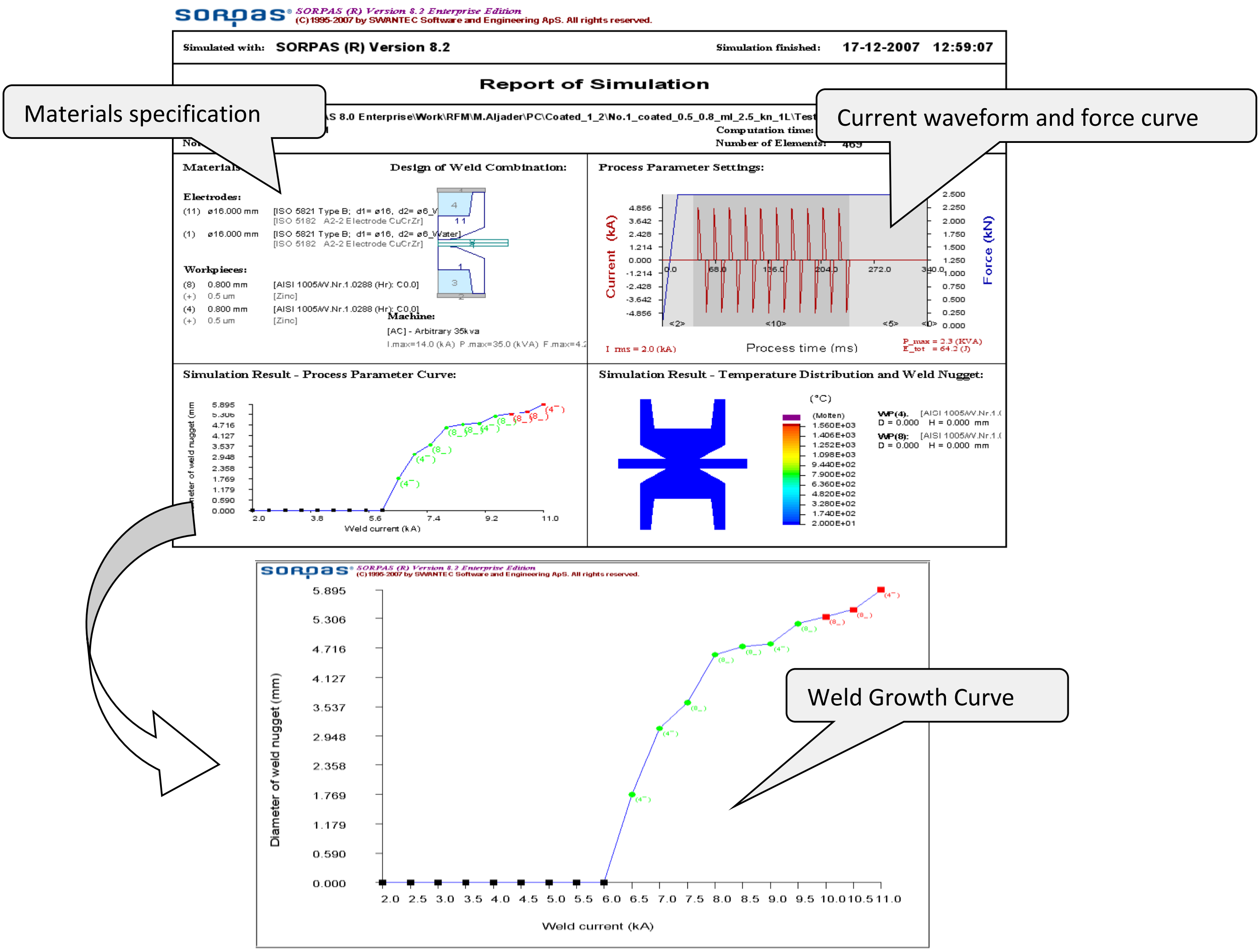

Figure 26: Representation of the welding profile, including materials specifications, current profile, weld growth curve profile

3.6 Summary

The correlation between the practical results obtained and the simulated results extrapolated by the SORPAS® simulation software proves that simulation software is a valuable asset that provides results to be compared with the practical results. Weld growth curves and weldability lobes have been simulated by the software, and a full report was presented.

Chapter 4

Experimental Results

4.1 Experimental monitoring

Figure 27 shows the spot welding machine used for the experimental trial which is a TECNA 4621 Pedestal Welder [42]. 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 [59]. Force is applied on the moving top arm through a foot pedal, while the bottom arm is fitted with sensors for real time spot welding process monitoring [60].

Figure 27: TECNA 4621 Spot Welding Machine [16]

Figure 28 shows the relevant position of sensors for optimum detection of welding parameters. The variables for the experiment are current, voltage, force, coolant and pressure. A Rogowski coil is used for sensing current, which measures the current flowing through the weld by inducing a voltage proportional to the value of the current at any particular time [17].

Signals from current sensors are routed through a buffer or amplifier circuit to a data logger in a computer.

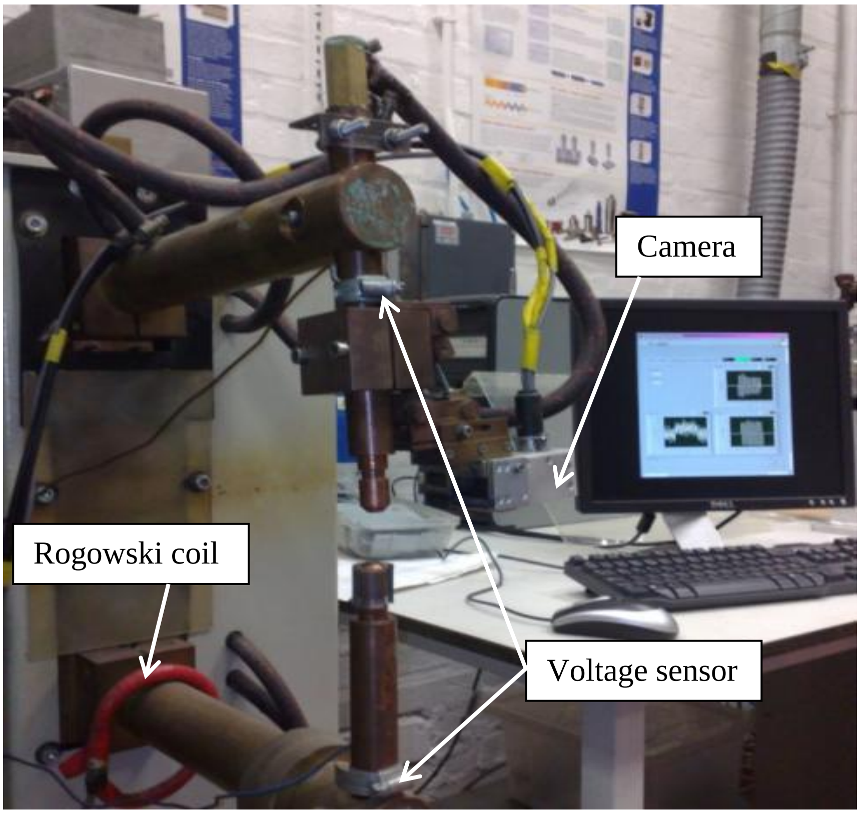

Figure 28: The Experimental sensors setup

The sensors are placed in positions that give the most effective detection. All these sensors have their readings captured using data acquisition boards and are 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 0.5sec before a weld to 0.5sec after a weld is saved for analysis.

4.2 Weld Growth Curve Results

The process of selecting a suitable current for performing a weld is based upon the parameters within the British standard [36]. This standard carries a guideline set of tables for the selection of welding current and welding time, extracts of which are reproduced in tables 2 and 3. Table 2 and Table 3 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 for uncoated steel because the process has to melt the coating before the actual spot welding can take place.

Table 2: Spot welding conditions for uncoated mild steel

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 3: 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

There is a range of parameters available for a given metal thickness. Which have been determined by the use of weld growth curves, and weldability lobes.

The range of weld types performed covers the following criteria:

- **No weld:** This occurs when there is insufficient current to melt the parent metal, as shown in Figure 29

Figure 29: No weld after destructive testing

- **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 30

Figure 30: Two metal sheets stuck together

- **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 BSI standard [36], 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. See Figure 31

Figure 31: Undersized weld when low current was used but the nugget was not fully formed

- **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 (expulsed metal), see Figure 32

Figure 32: Acceptable weld where the weld is fully formed

- **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, as shown in Figure 33

Figure 33: Occurs when excessive current applied

- **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, see Figure 34

Figure 34: Splash weld causing the electrodes to collapse into the metal

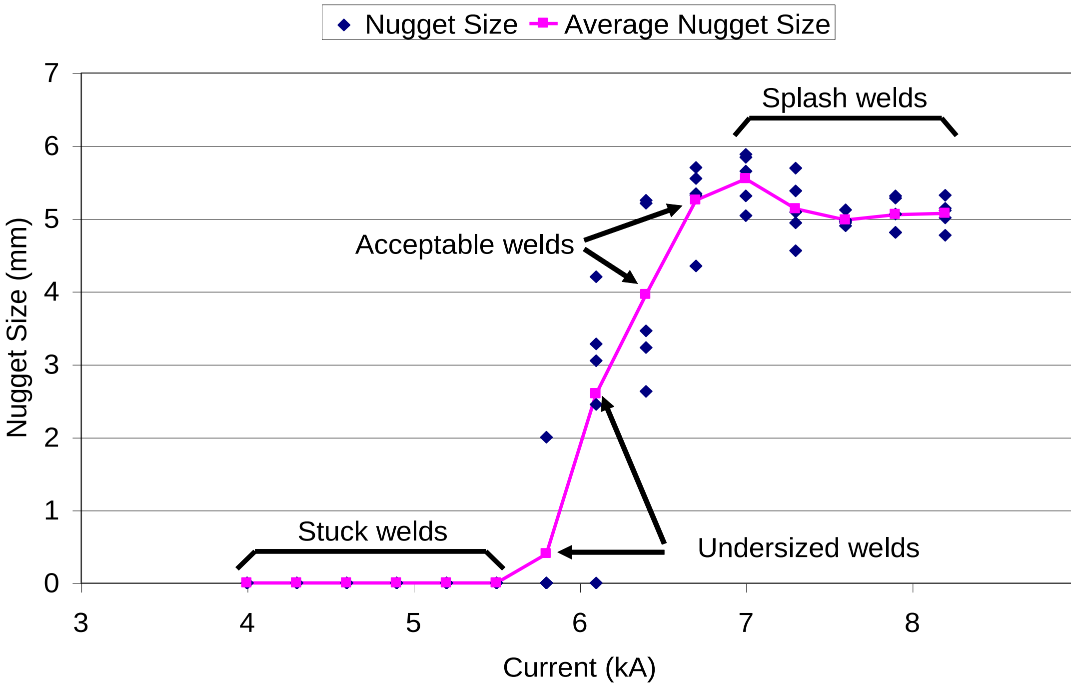

Figure 35: Weld growth curve for 0.8mm thick galvanised mild steel.

