Resistance Spot Welding of AlSi-coated Ultra High Strength Steel

An experimental study

KRISTOFER HJELMTORP
ABSTRACT

The automotive industry of today faces ever harder requirements from regulatory bodies to increase the fuel efficiency, reduce the carbon footprint and increase the safety of their vehicles. The problem is being tackled in different ways; one of them being the use of innovative materials to reduce the overall weight while improving the crash safety of the vehicle. One such material is 22MnB5, an ultra-high strength (UHS) boron-alloyed steel, capable of reaching tensile strength of 1900 MPa.

The weldability is a vital factor for applying boron steel in an efficient way into a vehicle construction. Resistance spot welding (RSW) is, among the different welding methods, the primary joining methods used within the automotive industry. The main challenges with RSW of UHS boron steel is the narrow welding window and increased risk of expulsion compared to conventional automotive steel.

The aim of this thesis was evaluating how the weldability of three-sheet UHS boron steel combinations could be improved by applying different innovative welding methods.

The methods investigated where; three-pulsed welding, two-pulsed welding with force profile and using hollow-cone electrodes instead of regular electrodes.

The different methods where evaluated with welding experiments and analysis of the nugget diameter, vicker hardness comparison and tensile strength test of welding nugget.

The results from this thesis shows that the current window of three-sheet combinations with UHS boron steel can be significantly improved by using hollow-cone electrodes in RSW. The results also showed that the width of the current window varied depending on the depth of the hole in the electrode, a deeper hole improved the current window but also increased the oxide build-up.

Applying a force profile with lowered electrode force during the welding sequence provided an improved process window compared to the constant electrode force when welding a three-sheet combination containing AlSi-coated boron steel.

A three-pulse welding sequence performed better than the reference two-pulse welding schedule but still not good enough to meet VCC acceptance criteria.
Sammanfattning

Bilindustrin står idag inför allt hårdare krav från tillsynsmyndigheter förbättra bränsleeffektiviteten, minska koldioxidavtrycket och öka säkerheten på deras fordon. Problemet angrips från ett flertal olika vinklar, varav en ökad användning av innovativa material för att minska den totala vikten samtidigt som fordonets kraschsäkerhet bibehålls eller ens förbättras. Ett sådant material är 22MnB5, ett höghållfast (UHS) borstål, kapabilt att uppnå brottgränser på 1900 MPa.


Målet med denna avhandling var att utvärdera hur svetsbarheten av tre-plåtskombinationer med höghållfast AlSi-belagt borstål kunde förbättras genom att applicera innovativa svetsmetoder.

De utvärderade metoderna var; tre-pulsad svetsning, två-pulsad svetsning med applicerad kraftprofil, samt användning av ihåliga elektroder istället för vanliga elektroder. Metoderna utvärderades genom svetsexperiment och analys av svetslobens storlek, vicker hårdhets mätning samt brottgränsmätning av svetslobo.

Resultaten från denna avhandling visar att svetsbarheten för tre-plåts kombinationer med UHS borstål kan förbättras avsevärt genom att använda ihåliga elektroder för punktsvetsning. Resultaten pekar också på att förbättringen beroende på hålets djup i elektroden. Ett djupare hål gav större förbättringar men ökade också uppbyggnaden av oxid och restmetall i elektroden.

Genom att applicera en kraftprofil, där elektrodkraften sänktes under svetsprocessen kunde svetsbarheten förbättras för två-puls svetsning, jämfört med att ha konstant elektrodkraft, vid svetsning av en tre-plåtskombination innehållande höghållfast AlSi-belagt borstål.

En tre-puls svetssekvens utförde bättre än referenspulssvetssschemat men fortfarande inte tillräckligt bra för att uppfylla VCC-acceptkriterierna.
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1 INTRODUCTION

To address the escalating concern regarding climate change due to CO₂ emission has driven legislators to increase the demands, seen in Figure 1, on automotive producers to reduce carbon emission levels throughout their product range [1]. The U.S Environmental Protection Agency has issued a final ruling to further reduce greenhouse gas emission to an average level of 163 grams/mile of CO₂ in 2025 increasing the demands on the automotive manufacturers [2]. To meet the demands of the future the automotive industry has taken upon itself to innovate with advanced design and materials. A critical area is the weight of the vehicle; a lighter vehicle will attain better fuel efficiency and a reduced carbon footprint.

![Figure 1: Global emission regulations](image)

The car industry has taken different roads to deal with this problem, some focusing on lightweight materials such as carbon fibres and aluminium, others on new car designs.

Volvo Car Company has chosen to increase the use of ultra-high strength (UHS) boron steels in their cars. The Body-in-White in the new XC90 contains up to 40% ultra-high strength steel (UHSS) as seen in Figure 2.
With increased use of UHSS in modern vehicles it is possible to further decrease the weight while maintaining, and even improving, crash safety, making it ready for the world of tomorrow.

But in order to complement the innovation in material usage within the car it is vital to make sure the production and manufacturing of the vehicle is keeping up with the pace of innovation.

Resistance spot welding (RSW) is the most common welding process for joining steel sheets in the car-body production and with the increasing demand for UHSS steels there is also an increasing need to study weldability of UHS boron steels which may otherwise limit its applicability. By optimizing and analysing resistance spot welding of these steels we enable more efficient and increased utilization of the steel.

One of the challenges with resistance spot welding of UHS boron steel is the generally narrower welding window and increased risk of expulsion compared to conventional automotive steels [4]. This can be partly attributed to the surface coating which is necessary as an oxidation barrier during forming of the steel [5]. Additionally, due to the higher alloying content compared to conventional steel, UHS boron steel exhibit a higher resistivity and thus during the welding procedures more heat is generated in the material. Together with a high resistive surface coating such as aluminium-silicon (AlSi), the risk for overheating and expulsion increases.

All these factors make AlSi-coated UHS boron steel a challenging material to obtain an approved welding process and welding quality with.
1.1 Aim
The aim of this master thesis is to increase the understanding of the problems and difficulty when resistance spot welding AlSi-coated UHS boron steel in multi-sheet combinations, and to provide Volvo with a more robust welding process for their specific material combinations.
2 RESISTANCE SPOT WELDING

2.1 History and background
RSW is a resistance welding method characterized by its small areas of joining, called spots. Unlike other welding methods, such as arc welding which uses an external source of heat to melt the welded material, resistance welding uses the innate electrical resistance in the material to generate heat by passing a current through the material. Among the different resistance welding methods, spot welding is the most commonly used and today as it is one of primary joining methods used within the automotive industry. The working principle behind RSW is to pass a current through two or more sheets of material which are pressed together by a pair of conducting electrodes. Because of the inherent electrical resistance in the material and the contact resistance between the sheets, enough heat generates to melts a spot between the sheets which, after the supply of current stops, solidifies and joins the sheets together.

The principle of resistance welding was discovered by an English physicist named James Joule in 1856. He managed to weld a bundle of wires by cover them with charcoal and then heat them with an electric current. It took several years before a practical application for this phenomenon was developed. In 1877 Professor Elihu Thompson invented a small low-pressure resistance welding machine. Welding was accomplished with this machine by causing the internal resistance in the work piece to generate the heat required to reach its plastic stage. Little progress was done in this area until World War II when the technique gained in popularity due to the rise of automobiles and its cost saving compared to other joining methods, such as riveting.

2.2 Physical phenomena in resistance welding
The fundamental part of resistance spot welding (RSW) is the physical phenomenon that generates heat in the material during the welding process. During the RSW process the joining surfaces undergoes five important stages; mechanical deformation, heating, melting, fusion and solidification.

2.2.1 Joule effect
The amount of heat generated when current is passing through the work piece during RSW can be described by Joule’s law,

\[ Q = I^2 Rt \]  

\( Q \) is the heat generated, \( I \) is the current passing through the workpiece, \( R \) is the total resistance and \( t \) is the time the current is allowed to flow though the circuit.

During the RSW process the resistance varies over time depending on the stage of the weld process. In order to obtain the correct heat energy Equation 1 is integrated over the duration of the weld process;
\[ Q_J(t) = \int_0^t I^2(t)R(t)dt \]  

For resistance welding the total amount of generated heat energy is not as relevant as the total heat generated at the individual resistance locations, or as the heating rate. The rate at which heat is generated has significant effect on the final microstructure of the weld [6].

### 2.2.2 Electrical resistance

The total resistance of a metal sheet stack is the sum the contact resistance between the electrode and the sheet (R1 and R5), the bulk resistance in the material (R2 and R3) and the contact resistance in the faying surface (R3), illustrated in Figure 3. The contact resistance is dependent on both temperature and pressure, while the bulk resistance is mainly affected by temperature and chemical composition [7].

![Figure 3: Resistance in a two sheet stack during RSW [6].](image)

### 2.2.3 Bulk resistance

The resistance in a material is dependent on the resistivity and the geometry of the material,

\[
R = \frac{\rho L}{A}
\]

Where \( R \) is the resistance, \( \rho \) is the resistivity, \( L \) is the length and \( A \) is the area. The bulk resistance is temperature depending for the all materials used in resistance spot welding and it increases with increasing temperature. The rate it increases varies significantly depending on the material and it has been reported that the resistivity increases with increasing alloying content in the steel [7]. As seen in Figure 4 the resistivity of mild steel is significantly larger than both Copper and Aluminium, at the same time it is very sensitive to changes in the temperature.
During the RSW procedure the Joule effect is heating the material, the resistivity increases and in turn contributes further to the Joule effect.

As copper alloys is commonly used as electrodes in RSW, the difference in resistivity between copper and steel results in a concentration of the heat generation in the steel, increasing the resistivity even further. This effect is amplified by the fact that the electrodes are usually water cooled.

### 2.2.4 Contact resistance

Contact resistance is, compared to bulk resistance, not only affected by the temperature but also the pressure from the electrodes and to some extent, the hardness of the sheet material. At the beginning of the welding process the electrodes squeeze the sheets together, forcing the faying surfaces into contact. Because of irregularities in the surface only a portion of the apparent surface area is in contact, these asperities create multiple points of connections where the current can pass between the sheets, see Figure 5. The result is a constricted current flow with high current density peaks at certain points along the surface. These points will be the place of concentrated heating in the initial stage of welding, leading to softening and then melting.
Figure 5: Constricted current flow between two sheets. [8]

Higher roughness will result in fewer asperities and higher resistance, while higher electrode force will flatten the asperities resulting in an increased contact area and lower resistance. Although, independent of the surface roughness the resistance will decrease during the welding process. As heat is generated at the faying surface and electrode-sheet interface, the materials will start to soften, increasing the contact area both in the electrode-sheet interface and the sheet-sheet interface.

