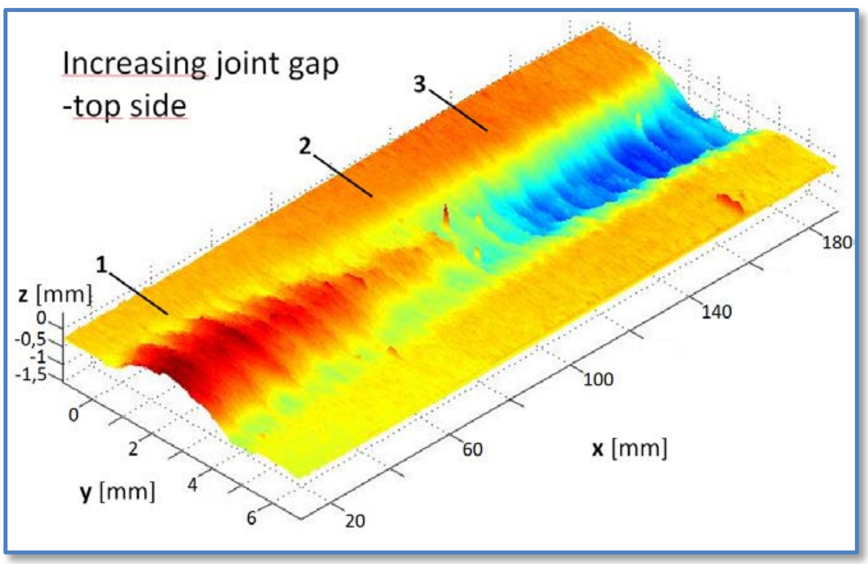
Public final report
Project:

ROBUHYB
Robust laser arc hybrid welding of thick section automotive components



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Subprogram Sustainable production technology

FFI

Innehåll

1. Executive summary

Laser Arc Hybrid Welding (LAHW), a combination of laser and arc welding, offers higher productivity compared to traditional welding techniques like arc welding. This is achieved by higher welding speeds and more advanced construction possibilities. Thus far, laser arc hybrid welding is not used in the Swedish engineering industry but there are already more than hundred installations worldwide. Scania has the ambition to implement laser hybrid arc welding, but development of a robust process and increased understanding of the weld during fatigue situations, especially concerning the weld upper geometry, are required.

The robustness of the process was studied with a new fully controlled and systematic traceability of tolerance. This is achieved by mapping parameters, measuring and studying edge variations from the forming, and creating an understanding of its impact upon the final weld by High Speed Imaging (HSI). Also the new arc welding process CMT (Cold Metal Transfer) was studied in combination with laser beam welding. During the project, sample workpieces and full-scale automotive components where welded with LAHW with respect to process robustness, coupled quality control and fatigue behavior.

Basic differences between three arc welding processes (Cold Metal Transfer – CMT, Pulsed, Standard) are investigated for each process function and process stability. Tolerance windows for the weld joint types that occur on the demonstrator are investigated and mapped for LAHW with CMT, as a technique for thick sheet metal products. The new systematic measurement method (pre-, post-scanning and HSI) has been further developed and applied on a complex automotive product. For a truck beamer all the twelve weld sections has been mapped and optimized. From the results, six journal and four conference papers has been produced and presented.

A new project (EU-FP7, HYBRO) continues where ROBUHYB ends. The HYBRO project continues with the same demonstrator and therefore works as an extension of ROBUHYB. It was prioritized to put more time to compare different techniques to get even better results. Within HYBRO there also are a 6 m long demonstrator from a French automotive company and two other Scania applications that are going to be investigated. Besides that, HYBRO is a good opportunity to collaborate with world leading partners that applies the new LAHW technique for high strength steels. Eight beamers have already been 3D-robot welded at LTU in a fixture made by Ferruform (Scania). Optimization of the demonstrator beamer welding continued when eight additional beamers where first tack-welded at LTU and later welded at Fronius (Austria, leading supplier of laser welding equipment) where additional errors were detected and therefore avoidable.

The whole chain from construction (production development in Södertälje) and material choice, cutting/forming, welding, finishing etc. (Ferruform in Luleå) was analyzed from an economic and practical point of view, in order to prepare introduction of LAHW in production.

2. Background

The project ROBUHYB is about introducing Laser Arc Hybrid Welding (LAHW) into Scania's production line at Ferruform in Luleå, as well as planning yet another product at the same company. The Ferruform AB factory in Luleå has about 600 employees and is fully owned by Scania. Scania's production development in Södertälje has also been involved in the project. With the welding method of today, GMA, root support is required (among others), material that is not needed when using LAHW.

To be able to weld the different applications there are certain requirements that needs to be fulfilled:

- Sufficiently high welding speed to reach productivity aims
- Sufficient power needed to achieve penetration depth
- Approved fatigue durability in the weld joint
- Approved weld according to standard SS-EN ISO 5817

Different weld techniques

Today, GMA-welding or powder arc welding is commonly used as traditional methods in the engineering industry. A promising option is laser welding, serving as a high potential/high risk method. Laser welding has the drawback that joint gaps cannot be bridged, but LAHW has properties that combines the strengths of both methods. LAHW is thus far a method that is not widely used. Welding companies lacks the experience and security that is needed to implement the method in a larger scale. Laser hybrid welding therefore requires to be further explored and developed, which is the aim of this project. Of special interest is the possibility to use the new kind of laser, fiber laser, with its inherent excellent properties.

<u>Laser Arc Hybrid Welding</u>

It has been known for many years that the combination of a laser beam, Fig. 1(c) and an arc weld (e.g. GMA, TIG), Fig. 1(a), combines many of the individual advantages of the different processes. By welding with laser-GMA, see Fig. 1(d),(e), the laser weld offers high welding speed and deep penetration with a broader top surface by the addition of material by the GMA. At the same time, the heat supply becomes lower as the welding speed is substantially higher than with pure GMA-welding.

