Degree project in Engineering mechanics
Second cycle 30 credits

**Projection Nut Welding to High- and Ultra-high Strength Steels**
Evaluating FEM Simulations of Nut Welds in SORPAS

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Abstract

In an effort to increase the fuel efficiency of cars more widespread use of higher strength steels is seen for their high strength-to-weight ratio. These steels are more limited in their formability and tendency to harden than conventional steels, complicating manufacturing. This thesis summarizes the available research on resistance projection nut welding to higher strength steels and investigates the accuracy of the simulation program SORPAS when simulating projection nut welds to AlSi-coated Boron steel. It was found that the greatest difficulties in welding coated ultra high strength steels were the metallurgical effects of both the high alloying content of the steel and the coatings interacting with the weld when melting. Although SORPAS was an intuitive program to use for resistance welding and had a wide library of materials available, it was not found to be able to predict the resistance characteristics or results of projection nut welds to coated Boron steel without significant changes to default material parameters. The biggest issue was the delaying effect the coating layer had on the peak resistance, something not observed experimentally. Better results are suggested to be possible after experimentally ensuring the properties of the materials used and importing those values into SORPAS.
Sammanfattning

I ett försök att öka bilars bränsleeffektivitet används i allt större utsträckning stål med högre hållfasthet på grund av deras goda förhållande mellan styrka och vikt. Dessa stål är mer begränsade i sin formbarhet och tendens att härda än konventionella stål, vilket försvårar tillverkning. Denna uppsats sammanfattar den tillgängliga forskningen om motständssvetsning med projektsmunter i höghållfasta stål och undersöker noggrannheten hos simuleringsprogrammet SORPAS vid simuleringsprojektsmunter- svetsar i AlSi-belagt borstål. Det konstaterades att de största svårigheterna vid svetsning av belagda ultrahållfasta stål var de metallurgiska effekterna av både stålets höga legeringsinhåll och beläggningarnas interaktion med svetsen vid smältning. Trots att SORPAS var ett intuitivt program att använda för motständssvetsning och hade ett brett bibliotek av tillgängliga material kunde det inte förutsäga motståndsegenskaperna eller resultaten av projektsmunter svetsar mot belagt borstål utan betydande förändringar av standardmaterialparametrarna. Det största problemet var den födröjande effekt som beläggningsskiktet hade på maximala resistansen, något som inte observerades experimentellt. Bättre överensstämmelse föreslås vara möjlig efter att experimentellt säkerställa egenskaperna hos de material som används och importera dessa värden till SORPAS.
Acknowledgements

There are many people I would like to thank for their help with this thesis work. First and foremost I want to thank the joining group at Swerim for being welcoming and engaged throughout my stay there. I am especially thankful to Klara Trydell, David Löveborn and Pia Borg for their great humor and constant willingness to help.

For coming in to watch over my thesis on short notice and for helping me set up my report and presentation I would also like to thank my supervisor at KTH, Carl Dahlberg.

I am grateful to Stefan Borg at Svetsradet for his vast technical expertise and patient explaining and for lending me his measuring equipment to use. The scope of my work would have been much more limited without his help.

Likewise, the guidance of Håkan Andersson at Gestamp HardTech was crucial for me as a student to understand how the work I would do was linked to real production. I want to thank him not only for teaching me so much but also for taking his time to show me around wonderful Luleå over the days I was there. I hope he has a retirement that is both fruitful and restful.

Finally, I want to extend a special thanks to Joakim Hedegård at Swerim for introducing me to welding, metallurgy and production. Listening to him during the IWE-courses is one of the fondest memories I have from my education and I am certain it has helped me in more ways than I know of.
Nomenclature

AC    Alternating Current
AHSS  Advanced High Strength Steel
BIW   Body-In-White
BM    Base Material
CP    Complex Phase
CS    Cross-section
DIN   German Institute for Standardisation
DP    Dual Phase
FEA   Finite Element Analysis
FZ    Fusion Zone
HAZ   Heat Affected Zone
HEX   6-sided Weld Nut
HP    High Performance Weld Nut
HSS   High Strength Steel
IF    Inter-Facial Failure
ISO   International Organisation for Standardisation
LME   Liquid Metal Embrittlement
MFDC  Medium Frequency Direct Current
PF    Plug Failure
PHS   Press-Hardenable Steels
PJ  Projection Plug Failure
PO  Push-out
PP  Partial Plug Failure
PT  Penetrant Testing
Q&P Quenching and Partitioning
RPW Resistance Projection Welding
RSW Resistance Spot Welding
SQ  Square Weld Nut
TRIP Transformation Induced Plasticity
UHSS Ultra High Strength Steel
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References
1 Introduction

This section presents the background, purpose and limitations of this Master’s thesis.

1.1 Background

It has been of interest for a long time to reduce the weight of vehicles to increase their fuel efficiency thus making them both more environmentally friendly and economically attractive to own long term. Following this trend, in 2020 European regulations limited CO$_2$ emissions to 95 g/km for new road cars, targeting a 30% further reduction by 2030. One broadly-adopted way of cutting the weight of the vehicle while maintaining its structural integrity is by more extensive use of higher strength steels such as High Strength-, Ultra High Strength-, or Advanced High Strength Steels (HSS, UHSS, and AHSS respectively). Some limitations to these steels are their decreased formability and increased tendency to harden after cooling due to their higher weight fraction of alloying elements.[1]

This reduced formability is cause for even more frequent use of joining methods, such as Laser Beam Welding (LBW), Resistance Spot Welding (RSW) and Resistance Projection Welding (RPW). The most commonly applied methods of welding in the automotive industry are methods with high efficiency and versatility, paired with small heat deformations. Projection nut welds mainly see use to attach fasteners for mounting components such as the front and rear axles. It has been noted that RPW done to higher strength steels can have a lower durability than those done to conventional steels, this is partially caused by the change in failure mode from a more ductile full plug failure (PF) in the sheet to a brittle inter-facial failure (IF) in the welds. These interfacial failures are unable to absorb the same amount of energy as the full plug failures, which gives the joint a lower strength and the body-in-white (BIW) a lower crash worthiness.[2, 3]
1 INTRODUCTION

Although both UHSS and projection nut welding are widely used in the industry, the amount of research covering nut welding to UHSS is not as abundant. In 2006, Hedegård and Tolf[2] remarked this lack of research and conducted the first comprehensive investigation into projection nut welding to higher strength steels. Since then more research has been published not only on RPW, but also simulations of RPW, to HSS and UHSS. It is with this background, together with both the improvements to the simulation software SORPAS and general computational power over the past years that this thesis will proceed.

1.2 Purpose

The purpose of this project is to summarize the available research on resistance projection welding to higher strength steels, and investigate the reliability and ease of use of the latest version of SORPAS 2D and 3D as simulation tools for predicting nut welding on coated ultra high strength steels.

1.3 Limitations

Realistically only a few of the many varieties of weld nuts can be tested for and likewise only a few sheet types can be used. In this thesis the experiments and simulations will be consequently be limited to only two types of nuts and one type of boron steel sheet.
2 Theory

This section will give a background to resistance welding and detail findings from available literature to be used as a reference when observing simulation results.

2.1 Resistance Projection Welding

In resistance welding, work pieces are joined together through means of electrical resistance while under a compressive force. The resistive heating is the greatest between the objects being joined, making for a concentrated weld. In resistance projection welding the current flows between two cooled electrodes usually made from a copper alloy and is concentrated between a number of small-area projections and a sheet. The projections melt or soften because of the generated heat, and are pushed into the other workpiece. The result can include a completely melted Fusion Zone (FZ) or remain in a solid state through forged welding, being joined together through the mixing of boundary atoms.

2.1.1 Joule Heating

The main physical phenomenon driving the welding is Joule heating, where the energy available in the circuit can be described as:

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

(1)

The heating generated \((Q_J)\) can be seen to be proportional to the resistance \((R)\) and the square of the current \((I)\). This explains why the heat is concentrated in the interfaces, as the resistances over the air gaps are much larger than the bulk resistances of the sheet or nut. It also shows the large effect of increasing the current on the energy generated, owing to their quadratic relationship. The reason the work pieces do not melt near the air gap in the two electrode interfaces is the substantial cooling from water flowing inside the electrodes. A diagram of the setup is illustrated in Figure 1.
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Figure 1: Schematic of a resistance projection welding process

Where the approximate path the current takes through the projections is drawn in. The total resistance between the electrodes can be summarized as:

\[ R = R_{E/N-Interface} + R_{Nut} + R_{N/S-Interface} + R_{Sheet} + R_{E/S-Interface} \]  \hspace{1cm} (2)

Which also shows that the higher the resistances of the sheet and nut are, the larger their share of the total resistance will be - meaning that the resistive heating becomes less focused in the interfaces.

2.1.2 Projections

Projections are generally sharp to ensure relatively high current density even after initial contact between work pieces. Recalling that the resistivity of materials increase with temperature, another contribution to resistance comes with the heating of the workpieces. When the projections yield and the contact area grows over the welding process the current density and thus generated heat decreases and the joining process halts. A measurement commonly taken after the process is a ratio called set-down $S$ which indicates how large the reduction of the initial projection height is, it is explained through equation (3) and Figure 2.
The right-most approximation is more straightforward to measure but its accuracy is dependent on the plastic deformation of the sheet and nut. If a high electrode force is paired with extended heating there may be too much yielding for the equation to remain accurate.

2.1.3 Process Parameters

The three main process parameters of RPW are the weld current, the electrode force and the weld time. The electrode force produces contact between the work pieces and at the electrode interfaces. An electrode force that is too large leads to a decrease in contact resistance between the sheets, and potentially unwanted cold plastic deformation. The weld time is the time during which the current flows through the work pieces; using a high current with a weld time that is too long may cause excessive expulsion or unnecessary heat treatment, while insufficient current or time will result in a smaller weld nugget or weaker bonding[4].
force and current curves for a typical projection nut welding process can be seen in Figure 3.

Figure 3: An idealized force and current diagram over the duration of an arbitrary weld process

2.2 Material Transformations

When heated carbon steels are rapidly cooled they form martensite, as the carbon atoms in solution in the FCC-structured austenite do not have time to diffuse and form stable cementite. A martensitic crystal structure is hard and brittle, with little elongation at failure. These types of embrittlement phenomena are some of the most important considerations when assessing the weldability of a material[1]. Other alloying elements play a part as well, and different indicative carbon equivalents are sometimes used to represent this. One such carbon equivalent used by the IIW for lower-alloyed steels looks as follows:

\[
CE = %C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Cu + \%Ni}{15}
\] (4)

The very localized application of heat in resistance type welding is what leads to the rapid cooling and formation of martensite in and around the weld. The resulting hardness profile of the weld metal can then increasingly change the frac-
ture mode from a more ductile plug failure, which can make better use of the high strength material of the sheet, to predominantly brittle inter-facial fracture in the faying surface.[2, 5]

### 2.3 Weld Nuts

The weld nuts presented in literature generally come in three different forms: Hexagonal weld nuts with three projections (HEX), round weld nuts with a fully annular projection (HP), and square weld nuts with four projections (SQ), Figure 4 shows examples of these three.

