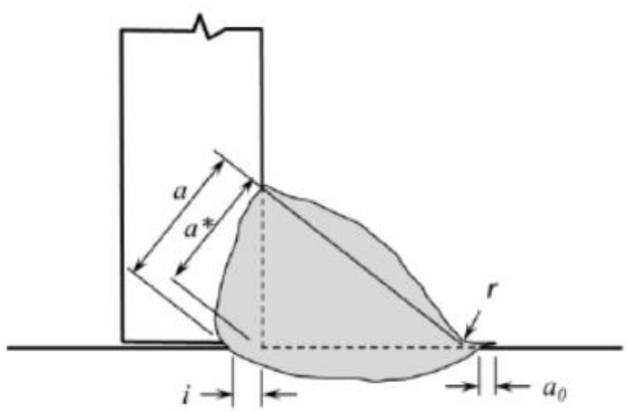
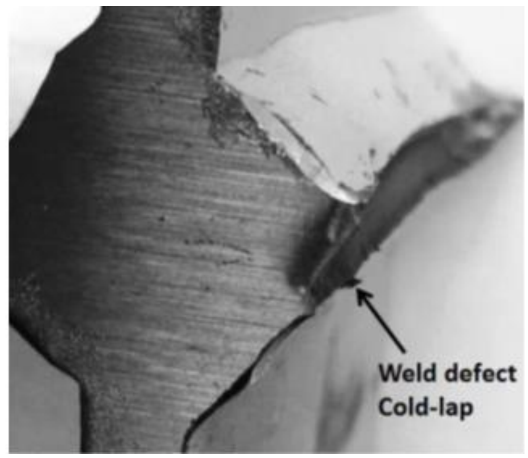
HIPFAT, High Performance weldments in Fatigue loaded vehicles - Understanding and controlling weld defect formation (Cold laps)

Public report





Project within FFI Hållbar produktion

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Content

1. Summary 3

2. Sammanfattning på svenska 4

3. Background 6

4. Purpose, research questions and method 8

5. Objective 12

6. Results and deliverables 13

6.1 Classical testing 13

6.2 Multifactorial trials 16

6.2.1 Experimental design 16

6.2.2 Reduction of factors and Augmented design 17

6.2.3 Verification runs 18

7. Dissemination and publications 23

7.1 Dissemination 23

7.2 Publications 23

8. Conclusions and future research 23

8.1 Conclusions 23

8.2 Future research 24

9. Acknowledgements, Participating parties and contact persons 25

10. References 26

1. Summary

Fatigue failures in vehicles or other welded structures are expensive and create risks for injuries. Small weld defects at the weld toe of fatigue loaded structures have a large influence on the fatigue life; the fatigue strength can be reduced with 50%. Small surface defects at the weld toe such as Cold laps are created when the weld pool with molten material does not fully merge with the base plate material, leaving a zone with a lack of fusion (i.e. a small surface crack). For an arc welded fatigue loaded structure with high weld quality, the ISO 5817 does not allow Cold laps larger than 0.1 mm. There are, however, no commercially available method for detecting these small defects, and little knowledge is gathered on how and when these cold laps are created and on how they can be avoided. Until today, no investigation exists on the full interactions in the surface where the weld transition and Cold laps are created, nor how a good weld transition without the presence of Cold laps can be achieved. There is an urgent need to identify the mechanisms and conditions when Cold laps are created and to develop a methodology for how to avoid them. When it comes to non-destructive testing (NDT) for the detection of cold laps, there is no fast and reliable NDT method available.

The project HIPFAT was created to address these issues. It spanned over 2.5 years and had a budget of 5.6MSEK, of which 2.8MSEK was funding from the FFI-program. Project leader was Swerim AB and academic research partner was KTH-Lightweight Structures. Chalmers University was also participating, as subcontractor to Swerim. The participating companies were: Volvo CE, SCANIA-FERRUFORM, HIAB, SSAB, ESAB, Voestalpine Böhler Welding Group, Linde, and SWC – The Swedish Welding Commission.

The main objectives for this project were to find and create means to avoid these detrimental surface defects that reduce the fatigue life significantly in welded structures. To achieve this, mechanism studies with different welding conditions were performed, utilizing both classical and multifactorial trials, destructive testing and NDT evaluations to identify possibilities for reliable detectability. *The over-all results from the project are:*

- Welding parameters influencing Cold lap formation have been identified and modeled in order to find welding parameter windows for where welding without cold laps is possible. This is described in chapters Results and Conclusions.
- A two-step bend test was developed to identify and quantify Cold laps.
- A development of a novel algorithm for data from laser scanning has shown to be successful in detecting Cold laps. This method is, however, limited to two types of Cold laps (of geometrical reasons).
- Recommendations have been developed for the most important settings, expressed as relation of welding voltage in respect to filler material types used.
- An observation regarding welding Heat input on Cold lap formation was made. With relatively high heat input, a threshold could be seen where from >1.0 - 1.2 kJ/mm and above, no Cold laps were observed. However, with Heat input <1.0 – 1.2 kJ/mm, specimens both with and without Cold laps were observed. Here, it

will be important to use optimal process settings, especially correct welding voltage, to avoid Cold laps.

- Within the process window for where it is possible to weld without Cold laps, other aspects of the weld's geometry could be optimized. Such as weld toe radius, weld penetration etc. This was made possible by a decoupled model in two steps: 1) select filler material and suitable welding voltage for this; 2) select parameters to fit wished weld geometry. Enabling the industry to further weld optimization and cost reduction.
- Results from the project have been disseminated in an open webinar with 40 participants from the industry, in an article in the welding branch magazine (Svetsen), in work groups at SWC and will be published in a coming scientific article and taught to students at both KTH and Chalmers.
- Increased knowledge and enhanced welding manufacturing in Swedish industry has been enabled through the mutual work in the project, leading to weld optimization both in respect to avoiding Cold laps and enhancing overall weld geometry, as given by the model from the multifactorial trials.

2. Sammanfattning på svenska

Haverier hos fordon eller andra svetsade konstruktioner är dyra och skapar risker för skador. Små svetsfel i svetstån hos utmattningsbelastade konstruktioner ger ett stort inflytande på utmattningslivet; utmattningsstyrkan kan minskas med 50%. Små ytdefekter vid svetstån, kallade Cold laps, skapas när det nedsmälta tillsatsmaterialet vid svetsning inte helt smälter samman med grundmaterialet, vilket lämnar en lokal zon med otillräcklig bindning. Detta ytliggande bindfel utgör en mindre spricka, som sedan tillväxer vid utmattningsbelastning. För en bågsvetsad utmattningsbelastad konstruktion med god svetskvalitet tillåter ISO 5817 inte Cold laps i storlekar större än 0,1 mm. Det finns emellertid ingen kommersiellt tillgänglig metod för att upptäcka dessa Cold laps och det är brist på kunskap om hur och när Cold laps skapas och även om hur de kan undvikas. Fram till idag finns ingen undersökning av de fullständiga interaktionerna i ytan där svetsövergången och Cold laps uppstår, och inte heller hur en god svetsövergång utan Cold laps kan uppnås. Det finns ett akut behov av att identifiera mekanismerna och förhållandena när Cold laps skapas och också att utveckla en metod för att undvika dem. När det gäller oförstörande provning (OFP) för upptäckt av Cold laps, finns det ingen snabb och pålitlig OFP-metod tillgänglig.

Projektet HIPFAT skapades för att adressera dessa problem. Det sträckte sig över 2,5 år och hade en budget på 5,6 MSEK, varav 2,8 MSEK finansierades från FFI-programmet. Projektledare var Swerim AB och akademisk forskningspartner KTH-Lättkonstruktioner. Även Chalmers Universitet deltog, som underleverantör till Swerim. De deltagande företagen var: Volvo CE, SCANIA-FERRUFORM, HIAB, SSAB, ESAB, Voestalpine Böhler Welding Group, Linde och Svetskommissionen.

