Innovative Methods for Welding Ultra High Strength Steel with Resistance Spot Welding

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Abstract

Resistance spot welding (RSW) is the most frequently used method for welding thin sheets in manufacturing industries such as the automotive industry, because of the high productivity of RSW. In order to reduce CO$_2$ emissions the automotive industry strives towards creating structures of light weight, this is partly achieved by the use of lightweight materials such as Aluminum and composite materials. In parts of the car body designed to protect the driver and passengers in case of a collision High strength steel is used due to its high strength and relative high ductility. High strength steels are called Ultra High Strength Steels (UHSS) with typical ultimate tensile strength of 700 up to 2000 MPa and elongation of 10-40%. Because of the strive against lighter structures and great safety demands UHSS materials is of great interest for the automotive industry in order to create strong structures of light weight. In welding of modern materials such as UHSS with RSW, achieving adequate weld quality is a challenge. Hence this thesis aims to investigate new innovative ways to broaden the area of use and include modern materials such as UHSS for the traditional method of welding such as RSW. In RSW elliptical shaped welds are created between two or more faying metal sheets by passing current through the sheets. The current is applied to the sheets by copper electrodes in contact with the sheets on each side. The geometrical shape of these electrodes will affect multiple welding parameters such as applied stress, current density, electromagnetic stirring, temperature gradients and the possibility for the welded material to thermally expand during welding. Hence the geometrical shape of the electrodes will affect the final shape and size of the weld nugget. In this thesis RSW electrode geometries are modified and tested. The weld properties from modified electrodes are compared to the weld properties from standard RSW electrodes with respect to process robustness, weld nugget shape and size, micro hardness and weld tensile strength. Various modified geometries are used, all modified geometries are designed in order to allow the welded material to expand more, compared to standard electrodes. Previous work has been done and shown that hollow electrodes that allow the welded material to expand can improve the weld quality and process robustness. However, this has been to the cost of nugget growth in the normal direction to the welded sheet, leaving a non-uniform surface. Hence the aim of this thesis is to investigate if it is possible to widen the current range in the weld lobe diagram when welding UHSS material combinations with RSW by the use of hollow electrodes without affecting weld quality negatively compared to standard electrodes. Weld quality in this thesis will be evaluated based on surface condition, mechanical strength, micro-hardness and weld nugget size. The modified electrodes have shown better weld properties with respect of current range in the weld lobe curves in most cases tested but not all of the material combinations tested compared with standard electrodes. The surface conditions of the welded specimens have been controlled by measuring any indent and raise by line laser scanning. Modified RSW electrodes has showed improved welding properties with respect to current range in the weld lobe curves compared to standard RSW electrodes when welding UHSS material combinations. However modified electrodes have shown a higher sensitivity to misalignment and angle fault. Several material combinations of UHSS that has shown non-weldable behavior with standard RSW electrodes have shown improved current range. In the best case the current range was increased to 3,9 kA for an UHSS material combination that is non-weldable with standard electrodes.
Sammanfattning

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1. Introduction

Resistance spot welding (RSW) is a widely used method of joining for manufacturing industries since its invention in 1886 by Elihu Thomson (Houldcroft, et al., JULY/AUGUST 1986). RSW produces small elliptical weld nuggets between two or more faying metal sheets, generally 2-6 mm in diameter. This is executed in a relatively short time of roughly 250 ms. The short weld time makes RSW a welding method with high productivity. Because of the high productivity it has been exceptionally popular in the automotive industry historically. In a typical car body there are 2000-5000 welds executed by RSW (Pouranvari, et al., 2007). Historically conventional mild steels with strengths up to 400 MPa are used for the car body. For such mild steels it is a well-known fact that it is relatively easy to achieve required weld quality through RSW in mild steel materials. However, since fuel consumption of cars is dependent on the weight, the automotive industry strives towards using lighter materials. Material requirement present in automotive industry due to risk of collision makes steel of high strength and relative high ductility of interest in parts of the car where deformation should be held under a specific limit in case of collision. The highest demand for low deformation in case of collision is found in the safety cage of the car designed to protect the passengers. Steels are continuously being developed by the steel manufacturers and novel steels of higher strengths have become more popular to use in the car body where deformation is to be kept under the acceptable amount to meet safety requirement in the case of a collision. These steels are named Ultra High Strength Steels (UHSS). UHSS show better properties relative to mild steels to be used in applications where high strength has importance while maintaining ductility matters also. The use of different materials in the car body of the new Volvo V60 announced in 2018 is illustrated in Figure 1. An exact amount of UHSS in the new Volvo V60 is not officially available. But in previous model of the Volvo XC 90 released in 2014 the percentage of UHSS used in the whole car body weight was 40%.

Figure 1 New Volvo V60 announced in 2018, materials used in car body and safety cage. (Volvo Car Group, 2018)

It is relatively problematic to achieve desirable weld result in UHSS through RSW (Larsson, et al., 2009), due to the widely different physical properties in UHSS. One common problem is caused by presence of surface coatings. Another challenge comes up when welding UHSS to traditional steels with dissimilar physical properties. Previous work has been conducted to show that a hollow electrode will allow an increased thermal expansion of the welded material and hence widen the current range in the weld lobe curves, in 2 sheet setup of Zn-coated mild steel (Yeom, et al., 2009) and 3 sheet setup of dissimilar steels (Donghyun, et al., 2016). However, this improvement in current range has been at the cost of nugget growth in the direction normal to the welded sheet. This nugget growth in direction normal to the welded sheet has resulted in a non-uniform surface. This indent and rise in the surface of the welded specimen is not desirable in many cases when the surface is subject to subsequent treatments, such as painting, or when the surface of the
2. **Hypothesis**

The goal of this thesis is to investigate innovative ways of improving the RSW process so that adequate weld quality can be achieved with modern steels such as UHSS. Weld quality in this thesis is evaluated based on current range in weld lobe diagram, surface conditions, solid mechanical properties, micro-hardness. These four aspects of weld quality will be investigated and compared to results obtained from welding with standard electrodes. Adequate weld quality will be defined as when the welding result from welding trials with modified electrodes are on par or better compared to standard electrodes in each of the weld quality sub categories. Hence the hypothesis of this thesis is that there is an electrode geometry that allows welding of UHSS material combinations through RSW with adequate weld quality, by allowing the welded material to expand in to the electrodes in the direction normal to the sheet welded. This hypothesis will be confirmed or rejected by investigating research questions as listed below.

1. Is it possible to replicate results from previous work. To widen the current range in the weld lobe diagram by the use of hollow electrode, without affecting solid mechanical properties negatively compared to standard electrodes?
2. Is it possible to widen the current range in the weld lobe diagram when welding UHSS material combinations with RSW by the use of hollow electrodes. Without affecting weld quality negatively compared to standard electrodes?

3. **Background**

In order to successfully improve the weld result through modification of the electrode geometries, a fundamental understanding of the RSW process is required. Hence this part of the reports aims to give a basic understanding in the RSW process, electrode geometries and its influence on weld results.

3.1 **Resistance Spot Welding**

The explanation of RSW in this thesis is divided into physical heating; bulk resistance, contact resistance and dynamic resistance; RSW parameters; Weld lobe curves; Shunting effect.

3.1.1 **Joules laws of heating**

In resistance spot welding (RSW) the weld nugget is achieved through Joules laws of heating also called Joule heating, which states that in any conductor the heat generated by current flow is directly proportional to the time of current flow and the square of the current (Crew, 1921). This is shown in (1) where \( Q \) is thermal energy \([\text{J}]\), \( I \) is electrical current \([\text{A}]\), \( R \) is electrical resistance \([\Omega] \) and \( t \) is time \([\text{s}] \) of current flow.

\[
Q = I^2 Rt \\
(1)
\]

If the weld current and resistance is variable Joule heating can be described by integrating (1) in respect to the time, this is shown in (2) where \( Q \) is thermal energy \([\text{J}]\), \( I \) is electrical current \([\text{A}]\), \( R \) is electrical resistance \([\Omega] \) and \( t \) is time \([\text{s}] \) of current flow.

\[
Q(t) = \int_0^t I^2(t)R(t)dt \\
(2)
\]

In RSW the effect of Joule heating is utilized by passing a current through the stack of welded sheet will be visible in the final product.
materials intended for welding, this is illustrated in Figure 2. Two copper electrodes apply pressure to each side of the material stack and current is passed through the material. The generated heat is proportional to the electrical resistance as described earlier in (1). Since the resistance of the copper electrodes is considerably lower than in the steel sheets, the weld nugget will form in between these sheets where the electrical resistance is highest. The copper electrodes are also water cooled which further prevent melting of the electrode and substrate contact area.

![Figure 2 Schematic of the RSW process (Kimchi & Phillips, 2018).](image)

### 3.1.2 Bulk resistance, contact resistance and dynamic resistance

A schematic illustration of relative electrical resistance for the RSW setup is show in Figure 3. Here starting from the top and 1, we have relatively low electrical resistance in the bulk material of the copper electrodes, as copper has significantly lower electrical resistance compared to steel even at elevated temperatures. In 2 a slight increase in electrical resistance due to contact resistance between the electrode and substrate surfaces, contact resistance is further explain later in this thesis. 3 is the bulk resistance of the steel substrate. 4 has the highest electrical resistance due to the contact resistance of the steel sheets, hence this is where first melting and weld nugget formation will occur. Then 5, 6 and 7 have similar properties as 3, 2 and 1 respectively due to symmetry.

![Figure 3 Relative resistance in the RSW setup. (Kimchi & Phillips, 2018)](image)

This schematic is at least true for the initial RSW setup. Two factors will affect the relative electrical resistance during the RSW process. Firstly melting of the substrate will cause the contact resistance between the sheets to be eliminated. Secondly the bulk resistance of the material will increase rapidly due to the temperature dependence of the materials resistivity. This can be understood from (3) and Figure 4.