![Figure 4: Different nut and projection geometries, left to right: HEX, HP, SQ](image)

The results from welding depend both on the material of the nuts, such as alloying elements, carbon content or coating[2, 6, 7]; as well as the geometry of the projections[2, 8, 9]. The geometry dependency does not, however, seem so great that the rounded projection shape and uncertainty from the cold drawing and forg-ing of the nuts makes a significant difference to final weld results; likely due to the early collapse of the nuts when welding[10]. What seems be of greater importance is the base width and height of the projections[9, 10], see Figure 5 for illustration. Hedegård and Tolf[2] also noted that some of their nuts had differing chemical analyzes on the top and bottom in their measurements, indicating another potential uncertainty. Nuts are often cut from a single rod when manufactured, which is un-
likely to have large variations in composition across its length, so this variance may be a product of measurements only.

![Figure 5: The base width and height of an SQ nut projection](image)

Different weld nuts have differing resistances towards fatigue, as M. Lindén tested in 2008\cite{11}. When comparing the SQ, HEX, and HP geometries he concluded that the SQ and HP weld nuts had similar fatigue lives, while the HEX nuts were much less resistant. In regards to fatigue theory the HP nuts with their annular projection and less severe geometric transitions would give the best fatigue life, but it might have lost some of that benefit due to the difficulty in achieving an evenly distributed load and heat transfer to the entire projection during welding.

When Lim et al. investigated the effect of the chemical analysis of nuts in 2016\cite{6} they looked at microhardness measurements and pullout tests. Fractography revealed shrinkage cavities and a smaller fusion zone for coated boron steel nuts, which is related to why they failed predominantly in inter-facial mode. A non-interfacial fracture was observed for carbon steel nuts, where failure was initiated in the region of the HAZ with reduced hardness, allowing for pull-out failure at a higher load. The nuts weldability was also compared through the available process window for current with and without coatings, with the available current range for the boron nuts being smaller.
Some widely used German standards for weld nut geometries are tabulated below, but geometry can vary substantially within the limits of the standards.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Weld nut</th>
</tr>
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<tbody>
<tr>
<td>DIN 927</td>
<td>Three-projections hexagonal nut without flange</td>
</tr>
<tr>
<td>DIN 928</td>
<td>Four-projections square nut</td>
</tr>
<tr>
<td>DIN 929</td>
<td>Annular projection hexagonal nut without flange</td>
</tr>
<tr>
<td>DIN 977</td>
<td>Three-projections hexagonal nut with flange</td>
</tr>
</tbody>
</table>

Table 1: Weld nut standards

### 2.4 Coatings

Many high strength steels have protective coatings against oxidation or decarburization. Zinc- or Aluminium-Silicon coated steels are common in the automotive industry. When heating up coated materials, as occurs during welding, the coatings can become problematic and limiting to the process window available. It has also been found that surface quality and the presence of grease or contaminants can significantly impact surface resistance, which is an integral part of resistance welding[12, 13]. However, an inherent feature of projection welding owing to its fast heating and high degrees of plasticity is the ability to efficiently remove coating layers from the interface, this helps to avoid some diffusion of embrittling alloying elements into the central weld[13]. Zinc layers of galvanized sheets and nuts for example are generally completely burned away during the welding process[2], while AlSi coatings are pushed to the peripheries of the faying surfaces[14]. After welding soot and oxides from the coating are commonly seen around the weld, owing to the temperatures being heightened but not reaching the melting point of the material[8], this appearance is pictured in Figure 6.
2 THEORY

Figure 6: Nut and sheet appearance after a weld, Soot is visible around the four projections

2.4.1 Zinc

When Zinc vaporizes it can cause spatter, which has been known to cause increased electrode degradation when resistance spot welding. For RPW, Paolo et al.[15] noted that when welding galvanized high strength steels alloying elements such as Zn, Fe and Al from the coating were transferred to the surface of the electrode causing an uneven increase in resistivity along its contact surface. They claimed that for welding a galvanized DP600 sheet and a flanged HEX nut the ability to withstand torque of the weld increased 30% between the 1000th and 5000th welded nuts, owing to this increase in resistive heating and decreased cooling capability by the electrode interface. For RSW hot dip galvanized sheets have been observed to be sensitive to surface breaking cracks, likely because of liquid metal embrittlement (LME) of the coating elements[16].

Wang Chenyu-Wangmin[17] tested different preceding surface treatments on galvanized steel sheets and found that they affected the weldability when projection welding significantly. Galvanized sheets without post-treatment and general cold-rolled steel sheets behave similarly when increasing the current - the strength of the weld increases at first but reaches a plateau after a certain current. Post treated galvanized sheets with either phosphate treatment or surface degreasing on
the other hand were found to be able to keep increasing their strength without a plateau for higher levels of current, enabling a better final resistance to torsional shear.

2.4.2 Aluminium-Silicon

Press-Hardenable Steels (PHS) are temperable UHSS that are generally coated with AlSi before hot-forming and quenching. The coating creates three distinct primary layers in the sheet surface: the uppermost aluminium matrix, the steel substrate as well as an interdiffusion layer between the two consisting of a complex morphology due to the diffusion of the two materials. If PHS remain under heating above the austinitization temperature for too long they are overheated and intermetallic phases are created that increase the size of the interdiffusion layer. It has been found that if the heat is maintained for too long during hot forming of a boron 22MnB5-AlSi steel the weld nugget size and pullout strength decreases when projection nut welding. The largest difference being observed between sheets kept at 700 and 1000 seconds at heightened temperature. The surface heterogeneities because of the intermetallic phases also cause uneven resistivities[18]. These can be factors to consider and document when undertaking projection welding to coated PHS, since some weld difficulties may be caused by insufficient consistency during the press hardening process rather than process parameters.

The presence of aluminium has also been observed to cause HAZ-softening in the sheet because of the formation of ferrite and tempered martensite[19] and an interdiffusion layer containing a large fraction of ferrite stabilizers can further hinder martensitic transformation[18]. When increasing the current for Al-steels the weld nugget will increase in diameter but might also cause coarse grains to form in the joint interface, leading to hardness differences between the softer HAZ and harder fusion line. If the area around the weld interface is heated and then cooled rapidly the protective layer there may crack or rupture. Lower heat can help this, but instead causes less good expulsion of inclusions of compounds and reduces the effective nugget diameter[13].
Kim et al. [7] found that when welding AlSi coated hot-stamped boron steel a high degree of heat was generated at the sheet surface in the intermetallic coating. The coating melted and was pushed to the edges of the projections in the initial stages of the weld, leaving alloying elements and oxides at the final faying surface periphery. This boundary of elements from the coating was prohibitive to further longitudinal expansion of the weld nugget, instead increasing its height. With limiting the load-bearing area a reduction in pull-out strength came with it. For uncoated boron steels the contact area expanded farther and the nugget was larger in the longitudinal direction, resulting in a stronger weld.

Using an infrared thermograph Vijayan et al. [20] inspected the weld process and found that the largest heat generation while nut welding a coated steel moved over time, starting in the nut-sheet interface, but then shifting inwards toward the sheet center through conduction. This loss of heat in the interface is another reason why coated steels have lower weldability than their uncoated counterparts. With the same settings the nugget diameter decreased by close to 20% and the weld strength in pull-out by a bit over 15% in their experiments.

2.5 Modes of Failure

The failure of projection welds are usually grouped into categories after the characteristics of their fractures. A full plug failure (PF) is one where the projection pulls out the material from the sheet underneath, while a partial plug failure (PP) only pulls out a portion of the sheet under the projection. These two failures both display some macro-scale ductile characteristics and therefore absorb more energy during fracture than a more brittle failure mode would[3]. Other more brittle failure mechanisms are interfacial failure (IF), where the fracture occurs across the faying surface inside the weld, and projection failure (PJ), where an incomplete collapse of the projection leaves a sharp notch that acts as a stress concentrator and initiates the crack[19], see Figure 7.
Figure 7: Sharp notch remaining after insufficient set-down is achieved

A change from PF to IF is therefore of interest because it has been believed to decrease the strength of the weld and energy absorbed during fracture, which for example would affect the crashworthiness of an end product in the automotive industry. In a study on the shear strength of two projection welded sheets Han et al. [5] observed that the use of high strength steel causes interfacial failures beyond the weld nugget diameter that would create a plug failure for conventional steels. The nugget width that they recommended to rectify this was up to 60% larger for DP600, DP780 and DP980 thin sheets than they were for the conventional steel grades. The shear resistance of sheets increases with their thickness, which has been found to result in fewer plug failures for larger thicknesses [2]. It should be noted however, that even with IF-type failures a high strength weld can be achieved when using UHSS [2, 3, 14].

In order to induce a ductile plug failure, the fused or forged metal bond must be stronger than the resistance to shear of the sheet, which becomes progressively more difficult as the strength of its material increases. During the study by Hedegård and Tolf for combinations of different nuts to 350YP, 600DP, HyTens1000 and 22MnB5 boron steels, the most common mode of failure by far was IF. Some PF
and PP were achieved even with purely solid state welding however, indicating the possibility of achieving more ductile failures even with no FZ[2].

2.6 Testing and Inspecting

There are a number of methods to measure or estimate the strength of the welds. Commonly applied mechanical tests are a torque test, a pull-out test, or a push-out test. The pull-out and push-out tests load the nut in the normal direction of the sheet, while the torque test measures the nuts resistance to twisting off around its axis[2, 14]. These tests can be conducted until failure, in a destructive fashion, or until some set resistance - in which case the test is non-destructive if the required resistance is met for the weld. The Volvo standard STD8632,4[21] is one standard that has set requirements for both torque and push-out tests of weld nuts for example. The standard also requires at least a partial plug failure for steels under a 600MPa yield limit, while IF is allowed for steels stronger than that, but in which case the faying surface must have dimples indicating some ductility. This should be verified through laboratory analysis.

In 2019 Luo et al.[19] analyzed the microstructure of the fracture surface for the different failure modes and documented their findings. When the projections failed in PF, many elongated dimples could be found with visible shear planes in the faying surface. The failure initiates in the location of maximum shear stress on the outside of the weld furthest from the thread and propagates inwards in a ductile manner before experiencing brittle final fracture with a flatter surface appearance. Furusako et al.[14] had similar findings where they used SEM to classify the two regions as a *good region* and *bad region*. They found that the strength of the weld had a linear relationship with the area of the good region, which is importantly distinct from having a linear relationship with the total area. EDX revealed that the bad region had a large quantity of oxides, particularly those from Mn and Si, which were rarely seen in the good regions of the weld.

In the cases with IF the sheet close to the outside of the nut showed shear plastic deformation and higher tensile stresses than the inside close to the thread. The
fracture surface towards the inside was found coarser with a cleavage river pattern. Prior to final fracture microvoids grew on the periphery of the faying surface, leading to a brittle final fracture towards the inside. Shrinkage and solidification cracks can further embrittle the fracture and change the propagation path of cracks[19].

The projection failure mode is a fully brittle failure with a smooth cleavage face caused by a sharp notch resulting from a not fully collapsed projection. Achieving proper set-down help avoid these types of failures[19].

Luo et al. also looked at the appearance of the HAZ after etching it with Nital. Areas of the HAZ undergoes austenitization and normalization during the welding process, and three distinct microstructures were detected in the sheet HAZ and nut HAZ respectively[19]. Because of the rapid cooling from the close-by electrode the HAZ is usually much smaller in the sheet than in the nut[8]. If a fusion zone is achieved, it has proven somewhat difficult to differentiate it from the HAZ when etching the cross-section with Nital, an etchant based on Picric acid provides better clarity in those cases[2].

