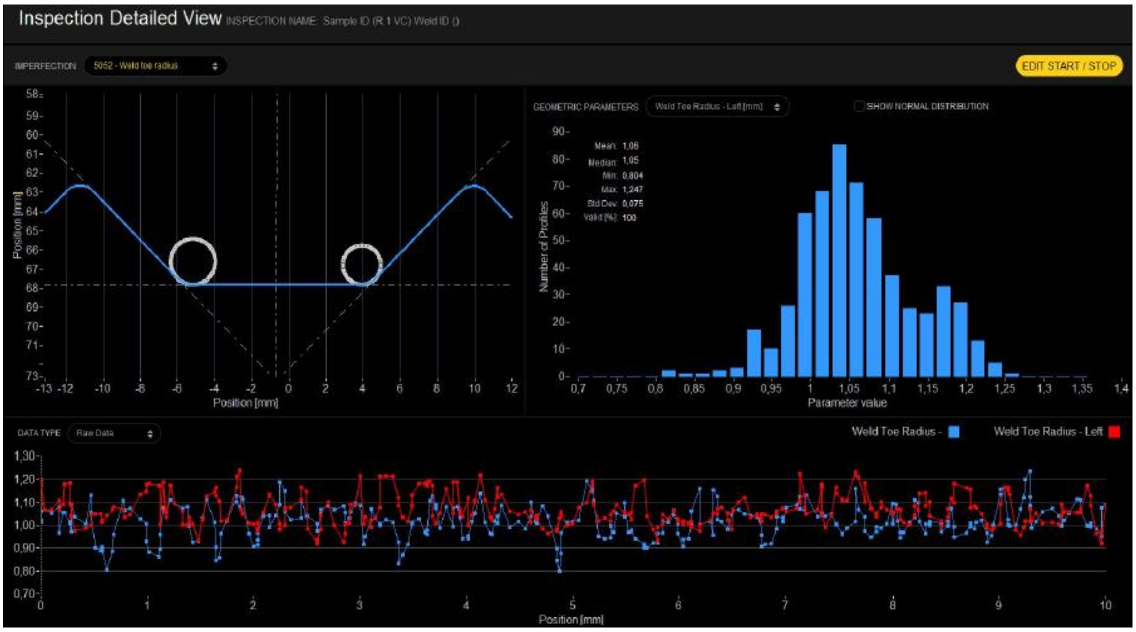
# Q-IN-MAN – New quality system for in-manufacturing-process control of welded structures subjected to fatigue loading

## Open final report to Vinnova

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# 1 Summary

This Q-IN-MAN project targeted three important research areas to solve issues and to be able to make full use of a new laser scanning technology for quality assurance of welded structures. These areas and connected research questions were:

1. DATA

The new system measures with higher accuracy and creates more detailed data. This creates two problems: one is data handling, and the second is that many welded components will (partly unjustified) fail in inspection when the quality limits used today for weldments are implemented directly into the new system. This is due to the fact that the weld geometry varies quite much along the weld and this has not been possible to quantify earlier with reasonable effort. So, more investigations are required to clarify which of all measured data that strongly govern the life and quality of a welded component, and therefore should be focused on in a new quality system adapted for automated inspection. Relevant quality level adjustments should also be determined for the weld classes. Research questions in this area were: Which of all data gathered are most important to ensure fatigue life, what amount of data are needed for the different quality levels, and how should the problems with short and small deviations from weld quality limits be handled.

2. IMPLEMENTATION

Different ways to implement an automated laser scanning weld quality measurement system should be investigated to determine appropriate methods and to give recommendations.

3. QUALITY MANAGEMENT

How should the quality management be organised to enable full use of digital scanning, minimise overwork and increase efficiency in manufacturing.

The project started 2018-04-01, had 5 work packages and was planned with 2,75 years duration. Due to delays (COVID), the project was prolonged with 3 months to 2021-03-31, i.e. 3 years. The total project budget was 7.8 MSEK, where of VINNOVA financed 3.6 MSEK.

The overall vision for the project was to develop and evaluate a new, process-integrated quality system with laser scanning of welds in a production line. Although this vision has not been reached in terms of a fully process-integrated system, the project has developed scanning routines and verified both the procedures and the accuracy of the measurement system. The project has also performed implementation trials, with the results varying from company to company depending on the part geometries but with identified way forward. The laser scanning techniques have been further developed during the projects run-time and fast scanning is possible today (General scan, 6m per minute). The Detailed scan procedure has almost reached the speed target on 2 m per minute (1.2-1.7m per minute today). Some companies have decided to start implementing laser scanning of welds in their quality assurance department as a part of the evaluations. Other companies have decided to go directly for an installation in the production line. Naturally, the choices are directly connected to their experiences made with laser scanning and the work will continue from this point.

One issue that will still be present for some time is that there are no standards for laser scanning of welds, nor are the quality levels adjusted to the accuracy of a laser scanner. Therefore, both manual evaluation and digital evaluation is expected to be utilised in parallel until the scanning technology results have been harmonised and can be cross-referred to earlier evaluations. Work to develop data that can be utilised for revising actual standards has been started but will need to continue. More research to fully understand the weld geometry influence on fatigue is also very interesting and important to perform - the laser scanner give large possibilities to build better models.

This project has been financed by the programme “Fordonsstrategisk Forskning och Innovation, FFI”. The FFI programme and its financiers are gratefully acknowledged.

## 2 Sammanfattning på svenska

Forskningsprojektet Q-IN-MAN adresserade tre viktiga områden för att kunna implementera ny laserbaserad skanningsteknik för kvalitetssäkring av svetsförband. Dessa områden var

1. DATA

Det nya laserscanningssystemet mäter med högre precision och genererar mer detaljerade data. Detta leder till att två problem behöver lösas: ett är själva datahanteringen (hur mycket data behövs och hur sänds, lagras och bedöms denna) och det andra är att många svetsade komponenter riskerar att underkännas med den nya teknologin då den ser och mäter mer och bättre. Små och korta avvikelser, som ofta hittas med laserscanning men inte med vanlig visuell kontroll, behöver kunna få en nyanserad bedömning. Vidare är det av intresse att klarlägga vilka av alla data som är viktigast att fokusera på för att säkra svetsarnas kvalitet med avseende på utmattning. Befintliga kvalitetsnivåer för svetsförband är avpassade för manuell mätning, är dessa adekvata för laserbaserad scanning?

2. IMPLEMENTERING

Implementeringstester ska göras för att hitta rätt metoder och kunna ge rekommendationer.

3. KVALITETSSTYRNING

Hur ska kvalitetsarbetet organiseras för att tillfullo kunna nyttja den nya scanningsteknologin, för att kunna minska överarbete, kassationer och öka effektiviteten i tillverkningen.

Projektet startade 2018-04-01, hade 5 arbetspaket och var planerat att löpa 2,75 år men pga COVID uppstod förseningar och projektet förlängdes till 3 år, till 2021-03-31. Total budget var 7,8 MSEK, varav 3,6 MSEK var från VINNOVA.

Den övergripande visionen för projektet var att utveckla och utvärdera ett nytt processintegrerat kvalitetssystem med laserscanning av svetsförband i en produktionslinje. Även om visionen inte nåtts gällande integrerat kvalitetssystem så har projektet nått långt ändå: projektet har utvecklat och verifierat rutiner för laserscanning, samt verifierat noggrannheten i mätsystemet. Projektet har även gjort implementeringstester, vilka visat olika resultat för olika produkter. En del tester har gått mycket bra medan andra behövde speciell anpassning av mätningarna. Detta kunde kopplas till olika komponentgeometrier och olika förbättringsmöjligheter har identifierats. Laserscanningsteknologin har utvecklats under projektet gång och idag är det möjligt med snabbscanning av svetsförband (Generell skanning, 6m/min) och rutinen för detaljerad scanning har nästan nått sitt mål om 2m/min (1,2-1,7m/min).

Några företag har nu valt att ta sitt nästa steg genom att börja implementera laserscanning i befintliga kvalitetsavdelningar, som en del i utvärderingarna som görs där. Andra företag siktar på att implementera sin scanning direkt i produktionslinjen. Detta är kopplat till det nuläge man sett för sina produkter och sin tillverkning, man arbetar vidare från denna punkt.

Något som kommer att kvarstå med påverkan ett tag är avsaknaden av standarder för laserbaserad scanning. Detta gör att den nya teknologin behöver gå parallellt med den gamla till dess att resultaten är överförbara mellan metoderna. Arbete med att ta fram relevant information för att kunna uppdatera eller ta fram nya standarder har startat men kommer att behöva fortsatt forskning. Även området att kunna bättre koppla samlad aktuell svetsgeometri till utmattningslivslängd är av stort intresse att fortsätta forskningen inom – nu när laserscanning kan ge perfekta underlag är möjligheterna stora att kunna ta fram bättre modeller.

Detta projekt är finansierat av programmet “Fordonsstrategisk Forskning och Innovation, FFI”. FFI-programmet och dess finansiärer tackas för stöd till projektet.

# 3 Background

An earlier project, FFI-ONWELD: "New ON-line method for quality assurance of WELDed structures" (Dnr 2013-04696, running Dec 2013 – Dec 2016) resulted in a new prototype system that enabled full laser scanning, un-biased and automated, quality judgement of welded structures. The system can measure full weld lengths and delivers many weld geometry parameters, objectively and with high resolution. The system with its components and measurement analysis is described in the ONWELD report [1]. This developed system opened theoretically for the possibility of in-manufacturing quality judgement and control as an alternative to post-manufacturing judgement, a new way of working with weld quality management and control.
The prototype was then further matured and developed into a product by the start-up company NWE / Winteria that was initiated after the ONWELD-project. (NWE has changed name to Winteria)
When the new measurement system was available on the market, possibilities should be taken to explore in-manufacturing quality judgement and addressing the hot topic: "how should the actual weld quality best be determined for laser scanning": It had become clear that the new measurement system can be much more accurate than other techniques and this created problems with weld quality judgements (limits for the quality levels) since many welds were classed as having lower quality, compared to results for the same welds when evaluated with manual inspection. The reason for this is that welds are not as even in geometry as it can be expected, and the new measurement technology record this very well – but the limits in the standards are set without an exception for, for instance, a very small or very short deviation (that the digital and automated system will find and report, but the manual inspector can be expected to miss). More research was needed to investigate the situation and propose solutions. The here reported project Q-IN-MAN addressed these areas.

