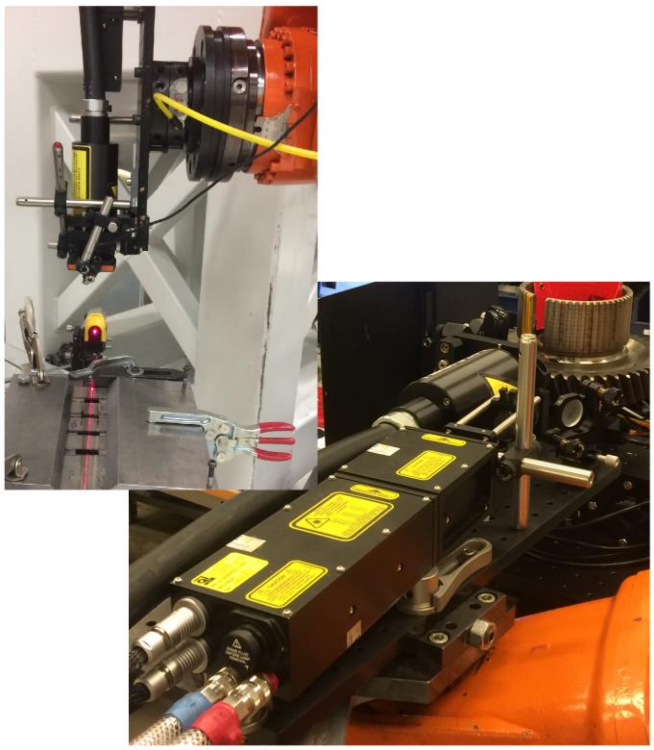
QUALITY II

Public version



Project within Sustainable Production

Authors Erik Lindgren, Mikael Malmström, Paul Janiak, Håkan Wirdelius, Ulf Sandström, Kent Stenberg

Date 2017-10-10

FFI Fordonsstrategisk Forskning och Innovation

Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which about €40 is governmental funding.

Currently there are five collaboration programs**:** Electronics, Software and Communication, Energy and Environment, Traffic Safety and Automated Vehicles, Sustainable Production, Efficient and Connected Transport systems.

For more information: www.vinnova.se/ffi

1. Summary

This research project has focused on the research and development of a non-destructive quality control method, non-contact laser ultrasound, for the quality control of welds and adhesive bonds. The non-contact feature makes the method interesting for automatic operation, and an in-line close to the welding or joining process non-destructive quality control method has been the vision for this project.

The main objective has been to strengthen the competitiveness of the Swedish industry. The quality of joints is critical in many industries and within many applications. Stable predictable manufacturing processes, in this case welding processes, are essential in order to manufacture predictable high quality products at a high level of competitiveness. Non-destructive quality control is important when developing and maintaining such processes. In addition, with improved non-destructive quality control systems improved joining processes and improved new material and material combinations can be deployed and with a higher automatization level of the quality control the cost can be reduced.

The participating companies have defined and prioritized the applications (weld types, geometries and defects of interest), fabricated samples, conducted additional non-destructive and destructive characterization prior to and after the LUS experiments, investigated the obstacles for an industrial implementation of the method, as well as hosted information dissipation seminars. The project coordinator and project leader Swerea KIMAB has developed a robot integrated laser ultrasonic inspection prototype, including hardware, procedures, and software algorithms. Theoretical work has been conducted in collaboration between Chalmers and Swerea KIMAB where the inspection has been simulated and the simulations used as input to the procedure and algorithm development.

The industrial robustness of the method has been proven at two industrial demonstrators: one at GKN Aerospace in Trollhättan and one at the laser manufacturing process integrator Permanova Lasersystem in Mölndal. The experimental setups developed in the laser lab of Swerea KIMAB was mounted on industrial robots and experiments performed.

A summary of the more concrete results is given in the rest of this summary. However, it is important to remember that proving that something is impossible is very difficult. Therefore, proving that something can be done is rather what we have done in most cases.

Laser butt welds in titanium and nickel based alloys: pore defects was detected; lack of fusion and crack like defects were detected (industrial demonstrator), some false indications and some missed defects raise questions; the thickness could be measured with an accuracy and precision of 5 micrometer with the LUS optics mounted on an industrial robot (demonstrator).

TIG butt welds in austenitic stainless steel: surface-breaking defects were detected with a high detectability; lack of fusion defects was also detected; low detectability of defects within the melted region of the weld due to the microstructure.

TIG fillet welds in austenitic stainless steel: surface-breaking defects were difficult to detect, possible due to the rough surface; not surface-breaking pores and lack of fusion defects could not be detected due to the combination of the microstructure and the geometry of the component/product.

MAG butt welds in duplex steel: porosity, inclusions, and lack of fusion defects, some defects were detected.

MAG butt welds in steel: the influence of the surface quality on the signal quality, the blasted surface had a considerable larger effect on the signal quality and the pickled and as cast surface were both similar and with less effect on the signal quality; crack-like defects were detected; excessive root penetration had a high detectability.

MAG fillet welds in steel: the weld penetration depth could be measured with access only to the surfaces where welding had been applied; cold lap defects, a non-destructive method to detect cold laps in sample coupons has been developed based on ultrasonic immersion tank testing in combination with laser surface geometry measurements, some tendencies to cold lap detection with LUS; solidification cracks, unknown applicability, did not detect any defects with the LUS method nor with any other characterization method.

Arc brazing overlap-fillet welds in steel: high signal quality but the signal response was complex and difficult to analyse reliably, in addition the critical defects were very small compared to the surface geometrical variations.

Laser overlap butt welds in steel: the weld bond width can be measured in transmission mode where access to both surfaces is required.

Laser butt welds in case hardened steel gearwheels: partial penetration depth and lack of fusion defects could be detected (industrial demonstrator); not all supplied gearwheel models could be inspected due to the complex and large variation in the geometry of the components/products; not all defects could be detected but procedure alternations was proposed; sensitive to positioning of the detection and generation spots, but robust enough to be successfully applied at the second industrial demonstrator; porosity of interest was too small in size to be detected.

Adhesive joints: the adhesion bond quality and adhesive width, the width could be measured in transmission mode, the bond quality could be measured but question marks remained; adhesion bond width could also be measured in reflection mode (single side access) on cured samples, uncured samples remain challenging; the surface damage at adhesive bond width measurements in reflection mode has been shown to be of approved production finish grade if the LUS settings are carefully adjusted.

2. Sammanfattning på svenska

Detta forskningsprojekt har fokuserat på forskning och utveckling av en metod, kontaktlöst laserultraljud, för oförstörande kvalitetskontroll av svetsar och limfogar. Att metoden är kontaktlös gör metoden intressant för automatisering och en in-line oförstörande provningsmetod som kan prova nära svets- eller limprocessen har varit en av de mer långsiktiga drivkrafterna för detta projekt.

Huvudsyftet har varit att stärka den svenska industrins konkurrenskraft. Kvaliteten på fogar är avgörande för många industrier och inom många tillämpningar. Stabila förutsägbara tillverkningsprocesser, i detta fall svetsprocesser, är viktiga för att på ett konkurrenskraftigt sätt kunna tillverka förutsägbara högkvalitativa produkter. Oförstörande kvalitetskontroll är en viktig komponent för att kunna utveckla och bibehålla sådana stabila processer.

Dessutom så kan förbättrade oförstörande kvalitetskontrollmetoder förbättra fogningsprocesserna som i sin tur möjliggör förbättrade material och materialkombinationer i olika produkter. Det förslagna systemet ska dessutom kunna automatiseras, vilket är tänkt att drastiskt kunna sänka kostnaderna för kvalitetskontrollen, speciellt om mer kvalitetskontroll behövs.

De deltagande företagen har definierat och prioriterat tillämpningarna (svetstyper, geometrier och defekter), tillverkat prover, utfört ytterligare oförstörande och förstörande karakterisering före och efter LUS-experimenten, undersökt hindren för en industriell implementering av metoden, samt varit värd för informationsspridningsseminarier. Projektkoordinatorn och projektledaren Swerea KIMAB har utvecklat en prototyp för robotiserad inspektion med laserultraljud. Detta har inkluderat framtagande av hårdvara, procedurer och mjukvarualgoritmer. Teoretiskt arbete har genomförts i samarbete mellan Chalmers och Swerea KIMAB där provningen med laserultraljud har simulerats och sedan använts främst som input till procedur och algoritmutveckling.

Metodens industriella robusthet har påvisats vid två industriella demonstranter. En hos GKN Aerospace i Trollhättan och en på hos Permanova Lasersystem i Mölndal. Permanova integrar olika tillverkningsprocesser med laser i industrin. Vid demonstratorerna så monterades prototypen, som tidigare i projektet utvecklats i laserlabbet hos Swerea KIMAB, i industrirobotar och experiment utfördes.

En del av arbetet har samordnats i symbios med andra gemensamma forskningsprojekt (främst projektet Automatisk inspektion och andra möjligheter vid introduktion av digital röntgeninspektion i tillverkningsindustrin, Vinnova 2015-04483) och resultat från andra gemensamma projekt har utnyttjats i detta projekt (främst projektet ONWELD, Vinnova, 2013-04696).

En detaljerad sammanfattning av resultaten ges i resten av denna sammanfattning. Det är dock viktigt att komma ihåg att det är mycket svårt att bevisa att något är omöjligt, det vi istället har gjort är att försöka visa vad som inte är omöjligt.

Laserstumfogar i titan- och nickelbaserade legeringar: Stora por-defekter i storleksordningen 0.5 mm porer hade hög detekterbarhet, mindre porer i storleksordningen 0.1 mm var möjligtvis detekterbara. Bindfel och andra spricklika defekter på grund av felaktiv inriktning av lasern vid lasersvetsning kunde detekteras (industriell demonstrator). En del möjliga falska indikationer och några missade defekter genererade en del frågetecken, det är inte helt lätt att ta fram vad som är sant/falskt med varken förstörande eller andra oförstörande provningsmetoder. Tjockleksmätning var intressant för tillämpningen svetsprocessoptimering in-line. Tjockleken kunde mätas med en noggrannhet och precision på 5 mikrometer, även när LUS-optiken monterades på en industrirobot (demonstrator).

TIG stumfogar i austenitiskt stål: Ytbrytande defekter, som är mycket relevanta inom biobearbetningsindustrin, hade hög detekterbarhet. Bindfel och spricklika defekter kunde också detekteras. Defekter som fanns inne i den uppsmälta delen av svetsen hade en mycket låg detekterbarhet på grund av mikrostrukturen.

TIG kälfogar i austenitiskt stål: Det var svårt att detektera ytbrytande defekter, möjligtvis på grund av den grova ytan. Icke-ytbrytande porer och bindfel kunde inte detekteras på grund av mikrostrukturen i kombination med den ogynnsamma svetspositionen i den tilltänkta verkliga komponenten/produkten.

MAG stumfogar i duplexstål: En del av defekterna porositet, inneslutningar och bindfel kunde detekteras, andra inte. Det var även en utmaning med referensmätningar för att få reda på vad som egentligen var sant/falskt. Det var svårt med den stora svetsgeometrivariationen. En del frågetecken kring tillförlitligheten kvarstår.

MAG stumfogar i stål: Ytans påverkan på signalkvalitéen utreddes lite mer i detalj, den blästrade ytan hade en större effekt på signalkvaliteten och den betade samt den som var gjuten var båda liknande och med mindre effekt på signalkvalitéen. Sprickliknande defekter kunde detekteras och likaså överdriven rot-penetration.

MAG kälfogar i stål: Inträngningsdjupet kunde mätas med tillgång till bara den ytan där kälfogen svetsades. Avancerad punktpositionering (till exempel industrirobot) och avancerade analysalgoritmer krävs dock. För detektion av cold laps (överrunnen svets) togs en oförstörande provningsmetod för provstavar, metoden bestod av en kombination av ultraljudsmätningar med en immersionstank (vattentank) och laserbaserad ytgeometrimätning. Det finns ingen etablerad metod för cold lap detektion varför utvecklingen av en in-line anpassad metod och procedur med LUS var svårt, därför togs detta steget istället. Det fanns dock tendenser till att LUS kunde detektera cold laps. Varmsprickor hade en okänd detekterbarhet eftersom inga sprickindikeringar kunde identifieras med LUS och därför prioriterades det inte att försöka identifiera sprickor med någon annan karakteriseringsmetod heller.

Båglödda överlapp-kälfogar i stål: En hög signalkvalitet men signalerna var komplexa och mycket svåra att analysera på ett tillförlitligt sätt. De kritiska defekterna var dessutom mycket små jämfört med ytgeometrins variationer vilket gjorde det ännu svårare.

Lasersvetsade överlappsfogar i stål: Svetsbredden kunde mätas men krävde åtkomst till båda ytorna och inte bara den där man hade svetsat.

Lasersvetsade stumfogar i kugghjul av sätthärdat stål: Partiellt penetrationsdjup och bindfel-liknande defekter kunde detekteras (industriell demonstrator). Inte alla levererade kugghjul kunde provas på grund av komplexa och stora variationer i komponenternas geometri. Inte alla defekter kunde detekteras men förslag på ändringar i proceduren som möjlig lösning har presenterats. Detekterbarheten är känslig för positionering av detektions- och generationsplatserna, varför någon form av kompletterande visuell spårning kan vara relevant, dock så var den tillräckligt robust för att användas framgångsrikt vid den andra industriella demonstranten hos Permanova. Den kritiska storleksgränsen för porer var för liten och dessa porer kunde inte detekteras. Men i ett annat gemensamt forskningsprojekt där digital röntgenprovning användes kunde även de relevanta små porerna ner mot 0.2-0.3 mm i 8 mm tjockt gods detekteras.