A weld growth curve, as shown in Figure 35, shows the growth curve produced for 2bar gas pressure on coated mild steel, resulting in an electrode force of 1.4kN. It 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'.

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, these are 6.2kA and 6.7kA. 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. If this is repeated for the following pressure and associated electrode forces 2.5bar (1.75kN), 3bar (2.1kN) and 3.5bar (2.45kN). in results in the growth curves are shown in Figure 36 (for uncoated steel) and Figure 37 (for coated steel), and the resultant weldability lobe for coated steel is shown in Figure 38

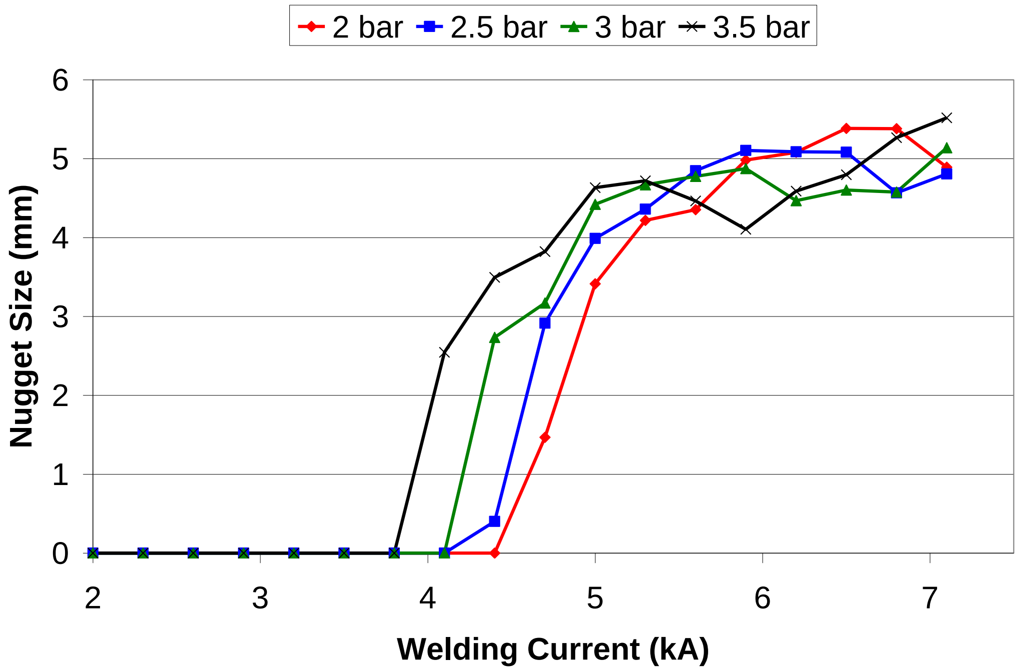

Figure 36: Weld growth curves for different electrode forces for uncoated mild steel

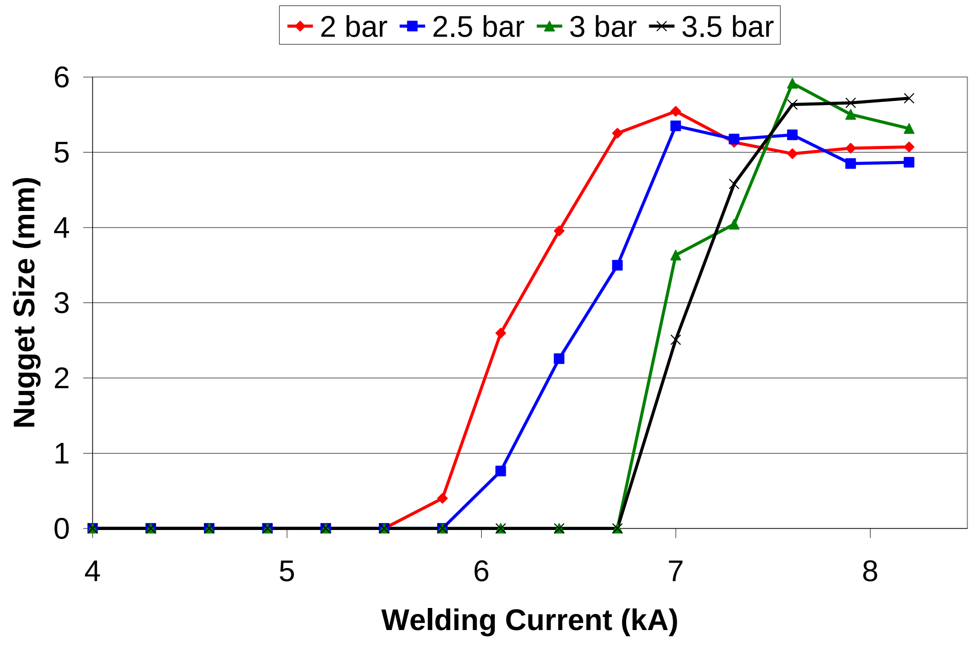

Figure 37: Weld growth curves for different electrode forces for coated mild steel

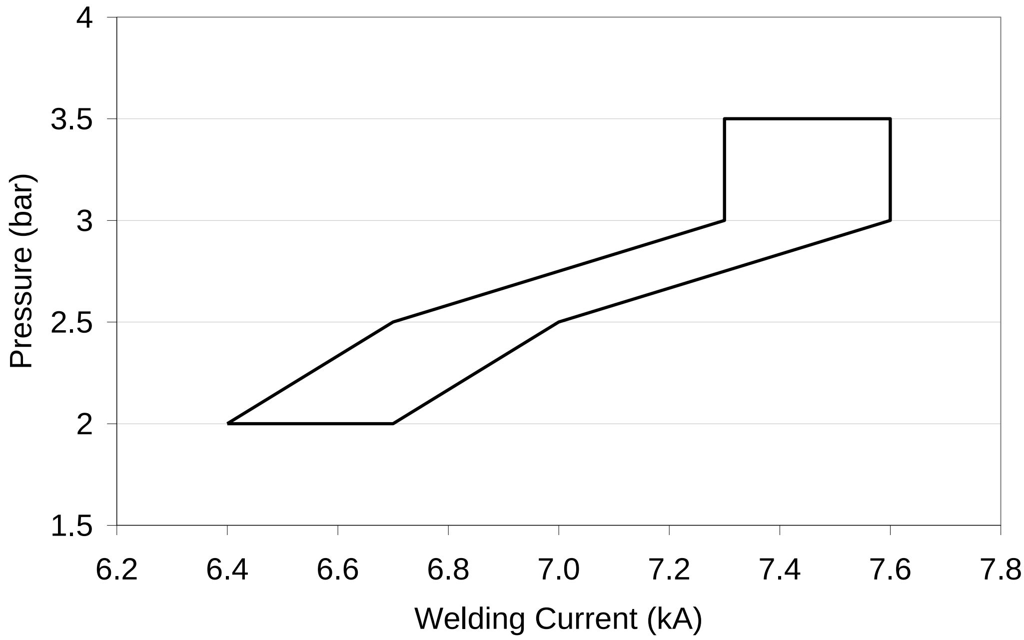

Figure 38: Resultant weld lobe for galvanised mild steel growth curves.

4.3 Electrode Tip Life and Weld Quality

To minimize 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 galvanizing 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 39 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 midpoint 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.

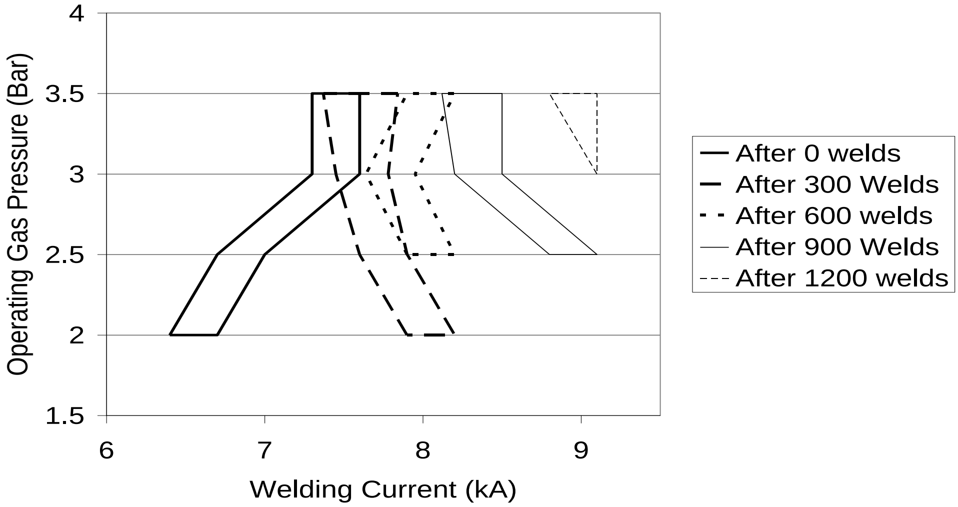

Figure 39: Weldability lobes for an increasing number of welds

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 40 shows the output of a curve fitting algorithm to the data in Table 3, which gives equation (1).

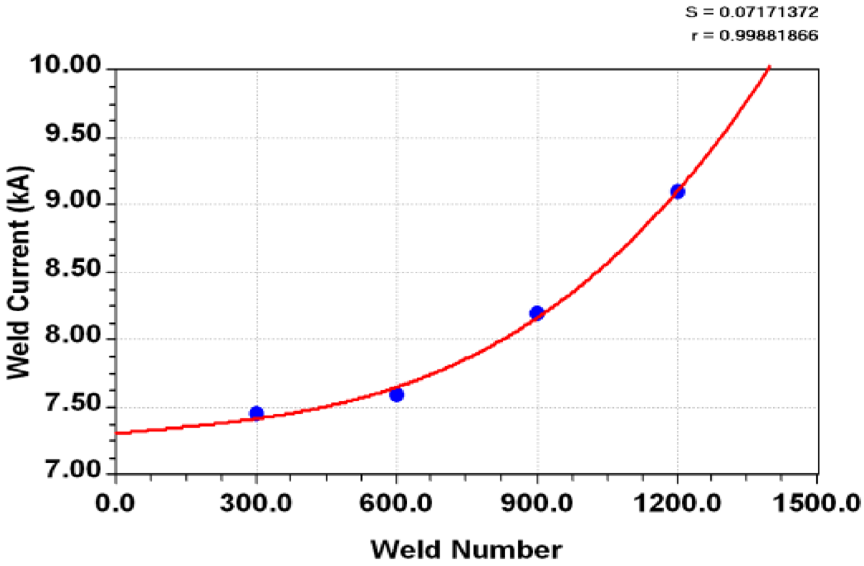

Figure 40: Curve fitting algorithm output for minimum current

$$\text{Welding Current} = 7.3 + 3.1\cdot 10^{-4} x - 1.1\cdot 10^{7} x^{2} + 9.2\cdot 10^{-10} x^{3} \quad (1)$$

Number of Welds	Minimum current (kA)
0	7.3
300	7.45
600	7.6
900	8.2
1200	9.1[a]

This setting produced nuggets of the minimum size, but they were splashing at the same time.