# 4 Objectives, Research questions and planning

The Q-IN-MAN project targeted three important research areas to solve the issues described in Chapter 3 and to be able to make full use of the new laser scanning technology for quality assurance of welded structures. These areas and connected research questions were:

1. DATA
   The new system measures with higher accuracy and creates more detailed data. This creates two problems: one is data handling, and the second is that many welded components will (partly unjustified) fail in inspection when the quality limits used today for weldments are implemented directly into the new system. This is due to the fact that the weld geometry varies quite much along the weld and this has not been possible to quantify earlier with reasonable effort. So, more investigations are required to clarify which of all measured data that strongly govern the life and quality of a welded component, and therefore should be focused on in a new quality system adapted for automated inspection. Relevant quality level adjustments should also be determined for the weld classes.
   Research questions in this area were: Which of all data gathered are most important to ensure fatigue life, what amount of data are needed for the different quality levels, and how should the problems with short and small deviations from weld quality limits be handled.
2. IMPLEMENTATION
   Different ways to implement an automated laser scanning weld quality measurement system should be investigated to determine appropriate methods and to give recommendations.
3. QUALITY MANAGEMENT
   How should the quality management be organised to enable full use of digital scanning, minimise overwork and increase efficiency in manufacturing.

The project started 2018-04-01 and was planned with 2,75 years duration. Due to delays (COVID), the project was prolonged with 3 months to 2021-03-31, i.e. 3 years. The total project budget was 7.8 MSEK, where of VINNOVA financed 3.6 MSEK.

The project had 5 work packages with content and initial planning as described below.

- WP1 Industrial input and requirements served as an input to the project, with questionnaires and interviews, defining the needs and demands.
- WP2 In-process quality management and industrial evaluation handled the research on IMPLEMENTATION and QUALITY MANAGEMENT (the two parts in WP2).
- WP 3 Relationship between measured weld geometry, quality levels, and fatigue performed research on 2 important aspects on DATA PARAMETERS: identifying the most important parameters on fatigue, and their interaction.
- WP 4 Data handling studied DATA COLLECTION and PRESENTATION: amount of data needed per scan for different quality levels, data speed and storage, and the need for adapted illustration of results.
- WP 5 Project management and dissemination was active during the projects run time. Dissemination activities started in 2020 and continued 2021.

Table 1. Gantt schedule for Q-IN-MAN, original planning. Project prolonged to Q1-2021 (COVID).

| | 2018 | | | 2019 | | | | 2020 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| WP no. | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| WP 1 | | | M2 | | | | | | | | |
| WP 2 | | | Part 1 → | → | → | → | M3 → | Part 2 → | → | → | M4, M5 |
| WP 3 | | | | | | M6 | M7 | | | | |
| WP 4 | | | | | | | M8 | | M9 | | |
| WP 5 | M1 | | | | | | | | | | M10, M11 |

# 5 Vision and Goals

The overall vision for the project was to develop and evaluate a new, process-integrated quality system with laser scanning of welds in a production line. To reach, the following goals were set:

- Identify and develop a new, smart, in-process quality management, utilizing the new techniques
- Evaluate how the new techniques and quality management can be built-into a production line
- Clarify the relationship between fatigue performance and measured weld geometry
- Determine which and how much of the different scanned data to focus on, to ensure quality
- Determine data handling techniques to enable high productivity in scanning and judgements
- Evaluation of the Quality management system in industrial production
- Develop Guidelines for the new integrated QA system

The Q-IN-MAN projects contribution to the FFI-targets was specified as follows:

Table 2. FFI-targets and Q-IN-MAN contributions.

| **Targets for the FFI Programme** | **Contribution from Q-IN-MAN** |
|---|---|
| *To increase the research and innovation capacity in Sweden and thereby ensure vehicle-industrial competitiveness and future jobs in the industry* | Participants in Q-IN-MAN are part of a strong hub for vehicle research, with broad network and dissemination capacity. Q-IN-MAN is also connected to several other FFI projects. |

| | |
|---|---|
| *To develop internationally connected and competitive research environments in Sweden* | International cooperation: IIW is one example where several participants have roles as Chair or Delegate. Research papers are often presented (Q-IN-MAN has contributed). |
| *To support participation of SME:s* | Winteria participating, a start-up company with the new quality system. |
| *To support participation of Tier 1,2,3 suppliers to the vehicle industry* | Winteria is a supplier to OEM:s in the vehicle and transport industry. |
| *To support cooperation between different branches* | The project established cooperation between vehicle, transport, aerospace, agriculture, and digitalisation / quality management branches. |
| *To support cooperation between University, Institute and Industry* | The project has cooperation between all mentioned parties: Universities, Institute and different Industrial branches. |
| *To support cooperation between different OEM:s* | Volvo, Scania, GKN, Toyota, HIAB, and Väderstad are cooperating in this project. |

It was also expected that Q-IN-MAN should contribute with the following results and deliveries:

- Clarification on which of all new measured data that strongly govern the fatigue life and quality of a welded component, and therefore should be focused on in a new quality system for auto-inspection.
- A higher resolution of the relationship between fatigue performance and measured weld geometry, how large deviations in measured data that can be tolerated before quality (fatigue life) is affected.
- Suggested adjustments in data handling, and of weld quality levels (ISO 5817, and similar).
- Identification and development of a new, smart, in-process quality management, utilizing the new techniques.
- Results from industrial trials with the quality system.
- A routine for the data handling for use in the developed quality management system.
- Evaluation of trials with the developed quality management system in industrial production
- Guidelines for the new integrated QA system
- Cooperation with other projects, especially FFI-PREMOD, FFI-HIPFAT, FFI-VARILIGHT
- PhD research and scientific articles.
- Broad dissemination activities and contribution to education at KTH, Chalmers and in companies.

TRL-levels:
The Q-IN-MAN project will utilize the Winteria system (former named WELDASSIST) that has TRL 7-8 in its functions – and develop a quality system around this technology, increasing the welding in-manufacturing quality inspection from TRL levels 4-5 to TRL 6-7.

# 6 Experiments and Results

## 6.1 WP 1 Industrial input and requirements

WP1 Industrial input and requirements served as an input to the project, with questionnaires and interviews, defining the starting point, needs and demands. Swerim and Toyota lead this work package and the work in WP1 is summarised below.

### 6.1.1 Costs related to weld quality, geometry and scanning

#### *6.1.1.1 Weld costs today*

The costs related to welding and weld quality can be divided into several categories:

- Inspection cost (personnel)
- Tool costs
- Delay cost
- Correction costs
- Too high-quality costs
- Late fault detection costs
- Excessive weld costs
- Missing weld cost
- Field campaign cost
- Damage & accidents during usage
- Cost due to error in manual inspection

#### *6.1.1.2 Cost impact with scanning system*

The cost impact of implementing laser scanning of welds depends on the specific case and the actual costs and ROI must therefore be assessed. The changes can be divided into different categories, see table below.

Table 3. Laser scanning cost impact analysis.

| **Cost increase** | **Cost decrease** | **Uncertain impact on cost** |
|---|---|---|
| • Tools & Equipment<br>• Workshop space<br>• Increase of fails & repair?<br>• Operator cost scan system<br>• Software license<br>• Server<br>• Network? | • Inspection (personnel)<br>• Too high quality<br>• Excessive weld<br>• Damage & accidents during usage<br>• Cost due to error in manual inspection<br>• Field campaigns<br>• Missing welds<br>• Late fault detection<br>• Better statistics for remedy of systematic problems | • Corrections<br>• Delays (lead time) |

### 6.1.2 Requirements for a future weld scanning system

Welds can be scanned either manually or automatically. Since todays weld measurements are performed with less accurate mechanical methods, much can be gained from just replacing mechanical measurements with manual laser scanning.

The possibilities with scanning and evaluation can be:

- Pre weld analysis (gap, location and alignment)
- Weld geometry compared to criteria
- Fatigue evaluation (sensitivity due to combinations of geometry)
- Identification of typical weld process problems
- Amount of excessive welding (throat thickness) & Excessive quality
- Continuous optimization of the production process

When comparing the manual and automatic methods, some general remarks about the applicability can be made:

Manual method:

+ Portable, can be used anywhere
+ No robot programming
+ Low tool cost
+ Doesn't require additional space
+ Doesn't interfere with the production process

- High personnel cost
- Scans are usually made long after production
- Lower scan quality than automatic scanning

Automatic method:

+ Low personnel cost
+ 24/7 operation possible
+ Early detection of defects, production stop
+ Tuning of weld parameters
+ 100% inspection rate feasible
+ Exact scan parameters possible
+ Pre weld scan possible (gap, location, alignment,…)

- Requires robot & programming
- May require extra space
- May increase cycle time
- Higher initial investment
- Less adaptable, depending on installation

#### *6.1.2.1 Manual laser scanning*

Manual laser scanning is performed with a handheld device by an operator. For reliable results, the operator must perform the scan with:

- steady speed
- steady distance to the weld
- correct angles to the weld (working, travel and rotation angles)

The handheld system should support the operator to perform an acceptable scan with indicators for the angles, speed and distances. Feedback to the operator could be both visual, audible and physical. The system should also register location and speed for the scan in order to determine weld length. Size of the system should be kept as small as possible in order to access confined spaces. Maximum scan speeds of up to 15 m/min should be possible. The sampling frequency at this speed can be reduced in order to determine basic parameters like throat thickness.

Interaction between system and operator could be handled both via controls and display on the handheld device or via a notepad, laptop etc. There should at least be a possibility to start and stop a scan with a button on the scanner. Identification of the scan data is in its simplest form done via naming of the scan file per weld, but the best solution would be the possibility to create scan scheme templates per component. The template would be attributed with drawing number and revision. Each weld is assigned an ID, weld type, dimension and length. Scan schemes can be created with a subgroup of the welds (small, medium or large scan). The welds included in a scan scheme could also be randomized. The operator can follow the scheme via pictures and drawings on the display. Scan frequency is pre-set in the template and speed, direction and orientation are shown in the display. Naming, evaluation, saving, statistics and repair decision is handled automatically.

Result feedback to the operator could primarily be:

- OK
- Repair
- Deviation, not optimal weld, info to prod unit (small defects, parameter adjustment, excessive weld etc)

The system should preferably be possible to use both standalone (with a computer) and online connected to a cloud solution. Network (Wifi) quality is not always sufficient in workshops which affects the possibility of a cloud solution. A network disturbance should not result in a production stop.  Furthermore, a cloud solution with external servers poses data integrity and security issues.