Contact resistance is affected by the surface conditions of the metal sheets. Dirt, oil, oxides and coatings changes the static contact resistance in varies degrees. Figure 6 illustrates how measured resistance values of 5A02 aluminium alloy sheets vary depending on the type of cleaning method used.

Figure 6: Measured resistance values depending on the surface cleaning method [6].
2.2.5 Total resistance

The sum of bulk resistance and contact resistance equals the total resistance over the electrodes. The total resistance during each stage of the process determines the heat generated in the material. Both the contact resistance and bulk resistance changes significantly during the process window, Figure 7 shows a typical resistance profile for an AlSi-coated steel during welding. This is termed the dynamic resistance profile. Several stages can be identified: [9]

0. Surface heating
1. Surface film breakdown
2. Softening of the coating
3. Coating melts
4. Bulk heating and melting
5. Nugget growth
6. Expulsion

![Figure 7: A generalized dynamic resistance profile for coated steels](image)

The initial spike in the resistance curve is attributed to the high resistance of the oxide coating.

Stage 1 follows with a sharp drop in resistance due to fritting; where the oxide film on top of the coating breaks down and asperities on the surface begins to crumble. During stage 2 the bulk material increases in temperature resulting in a rise in the resistivity. The heating is concentrated at the faying surfaces and electrode-sheet interface, softening and heating the coating.

This eventually results in the coating starting to melt in stage 3. As it proceeds the electrode force squeezes the melted coating outwards, displacing it at the faying surface. This simultaneously increases the contact area between the sheets and moves the sheets closer to each other, decreasing the resistance.

Stage 4 begins with the electrode pushing through the coating at the electrode-sheet interface due to the softening of the coating. It counteracts the increased resistance due to bulk heating resulting instead in lower resistance. It also further displaces coating in the
sheet/sheet interface in addition to reducing the asperities which further lowers the resistance. At the end of stage 4 the coating is forced away in the sheet-sheet interface and the bulk material is exposed.

The bulk material is reaching the point of melting in the faying surface which in stage 5 initiates into nugget formation and growth. The volume of melt increases, and the surrounding material softens because of the high temperature. The resistance curve starts a falling trend, due to the electrode closing in on each other and reducing the current path.

The last stage that can be observed is a small dip in the resistance curve if the weld process continues until expulsion. The molten metal can no longer be contained under the force of the electrodes and the molten metal escapes the weld zone, resulting in the small decrease in resistance as well as other factors such as loss of material and decreased strength of the joint [9].

2.2.6 Shunting effect

In RSW the previously made weld may affect the subsequently made welding spots depending on the distance between the spots due to the electric current diverting from the preferred path. This is termed electric current shunting; a schematic presentation of the phenomenon can be seen in Figure 8. When welding subsequent spot welds, the current can be increased depending on the number of welds in sequence. Otherwise the result could be insufficient weld nugget formation. All of the main welding parameters; current, time, electrode force, electrode geometry and specific material properties such as bulk resistance and surface influences the severity the shunting effect in different degrees.[10] The shunting effect is strongly affected by the bulk resistivity of the material. High conductive materials require larger space between the spot welds because of higher current losses due to shunting [6].

![Figure 8: Electrical shunting effect in resistance spot welding]
2.2.7 Seebeck effect

The Seebeck effect, together with the Peltier effect and the Thomson effect, are all three a part of the thermoelectric effect. The thermoelectric effect is the conversion of temperature difference to electric voltage or the reverse.

The Seebeck effect describes the conversion of a temperature gradient directly into electricity. If a body or circuit has two parts with different temperature, a current will be generated between them. This is because the temperature gradient in the body will cause charge carriers to diffuse from the hot side to the cold side.

2.2.8 Peltier effect

The Peltier effect is the phenomena describing how heat can be generated depending on the direction of the current. When the current is flowing from one body to another it will generate heat at one of the surfaces. If the current is reversed it will generate heat at the opposite surface.

The Peltier effect has minor importance for the temperature profile in RSW. For challenging sheet stack combinations where one of the sheets is more sensitive to overheating it can have a significant effect.

When testing difficult sheet stack-ups Volvo has it as best practice to always test the worst case regarding the Peltier effect. This means having the thicker outer sheet towards the positive electrode. In the case of equal thickness, the lower strength material shall be towards the positive electrode [12].

2.2.9 Thomson effect

The Thomson effect occurs when current flows through a body composed of single material which has a temperature gradient along its path, if one side of a metal sheet is warmer than the other. The result is that a continuous version of the Peltier effect can be observed, and heat will either be generated or dissipated, depending on if the current is flowing towards the cold or the hot side. If the temperature is rising along the current path; heat will be generated and in the reverse case heat is absorbed.

2.3 Resistance spot welding parameters

The resistance spot welding process is controlled by several different parameters. These parameters together with the physical phenomena and the welded material determine the results of the weld process.

2.3.1 Weld current

The current, $I$, is the principal welding parameter as it affects the generated heat, $Q$, by the square and is thus vital for the weld quality and the properties of the weld. If the current is too low the heat generated will be insufficient to create a large enough weld nugget. A too high current may lead to expulsion, damage to the electrode and surrounding equipment. Expulsion is an especially unwanted phenomenon in the automotive industry as it can result in reduction in weld strength, misalignment of the sheets, molten metal on equipment and
other parts of the vehicle which requires to be addressed further down the line. An example of expulsion when spot welding AlSi-coated boron steel can is shown in Figure 9.

![Image](image.jpg)

*Figure 9: The effect of expulsion is shown after a peel test on spot welded AlSi-coated boron steel.*

### 2.3.2 Weld time

The duration which the current flows through the workpiece is termed the weld time. The weld time is, as seen in Equation 2 a parameter in the Joule effect and is therefore of importance for the heat generation and the result of the weld. A too short weld time may result in either an insufficient nugget development or none at all, while too long time may lead to expulsion.

The weld time is measured in either cycles or milliseconds depending on the type of current regulator used. Traditionally, AC has been used and the weld time has been measured in cycles. Recently the use of MFDC has increased in popularity and thus the weld time is measured in milliseconds.

In the automotive industry there is an incentive to keep production times as short as possible to decrease the cost. Therefore, the weld time is typically kept as low as possible and it is common to regulate the weld current instead of the weld time to achieve adequate results.

### 2.3.3 Electrode force

The electrode force brings the sheets together and assures a sufficient connection during the entire weld process. The electrode force influences several factors during the weld process. A high force magnitude will lower the contact resistance between the sheets, decreasing the heat generated at the faying surface. This may lead to inadequate melting and nugget formation or that melt initiates at an undesirable location. The higher heat diffusion, because of the improved contact between electrode and sheet may also influence the melting and nugget formation negatively. Too high force increases the risk of deformations and damage to the welded material.

Too low force on the other hand increases the risk for excessive heat formation and expulsion. The force will not be able to counter-act the growing pressure from the liquid nugget during melting, which then can lead to expulsion between the sheets. Lower electrode force increases the contact resistance leading to increased heat generation and risk for expulsion. Too low force will also make the process more sensitive to misalignments of the sheets and the electrodes, which increases the risk for expulsion.
In automotive manufacturing, the electrode force is typically in the range of 3-6 kN, depending on the material properties, thickness and number of sheets. The difference in thickness between the sheets is a factor as well, with large differences the contact resistance has greater influence which in turn can be controlled by the electrode force. Most commonly used modern weld guns is capable of forces up to 5 kN.

### 2.3.4 Electrode geometry

The shape and size of electrode affects the contact area, which in turn changes the contact pressure and the current density in the sheets. A general guideline is that the diameter of the tip should be approximately $5\sqrt{t}$, where $t$ equals the thickness of the thickest sheet. Specific geometries of the electrodes are described in the international standard SS-EN ISO 5821:2009 [13].

It can be beneficial for the weld quality to use different electrodes on each side depending on the stack-up of the sheets. A smaller electrode can increase the current density, providing higher heat generation while a larger electrode can increase the contact resistance over the interface by distributing the force over a larger area and thus obtaining lower pressure.

Different types of electrodes can be seen in Figure 10.

![Figure 10: Different electrode geometries](image)

### 2.3.5 Electrode material

The main purpose of the electrodes is to conduct electric current to the sheets and press them together. Therefore, the important material properties are electric conductivity, thermal conductivity, compressive strength and hardness. It is important to find a balance between these attributes when selecting the electrode material. Copper and copper-based alloys are the most commonly used material, due to its high electric- and thermal conductivity.
By using different material for the electrodes, with different electric conductivity, it is possible to alter the heat balance in the sheets and achieve melting in otherwise difficult locations. The electrode materials are described in the international standard ISO 5182:2008 [13].

2.3.6 Electrode degradation

The contact between the electrode and sheet is of importance for several factors such as contact resistance, current density and electrode pressure. As such the condition of the electrode tip will significantly affect the weld result.

There are several different mechanisms contributing to the degradation of the electrode tip [14], most significantly:

- Softening of the electrode contact area
- Pitting and deformation of the contact area
- Alloy formation
- Recrystallization

Repeated temperature changes in the material can lead to softening of the electrode tip and increased deformation of the electrode. Continuously deformation can lead to an enlarged contact area and lowered current density. Pitting of the electrode area refers to a phenomenon where irregularities and cavities form on the tip of the electrode. This causes reduced contact area and localized spots with high heat generation which can lead to premature expulsion.

When welding coated steels such as galvanized- and aluminized steels the coating can interact with the electrode and form oxide layers on the electrode. The oxides will increase the resistance in the electrode/sheet interface, leading to higher temperatures, further degradation of the electrodes and increased risk for expulsion.

Recrystallization is the formation of new grains caused by increased temperature with deformation of the material. The result will be lowered hardness of the electrode tip.

Electrode dressing is a technique used to clean the electrodes between welding. A specialized tool is used which cuts away the upmost layer of the electrode as well as any oxides or alloy formation. The frequency of electrode dressing in production varies depending on the type of material used and welding parameters. Coated steel typically requires more frequent electrode dressing because of the tendency to form oxide layers on top of the electrodes. Higher currents and longer weld times also require higher frequency of electrode dressing as it degrades the electrodes faster.