Huvudmålen för detta projekt var att hitta mekanismerna som skapar Cold laps och hitta metoder för att undvika dessa skadliga ytfel som minskar utmattningslivet betydligt i svetsade strukturer. För att uppnå detta utfördes mekanismstudier med olika svetsförhållanden, förstörande provning och OFP-utvärderingar för att möjliggöra detekterbarhet. De övergripande resultaten från projektet är:

- Svetsparametrar som påverkar bildandet av Cold laps har identifierats och modellerats för att hitta parameterfönster där svetsning utan Cold laps är möjlig. Detta beskrivs mer i avsnitten Results & Conclusions.
- En tvåstegs bockmetod har utvecklats för att kunna kvantifiera Cold laps.
- Förbättrad laserskanningsalgoritm har utvecklats inom projektet, vilket möjliggör en ny metod för att upptäcka Cold laps. Två av tre typer av Cold laps (av geometriska skäl) är möjliga att detektera med denna metod.
- Rekommendationer för viktiga parameterinställningar har tagits fram, formulerade som val av optimal svetsspänning i förhållande till det tillsatsmaterial som används.
- En observation har gjorts för använd sträckenergi för de svetsade förband som studerats, här har ett tröskelvärde identifierats: när sträckenergin var relativt hög, omkring >1.0 - 1.2 kJ/mm och högre så har inga Cold laps observerats. Medan vid sträckenergier lägre än detta tröskelvärde, så har svetsar både med och utan Cold laps observerats. För dessa lägre sträckenergier kommer det vara viktigt att använda optimerade parameterinställningar, framförallt korrekt svetsspänning, för att kunna undvika Cold laps.
- Inom processfönstret där det är möjligt att svetsa utan Cold laps, optimerades andra aspekter av svetsgeometrin. Såsom svetståradie, svetsinträngning etc. Detta möjliggjordes genom en tvåstegs frikopplad modell där första steg är val av tillsatsmaterial och tillhörande lämplig svetsspänning, i steg 2 väljs sedan övriga parametrar så att önskad svetsgeometri nås. Detta gör det möjligt för industrin att ytterligare optimera svetsprocessen, öka hållfastheten och minska kostnaderna.
- Resultaten från projektet har spridits i ett öppet webinar med 40 deltagare från branschen, diskuterats i Svetskommissionens arbetsgrupper, publiceras inom kort i en artikel i branschtidningen Svetsen och kommer att publiceras i en vetenskaplig artikel. Blivande ingenjörer vid både KTH och Chalmers får ta del av både resultat och utvecklade metoder.
- Ökad kunskap om hur defekterna uppstår och förbättrade svetsprocesser i svensk industri har kunnat nås genom det gemensamma arbetet och resultaten från svetsoptimering avseende både Cold laps och svetsgeometri, möjliggjort via flerfaktorförsöken.

3. Background

Small defects at the weld toe of fatigue loaded structures can reduce the fatigue strength with 50%. In the 2017 published attachment of ISO 5817 – Quality Levels of Imperfections for fusion welded joints, it is stated that small defects at the weld toe reduces the fatigue strength significantly (see Figure 1). These small surface defects at the weld toe are termed Cold laps and are created when the melted weld filler material does not fully merge with the base plate material leaving a zone with a lack of fusion. For a welded fatigue loaded structure with good weld quality, the ISO 5817 does not allow Cold laps of the size larger than 0.1mm because the cold laps would then reduce the fatigue strength with 50%. There are, however, problems in detecting these small defects, lack of knowledge on how these cold laps are created and on how they can be avoided.

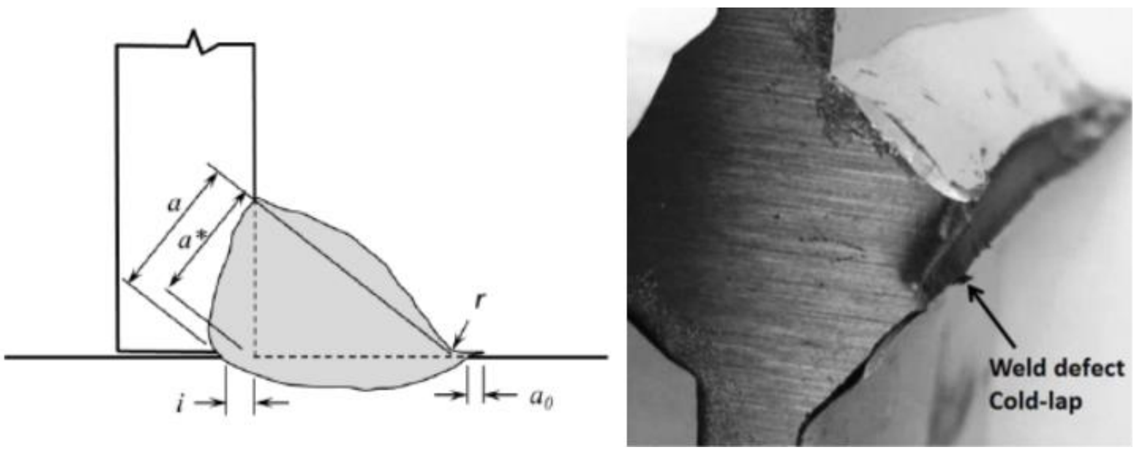

Figure 1) a) Fillet weld geometrical features which are influencing the fatigue strength;a0… cold lap depth [Source: supplement to ISO 5817] b) Fatigue tested welded specimen with cold laps indicated [Swerea KIMAB project, from 2016].

The ISO 5817 also states that for a high fatigue strength a large weld toe transition radius is needed. The large weld toe radius can be shaped when the molten weld filler material can wet the base plate material well, forming a smooth transition. The smooth transition must be without defects such as Cold laps otherwise the fatigue strength will be reduced by the defect. If the wetting is very good, the radius will be very good but the risk for Cold laps has also been shown to increase significantly although this is not always the case. If the wetting is bad, the weld transition radius will be quite small resulting in low fatigue strength. Hence, two different mechanisms must be understood and controlled in order to reach long fatigue life: weld toe defect formation (Cold laps) and weld toe radius formation.

When it comes to defect formation s at the weld toe; J. Hedegård et al. investigated the occurrence of cold laps on base plate material with mill scale and on various blasted surfaces [1]. It was concluded that Cold laps were observed more frequently when welding was performed on as-rolled plates (with mill scale) compared to blasted surfaces.

This shows that the base plate surface condition can have a significant influence on the Cold lap formation which could be related to the wetting and fusion capacity.

P. Li [2-6] investigated the cold lap formation in Gas Metal Arc welding of steels and classified three different types of Cold laps: spatter, overlap, and spatter-overlap Cold laps. The spatter Cold laps can be avoided if spatter free welding parameters can be used. Overlap cold laps can be avoided if welding is performed on a clean and preheated surface. (Comment: and, by avoiding excessive melting of filler material, in relation to the joint volume and travel speed.) Oxides with high melting temperature present on the plate surface – and on the surface of the weld spatter, was shown to increase the risk for receiving Cold laps and the risk was believed to increase with the oxide thickness.

The use of recent power sources and applying advanced pulsing could introduce a way to achieve high quality welds. No further investigations of using recent power sources have been found, and there are at least 1-2 more mechanisms for Cold laps creation than reported in literature so far.

When it comes to radius formation at the weld toe, the most analytical work has been performed by P Hammersberg and H Olsson [7]. They showed that welding gun angles do have a significant influence on the weld toe geometry. In addition to this, a recently finished project in the Centre of Joining and Structures at Swerea KIMAB (CJS today: in Swerim) showed that the base plate surface condition has an influence on the weld toe geometry, but more research is needed to establish how. Industry reported that shielding gas used during welding has also an influence, but no published report could be found.

Within the project consortia, extensive research have been focusing on classifying different weld defects (Cold laps, and more), local weld geometry and imperfections and to study their effect on the fatigue strength [8-10], which ultimately resulted in a new novel weld quality system [11, 12]. Remaining though, is the study of formation of defects such as Cold laps and understanding these mechanisms in order to avoid and/or minimize their occurrence.

To summarize, weld toe defects such as Cold laps or too small weld transition radius have a significant negative impact on the fatigue strength of welded structures and has therefore to be understood and controlled. Until today, no investigations exist on the full interactions in the surface where the weld transition is created, or how a good weld transition without the presence of Cold laps can be achieved.
Perfect welds in a production environment is difficult today since the process control and testing methods are insufficient. Hence, it is important to a) find these small weld defects with new NDT methods, and b) understand more of the mechanisms and conditions that create Cold laps, to be able to improve the welding process and product quality before the product leaves the factory (i.e. enable an efficient process optimisation and control). In the recently finished VINNOVA project ONWELD, weld toe radius measurement equipment was developed which can be used to assess the weld toe geometry and the transition radius (the system is further developed today, by Winteria). For detection of

Cold laps, only the destructive testing methods Holst testing and cross-section investigation are known but these are time consuming and must be further developed [8, 13]. When it comes to NDT for detection of Cold laps, no method is known to work yet, but many NDT methods have been developed further recently and will be evaluated in this project.