#### *6.1.2.2 Automatic laser scanning*

Automatic weld scanning means that the scanner is mounted on a robot and scans are performed according to a programmed scheme. The automatic system could be installed in individual robot cells where a 100% scan rate is possible. The scanner could either be mounted on the welding robot or on an additional robot. The possibility to do a pre weld scan of selected weld locations for misalignment, gaps and placement adds a lot of value. A useful feature would be the possibility to scan while welding is ongoing in the same robot cell. Scanning speeds of at least 2m per minute should be possible to avoid bottlenecks.

When focus is on low cycle time:

- Welding is ongoing continuously
- Scan performed after welding out of fixture or on in a duplicate fixture
- Requires additional robot and possibly a positioner
- Scanning is performed at the same speed as the welding, or faster

When focus is on low investment cost:

- Welding is interrupted for scanning
- Scanner is mounted on a tool changer on the welding robot

Scan speed is dependent on the scan frequency, influence on productivity, detail level and the accuracy required but a speed of at least 2 m/min with is needed in some cases.
A compromise can be to install a scan robot cell serving multiple welding cells. This would require identification of components to be scanned (if different) and a common reference point. A positioner may also have to be installed and require individual fixturing

#### *6.1.2.3 Scan software*

Some specific software functions have been mentioned in the previous chapters about manual and automatic scanning. Some further features suggested for the software are:

- Easy install
- Accurate & fast evaluation of the scans
- Adaptable criteria for weld geometry
- A minimum of repetitive input from the user
- Failed welds shall be listed
- A possibility to set limits and alert for excessive throat thickness (cost reduction)
- The possibility to create scan scheme templates
- Data storage on server of compressed data
- Possibility to identify a component from a tag/RFID
- Possibility to automatically assign an ID to a scan from a tag/RFID on the component
- Scans should have all needed metadata attached (when, where, by what, …)
- An ID system for referral to individual welds
- Statistical evaluation of stored scan data

Users should have different user interfaces depending on user category:

Table 4. User interfaces suggested for different user categories.

| | |
|---|---|
| • Robot cell operator<br>• Manual inspection operator | • Scan operation screen<br>• Pass/fail<br>• Detailed result of current scan |
| • Production engineer | • Statistics & alerts<br>  ○ Acc. fail per equipment<br>  ○ Acc. fail per component/weld<br>  ○ Fail type statistics<br>  ○ Excessive weld |
| • Production manager | • Fail per operator<br>• Comparison between production units/cells |
| • Quality personnel | • Overall fail rate over time<br>• Fail per department |

#### *6.1.2.4 Criteria for laser scanned welds*

Many companies use ISO 5817 as a basis for weld geometry criteria. This standard is adapted to mechanical measurement instruments performed by a human. It is essential to be able to certify components according to a harmonized international standard and until a new standard is developed a translation/adaption must be made for laser scanned welds. Some criteria are very hard to measure mechanically (without extra judgement), and companies may currently accept deviances from the standard that they are unaware of or disregard.
Volvo AB has a recently revised their corporate standard where the weld toe radii is one of the more important parameters and this is very difficult to measure correctly with manual methods. The laser scanner manages this very well, but the result can be that a short outlaying part with too small radii discards the weld from the specified weld class. This would in many cases not have been found with manual visual testing. An extra judgement or adaptation of the measurements need to be made for these cases.

The first adaption is to filter the laser measurement so that it reflects what a mechanical tool would measure. An example is the throat thickness where the filtering should use the most protruding scanned geometry over the corresponding mechanical tool thickness. It is also important to filter according to the short imperfection’s clause in ISO 5817.

Scan frequency and speed also influences the result and research should be performed to find suitable recommendations.

Furthermore, many companies may have to revise their criteria or specifications for geometry on certain welds, for example toe radiuses on welds with low fatigue loading. Criteria and scan parameters could perhaps be different for cases with and without fatigue loading.

The participating companies vary in size, level of production and production rate as well as internal and external requirements. What they all have in common is that welding is a major part of their production and quality assurance is essential. Including a large variety of companies in the project ensures that different points of entry is taken into consideration when developing the new technology. Some companies/applications require very detailed scanning while others are satisfied with less detail, the technology needs to meet both demands satisfactorily.

### 6.1.3 Quality control and Visual Inspection in the companies

Welding and type of joints vary between the companies. Most companies require weld class C, but some companies use up to 6 different levels of weld classes, and they also use their own standard for symbols. Critical welds which need special control are marked on weld drawings. Additional markups on weld drawings are areas where weld start and stop is not allowed. The most critical aspects of quality in production with regard to the actual weld are: dimensional control, weld toe radius and/or angle, undercut and throat thickness.

Naturally, as the companies differ there is also a variation in the amount of people working with quality control and how it is organized within the companies. For some companies most or all welding is done at different suppliers and there is a quality department which oversees incoming inspection. For companies with in-house welding, quality control is often performed by several departments. Visual inspection is performed by the operator during and after welding as well as by the operator during weld robot programming. Weld audit is performed by support functions with inspectors in production development. Among the companies the requirements on inspectors who perform visual testing/inspection varies from no specific requirements to internal or external training for several days. Since visual inspection is defined differently in the companies it is difficult to outline a set number of people working with visual inspection, from what can be gathered it varies from 2-3 up to 12 people.

## 6.2 WP 2 In-process quality management and industrial evaluation

In WP2, lead by HIAB and Swerim, scanning procedures were developed and verified, implementation trials were made and new possibilities in quality management was discussed. This is further described below.

### 6.2.1 Classic visual inspection versus laser scanning

Classic visual inspection is made according to the international standard EN ISO 17637. There is no standard for visual inspection and evaluation based on laser scanning equipment, but the philosophy and principles of EN ISO 17637 could also be used for laser scanning. The comparative steps are illustrated in the flow chart below in Figure 1.

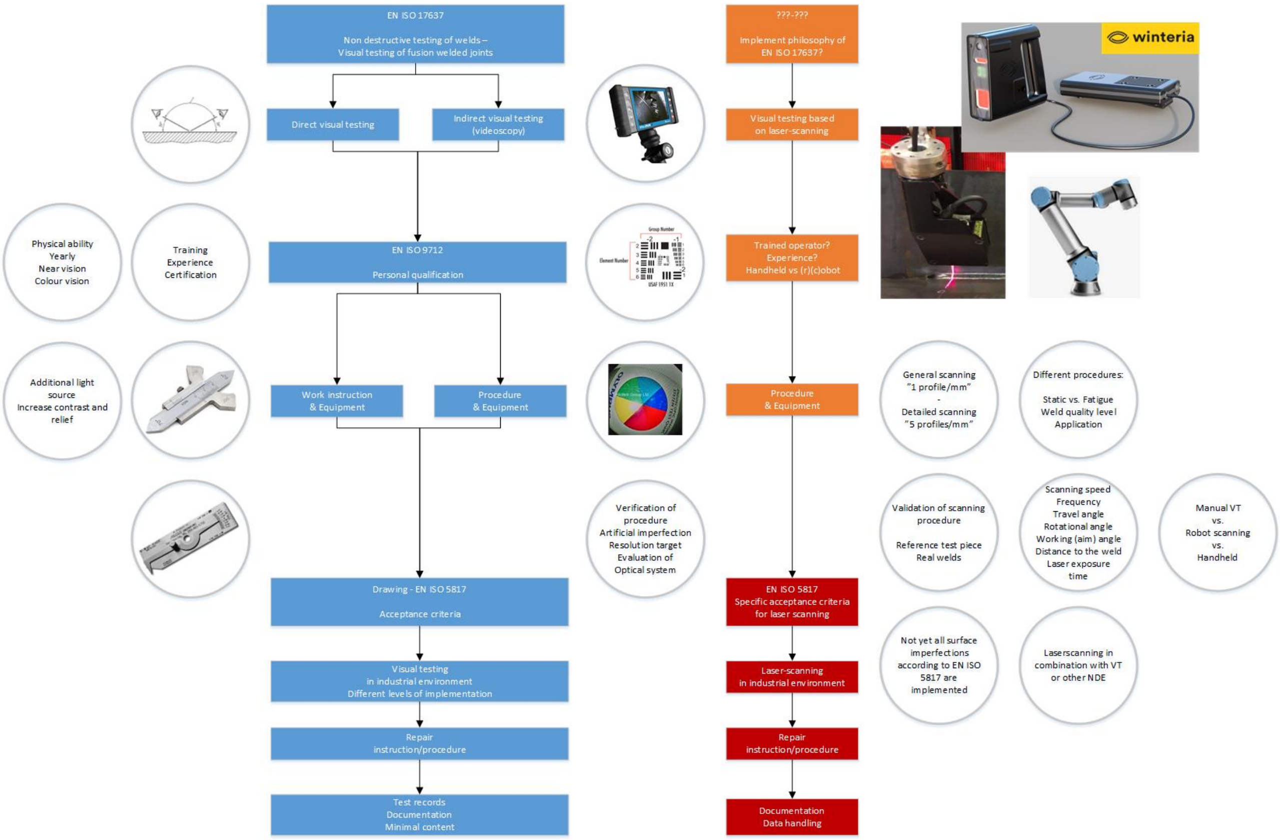


Figure 1. Visual inspection made according to EN ISO 17637 (left), and suggested method for visual inspection with laser scanning (right) and the same principles as in EN ISO 17637.

### 6.2.2 Scanning procedure

The line laser scanner has high accuracy, 4-7µm in z-direction (depth), but since it is a transverse line that is transported along the weld and the line geometries are captured as segments that will be used to build up a model of the weld geometry, the laser line will need to be quite perpendicular to the weld in order to capture the weld geometry correctly. Some deviations from the perfect scan position and orientation can be tolerated, but how large can these be before too large errors are created? And which frequency on the laser scanning is necessary to use in order to capture the weld geometry and eventual defects correctly? How fast can the travel speed be for the scanning for different demands? These questions needed to be answered in order to develop reliable scanning procedures and "standardized ways" to utilise laser scanning, i.e. first steps towards a standardization of laser scanning.