2.4 Equipment

A resistance spot welding setup consist of a combination of electrical and mechanical system. The setup should be able to deliver welding current under a certain weld time while clamping the pieces together with a specific electrode force. Most systems consist of a weld gun and a power source.

2.4.1 Weld guns

The purpose of the weld gun is to provide contact with the material, apply the correct electrode force to keep the sheets together and deliver the current through the material. A
weld gun is either automatic or manual. A manual gun requires an operator and the quality of the welding will be highly dependent on the skill of the operator. An automatic gun is operated by a robot, providing a high degree of precision and consistency. The downside with a welding robot is the inability to compensate for geometric differences and misalignments.

Weld guns may vary in how they generate the force and how they apply the force. The principle behind the generation of the kinetic force is either pneumatic or electric guns. The benefit with electric guns is that they are generally more powerful, exact and precise while pneumatic guns have the benefit of lower cost.

The two most commonly used designs for applying the force is a linearly moving electrode, C-guns, and X-guns; where two arms are rotating around the same axis and the momentum is transferred from the axis to the electrode tips. Linearly moving electrodes is advantageous because they provide the force directly towards the sheets and they require less space. The C-guns are generally more expensive than X-guns [15].

2.4.2 Power sources

Mid frequency direct current (MFDC) is the dominantly used power source in resistance spot welding. Compared to alternating current (AC), the traditionally used power source, they are more efficient and produce larger welds at lower currents. The different results between the two processes are believed to be caused by the contact resistance behaviours during welding, as well as the effects of the electrical inductance in the AC process [16].

2.5 Weld inspection and requirements

The inspection and evaluation of the welds are a critical component in all aspects of welding. A new material or sheet combination needs to be thoroughly tested to ensure it qualifies as weldable before it can be used in a production setting. Weldable is not a defined term since there are no universal accepted standard for weld quality. The American national standard (Standard Welding Term and Definitions, ANSI/AWS A3.0:2001) defines an acceptable weld as “a weld that meets the applicable requirements”, which means that it is up to the manufacturer to set the requirements for each application. At Volvo Car Corporation (VCC) the quality and testing of spot welds is regulated by the standards Spot Welding: Quality Assurance (VCS 8631,39), Spot Welding: Joint requirements (VCS 5621,19) and “Spot Welding. Design and dimensioning”. Additionally, the Ford Motor Company standards Resistance Spot Welding (ES-6M2A-1K251-AB) and Resistance Spot Weldability (TM7S7A-1K251-AA) have been used at VCC.

2.5.1 Evaluation attributes

The weld quality is evaluated by its physical characteristics and performance. The physical characteristics can be inspected by either destructive or non-destructive methods. The most common parameters evaluated after welding are: [6]

- Nugget size
- Penetration
- Indentation
- Cracks (surface and internal)
Among these attributes the nugget size is the most frequently measured and used for qualified evaluations. The nugget size represents the weld size in terms of nugget width or diameter. However, the nugget size alone is not sufficient enough to obtain a complete picture of the welds strength, other parameters such as penetration and indentation can be useful to complement the nugget size. Penetration can indicate the volume of material melted during the welding process and when welding three or more sheets it is vital to ensure penetration into all layers of material. Several of the above listed attributes are shown in Figure 11.

![Figure 11: Weld attributes revealed by metallographic cross sectioning of a spot weld [6].](image)

### 2.5.2 Weld performance

To evaluate the welds beyond the cosmetic and geometrical factors, weld quality is measured in strength and performance. The most relevant parameters are: [6]

- Tensile-shear strength
- Tensile strength
- Peel strength
- Fatigue strength
- Impact strength
- Corrosion resistance

Among these, tensile-shear strength is the most commonly used. It is relatively simple to measure and relevant for most applications. Both tensile-shear strength and cross-tensile strength has been shown to correlate well with nugget size for high strength steels, shown in Figure 12.
Figure 12: Relationship between nugget diameter, tensile-shear strength and cross-tensile shear strength in two 1.8 mm GA coated 780 MPa cold-rolled steel sheets [17].

2.5.3 Requirements

The weld quality requirements differs between manufactures and organizations due to “drastic differences in design, understanding and perception of weld quality” [6]. Generally, the requirement for nugget diameter is between $4\sqrt{\text{\varepsilon}}$ and $5\sqrt{\text{\varepsilon}}$ but as shown in Figure 13 it can vary drastically between organizations.
At VCC nugget size, indentation and penetration are evaluated in spot weld tests as well as a general assessment of the appearance, including cracks and porosity. Based on these parameters the weld is classified as successful, insufficient or defective.

### 2.5.4 Testing procedures

There are several different testing procedures which can be used to evaluate spot welds. The main categories are destructive testing and non-destructive testing.

### 2.5.5 Destructive testing

Destructive testing is the primary way of evaluating spot weld quality as it provides valuable information in a time-efficient way. The most common procedure in process optimization is button size measurement and failure mode determination after peel or chisel test.
In destructive testing the spot weld fractures predominantly in three different ways characterized by their appearance; plug or pull-out failure, partial plug failure and interfacial failure.

Plug failure is characterized by one of the sheet fracturing in a ring around the weld, leaving a “plug” sticking out of the other sheet.

In partial plug failure a part of the weld zone will fracture together with the sheet. This leaves only a portion of the plug still sticking out of the other sheet.

Interfacial failure happens when the fracture shears straight through the weld nugget, leaving half of the weld in each sheet and no nugget protruding out of the sheets. This typically happens when the energy into the material has been to low which results in insufficient melting, but it can also occur in otherwise acceptable welds in high strength steels with thick plates.

Spot welds are often measured using a calliper. In order to account for any irregularities in the geometry, two measurements should be taken at 90° to one another. If possible the maximum and minimum diameter should be measured, and an average diameter is then calculated.

When measuring a partial plug failure and interfacial failure, the true weld nugget dimensions are those of the rough fracture surface which also may be covered partially by the weld nugget.

The three different failure modes and directions on how to measure them is shown in Figure 14.

![Figure 14: Picture of plug failure, interfacial failure and partial plug failure and how to measure them.](image)

### 2.5.6 Chisel test

In a chisel test a tapered chisel is forced through the gap between two sheets towards the tested spot weld, until the sheets separate and the weld fractures. For three- or more sheets this will be done at each interface and each nugget will be measure separately. The failure mode of the weld should also be determined. It is important that the edge of the chisel does not touch the weld since this will influence the nugget size and failure mode.

It also possible to conduct chisel test in a non-destructive way. The process steps are similar, but the chisel is driven until the material close to the weld bends or yields. This is done to make sure that no fracture has occurred close or in the weld. Afterwards the sheet shall be restored back into their original shape.
2.5.7 Peel test
The peel test consists of removing one sheet from the other by peeling them apart. The sheet is separated at one end and one of the sheets are rolled up by a roller or pulled away by a gripper until the welds that are being tested are fully revealed and fractured. The nugget sizes and failure modes are measured in the same way as in the chisel test. Both chisel test and peel test are shown in Figure 15.

![Figure 15: Illustration of (a) Chisel test and (b) Peel test](image)

2.5.8 Metallographic testing
A metallographic test is done by cutting the weld through the centreline, then grinding, polishing and etching the sample. In this way it is possible to optically observe the microstructure of the weld and determine the nugget size, penetration depth, indentation and the width of the heat-affected zone.

A non-trivial source of error with metallographic testing is that a 3D-structure is examined with a 2D method. Parameters such as nugget size can be greatly affected by how close to the centreline of the weld the specimen is cut, leading to uncertainties in the result.

2.5.9 Non-destructive evaluation
Destructive testing has obvious disadvantages, since the tested parts needs to be destroyed. This method cost both substantial time and money and is only possible to use before or after the welding process is done. To remedy this a large effort have been put into developing non-destructive testing (NDT) methods for the automotive industry which able to detect parameters such as nugget size, expulsion, porosity and cracks. An important factor for
The automotive industry is the ability for a NDT method to work as an automatic quality control method for spot welds [18]. The most common NDT-methods used for spot welds are visual inspection (VT), penetrant testing (PT), eddy current testing (ET), ultrasonic testing (UT), magnetic particle testing (MT) and X-ray testing (RT). Other less used NDT methods are acoustic emission (AE), digital shearography and IR-thermography (IRT). In the automotive industry, the most common NDT method for evaluation of spot welds is ultrasonic testing but experiences from the industry has shown that the reliability is depending on the skill of the operator and the testing situation. Thermography has shown potential to be an automatic NDT method for quality control of spot welds in both 2 and 3-sheet welds that is applicable in the automotive industry [18].

2.5.10 Optimization of weld parameters

Weld parameters are optimized and evaluated by producing weldability lobes according to SS-EN ISO 14327 [19] in addition to any internal corporation standards. A weld lobe can either be 1-dimensional (1D) or 2-dimensional (2D) depending on the number of varied parameters through the test. A 1D lobe is produced by keeping two parameters constant, often the electrode force and the weld time while increasing the current step by step by a fixed value until expulsion occurs. A 2D lobe is produced in the same way except that two of the three parameters; weld current, weld time and electrode force are varied.

The lower limit of the weldability lobe is determined by the parameters that produce a nugget diameter equal to the minimum required nugget diameter. The upper limit corresponds to the highest parameters which produced an approved and expulsion-free spot weld. Weld lobes are produced through welding trials on standardized test coupons, shown in Figure 16.

A 1D weld lobe is shown in Figure 17, the red horizontal lines mark the lower and the upper limit of the weld lobe and the circle and triangle represents the nugget size of the first interface and the second interface respectively.

![Figure 16: Weld lobe produced on a spot weld test coupon.](image)
Figure 17: An example of a 1D weld lobe of a 2-sheet combination

A 2D weld lobe is shown in Figure 18, the electrode force has been kept constant while the weld current and weld time has been varied.

Figure 18: An example of a 2D weld lobe where the weld current and weld time has been varied [6].
3 HOT STAMPING OF HIGH STRENGTH STEELS

3.1 History and background

Press-hardening or hot-stamping was invented at Plannja Hard Tech [20] steel mill in Sweden which then became a part of SSAB Hardtech and later Gestamp HardTech. The process was exclusively used by SSAB until the patent ran out in the end of 1990 and the technology became available for everyone.