Limfogar: vidhäftningskvalitet och limbredd, bredden kunde mätas i tranmissionsläget (åtkomst till båda ytorna krävs), vidhäftningskvalitéen kunde mätas men vissa frågetecken kvarstår kring ett avvikande prov; limbredd kunde också mätas i reflektionsläget (krav på tillgång till bara en yta) på härdare prover, de ohärdade är fortfarande en utmaning. Ytskadorna i samband med limbreddsmätningarna i reflektionsläge har karakteriserats och bedömts vara tillräckligt små för att den uppmätta komponentens yta ska vara godkänd för produktion.

3. Background

Joining of materials and components are critical and highly important processes within many industries. The limitations and possibilities of joining are often at the focus when new materials or combinations of materials are introduced in the industry. Increased productivity and possibilities to an increased automatization are important factors at the development of new joining processes. In parallel with this development the demands on the quality control is also increasing with the possibility to design against even smaller tolerances. Today, much of the quality control of joints is done on the finished product, typically with a lot of manual labour, and it is often destructive. There is a large need for new effective methods for automated non-destructive quality control of joints.

Different joining methods all have in common that their requirements specifications have to be ensured by some kind of quality control. Non-destructive testing with ultra sound and X-ray radiography is common within industry. Additional destructive testing with random samples is also common. Today, many of the methods require a lot of manual labour and can in general not be performed on-line or in-line close in time to the welding process.

Load bearing designs are often make by joined structures. Breakdowns caused by fatigue are often related to questionable geometry of the resulting weld of some other failure in the join (1). This is well known but the defects are far from easily detected with the non-destructive testing methods and procedures of today. New advanced high strength steels can often result in a weight loss of 20-40 % for welded designs, however today production methods are lacking which can fulfil the fatigue requirements. New improved methods for quality control of welds would enable optimized design methods and therefore also the potential to increase the life of the fatigue loaded designs of high strength steels.

The use of mixed materials is expected to increase, for example in light weight designs. Joining of mixed materials subjected to fatigue loading is indeed a challenge. Adhesive joints are often the only alternative, however, today robust and effective methods to non-destructively evaluate the level of hardening or to detect defects in the join is lacking. A robust and reliable non-destructive method would enable the increased use of mixed material designs.

Overall, a non-destructive testing method that can be used on-line close in time to the welding process would also enable the possibility for a feedback loop and on-line welding process adjustment and optimization. Less scrapping would be achieved.

Ultrasound is a common technique for non-destructive quality control of welds. Defects not visible from the surface, internal defects, can be detected. Conventional ultrasonic testing has however a large limitation, the probes that are used to generate and detect the ultrasonic waves typically require some kind of couplant to the test object. The couplant can be water or some kind of gel, and the roughness of the surface should not be too large. This makes the method difficult to automate. In addition, the probes which have a finite size require access to the surface, which can be a problem with complex geometries.

A technique that recently has gotten large international attention when it comes to industrial on-line non-destructive characterization is the laser ultrasound (LUS). Lasers are used to both generate and detect the ultrasound, therefore it is both contact less and fast. Surfaces with higher roughness are believed to be less of a problem, complex geometries are also believed to be handled better with the LUS due to its potentially smaller requirements on access. There are commercial systems available that utilize LUS for the measurement of pipes during hot forming, this indicates that the technique is intrinsically robust. In this context, the vision is to utilize LUS for automatic fast on-line quality control of joints.

KIMAB has taken part in two earlier projects with the focus on quality control of joints which have received financial support from Vinnova: QUALITY – Advanced quality control of welded and adhesive joints, diarienr: 2014-00789 and Online-quality control of welding defects with contactless ultrasound within the automotive industry, diarienr 2012-02510. Both of the projects indicated that LUS had great potential for the application, however, further research and development was required.

4. Purpose, research questions and method

The project have developed and adjusted the LUS technology to facilitate an automatic non-destructive quality control of welds and adhesive bonds in an industrial environment.

The project plan has included both experimental and theoretical activities. Experiments in a controlled lab environment have been conducted where hardware, inspection procedures and analysis algorithms have been developed. A large set of samples, as in a large variation in type and defects, made with different welding methods and different critical defects of interest has been made by the participating companies. The samples have been characterised prior to and after the LUS experiments. Where relevant, the effect of LUS on the surface of the samples has also been characterized.

Experiments in an environmental similar to a production environment have been conducted at the welding lab at Swerea KIMAB as preparation for the additional two experimental industrial demonstrators that was planned for and held at both GKN and Permanova.

Preparations for an industrial implementation where obstacles and possibilities have been explored have been analysed.

Theoretical methods, have included simulation of probability of detection (POD) curves and development and usage of other simulation tools in order to better understand the experimental results, choose reasonable procedures (experimental setups), and to characterize the capability of the system also beyond the sample sets used.

5. Objective

The project has primary addressed the two FFI objectives increased competitiveness and cooperation transcendent over many industry branches as well as cooperation between SME, suppliers, OEMS, research institutes and academia.

A more resource effective production is important in order to maintain and strengthen the competitiveness of the Swedish industry. Technology that early in the manufacturing process can identify product or process deviations facilitates early corrections, leading to less scrapping and better material and energy resource efficiency. The objective of the project was to develop technology for improving the quality control of designs with welds and adhesive bonds. A breakdown due to failing join integrity can cause large economical damage but might also lead to large safety consequences. Due to the lack of acceptable weld quality control methods the number of spots welds in cars of today is unnecessary high, and fatigue loaded welds in trucks are made extra-large in order to compensate for possible defect welds. A reliable quality control system capable of verifying 100 % of all weld length would lower the required safety margins, and thus lower the required material and energy resources. In addition, weight savings would be possible due to lighter, smaller, and fewer welds. The introduction of new materials and material combinations requires joining methods that preserve the performance of the materials and produce reliable joints. It is important to be able to verify the integrity of the bonds without relying on resource intense random destructive testing alone. Reliable and robust automatic non-destructive quality control methods leads to new possibilities when it comes to faster deployment of new lightweight materials and new joining processes, which contribute to faster product development and increased competitiveness.

The project has brought together different industries in cooperation which all request improved technologies and methods for non-destructive quality control of welds and joints. Generic method development of algorithms and procedures for join quality assurance is useful for a large number of different applications and industry branches. The actual industrial implementation of the methods is typically less generic. However, the cooperation still facilitates that lessons learned from industrial integration and deployment can be shared. Companies from a number of industrial branches and of different size from different places in the value chain have participated. The developed technology will be primary used by welding companies but should be made available by suppliers of welding equipment. Swerea KIMAB has previously participated in EU-funded research projects where the laser ultrasonic technology has been utilized for material characterization and is internationally recognized within the field. In September

2017 KIMAB was the host for the 3rd International Workshop on Laser-Ultrasound for Metals.

6. Results and deliverables

A prototype for a new on-line quality control concept for welds and adhesive bonds has been derived. The prototype, consisting of hardware, software, and algorithms has been experimentally explored in both lab and production like environments. Its capability, applicability potential, has been evaluated for the many different applications that the industrial parts in the project defined and prioritized. Some of the applications where a higher potential was indicated was brought somewhat longer in development. Simulations of the sensitivity of the inspection procedures as well as some probability-of-detection (POD) curves have been done.

Two industrial demonstrators have been held where experimental equipment was brought to production similar environments at two of the participating companies. One was hosted by the aero-industry representative (GKN) and the other by the SME/system integrator representative (Permanova).

A seminar open to interested parties outside of the project was hosted by Volvo Cars and organized by KIMAB and Svetskommissionen. The seminar was intended to disseminate the project results to a broader audience but also to put the project in a wider context of quality control of welds and adhesive joints by the aid of invited presenters from both the industry and the academia.

Those were the four most important deliverables of the project and we believe that they have been delivered.

The project was expected to reach technology readiness level 6, that the system should have been verified in an environment similar to the production environment, and it is our conclusion that the project has verified this for a limited number of applications.

6.1 Experiments in both lab and production similar environments

The applicability of using the LUS method for each of the selected applications has been explored. For each of the applications the samples, additional characterization, experimental setup, analysis algorithms, and results are reported in each of the subsections below. In some cases additional simulations and mathematical modeling as well as brief literature studies have also been done and are reported. The industrial company with the largest interest and the sample supplier has been indicated within parenthesis in each of the section titles, but the applications have a lot of overlapping research questions and solutions.

Three applications were selected for two industrial demonstrators: detection of LoF like defects in butt welds due to misalignment of the laser welding beam (GKN) and high precision thickness measurements (GKN); detection of incomplete penetration depth as LoF like defects in butt welds on real complex components (VCE).

6.1.1 Laser ultrasonic experimental setup

The project has been active over three years, during that time KIMAB has been involved in many other LUS related projects. The LUS hardware pool has been shared among the projects and re-built many times into different setups. As a consequence KIMAB has invested in new equipment over the project time. In this section the general principles of laser ultrasonic is described, as well as the different lasers that have been utilized in the project at some time of the other. In addition, some general and often used pre-filtering methods are briefly described.

LUS-principle

Part of the text in this section is taken from the report of the pre-study project Advanced quality assurance of welded and adhesively bonded joints from 2014. The laser ultrasonic technique (LUS) is a fast (micro seconds), non-contact and in most cases non-destructive method for material analysis. The technique makes it possible to conduct material characterization such as measuring the mechanical properties, the microstructure and the detection and characterization of defects. One of the largest advantages with LUS compared with conventional NDT-methods is that it is a non-contact method. This makes is possible to use the technique for continuous quality assurance in harsh industrial environments without use for example some couplant such as for example water.

The principle of LUS is that a generation laser sends out a (short) high energy light pulse (1064 nm, 100 mJ/pulse, 8 ns). When the light pulse hits the sample surface the instant heat generation and material ablation generates ultrasonic waves in the material that start to spread through the material. To detect the ultrasonic signal, a frequency stabilized laser is directed towards the vibrating surface and the displacement or velocity of the surface Doppler shifts the frequency of the reflections. The Doppler shift is then measured with the aid of an interferometer.

Two different detection systems have been utilized in the project: a Fabry-Perot based (FP-system) and a system from TECNAR (www.tecnar.com) (TEC-system) consisting of a pulsed detection laser (PDL) together with a two wave mixing (TWM) interferometer.

In the FP-system a continuous laser operating at a single frequency is directed at the preferred detection point on the surface of the sample. The ultrasound generated on the sample will propagate through the sample and bounce back and forth in between the boundaries of the sample and induce surface vibrations. The reflected (and Doppler shifted) light is passed through an interferometer (Fabry-Perot) where the frequency modulation is converted into an amplitude modulation that can be observed on an oscilloscope. The oscilloscope is connected to a PC where the signal is analyzed. An overview of the system is shown in Figure 1.

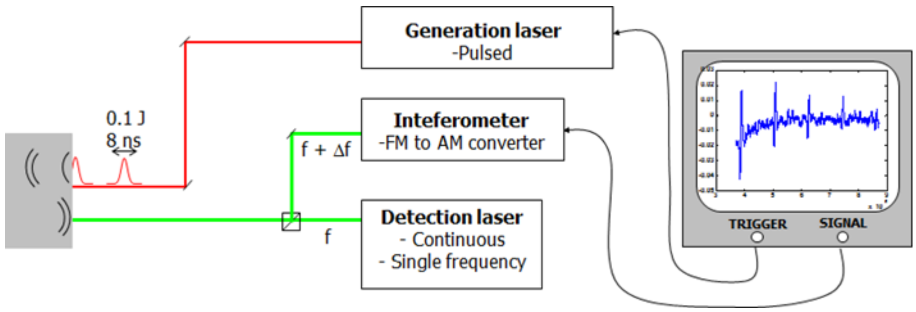


Figure 1. Schematic illustration of the laser ultrasonic setup with the Fabry-Perot detection system. An ultrasonic wave is generated in the sample by the pulsed laser. The ultrasonic wave causes vibration on the surface which is picked up by the detection laser. These vibrations will lead to a shift in the frequency of the reflected light. The interferometer converts this shift to an amplitude modulation that can be observed on an oscilloscope. (Taken from the report of the pre-study project QUALITY).

In the TEC-system a pulsed laser at 1064 nm is in the same way directed at the surface where the mechanical ultrasonic vibrations Doppler shifts the frequency. However, this system utilizes a photorefractive crystal to convert the Doppler shift to an amplitude modulation that is picked up by two photodiodes and a differential amplifier which then measure the actual displacement of the surface. Hence, the TEC-system measures displacement of the surface whereas the FP-system measures the velocity of the surface.

The generation laser and the detection laser cannot both have the same frequency if they are focused on the same point of the surface. If the same frequency must be used the distance between the detection and generation point must in most practical situations be around a few millimetres to protect the optics of the detection system.

