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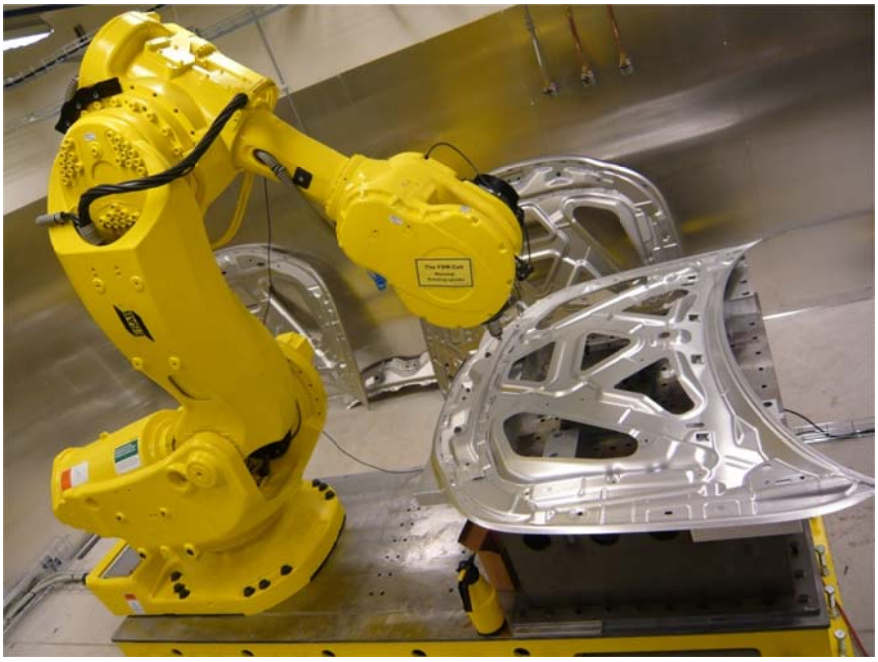
StiRoLight – Friction Stir Welding with Robot for Light Weight Vehicle Design



Project within: Sustainable Production Technology

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1 Executive summary

The target for the StiRoLight research was to identify and solve problems related to robotised Friction Stir Welding (FSW) in order to facilitate for use in Swedish vehicle industry. The driving forces for the project are mainly two: FSW is most suitable for lightweight material, and robots are most suitable to perform 3D-motions. Further, the automobile industry has great knowledge and experience from robotic solutions. The research questions are mainly related to the performance metrics of the robot to carry out FSW, and specifically to withstand reaction forces from the FSW tool as well as perform 3D welding operations. The robot is by itself compliant, which causes path deviations when it applies large forces, and solutions are sought for to mitigate these drawbacks. A thorough understanding of the system behaviour is needed and a number of experimental and theoretical studies have been performed. Promising results are obtained related to the robot's workspace and how to give corrective information to the robot control system when large forces are applied in different directions. Detailed studies have been performed concerning deflections in the robot kinematic structure in relation to the process forces, dependent on material properties and process control. These studies have included the deflections in relation to operating window for the process with respect to weld quality. This understanding is essential in order to be industrially accepted. Experiments have been performed in a demonstrator at Innovatum Technology Park complemented by initial studies at ESAB. The robotic solutions are very promising, and it has been identified some remaining issues considering automation, tooling and technology transfer to designers. The tooling issues were not addressed in the project and have been identified to be integrated with automation issues in future research.

Scientific results are presented at various conferences, e.g. at the FSW Symposium, and a peer review journal article is accepted for publication. A licentiate thesis describing the scientific findings will be finalized during the project period and officially presented and discussed later in Spring 2012.

The reason for the shown worldwide interest is that there hardly exist any robotic FSW-solutions except for a few laboratory systems, and the main problem lies in the compliancy of the robot. One reason can be that there are few research groups with competence and knowledge in solutions for both process and automation issues. When the compliancy problems are solved, the robotic FSW-solutions are expected to be a cost saving and quality increasing factor in automobile manufacturing. The StiRoLight project has done its best for this to come true in a near future by solving some problems and identifying new research issues.