The process has become increasingly popular since its inception with the number of parts produced reaching approximately 107 million parts/year in 2007 [21], with an approximately 110 production lines worldwide by 2009.

With the automotive industry’s continuously on-going struggle to minimize weight, to be able to meet the environmental regulations while keeping the safety requirements, several variants of high strength steel has been introduced into the car body. By implementing hot stamped steels in modern vehicles, it’s possible to significantly improve the safety for the passenger in a side impact and roll-over crash.

One such material is hot stamped boron steel which is capable of reaching strength values of 1500 MPa [22]. Saab Automotive AB was the first car manufacturer to introduce hardened boron steel into their Saab 9000 model in 1984. Since then it has become increasingly common for vehicle manufacturer to adopt hot stamped boron steels into their Body-in-white.

Volvo Cars has increased the use of boron steels in their cars over the years from 3% in 2000 to 38% in their 2015 XC90 as seen in Figure 19.

![Figure 19: Amount of boron steel in Volvo cars [3].](image)

The development of the hot stamping process has led to two different approaches, the direct and the indirect method.

The direct hot stamping process can be seen in Figure 20.
In the direct method, the steel is cut from a coil into the appropriate size and heated to 880-950 °C for 3-10 minutes. During the time in the heating furnace the steel becomes fully austenitic with high ductility. The steel is transported to a water-cooled die tool which presses the steel into the correct shape while simultaneously quenching it to 150 – 200 °C for 3-10 seconds, achieving martensitic microstructure.

The indirect method can be seen in Figure 21.

In the indirect method the steel sheet is first cold-formed close to its final shape before entering the heating furnace. This offers the possibility for more complex shapes and larger dimensions. The indirect method also offers the possibility to use conventional zinc-based coatings instead of aluminized which is commonly used in the direct method. The disadvantage is the additional cost because two forming tools are required.

### 3.2 Hot-stamped Boron steels

The boron steel commonly used in the hot stamping process is a low carbon steel alloy with boron. The addition of boron as an alloying element increases the hardenability of the steel significantly. An 0,002% addition of boron is equaling 0,5% manganese in hardenability. The composition of a few boron steel grades can be seen in Table 1. [24].
Table 1: Composition and strength of several boron steel grades [24]

<table>
<thead>
<tr>
<th>Steel</th>
<th>Al</th>
<th>B</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>N</th>
<th>Ni</th>
<th>Si</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>20MnB5</td>
<td>0.04</td>
<td>0.001</td>
<td>0.16</td>
<td>0.23</td>
<td>1.05</td>
<td>–</td>
<td>0.01</td>
<td>0.40</td>
<td>0.034</td>
</tr>
<tr>
<td>22MnB5</td>
<td>0.03</td>
<td>0.002</td>
<td>0.23</td>
<td>0.16</td>
<td>1.18</td>
<td>0.005</td>
<td>0.12</td>
<td>0.22</td>
<td>0.040</td>
</tr>
<tr>
<td>8Mn3CuB3</td>
<td>0.05</td>
<td>0.002</td>
<td>0.07</td>
<td>0.37</td>
<td>0.75</td>
<td>0.006</td>
<td>0.01</td>
<td>0.21</td>
<td>0.048</td>
</tr>
<tr>
<td>27MnCuB5</td>
<td>0.03</td>
<td>0.002</td>
<td>0.23</td>
<td>0.34</td>
<td>1.24</td>
<td>0.004</td>
<td>0.01</td>
<td>0.31</td>
<td>0.042</td>
</tr>
<tr>
<td>37MnB4</td>
<td>0.03</td>
<td>0.011</td>
<td>0.33</td>
<td>0.16</td>
<td>0.81</td>
<td>0.006</td>
<td>0.02</td>
<td>0.31</td>
<td>0.046</td>
</tr>
</tbody>
</table>

The microstructure of a 22MnB5 boron steel termed Usibor 1500P from ArcoMidall, before hot stamping can be seen in Figure 22. Before hot stamping the microstructure consist of a white ferrite phase with black spots of pearlite phases and the steel has a strength of about 600 MPa. During the heating stage in the hot stamping process the steel transforms to 100% austenite, the strength lowers to about 200 MPa and the strain rate increases to 26%. The steel is then quenched, which induces a diffusion-less transformation to a martensitic microstructure. The martensitic microstructure can be seen in Figure 23. The critical cooling rate needs to exceed 27 K/s down to 400 °C where the martensitic transformation, Ms, starts and 280 °C, Mf, where it ends.

The mechanical properties of the martensitic boron steel after quenching are highly dependent on the carbon content. An increase in carbon content increases the yield and ultimate yield strength. Additionally, Mn and Cr are known to have small effect on the strength, but they have far greater effect on the hardenability of the steel.
Figure 22: Microstructure of Usibor 1500P before hot-stamping [25].

Figure 23: Microstructure of Usibor 1500P after hot-stamping [25].
3.3 Coating systems for hot-stamped steels

3.3.1 Bare steels
Initially, when the hot stamping technology was developed mainly uncoated steel was utilized. However, today the coated steels are most frequently used, even though uncoated steels still are used to some extent. During the austenization heat treatment iron oxide is formed on the steel surface due to thermal oxidation. The mill scale is problematic as it hinders cooling from the die and oxide particle may adhere to die, causing surface damage. After press forming, the mill scale is removed by shot blasting or shot peening. During this process spherical steel particles, with a diameter of several hundred microns, are projected on the steel surface by high pressure gas. The impact removes the brittle surface oxides and introduces surface stresses on the steel. In the case of hot stamped parts with a complex shape, the oxide scales may still need to be removed manually. When the scale is removed by chromium shot blasting, a thin film of chromium and iron is left on the surface. After scale removal, the hot stamped parts are passivated and coated with primer paint.

3.3.2 Aluminized coating
There are two types of hot dipped aluminized coatings currently used for hot stamped parts in the industry today. The first and most common type is a coating which is an Al–Si alloy with a near-eutectic composition. This coating provides excellent resistance to both corrosion and oxidation in elevated temperatures. It is widely used as a coating on sheet steels for manufacturing automotive exhaust systems, heat shields, heating boilers, and cookers. The second type of aluminized coating consists of pure aluminium. Pure Al coating is mainly used where a highly reflective finish is important such as buildings and ventilations systems [25].

Al-Si coating is widely used for hot-stamped high strength steel such as boron steel. A thin layer of Al-Si is applied to the boron steel, usually by hot dipping into a molten Al alloy bath with a typically composition of 87wt% Al, 10wt% Si, and 3wt% Fe. The dipping temperature is typically 650-675°C and the unhardened steel is preheated to 20°C above the bath temperature before dipping. As seen in Figure 24, the coating before hot stamping is mainly pure Al and an intermetallic layer of Al₈Fe₂Si due to diffusion of iron. The Si addition to the aluminized coating is also essential to form a multi-layered microstructure.

![Figure 24: AS140 after hot dipping but before hot stamping](26)
The behaviour and structure of Al-Si coating after hot-stamping has been studied by several authors: [27], [28], [29].

The common understanding in these studies is that during heating in the furnace the top of the coating melts while the lower part reacts with the steel substrate. Fe diffuses upwards through the coating and Al diffuses from the coating into the base material, forming solid $\text{Al}_5\text{Fe}_2\text{Si}$ which after further diffusion transforms into $\text{Al}_5\text{Fe}_2$ with precipitations of $\text{Al}_2\text{Fe}_3\text{Si}_3$. After about 2 minutes heating $\text{Al}_5\text{Fe}_2$ transforms to $\text{AlFe}$. This begins at the steel/coating interface and grows further into the coating as heating time increases.

The coating thickness also increases with heating time and temperature and after hot stamping the coating is composed of multiple intermetallic layers. The topmost part of the coating is an aluminium oxide ($\text{Al}_2\text{O}_3$) layer which is formed when oxygen reacts with the heated coating. The $\text{Al}_2\text{O}_3$ layer inhibits further corrosion of the coating and attributes to the excellent corrosion resistance of the AlSi-coating [23].
4 STATE OF THE ART REVIEW

4.1 Welding of three- and four sheet stacks

There is a limited amount of research done on resistance spot welding of three and four sheet-stack combinations and especially involving hot stamped boron steels. Most published papers [29], [30], [26], are still focused on the resistance spot welding of two-sheet combinations. There have been a few studies [31], [32], [33], which have developed novel methods for addressing the problem with welding two thick sheets to one thin sheet. Achieving weld nugget growth into the thin/thick interface is difficult due of the closer proximity to the electrode compared to the thick/thick interface. This leads to both higher cooling effect, inhibiting penetration into the thin sheet and higher pressure over the interface, lowering the contact resistance.

Ikeda et al. [33] developed a method for welding three sheet stacks with different thickness by using two weld pulses with different electrode force. By initiating the welding with a short pulse with high current and low electrode force they managed to obtain a weld nugget in the thin/thick interface. The second weld pulse had lower relative current but higher electrode force and targeted melting in the thick/thick interface. A schematic picture can be seen in Figure 25.

![Figure 25: Description of low force/high current followed by low current/high force welding schedule](image)

The authors concluded that the method could be effective when welding three-sheet combinations with high sheet thickness ratio.

Donghyun et al. [32] investigated the effect of a conical shaped hollow electrode towards the thick/thick interface in three-sheet spot welding of advance high strength steels. A
A schematic figure of the authors setup can be seen in Figure 26. The use of conical shaped electrode reduced the risk for expulsion and widened the weld lobe for the tested sheet combination, compared to regular domed electrodes.

Figure 26: Schematic picture of three-sheet spot welding with one conical shaped hollow electrode and one regular electrode [34].

Wei et al. [35] researched the weldability of three high strength steels in different three-sheet combinations. They used galvanized 1000 MPa dual phase (DP) steel, a 980 MPa transformation induced plasticity (TRIP) steel and a 980 MPa twinned induced plasticity steel (TWIP). The conclusion was that the different heat conductivities, melting points and surface electric resistances of the steels resulted in the asymmetric weld nuggets of the dissimilar spot welds. The interface with the lowest expulsion occurring current in order was TWIP/TWIP, TWIP/TRIP, TRIP/TRIP, TWIP/DP, TRIP/DP and DP/DP.