To evaluate required frequency, scanning speed, scanning head orientation, angles and positioning, special reference blocks with artificial welds were created and 3D printed (see Figure 7). Evaluations were also made with test blocks and welds that had been used earlier in the companies and Swerim. The geometries of these blocks and welds were well known, through earlier or new verification measurements with other equipment (Swerim's Alicona equipment as one example).
With these test pieces, a 2-step multifactorial evaluation was launched. The set-up of the first step was broad with many parameters included and the goal for these tests was to perform screening – identify the important parameters that influence accuracy and cause errors. In the second step, these parameters were more thoroughly investigated with the goal to build models for error-causing. With these models developed, errors could be successfully simulated – and verified through laser scanning and evaluation. With the knowledge developed, scanning procedure tests were made at the test site at

HIAB. A method with two scanning procedures was developed, one for General scanning and one for Detailed scanning. These are illustrated in figure 2 below. The principle is to first perform a General scan of the whole weldment. This can be done at high speed, 6m per minute and results in one laser scan per mm and a good general image of the weld. Parts of the weld that has higher demands (higher fatigue load for instance), or positions found in the General scan that need more attention, will then be scanned again with higher resolution, a Detailed scan (approx. 5 laser scans per mm). The Detailed scan can be performed with 1.2-1.7 m/minute scanning speed at present.

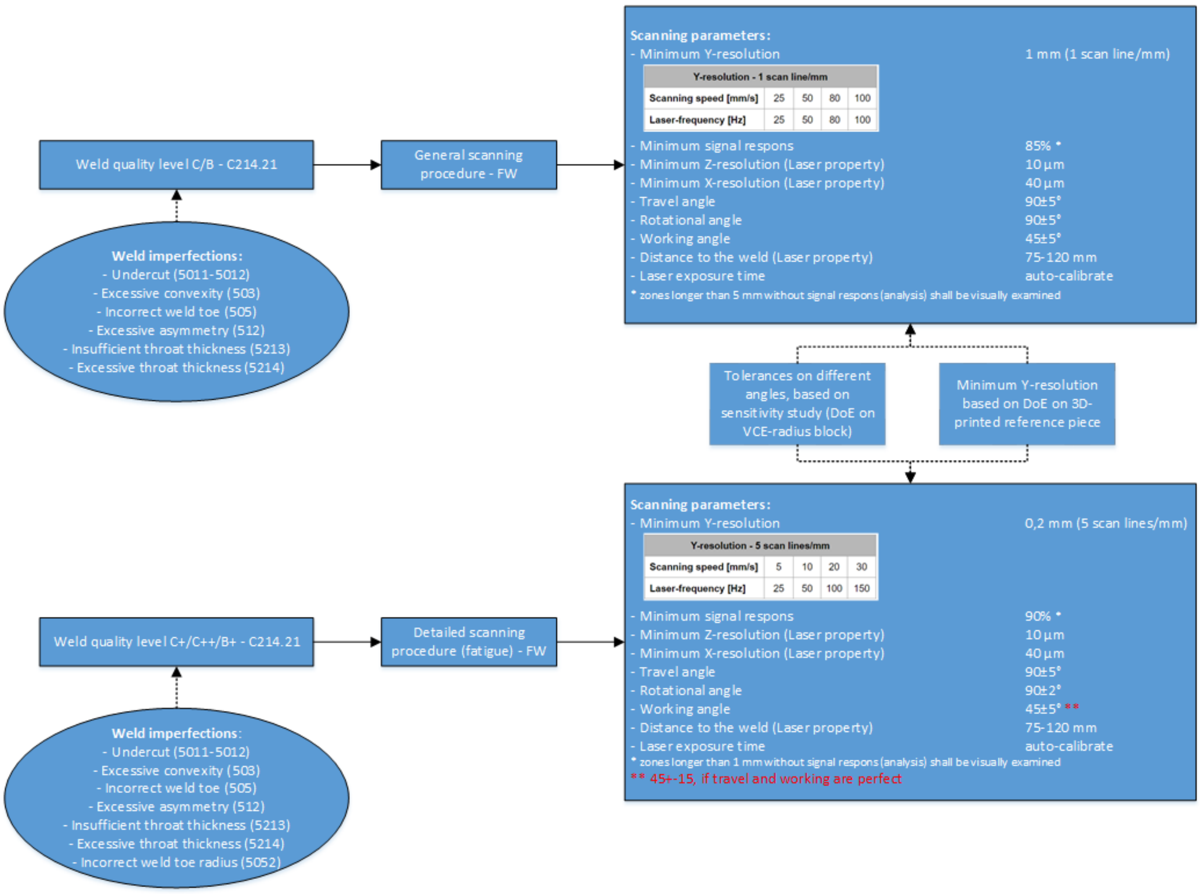


Figure 2. Developed scanning procedures: General scan (upper) and Detailed scan (lower).

Information about the axis and resolutions: (see also Figures 3-6)
X-resolution: laser property, distance between two points - typical value 0,04 mm
Y-resolution: scan lines per mm, depending on speed and frequency
Z-resolution: laser property - typical value 0,004-0,007 mm

Example Y-resolution of 1 scan line/mm:

| Y-resolution - 1 scan line/mm | | | | |
|---|---|---|---|---|
| Scanning speed [mm/s] | 25 | 50 | 80 | 100 |
| Laser-frequency [Hz] | 25 | 50 | 80 | 100 |

Example Y-resolution of 5 scan lines/mm:

| Y-resolution - 5 scan lines/mm | | | | |
|---|---|---|---|---|
| Scanning speed [mm/s] | 5 | 10 | 20 | 30 |
| Laser-frequency [Hz] | 25 | 50 | 100 | 150 |

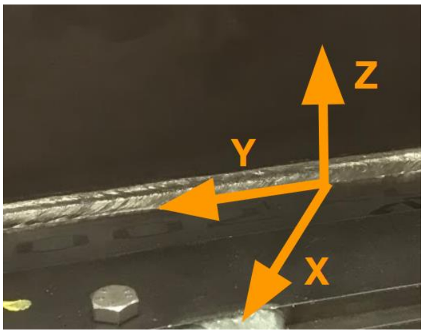

Figure 3. X, Y, and Z axis definitions.

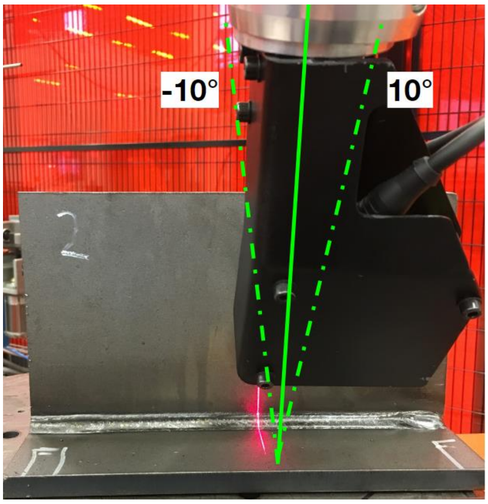

Figure 4. Travel angle definition and tolerances.

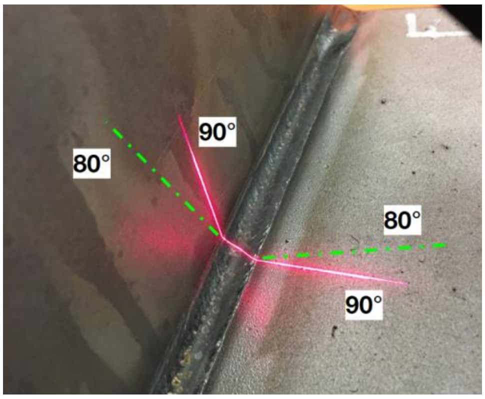

Figure 5. Rotational angle definition and tolerances.

Other information on settings and conditions used for the laser scanning:
Laser exposure time, typical setting "automatic"
Distance to the weld, laser property, typical value between 70-120 mm
Operator skills (experience) - for robot laser scanning not considered.
Test piece parameters: surface condition, straight/curved weld, weld quality level
Surface condition: rotating steel brush applied (taken as standard within the project)

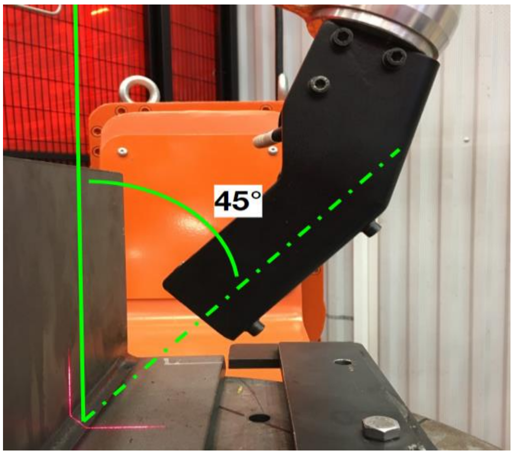


Figure 6. Working angle definition, tolerances are ±5 degrees.

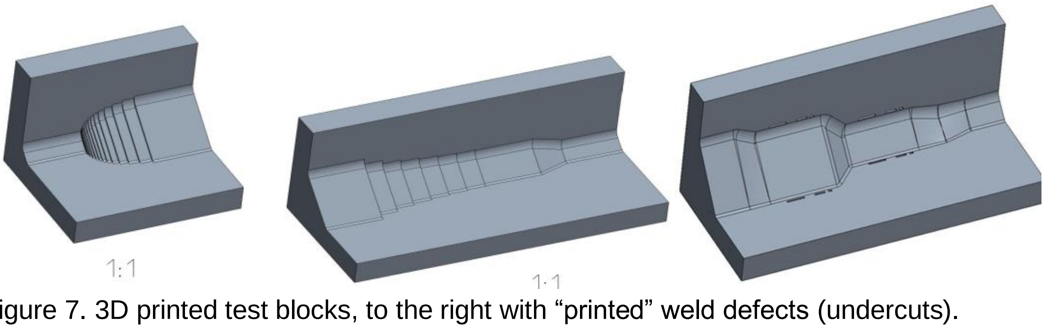


Figure 7. 3D printed test blocks, to the right with “printed” weld defects (undercuts).

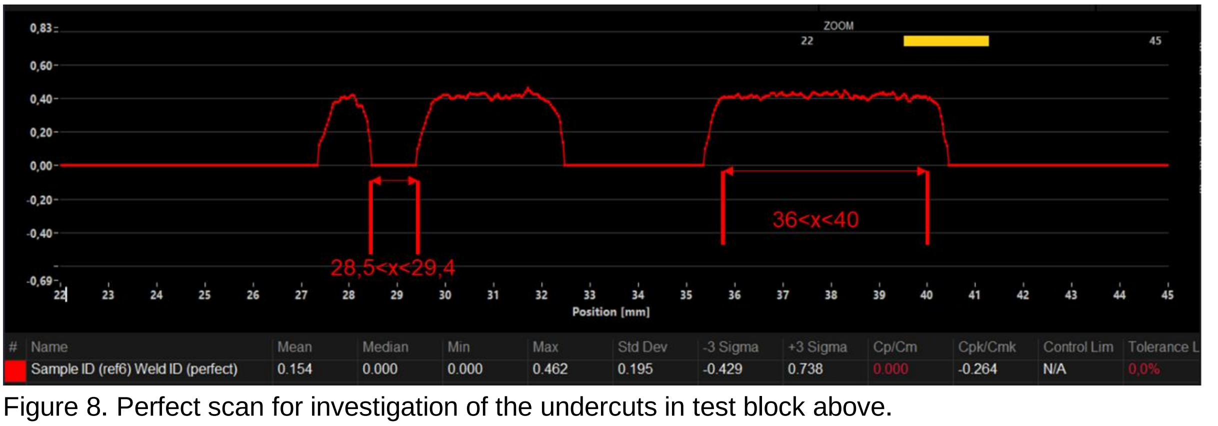


Figure 8. Perfect scan for investigation of the undercuts in test block above.