In equation (3) $R$ is electrical resistance [Ω], $\rho$ is resistivity [Ωm], $L$ is length of conductor [m] and $A$ is area of conductor [m$^2$].

$$R = \frac{\rho L}{A} \quad (3)$$

The temperature dependence of resistivity illustrated in Figure 4 will cause an increase in bulk resistance with increasing temperature as $R \propto \rho$ from (3). The increased resistance at increased temperature will cause more heat to be generated as $Q \propto R$ from (1). The temperature dependence of the bulk materials resistivity is the cause of the rapid nature of RSW.
Contact resistance heavily affects the RSW process as mentioned earlier. The amount of contact resistance is mainly a function of the electrode force, material surface conditions and the presence of oxides or coatings on the material surface. For example, the surface of aluminum is naturally covered in aluminum oxide (Al₂O₃) which acts as an insulator and hence need to be removed before RSW can be executed. This is usually done by chemical or electrical cleaning of the surfaces, or by the use of RSW copper electrodes which is specially designed for breaking the Al₂O₃ prior to welding. In the case of UHSS materials the presence of surface coatings often need to be taken into consideration before welding with RSW. These coatings are designed as corrosion protection and as an oxidation inhibitor during the manufacturing of the steel sheets. These coatings usually consist of zinc (Zn) or an aluminum silicon (AlSi) mixture. The Zn coating is applied through galvanization or submerging of the steel sheets in molten Zn. AlSi coatings are applied through submerging in melt solely.

The materials bulk resistance can be considered as independent of pressure (Zhang & Senkara, 2006), while contact resistance is a function of the electrode force applied from the RSW electrodes on the steel sheets. A larger electrode force will deform surface asperities and allow for a larger contact area, hence a larger electrode force will cause reduction in contact resistance. This is illustrated in Figure 5.

Considering Figure 5 it suggests that the electrode force should be chosen as low as possible to allow for a high contact resistance and a faster heat generation. While this is true, in practice this approach will cause problems. As the steel sheets are not processed to exact tolerances and have small deviations in surface roughness. Deviations in sheet thickness and sheet offset would result in large errors of the contact resistance, and in extension affect the weld nugget size which is heavily related to the welds mechanical properties (Zhang, et al., 2011). Another problem when using low electrode force would be the built-in inexactness of the equipment supplying the electrode force, as low deviations in electrode force will cause large deviations in contact resistance at a low electrode force. The contact resistance dependence of applied electrode force is shown in Figure 6. Considering Figure 6 it is clear that a small deviation in electrode force at low electrode forces will produce a larger error in contact resistance relative to a small deviation in electrode force at high electrode forces.
As bulk resistance is temperature dependent and contact resistance is dependent of electrode force, a more generic term is used to explain the total resistance in an RSW setup. This is called dynamic resistance and aims to give understanding of how bulk resistance and contact resistance changes over the period of the RSW weld cycle. An illustration of the dynamic resistance is shown in Figure 7. Here at the beginning there is a relatively high dynamic resistance due to the high contact resistance between the steel sheets. As the surface starts to soften and break down when the current is applied the dynamic resistance is decreasing due to the increased contact area between the steel sheets. The contact resistance continues to decrease but at one point the rapidly increasing bulk resistance caused by increase in temperature starts to dominate, the dynamic resistance increases as a result. Now rapid heating occurs as the heat generated is proportional to the resistance and the resistance is heavily temperature dependent. Shortly after first melting the dynamic resistance start to decrease again, this is due to the fact that the molten nugget between the steel sheets is now growing and providing the current to pass through a larger area and thereby lowering the current density and resistance. Indention of the copper electrodes does cause a shorter path for the current to pass through the material, this also results in a decrease in resistance as shown in (3). Finally, there is a rapid decrease in dynamic resistance, this is due to expulsion. Expulsion is when the molten nugget grows too big or when the hydrostatic pressure of the molten nugget caused by material expansion during heating and melting exceeds the pressure applied by the electrodes, so that liquid metal is rapidly pushed out between the steel sheets. Expulsion is further explained later in this thesis, as it is a non-desirable effect and a considerable quality risk for RSW. Expulsion is a defect which is generally a larger problem in UHSS and when welding dissimilar or coated materials, as the current range of the weld lobe curve often is smaller and currents used often is close to the expulsion limit.

Figure 6 The contact resistance dependence of electrode force (Kimchi & Phillips, 2018).

Figure 7 Change in dynamic resistance during an RSW cycle (DICKINSON, et al., 1980).

3.1.3 RSW parameters

The main RSW parameters consist of weld current, weld time and electrode force. The main RSW parameters will be explained briefly in following chapters.

3.1.3.1 Weld current

Weld current is the parameter most commonly altered in order to influence weld result in RSW, as the heat generation is proportional to the square of the applied current as shown in (1). Here a too low weld current will result in a too small nugget or no
bonding at all, a too large weld current will result in expulsion. Expulsion causes most of the molten metal to evacuate the intended weld area, resulting in a weaker weld as well as potential damage on surrounding parts and equipment. Typical weld currents used in RSW when welding steel are 5-10 [kA] (Andersson, 2013).

3.1.3.2 Weld time
In (1) we can see that the time elapsed during current flow affect heat generation and thus also weld results. However as the number of spot welds in one car body is in the order of thousands, weld time is usually kept to a minimum in order to keep production cycle times down. Typical weld times for RSW are 200-500 [ms] (Andersson, 2013).

3.1.3.3 Electrode force
Electrode force is a necessary parameter of RSW in order to handle potential geometrical variation in the material stack and to ensure a closed current loop. However as discussed earlier, excessive electrode force lowers the contact resistance and heat generation in the early stages of the RSW process, resulting in proposed nugget formation and increased weld time. It has been shown that overloading the electrode force reduces nugget size and mechanical properties of the weld (Pouranvari, et al., 2007). Typical electrode forces used in RSW are 3-6 [kN] (Andersson, 2013).

3.1.3.4 RSW cycle
An RSW cycle utilizes the parameters previously described and always contains steps of squeeze time, weld time and hold time. Squeeze time is the time it takes for the RSW equipment to reach desirable electrode force in order to hold the welded material in place during welding. Hold time is the time after weld current is applied but before force is released. The purpose of hold time is to allow for the water-cooled electrodes to transport heat from the welded sheet. In some cases hold time includes a temper time or temper current. Temper current is a current which is smaller in magnitude compared to welding current and the purpose of the temper current is to lower the cooling rate of the welded nugget. Temper current can be used in situations when martensitic transformation due to high cooling rate should be avoided. RSW cycles are often complex, especially in the case of RSW of UHSS materials. When welding UHSS the weld cycles are built up by pulsing the weld current in order to melt and remove surface oxides and coatings if present in a first current pulse, then subsequent weld pulses is designed to allow the weld nugget to grow to desirable size between the metal sheets. The aim of this method is to have a clean contact area between the metal sheets for the second weld pulse to achieve a weld nugget, as would be the case for non-coated steels. A schematic over the RSW cycle is shown in Figure 8.

3.1.4 Weld lobe curves
In order to determine the weld cycle results, the most common method used is weld lobe diagrams. Basically a weld lobe diagram shows how much the weld current can vary while maintaining an adequate weld nugget size. The lower quality limit for weld nugget size is determined as a function of sheet thickness $t$ [m] and can be expressed as $4\sqrt{t}$ [m]. Usually $t$ is determined from the thickness of the thickest outer sheets in a stack-up. The lower
limit of weld nugget size will vary in different industries and applications. The upper quality limit for weld nugget size is when expulsion occurs. Weld lobe curves is further explained in sections 3.1.4.3 and 3.1.4.4.

3.1.4.1 Nugget size

To measure the weld nugget formed between the metal sheets, the metal sheets are forced apart by a chisel and hydraulic press. The weld plug diameter is then determined through measuring over the nuggets largest diameter and perpendicular to its largest diameter, the total nugget diameter is defined as the mean of these two measurements. The measured nuggets can look different for different materials and welding parameters. A summary of the most usual fracture cases when chisel testing spot welds are shown in Figure 9.

![Figure 9](image)

**Figure 9** Different fracture modes when destructive testing of RSW welds. (Kimchi & Phillips, 2018)

In RSW of UHSS the most common fracture mode is button pull, also called full button pull. In the case of too low welding current or welding time UHSS show the no fusion fracture mode, also called interfacial fracture. Interfacial fracture is considered to have no nugget, even though the metal sheets are bonded interfacealy and have some mechanical strength.

3.1.4.2 Expulsion

Expulsion is the event that occurs when the hydrostatic pressure of the molten nugget becomes greater than the clamping force applied by the electrodes. Molten metal is rapidly pushed out of the fusion zone and to the surrounding area. This can be caused by too high welding time and welding current or insufficient electrode force. Instabilities in the process such as misalignments of the equipment and material stack may also cause expulsion. A simplified analysis of the force balance is presented by (Zhang & Senkara, 2006) and illustrated in Figure 10. In Figure 10 \( F_e, \text{ applied} \) is the squeezing force applied by the electrodes, \( F_n \) is the force from the molten nugget generated by pressure \( P \) acting on the solid base material, \( F_x \) is the compressive force acting on the faying surfaces and thus constraining the molten nugget. In this simplified model of expulsion occurs when \( F_n > F_x \).

![Figure 10](image)

**Figure 10** The force balance of the molten nugget and electrodes in RSW.

3.1.4.3 1D Weld lobe curves

One dimensional lobe curves, also called current range curves, is an experimental way of determining the robustness of an RSW setup. One out of three welding parameters is varied whilst the other two are kept constant, the result is collected as the size of the weld nugget. Usually weld current is varied while
electrode force and weld time is kept constant, since weld current is the most prominent RSW parameter given in (1). In the case of varying current, the 1D lobe diagram tells us during which span of current adequate weld nugget size can be achieved before expulsion occurs. An example of a 1D lobe diagram is shown in Figure 11.