Nielsen et al. [36] investigated the weldability of one thin, low-carbon steel welded to two thicker, high-strength steels of high-strength low-alloy (HSLA) 340, DP600, or TRIP700. They found that increasing the size of the electrode facing the thicker sheets improved the strength of the joint by increasing the size of the weld nugget, if the weld current and time was sufficient to form a weld nugget of the at least the size of that electrode. They observed that combinations with the zinc coated TRIP steel gave the least robust process with significantly lower expulsion limits and increased sensitivity to process variations. They argue that the zinc coating is the main factor influencing the weldability of the TRIP steel.

4.2 Influence of AlSi-coating on the weldability

The fact that the AlSi-coating has a significant influence on the weld result is well established. However, the different mechanisms affecting the weldability are not fully understood. The coating affects the contact resistance both between the metal sheets and between the electrode and the sheet. The influence changes during the welding procedure as the coating melts between the faying surfaces and is squeezed out forming a liquid halo.
around the faying surface. This liquid halo increases the contact area and provides additional pathways for the current to take [5].

Persson and Lindén [26] researched how the two different thicknesses of AlSi coating affected the weldability of 1 mm Usibor1500P steel. The two coatings compared in the study were AlSi80, 80 g/m², and AlSi150, 150 g/m². The study concluded that the use of three pulse welding was required to reach the minimum nugget size, both one and two pulses failed to create a large enough nugget before expulsion. AlSi80 showed a lower expulsion limit than AlSi150 while the minimum current limit was approximately the same, resulting in a narrower weld lobe for the AlSi80 coated sheets. As the thickness for the bulk material was the same, 1mm, the conclusion was that the difference must be explained by the thickness of the coating.

Persson [29] and Ighodaro et al. [37] showed that the AlSi coating in the sheet/sheet interface is pushed away from the faying surface after approximately 50ms into the welding sequence, when welding two-sheet AlSi coated boron steel combinations. Ighodaro et al. [37] also identified seven different stages in the dynamic resistance profile for hot-stamped AlSi-coated boron steel, they are described in section 2.2.4.

4.3 Welding of hot stamped Boron steels

The weldability of hot stamped boron steel seems to highly depend on thickness of the sheets. Ighodaro et al. [38] and Chang-Wok et al. [5] successfully welded 1,2mm thick AlSi-coated boron steel in a two sheet combination with a single pulse, obtaining a wide current range of 2,5 kA and 2 kA respectively.

Lindén and Janiak [39] were unable to obtain a satisfactory current range with a single pulse when welding 0,85mm thick sheets but with using a three pulsed welding sequence they successfully obtained a 1,8 kA current range. Lindén and Persson [26] obtained similar results when welding 1mm thin sheets. They were unable to obtain wide enough current ranges with a single and two pulses. With three pulses they obtained a 3 kA current window. The general strategy has been to use an initial short pulse to burn away the coating, a second pulse to obtain melting of the steel sheets and nugget formation, and last pulse to grow the nugget into desirable size. The two first pulses have been constant in current and only the third and last pulse has stepwise increased to obtain a 1D weld lobe.

It has to be taken into account that [39] and [26] both followed the Volvo standards and were using a shunt weld which [38] and [5] did not.

Hwang et al. [40] used pulsed welding to reduce the risk of expulsion and obtain a wider current range when welding AlSi-coated 1500MPa steel.
5 EXPERIMENTAL

5.1 Development of weldability lobe

All welding trials conducted in this thesis were made using Volvo Car Company (VCC) standard resistance spot welding (RSW) test coupons. The length and width are 125x38 mm and the thickness depends on the sheets being tested. The distance between the shunt spot and the investigated spot is between 20 to 40 mm for all tests in this thesis. One test spot, or two when using shunt spot, was welded per test coupon and if shunt spot is used only the test spot is measured. A schematic of the test coupon is shown in Figure 27.

![Figure 27: Test coupon for RSW welding used by VCC.](image)

5.1.1 Nugget requirement

In this thesis, the VCC standard Spot Welding: Joint requirements (VCS 5621,19) has been a guideline for size requirement for the weld nugget. The requirement is determined by the thinnest outer sheet as shown in Table 2.

<table>
<thead>
<tr>
<th>Thinnest outer sheet [mm]</th>
<th>Minimum nugget size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 1.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Over 1.2</td>
<td>6.0</td>
</tr>
</tbody>
</table>

However, because of the difficulty of welding AlSi-coated boron steel and its high strength the minimum nugget size is 4.5 mm even when welding sheets over 1.2 mm thickness. Volvo has determined that the nugget size must grow by at least 1.0 mm in size from the lower to the upper limit of the weld lobe to be approved. All three spots must reach the required nugget size.

The nugget measurement was done by calliper after a peel test using a Stenhøj hydraulic machine.

5.2 Metallographic preparation

The metallographic testing was done by grinding a cross-section of the test coupon according to Figure 28. The thickness of the grinding disk was considered, to offset from the centre of the weld. The samples were grinded with SiC grinding paper with P-grade ranging
from 400 to 2000 and in the end polished with diamond paper until a mirror finish were obtained. The etching solution used were Nital 2% and the etching time was between 10-20 seconds depending on the material.

The samples were hot mounted in bakelite and evaluated in light optical macroscopy. The optical microscopy used in this thesis was a Carl Zeiss Axio Zoom.V16

![Cross-section](image)

*Figure 28: Cross-section cut on a weld coupon.*

5.3 Welding equipment

Two different welding machines have been used throughout this thesis. The welding equipment has been used at Swerea KIMAB and is shown below in Figure 29 and Figure 30. The machines used were a Bosch 6000PSI with an ABB pneumatic X-gun and a Matuschek ServoSpatz M800LL with a C-type servo gun.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max electrode force: [kN]</td>
<td>7</td>
</tr>
<tr>
<td>Short circuit current: [kA]</td>
<td></td>
</tr>
<tr>
<td>Throat depth: [mm]</td>
<td>355</td>
</tr>
<tr>
<td>Current type</td>
<td>MFDC (100Hz)</td>
</tr>
<tr>
<td>Water cooling per electrode [l/min]</td>
<td>4</td>
</tr>
<tr>
<td>Weld control unit</td>
<td>PC-based BOS6000</td>
</tr>
<tr>
<td>Transformer</td>
<td></td>
</tr>
<tr>
<td>Inverter</td>
<td>Bosch 6000PSI</td>
</tr>
<tr>
<td>Welding gun</td>
<td>Manual pneumatic ABB GWT-X gun</td>
</tr>
</tbody>
</table>

*Figure 29: Bosch 6000PSI with an ABB pneumatic X-gun.*
<table>
<thead>
<tr>
<th>Max electrode force: [kN]</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short circuit current: [kA]</td>
<td>38</td>
</tr>
<tr>
<td>Throat depth: [mm]</td>
<td></td>
</tr>
<tr>
<td>Current type:</td>
<td>MFDC</td>
</tr>
<tr>
<td>Water cooling per electrode: [l/min]</td>
<td>4</td>
</tr>
<tr>
<td>Weld control unit:</td>
<td>PC-based Matuschek Servo studio</td>
</tr>
<tr>
<td>Transformer:</td>
<td>Expert 222kVA(4diod) 50 turn ratio</td>
</tr>
<tr>
<td>Inverter:</td>
<td>Matuschek Servo SPATZ M800LL</td>
</tr>
<tr>
<td>Welding gun:</td>
<td>Matuschek Servo gun C-type</td>
</tr>
</tbody>
</table>

Figure 30. Matuschek ServoSpatz M800LL with a C-type servo gun

Throughout the thesis, when not specified otherwise, B-cap electrodes 16/6 R40 were used for all experiments. The electrode geometry is shown in Figure 31.

Figure 31: Schematic of a 16/6 R40 B-Cap electrode, \(d_1 = 16\text{mm}, d_2 = 6\text{ mm}, R_1 = 40\text{ mm}\).  

5.4 Mechanical testing equipment

Peeling test were used to measure the nugget size of the spot after the welds were made. The peel test was done in a Stenhøj Universal testing machine, shown in Figure 32.
Figure 32: Stenhøj Universal testing machine.

Vickers hardness testing were made using KB 30 S vicker testing machine, shown in Figure 33.

Figure 33: KB 30 S vicker hardness testing machine.
The measurements were done automatically diagonally across the weld nugget as shown in Figure 34. HV 0.2 test force were used for all measurements.

Figure 34: The coloured line shows the where the vicker hardness measurements were done.

Tensile strength test was done at 10 mm/min until fracture.

5.5 Materials

All material used in the welding trials were supplied by VCC as weld coupons with dimension approximately as seen in Figure 27.

The AlSi-coated UHS boron steel was originally supplied by ArcelorMittal with the tradename Usibor 1500P. The different materials and coatings used in the welding trials is shown in Table 3 including the mechanical properties of the materials. The chemical compositions of the sheets are shown in Table 4.

Table 3: Coatings and mechanical properties of the materials used in the welding trials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Coating</th>
<th>Yield Strength [Mpa]</th>
<th>Ultimate Tensile Strength [Mpa]</th>
<th>Elongation to rapture [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>1100</td>
<td>1500</td>
<td>3</td>
</tr>
<tr>
<td>DP800</td>
<td>G150/50, UC</td>
<td>440 - 550</td>
<td>780 – 900</td>
<td>14</td>
</tr>
<tr>
<td>DP600</td>
<td>G150/50, UC</td>
<td>330 - 430</td>
<td>590 - 700</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4: Chemical composition of the materials used in the welding trials.

<table>
<thead>
<tr>
<th>Material 1</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>N</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Al</th>
<th>Nb</th>
<th>V</th>
<th>Ti</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usibor 1500P</td>
<td>0.22</td>
<td>0.2</td>
<td>1.1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.2</td>
<td>0.03</td>
<td>0.01</td>
<td>0.04</td>
<td>-</td>
<td>0.01</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>DP800</td>
<td>0.15</td>
<td>0.2</td>
<td>1.7</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.4</td>
<td>0.04</td>
<td>0.01</td>
<td>0.03</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DP600</td>
<td>0.1</td>
<td>0.2</td>
<td>1.6</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.4</td>
<td>0.04</td>
<td>0.01</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
The material sheet stack ups welded in this thesis are all presented below in Table 5. The combinations were chosen because of the difficulty to obtain an approved welding process with them with regular welding procedure or to study particular characteristics of the materials.