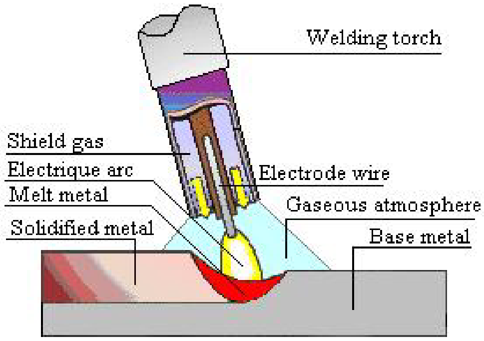


Figure 1(a) Sketch of GMA-welding

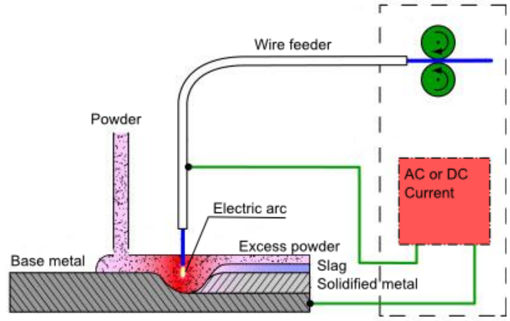


Figure 1(b) UP-welding

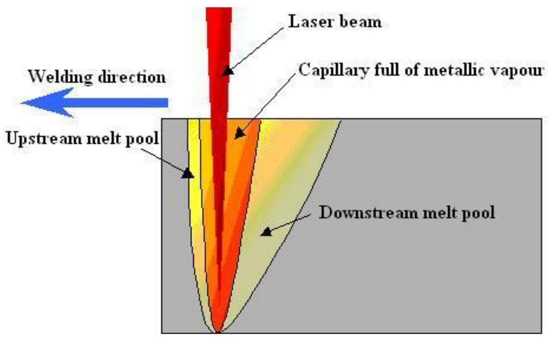


Figure 1(c) Laser welding with a keyhole

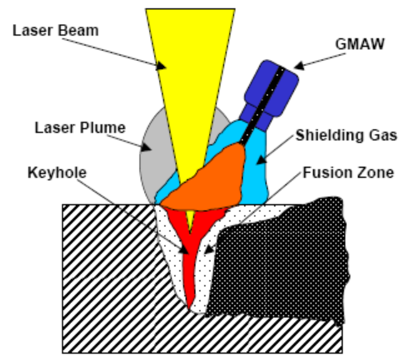


Figure 1(d)Laser Arc Hybrid Welding (Laser + GMA)

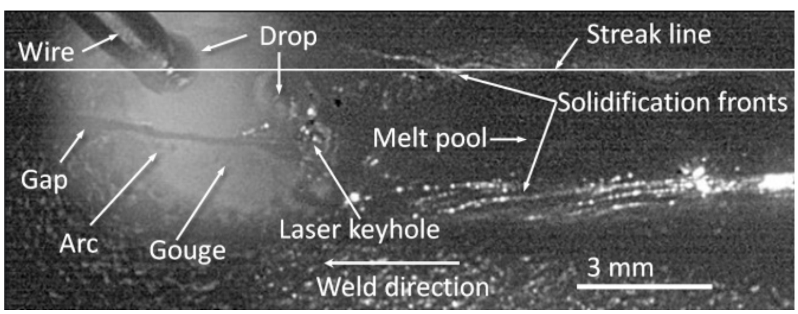


Figure 1(e) High Speed Image of laser arc hybrid welding (melt, laser keyhole, drops, arc, joint)

Figure 1. Welding methods, principle

LAHW offers good gap bridgeability and the method can be even cheaper than pure laser welding as the heat supply from the GMA results in a lower requirement of laser power.

The benefits compared to pure laser welding:

- Higher welding speed
- Lower capital needed, lowered by 30-40% since lower laser power is needed
- Less demands on joint preparation
- Control of the joint width and the joint design, Fig. 3(d)
- Possibility of controlling the metallurgical properties by the filler wire

Disadvantages:

- Only a few users, in other words there is lack of confidence in the process
- Many parameters to optimize
- Reach ability at complex geometries

However, there are a few applications internationally (more than 100 in the world, about 40 in Germany) that uses the technique in a very large scale. The Meyer shipyard, Germany, builds big passenger ships and uses LAHW at 50% (soon 75%) of their 900km/ship. By using this method, they avoid deformation corrections (about 20% of production costs). Within the automotive industry, LAHW is used e.g. by Volkswagen for welding of car doors or by Mercedes-Daimler for components. There is also multiple applications before an implementation within industries such as cranes, trains, construction machines, pipelines etc. In Sweden, only Duroc Rail AB in Luleå used LAHW between 2005 and 2012 to weld big high strength steel sheets for ore wagons and truck flatbeads in industrial production (with a CO_2-laser, Scania plans to use a fiber- or disc-laser with much shorter wavelength). ESAB got a LAHW laboratory for their customers.

Production perspective Scania

To continue to be strong on their market, Scania must lie in the forefront for effective production at the highest possible quality. Welding is a key technology for the company. Ferruform/Scania in Luleå uses the most weld filler wire in Sweden(!). Scania is interested in high tech methods like laser welding and LAHW since these are methods that can increase their productivity and enable a yet more innovative production development. However, LAHW is thus far a rarely used, high potential/high risk -technology that is difficult to control (especially for the new, otherwise promising fiber laser) and needs to be explored to get it to be as secure and robust as required to be used in production.