Table 3: Minimum current requirement as the number of welds performed increases.

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. Such factors which can affect the process in the factory are fluctuations in gas pressure affecting electrode force, material contamination, and electrode cooling.

An example of this can be seen in the weld lobe shown in Figure 39, where the minimum current required changes as the pressure changes. Also as the tip wears, the minimum force that can be used changes. This illustrates the limitation of the rule-based approach of attaining the minimum current and force in the spot welding process.

4.4 Practical Results of Weld Growth Curve on new Electrode tips

Tests have been carried out at different of pressures to determine the effect on the size and quality of the nugget. In order to age the tip 300 welds were carried out between each set of results.

For each pressure setting between 2 and 5bar in 0.5 increment 75 welds were carried out using 5 welds at each current. These welds were destructively tested using the peel test and the nugget diameter were measured and an average found for each current.

4.4.1 Weld Growth Curve (0-75) welds

The test material used a coated 0.8mm steel, which is used in the automotive industry. The water flow rate was 2l/min, and the current was varied between 4.0kA and 9.0kA. As shown in Figure 41 when the pressure was 2.0bar and 2.5bar with a current of 6.1kA, the nugget was produced but it did not meet the British Standard requirement. At a pressure of 2.0bar, the required nugget was produced, but at a current of 6.4kA, and at 2.5bar pressure with a current of 6.7kA the required nugget was also produced. When the pressure was increased to 3.0bar, the nugget started producing at 7.0kA, meeting the British standard requirement, but at 3.5bar a current of 7.0kA was insufficient. At 4.0bar and 7.1kA current the nugget was produced following the British standard requirement while using less energy. Finally at pressure 4.5bar and 5.0bar with a 7.6kA a nugget was produced although it was undersized.

To conclude, out of seven tests started from scratch with a brand new tip used in each test, and using the same settings in each test but at different pressures: it became clear that 4.0bar pressure is adequate with a 6.7kA current because it used less energy producing the nugget in accordance with the British standard requirements, than the other tests at different pressures used.

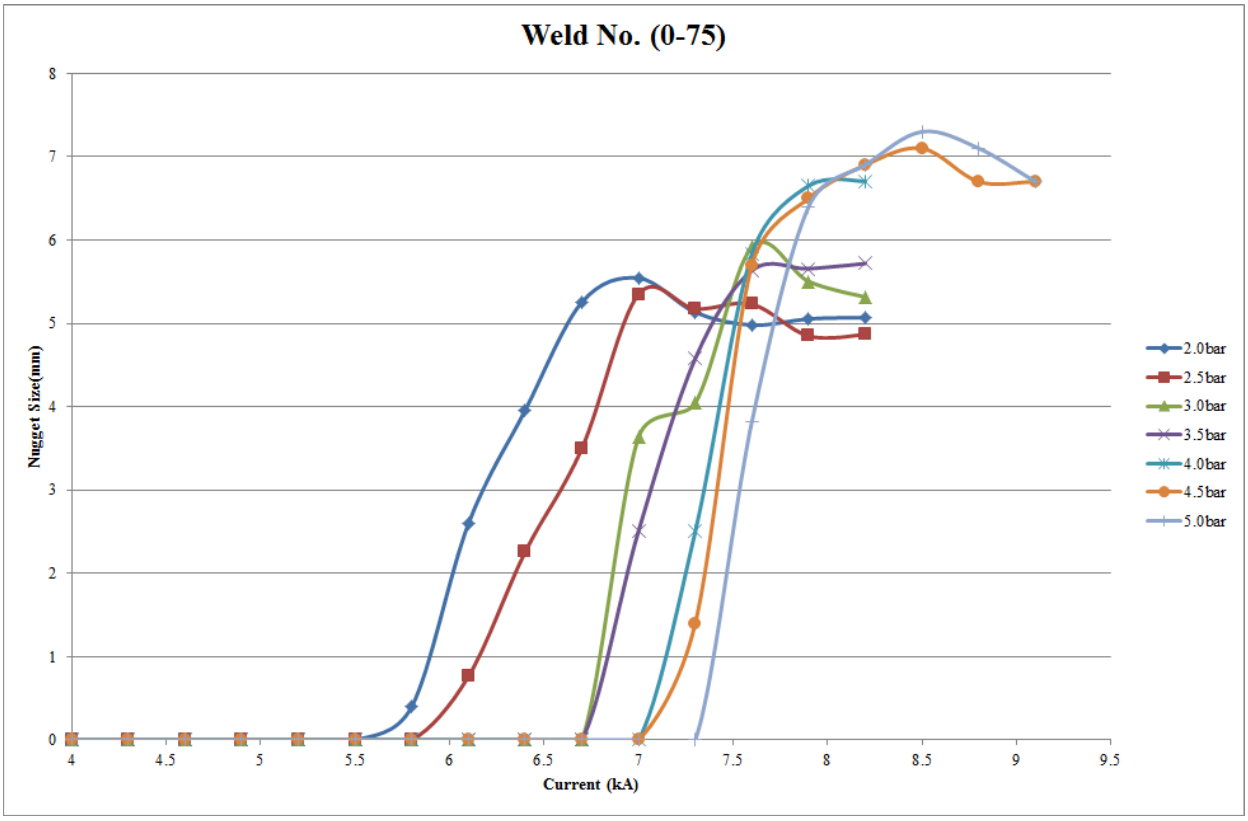

Figure 41: Points out practical representation of different pressures on a brand new tip

4.5 Practical Results of Weld Growth Curve on used electrode tips

Once the first 75 welds were completed, 300 further welds were then performed to wear the tip, without the nugget being measured.

4.5.1 Weld Growth curve (376-450) welds

The 75 welds were then repeated at each pressure with the same electrode tips. At a pressure of 2.0bar, a good nugget was only produced at 7.9kA. The same current was also required for pressure of 2.5bar and 3.0bar. At 3.5bar a very good weld was produced at 7.3kA current and at 4.0bar a good nugget was produced at 7.0kA. As the pressure increased to 4.5bar and

5.0bar, the nugget was produced at 7.0kA current, but it was undersized at only 30% of the BSR measurement, as shown in Figure 42.

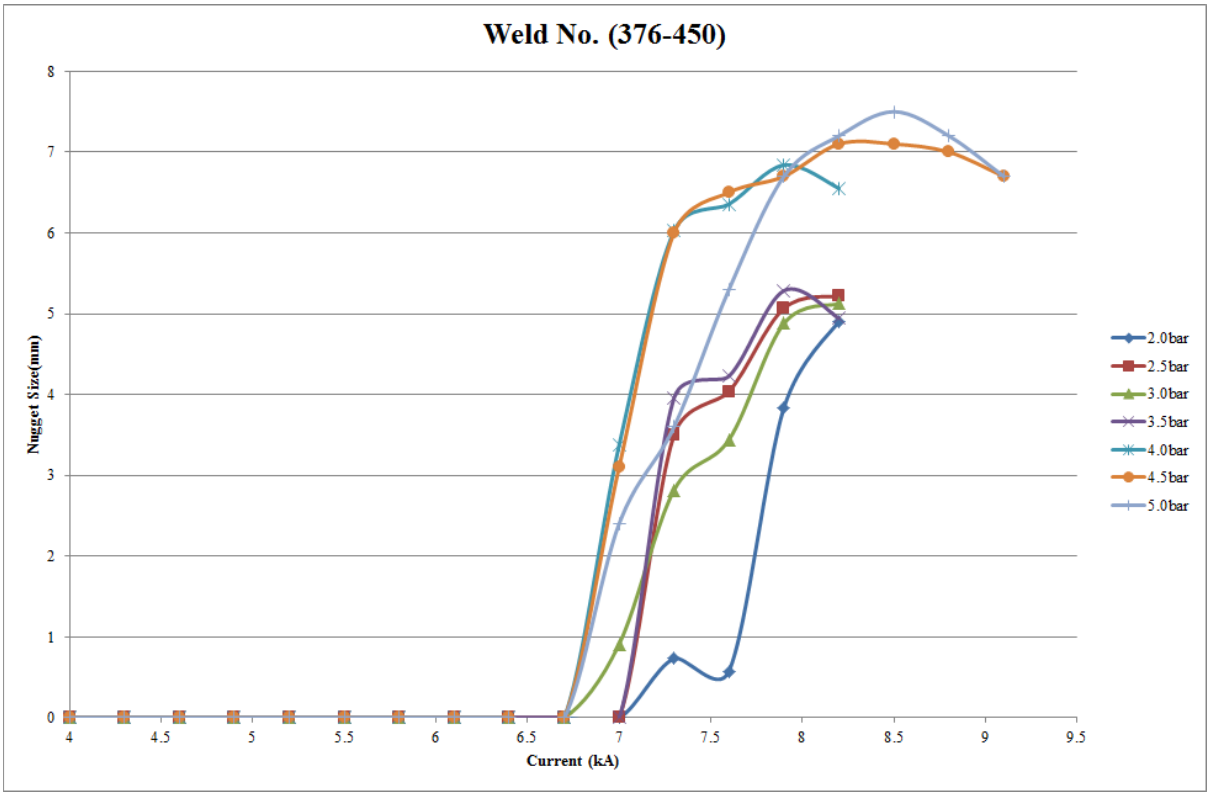

Figure 42: Points out practical representation of different pressures on a used electrode tip

4.5.2 Weld Growth curve (751-825) welds

After another 300 welds to age the tips, the measurements were repeated, and at a pressure of 2.0 bar all 75 welds were stuck, (no weld). Even at 2.5bar the 75 welds were very poor, and the size of the nugget was estimated about 50% or less of the BSR measurement. On the contrary at pressure of 3.0 and 3.5bar with a current of 7.6kA the nugget was produced with a good weld, meeting the BSR. On the other hand though, at pressure of 4.0bar and current

7.0kA, a very good weld was produced; which is the weld with the lowest energy used according to this test following the results shown in the figure below.