The partners include a system provider (ESAB Engineering AB), end users (Saab Automobile AB and AB Volvo) and research organizations (University West, Lund University and Innovatum Technology Park).

2 Background

The project was initiated from industrial interest in the promising joining technology *Friction Stir Welding* (FSW) for lightweight vehicles, more explicitly by Saab Automobile. Today's joining of aluminium in car factories is mainly conducted through mechanical fasteners like riveting or clinching, since fusion welding has several drawbacks, e.g. laser welding is difficult due to problems with reflections of the high power laser beam, and arc welding induces excessive heat input into the material. FSW is traditionally made in rigid machines with straight or rotationally symmetric joints, but such joints are very rare in a vehicle. So, when ESAB Engineering AB offered a robotized FSW-machine the implementation was foreseen to be realistic in the car factory. The much reduced deformation compared to traditional welding is further interesting also for other materials than aluminium, and AB Volvo through Volvo Aero wanted to investigate whether it could be used for fabrication in nickel-based components for lightweight aero engines. Since the FSW-process requires a high process force the robot will be subject to high demands, ABB wanted to be involved as well, but of different reasons only participated in the steering group and with valuable technical support during the project.

2.1 Snapshot project facts

Total budget	13.160.000 SEK
Project period	2009-01-12 (decision 2009-07-08) to 2011-12-31 (changed to 2012-03-31 due to delayed decision)
Grant from Vinnova	6.330.000 SEK (49% of total budget)
Vinnova Dnr	2009-00968
Project leader	Tommy Christensen, Saab Automobile Replaced by Anna-Karin Christiansson (HV) at Saab bankruptcy
Researchers	Jeroen De Backer, Gunnar Bolmsjö, Torbjörn Ilar, Anna-Karin Christiansson

2.2 Partners

The partners are divided into three main groups

- Industrial end users: Saab Automobile AB (project leader) and AB Volvo
- Industrial machine suppliers: ESAB Engineering AB (ABB withdrawn, but in reference group)
- Academic research and technology transfer: University West (HV) with Lund University, faculty of Engineering for supervision, Innovatum Technology Park

3 Objective

The objectives are both academic and industrial:

3.1 Scientific objectives

The academic goals were at project start set as

- Find solutions for the force-/position-problems associated with the compliant robot
- Provide knowledge and constraints based on the industrial applications
- A licentiate thesis at end of project

3.2 Industrial objectives

The industrial goals were at project start set as

- Introduction of FSW in vehicle industry
- Facilitate for lighter vehicles through new material combinations and continuous joints
- Transfer FSW-knowledge on the way to a mature manufacturing process

4 Project realization

4.1 Research organisation

A PhD-position was opened, and among eight applicants Mr Jeroen De Backer was appointed PhD-student registered at Lund University, faculty of Engineering with Prof Gunnar Bolmsjö as main supervisor. Local supervisor was Dr Torbjörn Ilar, and when he left for Luleå Technical University Ass Prof Anna-Karin Christiansson, HV, took his place. During the last year Prof Bolmsjö has been appointed full professor at University West with more close involvement in the project.

4.2 Project organisation

The project has been well organized by the project leader Mr Tommy Christensen at Saab through regular meetings every second week for technology transfer and technical discussions by those who were involved at each stage in the project. A steering committee was led by Prof Lars Pejryd, Innovatum, with members from all the partners and ABB. The steering committee has followed the progress and identified a strong interest for continued joint activities with a larger range of industrial partners.

4.3 Method

The work was divided into work packages with different responsibilities according to Figure 1. The bi-weekly meetings have been the tool for efficient coordination.