Currently, Scania has a fully automatic production line that laser weld shaft ends onto rear axles. This welding where previously made by GMA- and friction stir- welding. Productivity was substantially increased (higher welding speed, less milling as post treatment) shortly after the installation.

Compared to GMA/UP- welding, Scania is interested in LAHW mostly because of two reasons:

- Higher welding velocity than with pure GMA welding
- Root support elimination, due to the narrow laser weld

Compared to pure laser welding, LAHW is preferred due to, among other, the following reasons:

- Higher error margins at joint preparation can be allowed compared to pure laser welding
- A broader top surface is made where the surface geometry can be controlled, preferable for fatigue durability

2009 Scania together with LTU carried out the first year of a three year long project (look below "Others"!) about LAHW (with a 15 kW-fiber laser) on a rear axis as well as three other truck parts. Their (low volume-) production later moved abroad! – importance grows yet more to have competitive weld methods for the remaining products.

It was studied in the project ROBUHYB (i) the effect of lack of fusion and undercuts due to oxide layers and (ii) three tolerance dimensions in joint preparation (width, mismatch, surface position) upon weld geometry that could be clarified and measured with the help of a scanner (before/during/after welding), (iii) welding of demonstrators with final product size and geometries. High Speed Imaging was used as an important starting point in order to identify a robust/stable process window. Additionally, comprehensive mapping of parameters was carried out and evaluated. Some of these results are soon to be published. The CMT- (Cold Metal Transfer) arc weld process was tried in combination with laser, which directly led to promising results, which again could be understood through high speed imaging.

3. Objective

The project sought to substantially increase productivity in component manufacturing at Scania and strengthen Scania's competitiveness in the long run. It will also give opportunities for advanced product development, especially light weight construction through the use of steel with high durability. Additionally, Laser Arc Hybrid Welding is environmentally friendly since it uses less electricity and material (no root support needed, light weight construction for the beamer).

The project also results in synergetic effects for other automotive manufacturers in Sweden, especially those that uses thick sheet materials, e.g. Volvo AB (Volvo CE, Volvo Lastbil), Cargotech HIAB, BAE Hägglunds, and other component suppliers.

The project provides enhances the scientific competence and generates new knowledge in Sweden, both for the University and manufacturing- and supplier-companies (e.g. ESAB, SSAB, Outokumpu, Sandvik).

Important pioneering role in Sweden (hopefully the 2nd application in production, although the 1st was cancelled) as a reference to ensure assurance with other interested in laser arc hybrid welding, especially with the new fiber laser type.

For the first time a new method that verifies traceability of the full weld tolerance chain is presented: mapping of edge tolerances, filming and interpretation of process variations, measurement of variations in weld geometry (that reads the whole weld surface when welding demonstrators). Studies of the new arc process CMT (Cold Metal Transfer) together with laser welding.

4. Project realization

The work was divided in five work packages with the following content:

- WP 1. Development of a robust weld process
- WP 2. Development of robust weld process with seam tracker
- WP 3. Laser Arc Hybrid Welding of demonstrators
- WP 4. Fatigue testing of welded demonstrators
- WP 5. Analyses of economic calculations, welding samples and fatigue testing. Also pre-study for implementation

The project ran for two years, from Q3 2011 to Q4 2013. The work carried out in the earlier work packages was later applied for a full scale demonstrator in close to industrial conditions. The work was planned according to the schedule below:

	År / kvartal	**2011 /3**	**'11 /4**	**'12 /1**	**'12 /2**	**'12 /3**	**'12 /4**	**'13 /1**	**'13 /2**	**'13 /3**	**2013 /4**
WP1	Svetsprocess	x	x	L1 L2							
WP2	Svetsprocess/ fogföljning			x	x	M1 L3					
WP3	Svetsning demonstrator					x	x	x			
WP4	Utmattnings-provning						x	x	x	x	
WP5	Analyser, förstudie								x	x	M2 L4

A new EU-FP7 project, HYBRO, with LTU as coordinator and Scania as partner was approved Q3 2012. It is a three year long project with a budget of 1,6 mEuro, where 950 kEuro financed by the EU. It is an excellent synergetic continuation of ROBUHYB. The competence within the project with world leading partners within laser welding (RWTH and Fraunhofer Aachen/DE), high strength steel (Arcelor/BE, Thyssen/DE), hybrid welding equipment (Fronius/AT) and another automotive demonstrator (Liebherr/FR), will especially benefit Scania's demonstrator and LTU's knowledge. By the new EU-project, the application has a new scope and time horizon, especially for investigating the knowledge transfer and technology to other applications for Ferruform/Scania. Therefore, a part of the ROBUHYB project is transferred to the new HYBRO project (WP4 and partly WP2 and WP5). It turned out that the usage of a seam tracker is too bulky to be of any use on a demonstrator in a fixture. A part of the seam tracker's role will still be used and applied on the demonstrators by scanning and measurement of surfaces, joint variations and final weld geometry.

5. Results and deliverables

Today the laser hybrid welding process is commonly used with an electric arc (with material addition) in pulsed mode (GMA-P). The advantage of the pulsed mode against the continuous (Standard-) mode is a somewhat lower heat input and less smoke, but foremost a robust material transfer even at lower wire feed (deposition) rates. There exists many other arc modes besides these two, but they are not used in equal extent because they are mostly unique for each manufacturer. A short arc technique that have quickly gained fame is the new CMT- (Cold Metal Transfer) technique from Fronius (Austria). Advantages by this method are even lower heat input, less undercutting and less spatter. Disadvantages are lower penetration depth and limited deposition rate. Basic differences between three arc modes (CMT, Pulsed, Standard) are investigated for each process- function and stability. Differences in weld cross section geometries that are in part due to heat input can be seen in Fig. 5.1. The CMT-technique is especially developed for thin sheet welding, but it has proven for Laser Arc Hybrid Welding (LAHW) in this case (7 mm) to be working well also for thick sheets. The welding processes are also filmed using High Speed Imaging (HSI), a technique that allows the weld process and the melt to be seen despite the powerful light that is emitted from the process. An image with annotations from such film can be seen in Fig. 5.2.