The test block with undercuts were used to investigate possible scanning speeds and required frequency, in order to keep the information of 3 consecutive undercuts present along the “weld”.

Chalmers has made substantial contributions in planning and leading the multi-factorial evaluations and verification of the laser scanning based measurement system, and the scanning procedures developed. This evaluation work is extensive and would require 20-30 pages to be properly presented. The results from this work have therefore been condensed into the results presentation in this chapter. In the Guideline for laser scanning that will be launched later this year, the collected work on measurement system verification will be described.

Comparisons were made in this part of the work package between manual visual testing (operators in the companies) and laser scans performed with the developed scanning procedures, to validate the scanning procedures. These validations were made by 3 different persons independently.

During the project Q-IN-MANs run-time, Winteria had developed also a hand-held scanning unit (Winteria-Flex) and some trials were made also with this equipment. Comparisons were also made between the hand-held and the robot-mounted scanning systems. These trials were made on 5mm fillet welds as shown in figure 9 and 10 below.

Figure 9. Winteria Flex hand-held system measuring an a5 fillet weld.

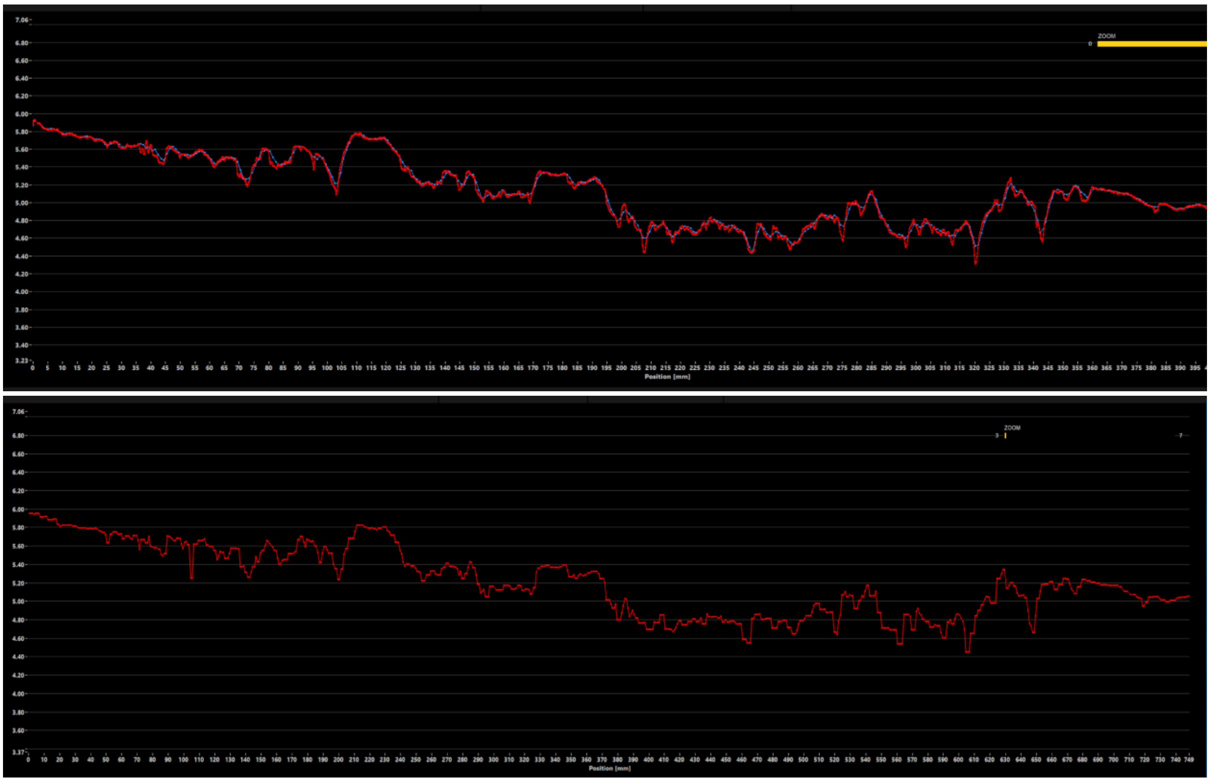

Figure 10. Robot scan versus handheld scan of the a5-fillet weld.

### *6.2.3 Experiences from testing implementing the laser scanning system*

In this work package, implementation trials were made by participating companies. HIAB, Volvo CE, and GKN are the companies with largest experience from laser scanning and these companies have during the project developed, or started to develop, strategies for implementation of the technology. Other companies made the first trials within the project and their experiences are presented below.

**Scanning of test components from production – Toyota Material Handling**

A test was carried out with a laser scanner mounted on a robot on test pieces from production. A component was selected, and ten test pieces were picked out randomly. Both a4 welds indicated in figure 11 were scanned.

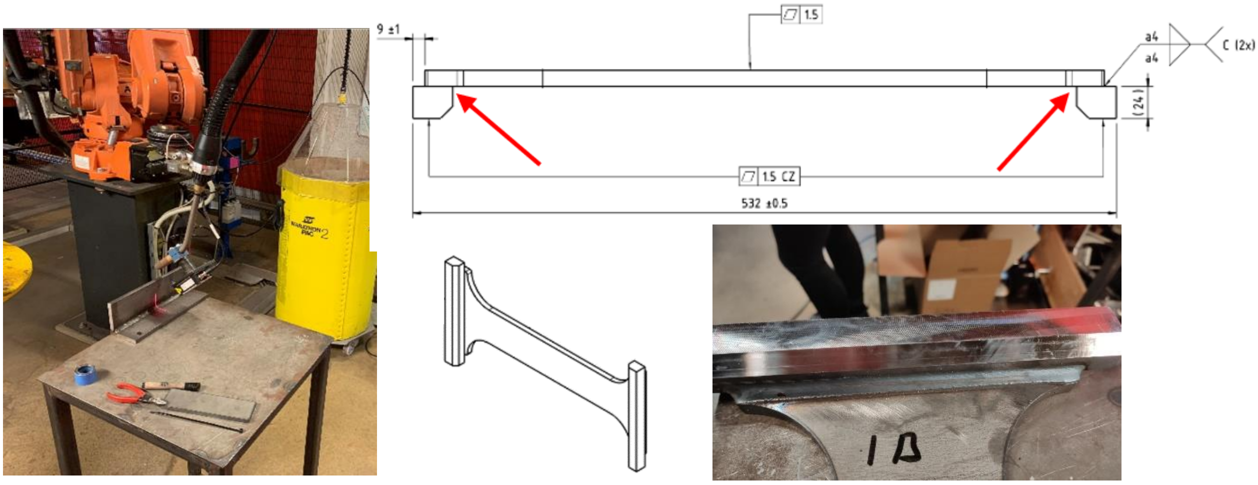


Figure 11. Robot cell & test piece

The test pieces are welded by a subcontractor and had passed manual inspection. Although the test pieces looked OK visually with smooth welds, laser scans revealed that they were failed. As shown in figure 12 below, the throat thickness was insufficient on many of the welds.

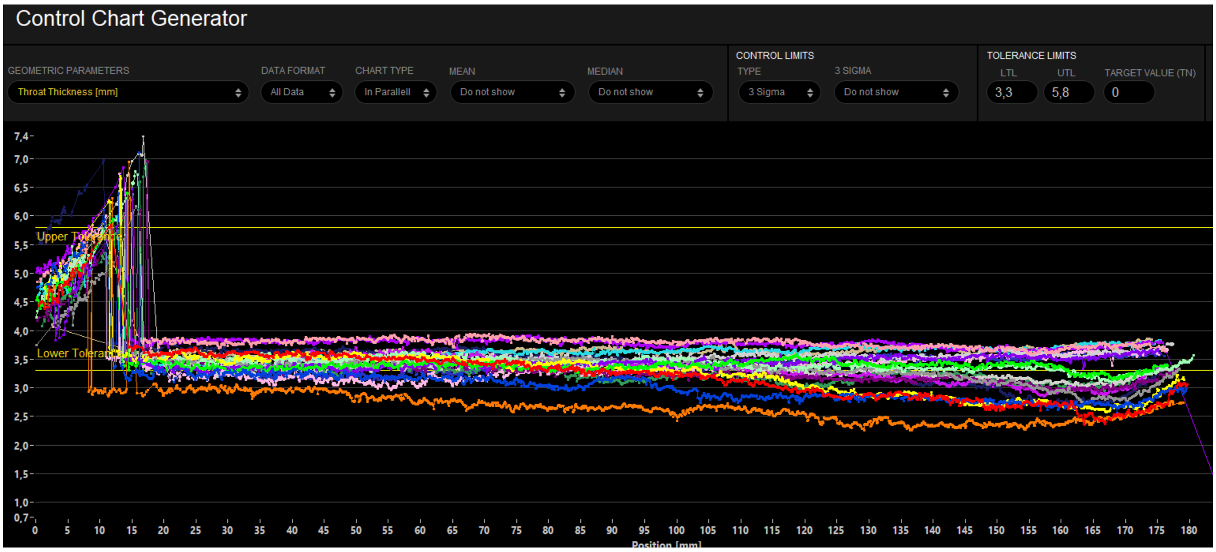


Figure 12. Insufficient throat thickness identified by laser scanning.

Some of the welds had also leg deviations, as seen in figure 13 below.