4. Purpose, research questions and method

The main purposes for this project were: firstly, to identify welding parameters influencing the formation of Cold laps, and secondly to investigate and develop novel methods for NDT that can discover Cold laps in welded structures. Today, no reliable method to quantify Cold laps in welded structures is available. Hence, in order to determine which welding parameters that are influencing Cold lap formation, a method for quantifying Cold laps had to developed first. A novel method for quantifying Cold laps were developed within this project (a two-step bend test) and is described below. After welding, samples were cut into smaller pieces as shown in Figure 2. The 65 mm pieces in each end were scrapped to ensure that no start/stop-effect influenced the samples intended for evaluation. The three 50 mm samples were evaluated for Cold laps and the two 10 mm samples were evaluated after macro preparation by light optical microscopy (LOM). ID-number and welding direction was marked in upper right corner of the specimens, as shown in Figure 2.

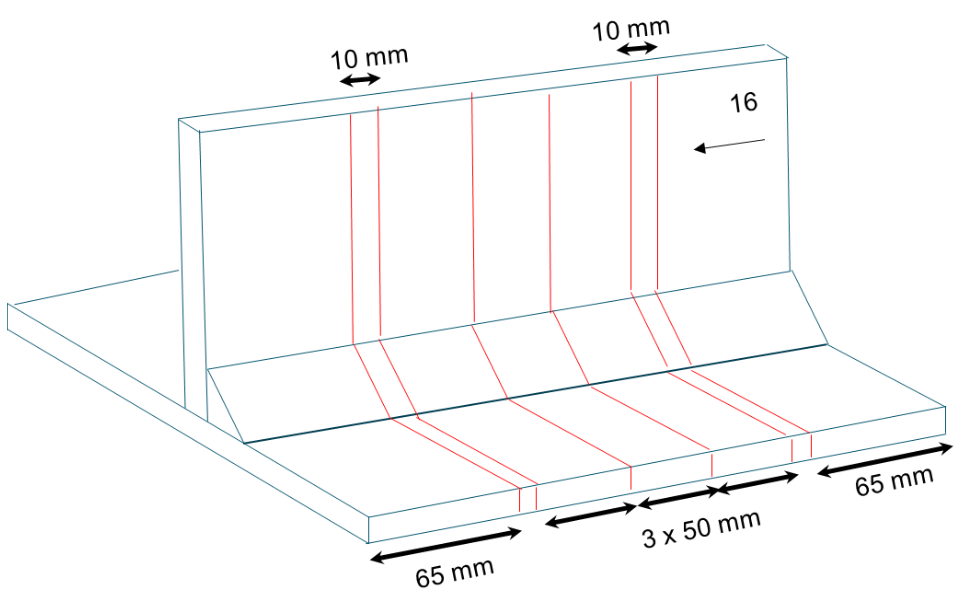

Figure 2 Illustration of how welded samples were cut into smaller samples before evaluation, ID-number and welding direction is marked in upper right corner.

The cut samples intended for cross sectioning and LOM were polished and important data for the weld's properties were measured. Aspects of the weld, measured by cross sectioning and LOM, included Throat thickness (a), Weld penetration (i), Weld side penetration (d), Weld reinforcement (h), Weld bead width (b) and Weld toe angles (α_1 & α_2). An example of results from weld cross sectioning and LOM is shown in Figure 3.

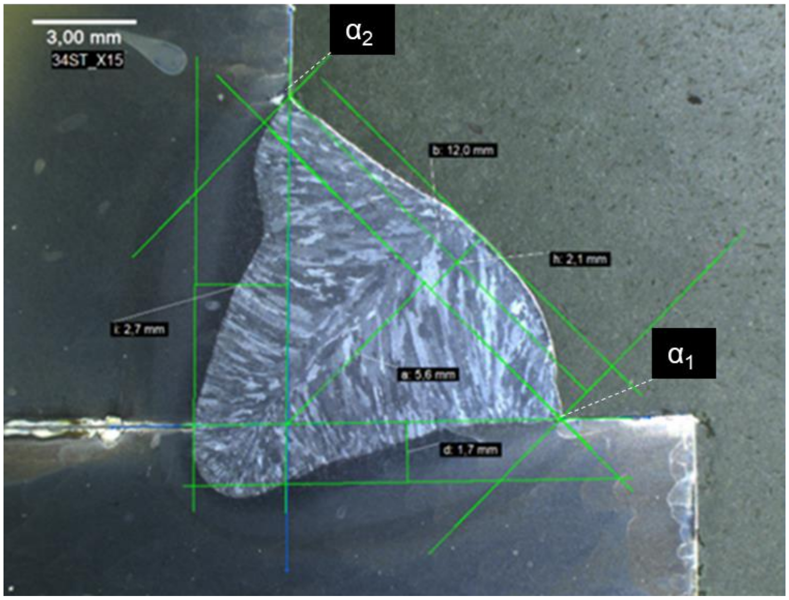

Figure 3 Example of measurements by cross section and LOM. Measured in LOM were: Throat thickness (a), Weld penetration (i), Weld side penetration (d), Weld reinforcement (h), weld bead width (b) and Weld toe angles (α1 & α2)

The weld geometry of the samples was measured with a line laser scanner and analysed with Winteria software. Data of the weld measured by Winteria software were Throat thickness, Weld toe radius, Weld toe angle, Undercut, Weld area and Weld area exceeding throat thickness. All measurements regarding weld toe were performed on the same weld toe (lower weld toe) evaluated for Cold laps only, the upper weld toe was not measured. An image from the laser scanning process and a schematic view of the weld profile obtained from the laser scan is shown in Figure 4.

Figure 4 Image of the laser scan process (right) and schematic view of the weld profile obtained (left).

The cut samples intended for Cold laps evaluation were painted with a thin layer of white developer paint, the developer paint is commonly used as an NDT method for detecting cracks. The purpose of painting the samples was to simplify the detection of possible Cold laps in the following evaluation steps of bend-testing and LOM. The samples intended for Cold lap evaluation were bend-tested in a hydraulic press subsequent to cutting and painting. The purpose of the bend testing was to induce a stress at the lower weld toe, enabling any Cold laps present at the weld toe during bending to open and detach from the base plate. The detachment of Cold laps from the base plate through bend testing enabled a possibility to quantify and measure Cold laps. A schematic view and an example of a bend tested sample is shown in Figure 5.

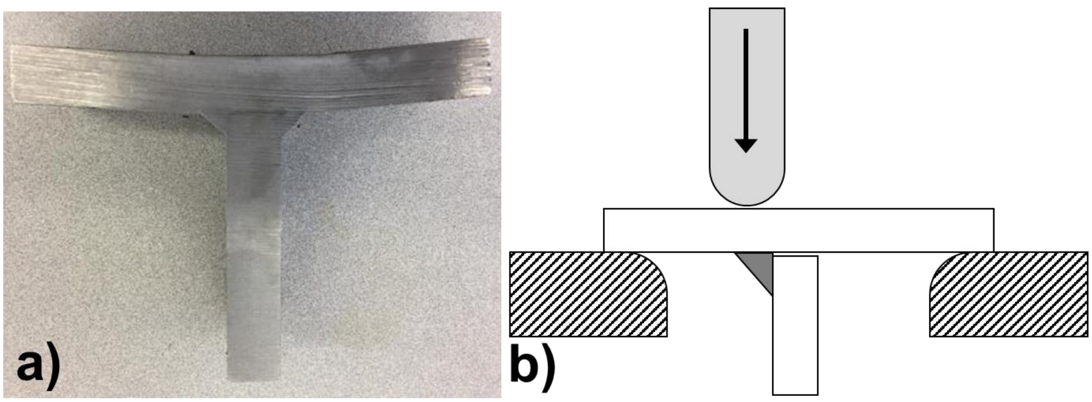

Figure 5 Bend testing: a) illustrates a slightly bent sample after bend testing. b) Schematic view of the bend-testing method. Note the tool positioning just above the weld toe.

After the samples were bend-tested, they were evaluated in LOM for Cold laps. Any Cold laps present in the samples were imaged from two directions in order to add robustness to the measuring method. The two directions the LOM images were obtained from were along the vertical, and the horizontal, plate, as visualised in Figure 6. Measurements obtained from the direction of the horizontal plate were subsequently used as data in both the classic testing and the multifactorial evaluations.