In resistance welding in general the geometry of the weld often seems indicative of its strength, which leads to many instances where mechanical testing is forgone for simpler measurements such as set-down, weld nugget diameter; or similar geometric measurements like weld width or height, or volume of molten material. There is often correlation between these measurements and the strength of the weld, but the previously mentioned distinction between good and bad sections of the weld by Furusako et al.[14] and observations in the original study by Hedegård and Tolf[2] that similar looking cross-sections could have differing torque or pull-out resistance call for some caution when relying on such measurements.

Torque tests with a torque wrench are often the simplest mechanical tests to perform, as machines and special fixtures can be avoided. One critical weakness is the inability to grip the outside of round nuts, leading to difficulty in determining their strength in relation to SQ and HEX nuts. To circumvent this some attempts have been made to find a correlation between the torque and pull-out test values for nuts, but those have come up inconclusive[2].
2.7 Fatigue

Not much literature is available on the fatigue testing of resistance nut welds, but some tests have been made. In 2008 Ringsberg[11] performed fatigue testing on different weld nuts through a fully reversed bending load. He investigated SQ, HEX and HP nuts welded to thin steel sheets. The fatigue cracks were observed to initiate on the edge of the weld where the grains had grown in the sheet and a geometric stress concentrator existed. The SQ weld and the HP weld showed similar fatigue results, despite the HP weld in theory having a smaller stress concentrating effect because of the fewer geometric transitions, likely because of the higher sensitivity of the HP nuts to non-parallelism during welding. The HEX 3-projection nuts were worse in fatigue life than the other two. For the square nuts, M10 nuts showed worse fatigue life than M8 nuts, however this could be an issue of not finding as ideal process parameters for the M10 nuts. Finally, thicker sheets showed less fatigue resistance than thin sheets and square nuts showed better fatigue resistance when bent towards a flat side rather than a corner. The scatter band of measured fatigue lives for identical tests was within a factor of 3, which is not particularly unusual in fatigue resistance.

A second investigation was conducted by Santana et al.[22] in 2022, where square nuts were subjected to fully reversed pull-out test instead of a bending test. The failure criterion was set as 3mm long crack visible through penetrant testing (PT). The findings largely coincided with those of Ringsberg, with the crack initiations being located around the square nut corners and having results with a similar scatter. The authors expected that different weld nut geometries create different localized stress concentrations which might be empirically reduced down to factors for generalization if enough tests could be performed.

2.8 Machine Control

Machines in use today come with three different power supply weld timers, alternating current (AC), mid frequency direct current (MFDC) and capacitor discharge
(CD). The most commonly used machines use MFDC, because of their higher efficiency and lack of zero-current crossovers that would allow the nut and sheet to cool when compared to AC. Force is applied through a hydraulic, pneumatic or electromechanical servo motor force system. The pneumatic design is the most common on account of its lower price and fast activation time. Hybrid designs are also available where the fast activation of a pneumatic or hydraulic design is combined with the better control of a servo motor force system. Other intrinsic mechanical characteristics of the machine also play an important role in influencing the welding process and weld quality. The stiffness, friction and dynamic mass of the system are all things that need to be considered - especially when moving from a practical frame to simulation[4].

2.8.1 Power Supply

There is some volume of available literature for both MFDC and AC power supplies, so far research using CD is rarer. This is likely because those machines are more expensive and not yet widely used. The benefits of AC is the rapid current build-up in the first half-cycle[2] which is beneficial to quickly generate heat, and further increases the resistivity of the material[3]. MFDC often cannot reach the current ramp up of first half-cycle AC, something Hedegård and Tolf[2] credits with observed higher strength nut welds for AC than MFDC. There is no indication if their weld schedule for the MFDC welds was optimal however, and controlling the current ramp-up through trigger-angle and pitch rather than current setting was not attempted. By setting a higher trigger angle of the silicon controlled rectifiers in the weld timer it is possible to use more of the available effect of the power source and thus allow the current to rise quicker at the expense of overshooting the set current. The larger the current increase every millisecond the larger the overshoot will be. The difference can be seen in Figure 8.
The maximum current reached is dependent on the resistance between the electrodes and does not depend on the final stable current. It is unadvised to set a too high trigger angle to begin with, as it can be hard to predict how high the peak will become.

One investigation into the utility of CD-welding when welding HEX nuts to AlSi-coated boron steel was performed by Cao et al. in 2019[23]. The characteristic fast discharge of a capacitor pack enables a very rapid current build up through the weld interface and enables a fast process, the authors observed cooling in excess of 106 K/s. These features were found to have many benefits with regards to resistance nut welding, with limited heat deformation and potential to more readily achieve fusion between the work pieces. In CD welding the voltage is the main governing parameter determining the resulting geometries of the weld, with both nugget depth and diameter increasing with voltage. It was observed that PF could consistently be achieved if the weld reached a certain nugget diameter $d_{cr}$, which was in contrast to what had been seen in other research papers using similar materials but MFDC or AC like those by Hedegård and Tolf[2] and Sejč et al.[12] If the weld current was increased too much both the strength and dimensions of the welds

Figure 8: A trigger angle pitch controlled rise for a 16 kA program over an 18 kA program without pitch control
would start decreasing because of the same expulsion phenomena seen with other power supplies.

Many of these findings are corroborated in the previously cited article by Luo et al.[19] which notes the limited heat deformation of CD as beneficial to thread integrity and also achieved more ductile failures with higher voltages. The latter article did not manage to achieve PF in such a consistent fashion as Cao et al., but did see a much higher frequency of partial plug failures after a certain voltage. Although the same sheet materials were used in the two articles, many things set them apart, such as the nut and projection dimensions - this could partly explain the difference in results.

The benefits of CD and the reasons behind them largely coincide with what is observed using a high trigger angle or short current rise time in MFDC. It could perhaps be concluded that it would be beneficial to control MFDC or AC machines to emulate the current histories of CD machines as much as possible then, although the maximum capacity of most conventional machines fall some ways short of peaks greater than 60 kA sometimes seen when using CD-welding. In a high-volume production perhaps the biggest obstacle to implementing CD is the penalizing recharge time between discharges. Another limiting factor to CD previously was that more volumetric projections such as those of HP nuts need very high total energy to be discharged quickly which older hardware was unable to deliver[24].

2.8.2 Machine Characteristics

With higher stiffness of the welder-arms any thermal expansion in the weldment becomes more difficult, resulting in a greater change of electrode force, and making expulsion happen later or be more easily avoided. A higher stiffness also directly affects the initial impact on workpieces and electrodes, which can cause dynamic effects and oscillations[4].

The mass of the moving parts of the machine is another contributing factor impacting the dynamic reactions during the first contact, but is generally negligible
during the rest of the welding unless very low electrode forces are used. Increased moving mass may add to the force impulse felt by the electrodes at initial contact, unnecessarily leading to electrode degradation and unstable contact if squeeze time is insufficient[4].

Friction in the mechanical system is closely related to the follow-up capabilities of the electrodes. Because friction resists movement it reduces the ability to adapt to nugget or weldment cooling and contraction during the hold stage, which may become a cause of internal discontinuities or voids. The reactive contribution to electrode force from friction during the weld time is too slow to help with resisting expulsion, other mechanisms such as locking the electrode in place after the set force has been met may instead help with this[4].

Regarding RPW, some characteristics when compared to RSW are a longer electrode travel and a solid state weld because any molten material is pushed outside the weld area by excessive force. This quickly leads to an increased weld area and a decrease in current density[25]. Larger electrode displacement and weld nut set-down have both been reported to correlate with larger variance in the weld quality[2, 9]. Nielsen et al.[10] reported that the set-down is also very sensitive to electrode travel, where 1 mm change in electrode travel could change the set-down of M10 SQ nuts by more than 8 percentage points.

Other difficulties often experienced with RPW are the narrow window of weld parameters, the lack of repeatability and the sensitivity to tolerances in relation to the height of the projections and hardness of the sheets[25]. If only three projections are used, there is guarantee of good contact for all projections, but as the number increases the chance of projections having poor contact do too if tolerances and electrode parallelism are not sufficient. Having imbalanced loading risks lack of bonding for some projections and increased likelihood of expulsion and internal spatter for others[2]. Figure 9 shows the result of a weld using an HP nut with an annular projection that received higher loading on one side than the other. Clear expulsion is visible on the side with less force applied.
2.8.3 In-process Control

Many studies have found some success in combating these difficulties through control of the force and current used. Hedégård and Tolf[2] noted the benefits of a fast initial current increase, and a plateau of higher current during the early stages of the weld time. Nielsen et al.[10] reiterated these advantages and explained that using a lower current for a longer time instead would not be able to recreate this effect because of the heat extraction from the electrodes and surrounding sheet.

In resistance spot welding using a pulsed schedule for the current has long been used to expand the operation window of the process and achieve desired metallurgical results[4]. Tawade et al.[26] used a pre-weld pulse with a higher current level than the main weld pulse when spot welding galvanized AHSS. This expanded the viable current range through early first-pulse vaporization of the Zinc coating and avoidance of late-weld spatter by reducing the continuous weld time that would have been used with an ordinary weld schedule. Lee and Chang[27] used a similar schedule to spot weld sheets of uncoated hot stamped boron steel and found the size of the weld nugget increasing, but also severe softening in the boundary between the FZ and the sub-critical HAZ. This softening due to tempering of the martensite in the material increased with higher currents and also caused a decrease in tensile shear strength of the weld - even with a mode transition from IF to PF and a larger nugget area. It is not certain how these findings would transfer to projection nut welding, where less fusion and higher degrees of plastic flow oc-
Another consideration when using pre-weld pulses in RPW is that an initial bonding of the projection-sheet interface could increase the contact area and thus decrease the achievable current concentration in the subsequent pulses. If the materials are allowed to cool enough between the first pulse and the second one, the same peak temperatures may no longer be reachable.

Post-weld pulse scheduling has also seen use in RSW as a way of tempering the weld. Studies on the effects of a tempering pulse on Q&P1180[28] and DP590[29] steels have shown results with increased cross-tension peak load resistance by 62-70%. The microstructure of the weld nugget went from fully lath martensitic to tempered martensitic and retained austenitic through recovery which gave the observed softening and increased toughness. In both studies, the positive impact from the increase in toughness and weld nugget size trumped the negative impact from the softening on the cross-tension strength of the weld, unlike what Lee and Chang observed when using a pre-pulse on the hot stamped boron steel. This could perhaps be a case of not setting optimal pulse-parameters in that study, or caused by the following main pulse. The best strength achieved through post pulsing was with cooling times between pulses of 1000 ms and 400 ms for the Q&P and DP steels respectively, times which are too long in a practical environment.

Mikno[25] found that using a lower initial force and increasing it over the weld time also was a viable way to achieve more consistent higher strength welds. A hybrid pneumatic and electromechanical force system (PFS, EFS) was what enabled additional control during the weld process, leading to lower cold plastic projection height reduction along with increased contact resistance and concentrating energy in a more favorable area. These hybrid force systems also helped to expand the window of process parameters and reduce the magnitude of initial electrode impact. EFS could help with higher force repeatability, but cannot apply full force as fast as pneumatic force systems can, having a 50-70ms delay. Thus combining these two, he meant, may net a more mechanically sound weld.