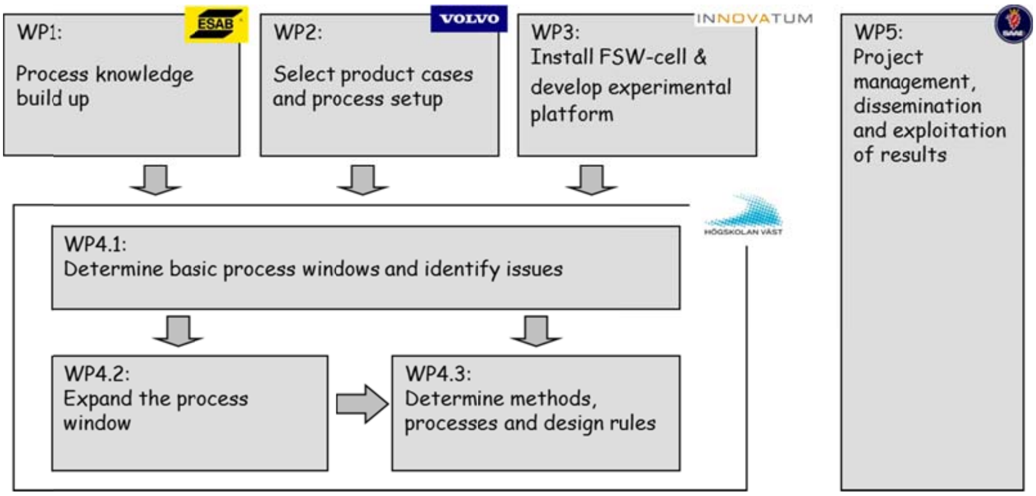

Figure 1. Project work packages with responsibilities indicated with logotypes.

4.4 Demonstrators

Early in the project, it was aimed to build two demonstrators for robotic FSW that could be easily implemented in production. Two different cases were selected for the demonstrators: one for car body parts in aluminium and one for aerospace parts in nickel-alloys.

The first demonstrator was built in close collaboration with Saab, see Figure 2. The inner panel of a car hood had to be joined with four reinforcement details: one for crash-safety, one for the gas spring holding the opened hood, and two for the hinges. These parts are in production joined by clinching but it was expected that lead time, weight and strength could be improved with FSW. Manufactured aluminium fixtures were "footprints" of the hood and served as backing material. The aluminium details were provided by Saab. The final part showed high-quality FSW joints. However, to fully utilize the advantages of FSW, the design should be optimised for this process, and a bachelor thesis work within the project has proposed new design solutions for these reinforcements. Furthermore, the importance of clamping was proven; insufficient clamping always resulted in weld defects. This is an extra aspect for production planners to consider, compared to the existing manufacturing methods.

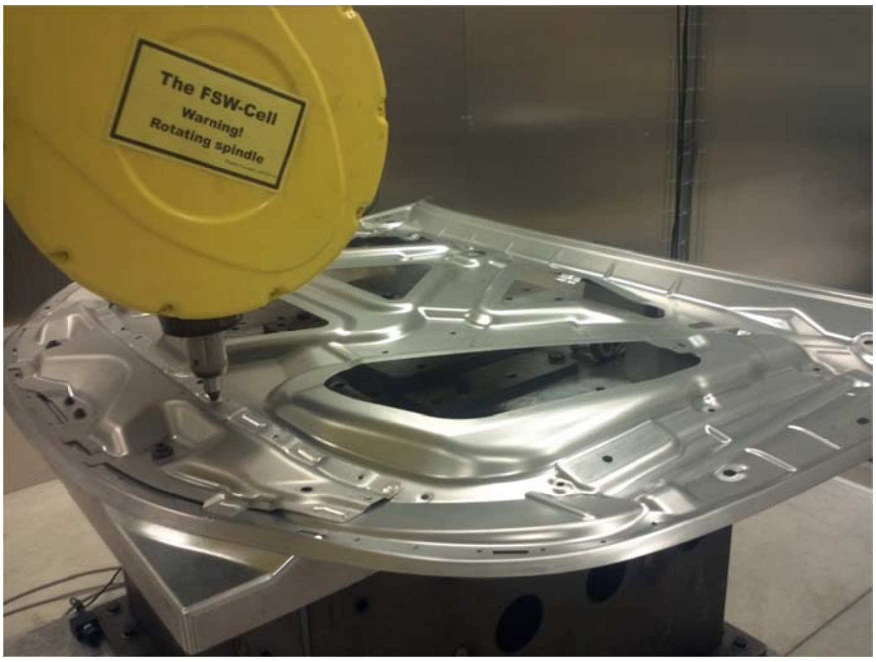

Figure 2. The FSW process ongoing in the Saab demonstrator.