### Table 5: Sheet stack-ups welded in this thesis.

<table>
<thead>
<tr>
<th>Stack-up ID</th>
<th>Sheet number</th>
<th>Material</th>
<th>Coating</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1 (+)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>DP800</td>
<td>GI50/50</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>3 (-)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>0.9</td>
</tr>
<tr>
<td>B1</td>
<td>1 (+)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>DP600</td>
<td>GI50/50</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3 (-)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>1.6</td>
</tr>
<tr>
<td>C1</td>
<td>1 (+)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>DP600</td>
<td>Uncoated</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3 (-)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>1.6</td>
</tr>
<tr>
<td>D1</td>
<td>1 (+)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>DP800</td>
<td>GI50/50</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>3 (-)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>1.4</td>
</tr>
<tr>
<td>E1</td>
<td>1 (+)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>2 (-)</td>
<td>DP800</td>
<td>GI50/50</td>
<td>1.3</td>
</tr>
<tr>
<td>F1</td>
<td>1 (+)</td>
<td>Usibor 1500P</td>
<td>AS75/75</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>2 (-)</td>
<td>DP800</td>
<td>GI50/50</td>
<td>1.2</td>
</tr>
</tbody>
</table>

### 5.6 Welding experiments

Three different welding methods were evaluated in this thesis to investigate their effect when welding the sheet combinations seen in Table 5. The results from each welding experiment is compared to a reference welding lobe which is welded with standard parameters used at VCC.
Below are a short description of each welding method and the equipment used.

### 5.6.1 Three-pulsed welding

In an effort to improve the weldability of three sheet stacks in combination with AlSi-coated boron steel a three-pulse welding sequence were developed during this thesis. This method has shown potential in earlier studies at Swerea KIMAB [39][30] for two sheet combination with AlSi-coated boron steel.

The first pulse was optimized to burn off the coating on the faying surfaces. The second pulse generated a nugget in one of the sheet interfaces and the last pulse achieved nugget formation in the second sheet interface.

When welding in industry an adaptive current profile is commonly used, this regulates the last pulse while keeping pre-pulses constant. Therefore, the current of the first two pulses were kept constant and the third pulse was varied. This makes it easier to translate the results in these tests to and industry setting.

The equipment and electrodes used in the three-pulsed welding experiments are shown in Table 6.

*Table 6: Welding equipment and electrodes used in the three-pulsed welding experiments.*

<table>
<thead>
<tr>
<th>Weld timer</th>
<th>Weld gun</th>
<th>Electrode upper</th>
<th>Electrode lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matuschek ServoSpatz M800LL</td>
<td>Matuschek Servo gun C-type</td>
<td>16/6 R40 Cu-Cr B-Cap</td>
<td>16/6 R40 Cu-Cr B-Cap</td>
</tr>
</tbody>
</table>

### 5.6.2 Varied electrode force

Kay Nigel [41] obtained a larger current range when welding 22MnB5 by reducing the electrode force during the welding procedure. This thesis investigates if a force profile can be applied to a two-pulse welding sequence with positive result.

The two-pulse welding sequence with constant electrode force as is commonly used at VCC when welding AlSi-coated boron steel is used as a base and reference.

When welding with a force profile in this thesis a high electrode force is used on the first pulse and during the pause time before the second pulse the electrode force is lowered with 1 kN.

*Table 7: Welding equipment and electrodes used in the varied electrode force welding experiments.*

<table>
<thead>
<tr>
<th>Weld timer</th>
<th>Weld gun</th>
<th>Electrode upper</th>
<th>Electrode lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matuschek ServoSpatz M800LL</td>
<td>Matuschek Servo gun C-type</td>
<td>16/6 R40 Cu-Cr B-Cap</td>
<td>16/6 R40 Cu-Cr B-Cap</td>
</tr>
</tbody>
</table>
5.6.3 Hollow-cone electrode

Research done by Donghyun et al. [32] and J Jun & S Rhee [42] showed the potential for hollow cone electrodes to increase the size of weldability lobes and reduce the risk for expulsion in both 2-sheet and 3-sheet combinations.

To evaluate if these electrodes has potential to increase the weldability of AlSi-coated boron steel in 3-sheet combinations several weldability trials with different sheets combinations were conducted.

The hollow-cone (h-c) electrodes were constructed from 16/6 R40 B-cap electrodes by drilling a hole in the centre of the electrode to the specified depth. It should be noted that the holes were hand drilled by the author and thus the depth values are averages, and the alignment of the hole could be improved.

To evaluate how the depth of the hole affects the welding results two sets of electrodes with different depth were constructed, one set with a hole depth of 1.5 mm and one set with 5 mm.

The two types of h-c electrodes used can be seen below in Figure 35.

![Figure 35: The two types of h-c electrodes used, left: 3.0/1.5 mm, right: 3.0/5.0 mm.](image)

Table 8 shows the welding equipment and the electrodes used in the hollow-cone electrode welding experiments.

<table>
<thead>
<tr>
<th>Weld timer</th>
<th>Weld gun</th>
<th>Electrode upper</th>
<th>Electrode lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bosch 6000PSI</td>
<td>ABB pneumatic X-gun</td>
<td>16/6 R40 Cu-Cr Hollow-Cone 3.0/1.5</td>
<td>16/6 R40 Cu-Cr Hollow-Cone 3.0/1.5</td>
</tr>
<tr>
<td>Bosch 6000PSI</td>
<td>ABB pneumatic X-gun</td>
<td>16/6 R40 Cu-Cr Hollow-Cone 3.0/5.0</td>
<td>16/6 R40 Cu-Cr Hollow-Cone 3.0/5.0</td>
</tr>
</tbody>
</table>
6 RESULTS

In the following chapter, the results from the experimental trials are described and presented. The trials are annotated as X-X1 in this thesis. The first letter represents the welding method, shown in Table 9, and the second letter and number combination stand for the material combinations shown in Table 5

Table 9: Identification for the welding experiments.

<table>
<thead>
<tr>
<th>ID</th>
<th>Welding Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Three-pulsed sequence</td>
</tr>
<tr>
<td>B</td>
<td>Varied electrode force</td>
</tr>
<tr>
<td>C</td>
<td>Hollow-cone 3.0/1.5 mm</td>
</tr>
<tr>
<td>D</td>
<td>Hollow-cone 3.0/5.0 mm</td>
</tr>
<tr>
<td>E</td>
<td>Tensile strength test</td>
</tr>
<tr>
<td>F</td>
<td>Electrode degradation test</td>
</tr>
<tr>
<td>R</td>
<td>Reference/Two-pulsed sequence</td>
</tr>
</tbody>
</table>

6.1 Performance of three-pulse welding

To evaluate the performance of the three-pulsed welding two welding trials where performed with two material combinations and the result is compared to the result when welding with two pulses as is the standard procedure at VCC.

6.1.1 Test A-A1

Test A-A1 were welded with sheet stack-up A1 with both three-pulsed and two-pulsed sequence welding. Welding parameters for the three-pulsed welding can be seen in Table 10. The result, a single current step, is shown in Figure 36. The reference result achieved with two pulsed sequence welding is shown in Figure 37.

Table 10: Welding parameters used in A-A1.

<table>
<thead>
<tr>
<th>Force [kN]</th>
<th>1-Current [kA]</th>
<th>1-Time [ms]</th>
<th>1-Paus [ms]</th>
<th>2-Current [kA]</th>
<th>2-Time [ms]</th>
<th>2-Paus [ms]</th>
<th>3-Current [kA]</th>
<th>3-Time [ms]</th>
<th>Cool time [ms]</th>
<th>Shunt distance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>8.5</td>
<td>100</td>
<td>40</td>
<td>8.5</td>
<td>100</td>
<td>100</td>
<td>See 1D-lobe</td>
<td>300</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>
Figure 36: 1-D weld lobe for A-A1, welded with three current pulses. Size of the process window equals a single current step.
6.1.2 Test A-B1
Test A-B1 were welded with sheet stack-up B1 with both three-pulsed and two-pulsed sequence welding. Welding parameters for the three-pulsed experiment can be seen in Table 11 and the result, a process window of 0.3 kA, is shown in Figure 38. The reference weld achieved with two pulsed sequence welding, resulting in a single current step window, is shown in Figure 39.

Figure 37: 1-D weld lobe for R-A1, welded with regular electrodes and two-pulsed sequence welding. No current window.
Table 11: Welding parameters used in A-B1.

<table>
<thead>
<tr>
<th>Force [kN]</th>
<th>1-Current [kA]</th>
<th>1-Time [ms]</th>
<th>1-Paus [ms]</th>
<th>2-Current [kA]</th>
<th>2-Time [ms]</th>
<th>2-Paus [ms]</th>
<th>3-Current [kA]</th>
<th>3-Time [ms]</th>
<th>Cool time [ms]</th>
<th>Shunt distance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>8.5</td>
<td>100</td>
<td>40</td>
<td>8.5</td>
<td>100</td>
<td></td>
<td>See 1D-lobe</td>
<td></td>
<td>300</td>
<td>200</td>
</tr>
</tbody>
</table>

Figure 38: 1-D weld lobe for A-B1, welded with three current pulses. Size of the process current window equals 0.3kA.
Figure 39: 1-D weld lobe for R-B1, welded with regular electrodes and two-pulsed sequence. The size of the current window equals a single current step.

6.2 Performance of varied electrode force
To evaluate the performance of the varied electrode force two welding trials where performed with two material combinations and the result is compared to the result when welding with constant electrode force as is the standard procedure at VCC.

6.2.1 Test B-B1
Test B-B1 were welded with sheet stack-up B1 with both varied- and constant electrode force. Welding equipment and parameters for the varied electrode force experiment can be seen in Table 7 and Table 12. The result, a current window of 0,9 kA with varied electrode force, is shown in Figure 40. The reference result achieved with constant electrode force, is shown in Figure 41.
Table 12: Welding parameters used in B-B1 and R-B1.