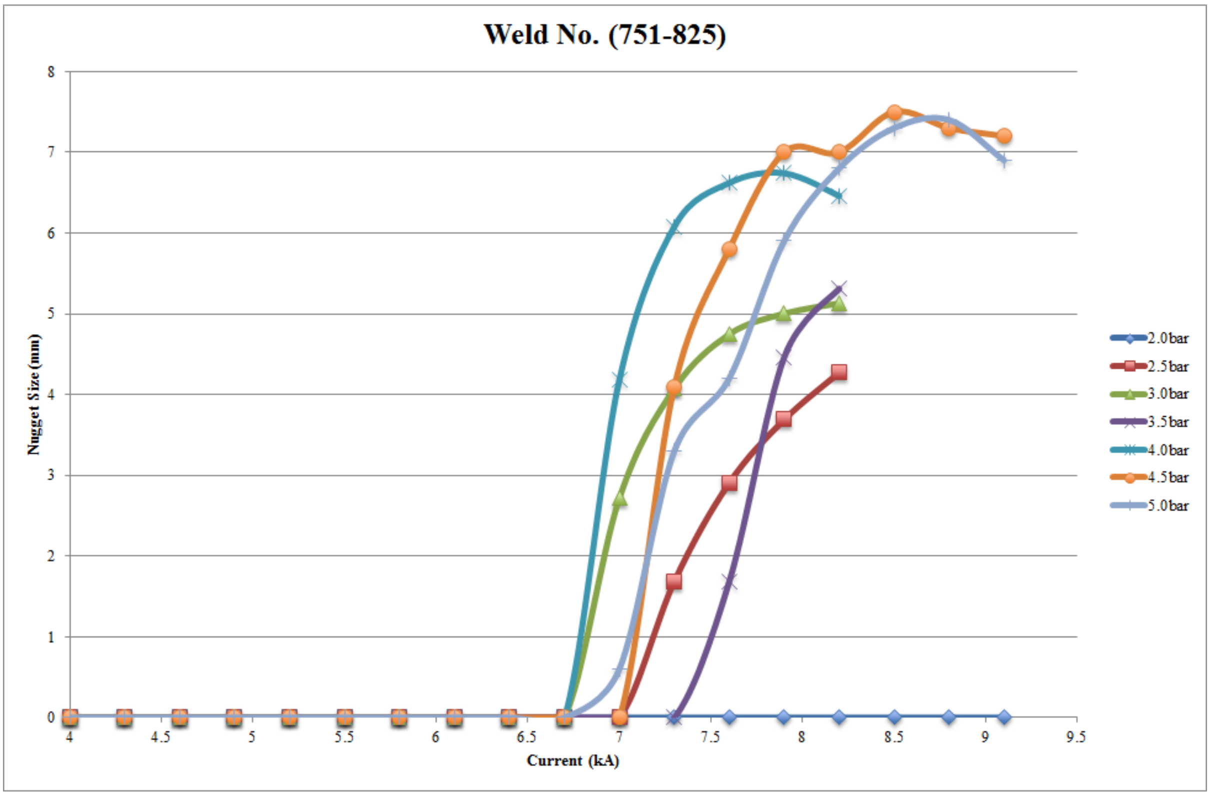

Figure 43: Points out practical representation of different pressures on a used electrode tip

4.5.3 Weld Growth curve (1126-1200) welds

The results of 2.0-3.0bar pressure show that the range of pressure has no effect on the quality of the weld nugget. However the pressures at 3.5bar and 4.0bar were a bit similar, as they were producing good welds at 7.0kA current while the pressure at 4.5bar and 5.0bar needed more energy to obtain the same quality of weld, even though the pressure was high. See Figure 44

To conclude, at 1100 welds the tip was producing the same quality welded nuggets, just as those nuggets would be produced at 750 welds. In this case that proves that when pressure is at 4.0bar it is the most productive.

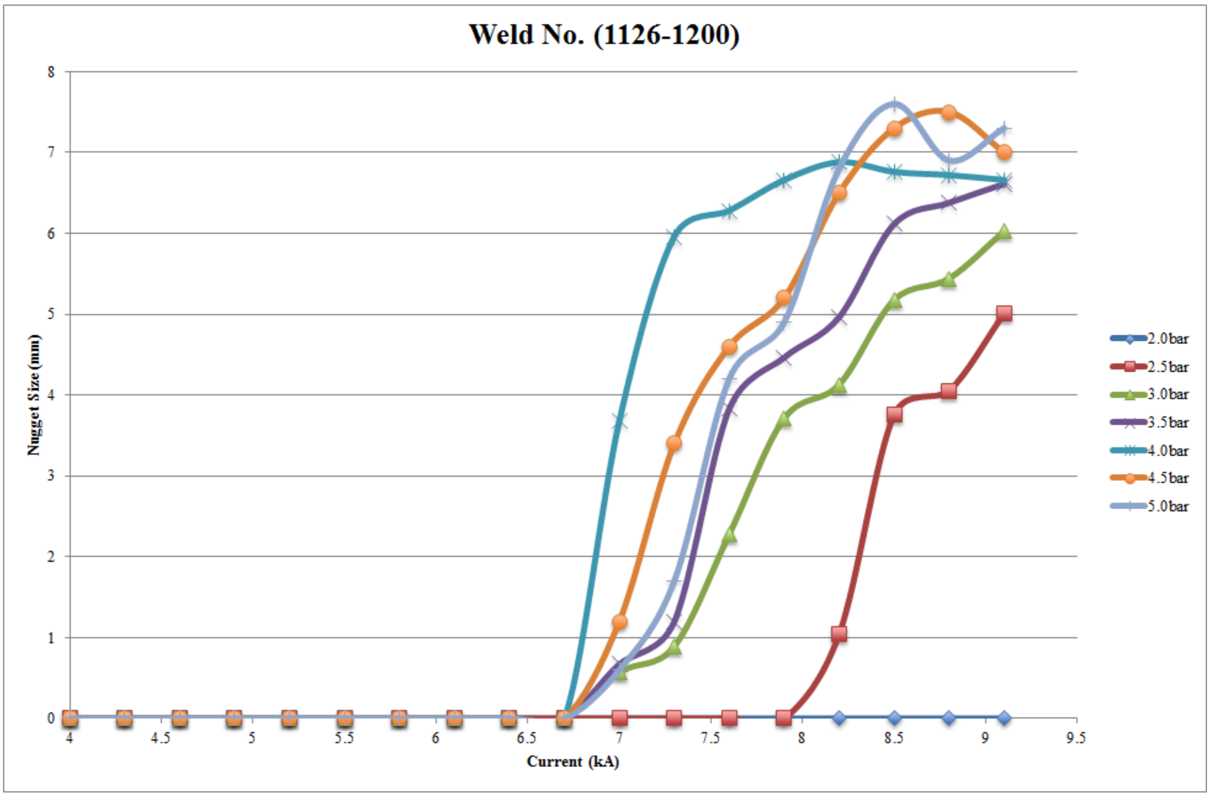

Figure 44: Points out practical representation of different pressures on a used electrode tip

4.5.4 Weld Growth curve (1501-1575) welds

As above when the pressure was at 2.0bar and 2.5bar there were no welds. At 3.0bar, nuggets were only produced for 15 welds out of 75 welds at a high current starting from 8.5kA. With a pressure of 3.5bar, the nugget started producing at 6.7kA according to the BSR. With a pressure of 4.0bar, however, very good welds were produced at 7.0kA current. At pressures of 4.5bar and 5.0bar acceptable welds were only produced at 7.9kA. Hence the 4.0bar pressure stands out through the results, as shown in the Figure 45

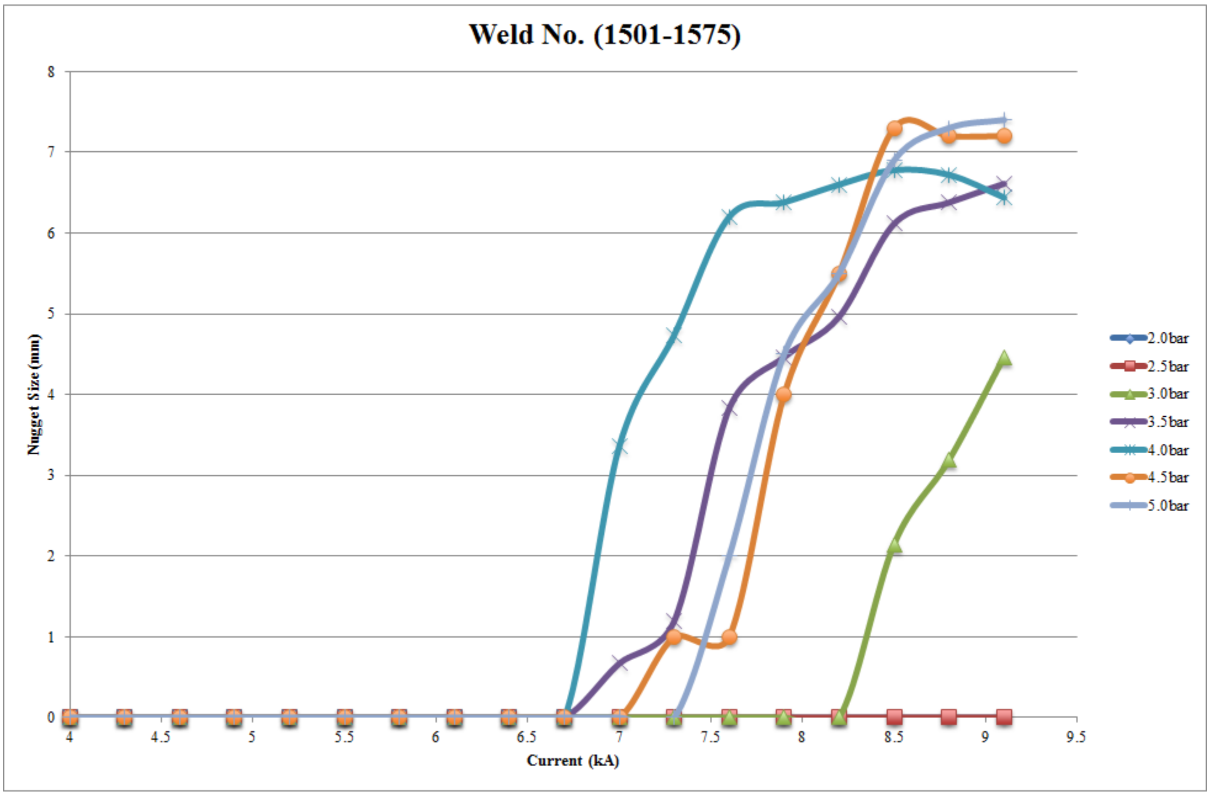

Figure 45: Points out practical representation of different pressures on a used electrode tip

4.5.5 Optimum weld pressure

Following all these tests it was concluded that the pressure works best at 4.0bar, in terms of producing a nugget. Therefore in Figure 46 all the results at pressure of 4.0bar in the previous tests are shown.