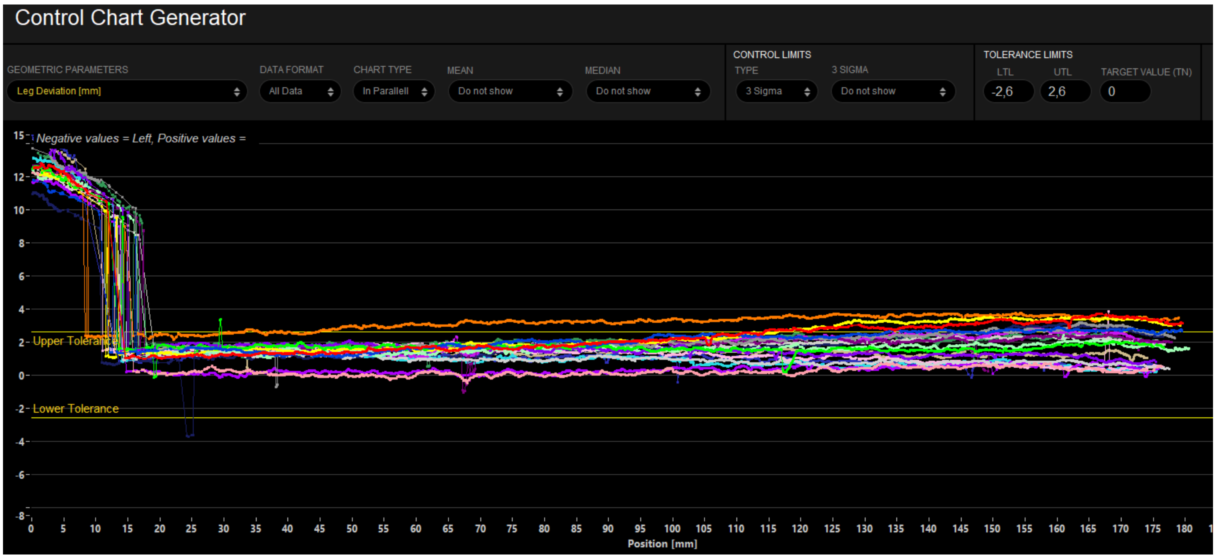

Figure 13. Weld leg deviations identified by laser scanning.

The leg deviation leads to most of the welds having a bead width corresponding to an ideal a4 (8 mm), which probably contributed to them being accepted in manual inspection. The subcontractor was contacted and subsequently made corrections in their production. New corrected components were then scanned again.

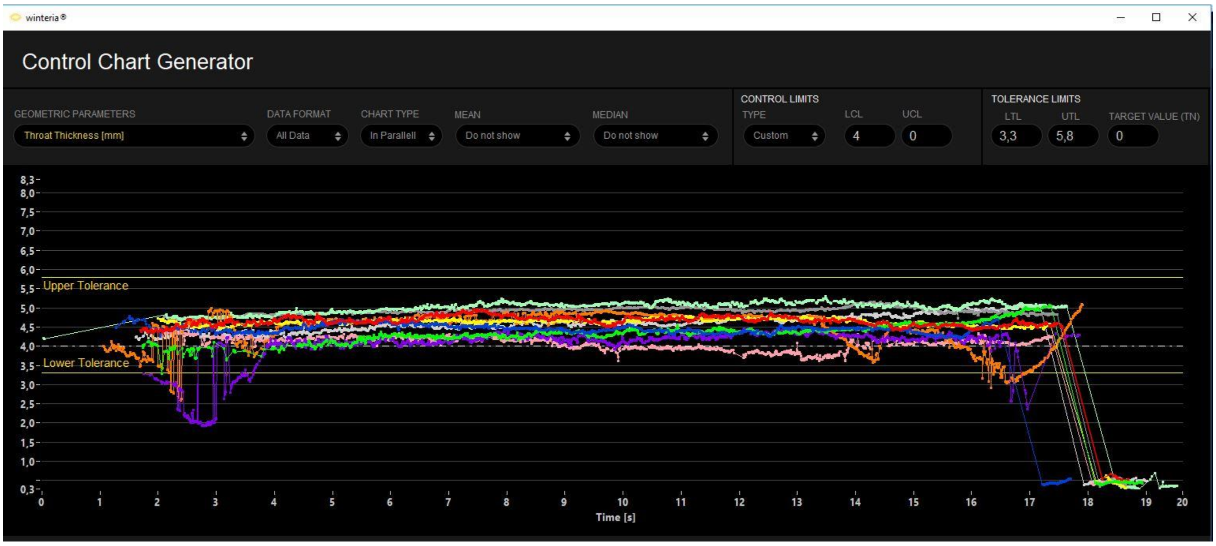

Figure 14. New throat thickness on revised components, measured by laser scanning.

Five corrected test components were scanned and found to be OK, see figure 14 above.
These tests have created interest within Toyota to continue to evaluate welded components and welding production with laser scanning. Discussions are on-going, but a logic next step would be to utilise scanning equipment in the quality department.

### Scanning of test components from production – Väderstad

Väderstad decided to evaluate possibilities to implement laser scanning in a high-volume welding cell with heavy inspection pressure on the operator. This welding cell produces wear components to combine harvesters and has large fixtures with 8 identical components welded in the same tempo. The welding is fast and during the robots welding time, the operator needs to unload and inspect the made parts in the other identical fixture plus reload with new parts in the fixture. The fixture with parts is shown in figure 15 below. The positioner in this welding cell has 2 identical sides with identical fixtures, one side is in welding, while the other side inspected+unloaded+reloaded.

Figure 15. Welded high-volume part for a combine harvester (left) and one side of the positioner with the parts mounted in the welding fixture (right).

The laser scanning trials had some initial problems identifying the welds, due to changes in the geometry along the scanned path, and also some problems with bright surfaces. One weld geometry started as a fillet weld while the end section resembled a butt weld. Solutions to these problems were identified successively later in the project by Winteria. Adapted programming is required, with crop windows utilised for the scanner to increase the weld identification capacity (inform the system where to search for a weld). A preferred solution by Väderstad is to have a very simplified information view for the operator, to reduce amount of information and focus on the important issues: OK / not OK. See figure 16.

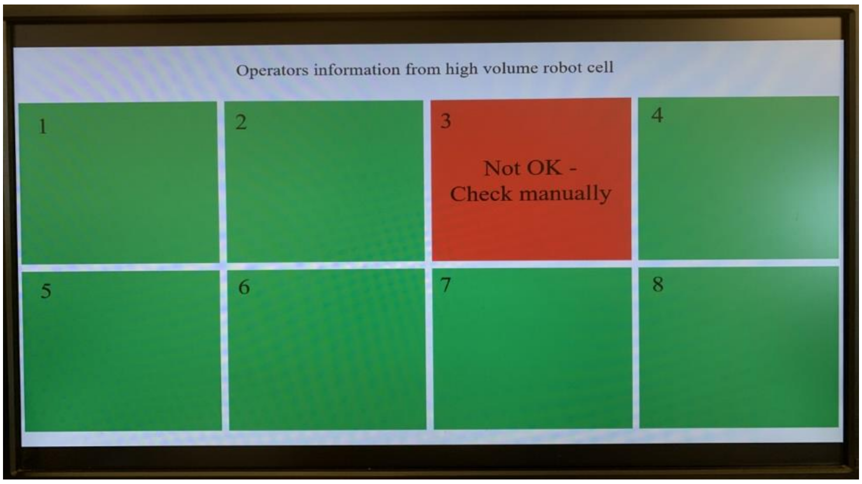


Figure 16. Wished graphical information to the operator of the high-volume welding cell.

(Note: a similar simplified view is available in the system now)

**Scanning of test components from production – Scania**
Scania decided to evaluate possibilities to perform quality evaluations on welds on a rear axles. Some of these welds have difficult geometries and some are more easy, with “standard weld geometries”. See figure 17 below.

Figure 17. The Scania type of rear axle used in test with laser scanning.

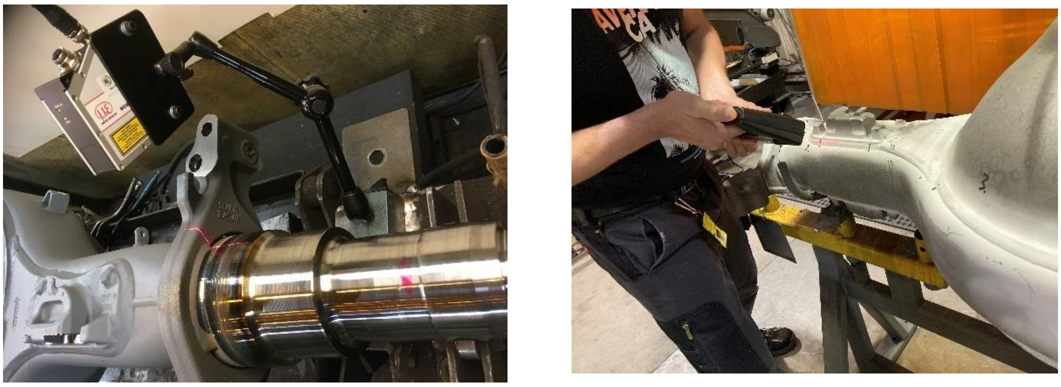

Figure 18. Welds scanned in rotomat fixture (left), and with handheld scanning equipment (right)

Rear axles were scanned in Scania with rotomat fixture and a handheld equipment as shown in figure 18 above, and also with robotic scanning at HIAB test lab. The results show that well defined welds such as fillet welds and butt welds are easily inspected by laser scanning, but other welds with varying geometries will need adapted programming, as in the case of Väderstad. See figure 19.

Figure 19. Welds on the rear axle: needing adapted programming (left) and direct scans OK (right).

The laser welds on the rear axles were also scanned and analysed, see figure 20. The resolution of the scans are very high – also the marker pen drawing on the welded component in figure 20 can be seen in the scan (see figure 20, in right image).

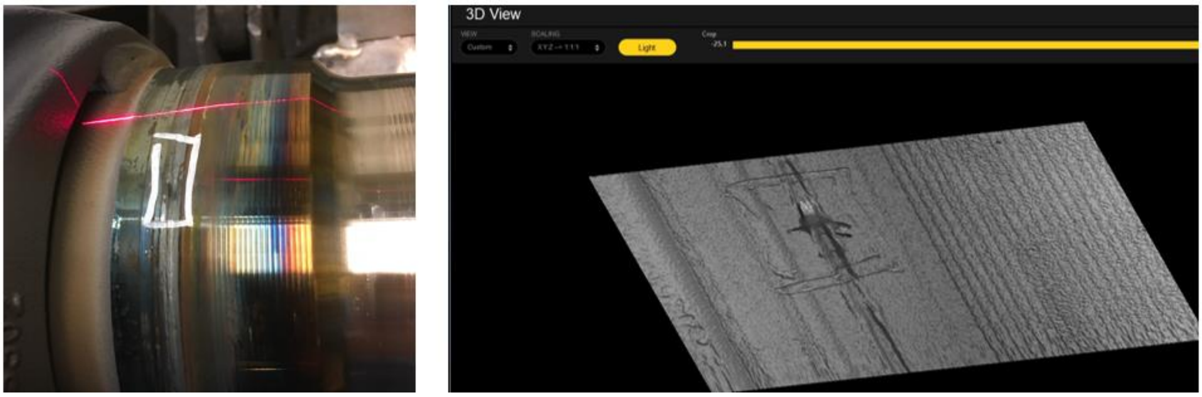

Figure 20. Laser weld on the rear axle (left) and surface information with high resolution from the scan.