The sampled signal response is similar to conventional ultrasonic, see Figure 2 for an example of a typical signal response, a so called A-scan (amplitude versus time plot). The different peaks correspond to different wave kinds and paths in the object. At the generation point ultrasonic surface waves (Rayleigh and creep) as well as ultrasonic bulk waves (longitudinal/pressure, transverse/shear) are created. At the interaction with defects and other boundaries additional mode conversion between the different the different wave kinds. As a result the A-scan quickly becomes complex to interpret. We will use the notation NS and NP to denote N number of ray paths of shear (S) and pressure (P) waves, that is a pressure wave that is generated, reflected into a pressure way and reflected again at some other point to a shear wave will be denoted 2PS. A series of A-scans, sometimes while both the generation and detection point or just one of them is moved, stacked with the positions versus time and color-coded amplitudes is called a B-scan. A good and still in many perspectives relevant introduction to the subject of ultrasonic material testing can be found in (2).

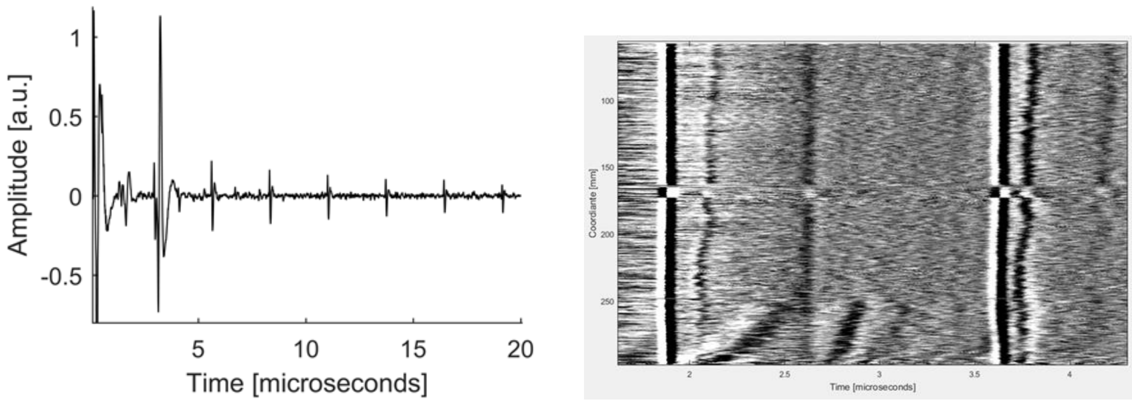


Figure 2. Example of the signal response and the commonly utilized visualisations: left) A-scan, right) B-scan.

The signal response is often scaled to the received light intensity, as a normalization procedure. In addition, unless otherwise noted, a band pass filtering (4-50 MHz) is performed prior to any other analysis.

List of lasers used

During the course of the project KIMAB has invested in new lasers. Two infrared (IR) generation lasers (1064 nm wavelength) have been used, both from Quantel, see Figure 3 and Figure 4. These two have been with the project since the start.

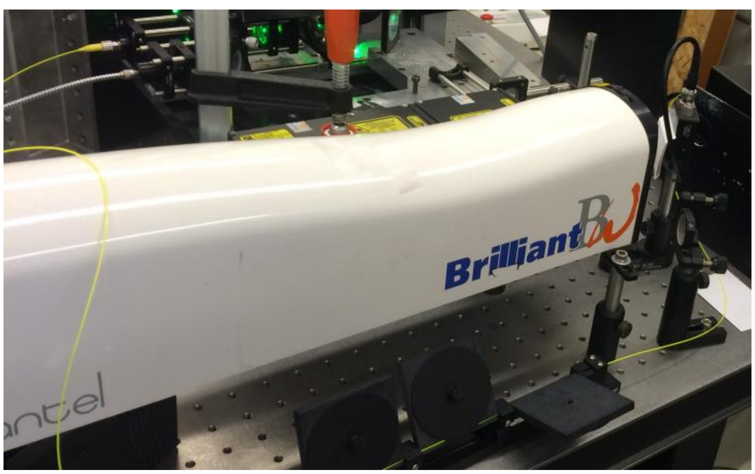


Figure 3. Quantel Brilliant, IR generation laser, commonly referred to as the large IR generation laser.

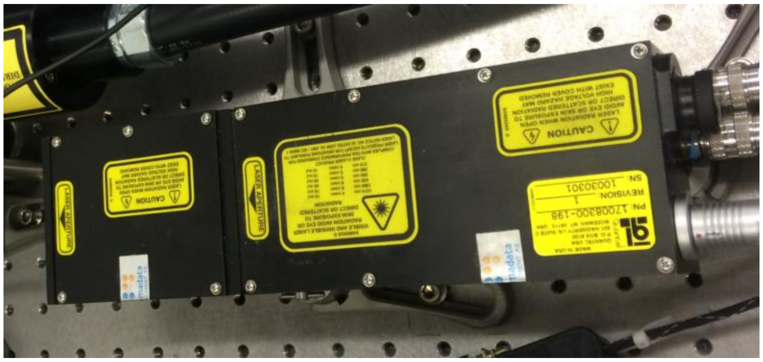


Figure 4. Quantel Ultra 100 BigSky IR generation laser, commonly referred to as the small generation laser.

The Fabry-Perot (FP-system) was driven by a continuous wave green laser from Verdi operating at 532 nm and a maximal power of 5.5 W. The spot size of the FP-system can be made small, typically ~200-400 µm in diameter.

Figure 5. The laser of the FP-system, the laser light is guided to the work piece, via multimode fibers.

Approximately half way into the project KIMAB invested in a detection laser system from TECNAR (www.tecnar.com), see Figure 6. The laser is also infrared with a wavelength of 1064 nm and, thus, cannot be used in reflection mode pointing at the same surface point as the generation point if an infrared generation laser is used. The system is less sensitive to surface conditions, since it features a high power pulsed laser (~500 W peak power). Although, this system has more power the smallest practically achievable spot size is rather large at around 800 µm in diameter.

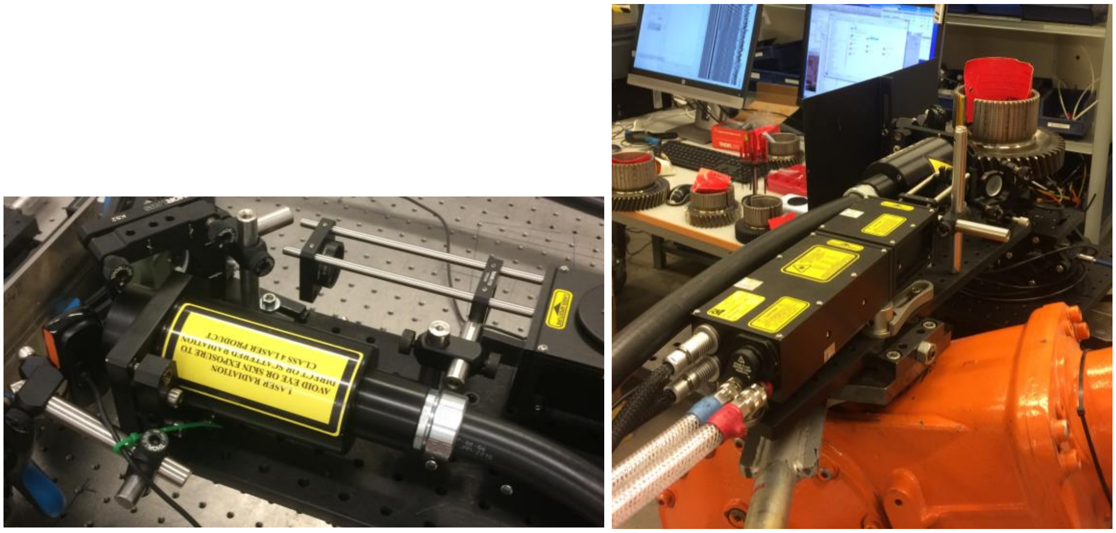


Figure 6. The lens-head of the TEC-system, left) in the lab and right) mounted together with the small IR generation laser on an industrial robot at the industrial demonstrator at Permanova.

Towards the end of the project KIMAB also invested in a green generation laser, see Figure 7. It is a high power (450 mJ IR and 220 mJ green) Q-smart 450 (The case says 850 but it is a 450) from Quantel operating at 532 nm. It was used together with the TEC-system and only used at a very limited set of experiments.

Figure 7. The green generation laser from Quantel.

6.1.2 Laser butt welds in Titanium- and Ni-base alloys, porosity (GKN)

Two different procedures have been evaluated: DSOE, generation and detection on different sides of the weld enforcement where the pores were supposed to act as either diffractors/reflectors (detect a high amplitude) or as absorbers (detect a decreased in a reference amplitude); SSOE, generation and detection same sides of the weld enforcement where the pores were supposed to act as diffractors/reflectors.

Large defects, at the order of 0.5 mm, can be detected with the SSOE-procedure. However the DSOE-procedure was more difficult to utilize, no new echoes from the pores could be identified and the frequency dependent attenuation analysis of the signal did not give any clear positive results. The simulations (see the POD section) also indicated that the DSOE-procedure would result in very small amplitudes of the signals on interest. The synthetic aperture focusing technique (SAFT) has been applied in order to increase the contrast to noise ratio and to interpret the measurement data of the SSOE-procedure, defects smaller than 0.5 mm are possibly detectable but further investigation is required.

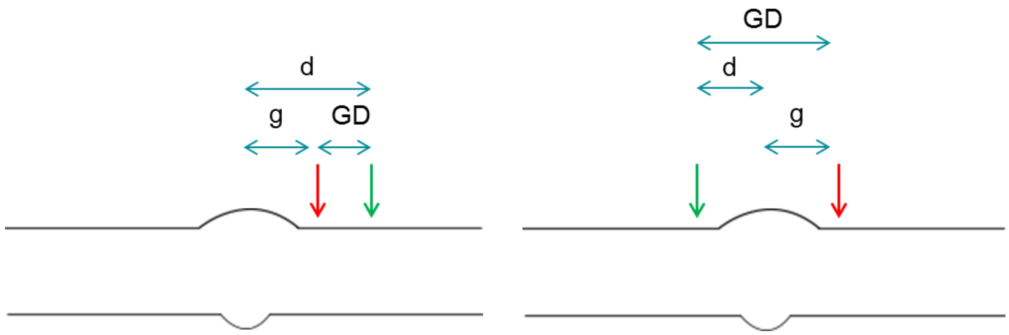


Figure 8. Same side of the weld enforcement (SSOE) and different sides of the weld enforcement (DSOE) procedures and the position parameter definitions.

6.1.3 Laser butt welds in Titanium- and Ni-base alloys, misalign (GKN)

The misalignment is detected with the LUS as crack like defects but there are question marks regarding the capability of the method. Two procedures, based on two different concepts were explored: one in which the defect will decrease the amplitude of a specific signal and one in which the defect will produce a high signal amplitude. An industrial demonstrator was held at GKN in Trollhättan; the LUS was mounted in an industrial robot and new samples were evaluated. The method has been proved to be both robust and somewhat portable. Half of the samples (the zigzag samples) evaluated at the industrial demonstrator presented many challenges that were not prepared for prior to the demonstrator in the lab. The smaller LoF defects around 5 mm and less were not detected and about some 10 mm length was the detectability limit. However making half of the sample more difficult was intentionally and to save resources, the other half (linear samples) represented an easier application.

Further investigations are proposed, for example a frequency based approach with a windowed Fourier transform or a Wavelet transform might be interesting to further explore, as well as more robust signal tracking algorithms for the analysis. Better control of the distance to the weld enforcement during the scanning would be preferred.

It is however our conclusion that we have shown that LUS has a high potential to be useful in detection of crack like defects due to misalignment in laser welds and that it is robust enough to be mounted on an industrial robot.

Background

In laser welding the alignment of the laser spot with respect to the actual interfaces to be welded together is important. If the spot drifts too far away a crack like defect forms as the interfaces are not welded together, see Figure 9. It is possible to compensate for misalignment simply by having a larger spot size, but the fundamental problem is still potentially there. The crack like defect is critical for the mechanical properties of the weld, and no such defects are permitted.

Figure 9. The misalignment of the laser spot in laser welding which result in a crack like LoF defect in the middle of the weld.

Results: the SSOE-procedure, industrial demonstrator

The industrial demonstrator was held at GKN's research and development facilities at Produktionstekniskt Centrum (PTC) in Trollhättan in January 2017. The TEC-system together with the IR generation laser was mounted on an industrial robot in one of GKN's laser welding research cells, see Figure 10. The environment was similar to an actual production environment. In addition to the application of detecting misalignment as LoF like defects the application to measure thickness with a high precision was also demonstrated. The thickness demonstration results are presented in section 6.1.4 instead.