The second demonstrator was mainly supported through AB Volvo and is aimed to show the capabilities of welding 3D structures in high-strength alloys with the robot system. A section of an aero engine component in a nickel-based alloy is to be welded in butt-joint configuration. A fixture was manufactured in the last quarter of the StiRoLight project. Due to delays from the FSW-tool manufacturer, the development was somewhat delayed due to late delivery of tools, but test welding of Inconel material was made at ESAB facilities providing valuable and important results within the project. The results from this demonstrator showed that FSW is possible and can deliver excellent weld quality. Moreover, the required forces for a successful weld could be reduced by parameter tuning and preheating, and thereby be feasible for the robot system. A special designed fixture has been developed to be able to obtain enough backing, see Figure 1Figure 3.

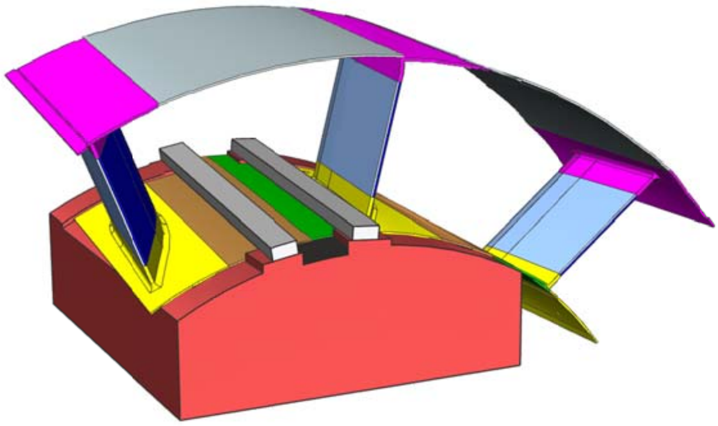

Figure 3. Demonstrator setup for FSW of high-strength alloys.

5 Results

The technology that is developed is of importance for all manufacturing industry that is approaching light weight technology. Robotic FSW is expected to take a larger percentage of joining technology in both small and large series.

Specific deliverables are shown in next section.

5.1 FFI-goals

The project contributes to the FFI overall goals in a number of ways:

- Contributes to low weight designs => lower energy consumption through increased use of new materials in vehicles
- Contributes to environmentally friendly manufacturing (compared to conventional welding) => no use of added material and almost no residual deformation
- Facilitates for use of simulation based manufacturing through virtual tools => less trials and error and shorter commissioning times
- Introduction of a new manufacturing technology => expected to give increased competitive advantages
- Increased knowledge of a novel manufacturing technology => knowledge-based production in Sweden
- Makes the designers aware of the novel technology => redesign is expected to give better performance and increased competitive advantages
- Industrial demonstrators => generates interests in the industrial sector
- Demonstrator at PTC => facilitates for and supports future research and development projects from both national and international horizons

5.2 Other goals

- All work to finalise the licentiate thesis has been made.
- Two bachelor thesis works have been performed addressing one demonstrator each => industrial benefits, valuable experience in the manufacturing education, valuable cooperation with industry
- Dissemination of results through several information channels and participation in the Swedish welding commission FSW-group => several industrial sectors are informed

6 Dissemination and publications

6.1 Knowledge and results dissemination

The demonstrator facility at HV and the neutral meeting place at Innovatum Technology Park has been an important driver for showing the possibilities of the process to a wider audience. This has been made possible through project workshops where national and international participants were invited and through regular open seminars at Innovatum. “Drivers of change” are identified in a continued project proposal that also takes material and tooling questions into consideration. This would together with increased efforts in involving designers lead to a wider use of light weight material in vehicle production. Further, involving more Swedish industries in the project would be beneficial not only for the automotive industry. Especially for SKB (Svensk Kärnbränslehantering) which is using the FSW technology to seal canisters with nuclear waste, it is vital to maintain the knowledge and increase the competence of FSW in Sweden.