3.1.4.4 2D Weld lobe curves
2D weld lobe curves is constructed from multiple 1D lobe curves, where one 1D lobe curve corresponds to two points in a 2D lobe curve. In the 2D lobe curve the axis consist of two out of the RSW parameters; weld current, weld time and electrode force. The way 2D lobe curves are constructed from 1D lobe curves is illustrated in Figure 12. 2D lobe curves provide a process window for which parameter values acceptable nuggets are produced.

3.1.5 Shunting effect
When RSW is used in manufacturing industries the material is generally joined in multiple locations called weld spots. This will allow for a small portion of the weld current to leak from the intended welding area through previously welded spots. This phenomenon is called the shunting effect, the amount of current leakage is dependent on the distance between the welded spots and the welded materials electrical conductivity. The shunting effect is illustrated in Figure 13.
Because of the shunting effect weld spots should be placed with a certain distance from each other in order to avoid large current leakage due to the shunting effect. Optimum distance between welded spots will vary from different materials and will not be investigated in this thesis. However a standardized so-called shunt weld will be placed at a controlled distance from all the investigated welds in this thesis, this is to imitate the environment present in the manufacturing industries. The dimensions of the welded specimens in this thesis are shown in Figure 14, including location of the shunt weld, marked with green. The investigated weld is marked with red.

![Figure 14 Dimensions of welded specimens used in this thesis. Test spot marked in red and shunt spot marked in green.](image)

### 3.1.6 Electrodes

Electrodes have multiple properties that need to be taken into consideration when choosing an electrode for RSW. The electrode material need to be strong enough to clamp the material intended to weld and have higher electrical and thermal conductivity than the material welded. Often electrodes are chosen from the strength of the base material, as when electrodes start to wear the area of the electrodes in contact with the base material is increasing due to so called mushrooming. This will lead to a lower current density and smaller weld nuggets. Choosing electrode is often a tradeoff between strength and electrical/thermal conductivity. As when strength is increased thermal and electrical conductivity is decreased (Kimchi & Phillips, 2018).

#### 3.1.6.1 Electrode materials

The electrodes used in this thesis are of type CuCr1Zr from manufacturer Luvata. The basic material properties are shown in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8890</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>385</td>
<td>[J/(kg*K)]</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>78</td>
<td>[% IACS*]</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>320</td>
<td>[W/(m*K)]</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient</td>
<td>17,6</td>
<td>[10^-6/K]</td>
</tr>
</tbody>
</table>

* % IACS = International Annealed Copper Standard. The % IACS values are calculated as percentages of the standard value for annealed high conductivity copper as laid down by the International Electrotechnical Commission.

Chemical composition of CuCr1Zr electrodes from Luvata is shown in Table 2.

<table>
<thead>
<tr>
<th>Element</th>
<th>[wt. %]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>0,5-1,0</td>
</tr>
<tr>
<td>Zr</td>
<td>0,05-0,15</td>
</tr>
<tr>
<td>Cu</td>
<td>bal.</td>
</tr>
</tbody>
</table>

#### 3.1.6.2 Electrode geometries

It is clear from previous work that the geometry of electrodes used in RSW influence current density, cooling rate and applied stress. Hence the geometry of the electrode also influences formation and final shape of the nugget (Chan, et al., 2006), (Li, et al., 2013). In RSW there is a wide array of standard electrode geometries available, which each may have suitable properties depending on the intended application. Some
examples of standard electrode geometries used in RSW are shown in Figure 15.

![Figure 15](image1.png)

**Figure 15** Examples of electrode geometries. *(SIS-Swedish Standards Institute, 1981)*

In this thesis exclusively electrodes with geometries of Type B is used, geometry showed in Figure 16 and measurements are shown in Table 3.

![Figure 16](image2.png)

**Figure 16** Geometry of electrode Type B used in this thesis. *(SIS-Swedish Standards Institute, 1981)*

In this thesis electrodes of sizes $d_1 = 16$ [mm] & $d_1 = 20$ [mm] are used. Full measurements are shown in Table 3. The standard electrodes are often referred to by the type and diameter $d_1$ and $d_2$ of the electrode. The larger outer diameter $d_1$ also referred to just outer diameter and the smaller diameter $d_2$ is referred to as flank diameter. The standard electrodes in this thesis will be referred to as 16/6 and 20/8 from the measurements of $d_1$ and $d_2$ given in Table 3. As all electrodes in this thesis are of type B all electrodes will be referred to by their measurements and the type will not be mentioned further.

<table>
<thead>
<tr>
<th>$d_1$ [mm]</th>
<th>$d_2$ [mm]</th>
<th>$R_1$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>50</td>
</tr>
</tbody>
</table>

An image of the standard electrodes used in this thesis is shown in Figure 17.

![Figure 17](image3.png)

**Figure 17** Standard electrodes Type B. Size 20/8 [mm] and 16/6 [mm].

### 3.1.6.3 Dressing of electrodes

During RSW the electrodes deform over time due to the exposure to mechanical stress at elevated temperatures. This deformation is highly dependent on the type of material welded since material with greater mechanical strength which will require a greater electrode force to be constrained during welding. Coatings on the welded material can affect the deformation process. For example Zn based material coatings is known to negatively affect the RSW process as the Zn has a relatively low melting temperature the Zn based coating will soften during welding and stick to the electrode surface resulting in inferior electrical conductivity in the electrode for subsequent welds. Diffusion of base material in to the electrodes can result in softening of the electrode tip which will accelerate the
deformation and decrease the electrical conductivity of the electrode. In order to remove contamination from the electrode tip and ensure the intended geometrical shape of the electrode a double sided rotating cutting tool is used while the electrodes are mounted in the RSW equipment. An example of the schematics of an RSW Dressing tool is shown in Figure 18.

![Figure 18 Schematic of RSW electrode Dressing tool. (Wesltd, 2018)](image)

The rotating cutting tool is placed between the electrodes mounted in the RSW equipment and the RSW equipment apply force to the electrodes. No current is applied to the electrodes while dressing the electrodes. Generally the electrode force used while dressing is lower than the electrode force during welding. Besides the obvious benefits of dressing the electrodes by removing contamination and ensuring geometrical shape, the Dressing tool can also decrease some of the effects of errors such as misalignment. Misalignments of the electrodes can to some extent be eliminated by dressing electrodes internally since the dressing is performed when the electrodes are mounted in the weld gun so that the surface processed by the rotating dressing tool will be parallel to the material intended to weld subsequent to electrode dressing.

### 3.1.6.4 Hollow electrodes

Previous work has been performed to modify the geometry of the RSW electrode in order to allow for better weld results in terms of current range in 1D weld lobe curves (Donghyun, et al., 2016), (Jun & Rhee, 2012), (Yeom, et al., 2009). The method used in these reports of modifying the geometry has proven to be effective in improving the current range of the 1D weld lobe curves. In three cases an electrode shape that allows for the molten nugget to expand in to cavities of the electrode has been used. An example of hollow electrode geometry used in (Jun & Rhee, 2012) is shown in Figure 19. Values from (Jun & Rhee, 2012), not presented in Figure 19, are depth of 3 mm and diameter of 4 mm.

![Figure 19 a) Dimensions of modified electrode used. b) Image of modified electrode. Both from (Jun & Rhee, 2012)](image)
In (Yeom, et al., 2009) no upper limit in the weld lobe curve was found even though the weld current was increased well above the expulsion limit for standard electrodes. Worth noting is that the minimum current to achieve minimum required weld nugget diameter does also increase with the modified electrodes in (Yeom, et al., 2009). In Figure 20 results from mechanical testing preformed in (Jun & Rhee, 2012) of a two sheet SPRC440 material combination is shown. Sheet thickness used in (Jun & Rhee, 2012) was 1 mm. It can be seen from Figure 20 that it is possible to achieve weld nuggets as strong, or in some cases stronger, with modified electrode compared to standard electrode. Worth noting about Figure 20 is that in the case of standard electrode; in Figure 19 a) the current steps used is close to the expulsion limit and there by no current step of greater magnitude can be used while in Figure 19 b) for the case of modified electrode no upper current limit for expulsion could be found. The lack of expulsion limit when welding with modified electrodes in (Jun & Rhee, 2012) means it is possible that available current steps of larger magnitude could give even greater mechanical strengths when testing tensile shear strength and cross tension strength.

![Figure 20](image-url) Tensile shear strength (TSS) and Cross tensile strength (CTS) for a) standard electrode and b) for modified electrode. (Jun & Rhee, 2012)

However, it has shown to be of the cost of profound indentation and raise of the visible surface in welded area, leaving a non-uniform surface which can be deemed as a defect in the case that the welded surface will be visible to the final costumer. An example of surface raise when using modified electrodes in previous work is shown in Figure 21 (Donghyun, et al., 2016). In Figure 21 a modified electrode has been used in combination with a conventional standard electrode. The modified electrode on the bottom side and standard electrode on the top side in Figure 21.

![Figure 21](image-url) Example of surface raise from use of modified electrode. (Donghyun, et al., 2016)
In this thesis the same mechanism of improved welding results will be utilized but with the ambition to improve the geometry of the electrodes cavity and hence the surface properties of the final welded specimen, so that the indentation and/or raise of the surface area of the weld is minimized.

### 3.2 Limitations

Some aspects of RSW have deliberately been left out of this thesis in order to maintain a reasonable scope of the thesis and an effective resource management. The aspect of RSW which are left out are as follows.

#### 3.2.1 Weld quality

Aspects of weld quality that will not be investigated in this thesis are listed in this section. These aspects of weld quality will not be investigated in this thesis since the test methods of these properties are time consuming and costly. These properties are deemed as not highly relevant in this early stage of investigation. However these properties of weld quality are important to consider if these modified electrodes will be introduced to production of applications subject to dynamic loads, corrosive environments and surface properties in applications subject to painting or other surface treatments subsequent to welding. Dynamic mechanical strength, corrosion resistance, surface condition are all properties that will not be investigated in thesis. Surface conditions will partly be observed in this thesis while welding with modified electrodes. However the surface conditions effect on subsequent treatments such as painting will not be investigated.