Until 1575 welds, with 7kA current, the nugget size conformed with the British Standards Requirements. Hence it ensures that this is the best result in comparison with the others.

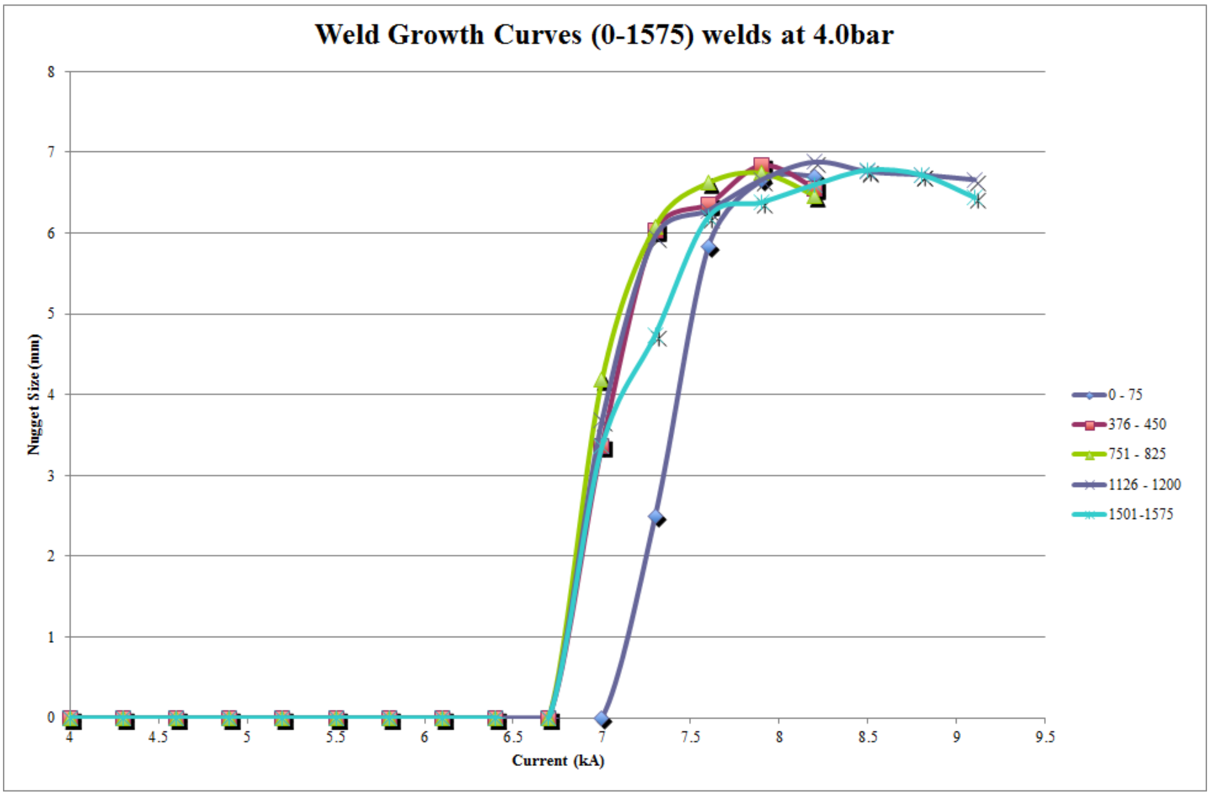

Figure 46: Practical representation of the weld current vs. the weld nugget diameter at 4.0bar

4.6 Theoretical and practical results

Figure 47 respectively show the differences between the theoretical and practical results of the weld growth curves (WGC). The theoretical WGC is a resultant from a simulation performed on SORPAS. The simulation was performed on the typical passenger vehicle's body of 0.8mm coated steel sheet and the other welding parameter included 1l/m water flow rate, 3.5bar pressure, current ranging from 2.0 to 11.0kA, with 0.5kA increments. The red points indicate splashes at the interfaces between the metal sheets, the black points indicate no weld and the green points indicate the welds with a nugget.

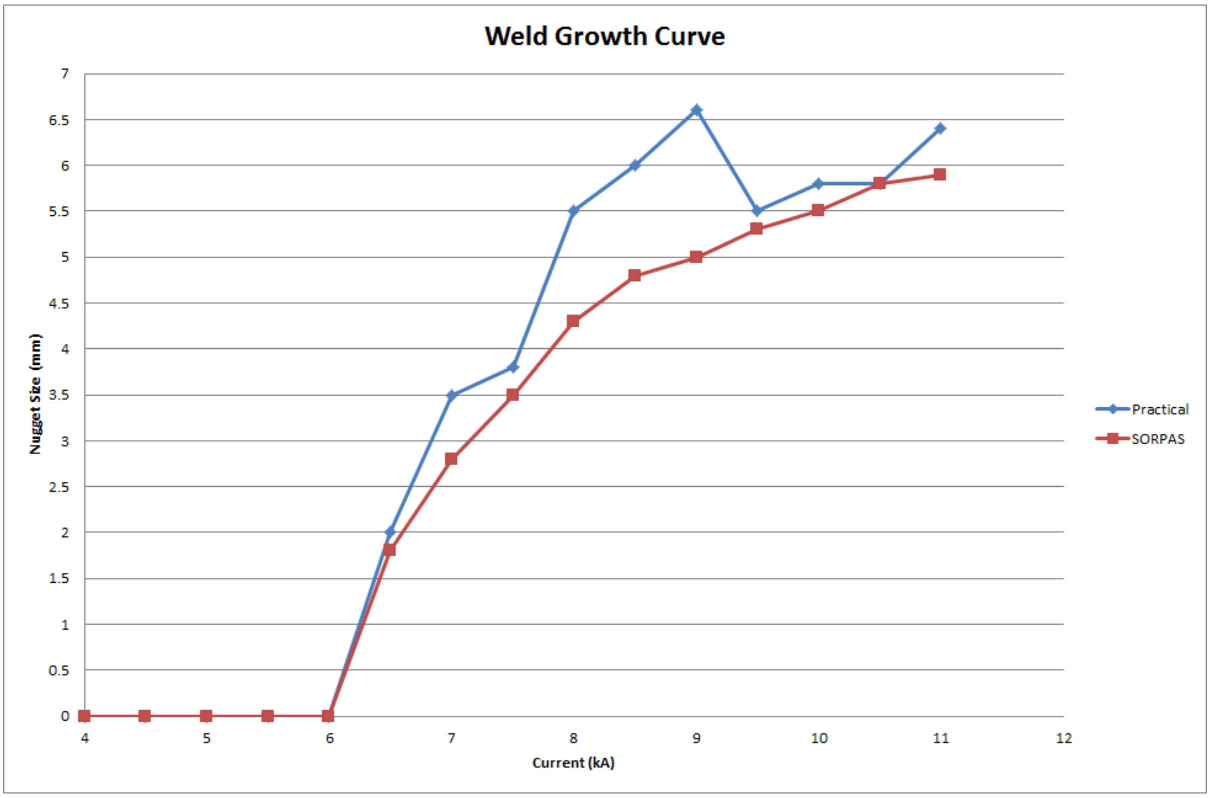

Figure 47: Theoretical and Practical representation of the weld current vs. the diameter of the weld nugget

4.12 Summary

The experimental results have shown that were different, currents and pressure loads, are each responsible for affecting the quality of the weld nugget. Variation in each of these parameters can preserve the life of the electrode tip. The number of successful welds per electrode tip pair was explained and it is generally more beneficial to have a higher yield per tip pair. Numerous test welds have been used to determine the optimal parameters for pressure, and current at different stages of the electrode tip age. The optimum conditions were determined to achieve the maximum yield of successful nuggets.

Chapter 5

Microwave Sensors Structure

5.1 Microwave Sensors

The bonding of plastic materials in the automotive industry requires testing in order to reassure the quality of the bond. The main body parts that are manufactured from plastic are on the bumper and the wings of the vehicle. Traditional methods of measuring ultra-small volumes and thickness of materials with high accuracy for quality control are lab-based and include standard UV-Vis measurements, mass spectrometry, amperometric sensors, fibre-optic sensors and MEMs [61]. However, when it comes to an in-situ real-time method capable of non-destructive assessment of material thickness, there is none readily available. Microwave sensing is a novel but rapidly developing technology which has been successfully used as a sensing method for various industrial applications including solution concentrations [62], fluid level measurements [63], material moisture content [64, 65], continuous process monitoring of biogas plants [66], determination of moisture content in soil [67] and in the healthcare industry, for example for real-time monitoring of glucose in diabetic patients [68, 69] and for non-invasive monitoring of bodily fluids [70]. Microwaves are largely used for material characterisation since they easily propagate through low-loss dielectrics and the amplitude of the electromagnetic wave reflected by or transmitted through a material obstacle strongly depends on the dielectric properties of the material itself.

A microwave system is able to adequately trace multiple phases in a complex fluid flow. For example, an electromagnetic wave cavity resonator was used to monitor the percentage volumes of each of the two phases (oil and gas) in the pipeline using the resonant frequencies shifts that occur within the resonator [71]. However, the microwave planar printed patterns for various sensing applications are increasingly used due to their versatility, flat profile and low weight. Their design can be tailored to suit particular applications, coupled with reliability and cost-efficiency. They are easily manufactured using common methods for printed circuit board production, and their impedance can be matched to the input line by altering the micro-strip line feed configuration. The patch antenna represents the frequency-selective element of a phase shift transistor oscillator. The active integrated antenna frequency of operation is determined by both the patch geometry and the electrical loads connected at the two microstrip ends [72]. For example, a coaxial-fed patch antenna suitable for non-destructive porosity measurements in low-loss dielectric materials has been reported [73]. The variation of the patch resonant frequency when it is put on the surface of the material under test was used to estimate the dielectric permittivity in the 2.4 GHz ISM frequency band. The estimated porosity was in good agreement with that obtained by conventional mechanical measurements, and the mean percentage error was less than 13.5%.

To clarify the principle behind electromagnetic wave sensing suggested in this work for volume/thickness measurements, it is worth mentioning that microwave sensors in the form of planar printed patterns operate based upon the fact that an object under test, such as a piece of plastic, when placed into the vicinity or in direct contact with a microwave sensor, interacts with the electromagnetic waves in a unique manner, which can be correlated with the properties of this material. In particular, the sensing is based on interaction with propagating or resonating modes within the material under test. By considering how the reflected (S_{11}) microwave signals vary at discrete frequency intervals, the change in the signal can be linked to the amount and type of material under test. The response of the sensor manifests itself as a resonant frequency change, attenuation of the signal or as a phase shift.

5.2 NDT of Material Type and Thickness using a Microwave Sensor

Sensors with the structure shown in Figure 48 operating at microwave frequencies were chosen for their versatile design that combines ease of manufacturing with the desired functionality. A distinct feature of the planar microwave sensors is their superior sensitivity to change close to the sensor surface, with this sensitivity decaying rapidly with distance away from the surface.