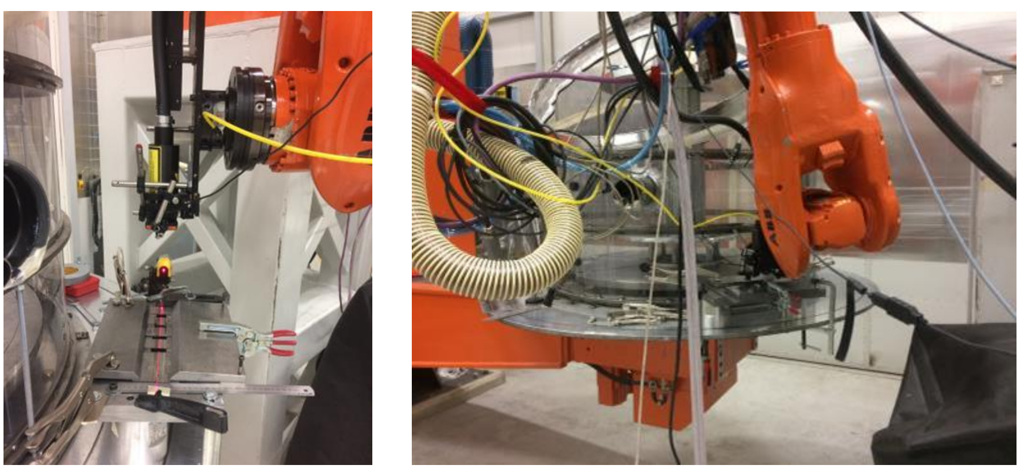


Figure 10. The LUS mounted on an industrial robot at GKN.

6.1.4 Laser butt welds in Titanium- and Ni-base alloys, thickness measurements (GKN)

The thickness variation in the welded base material can be as large at 10 % and the thickness measurements should be much lower in variation in order to be useful for in-line laser welding process optimization. As already shown in literature and commercial products, LUS can be used to measure thickness with high precision. Here we have shown that we can measure Inconel 718 thicknesses at around 3 mm with the precision about 5 micro meters. A calibration point is required where the thickness is measured with some other method than LUS, is will be dependent on material and its mechanical properties. The method has been shown to be robust at an industrial demonstrator held in an environment similar to the one in production. More robust peak tracking algorithms are required but the concept works.

Results: thickness measurements in a lab environment and at the industrial demonstrator

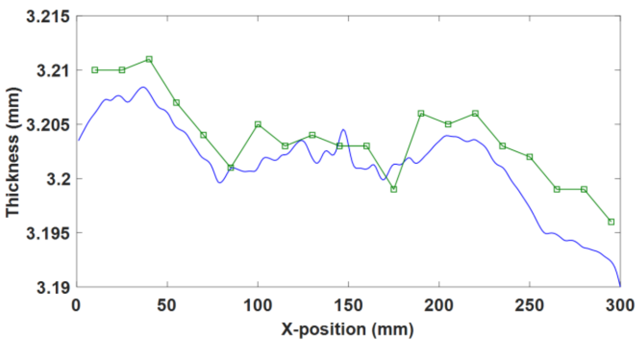


Figure 11. Experimental results from the lab in Kista. The green line is the results of thickness measurements with a micro meter caliper and the blue line is the results of the LUS measurements.

The results from the industrial demonstrator are shown in Figure 12 and Figure 13. A series of re-measurements, re-scanning, of the sample shows indicates the robustness of the method and procedure. The typical precision is the same as in the lab environment, even though the LUS optics head and the generation laser are mounted on an industrial robot. It is also evident that the large disruptive steps in thickness are due to failure to track the correct signal, echo amplitude, and not a failure of the concept. More robust tracking algorithms are required and out of the scope right now.

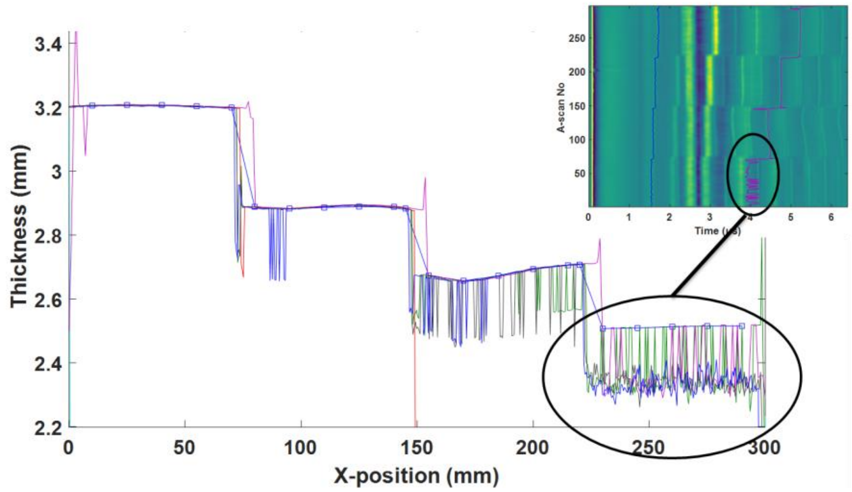


Figure 12. Experimental results from the industrial demonstrator at GKN. The micrometer results are indicated with the blue markers. The lines are from different re-measure runs of the LUS. Also shown is the B-scan where it is evident that the tracking of the signal of interest fails when the LUS-thickness varies a lot and not the concept in itself.

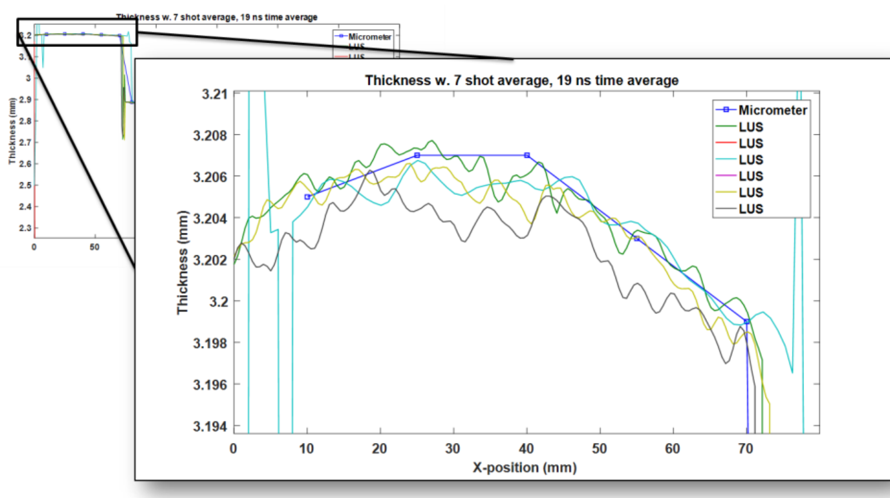


Figure 13. Results from the industrial demonstrator, a zoom in on one of the steps on the thickness wedge.

6.1.5 TIG butt welds in austenitic steel (GE)

A high detectability of surface-breaking pores has been demonstrated as well as a high detectability of lack of fusion. A low detectability of defects that are inside the melted region of the weld has been demonstrated, the reason for this is believed to be due to the columnar microstructure in the melted region.

6.1.6 TIG fillet welds in austenitic steel (GE)

We could not detect any surface-breaking defects with neither LUS nor VT. The surface wave amplitudes were rather noisy and that could be due to the rather rough surface of the samples. Defects that were not surface-breaking, pores and lack of fusion/low weld penetration, could not be detected due to the combination of the microstructure in the melted region of the weld and the weld position in the component/application. The influence on the signal quality of the surface quality has been evaluated. Two different surface conditions, not pickled and pickled, were examined. The spread between the sites is considerable, but there is a tendency for higher contrast to noise ratios for the pickled surface sample.

6.1.7 MAG butt welds in duplex steel, porosity, inclusions and lack of fusion defects (Scania)

Using the contrast to noise enhancing algorithm SAFT a lot of possible defect indications can be identified, some corresponding to the indications found with RT but most of them do not. The indications might be false positives, but if not, then the detectability limit of the conducted RT characterization suggests they are small in size, less than 0.3 mm. Some statistical approach should probably be explored, where the one-to-one mapping with destructive testing is not conducted but rather a statistical comparison. Overall LUS has shown medium-to-high potential, but further investigations are required.

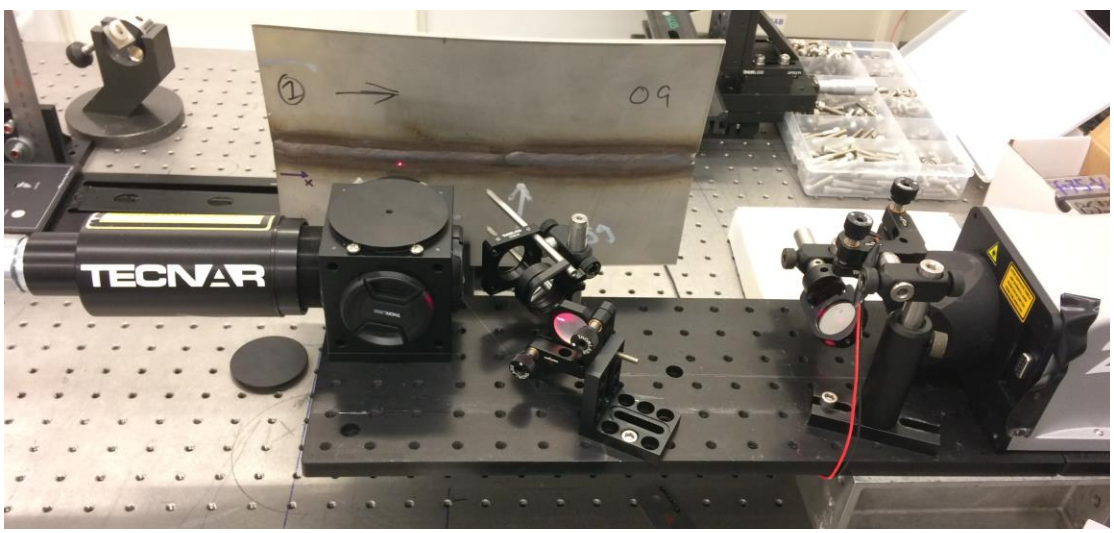


Figure 14. Experimental setup for the butt weld inspection, the TEC-system and the new green generation laser was used in reflection mode.

6.1.8 MAG butt welds in steel, cracks and crack-like defects (HIAB)

The effect of the surface quality on the signal response was evaluated with the average attenuation and the spread in attenuation. The base material was the same in all of the samples, a lower attenuation would be related to losses due to the surface. The blasted surface had a considerable larger effect on the average attenuation and the pickled and as cast surface were both similar and with less effect on the attenuation. All surface samples had similar, quite large, spread in attenuation values.

The excessive root penetration could possibly be detected. However, the echoes of the multiple S- and P-wave reflections were used and could perhaps also be attenuated by other effects, therefor the approach is questionable. A crack-like, probably a LoF defect, could be detected using the attenuation of the 2S echo.

6.1.9 MAG fillet welds in steel, penetration depth (HIAB)

We have restricted the inspection procedures to those requiring only access to the region or side of the join where the welding was done. Two procedures were simulated and experimentally indicated to work: one which might probe mid to high penetration depths (“same side”-procedure) and one that might probe a larger range of penetration depths (“different sides”-procedure). They both suffered from the complication of overlapping signals and might require scanning movements in two dimensions. In addition, they did not work with the TEC-system but only the FP-system. The hypothesis is that it might be related to the rather large spot size of the TEC-system or different sensitivity capabilities of the systems. The hardware integration with an industrial robot was shown to work, however, the application to measure fillet weld penetration depth did not work in the demonstrator. The hypothesis is that it might have been due to the differences between the TEC-system and the FP-system.

Background

The penetration depth is considered an important quality measurement of fillet welds as it affects the fatigue properties of the weld. There exist different definitions of the penetration depth, Figure 15 for two of them. In this report, penetration depth is defined as in the Volvo standard (I-mått).

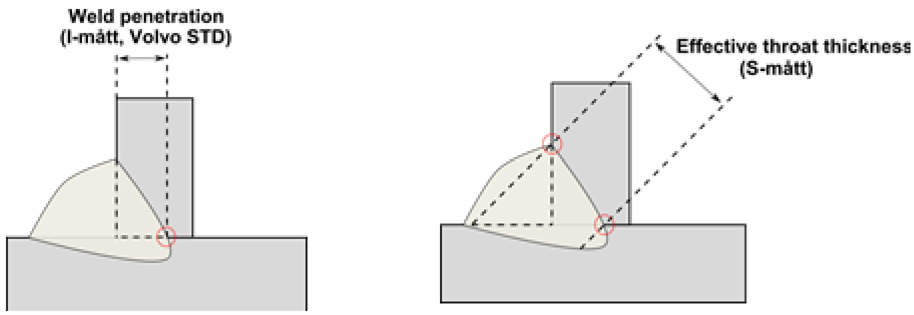


Figure 15. Weld penetration and effective throat thickness, in this report the Volvo standard is considered when we refer to penetration depth.

Results: Penetration depth measurements in the lab

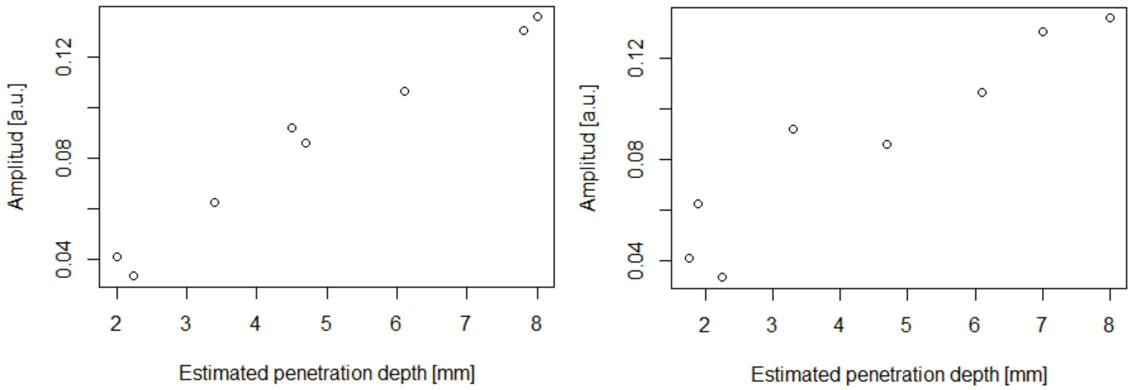


Figure 16. Results from the analysis of the LUS measurements. On the x-axis the estimated penetration depth is used and taken from the: left) the ultrasonic immersion testing on the same sample and weld position as measured with LUS; right) the destructive characterization of similar samples.