#### 3.2.2 Peltier Effect

Peltier effect can be described as when the electrons pass through material of different fermi levels the electrons change orbits. The Peltier effect is dependent of the direction of the current, the direction of the current will determine if energy is released or absorbed. The Peltier effect is described by (4) where $Q_p$ is heat generated by the Peltier effect [J], $I$ is current [A], $t$ is time [s], $\Pi_A$ and $\Pi_B$ are Peltier coefficients which are material dependent.

$$Q_p(t) = \int_0^t I(t)(\Pi_A - \Pi_B)dt$$  \hspace{1cm} (4)

The heat generated from Peltier effect is generally one order of magnitude smaller compared to the heat generated by the Joule effect (Löveborn, 2016). Hence in order to simplify the investigation in this thesis the Peltier effect will not be considered.

#### 3.2.3 Misalignment & Angle fault

Misalignment is a well-known source of error in RSW and can affect the robustness of the RSW setup heavily. Misalignment occurs when the two center lines of the upper and lower electrode are not completely aligned and, this is shown in Figure 22. Misalignment may cause a faster nugget formation at a given electrode force and weld time compared to
perfectly aligned electrodes.

**Figure 22** Misalignment with distance d between electrode center lines.

The faster nugget formation during misalignment is caused by the increased current density due to the decreased contact area. Even though misalignment may cause a faster nugget formation it is the cause of a less robust RSW process as misalignment causes expulsion at an earlier stage when compared to perfectly aligned electrodes. Previous work has been preformed (WEN, et al., 2009) where different misalignment distances d were tested and dynamic resistance recorded. It was found that expulsion occurred with increased misalignment distance d as shown in Figure 23 (WEN, et al., 2009). Hence misalignment is considered an error which is to be minimized in order to secure weld quality and robustness of the RSW process.

**Figure 23** The effect of axial misalignment on dynamic resistance. *(WEN, et al., 2009)*

Problem with decreased RSW process robustness due to misalignment is thought to be a greater problem when welding with modified electrodes compared to standard electrodes. The reason that the misalignment error is thought to be a greater problem when welding with modified electrodes is that in order to create cavities in the modified electrodes, contact area is inevitably removed. The decreased contact area of the modified electrodes will cause even greater current density in the case of misalignment compared to standard electrodes. The increase in current density will cause the welded nugget to form faster and possibly expulsion to occur earlier. The remaining contact area of the modified electrodes in the RSW setup with misalignment distance d is shown in side view in Figure 24 and in top view in Figure 25.
As the contact area of the modified electrodes is non-uniform during misalignment as shown in Figure 25 misalignment may cause a non-uniform weld nugget. It should be noted that the misalignment illustrated in Figure 24 and Figure 25 are schematic illustrations and not by any means measured values of misalignment distance $d$.

Angle fault is when the two center lines of the electrodes are not parallel. Angle fault may occur from multiple reasons such as flex in the RSW equipment, bent or crooked parts in the RSW equipment, poor fitting of the electrode to the RSW equipment. Angle fault can occur in one of the two electrodes separately or in both electrodes simultaneously. An example of angle fault in the upper electrode is shown in Figure 26.

In this thesis an additional potential source of angle fault is introduced during the manufacturing of the modified electrodes. The potential source of angle fault while manufacturing the modified electrodes occurs when the surface used for manufacturing and the surface used for welding is not parallel. The surfaces involved include the outer cylindrical surface that is gripped in order to suspend the electrode in the lathe and the inner conical surface of the electrode that is subsequently used when fitting the modified electrode in the RSW equipment. If the outer surface that is gripped in the lathe and the inner surface that is used for fitting the modified electrode in the RSW equipment are not parallel it will cause one or both of the
modified electrodes to apply the electrode force with an angle to the sheet. Hence angle fault can cause non-uniformity in indentation, current density, stress distribution and weld nugget. The misalignment distance $d$ will not be measured or attempted to control in this thesis as misalignment may occur from multiple reasons that are difficult to accurately control. However it is important to be aware of the effect of misalignment when evaluating RSW results and especially when preforming welds with electrodes of reduced contact area such as the modified electrodes investigated in this thesis. The negative effect of misalignment can to some degree be avoided by the use of a Dressing tool as described earlier in 3.1.6.3. As the Dressing tool is used when the electrodes is mounted in the RSW equipment if misalignment is present some of the negative effect of the misalignment can be eliminated due shaping of the electrode in the misaligned position. In this thesis the modified electrodes is produced in a lathe and it is possible that the suspended position of the electrode in the lathe differs slightly from the position in the RSW equipment. This possible small variation in positioning of the electrode would usually not be a problem for standard electrodes as Dressing tools are used after the electrodes are mounted in the RSW equipment to ensure the final shape and position of the electrode and contact area. However development and manufacturing of Dressing cutting tools in a time consuming and expensive procedure and will not be included for the modified electrodes investigated in this thesis.

4. Experimental

In the following chapters the material and methods used in this thesis will be explained. However no chapter of methodology or discussion about methods used will be included.

4.1 Material

Materials used in welding experiments are USIBOR1500P, DP600 and Zn-coated boron steel. The USIBOR1500P was included in multiple variations in this thesis and will forth be named by USIBOR followed by thickness and potential heat treatment. The thickness of the USIBOR steel varied with 1,1mm, 1,2mm, 1,4mm and 1,8mm. The heat treatment of the USIBOR is either not mentioned in the case of three sheet material combinations as the heat treatment of the USIBOR plates in three sheet material combinations are according to standard temperature and dwell time. The heat treatment of USIBOR sheets named 900s dwell time aims to simulate deviations in the manufacturing of the USIBOR sheets with prolonged dwell time. The USIBOR sheets with normal dwell time will be referred to at USIBOR 192s which refers to the normal dwell time of the USIBOR sheets. The chemical compositions of the materials are shown in Table 4. The material coating type and thickness are shown in Table 5. Some material composition and coating data are absent. This is because of that the material suppliers do not want to share the specifications of the material. In the case of the Zn-coated boron steel the only information provided to the author is that the material is of similar character as the USIBOR1500P, and has a Zn-based coating. The Zn-coated boron steel has been sand blasted subsequent to coating application. The sand blasting treatment has given the material a smooth surface. The effect on physical properties and purpose of the sand blasting treatment is unknown to the author but is still mentioned here as it may affect the weldability. The DP600 material is also of unknown composition to the author as the supplier does not wish to share that information. The only information available to the author about the material is that it is of dual phase nature and of ultimate tensile strength of roughly 600 MPa.
### Table 4 Chemical composition of materials used for welding experiments.

<table>
<thead>
<tr>
<th>Material</th>
<th>Usibor1500P</th>
<th>DP600</th>
<th>Zn-coated boron steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>*0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>*0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>*1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>*0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All materials used in this thesis had kind of surface coating. The coatings are designed for corrosion protection or to assist in the manufacturing of the metal sheets. The coatings have no purpose in welding of the metal sheets. Surface coating type and composition is shown in Table 5.

### Table 5 Surface coating type and composition of materials used for experiments.

<table>
<thead>
<tr>
<th>Coating type</th>
<th>Coating mass [g/m²]</th>
<th>Coating thickness [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usibor1500P</td>
<td>AS75/75</td>
<td>150</td>
</tr>
<tr>
<td>DP600</td>
<td>GI50/50</td>
<td>100 7</td>
</tr>
<tr>
<td>Zn-coated boron steel</td>
<td>Zn</td>
<td></td>
</tr>
</tbody>
</table>

**4.2 Modified Electrodes**

The modified electrodes were manufactured in two iterations MOD1 and MOD2. MOD1 was manufactured in ten variants were all had a spherical cavity in the center of the electrode contact area. The depth of the cavity was varied in three steps of 0.5, 1.0 and 2.0 mm0mm. Images of electrodes from MOD1 series are shown in Figure 27.

**Figure 27** Electrodes from MOD1 series.

When creating the cavities in the modified electrodes contact area is inevitably removed from the electrodes. The decreased contact area due to material removal when creating the cavities in the modified electrodes is expected to affect the current density and the applied stress to the welded material. In order to be able to investigate the influence of increased current density and applied stress a kind of hybrid electrodes was produced. The hybrid electrodes share the larger diameter of the standard electrodes of 16- and 20mm, but the smaller flank diameter of 6 and 8mm was increased so that after the hybrid electrodes had been modified with a cavity in the center of the contact area the total remaining contact area was equal to that of a standard electrode of same size. These hybrid...
electrodes are referred to as size of 16/6.6 and 20/10. Measurements of electrodes in MOD1 is shown in Table 6. The wider contact area of MOD1.4 and MOD1.8 is shown in Figure 27. After welding trials with electrodes from MOD1 had been performed the electrodes in MOD2 was created. In MOD2 the results from welding trials in MOD1 was taken in consideration. The results from welding trials in MOD1 will be discussed later in this thesis, but the geometries of the different variants in MOD2 will be explained below. The electrodes in MOD2 were created in four different geometries and will be referred to as MOD2.5, MOD2.6, MOD2.7 and MOD2.8. In the first variant of MOD2 referred to as MOD2.5 a kind of S-shape was utilized. The thought behind this S-shape was that the raise in the middle of the electrode would contribute with heat transfer from the center of the surface of the welded specimen to the water-cooled electrode. As well as reducing the current density from the edges of the weld. In MOD2.5 the shape of the cavity that allows for the welded material to expand is of a torus rather that of the spherical shape used in MOD1. The truncated angle of 30° and flank diameter of 8mm in MOD2.5 was kept in order to not change outer dimensions of the electrode. The purpose of the preserved outer measurements of the electrode is to make the modified electrodes more compatible with standardized production equipment and construction methods used today. In the case of MOD2.6 the flank angle of 30° was kept but the flank diameter was widened. The widened flank diameter was created in order to investigate if the increased contact area from the increase in flank diameter would contribute to weld quality. The cavity created in MOD2.6 was of spherical shape and of substantially larger volume compared to the other variants in MOD2. The thought behind the geometry of MOD2.6 was to see if increased contact area and a large volume of the cavity in the electrode could improve the weld quality. As mentioned earlier it is preferred to keep the flank angle of 30° and flank diameter of 8mm if possible due to compatibility with production units used today by the industries. However the geometrical shape of MOD2.6 could be of interest if it would prove to be able to achieve desirable weld quality where other electrodes cannot. MOD2.7 and MOD2.8 is of similar geometry with a rounded contact area of same shape in both cases. The difference between MOD2.7 and MOD2.8 is the geometrical shape and volume of the cavity designed to allow the welded material to expand. In the case of MOD2.7 the cavity is of the shape of an exponential cone and in the case of MOD2.8 the cavity is of spherical shape. It is of interest to investigate if the larger volume of the cavity in the case of MOD2.7 relative to MOD2.8 can improve the weld quality. It is deemed a considerable risk for material sticking from the welded material to the electrode with the sharp geometry in MOD 2.7. Schematic views of electrodes in MOD2 series is shown in Figure 28 and in Figure 30. Closer view of the contact area of the electrodes in MOD2 series are shown in Figure 29.
**Figure 28** Schematic view of MOD2 series.