6.2 List of important Workshops:

Spring 2009: A number of project internal workshops for defining the demonstrators.

Dec 2010: A two-day workshop with participants from Germany (HZG), Belgium (Cenaero), Sweden (University West, Sandvik, Lund University, AB Volvo, SAPA, ESAB, Innovatum).The workshop focused on identifying concrete applications for FSW in the transportation industries and on presenting state-of-the-art research to the industrial participants.

June 2011: A one-day workshop with participants from Sweden (ABB, Sandvik, Volvo Cars, ESAB, Innovatum, Volvo Trucks, Volvo Aero, Swerea/Kimab and University West). At this workshop the plans for continued project was formed with interests from the participants and from SAPA and SKB. A group was formed by University West and Kimab to write a proposal on joint efforts to arrive at a higher technology level for Swedish manufacturing industry.

6.3 Scientific Results

The project was able to identify the limitations of the robot system for performing FSW and a strategy is presented to overcome several of these limitations:

- It is observed that the material overheats during welding of complex geometries, causing the tool to sink through the softened material. A solution is to implement temperature control, adapting the downforce. This allows control of the heat input and prevents local overheating.

- The high process forces cause robot deflections, resulting in tool deviations. Initial welds often showed root defects due to these deviations. Several methods were examined and it is concluded that compensation is possible without extra sensors. The existing force sensor can be used for further compensation. This method is independent from the type of robot and works in the whole robot workspace.
- In a limited workspace around the robot, the deliverable robot force can exceed the specified payload up to three times. In this area, the robot can deliver enough downforce to weld high-temperature alloys such as stainless steel.
- The spindle motor in its present configuration is not powerful enough to weld high-temperature alloys. However, with modified gearing configuration, the torque is sufficient for these alloys.

The major scientific results identified in StiRoLight can be described by the block diagram in Figure 4. The green frame shows the controller, required to compensate for path deviations. The red frame indicates the required temperature controller to prevent overheating on complex geometries. Implementation of both controllers will allow fully-automated welding.

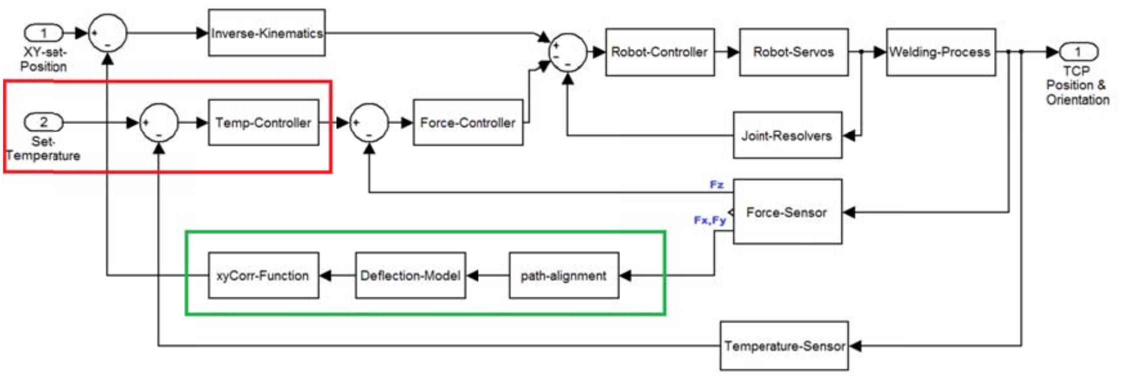

Figure 4. Control scheme for robotic FSW as part of a fully-automated production line. The green and red frames indicate two additional controllers for increased flexibility.