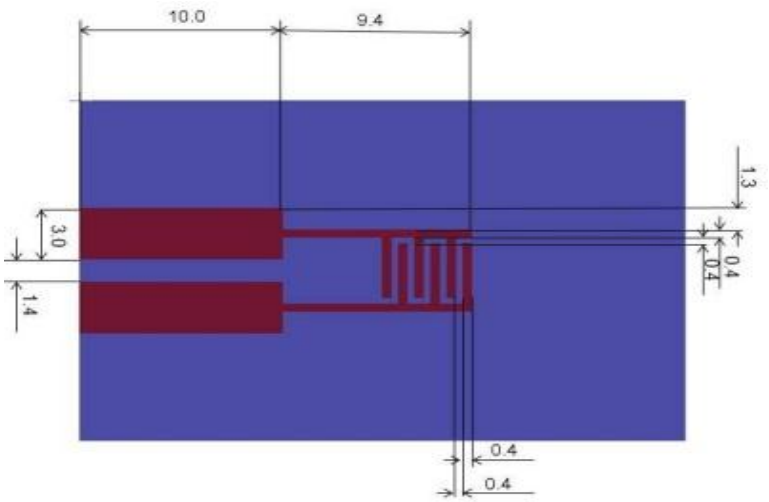

Figure 48: A printed Au pattern layout: all dimensions are in mm

5.3 Sensor Design

In this work, Au and Ag patterns in the form of interdigitated electrodes were printed on an FR4 substrate with 1.6 mm thickness and on DuPont™ Pyralux® AP polyimide flexible laminate, with 0.5mm thickness, substrates respectively to make the microwave sensors, as shown in Figure 49 . The thickness of both Ag and Au layers in all the sensors was 35 µm, and the bottom layers acted as a ground plane. The sensing area was 5×8 mm^2.

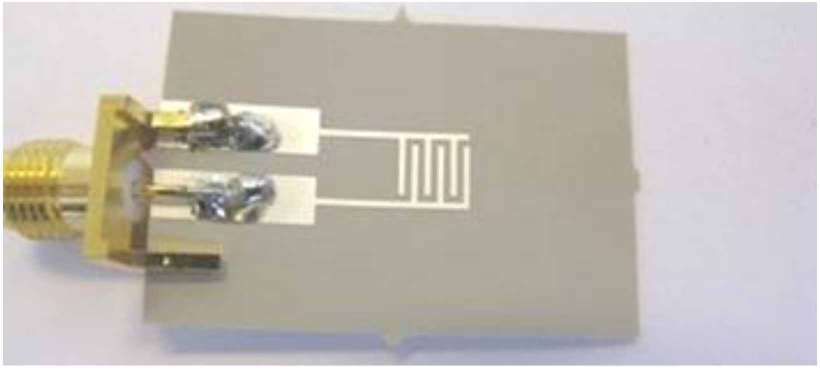

Figure 49: Microwave sensor with metal pattern, Ag pattern on polyimide flexible laminate substrate.

Figure 50, which illustrates the distribution of electromagnetic field emitted by the sensor as simulated using HFSS software. This is advantageous as it significantly reduces the chance of undesirable external factors influencing the sensor response.

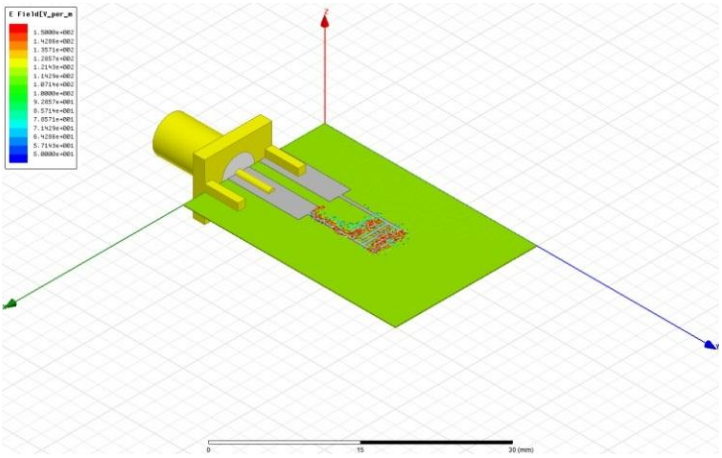

Figure 50: HFSS model of microwave sensor field.

5.4 Measurement Setup

The microwave sensors were attached to a Rohde & Schwarz ZVA24 vector network analyser (VNA) via a coaxial cable, as shown in Figure 51. Molex edge type SMA connectors [74] were used to connect the sensors via coaxial cable to the VNA. The sensor and associated equipment were all specified for 50Ω impedance, and the VNA was calibrated according to the manufacturer's specifications.

The data (60,000 points for each measurement) was captured in the frequency range of 1-15 GHz for the reflected (S_{11}) signals. All the measurements were performed at a constant temperature of 18 °C. Each sample was measured at least 5 times and the results were repeatable with less than 5% deviation and thus were deemed reproducible.

The response of each sensor was measured for air and then when in contact with varying thicknesses of polyvinyl chloride (PVC) plastic material to evaluate if the sensors responded differently. The spectra are plotted on common axes to illustrate that each sample has a unique response to the microwave signal resulting in resonant peaks occurring at different frequencies and this particular feature makes the developed sensors an attractive option for real-time monitoring.

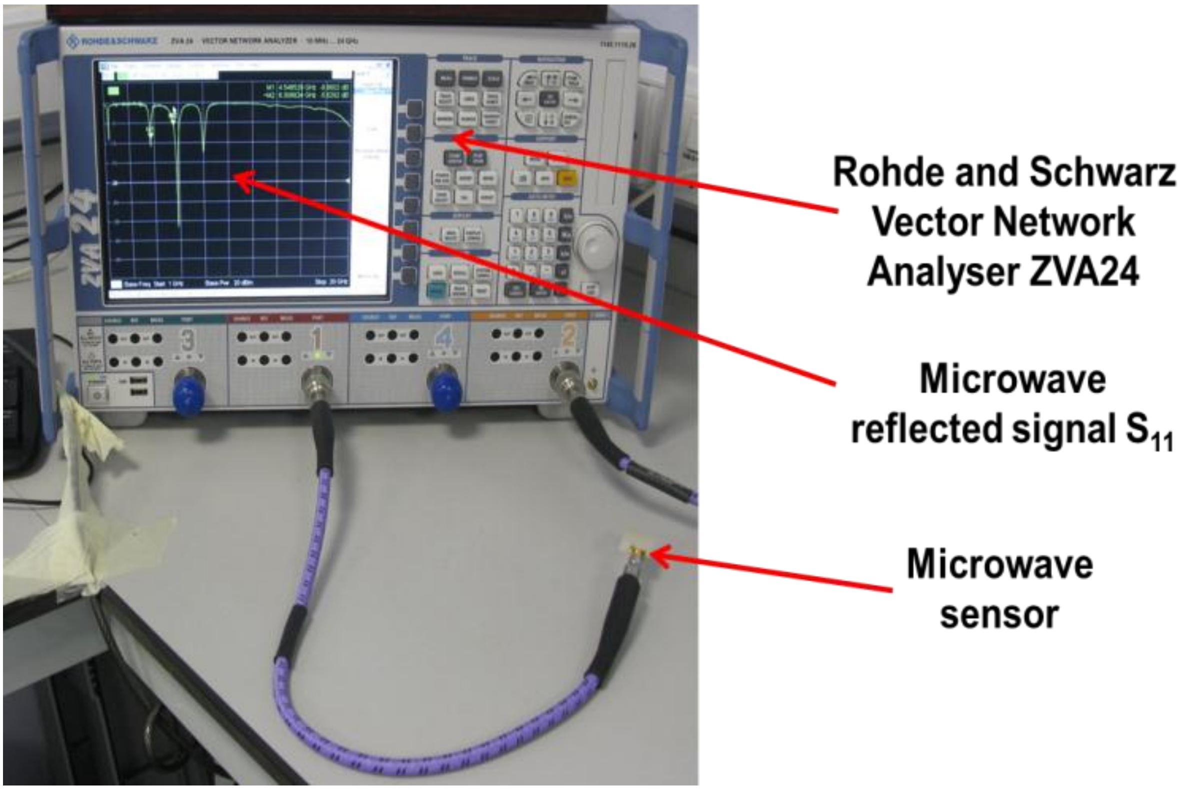

Figure 51: Measurement setup showing VNA and a microwave sensor connected via coaxial cable

5.5 Results and Discussion

The ability of the developed microwave sensors to non-destructively measure the thickness of the material, having access from one side only, was verified by placing pieces of PVC on top of the sensors, with their thickness ranging from 0.15 mm to 0.60 mm. Having examined the 1-15 GHz range, two distinct areas were focused on, since they gave the most pronounced change in the response, namely the focus was on the two resonant peaks in the 10.5-11.5 GHz and 5.0-8.0 GHz frequency ranges, as shown in Figure 52 and Figure 53 respectively.

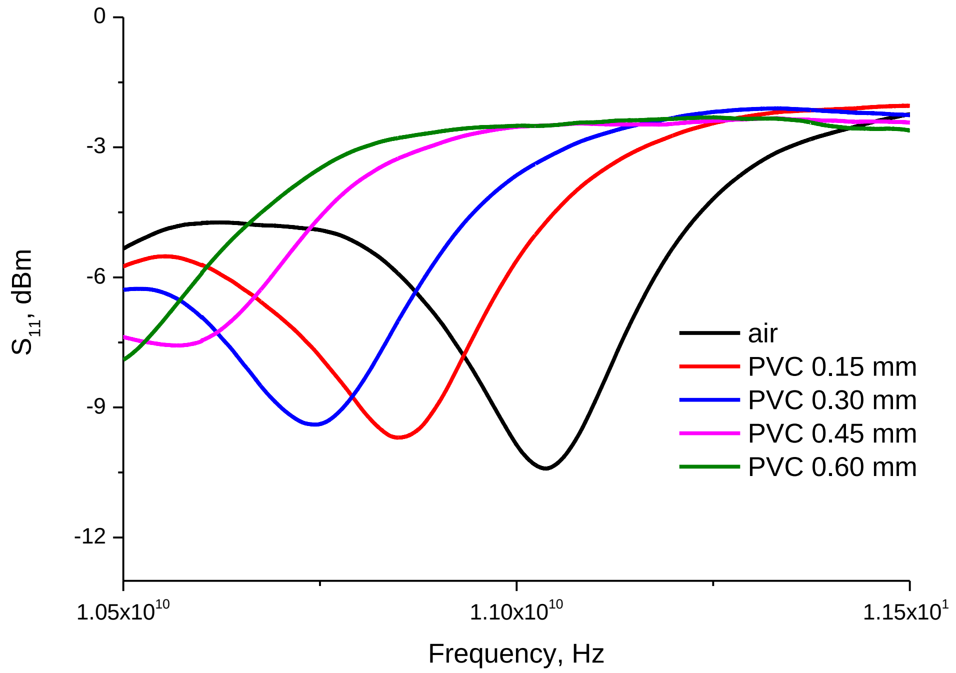

Figure 52: Dependence of S_{11} signal on the thickness of PVC, placed on top of the sensor with Au pattern on FR4 substrate, 1.05-1.15 GHz range.