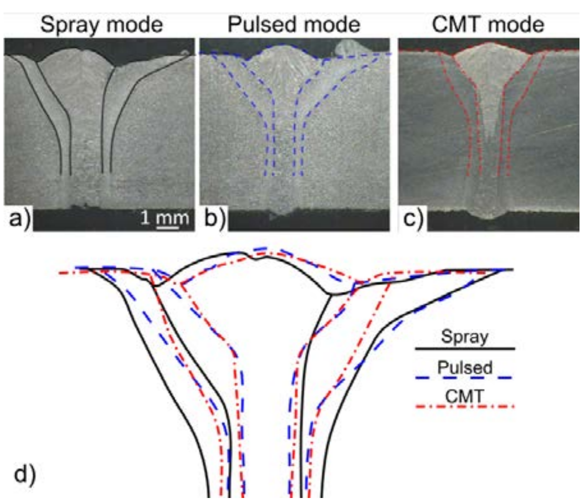


Figure 5.1. Comparisons of resulting weld geometries between different arc modes in laser arc hybrid welding. a) Standard [Spray], b) Pulsed, c) CMT) and d) a-c overlain

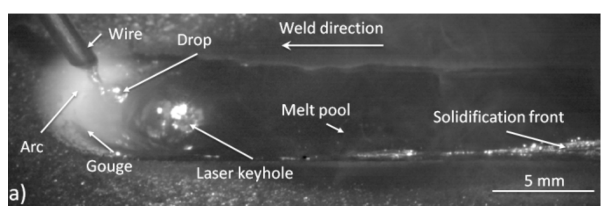


Figure 5.2. Frame from high speed imaging, showing laser arc hybrid welding, with annotations

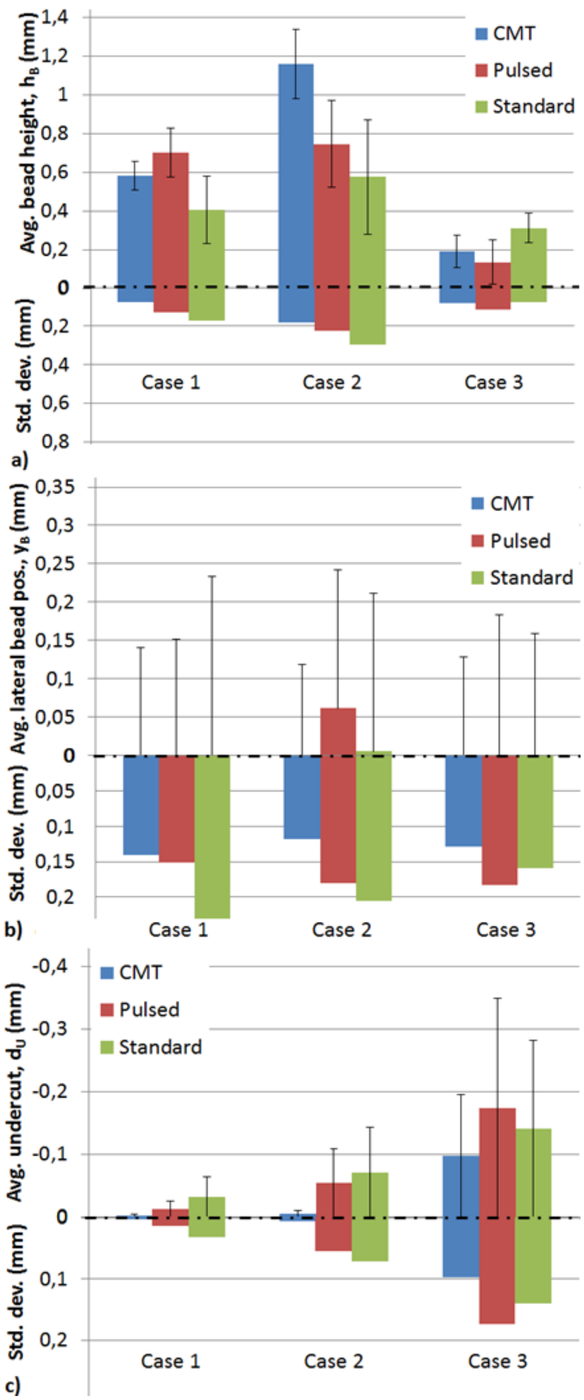


Figure 5.3. Stability comparison between three different arc modes in laser hybrid arc welding on a butt joint; Cold Metal Transfer (CMT), Pulsed and Standard. Case 1: 2m/min, case 2: 5m/min and case 3: 1,5m/min with 0,6mm gap. Standard deviation and average- a) height, b) deviation towards joint and c) undercuts

To follow the joint better so that the joint is not missed, or height differences are compensated for, a seam tracker is appropriate to use. Since the demonstrator will be laser cut the sample will therefore also be laser cut, which works well for the LAHW process. It has also earlier been shown that oxides from plate rolling cause undercuts [1], therefore the workpieces are etched or blasted prior to welding on both the demonstrators and the samples. For welding tests on sample workpieces an available seam tracker was used as a scanner to collect data about the final weld geometries, by which the welds and robustness between the arc modes can better be compared. The stability of the resulting weld geometry on a laser cut butt joint is compared between the three different arc modes in LAHW and the result can be seen in Fig. 5.3. When comparing the results, it is clear that the CMT- technique offers the most stable results and therefore that technique has foremost been further studied, including testing of tolerance windows of the demonstrators two main joint types, butt and T-joint. Optimization and comparison of the tests was conducted with production environment and productivity in mind.