Results: integration with an industrial robot

Measurement of the penetration depth of fillet welds was selected as the application for the initial experiments with the robot integration of the LUS measurement optics. The setup is shown in Figure 17.

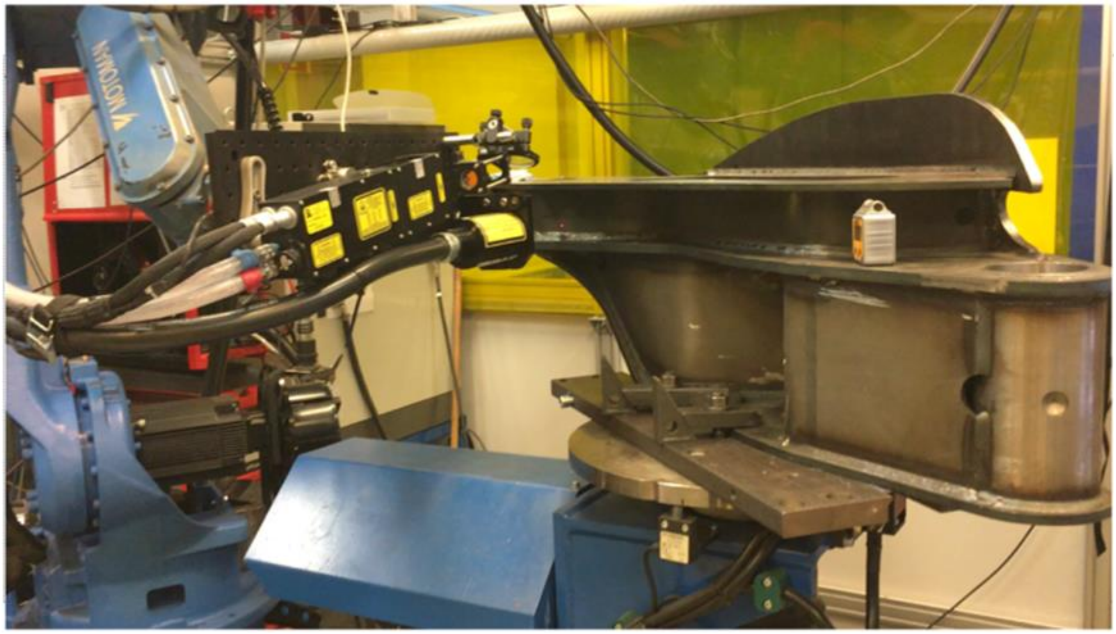


Figure 17. The integration of the LUS optics and measurement setup with an industrial robot, experiments in KIMAB:s welding lab in Kista late September 2016, also shown is a component with fillet welds from HIAB.

6.1.10 MAG fillet welds in steel, cold laps (HIAB)

Since there exists no non-destructive method to reliably detect cold lap defects, visual inspection is also difficult, and since the LUS procedure development would be very difficult without having such a method we have put some effort into deriving one. An alternative non-destructive cold lap characterization method requiring two separate measurement systems, an ultrasonic immersion tank testing setup and a laser based surface geometry measurement system, has been derived and tested. The results look promising but further destructive testing in order to verify the results are required. Some initial LUS measurements have also been done with promising results not contradicting the results of the other method. However, we did not have resources to pursue this any further, three different lab systems based on different methods was too complex to develop any further in this project.

Background

A cold lap defect is a welding defect that occurs when the weld enforcement at the toe of the weld is not in contact with the base plate (3), see Figure 18. The defect type is considered critical in some applications and a possible crack initiation point.

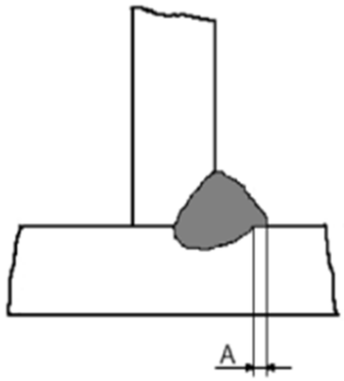


Figure 18. Illustration of the cold lap defect (A).

To our best knowledge there is no standard reliable non-destructive method available to detect cold laps in fillet welds. For example, the applicability of visual testing is not widely accepted in the community. Therefore, it is difficult the get any reference measurements on cold lap defect existence or position in the weld prior to the LUS experiments. Which became a problem since the detection of the cold laps with LUS was not that straight forward. Therefore we did some initial simple experiments with LUS and then proceed to define a non-destructive method, unsuitable for complex components or for in-line quality control in the production, which could be used to detect and position cold laps in fillet welds prior to the LUS procedure development.

6.1.11 MAG fillet welds in steel, solidification cracks

No non-destructive characterization was done prior to the LUS experiments, other than simple visual inspection. Since the LUS measurements failed to detect any possible solidification crack indication in the samples, and since the solidification cracks are typically very local there was no reason for conducting any destructive characterization. There was a plan to get the characterization done with radiographic testing in symbiosis with another research project, however it was never done due to resource limitations. Therefore, we cannot state whether the LUS technology is applicable or not for the specific application, simple, that we did not get it to work.

Background

Solidification cracks can be both surface-breaking and not surface-breaking. In this work we have focused on detecting not surface-breaking cracks, since, that is somewhat more difficult and general.

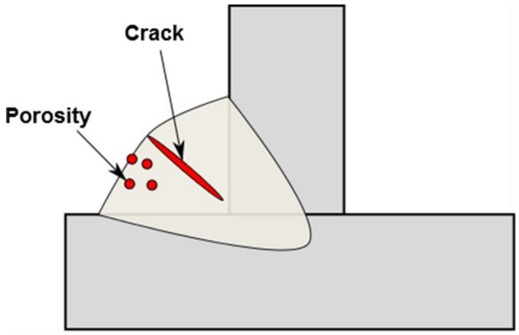


Figure 19. Illustration of the solidification cracks and porosity in the fillet welds.

6.1.12 Arc brazing overlap-fillet welds in steel (VCC)

The acquired B-scans are complex with signals close in time and the defects of interest are small (towards 0.25 mm) which we had difficulties with in for example the GKN and VCE applications. The overall signal quality is however good, which means one could potentially accept a decrease in signal amplitude at the increase of spatial resolution.

6.1.13 Laser overlap butt welds in steel (VCC)

The considered application was to quantify the weld width. The application to detect lack of fusion is similar, but no such samples were made. The TEC-system with generation and detection at the weld enforcement and used in transmission mode seems promising. However, the spot size is at the same length scales as the actual weld width and more measurements are required to rule out spurious correlations. The signal quality is high and the possibility to detect lack of fusion defects is probably high, no such samples were however made. The FP-system with generation and detection at the weld enforcement and used in reflection mode did not work, too rough surface is believed to be the reason. The FP-system with generation and detection at the base plate region outside of the weld enforcement region shows high signal quality but the A-scans are very complex.

6.1.14 Laser butt welds in case hardened steel gearwheels, penetration depth and lack of fusion (VCE)

Both the FP-system and the TEC-system have been evaluated in the lab on the gearwheels. The applicability and robustness of the TEC-system has also been demonstrated at an industrial demonstrator held at Permanova Lasersystem. Partial penetration and LoF like defects in the small gearwheels were detectable with two different procedures. The large gearwheels had a difficult to test geometry with the first proposed procedure. The second procedure believed to be less sensitive to the geometry and made possible with new hardware, showed great potential on the small gearwheels but resources was not left in the project to also evaluate it on the large gearwheels. Some LoF like defects were not detected and we believe that also the procedure needs to be changed into scanning more points, for example the generation-detection distance (GD) for the DSOE-procedure and both of the sides of the weld enforcement for the SSOE-procedure. However we did not have resources left in the project to prove it. One of the proposed procedures required only absolute amplitude thresholding and the other procedure required that the frequency content of the signal was taken into account also.

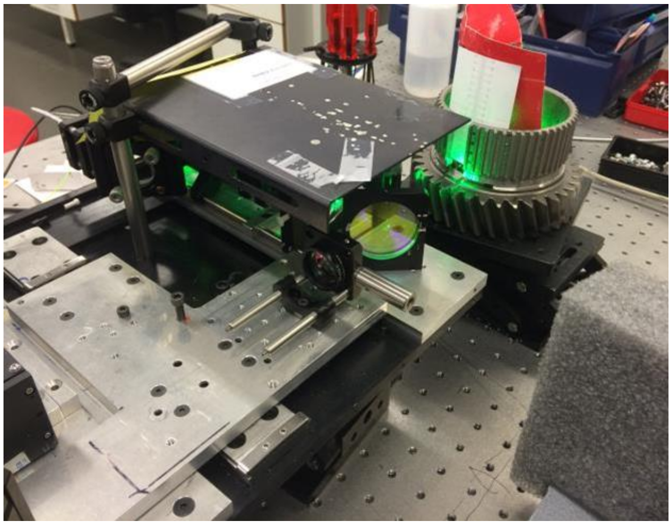


Figure 20. One of the setups in the lab, FP-system, the gearwheel is mounted on a motorized rotation stage.

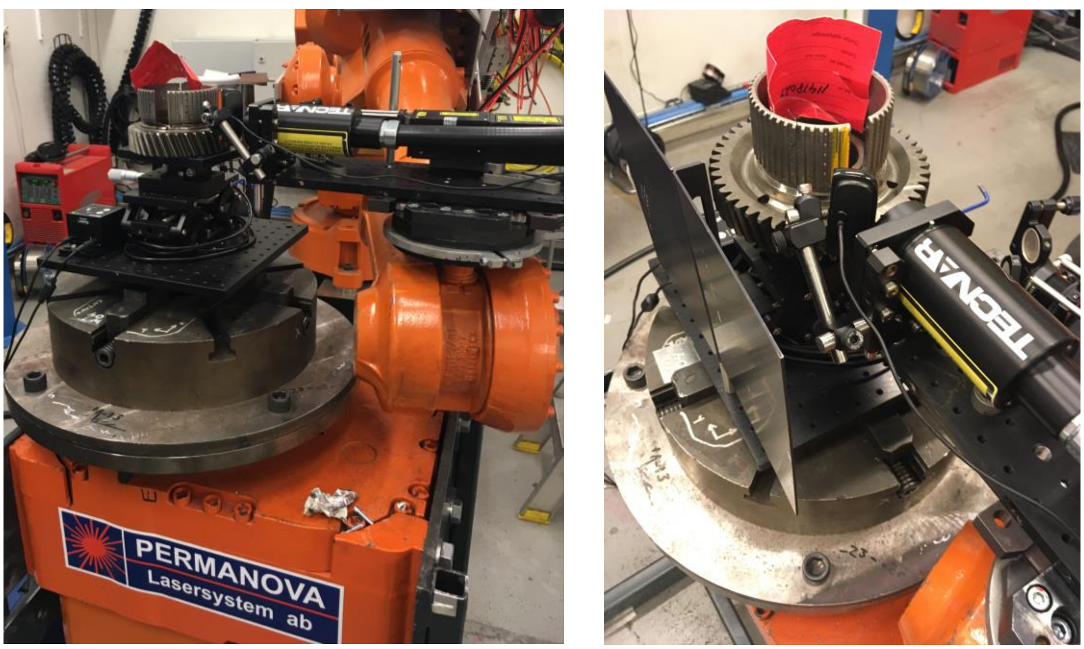


Figure 21. Pictures from the industrial demonstrator held at Permanova Lasersystem.

6.1.15 Adhesive joints (VCC, VTC)

The adhesion bond quality has been successfully measured in transmission, where access to both surfaces is required. However, one outlier raised some questions regarding the reliability of the procedure. Adhesion bond width has been successfully measured in both transmission and reflection mode (only single surface access is required) on cured samples. Uncured samples remain a challenge. The surface damage at adhesive bond width measurements with LUS in reflection mode has been characterized and its effect on further surface treatments has been explored. Very low power laser settings did result in production acceptable surface finish but not premium surface finish, further investigation is required.

Background

As indicated in (4) ultrasonic testing can be used for testing the quality of adhesive bonds of thin metal sheets. In the study conventional ultrasonic probes were used in a pulse echo setup (reflection mode, GD 0 mm). The adhesion quality of the first metal/adhesion interface was measured by approximating the reflection coefficient. The reflection coefficient was approximated by an averaging the ratio between the consecutive pressure wave echoes. The echoes from the second metal/adhesive interface they could only identified for thicker base plates (above 2 mm), and even at those conditions the contrast-to-noise ratio is very low. In another study (5) the first metal/adhesive echo contribution to the signal is subtracted by subtracting a base-line signal, taken in a no-glue region, from the signal. The attenuation of the echoes from the first metal-adhesive interface was again utilized to verify that interface quality. The second interface quality is instead measured by checking the phase of those echoes. When the adhesive-metal is not in contact there will typically be an air gap, the air gap will have lower acoustic impedance (density times velocity of the ultrasound) than both the adhesive and the metal. However, the metal has higher acoustic impedance than the adhesive, therefore, depending on the air gap the change in acoustic impedance will be positive or negative, and when it is negative the phase will change.