**Figure 29** Close view of the contact area of the electrodes in MOD2 series.

**Table 6 Specifications of electrodes in MOD1.**

<table>
<thead>
<tr>
<th>Name:</th>
<th>size: [mm]</th>
<th>d: [mm]</th>
<th>t: [mm]</th>
<th>r: [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOD1.1</td>
<td>16/6</td>
<td>0.5</td>
<td>1.0</td>
<td>4.2</td>
</tr>
<tr>
<td>MOD1.2</td>
<td>16/6</td>
<td>1.0</td>
<td>1.0</td>
<td>2.4</td>
</tr>
<tr>
<td>MOD1.3</td>
<td>16/6</td>
<td>2.0</td>
<td>1.0</td>
<td>1.9</td>
</tr>
<tr>
<td>MOD1.4</td>
<td>16/6,6</td>
<td>1.0</td>
<td>1.6</td>
<td>2.4</td>
</tr>
<tr>
<td>MOD1.4.2</td>
<td>16/6.6</td>
<td>0.5</td>
<td>1.6</td>
<td>4.2</td>
</tr>
<tr>
<td>MOD1.5</td>
<td>20/8</td>
<td>0.5</td>
<td>1.0</td>
<td>9.2</td>
</tr>
<tr>
<td>MOD1.6</td>
<td>20/8</td>
<td>1.0</td>
<td>1.0</td>
<td>4.9</td>
</tr>
<tr>
<td>MOD1.7</td>
<td>20/8</td>
<td>2.0</td>
<td>1.0</td>
<td>3.2</td>
</tr>
<tr>
<td>MOD1.8</td>
<td>20/10</td>
<td>1.0</td>
<td>2.0</td>
<td>4.9</td>
</tr>
<tr>
<td>MOD1.8.2</td>
<td>20/10</td>
<td>0.5</td>
<td>2.0</td>
<td>9.2</td>
</tr>
</tbody>
</table>
4.3 Method

Methods used in this thesis aimed to modify standard electrodes used in RSW of type B and evaluate the weld quality compared to standard electrodes. Manufacturing and measuring methods used are described in following sub chapters.

4.3.1 Manufacturing and Dressing of electrodes

The modified electrodes were manufactured in a CNC lathe of according to the geometries specified in previous chapter. The standard electrodes were dressed by a rotating pneumatic cutting tool while mounted in the RSW equipment. In some cases modified electrodes were dressed by rotating cutting tool with a cutting tool intended to dress standard electrodes. The purpose and results of dressing modified electrodes is shown and discussed in 5.1.

4.3.2 Welding equipment

The RSW equipment used in this thesis is from manufacturer Matuschek. Welding equipment specifications is shown in Table 7. Welding parameters used by the welding equipment varied with materials and electrodes used and will be specified with each welding result. In all cases a double weld pulse was utilized. The purpose of the pre-pulse in the double weld pulse setup is to remove surface coating present as described earlier in 3.1.3.4.

4.3.3 Metrological equipment

Different metrological tools have been used to measure the welded nugget and inspect surface conditions. The different metrological tools used included surface probe, line laser scanner and Vernier caliper. The different metrological equipment used is further explained in following sub chapters.

4.3.3.1 Electrode measurements

In some cases the manufactured electrodes were control measured with surface probe. This was to control geometrical conditions after manufacturing in lathe as the electrodes normally is not manufactured in a lathe. Welding test was done with standard electrode of different manufacturing methods in order to see the influence of the surface condition of the electrodes on the nugget growth and weld lobe diagram. The weld test consisted of standard electrodes manufactured and formatted in the traditional way by dressing the electrode in the RSW equipment. The other set of standard electrodes was formatted in a lathe to the same dimensions. The surface conditions were

<table>
<thead>
<tr>
<th>Equipment property</th>
<th>Equipment data</th>
</tr>
</thead>
<tbody>
<tr>
<td>MaxElectrode force: [kN] (daN)</td>
<td>8</td>
</tr>
<tr>
<td>Short circuit current: [kA]</td>
<td>38</td>
</tr>
<tr>
<td>Current type: [AC, MFDC]</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>
compared before the weld test. Measured values of interest from the surface probe test are surface roughness and the geometrical radius of the contact area of the electrode as given by Figure 16 and Table 3. After welding with the measured standard electrodes weld lobe diagrams was created. The weld lobe diagrams was then compared in order to see the influence of surface processing method on the weld lobe diagram. As no apparent major affect from the surface condition on the electrodes from the two different dressing processed was observed the results from surface probe measurements will not be included in 5.1 but will be included in 10.

4.3.3.2 Surface measurements
The surface conditions of welded specimens were measured with line laser scanner. The line laser measurements of the surface were done in order to understand how different electrode geometries would affect the surface at different welding currents. The measurement data obtained from line laser measurements was then plotted on a secondary axis in the weld lobe diagram. The purpose of plotting data from line laser measurements in the weld lobe diagram is to illustrate how the surface conditions will vary with varying weld current. When profiling the surface condition from line laser measurement the profile was characterized in three measurements. These three measurements was defined as Indent, Raise and Standard Indent (STD Indent). Indent is the mean value of the indent caused by the modified electrode measured from the material surface to the lowest point in the indent by four points of measurement. Raise is the highest point of the welded material surface caused by the expansion of the welded material in to the modified electrode. Raise is presented as mean value from two measurements. STD Indent is the mean value of the indent caused by the standard electrode measured from the material surface to the lowest point in the indent by two points of measurement.

![Figure 31 Schematic view of line laser measurements.](image)

Since most material combinations in this thesis are non-weldable a comparison with weld results from standard electrodes is impossible. Instead of comparing indentation with standard electrodes a general maximum indentation limit is set to 20% of the total thickness of the material stack. As raise in welded surface does not occur when welding with standard electrodes it will solely be observed how great the raise is and how it varies with weld current.

4.3.3.3 Nugget measurement
Welded specimens were destructively tested and measured. The destructive testing method will be described in 4.3.4. The weld plug was measured with a Mitutoyo Vernier caliper.

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4.3.4 Chisel test

The weld lobe diagrams were constructed from measurements from destructive chisel tests. Tool used for chisel test was a hydraulic press equipped with a chisel, shown in Figure 33. The two sheets are forced apart by the chisel and the weld plug is pulled out of one of the sheets and leaves a cavity. The weld plug is then measured from the sheet where the plug is attached. In the case of three sheet combinations the procedure is repeated and the weld plug diameter is measured for each interface.

4.3.5 Sample preparation and cross sections

Samples for cross section analysis include cross sections for light optical macroscope and micro hardness analysis through Vickers hardness measurements. All samples were cut with a rotation abrasive disc and subsequently molded in Stuers conductive plaster. The molded specimens were hand polished in multiple steps on sand paper of decreasing roughness in steps of p300, p420, P600, p1200, p2500, p4000. The specimens was polished by hand on polishing cloth with diamond suspension of decreasing roughness of 6 μm, 3 μm, 1 μm and 0,25 μm subsequent to polishing by sandpaper. Samples for light optical macroscope evaluation were etched in a Nital 5% solution for 30s.

4.3.6 Hardness test

In order to determine if the modified electrodes influence the micro hardness of the fusion zone (FZ) and heat affected zone (HAZ) compared with standard electrodes a 2D
Vickers micro hardness mapping was performed. The equipment was of manufacturer Qness. In the Vickers hardness 2D mapping a two-dimensional point grid was created over the cross section of the welded area. The Vickers equipment then make an indent of the surface and measure the diameter of the indent automatically and from the measured value calculate the hardness value of the area in HV1.

4.3.7 Mechanical testing
Welded specimens were tested for mechanical strength by shear tensile test and cross tensile test. The schematic of shear tensile test specimens was performed in two interactions and is shown in Figure 34 and Figure 35. The first iteration of shear tensile tests was non-successful in fracturing the weld in the specimens. Instead in the first iteration of shear tensile test as shown in Figure 34 the specimen was fractured in the base material in the relatively weak DP600 middle sheet. In order to evaluate the mechanical strength of the weld nugget performed by modified electrodes compared with standard electrodes it is necessary for the tested specimen to fracture in the welded area. Hence the results from tensile shear test iteration 1 will not be used for comparison with standard electrodes in this thesis. However the results from tensile shear test iteration 1 will be included in this thesis as it might be of interest for future work in the area.

Figure 34 Schematic of tensile shear test setup iteration 1.