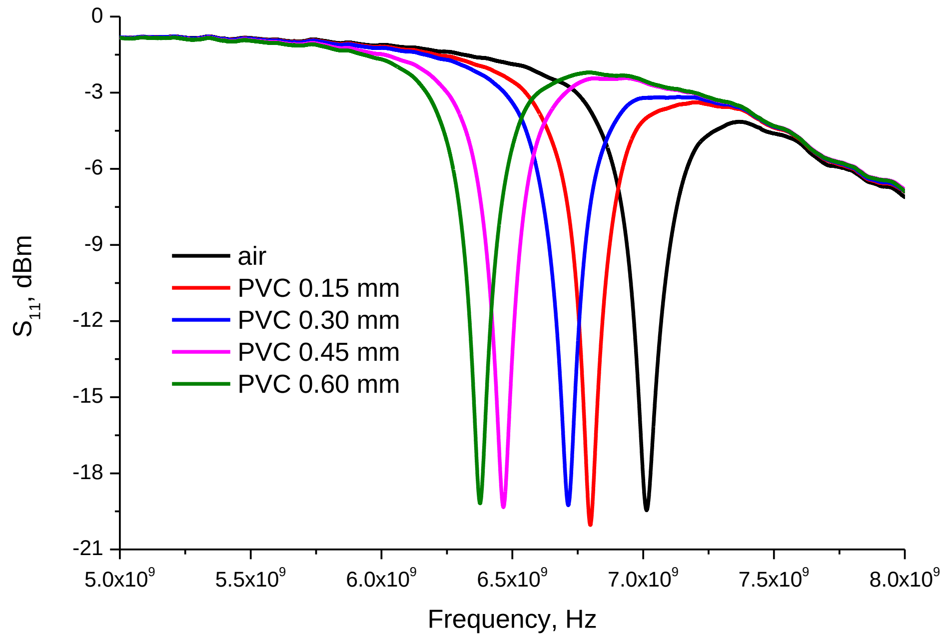

Figure 53: Dependence of S_{11} signal on the thickness of PVC, placed on top of the sensor with Au pattern on FR4 substrate, 5.0-8.0 GHz range.

Figure 54 provides the data for the calibration curve that traces the dependence of the resonant peak frequency on PVC thickness. The sensor shows a pronounced shift of the resonant peaks to lower frequencies with a linear dependence (R^2=0.9917).

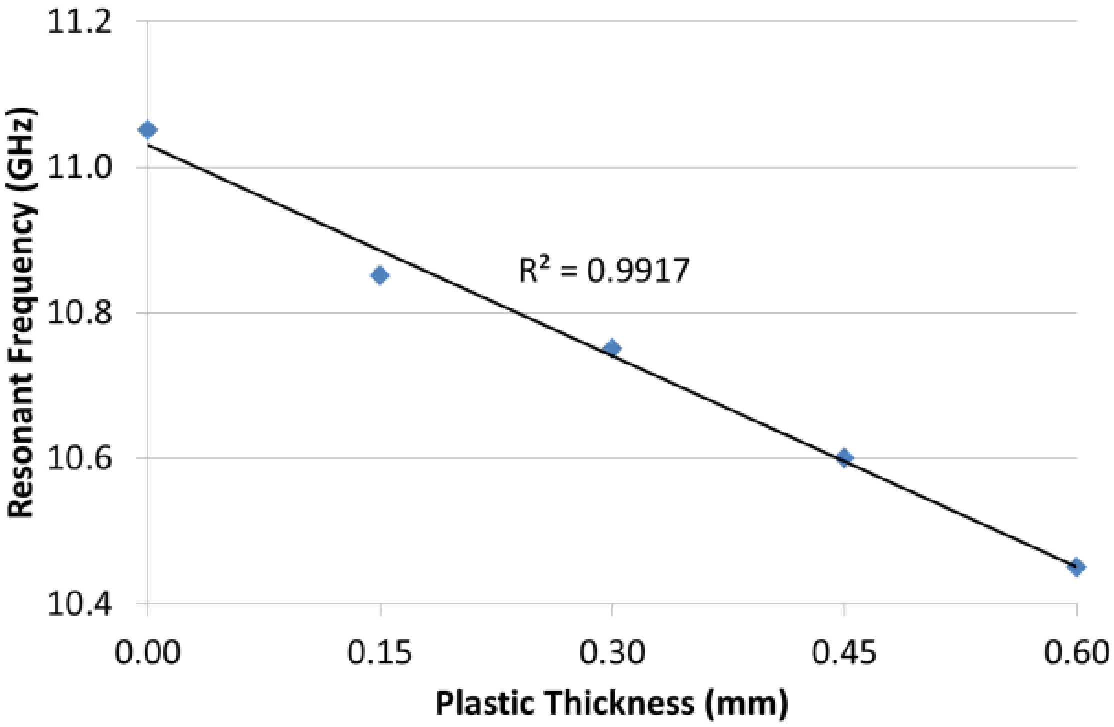

Figure 54: Change in the resonant peak frequency with the thickness of PVC in contact with the EM wave sensor.

5.6 Experimental Procedure for different Plastic materials

With 35 µm thick Au patterns printed on a 1.6 mm FR4 substrate acting as the sensing element, the sensor response was tested when in contact with transparent polyvinyl cellulose (PVC) sheet, High Density Polyethylene (HDPE) heavy duty plastic and dried plastic fusion (PF) glue (Pacer Technology 15277), as shown in Figure 55.

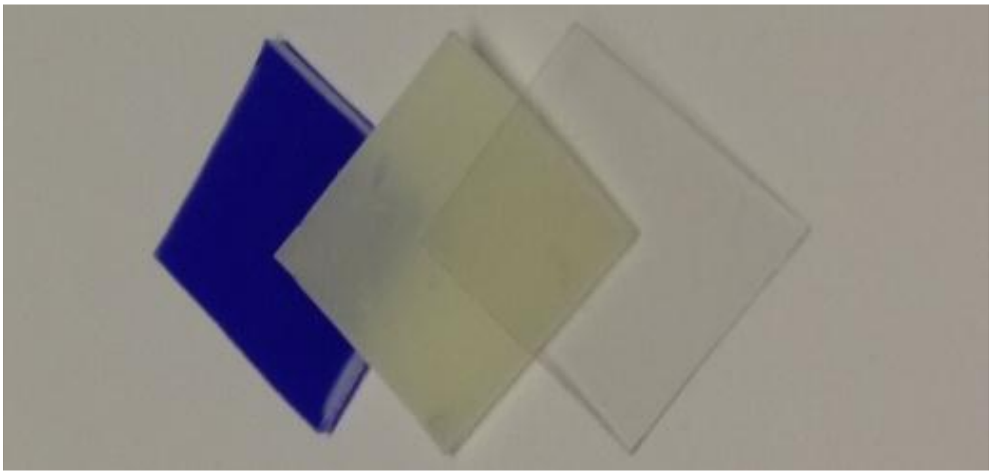

Figure 55: HDPE, PF glue, PVC samples.

The microwave sensors were again attached to a Rohde & Schwarz ZVA24 vector network analyser (VNA) via a coaxial cable and Molex SMA Connector, the data (60,000 points for each measurement) was captured in the frequency range of 0.1-15 GHz for the reflected (S_{11}) signals. All the measurements were performed at a constant temperature of 18 °C. Each sample was measured at least 5 times and the results were repeatable with less than 5% deviation and thus deemed reproducible.

5.7 Experimental Results of Plastic Thickness

Figure 56 depicts the microwave spectra for PVC, HDPE and PF glue samples of identical area, but various thicknesses. All spectra are plotted on a common graph to illustrate that each material has a unique response to the microwave signal resulting in resonant peaks occurring at different frequencies. This demonstrates the ability of the sensor to determine the type of material placed in contact with it.

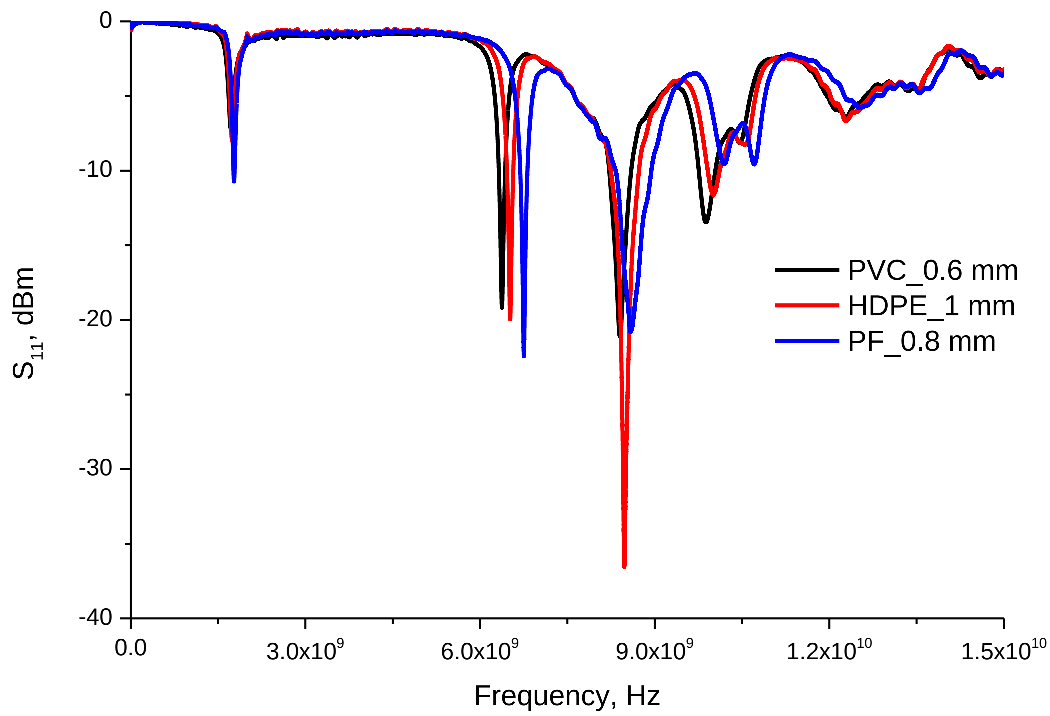

Figure 56: S_{11} signal dependence on the material type brought in contact with Au pattern on FR4 substrate, 0.1-15 GHz frequency range.