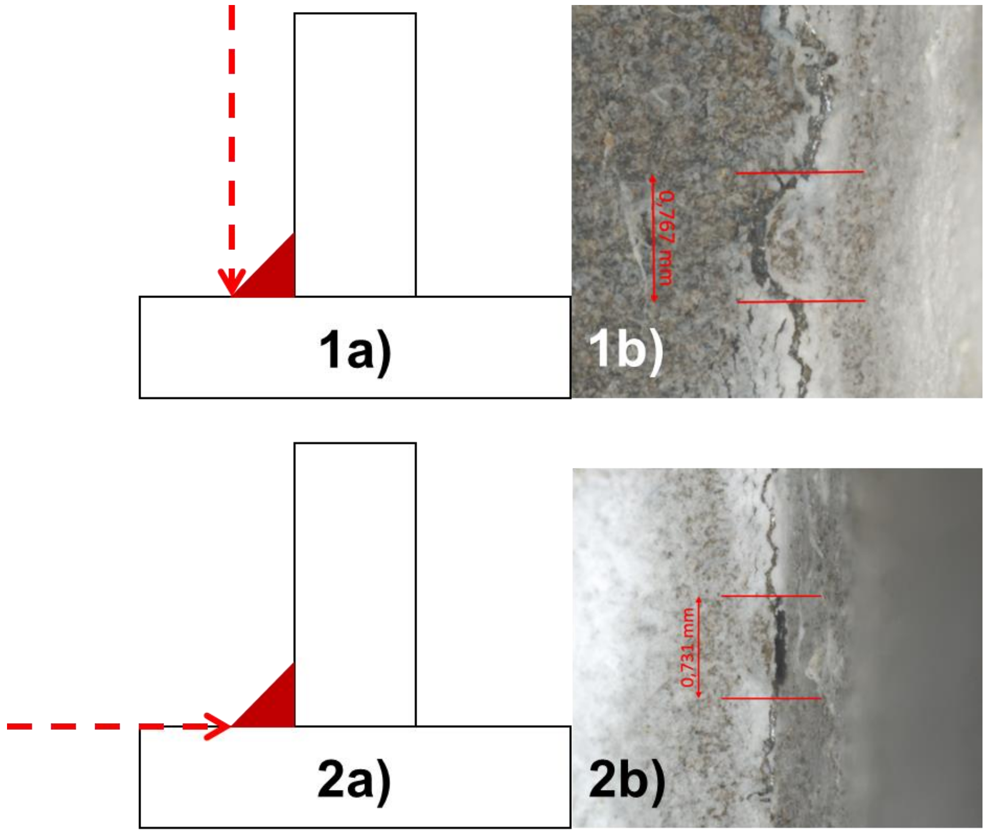

Figure 6 1a) Schematic view of LOM image obtained along the Vertical plate. 1b) Example of LOM image obtained in Vertical view. 2a) Schematic view of LOM image obtained along the Horizontal plate. 2b) Example of LOM image obtained in horizontal view.

Results from LOM evaluations were used both in initial classical testing evaluations and added to multifactorial software JMP in order to better evaluate the welding parameters influence on the Cold lap formation. The result parameters were presented as: Number of Cold laps per tested length of weld [#CL/mm], Average Cold lap lengths [mm] and percentage of Cold lap length in relation to total tested length [%].
During gas metal arc welding (GMAW) there are many parameters influencing the weld properties. In order to cover as many important welding parameters as possible in the evaluation for Cold laps, extensive work was performed to find parameter levels for all combinations of parameters and parameter levels that can produce a weld that is measurable for Cold laps. Pre-trials were performed to find suitable levels for each individual welding parameter so it would work for all combinations with other welding parameters. The parameters and their levels that was brought into the multifactorial trials are presented in Table 1.

Table 1 Welding parameters included in multifactorial trials and their levels.

Surface condition	Travel angle [°]	C02 [%]	He [%]	Travel [cm/min]	Filler material	Voltage [V] set	Site [location]	Stick out [mm]	Wire Feed [m/min]	Base material [Mpa]
Blasted	80	18	50	40	Solid	25	L1	28	12	700
As-rolled	120	8	0	60	Purus	35	L2	23	16	355
	100	25	30		Metal Core	30	L3	18		
							L4			

In this project various NDT methods were considered for development towards a method that can detect Cold laps. The method that, after an initial evaluation period, was finally chosen for the work to detect Cold laps was a development of an algorithm, treating laser scan data that can find Cold laps by fitting a radius to the weld toe that will reach a certain magnitude in the case of presence of Cold laps, this radius is illustrated in Figure 7. In the case of no cold laps the radius presented in Figure 7 will be very small and only locally in vicinity of the Cold lap reach a considerable magnitude. The local deviance in weld toe geometry could therefore be used as an indicator for presence of Cold laps while laser scanning welds with the Winteria system.

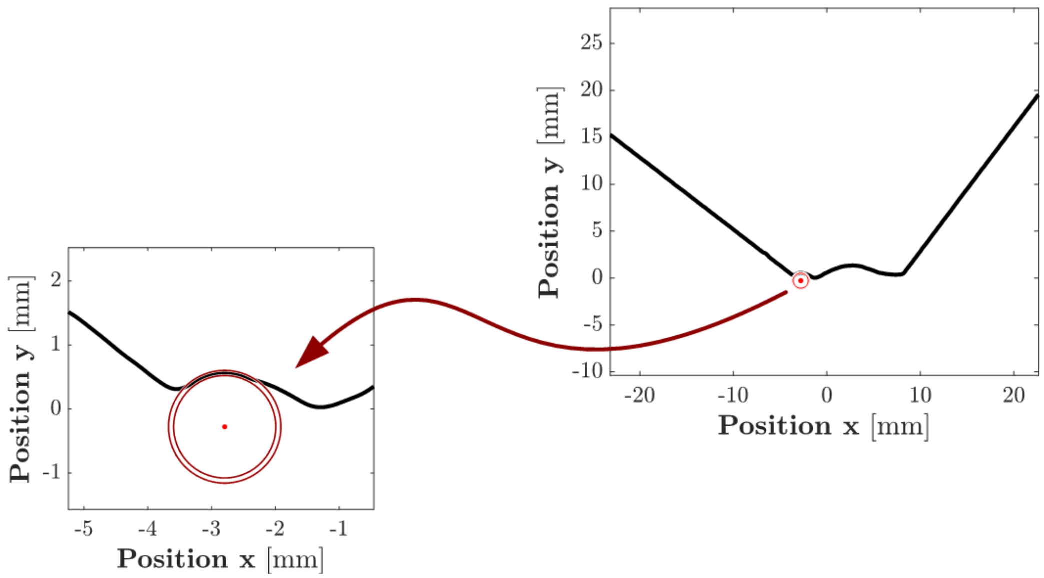

Figure 7 Illustration of radius fit algorithm for detection of Cold laps.

5. Objective

The main objectives for this project are increased weld quality and product life, improved manufacturing processes (Robust and efficient production), reduction of road transport environmental impact (Resource efficiency and reduced CO2 emissions), increased competitiveness for Swedish industry, and cross-industrial and scientific cooperation. These objectives will be addressed and met by developing tools and methods for defect-avoiding welding, and weld geometry optimisation.

6. Results and deliverables

The results from the project are presented in chapters below; Classical testing, Multifactorial trial and NDT evaluation.

6.1 Classical testing

In the initial stages of the project, the project participants from welding manufacturing industry were asked to deliver optimized welds of specified size and quality. The welded samples from the participating companies were specified to fulfil ISO 5817 weld class B, have a throat thickness of 5mm and weld penetration of 2 mm. Best productivity should be strived for, and the selection of welding parameters and methodology was free. The purpose was to identify successful paths and shared learning. Schematic view of the welded samples gathered from the participating companies is presented in Figure 8.

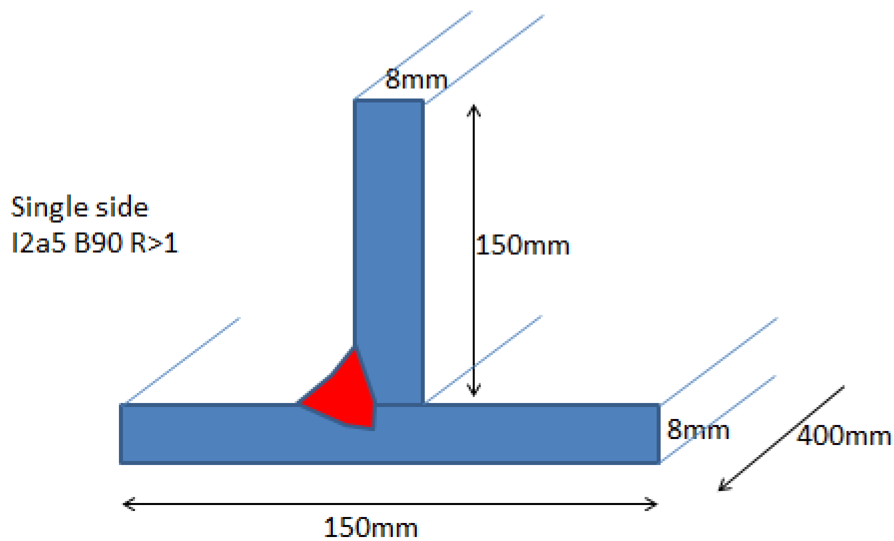

Figure 8 Schematic view of welded samples gathered from the participating companies for the classical testing.