Because of the unwanted fracture mode for cross tension test specimens are shown in Figure 36, a second iteration of tensile tests was designed and designed and the schematic of tensile test in iteration 2 is shown in Figure 35 and Figure 36. The schematic in Figure 35 and Figure 36 includes three sheet material combinations. In the case of two sheet material combinations the same setup was used but without the middle sheet and only the two outer sheets was welded and tensile strength is tested.

Figure 35 Schematic of tensile shear test setup iteration 2.

The specimens were constrained and pulled at a rate of 10 [mm/min] until fracture occurred. Data recorded during tensile testing includes applied force [kN] and displacement [mm].

Figure 36 Schematic of three sheet cross tension test setup. Applied force market in blue.
5. Results & Discussion
The results from modification iteration MOD1 and MOD2 will be presented separately in each sub category as follows. The result sub categories will be divided to weld lobe and surface, geometric measurements of electrodes, cross section analysis and mechanical testing.

5.1 Weld lobe and surface condition
Weld lobe diagrams was created in this thesis and most of them will be presented in the appendix section rather than in the results section as it is the authors belief that readers are interested in the value of the current range from the weld lobe diagrams rather than the whole diagram. However in case it would be of interest for future work the weld lobe diagrams will be presented in 10.

In order to provide a more holistic view of the weld results in terms of current range a summarizing view will be provided in Figure 48, Figure 49 and Figure 50. However a novel type of weld lobe diagrams was created in this thesis. The weld lobe diagrams were created in order to provide a comprehensible overview of the weld lobe combined with the surface condition of the welded specimen. Therefore a weld lobe diagram with a secondary axis was created. In the combined weld lobe and surface condition diagram the main axis is identical to a conventional weld lobe diagram with nugget diameter [mm] plotted on the vertical axis and weld current [kA] plotted on the horizontal axis. In the combined weld lobe and surface condition diagram a secondary vertical axis was added where indentation and raise were plotted [mm]. The secondary axis of the combined weld lobe and surface condition diagram was created so that origin of the secondary axis is coinciding with the minimum nugget demand that is plotted as a dashed horizontal line from the main horizontal axis. The coinciding of origin on the secondary axis and the dashed horizontal line of the main axis representing minimum nugget demand enables the reader to interpret the dashed horizontal line of the diagram as both minimum nugget demand from the weld nugget measurements as well as the surface of the material welded from the line laser measurements creating a more holistic view of the weld result obtained.

In Figure 37 and Figure 38 combined weld lobe and surface condition diagrams of Zn-coated boron steel is presented. In the case of Zn-coated boron steel no acceptable weld nugget could be achieved with standard electrodes so each current step with approved weld nugget diameter with modified electrodes is an improvement compared to standard electrodes. The surface conditions of the welded specimen are represented in Figure 37 as indent and raise. The measuring point of indent and raise is defined earlier in Figure 31. From Figure 37 it can be seen that a current range of 0.6 kA with a largest indent of 0.06mm or 2.5% of the material stack thickness and a largest raise of 0.4mm or 16.7% of the material stack thickness.

![Figure 37 Combined weld lobe and surface condition diagram. For electrode MOD1.4.2, modified against modified electrode and Zn coated boron steel.](image-url)
Figure 38 one of the modified electrodes is exchanged to a standard electrode. The purpose of this modified to standard electrode setup is to investigate if it is possible to achieve an approved weld in otherwise non-weldable material combinations with a standard electrode on one side, in this case the purpose of the standard electrode would be to leave a surface condition free from raise. A surface free from raise could for example be desirable in the case that the welded part is to be fitted to other part with strict geometric surface tolerances subsequent to the welding. In Figure 38 it can be seen that with a modified electrode to standard electrode setup for the Zn-coated boron steel material it was possible to achieve a current range of 0.6 kA with a largest indent from the standard electrode of 0.15 mm or 6.3 % of the material stack thickness and largest indent from the modified electrode of 0.07 mm or 2.9% of the material stack thickness. Largest raise on the surface on the side of the modified electrode was 0.4mm or 16.7% of the material stack thickness.

Manufacturing of the USIBOR steel sheets which is believed to affect the RSW weldability negatively. In the case of USIBOR 1.1 mm with extended dwell time of 900s no acceptable weld nugget could be achieved with standard electrodes so each current step with approved weld nugget diameter with modified electrodes is an improvement compared to standard electrodes. From Figure 39 it can be seen that a current range of 0.6 kA with a largest indent of 0.09mm or 4.1% of the material stack thickness and a largest raise of 0.39 mm or 17.7% of the material stack thickness.

In Figure 39 combined weld lobe and surface condition diagram of USIBOR 1.1mm boron steel with extended dwell time of 900s. In Figure 40 an identical setup to that in Figure 39 is presented with the exception that one electrode is exchanged to a standard electrode in the same manner as described earlier. From Figure 40 it can be seen that one approved current step can be achieved, which means that the current range is equal to zero. However, in this thesis one approved current step will be considered to have a current range of 0.15 kA with the motivation to be able to distinguish between weld lobe diagrams of not approved current step and weld lobes of one approved current step.

Figure 38 Combined weld lobe and surface condition diagram. For electrode MOD1.4.2, modified against standard electrode and Zn coated boron steel.

In Figure 39 combined weld lobe and surface condition diagrams of USIBOR 1.1mm which has been exposed to and extended dwell time of 900 s, 900s. The purpose of the extended dwell time is to simulate variations in the manufacturing of the USIBOR steel sheets which is believed to affect the RSW weldability negatively. In the case of USIBOR 1.1 mm with extended dwell time of 900 s no acceptable weld nugget could be achieved with standard electrodes so each current step with approved weld nugget diameter with modified electrodes is an improvement compared to standard electrodes. From Figure 39 it can be seen that a current range of 0.6 kA with a largest indent of 0.09mm or 4.1% of the material stack thickness and a largest raise of 0.39 mm or 17.7% of the material stack thickness.

Figure 39 Combined weld lobe and surface condition diagram. For electrode MOD1.4.2, modified against standard electrode and USIBOR 1.1mm boron steel with extended dwell time of 900s.

In Figure 40 an identical setup to that in Figure 39 is presented with the exception that one electrode is exchanged to a standard electrode in the same manner as described earlier. From Figure 40 it can be seen that one approved current step can be achieved, which means that the current range is equal to zero. However, in this thesis one approved current step will be considered to have a current range of 0.15 kA with the motivation to be able to distinguish between weld lobe diagrams of not approved current step and weld lobes of one approved current step.
In one observed case the modified electrode preformed worse compared with a standard electrode. The case of worse results from modified electrodes compared with standard electrodes is shown in combined weld lobe and surface condition diagram in Figure 41 and Figure 42 with material combination of USIBOR 1.1mm 192 s dwell time. Figure 41 shows the case of standard against standard electrode and Figure 42 shows the case of modified electrode. No obvious explanation to the poor performance of the modified electrode in Figure 42 was apparent. However it is by the author deemed as the most probable reason that the modified electrodes uses in acquiring the results in Figure 42 has been misaligned or manufactured with an angle fault resulting in a non-robust weld result. Important to note about the statement regarding the welding result presented in Figure 41 and Figure 42 is that misalignment and angle fault has not been controlled or measured by the author. However, the same material combination has shown welding results with modified electrodes that has greater current range compared to standard electrodes in the 20/8 mm size that is presented in Figure 50.

The indentation of modified electrodes compared to standard electrodes is preformed from results in Figure 41 and Figure 42 from different current steps but similar nugget size. The current step in the case of standard electrode is 6 kA, 4,45 mm weld plug diameter and 0,11 mm indentation. The current step in the case of modified electrodes 6,9 kA, 4,45 mm weld plug diameter, 0,10 mm indentation and raise 0,38mm.
nugget with increased current will be an improvement in regard to current range. The current range from Figure 43 is 3.9 kA. As Figure 43 represents results from a three-sheet material combination each current step is represented by two measurements with denomination 1-2 and 2-3. The denominations 1-2 and 2-3 are explaining between which two sheets counted from the top electrode the measured nugget is located. Material welded in Figure 43 is two sheets of USIBOR 1.4 mm with a sheet of DP600 1.8 mm in the center of the stack. The surface conditions of the welded specimen are represented in Figure 43 as indent and raise. The measuring point of indent and raise is defined earlier in Figure 31. From Figure 43 it can be seen that the indent and rise are rather constant when increasing current until current is approaching expulsion. Greatest measured indentation was at 11.5 kA current step and of value 0.23 mm. The indentation of 0.23 mm represents 5% of the total material stack. The largest measured value of raise was at current step 10.1 kA and of value 0.34 mm or 7.4% of the material stack thickness.

As the results from surface conditions measurements by line laser scanning showed that indentation is not greater when welding with modified electrodes compared to standard electrodes in MOD1 series the surface condition measurements was not performed in MOD2 series. From results in MOD1 series it was observed that the misalignment or angle fault was a larger issue in the case of 16/6 mm electrodes than in the 20/8 mm electrodes and hence the manufacturing of electrodes in MOD2 series was limited to include only electrodes of size 20/8. Efforts to avoid problems with potential misalignment and angle fault were not in the scope of this thesis. However, a discussion with tool manufactures was initiated in order to enable internal Dressing of modified electrodes in the RSW equipment for future work. As the weld lobes from MOD2 series
exclusively includes nugget size and current range the weld lobes of MOD2 series will be presented in section 10 and a summarized view of the current range will be presented in Figure 50.