<table>
<thead>
<tr>
<th>ID</th>
<th>1-Force [kN]</th>
<th>1-Current [kA]</th>
<th>1-Time [ms]</th>
<th>1-Paus [ms]</th>
<th>2-Force [kN]</th>
<th>2-Current [kA]</th>
<th>2-Time [ms]</th>
<th>Cool time [ms]</th>
<th>Shunt distance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-B1</td>
<td>4.5</td>
<td>8.5</td>
<td>100</td>
<td>40</td>
<td>3.5</td>
<td>See 1D-lobes</td>
<td>390</td>
<td>200</td>
<td>30</td>
</tr>
<tr>
<td>R-B1</td>
<td>3.5</td>
<td>8.5</td>
<td>100</td>
<td>40</td>
<td>3.5</td>
<td>See 1D-lobes</td>
<td>390</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 40: 1-D weld lobe for B-B1, welded with varied electrode force. Size of the process current window equals 0.9 kA.
Figure 41: 1-D weld lobe for R-B1, welded with regular electrodes, two-pulsed sequence and constant electrode force. The size of the process window equals a single current step.

6.2.2 Test B-C1

Test B-C1 were welded with sheet stack-up C1 with both varied- and constant electrode force. The materials, dimensions and equipment are shown in Table 5 and Table 7. The welding parameters is shown in Table 13. The result, a current window of 2,1 kA with varied electrode force, is shown in Figure 42. The reference result, a current window of 1,2 kA, achieved with constant electrode force, is shown in Figure 43.
Table 13: Welding parameters used in B-C1 and R-C1.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B-B1</td>
<td>4.5</td>
<td>8.5</td>
<td>100</td>
<td>40</td>
<td>3.5</td>
<td>See 1D-lobe</td>
<td>390</td>
<td>200</td>
<td>30</td>
</tr>
<tr>
<td>R-B1</td>
<td>3.5</td>
<td>8.5</td>
<td>100</td>
<td>40</td>
<td>3.5</td>
<td>See 1D-lobe</td>
<td>390</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 42: 1-D weld lobe for B-C1, welded with varied electrode force. Size of the process window equals 2.1 kA.
6.3 Performance of Hollow-Cone Electrode

To evaluate the performance of the hollow cone electrode several welding trials where performed with different material combinations and the result is compared to the result when welding with regular non-hollow electrodes. The selected material combinations had not fulfilled the requirements when welded with standard electrodes.

6.3.1 Comparison between hollow-cone and regular electrode

The hollow-cone electrodes were evaluated by welding a series of material combinations with the same equipment and process parameters with different electrodes presented in Table 8.
6.3.2 Test C-A1

Table 14: Welding parameters used in C-A1 and R-A1.

<table>
<thead>
<tr>
<th>Force [kN]</th>
<th>1-Current [kA]</th>
<th>1-Time [ms]</th>
<th>1-Paus [ms]</th>
<th>2-Current [kA]</th>
<th>2-Time [ms]</th>
<th>Cool time [ms]</th>
<th>Shunt distance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>8.5</td>
<td>100</td>
<td>40</td>
<td>See 1D-lobe</td>
<td>390</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>

Test C-A1 was conducted on a sheet combination consisting of two AlSi-coated Usibor 1500P sheets on the outside and a zinc galvanized DP800 sheet on the inside. The exact dimensions, equipment and welding parameters are shown in Table 5, Table 8 and Table 14. The required quality was not achieved when welding this combination with standard electrodes, as seen in Figure 45. However, welding with hollow-cone electrodes, shown in Figure 44, resulted in a current range of 2.2 kA.

![Weld loob 1-D](image)

*Figure 44: 1-D weld lobe for C-A1, welded with hollow-cone 3.0/1.5 electrodes. Size of the process current window equals 2.2 kA.*
6.3.3 Test C-B1

Table 15: Welding parameters used in C-B1 and R-B1.

<table>
<thead>
<tr>
<th>Force [kN]</th>
<th>1-Current [kA]</th>
<th>1-Time [ms]</th>
<th>1-Paus [ms]</th>
<th>2-Current [kA]</th>
<th>2-Time [ms]</th>
<th>Cool time [ms]</th>
<th>Shunt distance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>8.0</td>
<td>100</td>
<td>40</td>
<td>See 1D-lobe</td>
<td>550</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>

Test C-B1 where conducted on a sheet combination consisting of two AlSi-coated Usibor 1500P sheets on the outside and a zinc galvanized DP600 sheet on the inside. The exact dimensions, equipment and welding parameters are shown in Table 5, Table 8 and Table 15. The required quality was not achieved when welding this combination with standard electrodes, as seen in Figure 47. However, welding with hollow-cone electrodes, shown in Figure 46, resulted in a current range of 2.4 kA.
Figure 46: 1-D weld lobe for C-B1, welded with hollow-cone electrodes. The size of the process window equals 2.4 kA.
Figure 47: 1-D weld lobe for R-B1, welded with regular electrodes. The size of the process current window equals a single current step.

6.3.4 Comparison between different depths of the hollow-cone electrode
The following welding trials were conducted to see how the depth of the hole affects the welding performance. Two pair of electrodes with different hole depth were used. The first pair was the same as used in test C-D1 with 1.5 mm hole depth and the second was used in test D-D1 had a hole depth of 5 mm.
6.3.5 Test C-D1 and D-D1

Table 16: Welding parameters used in D-D1.

<table>
<thead>
<tr>
<th>Force [kN]</th>
<th>1-Current [kA]</th>
<th>1-Time [ms]</th>
<th>1-Paus [ms]</th>
<th>2-Current [kA]</th>
<th>2-Time [ms]</th>
<th>Cool time [ms]</th>
<th>Shunt distance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>8.0</td>
<td>100</td>
<td>40</td>
<td>See 1D-lobe</td>
<td>550</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>

Test C-D1 and D-D1 where conducted on a sheet combination consisting of two AlSi-coated Usibor 1500P sheets on the outside and a zinc galvanized DP800 sheet on the inside. The exact dimensions, equipment and welding parameters are shown in Table 5, Table 8 and Table 15. This combination was successfully welded with both hollow-cone 3.0/1.5 electrodes with a current range of 2.1 kA, seen in Figure 48, and hollow-cone 3.0/5.0 electrodes with a welding window of 2.7 kA, seen in Figure 49. This can be compared to the reference which was welded with regular electrode and resulted in a current window of single current step shown in Figure 50.
Figure 48: 1-D weld lobe for C-D1. Welded with hollow-cone 3.0/1.5 electrodes. The size of the current window equals 2.1 kA.
Figure 49: 1-D weld lobe for D-D1. Welded with hollow-cone 3.0/5.0 electrodes. Welding window equals 2.7 kA.
Figure 50: 1-D weld lobe for R-D1. Welded with regular electrodes. Current window equals a single current step.

6.4 Metallographic examination and Vickers test

A metallographic examination of the spot welds from test B1 was done and the nugget diameter were measured. The purpose was to see how the melted metal flows into the holes in the electrodes and evaluate the occurrence of voids or cavities in the centre of the spot weld.

Vickers hardness measurement were also performed on the spot welds in test B1 with hollow-cone electrodes 3.0/5.0 and compared to spot welds made with regular electrodes, the result is shown in Figure 51.
Figure 51: Vickers hardness comparison between spots done welded H-C electrodes and regular electrodes.
6.5 Tensile strength test

The strength of the spot welds was evaluated by shear tensile testing of material combination E1. Two test series were welded, one with standard electrodes and one with hollow-cone electrodes. The current steps were chosen in order to achieve similarly sized nuggets between the two-test series.

6.5.1 Test E-E1

The sheet stack up used in this test was E1.
Table 17: Welding equipment and electrodes used in D1.

<table>
<thead>
<tr>
<th>Series</th>
<th>Weld timer</th>
<th>Weld gun</th>
<th>Electrode upper</th>
<th>Electrode lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bosch 6000PSI</td>
<td>ABB pneumatic X-gun</td>
<td>16/6 R40 Cu-Cr Hollow-Cone 3.0/5.0</td>
<td>16/6 R40 Cu-Cr Hollow-Cone 3.0/1.5</td>
</tr>
<tr>
<td>2</td>
<td>Bosch 6000PSI</td>
<td>ABB pneumatic X-gun</td>
<td>16/6 R40 Cu-Cr B-Cap</td>
<td>16/6 R40 Cu-Cr B-Cap</td>
</tr>
</tbody>
</table>

Table 18: Welding parameters used in E-E1.

<table>
<thead>
<tr>
<th>Force [kN]</th>
<th>1-Current [kA]</th>
<th>1-Time [ms]</th>
<th>1-Paus [ms]</th>
<th>2-Current [kA]</th>
<th>2-Time [ms]</th>
<th>Cool time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>8.0</td>
<td>100</td>
<td>40</td>
<td>See Figure 53</td>
<td>550</td>
<td>200</td>
</tr>
</tbody>
</table>

Average Tensile strength/strain of regular and hollow-cone electrodes

![Graph showing average tensile strength/strain for regular and hollow-cone electrodes](image)

Figure 53: The average tensile strength/displacement of regular and hollow-cone electrodes depending on the current used.
6.6 Electrode degradation test

An important factor to consider when implementing a new type of electrodes into production is the rate of degradation of the electrode and how it affects the weld results. A dressing schedule needs to be created to make sure that the welding result does not suffer from electrode degradation in production.

6.6.1 Test F-F1

To evaluate the hollow-cone electrodes in this aspect a stress test where conducted to see how the electrodes behave during prolonged use without maintenance. A series of 105 spot were welded, five per weld coupon, with hollow-cone 3.0/5.0 electrodes in a single series without any maintenance. The materials and sheet dimensions are shown in Table 5, the welding parameters in Table 20 and the equipment used in Table 19.

Figure 54: Tensile strength in relation to nugget size for spots welded with H-C electrodes and Regular electrodes.
Table 19: Welding equipment and electrodes used in F-F1.

<table>
<thead>
<tr>
<th>Series</th>
<th>Weld machine</th>
<th>Weld gun</th>
<th>Electrode upper</th>
<th>Electrode lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bosch 6000PSI</td>
<td>ABB pneumatic X-gun</td>
<td>16/6 R40 Cu-Cr Hollow-Cone 3.0/5.0</td>
<td>16/6 R40 Cu-Cr Hollow-Cone 3.0/1.5</td>
</tr>
</tbody>
</table>

Table 20: Welding equipment and electrodes used in F-F1.