The companies providing the welded samples for this classical testing was paired into groups of two, each group assigned with varying prerequisites for welding. The welding prerequisites varied between the groups were Steel grade (Yield strength), Shielding gas, Filler material and Surface condition. The test matrix for the classical testing is listed in Table 2. In total, 23 welded samples were acquired from the industry. These were bend tested and evaluated for Cold laps, and 6 of these samples contained Cold laps.

Table 2 Welding prerequisites for classical testing.

Group	Location	Steel grade: [Mpa]	Surface Conditon:	Sheilding gas:	Filler material:
1	L2 (HIAB) & L4 (Böhler)	700	Pickled	Mison 18	Solid wire
			As-Rolled		Metal cored wire
2	L6 (VCE) & L5 (Ferruform)	355	Blasted	Mison 8	Solid wire
		500	As-Rolled		Metal cored wire
3	L1 (AGA/Swerim) & L3(ESAB)	960	As-Rolled	Mison 8	Solid wire
			Blasted	Mison 18	
				C8He30	

After the evaluation of Cold laps in the welded samples, the results of Average number of Cold laps were plotted against the welding prerequisites such as Surface condition, Filler material, Shielding gas and Steel grade. The 95% confidence interval for these averages were calculated and market in the plot as well and is presented in Figure 9. As can be seen from Figure 9, a difference in Average number of Cold laps per welding condition can be observed. However the 95% confidence intervals for the mean values in Figure 9 are overlapping in all cases and hence no factor can be concluded to have any significant influence on Cold lap formation, from these observations from classical testing. Further welding trials were therefore added and evaluated in multifactorial trials and JMP software.

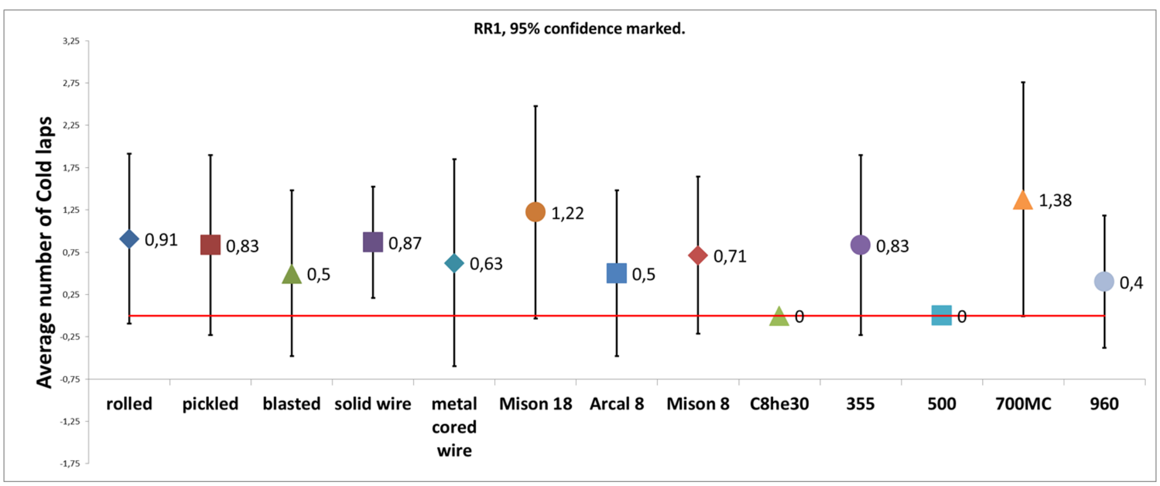

Figure 9 Results from classical testing, Average number of Cold laps per welding condition and 95% confidence interval marked.

From the classical welding trials and Cold lap evaluations, the influence of the welding Heat input [kJ/mm] was investigated, where welding Heat input [kJ/mm] was plotted against the sum of measured Cold lap length [mm]. For the observations in the classical welding trials it was seen that for a Heat input above a certain level, above 1.2 [kJ/mm], no Cold laps were present. However, below Heat input of 1.2 [kJ/mm], welds with and without Cold laps were observed. The results of Heat input on Cold lap formation in classical trials are visualized in Figure 10. It was also observed that C8He30 shielding gas trials received no Cold laps. With the results from Figure 10 at hand, the project consortium was interested to see if the influence of welding Heat input on Cold lap formation would apply also to welded samples outside of these rather limited observations in the classical trials and the question was raised to another Vinnova project consortium, if welded samples from the PREMOD project could be evaluated also in the aspect of searching for Cold laps. The PREMOD project consortium approved that the HIPFAT project could evaluate the welded samples from PREMOD for Cold laps. The measured and recorded Heat input for the PREMOD samples were evaluated in respect to Cold laps and the results are presented in Figure 11, where a similar characteristic to that of Figure 10 can be observed. For the PREMOD samples, no Cold laps were observed for a Heat input above 1.0 [kJ/mm], but with a Heat input below 1.0 [kJ/mm] samples with and without Cold laps were observed. The results from Figure 10 and Figure 11 led to the observation that with a Heat input above a certain level, no Cold laps can be found, i.e. a Heat-input-threshold can be discussed. Below that certain Heat input threshold, both samples with and without Cold laps will be found. Leading to the insight that Heat input parameters of Voltage, Current and Welding speed may have influence on Cold lap formation here. However, it would seem that these parameters cannot account for all variation and influence on Cold lap formation, as for relative low Heat input both samples with and without Cold laps have been observed in both the classical trials and in the PREMOD samples (PREMOD utilised multifactorial testing). These results regarding Heat input and its influence on Cold lap formation sums up the classical testing in the project, all welding prerequisites were further tested and evaluated for Cold laps in subsequent Multifactorial trials which is presented in Chapter 6.2 below. Multifactorial trials were judged to be needed to evaluate and clarify influencing parameters (on Cold laps) and establish the interactions on different levels between the parameters.

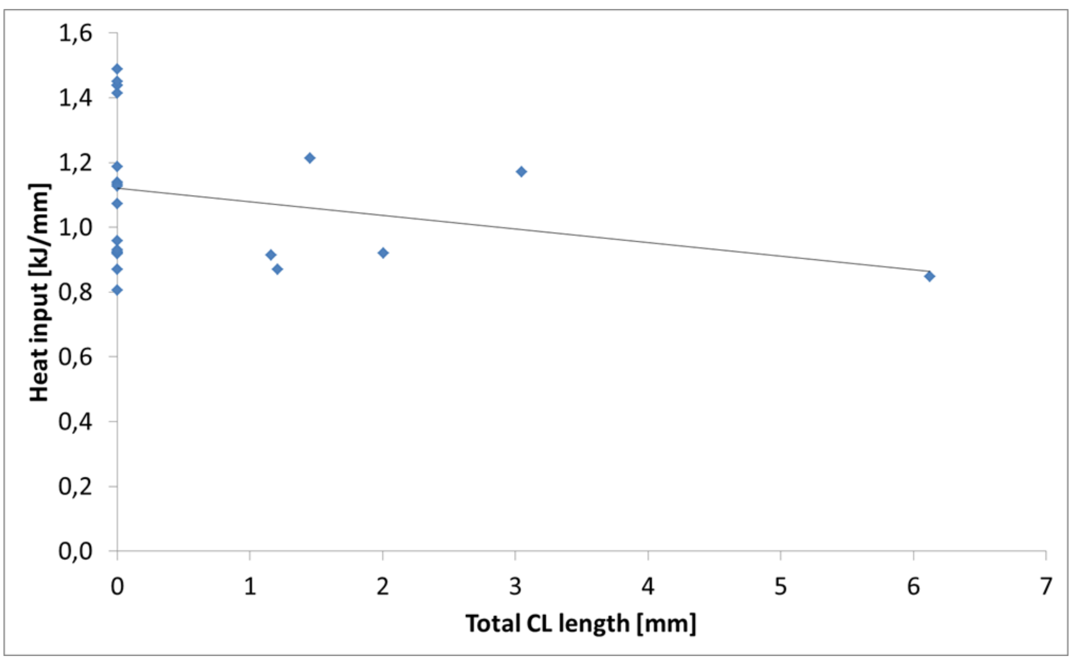

Figure 10 Results from classical trials, influence of Heat input [kJ/mm] on the sum of measured Cold laps [mm]. Heat input above 1.3 kJ/mm results in zero Cold laps found