To map the process stability, a systematic measurement method is used, which includes surface profile scanning and HSI. Tolerance windows are attained by scanning the surface of the demonstrator joints while setup in a fixture. Then the found variations can be weld tested on workpiece samples with an even greater margin while at the same time using HSI, after which the final weld is scanned and an analysis of the process robustness can be made. Testing of the tolerance windows was made by testing the geometrical variations one at a time, Fig. 5.4. Geometrical variations that can occur are joint dislocation, weld gap size variation or height dislocation of both or one of the workpieces. An example of scanned surfaces when these variations are tested can be seen in Fig. 5.5.

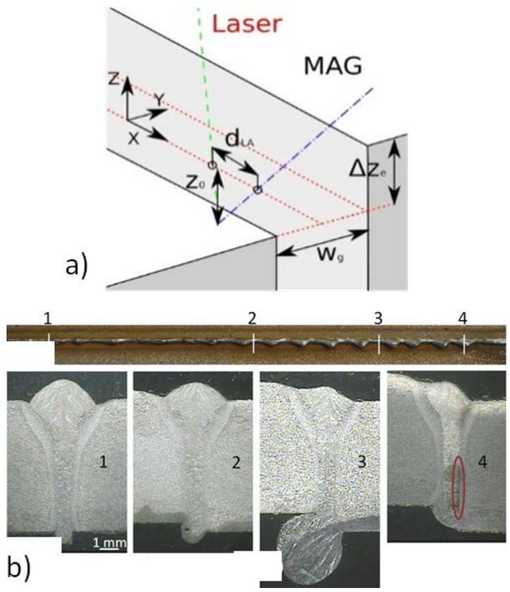


Figure 5.4. a) Illustration with dimensions of possible geometrical joint variations. b) a welded root side as an example of what can happen if one of the plates have height dislocation.

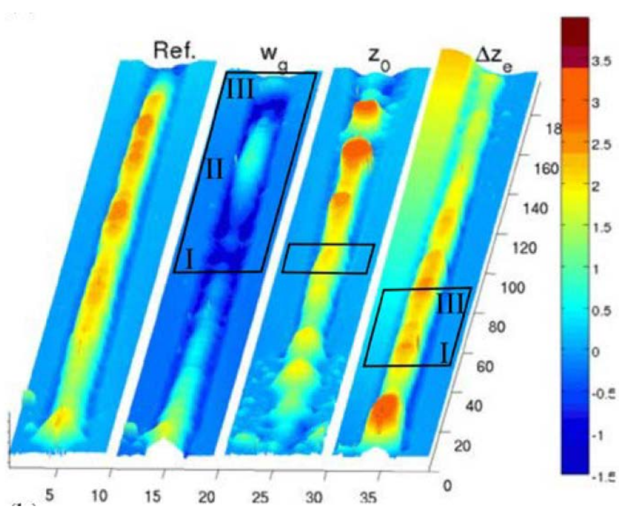


Figure 5.5. Scanned weld surfaces where geometric joint variations have been tested systematically.

Set-up of the hybrid process head is for the T-joint set to be the same as for welding butt joints because of implementation in future production, which is not optimal for the welding process. Due to an unintentional error in the cutting process, the beamer edges got a varying V-gap along the length of the weld. It showed that the tolerance window from the sideward plate is small with this process head set-up, only ±0,2mm to be in the optimal regime. This requires accurate programming and movement precision by the robot to attain approved welds. Examples of cross-cuts on sample workpieces with approved fillet welds can be seen in Fig. 5.6. The surface geometry is most important for fatigue, so that the small occurrence of pores does not need to be further minimized.

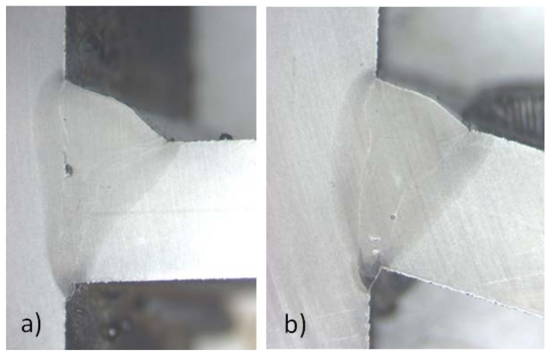


Figure 5.6. Cross cuts for weld experiments for T-joints with a) I- and b) V-gap

After the systematic measurement method (pre- and postscanning and HSI) was used to optimize (also mapping the process and results) the different weld sections, welding of the demonstrator beamer could start. How the demonstrator is put together and the location of the different weld sections is seen in Fig. 5.7. The beamer parts are mounted in a fixture made by Ferruform (Scania) and the parts are tack welded as to not deform during welding. The welding is conducted first on the halves and later at the end pieces. Weld section 1-3 (butt joint, I-gap) on the beamer halves is welded together in one weld run. Due to reachability constraints the welding head is leaned in section 1 and 3 which requires some adaptation of the process. Section 4-12 is run in one weld run where the gap is changing between sections.