What limits the process parameters is essentially too little bonding and inadequate strength on the low end, and excessive expulsion or thread deformation on the high end[2]. A higher current demands a higher force to avoid excessive expulsion and
spatter, but a higher electrode force cannot help avoid thread deformation in the same way. When using a high-current, high-force setup Pavol Sejč et al.[12] noted that even if some expulsion was observed and the weldments became quite severely distorted, a strength more than twice that of one done on low-current low-force settings was achieved. This might indicate that sufficient strength can be achieved even with moderate expulsion, and the process window may be expanded towards higher settings if the thread allows it. Another observation was that the low-current low-force setup failed to evaporate the Zinc of the galvanized sheets and led to an increased Zinc-concentration in the transition area.
The Finite Element Method (FEM) is a procedure to numerically find approximate solutions to the partial differential equations (PDE) describing the behavior of a system. The system is discretized into elements where the PDEs are solved numerically, which makes it possible to come to an approximate solution to very complex systems that would be difficult or impossible to solve analytically. It can be an effective way to save money and time on physical testing, or imagining how a real life system would behave. SORPAS is an FEM-program specifically designed for resistance welding, and exists in both 2D and 3D versions which work in different but similar ways. This section will discuss how the finite element method is implemented in SORPAS, the previous numerical studies that have been conducted on the subject, and which sources of error might be relevant.

3.1 Earlier Simulations

There have been a number of studies and articles published on the simulation of nut projection welding. One of the earliest was in 2010 when Lindén[8] attempted to recreate the experiments conducted by Hedegård and Tolf in SORPAS2D version 9.8, and use the program to optimize the geometry of the weld nut projections.

The experiment was limited to the axisymmetric HP weld nuts, because the program was still limited to the 2D space then. He concluded that it would be difficult to use SORPAS to accurately simulate the behavior and results of the welding process, one source of error mentioned was the exclusion of the Zinc coating on the weld nuts during simulations, as it was deemed too complex to accurately model. SORPAS does have capabilities for adding coatings in the program, what effect such coatings would have in comparison to added computational time, was however not investigated.

The optimization of the projection geometry proved inconclusive as well, with the final optimized geometries standing on equal footing with the original designs. The
optimization was only carried out with respect to the geometry of the projection, no attempts were made at altering the flange thickness or other measurements.

Another attempt at accurately simulating the nut welding process in SORPAS3D was published in 2015 by Nielsen et al.[10] who commented on the complexity of the three-dimensional electro-thermo-mechanical interdependent contact problem that was being modeled. They investigated the frictional conditions of the contact modeling used and surmised that finding and using a correct friction factor during modeling is an important part of producing weld geometries matching practical experiments. They concluded that the simulations could be a helpful tool to reduce the amount of trial-and-error while selecting welding parameters but could still not reliably give results matching those from the experiments.

Using a frictionless contact resulted in excessive sliding near the base of the sheet, giving a larger contact area more rapidly with a concave appearance, while a full stick contact gave a conservative estimate of the area and induced convex barreling. A frictional factor of around 0.80 seemed to best catch the real behavior of the square M10 nut simulated, but ideally a temperature dependent friction factor was suggested to be used if it could be accurately measured.

FEM always predicted more set-down than what was recorded in the experiments, no matter what frictional factor was used. For lower currents frictionless contact gives the largest set-down because of the lesser mechanical resistance, but for higher currents a frictionless contact instead decreases set-down because of the quickly growing area leading to decreased heating. Choosing the optimal friction factor helped in reducing the set-down, closer to the measurements of experiments.

Using a more all-purpose FEM program, ABAQUS, Han et al.[9] also tried simulating projection nut welding intending to optimize the projection geometry of SQ nuts. They employed the Taguchi method to isolate the effects of different parameters, and tried to optimize them by maximizing the set-down (S) and minimizing the time until half set down is reached (t_{set}). The designs optimized this way were remarkably similar to the original M10 design defined by DIN 928. The largest final error in set-down was relatively low, within 12% for an M8 nut - it was within a
scatter of the experimental set-down and was not strictly higher as it was in the simulations of Nielsen et al. [10]

3.2 Formulation of Equations

When simulating the welding process using an FEM approach, several non independent physical processes must be considered. In SORPAS this is done through three separate but closely interlinked modules, considering the mechanical, thermal and electrical sides of the problem. SORPAS is a commercial software, and the specific workings behind its simulations are therefore not publicly known, but in an article written by among others developers behind SORPAS [30] some insight is provided.

3.2.1 Mechanical Module

The mechanical module uses the finite element flow formulation, with the following weak variational form

\[ \int_{V} \bar{\sigma} \delta \dot{\varepsilon} dV + K \int_{V} \dot{\varepsilon}_{ii} \delta \dot{\varepsilon}_{jj} dV - \int_{S_{t}} t_{i} \delta u_{i} dS + \delta \Pi_{C} = 0 \] (5)

Where the first term pertains to the internal energy rate of plastic deformations in the domain, \( V \). Before reaching a vicinity of the yield stress of the material the elements are strictly elastic and only the elastic energy is computed. For projection welds this is generally a small part of the process [30]. The second integral is there to impose incompressibility to the problem, \( \dot{\varepsilon}_{kk} = 0 \). \( K \) is a large positive number proportional to the mean stress according to

\[ K \dot{\varepsilon}_{kk} = 2\sigma_{m} \] (6)

The third term accounts for the work done by the traction over the surface of the domain. The fourth and final term is there to impose a certain type contact mechanics to the problem, further explained later on.
3.2.2 Thermal Module

The thermal module is based on the Galerkin method of heat transfer expressed

$$\int_V k_T \delta T dV + \int_V \rho_m c_m \dot{T} \delta T dV - \int_V \dot{q} \delta T dV - \int_S k_T \delta T dS + \delta \Pi_T = 0$$

(7)

The first addend considers the heat conduction through the volume and the second the rate dependent energy stored due to temperature change, while the third and fourth terms relate to the heat generation or loss rate in the volume and at the surface of the domain respectively. Once again, the final term relates to the contact conditions of the problem.

For the first two terms, the most important constants are the thermal conductivity $k$, the mass density $\rho$ and the heat capacity $c_m$ of the materials. The third and fourth terms are controlled by the different fluxes of heat, $\dot{q}_i$ listed in equations (8).

$$\dot{q}_{\text{plastic}} = \beta \dot{\sigma} \dot{\varepsilon}$$
$$\dot{q}_{\text{electrical}} = \rho \dot{J}^2$$
$$\dot{q}_{\text{convection}} = h(T_s - T_f)$$
$$\dot{q}_{\text{radiation}} = \varepsilon_{\text{emis}} \sigma_{SB} (T_s^4 - T_f^4)$$
$$\dot{q}_{\text{friction}} = \tau_f |v_r|$$

(8)

Here, further important controllable material constants are used: $\beta$ is a constant that describes how much heat is generated from the yielding of the material, $\rho$ is the electrical resistivity. These first two heat fluxes are used in the third term of equation (7), while the latter three are evaluated over the surface in the fourth term. $h$ is the heat transfer coefficient for convection, $\varepsilon_{\text{emis}}$ is a constant of emissivity describing the amount of heat radiated from the surface and $\tau_f$ is the shear stress doing work coupled to friction.
3.2.3 Electrical Module

The current flow is controlled through the differences in the electric potential across the volume and surfaces, the governing equation looks like:

\[
\int_V \Phi_i \delta \Phi_i dV - \int_S \Phi_n dS + \delta \Pi = 0 \tag{9}
\]

Where \( \Phi_i \) are the potential gradients. At the power supply and the free surfaces the gradients are zero, the potential there is the set to \( \Phi_0 \) or 0 respectively. The current density at each point is controlled by the potential gradient and the resistivity as:

\[
J_i = \frac{\Phi_i}{\rho} \tag{10}
\]

The average resistivity at the interface \( \rho_c \) is computed as

\[
\rho_c = \frac{3\sigma_{soft}}{\sigma_n} \left( \frac{\rho_1 + \rho_2}{2} + \gamma \rho_{contaminant} \right) \tag{11}
\]

Here, the fraction between the flow stress of the softer contact material \( \sigma_{soft} \) and the normal pressure \( \sigma_n \) represents the relative size of the contact area; the factor in parentheses is the average contact resistivity with an optional added contaminant resistivity and scaling parameter \( \gamma \).

3.2.4 Contact Considerations

The previously mentioned contact mechanics terms are for enforcing that the elements on either work piece that are in contact with each other behave in a physical way. The first expression below is for penalizing the work pieces penetrating into each other, and the other for penalizing sliding between the workpieces if full stick contact is used.
\[ \delta \Pi_C = P \sum_{c=1}^{N_c} g_n^c \delta g_n^c + P \sum_{c=1}^{N_c} g_t^c \delta g_t^c \]  

(12)

\( g_n^c \) is the normal gap velocity and \( g_t^c \) is the tangential gap velocity. If frictional sliding is used the second term is ignored, and added shear stresses are implemented according to a combination between the Amonton-Coulomb frictional model and the law of constant friction, see equation (13).

\[
\tau_{fAC} = \mu \sigma_n \\
\tau_{fConst} = m k
\]

(13)

Here \( \mu \) is the friction coefficient, \( \sigma_n \) is the compressive stress normal to the surface, \( m \) is the friction factor coupled with the tangential shear flow stress \( k \). In SORPAS the linear relationship \( m = \sqrt{3} \mu \) is assumed, simplifying the frictional shear stresses to be described by a single constant.

The contact terms seen in the thermal and electric modules are there to enforce continuity between the elements in the interface and make certain that the temperature and electric potential are equal on both sides of the interface. They are expanded in equations (14) and (15) - \( P \) is a usually large constant controlling the degree of penalization, observe that the two equations do not share the same value of \( P \).

\[ \delta \Pi_T = P \sum_{c=1}^{N_c} T_d^c \delta T_d^c \]  

(14)

\[ \delta \Pi_\Phi = P \sum_{c=1}^{N_c} \Phi_d^c \delta \Phi_d^c \]  

(15)
3.2.5 Elements

All of these equations are evaluated in SORPAS using hexahedral eight-node elements or four-node quadrilateral elements where each node has up to five degrees of freedom. Two or three for the different normal directions of plastic flow in the mechanical module, one for the scalar field of temperature, and one for the electric potential[25].

3.3 Working in SORPAS

SORPAS is a very specific software, and working with it is often closer to working with a weld timer than conventional FEM programs. This section details the workflow in SORPAS2D and SORPAS3D respectively and aims to provide insight into the possibilities and limitations with the two programs.

3.3.1 Geometry and Mesh

Geometry in SORPAS3D is generated together with the mesh through 6-face cuboid elements, the base element and coordinate menu is shown in Figure 10.

How each cuboid is sub-divided into quadrilateral elements is controlled for each cartesian dimension separately, and can be weighted towards any of the eight corner nodes or to the center between them. When combining base elements to create a model the subdivisions must intersect perfectly between boundaries to achieve continuous shape functions, this complicates building more intricate models. Setting any two corner nodes to the same coordinate to achieve tetrahedral elements or triangular shapes is also not advisable, as these more often cause a diverging solution while under deformation.
In SORPAS2D the geometry is generated largely separate from the mesh. The geometry object is created through a set of points enclosing its shape. A quadrilateral mesh is then generated automatically for all objects. The discretization is defined via a maximum total element count and their relative distribution is controlled through either density control points, or a localized refinement rectangle. Although this does not offer as exact control as the manual method in SORPAS3D it is much faster to use, and the relative densities set by control points make mesh convergence studies much simpler.