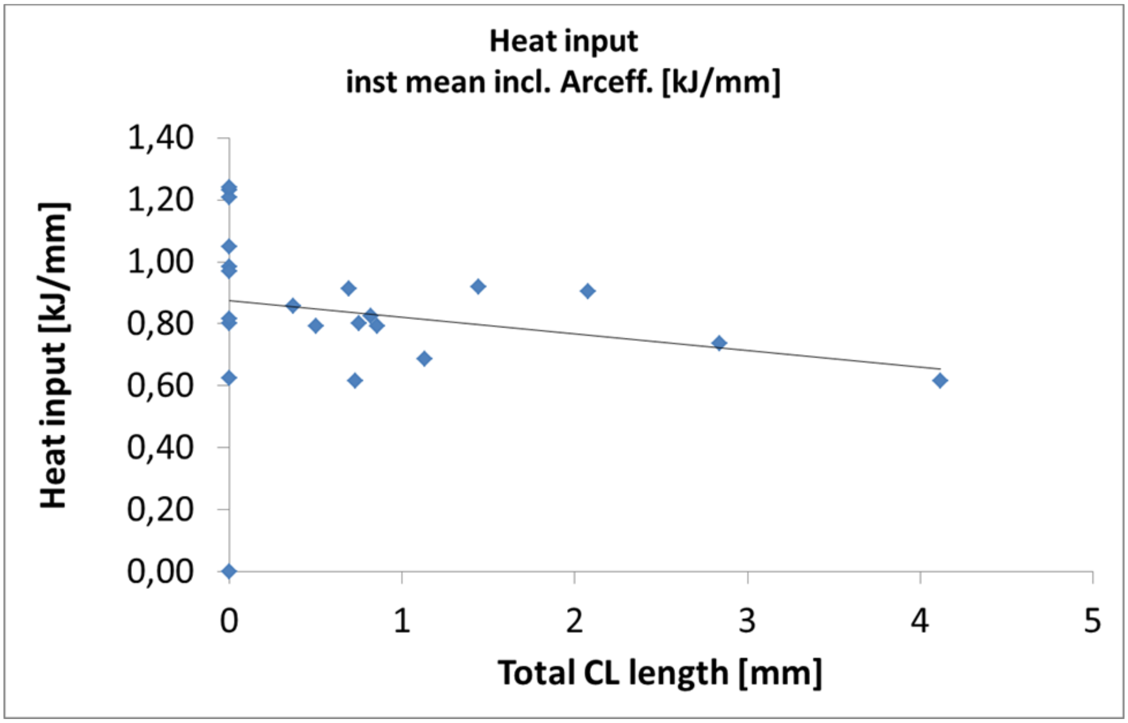

Figure 11 Results from PREMOD samples, influence of Heat input [kJ/mm] on the sum of measured Cold laps [mm]. Heat input above 1.0 kJ/mm results in zero Cold laps found

6.2 Multifactorial trials

Below are the stages and results from the multifactorial trials presented.

6.2.1 Experimental design

For the multifactorial trials, the gathered knowledge and expertise in the consortium were used in order to decide which factors to bring into the multifactorial trials for maximum coverage with reasonable number of investigations. In total, 11 factors and 11 interactions were brought into the initial experimental design. The experimental design was performed in the Design of experiment (DoE) software JMP, and a Custom design was created with factors as shown in Figure 12.

Intercept
Surface condition
Travel angel [°]
C02 [%]
He [%]
Travel [cm/min]
Filler material
Voltage [V]
Site
Base material
Stick out [mm]
Wire Feed [mm/min]
Surface condition*Travel [cm/min]
Surface condition*C02 [%]
Surface condition*Filler material
Surface condition*Travel angel [°]
Travel angel [°]*Travel [cm/min]
Surface condition*Wire Feed [mm/min]
Surface condition*Voltage [V]
C02 [%]*Voltage [V]
C02 [%]*C02 [%]
He [%]*He [%]
Stick out [mm]*Stick out [mm]

Figure 12 Factors and interactions brought into the Custom design created in DoE software JMP.

The DoE software JMP created a test matrix consisting of 36 runs for the above-mentioned factors and interactions. The purpose of these 36 runs was to eliminate factors that do not have an influence on Cold lap formation and subsequently add additional runs to increase the test resolution regarding the factors that do have an influence on Cold lap formation.

6.2.2 Reduction of factors and Augmented design

16 new runs and additional Sites were added, the new experimental design with 16 additional test runs is called the Augmented design. The purpose of adding multiple sites to the matrix was to see if the welding equipment used would have an influence on Cold lap formation, with otherwise same or very similar, settings for the remaining welding factors. The additional 16 runs and their factor levels are visualised by the green diamonds in Figure 13. It can be seen in Figure 13 that the Stick-out has only one factor level represented in the Augmented design by Green diamonds. The reason for this is that Stick out showed to have no influence on Cold lap formation. All other factors excluding Stick-out, gained test resolution by an increased number of test runs over varying factor levels, as can be seen in Figure 13. The green diamonds in Figure 13 represent the added 16 runs in the Augmented design adding results to factor levels that were not included in the original 36 run experimental design.

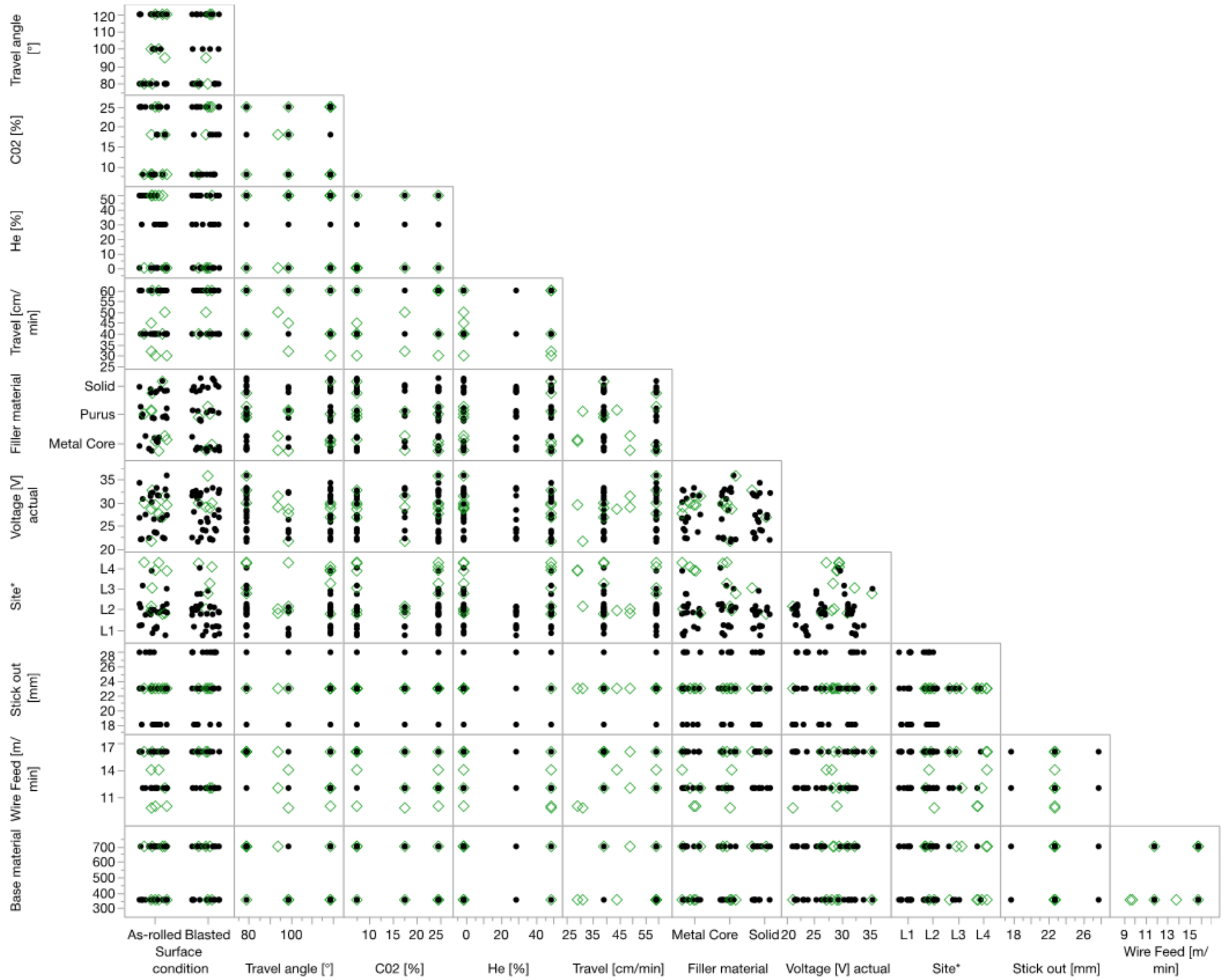

Figure 13 Factors and factor levels for the 36 run experimental design represented by black dots, and the 16 run Augmented design represented by Green diamonds.