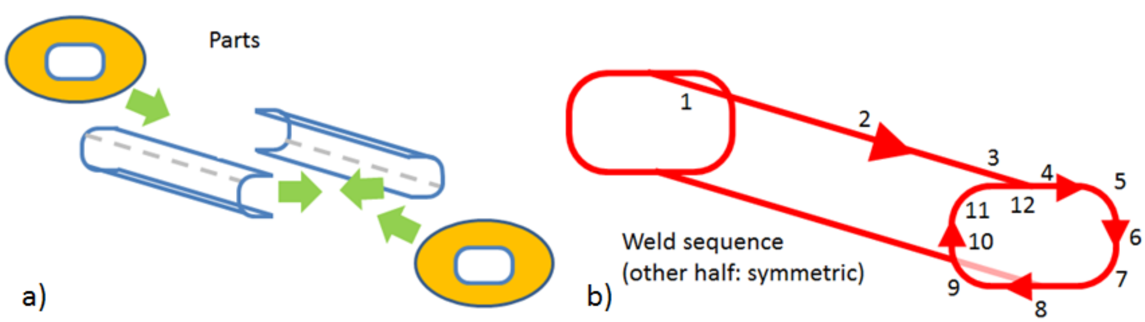


Figure 5.7. a) how the parts of the beamer (halves and ends) are put together. b) weld sections for half of the beamer, where section 1-3 is run in one and 4-12 is run in one weld

To use the existing seam tracker on the demonstrator beamer in the fixture proved impossible due to reachability constraints. The scanner head is too far away from the weld process and is also too bulky as it gets in the way of the processing head so that it cannot reach to weld the full length of the beamer. A new type of joint tracker is needed if seam tracking is to be applied, one that takes less space and comes closer to the weld process. Alternatively a seam finder could be used, that scans the surface prior to welding and reprograms the robot track before welding, but this solution will nearly double the total time for welding which contradicts future production rate.

Welding of section 1-3 worked well on most demonstrator beamers. Sometimes root dropout or pores occurred, mainly due to unclean (oil residues from forming was present) weld surfaces before welding. Figure 5.8 shows a typical cross section of one butt weld on a demonstrator beamer.

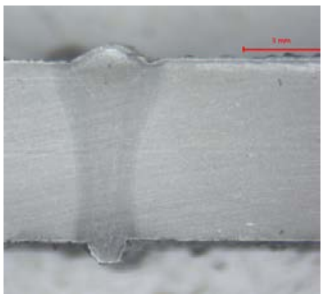
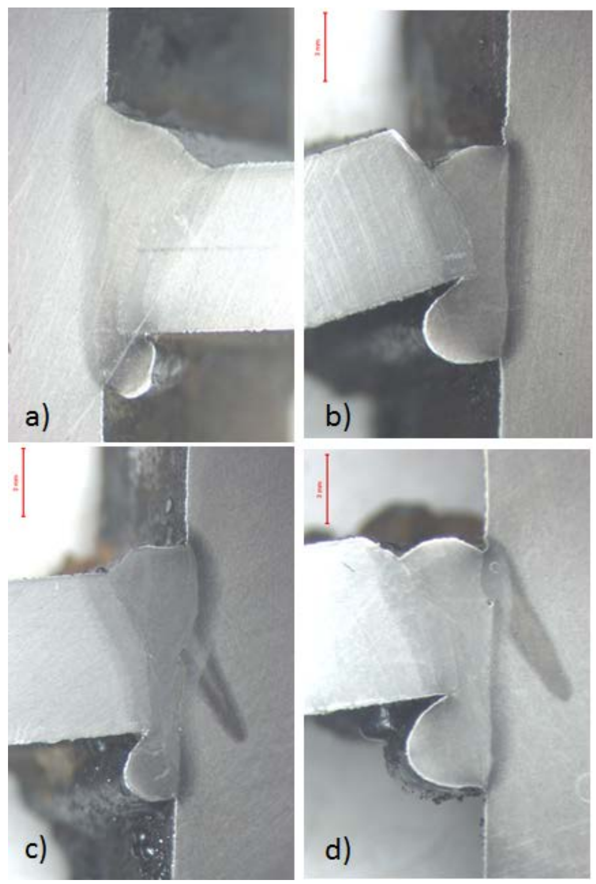


Figure 5.8. Cross section from a butt joint from a welded demonstrator beamer. Largely defect free, but small amounts of pores was often present

Welding of the T-joint caused many problems and the largest reason for this was small process window and the varying gap along the length of the weld. Many problems concerning the robot guiding (accuracy), power source, linearization of the parts etc. was solved, but a fully approved (fillet welds) demonstrator beamer was still not produced. When no more remaining errors was found, a decision was made to improve the conditions for welding by milling the beamer halves so that the varying gap was eliminated and only an I-gap for the T-joint was present along the end piece. Still, this was not sufficient due to the narrow process window (partly due to the non-optimal process head setup) and another decision was made, to weld only 6 mm instead of having full penetration (7 mm). This will counter



Figur 5.9. Tvärsnitt från svetsad kälfog på demonstratorbalk. a) godkänd delsvets, b) nedsjunkning av svets, c) delad laserstråle och d) kombination av b-c)

the problems of root sacking and therefore makes the process window larger, but this solution can impact the final fatigue properties of the beamer. When these decisions was made, good quality welds could be attained, leaving only some local problems of root dropout (due to heat conductivity, same places on every beamer) and corner welding (position and speed) adjustments. Figure 5.9a-d shows example cross sections of a fillet weld from welded beamers, where a) shows an approved weld, b) shows (the big problem of) root dropout. In c) the laser beam was split, probably due to hitting the filler wire and d) show a combination of both root dropout and split beam. Pores are present, but for fatigue these are a minor concern (unless at the surface of the weld) and do not need to be minimized further. In total, there has been 16 beamers welded, where 6 was nearly fully approved for fatigue testing. Additional beamers will be welded and fatigue tests will take place under the new EU FP7-project HYBRO.

From an analysis of the demonstrator welding and the problems that occurred, the flowchart in Fig. 5.10 was produced. The flowchart is intended to be used as a planning tool in future projects to accomplish reliable implemented welds.