3.3.2 Contact Interfaces

The equations for the contact behavior described in Section 3.2 are solved in specific pieces of geometry in SORPAPS called interface objects. An interface is added as a thin solid element layer between any two surfaces in contact, such as the two electrode-workpiece interfaces and the nut-sheet interface. The mesh of the interface object will match the mesh of the object it is attached to, and the resistivity and melt temperature of the interface are taken as an average between the two adjacent objects. How the nut-sheet interface object is attached to the sheet in SORPAS3D can be seen in Figure 11.
The recommended interface thickness is between 5-50 $\mu$m. For RSW a thicker layer is recommended compared to RPW, and if coatings are used a slightly thinner interface may be used.

3.3.3 Material Database

Section 3.2 showed the many constants in control of the numerical solutions. Most of these constants are set under the material library tab, where many preset materials are already available. The parameters that are temperature dependent are interpolated from a number of points set in the material library, illustrated in Figure 12.
Other important material data concerning the microstructure and tendency for hardening and cracking are visible on the right side of the figure. There is data controlling which phases will be present in the material after welding, depending on the temperatures reached and the cooling time from the temperature for martensite and ferrite formation. Also considered are the volume expansion or contraction from phase transformations. The friction factor that will be utilized in the interface depends on the friction factor set for the materials next to it.

The material flow stress depends on both the temperature and viscoelastic- and viscoplastic effects according to a modified Swift model with an added strain rate component. It could be said that at each temperature there is a flow stress surface generated dependent on both the total strain $\varepsilon$ and strain rate $\dot{\varepsilon}$ as

$$\sigma_{\text{flow}}(T, \varepsilon, \dot{\varepsilon}) = C(T) \cdot (\varepsilon + B(T))^n(T) \cdot \dot{\varepsilon}^m(T)$$  \hspace{1cm} (16)
To avoid singularities in areas with very little deformation strain rates under a certain threshold $\dot{\varepsilon} < \dot{\varepsilon}_0$ are instead set to the minimum strain rate value of $\dot{\varepsilon}_0$\cite{30}. This threshold was not found to be adjustable by the user in SORPAS.

The flow stress of the softest material in contact has a proportional effect on the contact resistance used according to equation (11). This means having reliable flow stress data is crucial to achieve reliable contact resistance and therefore Joule heating.

Acquiring enough data for a material to fill the Swift model is likely the biggest challenge for users in adding new materials in SORPAS to use for simulations.

### 3.3.4 Coating Settings

Coatings in SORPAS are added as thin layers of a different material, the object menu is shown in Figure 13.
The thickness is defined before adding the layer. When simulating spot welds in SORPAS2D weight per surface area can be used as an input instead of thickness, which is commonly how coatings are specified in reality.

When using both a coated nut and coated sheet the material properties of the contact will be an average of the two coatings until they are squeezed out initiating at 80% of their melting point and completing at 5% over their melting temperature as a default. These two squeeze-out temperatures can instead be set manually if such data is at hand. Zinc coatings especially, with their low melting point just over 400°C will significantly impact the interface averaged melting point and thus evaluating results such as total melted area.
3.3.5 Machine Control

The prompt for defining the weld programs in SORPAS is very reminiscent of those for real resistance welding machines. The squeeze, weld, hold and off times are set separately. The total weld time is defined through the summation of any number of pulses and their up-slope, weld, down-slope, and cool times. This is shown in Figure 14. The idle time is used in multi-weld processes to use large time stepping for faster cooling simulation.

![Parameters in SORPAS weld settings menu](image)

Figure 14: Parameters in SORPAS weld settings menu

The electrodes can be force controlled, velocity controlled, or mixed. In mixed control mode a force can be deployed in the first step and then the velocity can be set to 0 in the second, emulating locking the electrodes. It is possible to import any recorded current curves into the program.

3.3.6 Simulation Control

The options for the simulation considerations are similar between both the 2D and 3D versions, Figure 15 shows the available settings.
Different modules are available as options for the simulation. The mechanical, thermal and electrical modules are detailed in Section 3.2 and are all essential to the welding process. Aside from those, *Thermal Stresses* considers the expansion and contraction during cooling, *Unloading/Residuals* computes the residual stresses and material relaxation in the Off-time after electrodes are separated, *Elastic Loading* computes elastic deformation during squeeze time, especially in the sheet. Some computations can be avoided by turning off the modules which are not relevant to the particular result that is evaluated. If only the weld nugget size is of interest the residuals will not be essential for example, as they are only computed in the off-time after the weld.

The time stepping must have a set value for each individual process, the processes with steep gradients require the finest time stepping. The time steps for the weld process especially is often set significantly shorter than the other processes, as the heating and yielding are both fast and non-linear. A downside to this method of
time-stepping is that it requires the same time step to be used for both the initial rapid heating and yielding and the consequent slow heating when current density has diminished. This makes for unoptimized simulations time-wise, where even the more linear changes occurring within the weld-time will still use very fine timestepping.

3.3.7 Batch-simulating and Weldability Lobes

SORPAS can run a queue of simulations, a *batch*, which is useful when wanting to vary parameters or run many different simulations with minimum delay. It can also automatically generate weld lobes defined by an interval of electrode force, current, and weld time. Two parameters can be varied in one lobe, and the lobe will declare which weld settings generate a melt or have excessive spatter. An example result is illustrated in the diagram in Figure 16.

Figure 16: 2D Weldability lobe over current and force, filled black boxes signifies melt and red triangles high likelihood of spatter
3.4 Sources of Discrepancy

A number of things can be observed mutually across the three studies summarized in Section 3.1 which can be cause for discrepancies between the results observed through simulation and through practical experiments.

3.4.1 Current History

The current used in the simulations held a constant value with either an ideal infinite up-slope, or with small ramp-ups and ramp-downs. In some cases this could closely resemble the real curve but in other cases, if trigger angle control was used or the machines current rise time was limited for example, the resemblance might be further off. Both SORPAS and ABAQUS can import real measured current curves, more representative of the machine being used experimentally. Using idealized curves could be a source of error in the results, even if the average current is the same over the process, chiefly because of the heat extraction of the electrodes. The difference between the input current and a recorded history is shown in Figure 17.

![Figure 17: Current measurement over a weld program plotted over the ideal current curve](image)

Figure 17: Current measurement over a weld program plotted over the ideal current curve
When simulating, the error for simpler programs can be minimized by using slopes to take after a measured or predicted curve, as seen in Figure 18.

Figure 18: Current measurement over a weld program plotted over an adjusted ideal current curve

### 3.4.2 Electrode Force History

The same thing said regarding true current values can be said for the electrode force values as well, however the force is often less variable than the current, especially if the machine has enough follow-up and is lighter. A simple program used by Nielsen et al.[10] in their simulation for example closely resembled the history that was later measured from the machine.

### 3.4.3 Weld Strength

Another issue could stem from the fact that only the geometry has been used as reference for the deviation from practical experiments. The point of interest of the welds in the end is their strength, and as pointed out in Section 2 the geometry measurements may not always be indicative of that - integrating a simulation of strength into the numerical study would perhaps seem more compelling then. This
would however increase simulation time, and the resulting strength would still be decided by the preceding simulated weld process.

### 3.4.4 Material Constants and Coatings

As seen in Section 3.2 there are numerous material parameters to consider, many of which are variable under temperature or are rate dependent. If these do not resemble their true counter-parts the simulated result will deviate from experiments, even if the model is sound. SORPAS has a built in material library where these parameters are preset, but editable. In his Master’s thesis, David Löveborn\[31\] used SORPAS to simulate spot welds, and applied other software such as ThermoCalc and IDS to compute the temperature dependent thermal and electrical conductivity values to compare their results with the built in ones. He found that the values for resistivity and conductivity followed closely enough that using the built in values from the SORPAS library was unlikely to markedly change the simulation results compared to using the values generated by other more specialized software. There was, however, a difference between the flow stress curves for materials in the SORPAS library and those he found in literature. These types of dissimilarities should be considered before simulating if possible.

The feature SORPAS has for coatings can generate a thin layer of material around a work piece, for example a Zinc or AlSi coating. This layer would contribute with separate material parameters from the work piece under it, and would then be "squeezed out" or removed after a certain temperature is reached. This behavior however will not capture the additional metallurgical phenomena discussed in Section 2.4 and 2.6 where diffusion of coating elements into the weld or base material occurs, and some coating elements can remain and oxidize in the faying surface. Because of how closely linked this problem is with the failure of the weld and how much of any given bond area is load bearing, it is likely one of the largest sources of errors that must be considered when simulating coated materials.
3.4.5 Tool and Material Inconsistencies

In a real production environment tools wear over time, and work pieces can differ both in shape and material properties. Because electrodes and die are used over a span of time before they are changed, hot forming- and weld results will not remain the same over the tool lifetimes. This raises the question of which result to aim for when attempting to accurately simulate the nut welds - the results from a work piece formed in a new die and welded with a new electrode, or some average weld result measured over longer periods of time.

Described in Section 2.4 was the time-under-temperature dependent nature of the interdiffusion layer in the coating. If production is stopped for any reason sheets can be in the furnace for extended lengths of time, and the interdiffusion layer will grow. Some stoppage in production is generally unavoidable, so limits are set for how long the dwell time in the furnace can become before the sheets need to be discarded. Within that allowed interval the sheets with the longer dwell times will have lower weldability[18], another issue which would need to be averaged when validating.
4 Methodology

This section will describe how the process of simulating and validating will be done and what considerations will be made for both the 2D and 3D cases.

4.1 Materials

The UHSS this thesis will focus on is coated boron steel - sheets of USIBOR1500P AS150, which is a 22MnB5 steel. USIBOR1500P AS150 has an AlSi coating at 60-100 g/m$^2$ and a minimum thickness of 20 µm. USIBOR1500 is available in the SORPAS material library and is used for the sheets, and they then have an additional Al-Si coating added on top of it - also available in the SORPAS material library.

Only HP and SQ nuts will be used. Both nuts are Zinc-coated and made from some carbon steel, all material properties are not known however, and assumptions will be made within SORPAS for the unavailable data. The HP nuts have M6 threads, while the SQ nuts have 8 mm unthreaded holes meant for M8 bolts. The nuts are cold drawn, and therefore approximated as a cold-forming BH260 steel from the SORPAS library. The weld nuts can be seen in Figure 19.
4.2 Validations

Foremost, two types of validating is done for the simulations - geometric and mechanical. The set-down and melt between sheet and nut are measured and compared between the numerical solutions and the practical experiments. In SORPAS2D this is done directly by measuring the final gap in the cross-section, and in SORPAS3D the quarter-model is bisected across its diagonal and the cross-section inspected from there. Experimentally the welded nuts are cut, polished (320-800-1200-2400-4000 grit) and etched with a Picric acid based etchant (4 g picrid acid, 1.6 g copper chloride, 0.5 ml Agepon, 100 ml distilled water) for five seconds at room temperature.

The resistance to normal loading of the welds is also compared. In SORPAS2D this is evaluated as cross-tension strength within the weld lobe functionality, and in SORPAS3D a strength testing module is used, displacement controlled at 0.2 mm/s. Experimentally, push-out tests are performed according to Figure 20 with a constant crosshead displacement of 2 mm/min and sampling frequency of 7 Hz for the unthreaded SQ nuts. For the HP-nuts a similar test is done, but an M6 bolt is screwed into the nut and the displacement is then applied to the head of the
bolt. The faster displacement numerically is used to reduce simulation time, but is still assumed to be slow enough that rate-dependent phenomena do not markedly change results.