The change in resonant peak frequency or its amplitude can be used as a real-time measure of the material thickness.

5.8 Experimental Results of glue settling

The sensor was also used to monitor the changes that occur as a sample of plastic fusion (PF) glue (Pacer Technology 15277) sets. A small quantity of glue was applied directly to the sensor as shown is Figure 57

Figure 57: PF glue sample placed on the microwave sensor

Figure 58 shows the changes experienced by the S_{11} signal with time, focusing on a single resonant peak at 6.6-7.1 GHz. As the glue sets into its dried state, this resonant peak gradually shifts to the higher frequencies, accompanied by the change in the peak amplitude. Significant changes with time in the sensor response as a result of the changing properties of the PF glue were observed for another resonant peak, manifesting at the 8.2-9.0 GHz frequency range. The most pronounced change is the decrease in the peak amplitude with time, which is correlated with the solidification of the glue components with time into a final settled state.

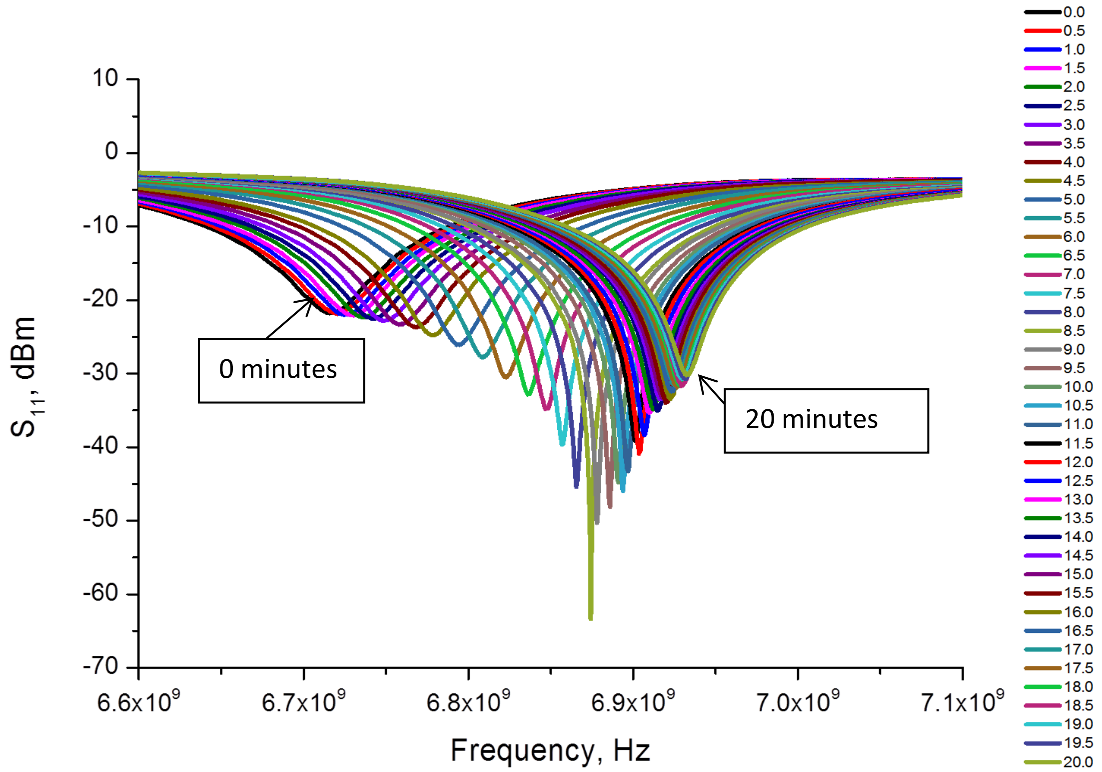

Figure 58: Change in S_{11} signal with time (in min) for microwave sensor in contact with drying PF glue, focusing on resonant peak at 6.6-7.1 GHz frequency range.

For industrial automated process control it could be more convenient to have a simple calibration curve to trace the solidification/bonding state of the glue components in real time. As an example, the dependences of S_{11} signal amplitude versus time for two selected frequencies, 6.7 GHz and 8.5 GHz, are plotted in Figure 59. According to the manufacturer specification, PF glue sets in around 10 min, depending on the temperature and humidity. From the graphs in Figure 59 it follows that after 6-7 min the signal amplitude reached already its maximum and entered a plateau, or saturation stage, which correlates with the complete solidification condition of the glue.

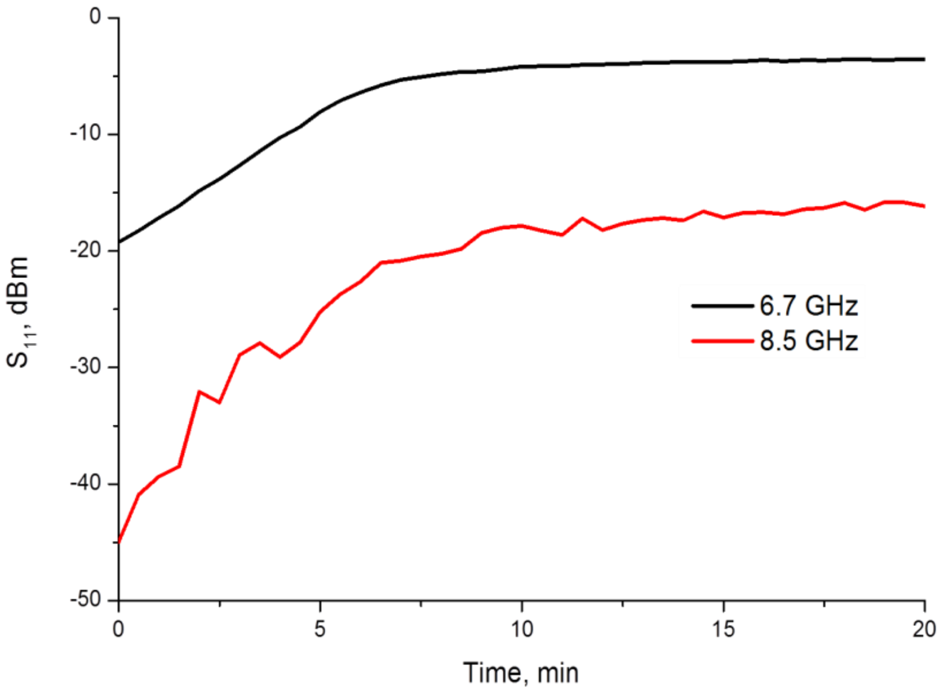

Figure 59: Dependences of S_{11} signal amplitude versus time at two selected frequencies, namely 6.7 GHz and 8.5 GHz, which can be used as a calibration curve for the real-time monitoring of glue settling state and industrial process optimization.

5.9 Summary

This research was driven by the industrial need for a novel real-time non-destructive method of measuring glued plastics. Microwave sensors were developed for this purpose and successfully tested in the 1-15 GHz frequency range. It has been clearly shown that the resonant peaks shift and their amplitude changes depend on the material type and thickness, and for PF glue, these variations have also been shown during the setting process.

Chapter 6

Conclusion & Future work

Quality control of a spot weld can only be decided after thorough analyses offline, and this costs time and money; this analysis can use either destructive or a non-destructive testing methods. So in addition to the costs of halting the production line to perform the quality control procedure –the outcome of which will decide the fate of the entire batch- destructive testing adds to these costs by destroying the sample itself; not only is it more expensive, it is also a less secure method of ensuring the integrity of an entire batch. A non-destructive method of testing would enable the manufacturer to test every single vehicle, every single weld online during the production, and that would be a huge leap for the automotive industry in terms of saving time and reducing losses, while providing an energy-efficient approach to manufacturing.

In a spot welding process it has been shown that an electrode tip can be used for more than the automotive industry recommended lifespan (approximately 600 welds) by reducing the current to the minimum value in order to produce an acceptable weld, and thereby achieving 1200 welds per electrode tip lifespan. This has the advantage of reducing the energy consumption for the welding process, which will have a positive impact both environmentally and financially, by greatly reducing the amount of current being consumed, and the expulsion that can result from it as well as decreasing the volume of carbon dioxide emissions. This enhancement is currently undergoing further development, which will enable the process to consume less energy by reducing the electrode force to a minimum.

During the 21,000 welds performed during the course of this project, It was possible to find the optimum conditions in which a weld is produced that yields excellent strength and quality, whilst providing a highly energy-efficient and environmentally friendly impact. As shown in section 4.5, the optimum conditions in terms of tip longevity for performing a spot weld are at 4.0 bar.

The systematic evaluation of a large combination of variables during this research has proven to be very successful. The novel non-destructive testing method for plastic bonding has achieved a method that can distinguish the difference between the thickness of plastic materials, and to monitor the point at which the adhesive sets. The adhesive used in a plastic weld would provide the required support and strength. This new potential approach could –if researched and investigated- provide significant savings and sustainability in the automotive industry.

The future development of this method is to design and incorporate a sensor into every car, to distinguish the quality of the bonded plastic parts and further development into a notification system to be adapted into a vehicle's instrument's panel. This could be particularly useful in monitoring the status of the adhesive from the effects of stresses and strains from different driving and weather conditions over time. The sensor could be used with other vehicles such as airplanes, yachts, and in any other applications where a plastic bond is crucial to the operation and safety of the overall system.

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1. M. Al-Jader, J. D. Cullen, N. Athi, A. I. Al-Shamma’a, SPOT WELDING THEORETICAL AND PRACTICAL INVESTIGATIONS OF THE EXPLULSION OCCURRENCE IN JOINING METAL FOR THE AUTOMOTIVE INDUSTRY pp 425-430, 14th-16th December 2009, Abu Dhabi, UAE Second International Conference on Developments In E-Systems Engineering, 2009 ISBN 978-0-7695-3912-6.
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4. M. Al Jader, O. Korostynska, A. Mason and A. I. Al-Shamma’a, ELECTROMAGNETIC SENSOR FOR NON-DESTRUCTIVE EVALUATION OF MATERIAL THICKNESS PROFILE, 8th Built Environment and Natural Environment (BEAN) Conference, 6th June 2013, Liverpool, UK, pp. 9-10.

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6. M. Al-Jader, O. Korostynska, A. Mason, and A. I. Al-Shamma'a, NON-DESTRUCTIVE DETERMINATION OF MATERIAL TYPE AND THICKNESS PROFILE WITH PLANAR MICROWAVE SENSOR. International Microwave Power Symposium (IMPI 47), Rhode Island, USA, June 25-27, 2013, pp. 151-154, IBSN: 978-0-956274748. 4.
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