6.2.3 Verification runs

From the experimental and augmented design and the Cold lap evaluations from these samples, it was found that only two factors and one interaction have strong influence on the Cold lap formation. The factors strongly influencing Cold laps were Voltage and Filler material, and the interaction was the interaction between Voltage and Filler material. Even though only two factors and one interaction were influencing the Cold lap formation, the remaining factors influenced other important aspects of the weld geometry. This was utilized in an decoupled model, by firstly using the factors influencing Cold lap formation to minimize the amount of Cold laps and secondly to use the other factors to be able to optimize the geometric aspects of the weld such as Weld penetration (i), Throat thickness (on target = 5 mm) and Weld toe radius. From this decoupled model, two verification runs were first modelled in the software, then welded and evaluated for Cold laps and laser scanned for weld geometry. The purpose was to produce both best and worst case with respect to Cold laps but within the process window of an acceptable weld. Two replicates of the verification runs were also performed in order to add data in the verification. Factor levels were chosen by the model for minimizing Cold laps. While keeping the Throat thickness on target 5 mm, maximizing the Weld toe radius and Weld penetration is represented by run ID 101 and its replicate 103 in Figure 14. The runs for maximizing Cold laps and keeping Throat thickness at target of 5 mm and maximizing Weld toe radius and Weld penetration is represented by run ID 102 and its replicate 104.

Run ID	Data Set	Surface condition	Travel angle [°]	C02 [%]	He [%]	Travel Speed [cm/min]	Filler material	Voltage [V] actual	Site*	Stick out [mm]	Wire Feed [m/min]	Base material [Mpa]
101	Verification	As-rolled	80	8	0	32	Solid	29,7	L6	23	9,8	355
102	Verification	As-rolled	80	8	0	30	Solid	21,5	L6	23	9,9	355
103	Verification	As-rolled	80	8	0	32	Solid	30	L6	23	9,8	355
104	Verification	As-rolled	80	8	0	30	Solid	22	L6	23	9,9	355

Figure 14 Minimized Cold laps and maximized Weld toe radius and weld penetration while keeping throat thickness on target 5mm is represented by run ID 101 and its replicate 103. Maximized Cold laps and all other keept the same are represented by run ID 102 and 104.

When the verification test runs from the model represented in Figure 14 were evaluated for Cold laps, laser scanned for weld geometry and cross sectioned for measuring, the predicted results from the model could be compared to the measured results from the specimens. The comparison between predicted values from the model and the measured values from the specimens are presented in Figure 15 below. Here it can be seen that in both cases where Cold laps were minimized in the model, no Cold laps were found in the specimens. And for the specimens where Cold laps were maximized in the model, Cold laps were found in the samples. The developed bend-test in combination with LOM examinations, and laser scanning, were utilised also in these examinations.
To be noted for the decoupled model where other important aspects of the weld were optimized while minimizing/maximizing Cold laps, is that the model could accurately predict Throat thickness and Weld penetration very well. Weld toe radius was not, however, accurately predicted, Weld toe radius is one of the geometric aspects of the weld which is most difficult to measure and produced a lot of scatter while measuring which might be an explanation to why the weld toe radius was not very accurately predicted by the model.

Run ID	Cold Laps [#/mm]	Predicted Cold Laps [#/mm]	Mean Throat thickness [mm]	Predicted Mean Throat thickness [mm]	Weld toe radius left [mm]	Predicted Weld toe radius left [mm]	Weld penetration i [mm]	Predicted Weld penetration i [mm]
101	0,00	0,01	5,2	5,0	0,34	0,43	2,7	2,6
102	0,03	0,12	4,9	4,8	0,23	0,42	1,8	1,5
103	0,00	0,01	5,3	5,0	0,39	0,43	2,7	2,6
104	0,03	0,12	5,2	4,8	0,33	0,42	1,8	1,5

Figure 15 Comparison of predicted values from the model and measured values from the verification samples.

Even though optimizing weld geometry was not the main scope of this project, the utilization of a decoupled model as described above has emerged to be a possible guide for welding companies: to choose filler material and its suitable welding voltage first, in order to avoid Cold laps, and then to use all other factors/parameters to optimize the weld

geometry with high accuracy ensuring both a defect free and a strong weld. This was the methodology developed.
During this project, however, only the lower weld toe towards the base plate has been in focus, only this has been evaluated for Cold laps and measured by laser scanning. As shown above in Figure 15, Cold laps and weld geometry of the lower weld toe can be predicted accurately. Still, when considering the whole weld geometry of the optimized weld in the Verification trials, it can be seen that the weld contains a defect of other nature than Cold laps. There is an Undercut present in the upper weld toe in the sample with Cold laps minimized (ID 101 & ID 103) as shown in Figure 16. This is an important lesson when utilizing predictive modelling, that the factors that are measured and modelled are accurately predicted but the factors left out of the model are of course not included and therefore not predicted accordingly. In this case it was assumed that conditions for the upper weld toe would not influence the lower weld toe and the overall weld geometry, but this showed to be not completely true and in order to accurately optimize and predict a complete weld geometry, all aspects need to me measured and accounted for. Only what is measured and modelled can be predicted. Still, the model can be completed with additional work – and then include full weld geometry prediction.

Figure 16 Cross-section of verification run ID 103, weld with minimized Cold laps, however with an undercut present in upper weld toe (upper toe not included in the model).

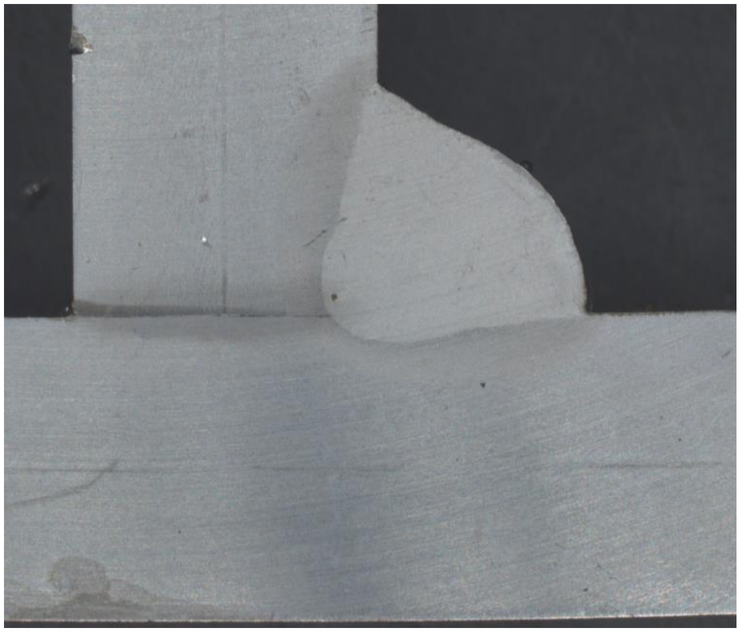

Figure 17 Cross-section of verification weld, run ID 102, with Cold laps maximized.

The main findings from these multifactorial trials regarding Cold lap formation is the strong influence from welding voltage, Filler material type and the interaction between these two. In other words, there is an optimal setting of welding voltage that is different depending on which type of Filler material that is used. This is visualised in the response surface shown in Figure 18. The results should be interpreted as follows: For Solid wire and Purus wire, many Cold laps have been found at relatively low welding voltage. With increasing welding voltage, the Cold lap formation is rapidly decreasing, with a minimum number of Cold laps at roughly 32 Volts in these trials. When considering the Metal cored wire filler material, the relation of welding voltage and filler material is somewhat different compared to Solid – and Purus wire. For Metal cored wire, a minimum number of Cold laps are found at roughly 28 Volts in these trials, and the number of Cold laps then increase with both increased and decreased welding voltage. Generally, metal cored wire produced less Cold laps compared to Solid – and Purus wire, but it is important to note the second degree optimum for the metal cored wire, requiring a careful calibration and an optimal setting of welding voltage in order to avoid Cold laps for metal cored wire. The Solid – and Purus wire produced more Cold laps in these trials compared to metal cored wire. The number of Cold laps for Solid – and Purus filler material is however rapidly decreasing with increased welding voltage, leading to the recommendation to ensure that an adequately high welding voltage is used for Solid – and Purus wire to avoid Cold laps. Important to note is that it is possible to weld without receiving Cold laps with all Filler materials tested in this project, but quite different welding voltage will be required to avoid Cold lap formations. So extra attention should be made on the setting of welding voltage, not only adjusting the voltage to suitable arc type (more fine-tuning to avoid Cold laps is recommended).