![Figure 20: Diagram of the push-out strength test setup](image)

For each validation attempt, four nuts will be welded and their respective results averaged. Although a larger number would give more statistically relevant results, the cost of strength testing and time-consuming nature of material test preparation prohibited this.

Because of how integral resistance is to Joule heating, reference measurements are also taken during the experimental welds. The measurements are taken over the entire weld machine, then a measurement without work pieces mounted is subtracted from those total measurements to isolate the resistance over the sheet and nut.
4.3 Equipment

The weld machine is a NIMAK BMP-6-2/100MF (2004) with 1000Hz MFDC and a 100 kVA transformer (20%). The machine is rated at 30 kA circuit current and 12kN electrode force. It uses a Matuschek Auto SPATZ M600 inverter controlled through a PC running Matuschek SPATZ AS-01.

When welding HP-nuts the machine is mounted with a hollow top electrode to give room for the hat of the HP-nut and more directly apply force to its projection, while the top electrode is flat when welding SQ nuts. The bottom electrode for both nut types is flat and has a guiding pin resting on a spring attached to help center the nuts. Both electrodes are water cooled at a rate of 4 l/min. The two setups are pictured in Figure 21.

Figure 21: The two electrode pairs used for the HP (right) and SQ nuts (left)
External measurements of current, voltage and resistance are taken on a Matuschek SPATZ MULTI-04 and imported to a computer via SPATZ-PC. The measurement equipment itself has a maximum inaccuracy of around 10%.

The simulations are done on a system running Windows 10 with an Intel Core i7-6700 CPU @3.40 GHz, a NVIDIA GeForce GTX 750 Ti graphics card and 16 GB RAM.

A Servo-hydraulic MTS testing machine equipped with a 50 kN load cell will be used for strength testing controlled with the software MultiPurpose Testware (MPT).

4.4 Software and Models

SORPAS2D version 14.6 and SORPAS3D version 6.6 will be used with geometries created to resemble the real life nuts and sheets as closely as possible.

4.4.1 SORPAS2D, HP-nut

SORPAS2D is used to simulate the HP nuts under an assumption of their rotational symmetry, the cross-sectional model drawn in SORPAS is shown in Figure 22.
Because of the hollow upper electrode and its slight curvature the contact area between the top electrode and nut can be observed to be quite small, but almost immediately over the projection. The cyan areas inside of each electrode represents the area that is water cooled. The cooling rate is set to 4 l/min, matching the practical flow.

A mesh convergence study is made to decide how fine the discretization used in the experiments will be. Figure 23 shows the meshes at different demanded element counts, and Figure 24 shows how the results converges and computation times increases with finer discretization.
4 METHODOLOGY

Figure 23: Increasing total maximum element count in the model

(a) 1000 total elements
(b) 2500 total elements
(c) 4100 total elements
(d) 5900 total elements

Figure 24: Mesh convergence study showing maximum weld nugget width in the sheet on the left y-axis and computation time on the right y-axis
Looking at the mesh convergence, a maximum element count of 3500 will be set for
the numerical studies using the model.

For the validating simulations every available module will be used and enough off-
time is used to completely cool the weld. The time stepping follows a $1 - 0.2 - 1 - 10$
regime where the squeeze time and hold time will compute every millisecond and
the weld time five times every millisecond. The cooling during the off-time is seen
as slow enough that one computation every tenth millisecond suffices. Following
this, the 2D simulations take 2-5 hours to finish, depending on the maximum tem-
perature reached.

4.4.2 SORPAS3D, SQ nut

SORPAS3D must be used to simulate the SQ nuts because of their shape, but only
one quarter of the nuts need to be modeled due to its symmetry. The model cre-
ated in SORPAS3D is shown in Figure 25. Some details are left out when com-
pared to the real nuts, but the most important factors such as the weld nut height
and projection geometry are a good match.
Another mesh convergence study is made for the 3D case to find mesh independence. As a consequence of how the mesh is generated, described in Section 3.3, only the nut is refined while the sheet is kept at a constant relatively fine mesh. The thought behind refining the mesh of the nut is that the deformation and melt of the projection reduces its mesh density over time, and that the increase in contact area caused by the projection deformation strongly affects the current density. The sheet experiences much less deformation and its mesh does not equally affect the current density fall-off.

Figure 26 shows the meshes at different asked for element counts, and Figure 27 shows how the results converges and computational time increases with finer discretization.
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(a) 510 nut elements
(b) 1320 nut elements
(c) 2674 nut elements
(d) 5104 nut elements

Figure 26: Increasingly fine discretization of the nut on a constant-mesh sheet

Figure 27: Mesh convergence study showing melted area in the nut-sheet interface on the left y-axis and computation time on the right y-axis
The graph cannot be said to conclusively give an element count after which the result is converged, but further refinement is not deemed feasible due to the extending simulation time. More advanced programs can more than double the basic simulation time illustrated in orange, and simulations of that length would not be attractive to work with. Looking at the final nuts, a mesh with around 4000 elements was chosen for further validation.

In both the 2D and 3D simulations, but especially the 3D ones, programs using a higher current for a shorter amount of time will be used to minimize time consuming simulations because of the fine time-stepping mentioned in Section 3.3. This is not seen as a big limitation, since those types of programs were observed to also be able to give sufficiently strong welds in the literature study done in Section 2. It does however mean that primarily one-pulse programs without ramp-downs will be validated. The weld programs are further presented in Section 4.5.

In the weld simulation all available modules are used, and the same time-stepping regime that was described in the 2D-section. These simulations then take 24-32 hours to finish on the listed hardware, depending on the maximum temperature reached and if strength testing follows the welding.

Four different iterations of both the 2D and 3D CS simulations are done in SOR-PAS. The default values for the friction coefficient of the materials \( m = 0.3 \) is compared to the optimal friction factor for likeness according to literature \( m = 0.8 \). For both of these friction factors one simulation with default contaminant contact resistance \( \gamma = 1 \) and one with a \textit{dirty} contact surface \( \gamma = 5 \) are conducted.

The simulated 3D push-out test does not perfectly match the experimental one, because the elements to apply displacement to can only be chosen by defining a selection cuboid with intervals and not something curved. The simulated strength test instead had its displacement applied to the entire top surface of the nut, fixing the bottom surface of the sheet. For this reason only the maximum force is looked at, since force over displacement curves would not be comparable. In both SOR-PAS2D and SORPAS3D every available module is active, and high friction (\( m=0.8 \)) and normal surface resistance (\( \gamma = 1 \)) is used.
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4.5 Weld Programs

The exact weld programs used are not seen as essential for the validation as long as the settings used match for both the numerical and experimental work. The programs used are still considered to have a reasonable similarity to those used in production.

Because melt is validated for, it is desirable to have a range of programs that covers samples both with and without reaching melt. Achieving melt for RPW is however not entirely straightforward, as outlined in Section 2, which complicates finding a weld current high enough the generate it without causing spatter. The upper limit of current and weld time was in practice set by when there was an overhanging risk of workpieces sticking to- or damaging the electrodes.

One occurrence of such damage can be seen in Figure 28. Material from the sheet becomes embedded in the electrode and causes a spot of uneven resistivity which gives noticeable results on following welds. The underside of sheets with SQ nuts welded to them after the embedding are pictured.

Figure 28: A spot of different metal attached to an electrode after an earlier expulsion causing inhomogeneous resistivity on its surface and affecting weld heating

When validating against the push-out strength (PO) instead of the cross-section melt (CS) the weld programs used higher forces in general to suppress expulsion,
since no attempt at seeing the melt would be made. The CS programs will be used
when measuring the set-down. The different variations used are detailed in Table 2.

<table>
<thead>
<tr>
<th>Program</th>
<th>Force [kN]</th>
<th>Current [kA]</th>
<th>Weld time [ms]</th>
<th>Hold time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP Nut (CS)</td>
<td>8</td>
<td>16, 18, 20</td>
<td>100</td>
<td>90</td>
</tr>
<tr>
<td>HP Nut (PO)</td>
<td>8, 9</td>
<td>16, 18, 20</td>
<td>100</td>
<td>90</td>
</tr>
<tr>
<td>SQ Nut (CS)</td>
<td>7</td>
<td>16, 18, 20</td>
<td>110</td>
<td>90</td>
</tr>
<tr>
<td>SQ Nut (PO)</td>
<td>9</td>
<td>18, 20, 22</td>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 2: Weld programs run for different validations

Slight alterations were made to the program when moving it to the numerical
frame. The practical squeeze time was 300ms to ensure no dynamic effects were
still present in the work pieces after initial electrode contact, whereas no such ef-
ficts exist in SORPAS. Following the SORPAS2D manual, squeeze times can be
significantly shorter in simulation for this reason, and thus only 60ms was used.
Another change made was to the slopes of the force and currents used when simu-
lating. To better match the measured current histories like observed in Section 3.4
a 10ms ramp-up and 2ms ramp-down was added to the current in SORPAS. These
changes are illustrated for the SQ nuts (CS) in Figure 29.
Figure 29: Weld current and electrode force for the SQ Nut (CS). Force on the left and current on the right with the three different levels of current included
5 RESULTS

5 Results

This section will describe the results of the attempts at validating SORPAS simulations according to Section 4. A representative set of results is presented, the complete results can be seen in the Appendix.

5.1 Cross-section

One pair of cross-sections each for two levels of current, 16 kA and 20 kA, is shown in Figure 30 and Figure 31 respectively.

Figure 30: A set of cross-sections of an HP nut weld at 16 kA
5 RESULTS

Figure 31: A set of cross-sections of an HP nut weld at 20 kA

There is no melt evident at all in the microstructure, this was the case for all sets of HP nuts welded at all three current levels. The projections are only partially collapsed, even for the 20 kA welds, and no large expulsions are visible. The two opposing projections are similarly sized, indicating an even distribution of the electrode force, but some differences in size can be seen. The two bottom leads of the threads are either melted or deformed for all current levels, but no issue was found inserting a matching bolt.

These real cross-sections is compared with simulation results running the same settings, presented in Figure 32 and Figure 33. The friction factor and resistance from contaminants are varied.
Figure 32: Appearance of the four simulation scenarios for an HP nut weld, 16 kA
Three out of the four results look very similar geometrically, with only the high friction, dirty contact case showing a distinct appearance. This case seems to achieve a significantly higher degree of heating, as evidenced by the clear melt seen in the 20 kA case. There was also melt observed for the same case at 18 kA. No melt was achieved experimentally at either of these current levels, perhaps indicating that a lower friction factor or contact resistance would be preferable.

As a reference on the cross-sections appearance, the simulations can be overlayed the experimental results. The semblance of the nut and projection is compared in Figure 34.
(a) 16 kA Weld current  
(b) 20 kA Weld current

Figure 34: Appearance comparison of the $m = 0.3$, $\gamma = 5$ simulation for two HP weld nuts

The general match here can be said to acceptable, although there was no melt to compare to. The general mismatch seems to be a consequence of the nuts having some mobility around the centering pin, not being perfectly aligned around the center of the in the sheet.

The same type of results are also observed for the SQ nuts, comparing them to SORPAS3D. Two sets of cross-sections are illustrated in Figure 35 and Figure 36 using 16 kA and 20 kA respectively.
The projection shape is stochastic and deformed after the weld. Here, melt is consistently achieved for all three levels of current. Another striking feature of the welds are the voids found inside the melt, sometimes taking up a considerable part
of the total melt diameter. Both the diameter of the melt and the voids are marked out and measured. The fact that the voids often only occur on one of the two projections is likely a sign of the electrodes not being quite parallel, and the nut not being mounted perfectly centered. The size of the melt does not seem to affect whether or not there is a cavity.