When welding with modified electrodes of MOD2 series an attempt to measure influence from misalignment and angle fault was performed. The attempt to measure influence from misalignment and angle fault consisted of Dressing the modified electrodes internally in the RSW equipment by a rotating cutting tool. Important to note is that the rotating cutting tool was not designed to create the modified geometries but is of a standardized sort designed to format standard electrodes. Hence the surfaces of the cavities of the modified electrodes was not formatted by the standardized cutting tool whilst the surfaces of the 30° flank and contact area of the modified electrodes was formatted by the standardized cutting tool. The propose of this Dressing of modified electrodes by standardized cutting tool was as mentioned earlier to avoid misalignment, needless to say it would have been desirable to perform the Dressing with a cutting tool that processes all of the surfaces of the modified electrode but the manufacturing of such cutting tool was not in the scope of this thesis. An example of a modified electrode before and after Dressing with standardized cutting tool is shown in Figure 45 and the weld plug shape after chisel test before and after Dressing with standardized cutting tool is shown in Figure 46.

The results from Dressing modified electrodes with standardized cutting tool would imply that there is misalignment or angle fault present in the modified electrode or electrodes subsequent to manufacturing in the lathe. As can be seen in a) from Figure 45 a non-uniform wear is present on the contact area of the modified electrode. The non-uniform wear of the electrode surface combined with the non-uniform weld plug in Figure 46 would suggest a misalignment or angle fault in the electrode is present. These results alone is not enough to determine between the errors nature of misalignment or angle fault as the two can show similar results of a half-moon shaped weld plug. It is intuitive how an angle fault can generate a half-moon shaped weld plug but misalignment can
produce similar shape in weld plug in case of modified electrodes, this is illustrated in Figure 25. Important to note about the case of misalignment or angle fault in Figure 45 and Figure 46 is that the current range in the weld lobe diagram is greater in the case of the non-formatted modified electrode than in the case of the formatted modified electrode. The current range from the weld lobe diagram is represented in Figure 50 under MOD2.8 as USIBOR 1.1mm 192 s dwell time (Formatted) and USIBOR 1.1 mm 192 s dwell time (Non-Formatted). From Figure 50 it can be seen that the difference in current range is 0.6 kA in the case of formatted electrode and 1.95 kA in the case of non-formatted modified electrode. The phenomenon of nugget growth during misalignment and angle fault is discussed briefly in 3.2.3 and can be explained by a faster weld nugget formation due to increased current density caused by decreased contact area during misalignment or angle fault. Another explanation to the decreased current range in the weld lobe diagram of the formatted modified electrode compared to the non-formatted could be that during dressing of the modified electrodes with standardized cutting tool material is removed from the contact area of the modified electrode which in turn will result in a shallower cavity that allows for the welded material to expand in to. Even though the current range of the weld lobe diagram is greater in the case of misalignment or angle fault of the particular case presented in Figure 45 and Figure 46 misalignment and angle fault is generally causing a less robust process and should be avoided. It can also be seen from Figure 45 and Figure 46 that misalignment or angle fault that results in non-uniformity in the wear of modified electrodes and weld nugget formation can be avoided by the dressing of electrodes internally in the RSW equipment which is of great importance for potential future work with modified electrodes in RSW.

In Figure 48 and Figure 49 a summarized view of welding results from the current range in the weld lobe diagrams from welding trials in MOD1 series is presented. It can be seen in Figure 48 that modified electrode MOD1.4 showed best results in the 16/6 mm size and in Figure 49 it can be seen that the electrode with ID MOD1.8.2 showed best results in the weld lobe diagrams. Both MOD1.4 and MOD1.8.2 had the broaden flank diameter to allow a contact area identical of a standard electrode of same size and the difference of the two is the depth of the cavity created to allow material to expand in to the electrode.

As a large number of variables was introduced when creating the electrodes in MOD1 series combined whit a large number of material combinations, an attempt to find an expression of the variables as a function of current range was performed before producing MOD2 series. This expression is shown in (5) where $E_v$ is the combined parameter of the geometric variables of the modified electrodes MOD1 series to be evaluated. $A$ is the contact area of the modified electrode, $V$ is the volume of the cavity in the modified electrode, $r$ is the radius of the spherical cavity and $d$ is the depth of the cavity.

$$E_v = \frac{(A * V * r)}{(1 + d)} \quad (5)$$

From welding results in MOD1 series a correlation between $E_v$ and current range was observed. This correlation is shown in Figure 47.
Important to note about (5) and Figure 47 is that $E_v$ is by no means a universal truth describing the geometrical variables influence on weld lobe result but rather a tool that can help point modified electrode design in the right path. $E_v$ was used in this thesis in an attempt to understand how the different geometrical parameters of the modified electrodes affected the results in the weld lobe. To summarize the interpretation of the geometrical variables of modified electrodes in MOD1 series through $E_v$, a larger area $A$ is positive for weld lobe results as a larger area can handle misalignment and angel fault better that a smaller area, A larger volume of the cavity $V$ will allow for the welded material to expand in to the electrode to a larger degree and hence widen the current range by proponing expulsion, a large radius $r$ of the spherical cavity will allow for the available contact surface inside the cavity to come in contact with the welded material at a faster rate contributing with added surface area during welding which in turn contributes with lower current density and cooling of the surface of the welded material, the depth of the cavity $d$ is affecting the weld lobe results negatively as the available surface area in the center of the cavity never comes in contact with the welded material during welding contributing to enlarged current density and lack of cooling in the center of the weld in the case of large values of $d$. These concepts of geometrical variables were utilized in creating the modified electrodes in the MOD2 series. In the MOD2 series of modified electrodes spherical contact area as used in all cases to ensure that the contact area of the electrode would rapidly increase during welding as the welded material is softening and the modified electrode is pressed in to the welded material. The volume of the cavities of the modified electrodes was kept relatively small in all cases except in MOD2.6 where the purpose was to investigate an exceptionally large volume of the cavity. The large volume of the cavity in the case of MOD2.6 resulted in melting and sticking of the surface of the welded material to the electrode and hence MOD2.6 is deemed as non-desirable regardless of the current range. MOD2.7 and MOD2.8 identical to the point of transition radius in the center of the electrode cavity where MOD2.7 had sharp transition radius but larger volume of the cavity and MOD2.8 had a smoother transition radius but smaller volume of the cavity. As MOD2.7 showed worse results in the weld trial of three sheet material combination compared to MOD2.8, MOD2.7 was not included in subsequent weld trials. All of the weld results from MOD2 series are summarized in Figure 50.

Figure 47 $E_v$ plotted against mean value of current range of all weld trials from MOD1 series, trials from standard electrodes included.
Figure 48 Summary of weld results in MOD1 series for electrode size 16/6 mm.

Figure 49 Summary of weld results in MOD1 series for electrode size 20/8 mm.
5.2 LOM & Hardness

From MOD1 series one cross section was selected and analyzed by LOM and Vickers hardness. The Modified electrode and material combination selected for cross section analysis was MOD1.8.2 with three sheet material combination consisting of two USIBOR 1.4mm sheets whit one DP600 sheet in the center. The LOM image of the cross section is shown in Figure 51. The weld nugget in Figure 51 was measured to 8.95 mm and the pore located in the center of the weld to 2.11 mm or 23.6% of the nugget diameter.

A 2D-Vickers hardness mapping was conducted over the same cross section and shown in Figure 52.
The purpose of preforming a 2D mapping of Vickers hardness testing instead of a line scan which is generally used when analyzing RSW spots was to see if non-uniformity in the hardness profile was introduced with the novel modified electrodes. From Figure 52 no non-uniformity can be observed as the hardness profile is symmetric over the cross section. The values of the hardness are not deviating from values found in literature of similar material welded with standard electrodes (Thibaut, et al., 2016).

In all cross sections from modified electrodes in MOD2 series misalignment or angle fault was observed with non-uniform nugget formation as a result. Cross sections from MOD2 series are shown in Figure 53 to Figure 61. From Figure 53 the weld plug diameter was 3.67 mm and the pore 1.19 mm.

In Figure 54 the weld plug diameter was 5.16 mm and the pore 0.63 mm.

In Figure 55 the weld plug diameter was 5.24 mm and the pore 2.5 mm.

In Figure 56 the weld plug diameter was 4.05 mm and the pore 0.36 mm.

In Figure 57 the weld plug diameter was 6.85 mm and pore 2.09 mm.
In Figure 58 the weld plug diameter was 8.98 mm and pore 2.18 mm.

In Figure 59 the weld plug diameter was 5.77 mm without apparent pore.

In Figure 60 the weld plug diameter was 6.39 mm and pore 1.65 mm. Important to note about the weld represented in Figure 60 is that expulsion occurred, as no achievable current step was achievable with standard electrodes.

In Figure 61 the weld plug diameter was 6.7 mm and pore 1.00 mm. Important to note about the weld represented in Figure 61 is that expulsion occurred, as no current step was achievable with standard electrodes.

5.3 Electrode measurements

As modified electrodes in this thesis was manufactured in an external lathe rather than formatted internally in the RSW equipment by a rotating cutting tool that has been described
earlier in 3.1.6.3 the effect of lathe processing was of interest to investigate. The effect of lathe processing on weld results in respect to the weld lobe diagram was investigated using two sets of 20/8 mm standards electrodes. Two of the electrodes were processed by external lathe and two electrodes by rotating cutting tool internally in the RSW equipment. Both sets of electrodes were shaped according to Figure 16. Subsequent to processing the two electrode sets was measured by surface probe in order to determine potential differences in shape and surface roughness of the two shaping methods. The shape measured on the two electrode sets was the radius $R_1$ in Figure 16. Subsequent to surface probe measurements the two electrode sets were compared in weld lobe diagrams. The standard electrode dressed in an external lathe showed a current range of 1.8 kA while the standard electrode dressed by a regular rotating cutting tool showed an current range of 1.5 kA. Both weld lobes were performed on USIBOR 1.2mm standard dwell time. The results from lathe dressed and rotating cutting tool dressed standard electrodes is from a very limited number of weld trials. Because of the limited number of weld trials in the lathe and rotating cutting tool dressing of standard electrodes it is not possible to accurately say if the change in surface condition of the standard electrodes due to dressing in lathe or rotating cutting tool has any influence on the weld lobe diagram. However it can be concluded that the difference in surface condition of the standard electrodes dressed by lathe and rotating cutting tool has no major effect on the weld lobe diagram. Roughly a 20% larger current range in the case of lathe dresses compared to rotating cutting tool dressed standard electrode. The weld lobes from the weld trials with standard electrodes dressed in lathe and rotating cutting tool can be found in 10.