With LUS the thickness requirements on the base plates might perhaps be relaxed some, since in the LUS case the pulses are short in time, however the overall overlapping is still difficult to handle. In addition, the contrast-to-noise ratios, especially for the second adhesive-metal interface is predicted to be even lower.

6.2 Simulations of POD curves

Author: Håkan Wirdelius at Chalmers University of Technology

6.2.1 Identification of essential parameters

A parameter study of the developed LUS model was performed in order to validate the amplitude distribution. In this section we'll focus on the effects due to:

- Variation of the frequency content (centre frequency and bandwidth) of the ultrasonic pulse
- Size of the excitation spot
- Measurement position of the pick-up laser spot

The variation of the position of the measurement laser spot is incorporated into the 2 other studies. These parameter studies are essential since there are different material related parameters that also may influence the divergence and received energy to the receiver.

Effect of the frequency content

One of the investigated essential parameters was the frequency content of the ultrasonic pulse produced on the surface of the component by the laser. In Figure 22 the signal response in time as function of specified centre frequency, in a prescribed cosines-square distribution, is presented. Four different frequencies, all with 80% bandwidth (6dB drop), were simulated. The normalized received signals at two different positions are depicted in the figure.

Figure 22. The signal response as function of centre frequency, when the detection is on opposite side directly beneath the LUS source (the upper figure) and position x=3 mm (the lower figure).

Corresponding simulations with one centre frequency (20 MHz) but with varying bandwidths are provided in Figure 23. The variations in frequency content correlates to laser mode instabilities and pulse duration and indicates a rather stable NDT system when it comes to receive amplitude level. At least above 10 MHz and limited variation in bandwidth. It should though be noted that variations in surface conditions on addressed component that could interfere (e.g. oxides and surface roughness) are not accounted for at this stage.

Figure 23. The signal response as function of applied bandwidth, when the detection is on opposite side directly beneath the LUS source (the upper figure) and position x=3 mm (the lower figure).

Effect of the laser excitation spot size

The size of the boundary condition that models the laser induced ultrasonic energy has also been investigated. This correlates to the actual laser spot size together with any defocussing effect caused by any change of distance to the surface. The result from this study is presented in Figure 24. In all the simulations the centre frequency was specified as 5 MHz and with 80% in bandwidth. As can be deduced from the figure the actual size seems to have an impact, at least when the diameter is larger than the wavelength (~1.25 mm). Below this value the LUS is closely acting as a point source. In all simulations the amount of absorbed laser energy is kept constant.

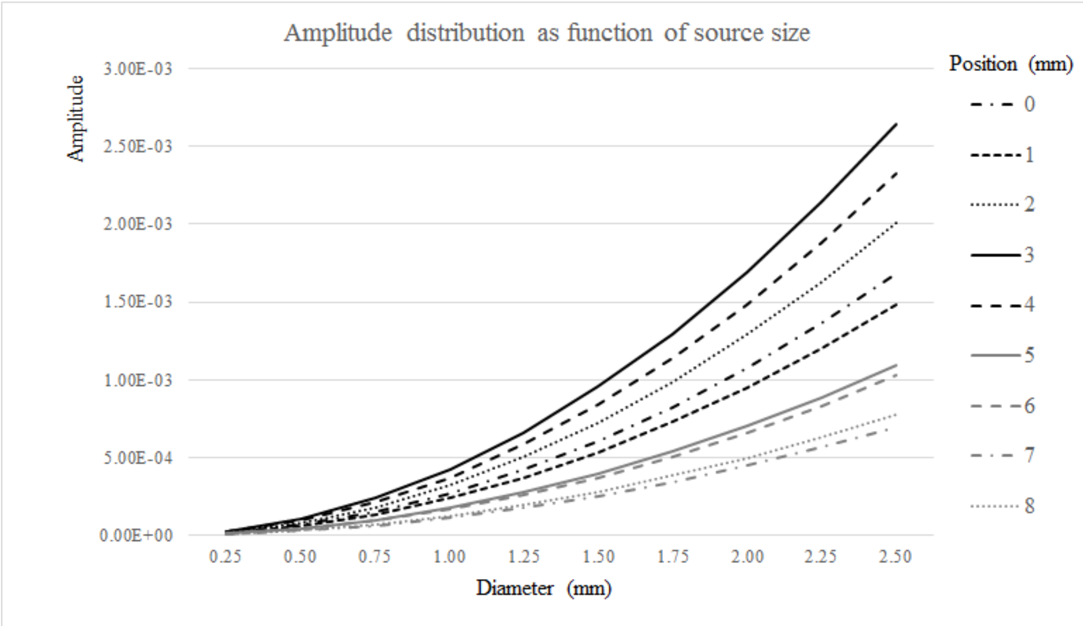


Figure 24. The maximum amplitude as function of used spot size. The detection is on opposite side from directly beneath the LUS source towards 8 mm aside.

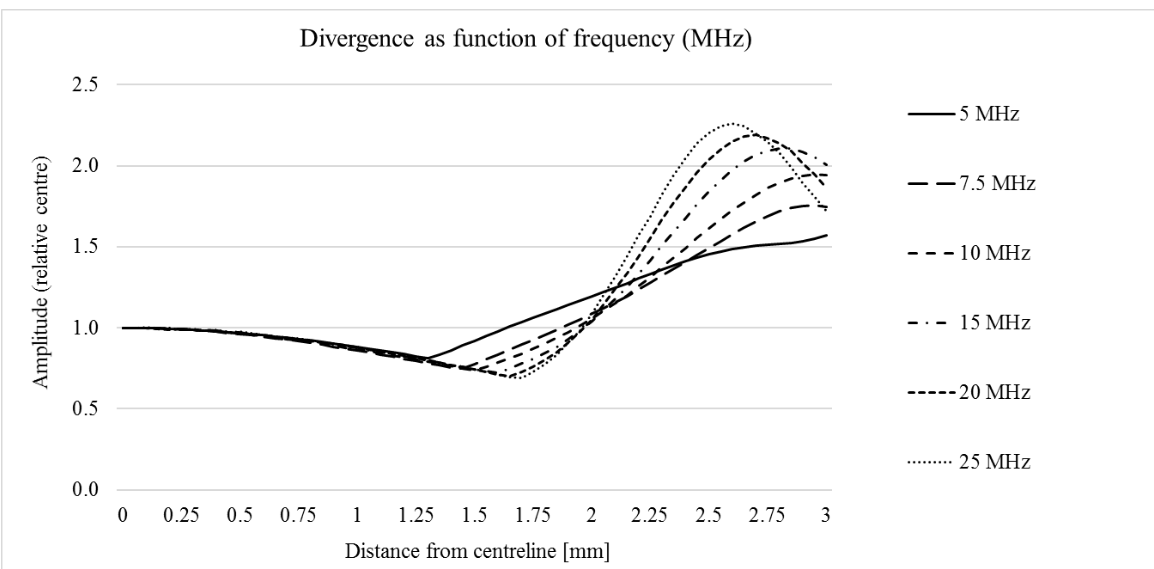


Figure 25. The amplitude distribution on the opposite side versus the lateral measurement position (position x = 0 mm corresponds to the position directly beneath the LUS source), as function of centre frequency in the spectrum.

In conventional ultrasonic technique, the divergence of the probe is closely related to the size of used piezoelectric crystals and/or their projections on the component. A point source is much less depending on actual spot size. This is to some extent confirmed by

Figure 24 since the amplitude distribution for position 0 and 1 mm is almost identical. As can be deduced from Figure 25 the amplitude distribution is also rather independent on used centre frequency, i.e. close to the centreline. The distribution of the shear wave part that dominates above 40 degrees, is though visibly depending on used centre frequency.

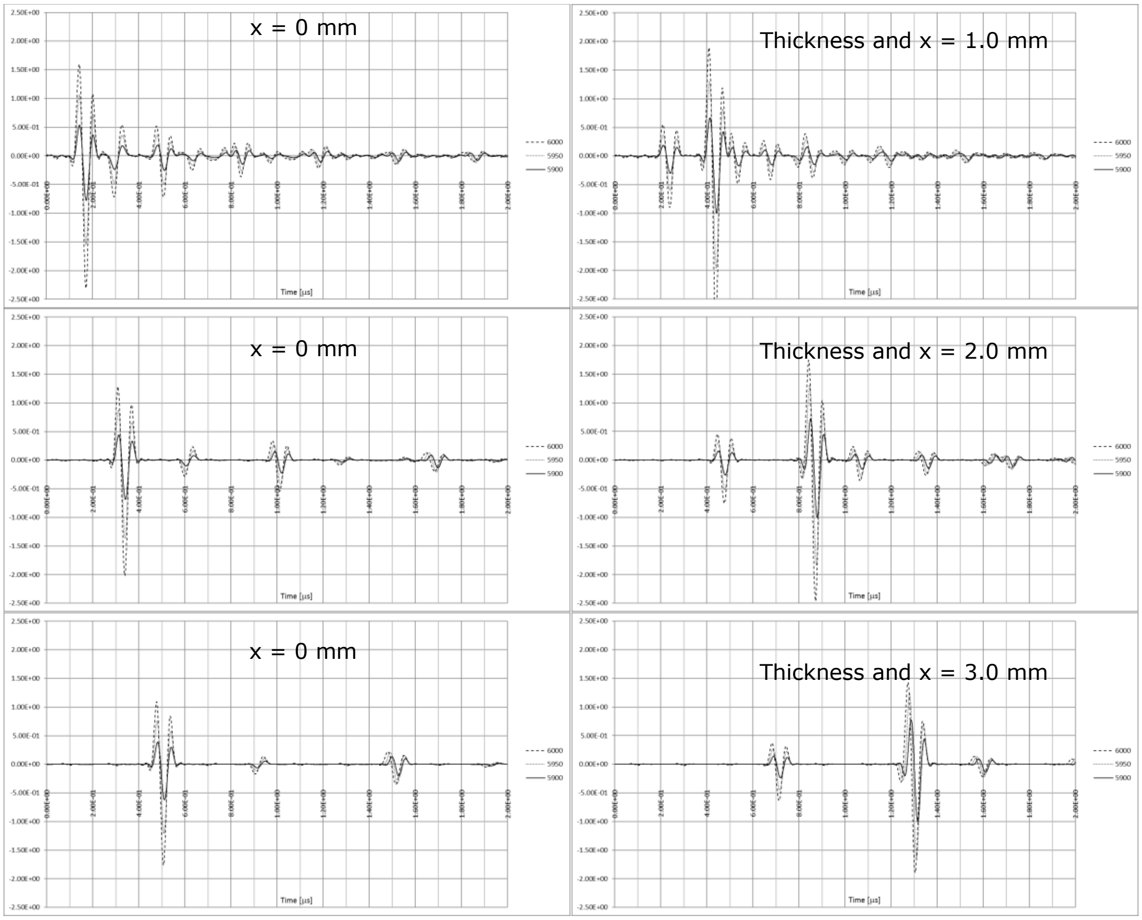


Figure 26. Simulated signal response for three different thickness of conventional steel strips (1, 2 and 3 mm) with three different wave speeds. The plots to the left are measurements beneath the generating laser (x=0) and to the right the measurements are at a

6.2.2 Experimental validation of the LUS model

To validate the modelling results, measurements were performed on an aluminium plate with a thickness of 2.84 mm. The ultrasonic wave was generated on one side of the plate and the generated wave field was then measured as the normal displacement on the opposite surface. At the first position the generation and detection laser beams are the directly opposite of each other (illustration in Figure). Measurements and simulations are compared at four different positions. The measured data is found in the left column in Figure 27. As can be deduced the first echo is not clearly visible since the laser generation pulse temporally affects the detection sensitivity of the interferometer. This effect is not included in the idealized model. Aluminium as material is chosen since the ultrasonic damping in this kind of material is recognized to be very low. Even so the measurements identify a rather strong damping as function of distance (position 7 mm in Figure 27). Also the strong shear wave component that in normal case should be generated by a point source (strongest close to 45 degree) together with mode converted contributions are not that pronounced in the measurements that could be expected theoretically.