Comparing these images to the simulations in the figures below, the contrast is quite stark.

Figure 37: Appearance of the four simulation scenarios for an HP nut weld, 16kA
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No melt is achieved in any simulations, not even the high friction dirty contact which had the highest heat generated for the 2D cases. The appearance of the deformed projection is also much more continuous, not having the same ”feet” sticking out from the side that the experimental nuts have. Finally, the voids seen are not found possible to achieve in SORPAS, since it would require the separation of the mesh. Note that the gaps seen in some simulation results seems to be a visual artifact from cutting through the middle of an element when inspecting.

The appearance of the simulations are again overlayed a 20 kA welded nut, see Figure 39.
Here, the difference in geometry between the collapsed projections is clear. The melt for this particular nut was circled for clarity, looking at which it seems the location of the highest generated heat is different between simulation and reality. The simulation seems to consistently assume that the melt will be centered right in the interface and have an elliptical appearance, while the real melt extends further downward into the sheet and has a more square-like appearance. This agrees with the findings of Kim et al. [7] and Vijayan et al. [20] described in Section 2.4.2.

The voids observed in the SQ cross-sections are assumed to be shrinkage cavities. These cavities emerge when the melt begins to solidify and the areas that cool first will contract and pull the rest of the melt towards it, leaving an empty spot in the final point to solidify. Applying enough force on the melt is a possible way to counteract this, but it is likely that the solid state material surrounding the melt will receive most of that load, making it difficult to direct the force to the melt specifically.
Another suggestion at first was that these cavities were caused or intensified by the melted coatings. To control for this a cross-section for an uncoated SQ nut and Docol Boron02 sheet was inspected, seen in Figure 40.

Figure 40: A reference simulation without any coating still showing cavities in the cross-section

The same phenomenon is still plainly visible for this case, lending more credence to the shrinkage cavity assumption.

### 5.2 Set-down

The measured and simulated set-down results are presented in Tables 3 through 6. The average set-down of the four nuts welded is presented, as well as the results standard deviation normalized against their average.
5 RESULTS

<table>
<thead>
<tr>
<th>Current</th>
<th>Average set-down</th>
<th>Relative standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>55.00%</td>
<td>7.36%</td>
</tr>
<tr>
<td>18kA</td>
<td>65.38%</td>
<td>4.07%</td>
</tr>
<tr>
<td>20kA</td>
<td>75.38%</td>
<td>3.73%</td>
</tr>
</tbody>
</table>

Table 3: HP nut set-down from experiments with an 8 kN force

<table>
<thead>
<tr>
<th>Current</th>
<th>( m = 0.3, \gamma = 1 )</th>
<th>( m = 0.3, \gamma = 5 )</th>
<th>( m = 0.8, \gamma = 1 )</th>
<th>( m = 0.8, \gamma = 5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>43.65%</td>
<td>49.18%</td>
<td>46.07%</td>
<td>62.18%</td>
</tr>
<tr>
<td>18kA</td>
<td>50.27%</td>
<td>57.97%</td>
<td>55.41%</td>
<td>67.16%</td>
</tr>
<tr>
<td>20kA</td>
<td>58.98%</td>
<td>65.05%</td>
<td>62.49%</td>
<td>73.38%</td>
</tr>
</tbody>
</table>

Table 4: HP nut set-down from simulations with an 8 kN force

<table>
<thead>
<tr>
<th>Current</th>
<th>Average set-down</th>
<th>Relative standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>88.25%</td>
<td>4.66%</td>
</tr>
<tr>
<td>18kA</td>
<td>93.50%</td>
<td>4.14%</td>
</tr>
<tr>
<td>20kA</td>
<td>96.25%</td>
<td>2.73%</td>
</tr>
</tbody>
</table>

Table 5: SQ nut set-down from experiments with a 7 kN electrode force

<table>
<thead>
<tr>
<th>Current</th>
<th>( m = 0.3, \gamma = 1 )</th>
<th>( m = 0.3, \gamma = 5 )</th>
<th>( m = 0.8, \gamma = 1 )</th>
<th>( m = 0.8, \gamma = 5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>84.70%</td>
<td>86.10%</td>
<td>84.70%</td>
<td>86.30%</td>
</tr>
<tr>
<td>18kA</td>
<td>96.10%</td>
<td>97.00%</td>
<td>96.10%</td>
<td>97.00%</td>
</tr>
<tr>
<td>20kA</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 6: SQ nut set-down from simulations with a 7 kN electrode force

The set-down expectedly increases with the current, while the relative standard deviation goes down. The set-down of the simulated nuts can be said to be relatively close to that of the real ones on average, but no settings find a close match for both nuts and all current levels. The best match is different for different current levels,
and the best overall match across all current levels is the high friction, dirty contact case for the HP case but the low friction, dirty contact for the SQ nuts.

5.3 Push-out Strength

The strength of the weld can be said to be the most important result to validate, inappropriately then, this is also where the largest discrepancies exist. The experimental results are listed in Tables 7 through 10.

<table>
<thead>
<tr>
<th>Current</th>
<th>Average strength</th>
<th>Relative standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>832N</td>
<td>49%</td>
</tr>
<tr>
<td>18kA</td>
<td>1647N</td>
<td>8%</td>
</tr>
<tr>
<td>20kA</td>
<td>2319N</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 7: HP nut push-out strength from experiments with an 8 kN electrode force

<table>
<thead>
<tr>
<th>Current</th>
<th>Average strength</th>
<th>Relative standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>198N</td>
<td>114%</td>
</tr>
<tr>
<td>18kA</td>
<td>1732N</td>
<td>9%</td>
</tr>
<tr>
<td>20kA</td>
<td>1946N</td>
<td>28%</td>
</tr>
</tbody>
</table>

Table 8: HP nut push-out strength from experiments with a 9 kN electrode force

<table>
<thead>
<tr>
<th>Current</th>
<th>Average strength</th>
<th>Relative standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>18kA</td>
<td>2919N</td>
<td>19%</td>
</tr>
<tr>
<td>20kA</td>
<td>4979N</td>
<td>11%</td>
</tr>
<tr>
<td>22kA</td>
<td>6501N</td>
<td>9%</td>
</tr>
</tbody>
</table>

Table 9: SQ nut push-out strength from experiments

Just like with the set-down, strength generally increases and spread decreases with higher currents. Using 9 kN of electrode force rather than 8 kN decreased the
strength of the weld for these currents, and substantially increased the standard deviation of the set. Overall the strengths can be said to be low, even the stronger SQ nut welds are still quite weak. This is a consequence of spatter limiting the maximum current, and simulation time limiting the maximum weld time.

Unfortunately no validation can be made in SORPAS2D for the HP nuts, as no way was found for the weld lobe functionality to give cross-shear tension strength when no melt had occurred. The strength does not appear to take solid state bonding into account, even though that module was activated. SORPAS3D can produce a strength test on the other hand, the results of which is presented in Table 10.

<table>
<thead>
<tr>
<th>Current</th>
<th>Maximum strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>18kA</td>
<td>22220N</td>
</tr>
<tr>
<td>20kA</td>
<td>24638N</td>
</tr>
<tr>
<td>22kA</td>
<td>26020N</td>
</tr>
</tbody>
</table>

Table 10: SQ nut push-out strength from simulations with a 9 kN electrode force

The simulated strength is overly exaggerated, and that is for weld programs where no melt has been achieved in the cross-section - despite it seeming likely to exist in the real welds, from the results in Section 5.1. This means that SORPAS overestimates the strength of the solid state bonding achieved, while simultaneously underestimating the amount of heating achieved during welding. It is not strange that the largest difference between experiments and simulations was for the strength tests, as they build upon the earlier weld simulations and therefore compound on any faults in those processes.

## 5.4 Resistance

Comparing the logged resistances between real and simulated welds can show what some sources of errors may be. Resistance measured when welding an SQ nut over 110 ms with 20 kA is compared to the total resistance for the same weld in SORPAS3D in Figure 41.
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Figure 41: Resistance over the nut and sheet over the weld time comparing an experiment to SORPAS3D

It is clear that both the maximum resistance reached, and when that occurs during the weld time differ significantly between the experiment and simulation. The effect of adding a dirtier contact to this simulation is explored in Figure 42.

Figure 42: Comparison of the SORPAS3D resistance curve with the default versus dirty contact resistance ($\gamma = 1, \gamma = 5$)
This shows that, because the maximum resistance does not occur immediately, changing $\gamma$ does not change the maximum resistance reached. When removing the coating from the model this issue stops occurring, see Figure 43 of two simulations done of the same process in SORPAS2D.

Figure 43: Comparison of the resistance curves for a coated and uncoated simulation in SORPAS2D

This shows that the effect of coatings in SORPAS with the settings used changes the resistance history in a way that is not representative of what happens when welding coated materials experimentally. The uncoated simulations are a better match resistance-wise to the experiments than the coated simulations are. If the maximum resistance reached is in the beginning of the weld time, as seen in the right figure, it can be better controlled through variation of the contaminant contact resistance.
6 Discussion

Very few conclusions could be drawn from the cross-sections of HP-nuts. This was largely because a weld program that would produce melt was not achieved experimentally. Increasing the current beyond 20 kA for the nuts used caused weld splash and the work pieces to stick to the electrodes, which is the reason it was not done. If a higher cooling rate than 4 l/min was used perhaps more options would be available.

Because of where the push-out test displacement was simulated, a lesser bending moment was likely experienced by the simulated welds than the real ones. The push-out tool used in experiments applies a displacement around the nut hole causing a larger bending moment to affect the inner edge of the welds as compared to when a surface displacement is applied to the top of the nut in simulations. This can explain some of the difference observed between the two.

Another factor affecting the strength test is uneven contact between the four projections. In an experimental frame it is very hard to achieve perfectly even contact when more than three projections are used, leaving some weaker than others. In the real push-out tests the weakest projection fails first, increasing the load on the other three - in other words the weakest projection controls the strength of the nut weld. This variation is an intrinsic part of projection nut welding, and part of what makes simulating the weld strength difficult.

The delayed maximum resistance in simulations seems to be caused the squeeze-out mechanic of the coatings in SORPAS. Before reaching the squeeze-out temperature of the Zn- and AlSi coatings respectively the resistance in the weld interface depends on the resistance of those two materials and their flow stress curves, all of which are lower than the respective values for the steels. This causes the response in the initial stages of the weld time where resistance is supposed to be the largest to be muted because the coatings are not yet squeezed out; once they are the second peak happens.
The problems with the coatings could likely be minimized by reducing their squeeze out temperatures, or removing them completely. Another option would be to create a new material in the library which behaves like the coating at low temperatures but like the sheet material at high temperatures, manually controlling the change in resistance. Had this been investigated in advance, maybe a better model for matching the resistance curves between simulations and reality could have been used for all remaining tests.

If using the coating feature in SORPAS was found not to work, another method of work would be simulating welds without any coating, and experimentally attempt to find some reduction factor in strength or weld nugget width which could account for the differences in results. If such a connection could be found weld planning using FEM may be more achievable.