<table>
<thead>
<tr>
<th>Force [kN]</th>
<th>1-Current [kA]</th>
<th>1-Time [ms]</th>
<th>1-Paus [ms]</th>
<th>2-Current [kA]</th>
<th>2-Time</th>
<th>Cooltime [ms]</th>
<th>Shunt distance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>8.0</td>
<td>100</td>
<td>40</td>
<td>7.8</td>
<td>300</td>
<td>200</td>
<td>20</td>
</tr>
</tbody>
</table>

The degradation of the electrodes can be seen in Figure 55. The nugget size increases steadily during the experiment due to the increased heat generation caused by the increased contact area; this is shown in Figure 56. “Spot one” is the first spot welded on each new coupon and “Spot two” is the second spot welded on each coupon. The shunt distance was set to 20 mm. Spot three, four and five on each coupon have not been measured but are counted in the total number of spots welded.
Figure 55: From left to right, top to bottom. H-C bottom electrode degradation after; 1 spot, 20 spots, 40 spots, 60 spots, 80 spots, 105 spots. Magnification 2x.
Figure 56: The nugget size growth during the electrode degradation test. Second spot is welded 20 mm from the first spot.

6.7 Overview of welding results

Table 21 shows an overview of the results obtained from the welding experiments in this thesis. The same overview is also shown in Figure 57.
Table 21: Overview of the results from the welding experiments. The obtained current ranges for each sheet stack-up.

<table>
<thead>
<tr>
<th></th>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-Pulse Welding</td>
<td>Single current step</td>
<td>0.3 kA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Varied Electrode Force</td>
<td></td>
<td>0.9 kA</td>
<td>2.1 kA</td>
<td></td>
</tr>
<tr>
<td>Hollow-Cone 3.0/1.5</td>
<td>2.2 kA</td>
<td>2.4 kA</td>
<td></td>
<td>2.1 kA</td>
</tr>
<tr>
<td>Hollow-Cone 3.0/5.0</td>
<td></td>
<td></td>
<td></td>
<td>2.7 kA</td>
</tr>
<tr>
<td>Reference (two-pulse)</td>
<td>No current step</td>
<td>Single current step</td>
<td>1.2 kA</td>
<td>Single current step</td>
</tr>
</tbody>
</table>

Figure 57: Overview of the results from the welding experiments. The obtained current ranges for each sheet stack-up.
7 DISCUSSION

7.1 Three-pulsed welding

The results from the three-pulsed welding experiments, Test A-A1 and Test A-B1, shows that can be successfully used to improve the welding current range for three sheet stack-ups incorporating ultra-high strength boron steel.

The additional welding step is thought to provide finer incremental increase in nugget size making it possible to achieve one or more approved current steps. The second pause step provides additional cooling during the welding process which is thought to reduce the risk for overheating and in the end; expulsion.

However, in these tests the improvements where not sufficient enough to meet the demands on the weld quality. The disadvantage with three-pulsed welding is that it introduces additional complexity with the third current step and the second pause step which both needs to be optimized to attain satisfactory results.

Janiak et.al [39] theorized an additional beneficial factor could be that the first pulse burns of the AlSi coating leading to a more stable weld nugget growth with the following two weld pulses. They achieved similar results applying sequenced three-pulsed welding to two-sheet stack of 0.82 mm boron steel. Single and two-pulse did not give an approved weld lobe, but three-pulses resulted in a 1,8 kA process window.

7.2 Varied electrode force

The results from using varied electrode force in Test B-B1 and Test B-C1 shows a significant increase in the current range compared to welding with constant electrode force. Varied electrode force achieves an improved weld process for the B1 sheet stack-up compared to both the reference- and three-pulse welding process.

By lowering the electrode force during the welding process, the pressure on the molten nugget is reduced. The balance between the hydrostatic pressure from the molten metal and the pressure from the electrodes then shifts in favour of the molten metal allowing it to increase in size without causing expulsion. The higher electrode pressure reduces the energy generated initially and thus reducing the risk for overheating and expulsion early in the welding process. These two factors are thought to contribute to the improved performance of varied electrode force compared to constant electrode force in Test B-B1 and Test B-C1.

Test B-B1 and Test B-C1 shows the difference between welding with an uncoated- and a GI50/50-coated middle sheet. The GI50/50 coated DP600 sheet decreases the weldability heavily for both the reference and varied-electrode-force welding.

7.3 Hollow-cone electrodes

The results from Test C-A1 and Test C-B1 shows that the hollow-cone electrodes can achieve superior result, when welding sheet combinations containing AlSi-coated UHS boron steel, compared to conventional electrodes. The conventional electrodes failed to provide an approved current range for the two material combinations. Using the same material and
welding parameters for the h-c electrodes are shown to achieve a wide process window. The hollow-cone electrodes consistently provided large process windows compared to conventional electrodes in all welding experiments.

The cause of this is thought to be twofold [32],[42]. The first is that the cavity in hollow-cone electrode provides a pathway for the heated and melted material to expand into. Without the hole the molten metal expands towards the edges of the faying surface until the hydrostatic pressure in the melt exceeds the pressure from the electrodes which leads to expulsion of the weld. By allowing the melted metal to expand into the electrode instead of to the sides it is possible increase the upper current limit of the weld lobes and achieve sufficiently larger nugget sizes. How the metal expands into the cavity can be seen in the cross-section images in Figure 52.

The second factor is the increased current density over the faying surfaces. The hollow-cone electrodes have a reduced contact area towards the sheets. This leads to an increased current density not only at the electrode/sheet interface but also at the edges of the faying surface at the sheet/sheet interface. An increased current density should, according to the Joule effect, lead to more heat being generated at the faying surface and potentially breaking and pushing the oxide to the side more rapidly.

The effect of the depth of hole in the hollow-cone electrode is shown in Test C-D1 and D-D1. The 5-mm hole depth achieves an improved current range of 0,6 kA compared to 1.5 mm hole depth. Expulsion happened at similar nugget sizes, 7.67/7.54 mm nugget size for 5 mm hole depth and 7.59/7.40 for 1.5 mm hole depth as seen in Figure 49 and Figure 48, and at lower welding currents the performance is similar. This indicates that when the current increases, more of the molten metal expands into the electrode and for the 1.5 mm deep h-c electrodes the metal makes contact with the “ceiling” of the electrode leading to a more rapid nugget growth. This phenomenon does not appear with the deeper 5.0 mm deep h-c electrodes and therefore a wider process window is obtained.

Another possible advantage with using h-c electrodes with a deeper 5 mm depth is the reduced need for dressing. During welding with the h-c electrodes oxides and metal from the sheets get struck in the hole, reducing its size. However as shown in Test F-F1 the h-c electrodes can successfully weld over a hundred spot welds without requiring tip dressing and hole dressing. An increase in nugget size from 4,83 mm on the first spot to 5,89 mm on spot 101 where observed and should be taken into consideration when creating weld schedules. It should be noted that the higher current required to obtain similar nugget size with h-c electrodes compared to regular electrodes will increase the electrode degradation.

To reduce the build-up of oxide and metal in the cavity of the h-c electrode measures such as hole dressing could be applied but that would require specialized tool to be constructed. Another option which was not tested in this thesis is to use low-surface-energy coating on the inside of the hole to reduce the tendency of oxide and metal from the sheet to stick inside the hole of the electrode.

When comparing mechanical properties of spots welded with h-c electrodes and regular electrodes the Vickers hardness is similar as seen in Figure 51. In tensile strength, shown in
Figure 53 and Figure 54 the result differs between h-c electrodes and regular electrodes. At lower nugget sizes, $d < 5.2 \text{ mm}$, the h-c electrode welds have lower tensile strength but at higher nugget sizes, $d > 5.2 \text{ mm}$, the results show that h-c electrodes provide spots with higher tensile strengths in relation to nugget size.

The main difference between the welded spots that should affect the tensile strength is the appearance of the spots, electric current and cooling from the electrode. Spots welded with h-c electrodes have a distinct cone protruding outward from the sheet. How this would affect the tensile strength is difficult to say. If possible, it would be beneficiary that the protruding cones are as spherical as possible to avoid crack initiation points. This can be achieved by drilling the holes with round drill heads.

The second factor, electric current, differs in the way that it requires higher current when welding with h-c electrodes to achieve the same nugget size as when welding with regular electrodes.

The third factor is the cooling from the electrode. Because of the design of the h-c electrode the contact area to the sheets are lower and this should provide less cooling from the electrodes. The result could be higher toughness in weld material.

During welding with the hollow-cone electrodes it was noted that they performed consistently worse directly after the hole had been drilled but after a couple of welded spots the sharp edges were rounded off and they performance became better and stable. This indicates that the performance could be improved by optimized the production of the electrodes. Using industrial precision for the alignment of the hole as well as an optimized drill head for manufacturing of smoother hole geometries could potentially lead to more stable performance and less wear on the electrode.

However, if the h-c electrodes are to be applied in production the question of how to maintain and dress the electrodes needs to be considered. The tools currently used in production does not clean the hole in the electrode thus a special tool and/or procedure is necessary.
8 CONCLUSIONS

Welding trials at VCC has shown that it is especially challenging to spot weld three-sheet combinations combining GI50/50 coated DP steel sandwiched with AS75/75 coated Usibor 1500P sheets using conventional welding techniques. This thesis evaluates three different techniques to improve the welding performance of ultra-high strength boron steel.

- A three-pulse welding sequence performed better than the reference two-pulse welding schedule but still not good enough to meet VCC acceptance criteria.
- Applying a force profile with lowered electrode force during the welding sequence provided an improved process window compared to the constant electrode force when welding a three-sheet combination containing AlSi-coated boron steel.
- Hollow-cone electrodes performed significantly better when welding three-sheet combinations containing AlSi-coated boron steel in all welding trials compared to regular electrodes. Spots welded with h-c electrodes performs both slightly worse and better in tensile strength tests depending on the nugget size compared to regular electrodes.
9 \hspace{1cm} FUTURE WORK

The results in this thesis demonstrate that hollow-cone electrodes can improve the weldability of AISI-coated boron steel by increasing the welding window significantly over regular electrodes. Further research should investigate the stability and wear on the hollow-cone electrodes to determine if they can be applied to an industry production setting.

This thesis has determined that hollow-cone electrodes provide a larger welding window but more knowledge about how the welding processes differ when using hollow-cone electrodes is needed in order to understand what contributes to the hollow-cone performance over conventional electrodes.

Swerea KIMAB will start a new project which builds upon this thesis to investigate the use of hollow-cone electrodes in resistance spot welding.
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