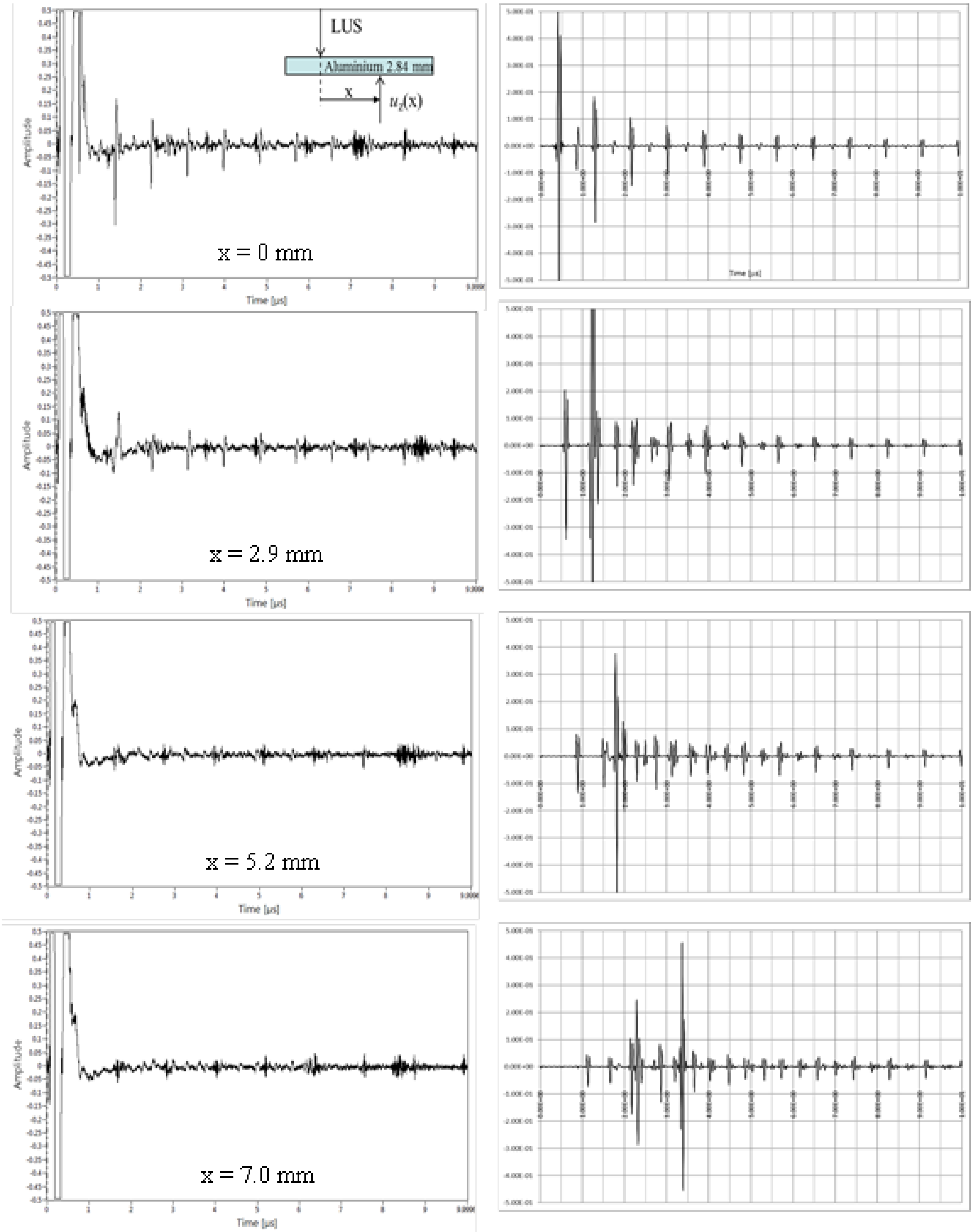


Figure 27. The measured (KIMAB) and simulated signal response (right) at four different positions (0, 2.9, 5.2 and 7 mm). The detection is on opposite side directly beneath the LUS source (x=0).

6.2.3 Comparison between two different set-ups (pulse echo, PE and time of flight, TOFT).

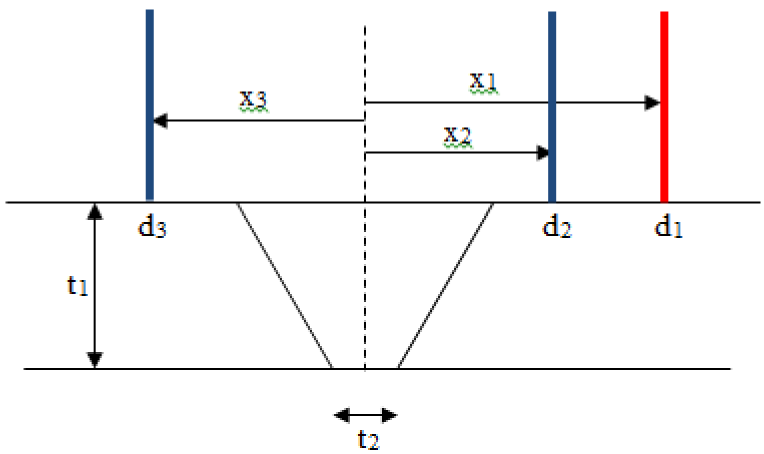


Figure 28. The two different UT measurement set-ups used in comparison. In pulse echo the transmitter and receiver position are identical (x1=x2=3 mm) while they are at opposite side of the weld in TOFT position (i.e. x3=-x1=-3 mm). Thickness of the steel component was prescribed as 5 mm.

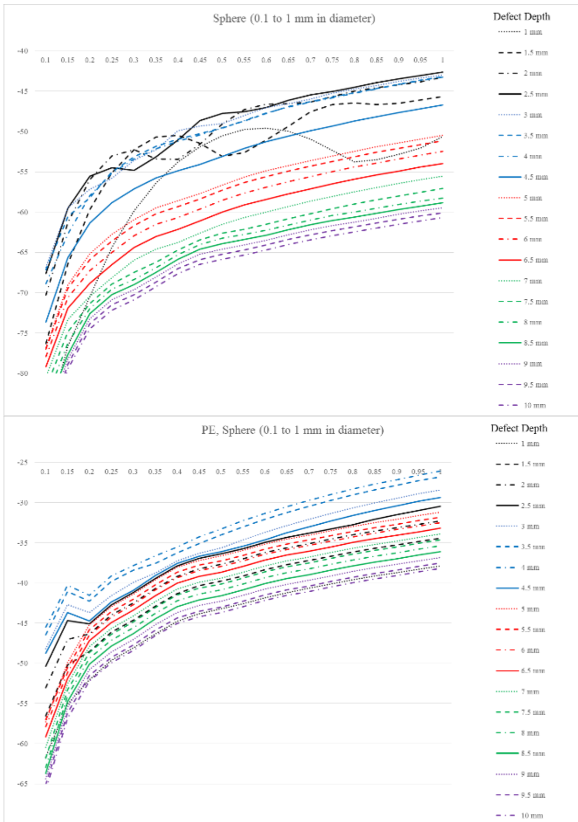


Figure 29, The maximum signal response (dB) as function of the size and depth of a spherical defect (pore). The result to the left is from the TOFT simulation and to the right is the result from the PE set-up.

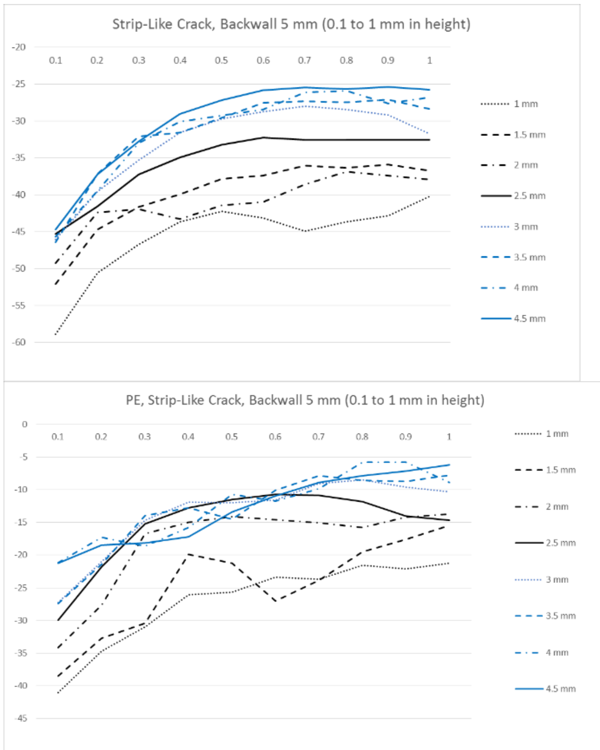


Figure 30. The maximum signal response (dB) as function of the size (i.e. height) and depth of a vertical flat defect (lack of fusion). The result to the left is from the TOFT simulation and to the right is the result from the PE set-up.

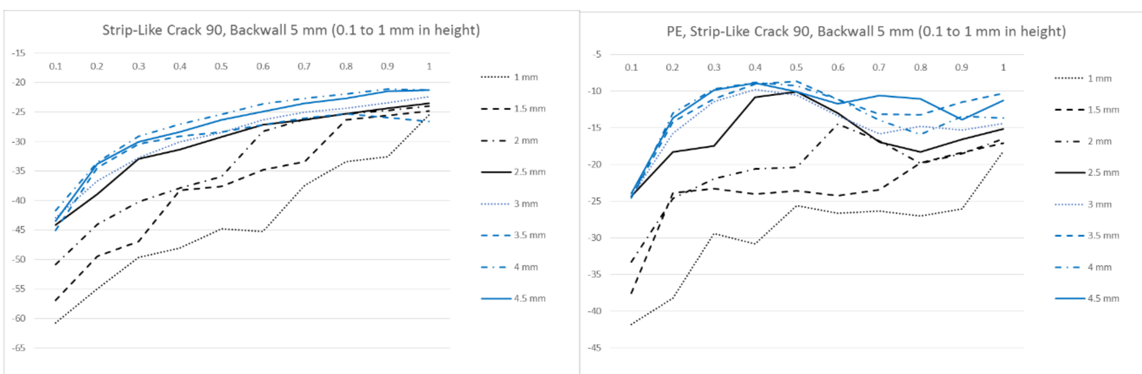


Figure 31. The maximum signal response (dB) as function of the size (i.e. height) and depth of a horizontal flat defect (lack of fusion). The result to the left is from the TOFT simulation and to the right is the result from the PE set-up.

As can be identified in Figure 29 to Figure 31 the pulse echo set-up in general gives more than 10 dB higher maximum signal response throughout these 1042 different simulations (defect types, sizes and depths). As a consequence, this set-up was chosen as UT measurement technique and a procedure that specified the inspection situation and analysis was provided by Swerea KIMAB.

6.2.4 POD as a quantification of the capacity of a NDT system

In order to quantify the inspection reliability the methodology of probability of detection (POD) was developed by the aeronautical industry in the early 1980's. This statistical tool reduces the number of artificially produced artefacts that needs to be introduced into the test blocks in order to get statistically valid information of the detection capacity, even though its legitimacy is limited to very restricted conditions.
Even though this procedure reduces the number of defects, it includes a large number of inspections and personnel and these campaigns thus tend to be time consuming and very expensive. This paper address the development of a procedure for generating POD based on synthetic data using NDT simulation software. The intention is to have an optimized experimental phase combined with much more efficiently retrieved simulated data. This has been achieved by fitting a multi-parameter prediction model to ultrasonic simulation software (simSUNDT) in an orthogonal design of experiments.

The probabilities of detection as function of defect size (POD curves) were generated by Monte Carlo simulation introducing variations in the control factors with a physical interpretation in the emulator.

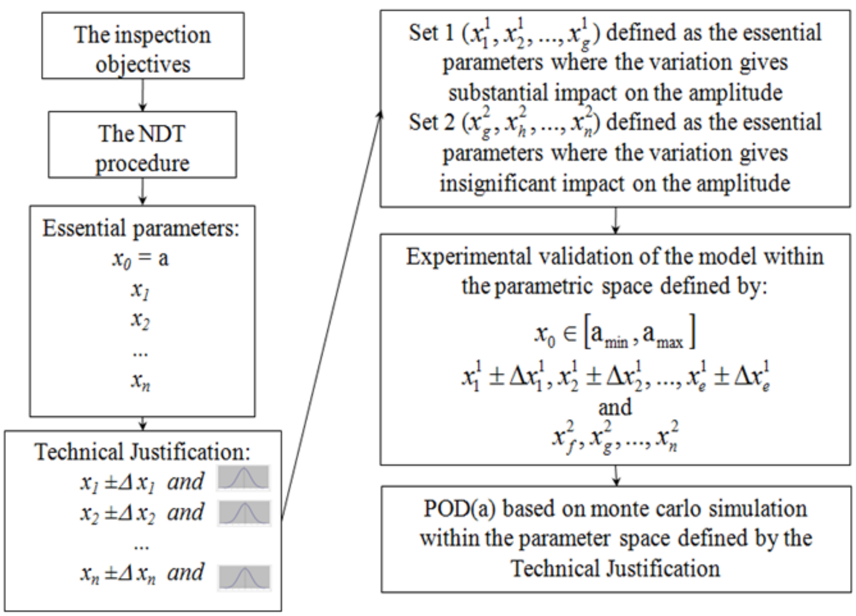


Figure 32. The methodology to identify the parameter space that constitutes the meta-model and the following Monte Carlo simulations.

Based on an existing procedure all identifiable parameters are subdivided into influential and essential parameters according to the definition:

- Influential parameters can potentially influence the outcome of an inspection.
- Essential parameters are those influential parameters whose change in value would affect an inspection in such a way that the inspection could no longer meet its defined objectives.

In this case a plausible procedure were proposed and investigated. Essential parameters that are identified as Set 1 must be specified with correlating uncertainties and their distribution. All parameters, that was available in the mathematical model of the NDT system, and their impact on the system capacity in detection (signal response above a specified level) was investigated.