The main issue experienced when using SORPAS as a tool for predicting nut welds to coated steels is that some settings benefit certain validations but are detrimental to others. The contact settings that give the most accurate set-down for some nuts do not do so for other nuts, and the settings that give the closest match in appearance are also different to the ones that give the most accurate set-down. No melt was achieved in simulation but the welds were still much stronger than the real ones, which leaves one wondering whether to increase or decrease the current for example. It could be that this no longer is the case when the previously listed issues with the model are sorted out, as SORPAS has been found to work well previously for resistance spot welds in particular.

Although no means of validation in this thesis gave positive results, it is too early to categorically say that SORPAS cannot be used to predict projection nut welds to coated higher strength steels. All simulations run built upon the material parameters set for the USIBOR1500 and Zn- and AlSi coatings, which means that issues in the results may stem from issues in the material parameters. Other sources of error that could be varied further are the chosen coating- and interface thickness and electrode cooling. In the end it is not feasible to tune every parameter to make the simulation work, so a majority of default values should be serviceable if simulation work is to be relevant in prediction and weld planning. Using only a few material
combinations in a large volume of simulations would be ideal if material parameters are to be validated before simulating.

The effects of the shrinkage cavities were not investigated, and no literature on the topic for projection nut welding was found. Some cavities can grow large, taking up a good portion of the melt, at which point it would feel unlikely that it would have no effect on the mechanical properties of the weld. It seems likely these cavities could serve as initiation points for fatigue cracks.

Something to consider when observing the sheets that the nuts were pushed out from is that some of the indentations that look like the result of a plug failure may instead be the bottom side of a shrinkage cavity. It is thus important to inspect both the nut and sheet to see if there is a matching plug opposing the hole found, or instead another hole. Because of the low sample size of nuts in this study, no conclusion was drawn on the correlation between type of failure and push-out strength.
7 Conclusions

- Higher strength steels are more difficult to use in RPW because their significant hardening and higher resistivity reduces the process window that can give strong welds.

- The effect coatings has on weld result can be said to be mainly metallurgical, with diffusion and oxidation causing weak bonding between nut and sheet and segregation limiting weld nugget expansion. This along with spatter during the process further limits the available process window.

- SORPAS is easy to use as a simulation program and easy to understand for someone with experience in resistance welding. It has a large material database and possible result evaluations, but is limited in its model building and simulation time-stepping customization.

- SORPAS was not found to be able to predict the resistance characteristics or results of projection nut welds to AlSi-coated USIBOR1500 steel without changes to default material parameters. The biggest issue was the delaying effect the coating layer had on the peak resistance, something not observed experimentally. The intrinsic variability of projection nut welding is also a difficult thing to simulate, where real welds seldom have equally strong bonds in every projection.

- Better results are likely possible after ensuring the properties of the materials used and accounting for the metallurgical effects of the coating in some other way, such as a reduction factor for strength or weld nugget width.
References


REFERENCES


Appendix

Cross-sections

16 kA HP Nuts

(a) $m = 0.3$, $\gamma = 1$

(b) $m = 0.3$, $\gamma = 5$

(c) $m = 0.8$, $\gamma = 1$

(d) $m = 0.8$, $\gamma = 5$

Figure 44: Appearance of the four simulation scenarios for an HP nut weld at 16 kA
A) Note: the wave-like patterns are the result of the etchant running, not structural

B)

C)

D) Note: Slight differences in coloration is caused by small differences in etch time

Figure 45: Appearance of the four welds of HP nuts at 16 kA
Figure 46: Appearance of the four simulation scenarios for an HP nut weld at 18 kA
A) Note: The yellow cloud-like pattern close to the bottom sheet is dissolved marker ink, the yellow hue in the threads is from the etchant leaking in slightly through the mounting.

B)

C) Note: The white larger scratches are mistakes from the tip of the acetone bottle touching the metal when rinsing.

D)

Figure 47: Appearance of the four welds of HP nuts at 18 kA
20 kA HP Nuts

(a) $m = 0.3$. $\gamma = 1$

(b) $m = 0.3$. $\gamma = 5$

(c) $m = 0.8$. $\gamma = 1$

(d) $m = 0.8$. $\gamma = 5$

Figure 48: Appearance of the four simulation scenarios for an HP nut weld at 20 kA
Figure 49: Appearance of the four welds of HP nuts at 20 kA
Figure 50: Appearance of the four simulation scenarios for an SQ nut weld at 16kA
B) Note: Clear miss of the center of the nut after cutting too close and over-polishing. Importance of doing several identical tests

D) Note: A cracked mounting resulting in etchant getting stuck inside, makes over-etching and achieving unclear results easier, but results can still be seen

Figure 51: Appearance of the four welds of SQ nuts at 16 kA
18 kA SQ Nuts

(a) $m = 0.3$. $\gamma = 1$

(b) $m = 0.3$. $\gamma = 5$

(c) $m = 0.8$. $\gamma = 1$

(d) $m = 0.8$. $\gamma = 5$

Figure 52: Appearance of the four simulation scenarios for an SQ nut weld at 18kA
A) Note: Very large void

B)

C)

D)

Figure 53: Appearance of the four welds of SQ nuts at 18 kA
20 kA SQ Nuts

(a) $m = 0.3. \gamma = 1$    (b) $m = 0.3. \gamma = 5$

(c) $m = 0.8. \gamma = 1$    (d) $m = 0.8. \gamma = 5$

Figure 54: Appearance of the four simulation scenarios for an SQ nut weld at 20kA
A) Note: The rings outside some shrinkage cavities are from excessive etchant flowing up from the cavity when rinsing and drying.

Figure 55: Appearance of the four welds of SQ nuts at 20 kA
Set-down

HP Nuts

<table>
<thead>
<tr>
<th>Current</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Avg</th>
<th>St.Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>91%</td>
<td>87%</td>
<td>83%</td>
<td>92%</td>
<td>88.25%</td>
<td>4.66%</td>
</tr>
<tr>
<td>18kA</td>
<td>95%</td>
<td>98%</td>
<td>92%</td>
<td>89%</td>
<td>93.50%</td>
<td>4.14%</td>
</tr>
<tr>
<td>20kA</td>
<td>99%</td>
<td>94%</td>
<td>98%</td>
<td>94%</td>
<td>96.25%</td>
<td>2.73%</td>
</tr>
</tbody>
</table>

Table 11: HP nut set-down % of the four welds for each current level

<table>
<thead>
<tr>
<th>Current</th>
<th>( m = 0.3 ), ( \gamma = 1 )</th>
<th>( m = 0.3, \gamma = 5 )</th>
<th>( m = 0.8, \gamma = 1 )</th>
<th>( m = 0.8, \gamma = 5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>43.65%</td>
<td>49.18%</td>
<td>46.07%</td>
<td>62.18%</td>
</tr>
<tr>
<td>18kA</td>
<td>50.27%</td>
<td>57.97%</td>
<td>55.41%</td>
<td>67.16%</td>
</tr>
<tr>
<td>20kA</td>
<td>58.98%</td>
<td>65.05%</td>
<td>62.49 %</td>
<td>73.38%</td>
</tr>
</tbody>
</table>

Table 12: HP nut set-down % in the four simulation scenarios for each current level

SQ Nuts

<table>
<thead>
<tr>
<th>Current</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Avg</th>
<th>St.Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>56.92%</td>
<td>55.38%</td>
<td>58.46%</td>
<td>49.23%</td>
<td>55.00%</td>
<td>7.36%</td>
</tr>
<tr>
<td>18kA</td>
<td>66.15%</td>
<td>61.54%</td>
<td>66.15%</td>
<td>67.69%</td>
<td>65.38%</td>
<td>4.08%</td>
</tr>
<tr>
<td>20kA</td>
<td>73.85%</td>
<td>78.46%</td>
<td>76.92%</td>
<td>72.31%</td>
<td>75.38%</td>
<td>3.73%</td>
</tr>
</tbody>
</table>

Table 13: SQ nut set-down % of the four welds for each current level

<table>
<thead>
<tr>
<th>Current</th>
<th>( m = 0.3, \gamma = 1 )</th>
<th>( m = 0.3, \gamma = 5 )</th>
<th>( m = 0.8, \gamma = 1 )</th>
<th>( m = 0.8, \gamma = 5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>84.70%</td>
<td>86.10%</td>
<td>84.70%</td>
<td>86.30%</td>
</tr>
<tr>
<td>18kA</td>
<td>96.10%</td>
<td>97.00%</td>
<td>96.10%</td>
<td>97.00%</td>
</tr>
<tr>
<td>20kA</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 14: SQ nut set-down % in the four simulation scenarios for each current level
Push-out

HP Nuts

<table>
<thead>
<tr>
<th>Current</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Avg</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>296.12N</td>
<td>1144.63N</td>
<td>728.50N</td>
<td>1157.37N</td>
<td>831.66N</td>
<td>49.16%</td>
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<tr>
<td>18kA</td>
<td>1814.80N</td>
<td>1673.22N</td>
<td>1592.22N</td>
<td>1509.42N</td>
<td>1647.41N</td>
<td>7.90%</td>
</tr>
<tr>
<td>20kA</td>
<td>2220.67N</td>
<td>2523.25N</td>
<td>2348.92N</td>
<td>2184.59N</td>
<td>2319.36N</td>
<td>6.60%</td>
</tr>
</tbody>
</table>

Table 15: HP nut push-out strength for the four welds with 8 kN electrode force at each current level

<table>
<thead>
<tr>
<th>Current</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Avg</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>16kA</td>
<td>515.95N</td>
<td>86.89N</td>
<td>0.00N</td>
<td>187.77N</td>
<td>197.65N</td>
<td>114.16%</td>
</tr>
<tr>
<td>18kA</td>
<td>1847.17N</td>
<td>1808.86N</td>
<td>1764.13N</td>
<td>1509.42N</td>
<td>1732.39N</td>
<td>8.80%</td>
</tr>
<tr>
<td>20kA</td>
<td>1198.64N</td>
<td>2523.25N</td>
<td>2011.62N</td>
<td>2051.64N</td>
<td>1946.29N</td>
<td>28.25%</td>
</tr>
</tbody>
</table>

Table 16: HP nut push-out strength for the four welds with 9 kN electrode force at each current level

Figure 56: Weld lobe of cross tension strength for simulation using $m = 0.8, \gamma = 1$
SQ Nuts

<table>
<thead>
<tr>
<th>Current</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Avg</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>18kA</td>
<td>2514.77N</td>
<td>3671.46N</td>
<td>2991.23N</td>
<td>2498.62N</td>
<td>2919.02N</td>
<td>18.88%</td>
</tr>
<tr>
<td>20kA</td>
<td>4430.84N</td>
<td>5691.95N</td>
<td>4843.72N</td>
<td>4951.45N</td>
<td>4979.49N</td>
<td>10.55%</td>
</tr>
<tr>
<td>22kA</td>
<td>7449.39N</td>
<td>7334.82N</td>
<td>6209.00N</td>
<td>6501.70N</td>
<td>6873.73N</td>
<td>8.91%</td>
</tr>
</tbody>
</table>

Table 17: SQ nut push-out strength for the four welds at each current level

<table>
<thead>
<tr>
<th>Current</th>
<th>Maximum strength</th>
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<tbody>
<tr>
<td>18kA</td>
<td>22220N</td>
</tr>
<tr>
<td>20kA</td>
<td>24638N</td>
</tr>
<tr>
<td>22kA</td>
<td>26020N</td>
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</tbody>
</table>

Table 18: SQ nut push-out strength from simulations using \( m = 0.8, \gamma = 1 \)