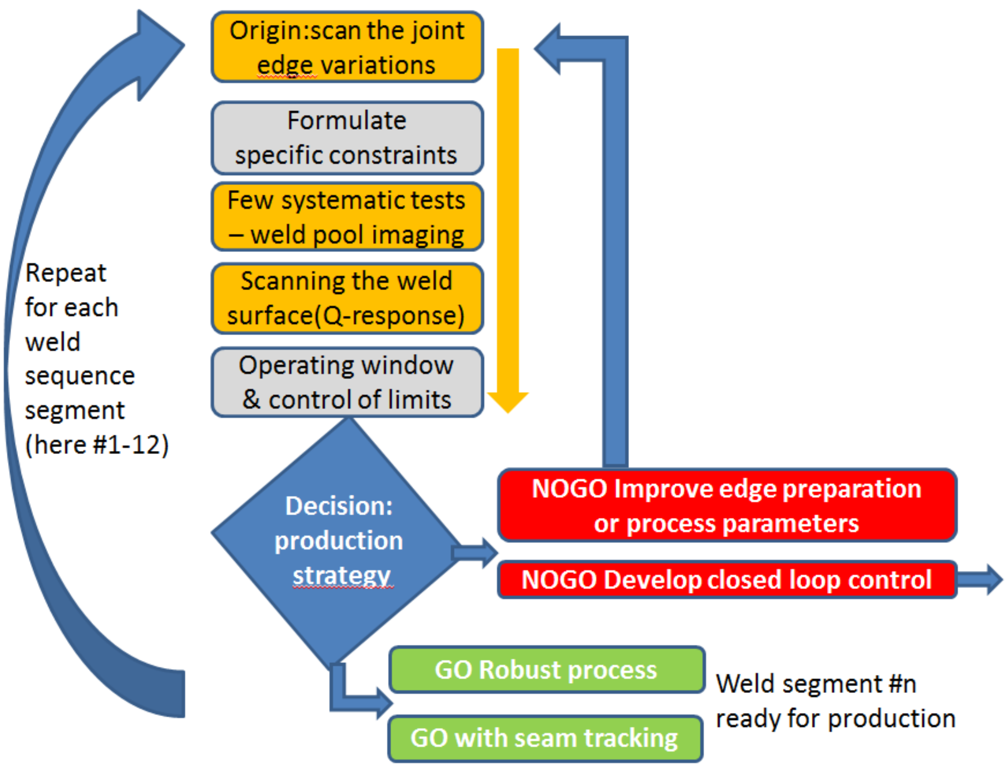


Figure 5.10. A planning tool flowchart for ensuring reliable welds when implementing welding on a demonstrator

Due to the new EU FP7-projektet HYBRO the work is continued with the demonstrator and other hybrid weld techniques can be explored to further widen the process window. The contents of WP4 (fatigue tests) has therefore been moved into the new project. It is a good opportunity to collaborate with world leading partners in implementing the new laser arc hybrid welding technique for high strength steels.

5.1 Contribution to FFI-goals

It has in the project been created many results and knowledge, especially for Scania, but also for other Swedish automotive industries. This will lead to a fast and competitive production with smart light weight constructions. The demonstrator is on the way of becoming the expected high volume pioneer-application of laser arc hybrid welding in Swedish industry, especially due to the accompanying implementation method. Implementation of the new modern welding technique laser arc hybrid welding demands a relatively high production support to be financially viable. When production starts, Scania will be able to produce stronger beamers at a lower price and energy consumption than the ones produced today. Furthermore, investments in modern technology also bring new knowledge and development which can motivate other companies to also start using the technology on other component types. This will increase knowledge and competence at Scania and other Swedish automotive industries. Communication between Scania and LTU has been strengthened and will proceed both during and after production introduction.

5.3 Achieved project objectives

Deliverable (L1): Mapping of the geometrical process window has been made for the demonstrator (7 mm butt- and T-joint) and for the rear axel housing (10 mm butt joint).

Theory for the welding process has been made at high scientific level, especially regarding undercuts as a critical quality criterion.

L2: Process window for optimized laser arc hybrid welding has with success been made with a new technology, the GMAW-CMT which for the first time was used for thick sheet welding.

A new tolerance tracking method has been created and is now usable.

Goal L3 and L4 has not been completed since a new complementary EU FP7 project was granted (HYBRO), which LTU coordinates and where Scania participates. It was decided to postpone the welding and fatigue testing of the demonstrators and seam tracking into HYBRO, and instead deepen L1 and L2 in ROBUHYB.

L3: Increased process window for seam tracking: has not been made; but the seam tracking equipment has been used to a large extent for scanning. Essentially produced is also the robustness of the process regarding lateral displacement which can be predicted by seam tracking; investment in modern equipment required.

L4: Acceptable demonstrator (rear axle housing) that is fatigue tested, comparative studies also for demonstrator beamer, pre-study and decision making has not been made. Eight demonstrators have been welded, but yet not with satisfactory weld quality (therefore not yet fatigue tested), due to some practical aspects that needs to be sorted out, plus that the process is further optimized. In HYBRO, welding and fatigue testing of several demonstrators is under preparation. In the beginning of the project, the demonstrator beamer changed from the rear axle housing to the current, more challenging beamer since it is more current. Although, some samples has still been made and process windows has been created for the rear axle housing.

5.4 The project goal relative to the programme goal

As planned, the project achieved the overall goals of the program in the application:

Significantly increased productivity in the component manufacturing at Scania, which in the long-term will strengthen Scania's competitiveness. It also gives opportunities to a more advanced product development, especially light weight construction by use of steel with higher strengths. Furthermore, laser arc hybrid welding is more environmentally friendly since it has less electricity and material consumption, but also lower weight in the products (no need for root support and light weight construction of beamer).