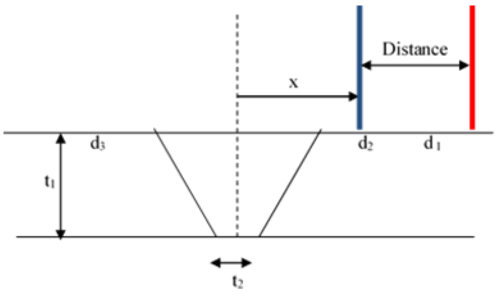


Figure 33. The pulse echo set-up with parameters that are identified as essential to the outcome of the inspection (either Set 1 or Set 2).

Set 1 parameters		
Defect size/width (a)	0.05-1 mm	
Object thickness (t)*	3.2 mm	
Defect tilt angle (α)	0°	±5°
Defect depth	1.75 mm	±0.75 mm
Defect position	0 mm	±1 mm
Transducer	0.55	±0.15 mm
Receiver	0.15	±0.05 mm
Distance T-R	6.7	±0.25 mm

Set 2 parameters	
Centre frequency	8 Mhz
Bandwidth	75%
Couplant	0.4
Wave speed (C_L)	5900 m/s
Wave speed (C_S)	3230 m/s

Figure 34. The methodology to identify the parameter space that constitutes the meta-model and the following Monte Carlo simulations (DSD model fit).

Run	Distance (GD)	Transmitter (ds)	Receiver (dm)	Defect depth (z0)	Defect Height (h0)	Position (y0)	Defect tilt (alfa0)	max amp [dB]
1	6.7	0.7	0.2	-1	1	1	5	-40.6
2	6.7	0.4	0.1	-2.5	0.05	-1	-5	-76.7
3	6.95	0.55	0.1	-2.5	0.05	-1	5	-72.2
4	6.45	0.55	0.2	-1	1	1	-5	-39.9
5	6.95	0.4	0.15	-2.5	1	1	-5	-47.4
6	6.45	0.7	0.15	-1	0.05	-1	5	-63.8
7	6.95	0.4	0.1	-1.75	1	1	5	-51.3
8	6.45	0.7	0.2	-1.75	0.05	-1	-5	-57.9
9	6.95	0.4	0.2	-1	0.525	-1	-5	-48
10	6.45	0.7	0.1	-2.5	0.525	1	5	-41.1
11	6.95	0.4	0.2	-1	0.05	0	5	-64.3
12	6.45	0.7	0.1	-2.5	1	0	-5	-49.4
13	6.95	0.7	0.1	-1	0.05	1	0	-68.4
14	6.45	0.4	0.2	-2.5	1	-1	0	-49.2
15	6.95	0.7	0.1	-1	1	-1	-5	-57.1
16	6.45	0.4	0.2	-2.5	0.05	1	5	-61.7
17	6.95	0.7	0.2	-2.5	0.05	1	-5	-55.6
18	6.45	0.4	0.1	-1	1	-1	5	-62.6
19	6.95	0.7	0.2	-2.5	1	-1	5	-42.5
20	6.45	0.4	0.1	-1	0.05	1	-5	-74.6
21	6.7	0.55	0.15	-1.75	0.525	0	0	-41.6

Figure 35. The DOS (design of simulations) that first was used evaluate the uncertainties in Figure 13 and then as the basis of a meta-model of the inspection.

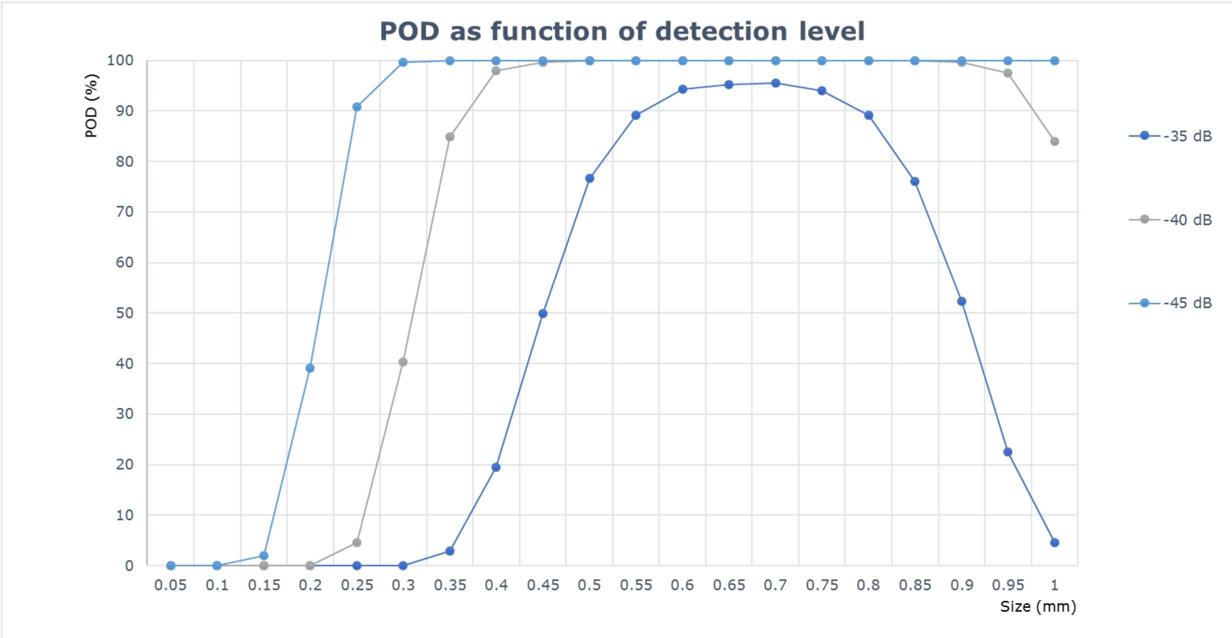


Figure 36. The different POD curves based on three different detection levels (-35, 40 and -45 dB). Each point is based on the outcome of 5000 simulations with the meta-model and the POD value then represent percentage of the 5000 defects that were detected.

6.3 Preparations for an industrial implementation (Swedish)

Author: Ulf Sandström, Permanova Lasersystem AB

In both of the industrial demonstrators in the project the welds that were selected to be evaluated turned out to be laser welds. There were other applications for which the LUS also had indicated a high applicability potential, but the laser welds have some properties that perhaps makes them somewhat easier to nondestructively evaluate with LUS. For example the ratio between the thickness of the welded base material and the width of the melted region in the weld is typically rather small, and the weld geometry variation (enforcement height and shape) along the weld length is also typically small. To get the laser spots in the right positions in terms of hardware setup and getting a signal, access around the weld, is also likely to be doable with the LUS since the weld was put there once with the laser welding setup. The safety issues with the LUS setup has often already been solved at the installation site if it is laser welds that should be quality controlled. Often, since that is not true in all cases. And finally, both laser welding and laser ultrasonic testing obviously involves high power lasers, and critical laser competence might already exist if laser welds are already produced.

Therefore, Permanova Lasersystem AB was included in the projects, as a system builder and integrator or equipment and processes related to material processing with lasers. In this section (written in Swedish) a background of material processing with lasers with a focus on welding will be given. The background will cover the lasers, the manipulators, safety enclosure issues, as well as a survey of currently industrially available process control systems. The overall aim has been to try to see what equipment can be re-used. Can the same industrial robots and manipulators be used? Can the same laser safety enclosures be used?

This part of the report is not included in this public version.

6.4 Contributions to the FFI program objectives

The objective of the FFI program that the project has mainly contributed to has been to strengthen the international competitiveness of Swedish industry. A specific non-destructive quality control method has been developed and evaluated on many different welds and joints, of many different materials with many different defects to detect and characterize. This has put questions and research concerning the non-destructive testing of and the quality control in general of joints in focus. Collaboration between many parts of the value chain has been central with different industries, SME:s and large companies, academia, and the research industry all represented in the project. Industrial demonstrators both in the industry and at an industrial integrator of laser weld systems have been held. Multiple seminars at the participating companies with participants from outside of the project group have been held, as well as a larger open broadening seminar with invited speakers from outside of the project.

The project has contributed to the specific objectives of the sustainable production program by:

- Increased process control and reduced lead times: A new quality control system can potentially minimize the manufacturing of defect products which will lead to decreased material and energy consumption.
- Increased competitiveness: Products with improved performance.
- Improved quality and reduced weight: Reliable joints leads to an increased deployment of high strength steels and new lightweight materials.
- Cost reductions and reduced impact on the environment: New design possibilities which facilitate less consumables, individualized requirements and decreased tolerances (safety factors). In the long run increased quality might also facilitate increased re-usage, re-pair, and, re-manufacturing which is important in order to reduce the overall environmental footprint of our production (circular economy).
- Quality: this is at the focus of the project since a non-destructive quality control method has been developed.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Internal seminars at some of the participating companies (VCE, VTC, GE, HIAB). An external seminar with invited speakers also from outside of this project was held at Volvo Cars in Göteborg .Two industrial demonstrators have been held, one at Permanova focusing more on practical industrial implementation issues and one at GKN Aerospace focusing more on the feasibility of using LUS for the specific application in an industrial environment.
Be passed on to other advanced technological development projects	X	There are a number of continuation project ideas mainly at TRL levels 3-7.
Be passed on to product development projects	X	The possibility to use LUS for high precision thickness measurements performed in-line close to (laser) welding in order to achieve better process control might be suitable for this step. The technology is available and we have shown in the project that it is applicable. However, numerous additions at lower TRL levels are possible.
Introduced on the market		We believe the technology maturity is too low for the application of weld defect detection and characterization, the thickness measurement for process control, at mentioned above, is however at a higher maturity.

Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

No peer-reviewed publications have been produced in this project and in the project plan none was planned for. The reason is that much of the work concentrated on trying to experimentally approximate the applicability of and make proof-of-concepts for LUS to be used for the quality control of the joints for the rather large number of sample and application types. Such a study is difficult to publish, in contrast to more in depth studies on one single sample type or application.

A detailed research report containing more details than the public report has been compiled and distributed within the project group.

8. Conclusions and future research

Laser ultrasonic has shown a large potential to be applicable for defect detection and characterization in many different weld and joint types, geometries, welding procedures, and materials. However, each application is difficult to optimize and set up the system to handle, and a lot of prior assumptions (as always in non-destructive evaluation) are required.

Overall the method, stable sampling of data, is robust and we have shown that it can be utilized in a production similar environment. The procedures and analyses are not always robust though, and further research and development is required before it can be industrially deployed.

Welds with small variation in outer weld enforcement geometry and small narrow welds with respect to the overall thicknesses involved, which are the typical properties of laser welds, seem to be easier to inspect with the laser ultrasound. For example, algorithms that increase the contrast-to-noise-ratio are easier to apply in such conditions. Therefore, we believe that the first number of industrial deployment of laser ultrasound inspection of welds and joints are most probably going to be on laser welds.

Much more research and development is required, and all of the possibilities with different procedures, setups, and analysis algorithms have for certain not been exhausted and tried all ready. For example, it is our strong belief that if all of the applications in this project were re-evaluated today, at the end of the project, with all the new experimental equipment that has been invested in and with all the procedure and analysis knowledge that have been acquired, then in most of the cases the LUS capability would be increased.

9. Participating parties and contact persons

Former contact persons that participated to a large extent to the project have been included and are indicated with the notation FCP.

Swerea KIMAB: Erik Lindgren (Project leader 2017-01-24 to 2017-10-10), Mikael Malmström, David Malmström, Peter Lundin (Project leader 2016-06-13 to 2017-01-23, FCP), Eva Lindh-Ulmgren (Project leader 2014-10-01 (beginning) to 2016-06-12), Jacek Komenda, Paul Janiak, Karl Fahlström.

Chalmers University of Technology: Håkan Wirdelius.

Volvo Construction Equipment in Eskilstuna: Hans Torstensson.

Volvo cars: Oscar Anderson, Johnny Larsson (FCP), Gert Larsson (FCP).

Volvo Group Trucks Operations in Umeå: Johan Åström, Kent Stenberg, Samuel Bäckström (FCP).

HIAB Cargotech: Svante Widehammar, Lars Rydahl (FCP), Eric Lindgren (FCP).

GKN Aerospace Sweden: Per Henrikson, Jan O Lundgren (FCP).

Permanova Lasersystems: Arash Moini, Ulf Sandström, Niclas Wikström (FCP).

Scania: Mattias Olsson.

GE Heath Care: Lars G Eriksson.

10. References

1. *Weld toe geometry: a factor determining the fatigue behaviour of butt welds.* **K. Hentschel, et al.** 1987, Welding international, Vol. 9, ss. 865-870.
2. **J. Krautkrämer, H. Krautkrämer.** *Ultrasonic Testing of Materials.* Berlin : Springer, 1990.
3. **Li, P.** *Experimental Study on Cold Lap Formation in Tandem Gas Metal Arc Welding (Licentiate Thesis).* Göteborg : Chalmers University of Technology, 2011.
4. *Ultrasonic testing of adhesive bonds of thin metal sheets.* **L. Goglio, M. Rossetto.** 1999, NDT & E International, Vol. 32, ss. 323-331.
5. *Pulse-echo NDT of adhesively bonded joints in automotive assemblies.* **S. Titov, R. Maev, A. Bogachenkov.** 2008, Ultrasonics, Vol. 48, ss. 537-546.