The experiences from the scanning evaluations in Scania show that all welds cannot directly be analysed by laser scanning. And quality evaluation vs. the laser weld standard SS-EN ISO 13919-1 is of interest to also have incorporated in the automatic evaluation in the system. A logic next step would be to have laser scanning accessible in the quality evaluation department for evaluations, and to continue to develop scan ability for the welds on the rear axle (program the system for the welds).

#### *6.2.4 Quality management work*

The project should discuss and develop other and more efficient ways to organise the weld quality evaluation work, how to best utilise the possibilities with laser scanning. This part of the project has worked with questionnaires, work shops and interviews. A meeting was also held with the Swedish Welding Commission work group AG48 on the present position in the project work and recommendations were discussed. However, no main direction has emerged – the participating companies have different products, demands, organisations and culture. The scanning implementation trials have also shown different results and selected approaches for next step. Laser scanning equipment will in some cases be installed in the present quality department first, to learn and further develop with the technology. And in other cases, the scanning will enter directly into the manufacturing cells (the first cases now being prepared for installation). The present situation with standards lacking update for laser scanning: weld inspection and weld quality standards, is unsatisfactory. New efforts will be made to find possibilities to increase activities in this area.

## 6.3 WP3 Relationship between measured weld geometry, quality levels, and fatigue

This work package investigated the relationship between measured weld geometry, determined weld quality, and predicted and reached fatigue performance for the welded joint/specimen. One part of the work package consisted of analysis of a large number of welded test specimens. These were laser scanned and the geometries entered and evaluated with FEM to make fatigue life predictions for each specimen and to start building a generic prediction model. The vision is to be able to predict a fatigue life after laser scanning a weldment. The idea was also to utilise these predictive models to investigate which geometric deviations, and scanned parameters, that were most influencing on fatigue. And ideally, to be able to see interactions between different but closely oriented geometric deviations. In this work package, fatigue testing was also made with test series with different controlled geometrical deviations. KTH lead this package that is described more below.

Detailed simulations of scanned fatigue test specimens has been carried out to investigate the correlation between the variation in weld geometry and the fatigue strength. This is schematically presented in Figure 21 and the steps are described below.

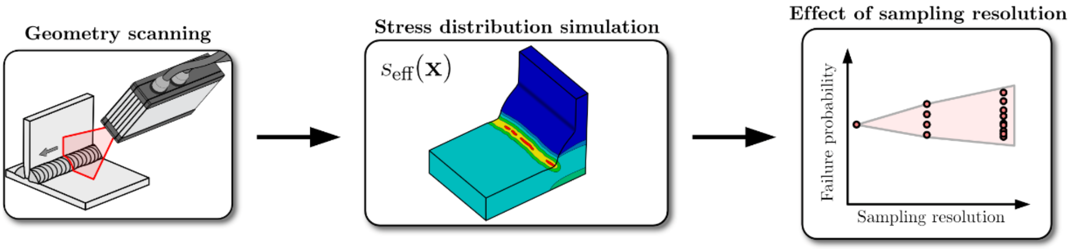


Figure 21. Method for assessing relationship between true weld geometry and fatigue strength

1. **Geometry scanning.** The geometry of each test specimen is scanned using the Winteria ® qWeld to capture the detailed geometry of the welded joint, which is used to digitally recreate the specimen. The quality of each specimen is assessed using the Winteria ® algorithm to extract how geometrical parameters such as the weld toe radius and the weld toe angle vary along the welded joints, see figure 22.
2. **Stress distribution simulation.** The digitally recreated specimens, presented in figure 23, are simulated numerically using FEM to capture the stress distribution that the same specimen is generating in the experimental testing. The boundary conditions implemented in the simulation are equivalent to the experimental test setup used. These includes both the straightening of the specimen when the specimen is clamped into the grips of the test rig as well as the cyclic force applied. The simulation time for each specimen is around 1h using a desktop workstation [Intel(R) Core(TM) i9- 10940X (14Core, 3.30GHz)/64GB RAM].

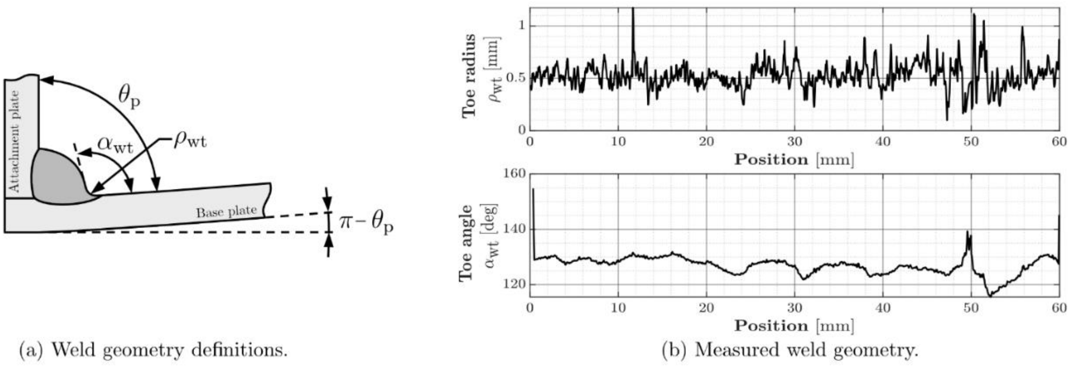


Figure 22. Detailed variation of weld toe radius and toe angle along the weld.

The stresses at the surface of each welded joint are integrated using a weakest link area model to give one equivalent stress value for each specimen. This equivalent stress incorporates both the effect of the nominal stress as well as the local stress concentrations in weld to give a representative value of the fatigue strength of the specific specimen at a given number of cycles.

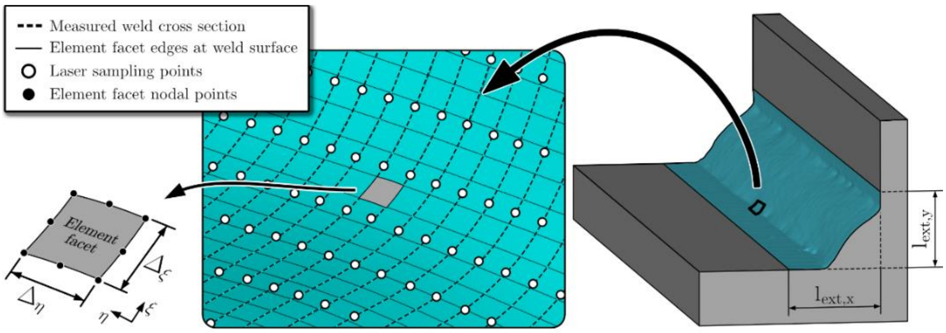

Figure 23. Digitally recreated weld specimen with true weld geometry directly modelled.

3. **Effect of sampling resolution.** The sampling resolution for the tested specimens are varied to study how the error in prediction accuracy grows with reduced information of the weld geometry. The down-sampling is achieved by excluding weld sections, as presented in figure 24, from the Winteria ® scanning which were carried out at a sampling resolution (distance between sampled sections) of 50 µm. This makes it possible to analyze the following down-sampled resolutions: 100 µm, 200 µm, 250 µm, 500 µm, 1000 µm, 2000 µm and 5000 µm.

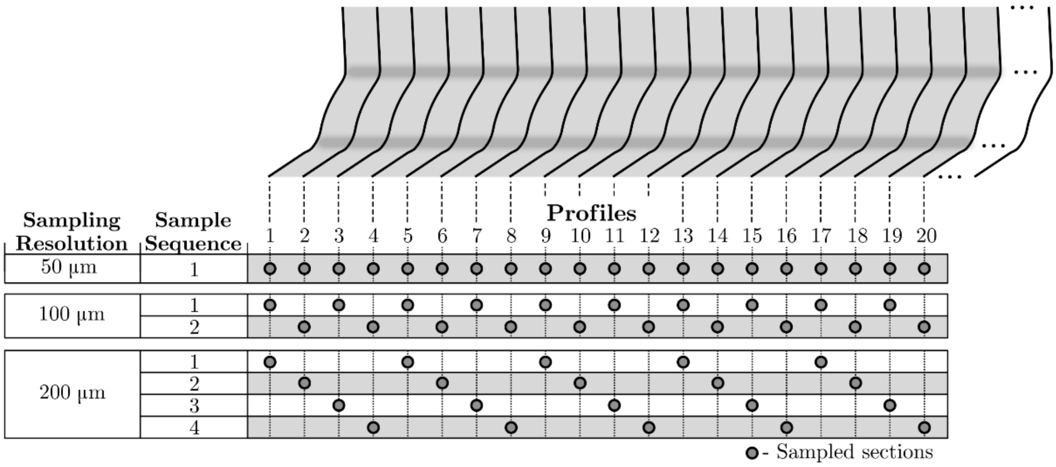


Figure 24. Down-sampling of scanned weld sections to replicate scanning at lower sampling resolution.

The results show how the mean relative prediction error grows with decreasing sampling resolution, see figure 25. It is also evident that there is a higher uncertainty in the predicted values for lower sampling resolutions. When scanning at lower sampling resolutions the starting position will determine to a higher degree which weld sections that are included in the analysis. This means that the choice of location for the first scanning profile will in these cases have a higher influence on the predicted failure probability for lower resolution.