The project will also give synergetic effects for other automotive manufacturers in Sweden, especially those that uses thicker sheet materials, e.g. Volvo AB (Volvo CE, Volvo Lastbil), Cargotec HIAB, BAE Hägglunds, and other component suppliers.

The project enhances the scientific competence and new knowledge in Sweden, both for the university and for manufacturing and supplying companies (e.g. ESAB, SSAB, Outokumpu, Sandvik).

Important pioneering role in Sweden (can become the 2nd application in production, although the 1st was cancelled) as a reference to ensure assurance with other interested in laser arc hybrid welding, especially with the new fiber laser type.

The project has resulted in a Licentiate degree and will be part of corresponding Ph.D degree (Jan Frostevarg, previously Karlsson) and another one licentiate and hopefully also a PhD. Degree (Javier Lamas).

6. Dissemination and deliverables

6.1 Knowledge and results dissemination

Knowledge and dissemination of results has occurred mainly through the following activities:

- Information about the project can be found at the scientific groups LTU-web page
- Publications in international scientific journals and at international conferences
- Continuation in EU-FP7-RFCS-projekt HYBRO where LTU is coordinator
- Distribution in thematically similar scientific projects, especially FiberTube Advanced (VINNOVA), PROLAS (EU Interreg IV A Norr), IndLas (EU Mål 2), as well as commissioned research (different Swedish companies, also e.g. SINTEF Trondheim/Norway and Aker Verdal/Norway)
- Distribution in new collaborative projects (exchange) with thematically similar excellence: Chosun University/Gwangju, KAIST/Daejeon, RIST/Pohang, all South Korea (financier STINT), Osaka University, Japan (financed internally through Osaka University)
- Distribution in Swedish (Lasergruppen/Welding commission) and international (IIW, EWF) networking organisations.
- Many daily talks with relevant Swedish companies (e.g. VCE, Gestamp, ESAB) and Swedish research groups (e.g. KIMAB, HV, KTH, LTU-internal).
- Discussions in planning of new national and international scientific research applications.
- Semi-annual seminars implemented at LTU where ongoing project results has been distributed internally.

Scania- and Ferruform-internal
The project has contributed towards an understanding for how laser arc hybrid welded papers should be designed, by which the conditions are from a production perspective and also contributed towards an innovative thinking regarding the design of laser arc hybrid welded components.

6.2 Publications

International scientific journal publications

1. Karlsson, J., P. Norman, J. Lamas, A. Yañez, A. F. H. Kaplan: Observation of the mechanisms causing two kinds of undercuts during laser hybrid arc welding, *Applied Surface Science*, v 257, pp 7501-7506 (2011).
2. Moradi, M., M. Ghoreishi, J. Frostevarg, A. F. H. Kaplan: An investigation on stability of laser hybrid arc welding, Optics and Lasers in Engineering, v 51, pp 481-487 (2013).
3. Moradi, M., M. Ghoreishi, J. Karlsson, T. Ilar, A. F. H. Kaplan: Parameter dependencies in laser hybrid arc welding by Design-of-Experiments and a mass balance, submitted (under revision) to J Laser Appl (2014).
4. Kaplan, A. F. H., J. Frostevarg and J. Powell: A procedure to fully control and trace the weld quality for laser-arc hybrid welding under production conditions, Int. J. Manufacturing Research, in press (2014).
5. Frostevarg, J., A. F. H. Kaplan and J. Lamas: Comparison of CMT with other arc modes for laser arc hybrid welding of 7 mm steel, submitted (under revision) to Welding in the World (2014).
6. Frostevarg, J. and A. F. H. Kaplan: Undercut suppression in laser arc hybrid welding by melt pool tailoring, submitted to Journal of Laser Applications (2014).

International conferences:

7. Kaplan, A. F. H., J. Lamas, J. Karlsson, P. Norman, A. Yañez: Scanner analysis of the topology of laser hybrid welds depending on the joint edge tolerances, 12th NOLAMP conference, June 27-29, 2011, Trondheim, Norway, Ed. E. Halmoy (2011).
8. Kaplan, A. F. H., J. Karlsson, J. Powell: A procedure to fully control and trace the weld quality for laser-arc hybrid welding under production conditions, Proc. SPS 12, Linköping, Nov. 6-8, 2012 (2012).
9. Karlsson, J., A. F. H. Kaplan: Comprehensive monitoring and control of laser hybrid arc welding in industrial production, Proc. ICALEO, Anaheim/LA, CA, USA, September 24-27, 2012, LIA, #605, pp 220-227 (2012).
10. Frostevarg, J. and A. F. H. Kaplan: Differences between arc modes in laser hybrid welding upon weld bead stability and undercut formation, Proc. NOLAMP 14, August 26-28, 2013, Gothenburg/Sweden (2013).

7. Conclusions and future research

- An economic and technically very promising but complex welding method, laser arc hybrid welding, has been examined. Especially examined for a demonstrator of an automotive component.
- Since laser arc hybrid welding is not used in engineering industry today, even though there are more than 100 installations world-wide, the project could lead to a pioneering application in Sweden with LTU as a world leading research group.
- The new technique to combine the laser beam also with CMT-arc welding showed to be promising even for thick sheet metals.
- Robustness (”well-tried”) is important for manufacturing in an industrial environment; the new method of analyzing that was developed (joint-scanner, process filming, weld result scanning) is promising in order to quantitatively be able to determine the robustness within these limits.
- A new EU-FP7 project has been made, with LTU as coordinator and Scania/Ferruform as partners. The investigation of the current, and a few other, applications will take place within the new project. This will be conducted with world leading groups within laser welding, welding system developers and automotive weld applications.
- Additional common research projects are planned.
- On the whole, ROBUHYB has created excellent results of a still very promising weld method that in the long run could be of a very high economic and technical use in the Swedish automotive industry.

8. Participating parties and contact person

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