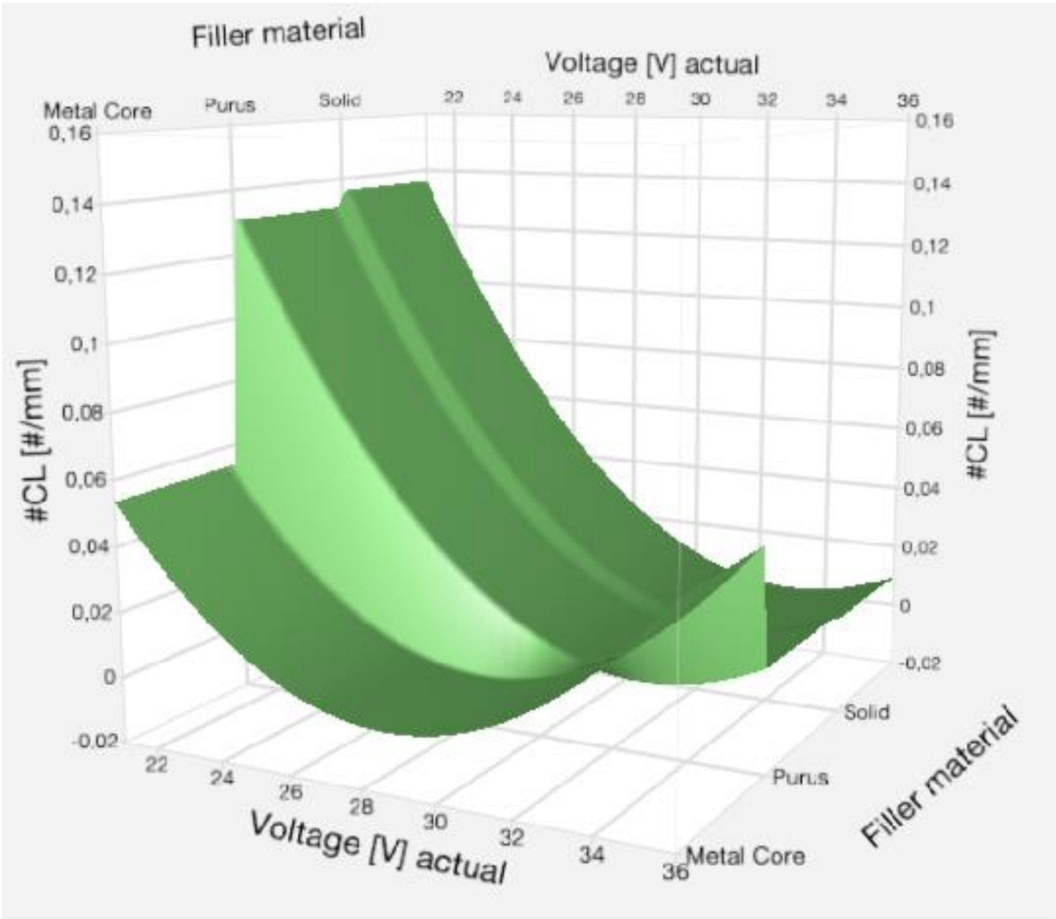

Figure 18 Response surface for Number of Cold laps per tested mm [#CL/mm], Filler material and Voltage actual (Measured Voltage).

An important comment about the welding voltage and the results in Figure 18, is that in the results, the term actual voltage is used. The actual voltage is the measured voltage during welding, as opposed to the set voltage which is the voltage set on the welding equipment prior to welding.

During the multifactorial trials in this project, a site-depending correlation to Cold lap formation was observed when only looking at the voltage as the set value on the welding equipment prior to welding. This site-dependency was however eliminated in the model when the set voltage was exchanged to the measured voltage or Voltage actual, as it is named in the results. This observation regarding the site-dependency and varying difference between set and actual voltage between sites, led to the conclusion that it is of great importance to perform pre-trials and determine the specific site's actual voltage since the actual voltage may vary significantly depending on welding equipment used, length of the electric cables to the welding equipment, etc. And as mentioned earlier, it is also of great importance to evaluate the optimal welding voltage, regarding both a stable arc type and avoidance of Cold laps – the arc will need to be able to heat the region where the weld transition will land.

7. Dissemination and publications

7.1 Dissemination

Results from the project have been disseminated in an open webinar with 40 participants from the industry, in work groups at SWC and will be published in a coming scientific article and taught to students at both KTH and Chalmers. HIPFAT results will also shortly be presented in an article in the welding branch magazine (Svetsen).

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Dissemination by seminars, conferences, articles
Be passed on to other advanced technological development projects	(X)	Possibly, to power source manufacturers
Be passed on to product development projects		
Introduced on the market	X	As recommendations and Guidelines
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

International publications are planned (in IIW, both on multifactorial trials and the NDT method development).
Popular article in Swedish is written (soon published in "Svetsen"): "Vad vet vi om cold-laps – går de att undvika?"

8. Conclusions and future research

8.1 Conclusions

In this project, the goals were to identify factors and mechanisms influencing Cold lap formation and to provide guides for how to avoid these small surface defects, as well as to investigate novel NDT methods that can detect Cold laps. A wide variety of welding parameters have been tested and evaluated in respect to Cold laps formation, in both classical and multifactorial welding trials. The factors and interactions of factors that have strong influence on Cold lap formation have been identified, models have been created in order to both understand the interactions and to give recommendations on how to set the welding process to avoid Cold laps. The recommended parameter settings have been verified in verification welding trials. The conclusions from this project are summarised as:

- Welding voltage, Filler material type and the interaction between these two parameters have shown to have the strongest influence on the Cold lap formation.
    - Different Filler materials have different optimal welding voltage in respect to avoidance of Cold laps (also among solid wires).
- From multifactorial trials it has been possible to predict the presence of Cold laps by modeling the levels of the factors, especially welding Voltage (actual voltage) and Filler material type used.
- Optimal Welding voltage has varied between the various sites and welding equipment used in the project; hence it is an important conclusion that the site-specific optimal voltage will have to be identified (tested) in order to accurately be able to avoid Cold laps. The voltage is an important parameter, not least for setting the arc type and adjusting the arc length, but the findings in this project show that an even stronger focus should be made at finding the optimal, Cold laps avoiding, voltage setting for each filler material.
- A two-step bend test has been developed to identify and quantify Cold laps. This bend test can be used to verify suitable welding parameters.
- A development of a novel algorithm for data from geometric laser scan has shown to be successful in detecting Cold laps. This method is, however, limited to the two types of spatter induced Cold laps due to the geometric nature of these Cold laps (detectable for the laser scanner).
- From classical testing an observation regarding welding Heat input on Cold lap formation was made. With relatively high Heat input, a threshold could be seen where from >1.0 - 1.2 kJ/mm and above, no Cold laps were observed. However, with Heat input <1.0 – 1.2 kJ/mm, specimens both with and without Cold laps were observed. Here, for the low Heat input, it will be important to use optimal process settings, especially correct welding voltage, to avoid Cold laps formation.
- During multifactorial trials and modeling of welding parameters in respect to Cold lap formation, many other aspects of the weld were measured and documented. This enabled the creation of a decoupled model, which have been shown in verification welding trials to be able to accurately predict presence of Cold laps and simultaneously optimize other aspects of the weld. The other aspects optimized by the decoupled model were: Throat thickness, Weld toe radius and Weld penetration.

8.2 Future research

In a future work it will be interesting to enhance the predictive model by including also the upper weld toe and its properties. It is also important to evaluate the findings in a broader environment, in order to see if the guides developed in this project regarding welding voltage and filler material can be applied to other welding positions and conditions. It would also be of great value to continue the work started, to fully optimize multiple aspects of the weld geometry through multifactorial trials and modelling. When the upper weld toe is successfully included in modeling and a variety of welding positions evaluated, this improved model could optimize a weld geometry holistically and ensure a defect free and strong weld. And it will be very important to fully develop the NDT method in Winteria, and in other possible systems.

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