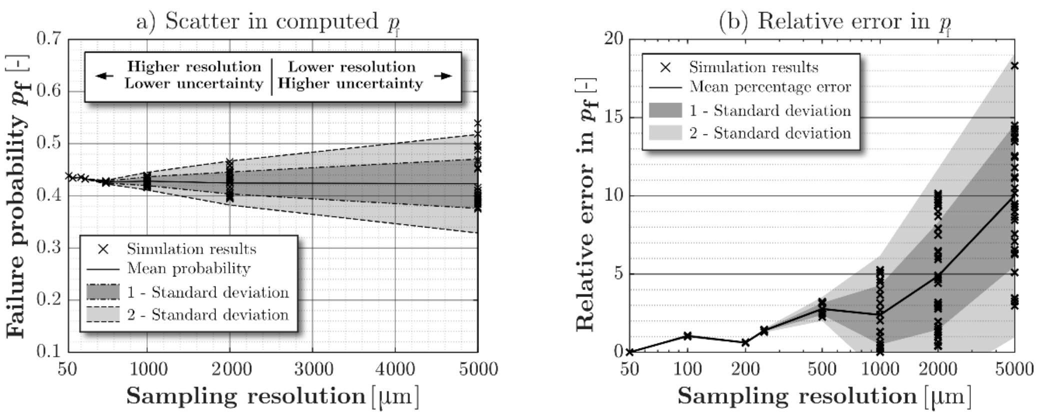


Figure 25. Influence of scanning resolution on the prediction accuracy of the weakest link area model.

These results on scatter and prediction of relative error confirm that the set-up for the developed scanning procedures in the project are correct.

The methods developed and utilised by KTH have been quite successful but since FEM simulations are needed, it would be interesting to find a less resource demanding method for the future when fatigue life shall be predicted.

## 6.4 WP 4 Data handling

This work package should in cooperation with WP2 determine how many data points and what scan frequency that are needed for different qualities and joint types, and what speeds that can be reached.
A routine for the data handling in the scanning should also be developed. The data resolution, scanning speed and set-up, as well as the data generated for the different scanning procedures are summarised in the tables 5 and 6 below. The data amount is given "per meter weld length". Data handling and evaluation is made by sending to a server, where the data is stored and analysed.
The work package should also, in cooperation with WP2 and WP3, evaluate how insignificant errors could be handled (for example short imperfections that are under allowed limit, but would likely have been missed in manual visual inspection – and are judged to have little impact on quality). An example is shown in figure 26 below. The developed solution has been made by utilising an adjustable filter setting that will need to be set from case to case. This may need considerable work before knowing that a filter setting is made of the right type and level, but it is the best way forward while waiting for either new standards to be developed or conclusive research on fatigue prediction reached (described in WP3).

Table 5. Data resolution, set-up and speeds for the scanning procedures developed.

| **Robot scanning** | **General scanning** | **Detailed scanning** |
|---|---|---|
| Minimum Y-resolution | 1 mm | 0,2 mm |
| Minimum scanning speed | ≥ 8,4 m/min | ≥ 1,7 m/min |
| Minimum signal response | 85%* | 90%** |
| Travel angle | 90 ± 5° | 90 ± 5° |
| Rotational angle | 90 ± 5° | 90 ± 2° |
| Working angle | 45 ± 5° | 45 ± 5° |

Table 6. Data amount generated "per meter weld" for the scanning procedures developed.

| **Robot scanning** | **General scanning** | **Detailed scanning** |
|---|---|---|
| Uncompressed (29XX) | 5.12 MB/m | 25.6 MB/m |
| Compressed (29XX) | 1.02 MB/m | 5.12 MB/m |
| Compressed w backup (29XX) | 2.04 MB/m | 10.24 MB/m |
| Compressed w backup (30XX) | 3.28 MB/m | 16.38 MB/m |

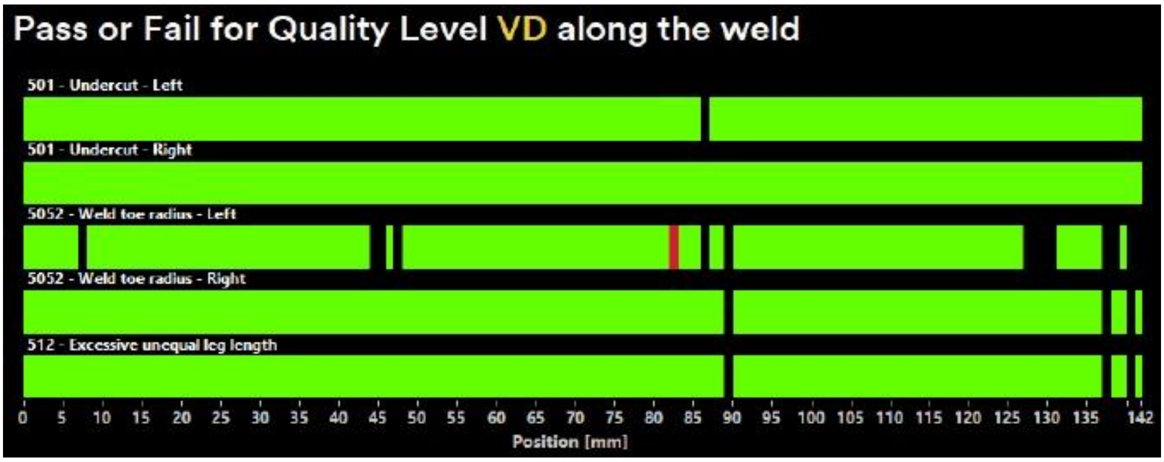

Figure 26. Example of scanning result with one short (red) imperfection, not fulfilling specified weld class (weld quality), but judged to have very little significance. Black parts are missed area in scan.

# 7 Conclusions and Goal achievement

The overall vision for the project was to develop and evaluate a new, process-integrated quality system with laser scanning of welds in a production line. Although this vision has not been reached in terms of a fully process-integrated system, the project has developed scanning routines and verified both the procedures and the accuracy of the measurement system. The project has also performed implementation trials, with the results varying from company to company depending on the part geometries but with identified way forward. The laser scanning techniques have been further developed during the projects run-time and fast scanning is possible today (General scan, 6m per minute). The Detailed scan procedure has almost reached the speed target on 2 m per minute (1.2-1.7m per minute today). Some companies have decided to start implementing laser scanning of welds in their quality assurance department as a part of the evaluations. Other companies have decided to go directly for an installation in the production line. Naturally, the choices are directly connected to their experiences made with laser scanning and the work will continue from this point.
One issue that will still be present for some time is that there are no standards for laser scanning of welds, nor are the quality levels adjusted to the accuracy of a laser scanner. Therefore, both manual evaluation and digital evaluation is expected to be utilised in parallel until the scanning technology results have been harmonised and can be cross-referred to earlier evaluations. Work to develop data that can be utilised for revising actual standards has been started but will need to continue.

The following goal achievements are reported: (colours indicate fulfilment)

- Identify and develop a new, smart, in-process quality management, utilizing the new techniques
- Evaluate how the new techniques and quality management can be built-into a production line
- Clarify the relationship between fatigue performance and measured weld geometry
  (FEM-simulation make this possible, but a faster method will be needed)
- Determine which and how much of the different scanned data to focus on, to ensure quality
  (a filter or method need to be set from case to case)
- Determine data handling techniques to enable high productivity in scanning and judgements

- Evaluation of the Quality management system in industrial production
  (laser scanning and measurement system evaluated, not a full QA system)
- Develop Guidelines for the new integrated QA system
  (Guidelines are in writing for laser scanning of welds, not comprising the whole QA system)
- Contribution to FFI-targets as indicated in Table 2
- Clarification on which of all new measured data that strongly govern the fatigue life and quality of a welded component, and therefore should be focused on in a new quality system
  (Important factors identified, but full inter-action between parameters not).
- A higher resolution of the relationship between fatigue performance and measured weld geometry, how large deviations in measured data that can be tolerated before quality (fatigue life) is affected.
- Suggested adjustments in data handling, and of weld quality levels (ISO 5817, and similar).
- Results from industrial trials with the system.
- A routine for the data handling for use in the developed quality management system.
- Cooperation with other projects, especially FFI-PREMOD, FFI-HIPFAT, FFI-VARILIGHT
- PhD research and scientific articles.
- Broad dissemination activities and contribution to education at KTH, Chalmers and in companies.

# 8 Continued research

There are mainly two areas where continued research is highly important:

1. Laser scanning and Acceptance criteria: more research on different deviations, short imperfections – when are these neglectable and when not. Included in this scope is research needed to change ruling standards or develop new (a standard for laser scanning for instance). Also incorporated here is the need for updating the weld quality standards such as ISO 5817, and 13919-1 for steel and ISO 10042 and ISO 13919-2 for aluminium)

2. Fatigue life predictions based on laser scanned welds (fast and "automated" predictions via algorithms). A vision here is to be able to specify – and through scanning verify – a certain fatigue life (not necessarily a weld quality or weld class).

# 9 Publications and Dissemination

The project results will be utilised in many ways, see table 7.

Table 7. Intended use of project results indicated.

| How are the project results planned to be used and disseminated? | Mark with X | Comments |
|---|---|---|
| Increase knowledge in the area | X | |
| Be transferred to other advanced development projects | X | |
| Be transferred to product development project | X | |
| Introduced on the market | X | |
| Use in legislation, regulations or politics | X | |
| Use in teaching | X | |

The following publications have been developed in the project:

| Title | Main author | Co-authors | Journal/ Conference | status |
|---|---|---|---|---|
| Digital scanning of welds and influence of sampling resolution on the predicted fatigue performance: Modelling, Experiment and Simulation | Gustav Hultgren | Leo Myrén, Zuheir Barsoum, Rami Mansour | MDPI Metals | Under review |
| Fatigue assessment in welded joints based on geometrical variations measured by laser scanning | Gustav Hultgren | Zuheir Barsoum | Journal: Welding in the World | Published: 31 July 2020 |

The following (external) dissemination activities have been made so far:

- Q-IN-MAN Presentation in Swedish Welding Commission group AG 48 2019-03-13
- FFI-conferences: 2018-05-13, and 2020-09-29
- Q-IN-MAN open seminar 2021-04-29 with 89 participants

# 10 Acknowledgements

The project has been financed by the programme "Fordonsstrategisk Forskning och Innovation, FFI". The FFI programme and its financiers are gratefully acknowledged.

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2. SS-EN ISO 17637: 2016 Non-destructive testing of welds — Visual testing of fusion-welded joints
3. SS-EN ISO 5817:2014 Kvalitetsnivåer för diskontinuiteter och formavvikelser för svetsförband i stål, nickel, titan och deras legeringar.
4. Volvo STD 181-0004 Fusion welding, Weld classes and requirements, Life-optimized welded structures
5. G. Hultgren, Z. Barsoum, Fatigue assessment in welded joints based on geometrical variations measured by laser scanning, WiW July 2020.