5.4 Tensile testing

Tensile test from iteration 1 is shown in Figure 62. As mentioned earlier the tensile test design of iteration 1 is considered a failure as the fracture occurred in the base material of the DP600 steel sheet. The fracture of the base material is caused by the test design that allows for the weld to experience half of the stress applied where the test design in iteration 2 allows for each weld to experience the total applied stress. The stress distribution from iteration 1 and iteration 2 can be understood from Figure 34 & Figure 35.

![Tensile test iteration 1. MOD1.8.2 2x USIBOR1.4mm 1x DP600 1.8mm](image)

Figure 62 Tensile test from iteration 1.

The only conclusion that can be drawn from tensile test iteration 1 is that each of the welds is stronger than half of the maximum force recorded $F_{MAX}$ during tensile testing. From tensile test in iteration 1 10 test was performed with a mean $F_{MAX}$ of 41.8 kN with a standard deviation of 0.4 kN. Hence the welds in iteration 1 experienced a mean value of $F_{MAX}$ at 20.9 kN without fracturing the weld.

Tensile test from iteration 2 is shown below in Figure 63, Figure 64 & Figure 65. Important to note from tensile test in iteration 2 is that different weld current was used. The different weld currents were used to achieve identical weld nugget size of the welded specimens prior to tensile testing. Three weld trials were
performed to find the specific nugget size of each material combination and electrode. The specific nugget size used in tensile tests of the three sheet material combinations represented in Figure 63 & Figure 64 was 6.6 mm. The specific nugget size used in two sheet material combination represented in Figure 65 was 6.0 mm. Another important note about tensile test in iteration 2 is that the material combinations represented in Figure 63 & Figure 64 is as mentioned before non-weldable with standard electrodes. The non-weldable with standard electrode material combinations represented in Figure 63 & Figure 64 means that each of the welds executed by standard electrode has been subjected to expulsion and is of mean nugget size value of 6.6 mm. All fractures in test from iteration 2 were in the welded area. From Figure 63 & Figure 64 tensile tests results from three sheets material combination is shown. In Figure 65 tensile test results from two sheet material combination is shown.

Figure 63 Tensile test from iteration 2. MOD2.5 (blue) and Standard electrode (red). For three sheet material combination of 2x USIBOR 1,8mm 1x DP600 1,8mm.

The maximum force recorded during tensile testing $F_{\text{MAX}}$ was gathered as mean value and represented in Figure 66. From Figure 66 it can be seen that MOD2.5 showed lower values of $F_{\text{MAX}}$ in the case of two sheet combination 1.1 mm USIBOR 192s standard dwell time and in three sheet combination of 2xUSIBOR 1.8mm 1xDP600 1.8mm compared to the standard electrode. However MOD2.5 showed greater mean value of $F_{\text{MAX}}$ in the case of three sheet material combination of 2xUSIBOR1.4mm 1xDP6001.8mm compared to standard electrode. MOD 2.8 showed greater values of $F_{\text{MAX}}$ in both cases measured.

Figure 64 Tensile test from iteration 2. MOD2.5 (blue), Standard electrode (red) and MOD2.8 (green). For three sheet material combination of 2x USIBOR 1,4mm 1x DP600 1,8mm.

Figure 65 Tensile test from iteration 2. MOD2.5 (blue), Standard electrode (red) and MOD2.8 (green). For material combination of USIBOR 1,1 mm 192s dwell time.
of the three-sheet material combination of 2xUSIBOR1.4mm 1xDP600 1.8mm and the two-sheet material combination 1.1 mm USIBOR 192s standard dwell time compared to standard electrode. No measurement of three sheet material combination 2xUSIBOR 1.8mm 1xDP600 1.8mm with electrode MOD2.8 was performed due to lack of material.

Figure 66 Summary of tensile tests from iteration 2 with values of $F_{MAX}$ for each electrode and material combination. Standard deviation marked in black bars.

6. Conclusions
This thesis aimed to show that it is possible to weld UHSS material combinations with modified electrodes in RSW. The weld lobe curves have shown better results in all except one case for the modified electrodes, which is an exceptional result in itself considering that all UHSS material combinations in this thesis except one is non-weldable with standard electrodes. Ironically the UHSS material combination that is weldable with standard electrodes is the same as the only UHSS material combination non-weldable with modified electrodes. Surface conditions have been measured and showed smaller indentations compared to standard electrodes. However, a small raise of the surface is apparent. Problems of misalignment have shown to be a large problem when manufacturing and welding with modified electrodes. However tests have shown that dressing internally in the RSW equipment can decrease the problem with misalignment and angle fault. Vickers harness measurements have been performed and shown symmetric hardness profiles of hardness magnitudes similar to that found in literature when welding with standard electrodes.

To conclude and answer the research questions from the hypothesis:

1. It has been shown that it is possible to widen the current range in the weld lobe diagram of otherwise non-weldable UHSS material combinations by the use of modified hollow electrodes without affecting the solid mechanical properties negatively.

2. It has been shown that it is possible to widen the current range in the weld lobe diagram of otherwise non-weldable UHSS material combinations by the use of modified hollow electrodes without affecting the solid mechanical properties, micro hardness, negatively compared to standard electrodes. However a small raise in surface of welded specimens seem unavoidable.

7. Future work
Even though the method of modified electrodes with cavities shows very effective in widening the current range in the weld lobe diagram it is a method of high sensitivity and low robustness. For future work be conducted in the area it is the authors recommendation to develop rotating cutting tools for dressing the modified electrodes internally in the RSW
equipment in order to minimize misalignment and angle fault.

8. Acknowledgement
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10. Appendix

10.1 Weld lobe diagrams
A complete collection of weld lobe diagrams that has not been included in 5.1 is presented below. The results will not be discussed here but rather in 5.1 from the summarized weld lobe results.

Figure 67 MOD1.1 two sheet USIBOR 1.2mm standard dwell time.
Figure 68 MOD1.1 two sheet USIBOR 1.2 mm extended dwell time.
Figure 69 MOD1.2 two sheet USIBOR 1.2mm standard dwell time.
Figure 70 MOD1.2 two sheet USIBOR 1.2mm extended dwell time.
Figure 71 MOD1.3 two sheet USIBOR 1.2 mm standard dwell time.
Figure 72 MOD1.3 two sheet USIBOR 1.2mm extended dwell time.
Figure 73 MOD1.4 two sheet USIBOR 1.2 mm standard dwell time.
Figure 74 MOD1.4 two sheet USIBOR 1.2mm extended dwell time.
Figure 75 Standard electrode dressed in rotating cutting tool. Two sheet USIBOR 1.2 mm standard dwell time.
Figure 76 Standard electrode dressed in lathe. Two sheet USIBOR 1.2 mm standard dwell time.
Figure 77 Standard electrode. Two sheet USIBOR 1.2 mm extended dwell time.
Figure 78 Standard electrode two sheet Zn coated boron steel.
Figure 79 Standard electrode two sheet USIBOR 1.1 mm extended dwell time.
Figure 80 MOD1.5 three sheet combination 2xUSIBOR 1.4mm 1xDP600 1.8mm.
Figure 81 MOD1.6 three sheet combination 2xUSIBOR 1.4mm 1xDP600 1.8mm.
Figure 82 MOD1.7 three sheet combination 2xUSIBOR 1.4mm 1xDP600 1.8mm.
Figure 83 MOD1.8 three sheet combination 2xUSIBOR 1.4mm 1xDP600 1.8mm.
Figure 84 Standard electrode three sheet combination 2xUSIBOR 1.4mm 1xDP600 1.8mm.
Figure 85 MOD2.5 electrode three sheet combination 2xUSIBOR 1.4mm 1xDP600 1.8mm.
Figure 86 MOD2.5 dressed electrode two sheet USIBOR 1.1 mm standard dwell time.
Figure 87 MOD2.5 dressed electrode two sheet combination Zn coated boron steel 1.2 mm.
Figure 88 MOD2.5 dressed electrode two sheet combination of USIBOR extended dwell time 1.1 mm.
Figure 89 MOD 2.6 electrode three sheet combination of 2xUSIBOR 1.4mm 1xDP6001.8 mm.
**Figure 90** MOD 2.7 electrode three sheet combination of 2xUSIBOR 1.4mm 1xDP6001.8 mm.
Figure 91 MOD 2.8 electrode three sheet combination of 2xUSIBOR 1.4mm 1xDP6001.8 mm.
Figure 92 MOD2.8 dressed electrode two sheet combination USIBOR standard dwell time 1.1 mm.
Figure 93 MOD2.8 dressed electrode two sheet combination Zn coated boron steel 1.2 mm.
Figure 94 MOD2.8 dressed electrode two sheet combination USIBOR extended dwell time 1.1 mmm
Figure 95 MOD2.8 electrode two sheet combination USIBOR standard dwell time 1.1mm.
10.2 Electrode Measurements

Results from surface probe measurements are presented below. The measurements was preformed to see if the lathe dressing and rotating tool dressing of standard electrodes had any influence on the weld lobe diagrams. The average surface roughness $Ra$ for the electrodes dressed by rotating cutting tool was $Ra = 0.6$ and the average surface roughness for the electrodes dressed in a lathe was $Ra=0.73$.
Figure 97 Surface probe measurement of standard electrode dressed with rotating cutting tool. Measurement 1.

Figure 98 Surface probe measurement of standard electrode dressed with rotating cutting tool. Measurement 2.
Figure 99 Surface probe measurement of standard electrode dressed in lathe. Measurement 1.

Figure 100 Surface probe measurement of standard electrode dressed in lathe. Measurement 2.