The above described work has been published on several occasions. The PhD-student in the StiRoLight project, Jeroen De Backer, has taken part in various scientific conferences and presented the project and its progress. Some will take part in the near future but are prepared during the project time:

"A local model for online path corrections in Friction Stir Welding": Presented paper at the Friction Stir Welding & Processing Conference (FSWP 2010) in Lille, France, February 2010: – Appendix 1

The paper was written together with Dr Mikael Soron (ESAB – first author) and was a first step towards path compensation of robot FSW. It was observed in welding tests that the robot tends to deflect, due to the high process forces. A model was presented that is able to compensate the robot path in a limited workspace producing a path along the weld line and a good weld quality. The model is based on the relation between side forces and microscopic measurements on welded parts. Mikael Soron, Jeroen De Backer and Torbjörn Ilar attended the conference and the paper was presented by Jeroen De Backer, and it was received with great interest.

"Friction Stir Welding with Robot for Light Weight Vehicle Design": Presented paper at the FSW symposium i Lübeck, Germany, May 2010 – Appendix 2

The FSW Symposium is a biennial conference and is considered as the biggest conference on FSW where all the major researches were represented, including Wayne Thomas, the inventor and patent-holder of the FSW process. The paper presents the StiRoLight research project and the milestones that should be reached in order to implement FSW in the automotive production line. Furthermore, the state-of-the-art in robotic FSW and challenges associated with the use of robots were discussed. Our paper was selected as conference highlight and Mikael Soron presented as key note speaker. Jeroen De Backer and Anna-Karin Christiansson attended the conference. The paper is included in the digitally published conference proceedings. A study visit to the HZG-facilities in Geesthacht, Germany, was included in the conference. HZG is one of the leading research centers within the area of FSW. This resulted in a study visit of their researchers to PTC in Trollhättan during the workshop of December 2010. They expressed their interest in further collaboration with PTC and the industrial partners of StiRoLight.

"Surface Quality and Strength in Robotic Friction Stir Welding of Thin Automotive Aluminium Alloys": Presented paper at the Swedish Production Symposium - SPS11, May 2011: – Appendix 3

At the Swedish Production Symposium in Lund, a paper was presented about the weld quality and visual quality of automotive aluminium alloys. One part of the study showed the robustness of the welding process; by changing process parameters, the variations in tensile strength were shown to be limited. Furthermore, the visual quality of the weld is analysed by roughness and waviness measurements. This is important for the application domain of FSW. It was shown that with the present fixturing and tools, the surface quality is insufficient for use on class-A surfaces, i.e. the outer body parts of the car. Finally, the paper suggests a method for the operator to detect welding defects and get an impression of the weld quality by "human-eye inspection". This is important for production, where not each sample can be analysed by destructive testing. The paper was presented by Jeroen De Backer and is included in the printed conference proceedings.

Presented paper at the Aerospace Materials conference (Aeromat 2011) in Long Beach, USA, May 2011: "Investigation of Techniques for Online Path Compensation in Robotic Friction Stir Welding" – Appendix 4

The Aeromat conference in Long Beach, USA, was mainly dedicated to new aerospace materials and included a section "Welding and Joining Technologies and Methods". A paper about robotic FSW was presented by Jeroen De Backer and also Mikael Soron attended the conference. The focus in this paper is on two measurement methods for path deviation and a strategy for online path compensation. Besides, the possibility of using a robot system was highlighted. Several companies showed their interest in our research such as Embraer, which is Brazil's biggest airplane manufacturer and leader in FSW. So far they use purpose-built machines but are very interested in robotisation because of the high flexibility.

"Investigation of Path Compensation Methods for Robotic Friction Stir Welding": Accepted for publication in Journal "Industrial Robot": –Appendix 5

This journal paper is a conclusion of all work done on path compensation since the start of the project in 2009. The paper shows the evolution from model for local workspace to a sensor-based path compensation method in a global workspace and gives better insight in the FSW process forces. The novelty in the paper is the study of lateral process forces, which is not of interest for most FSW research as the typical machines are very stiff and do not deflect. Furthermore it presents a method to compensate deviations in FSW in the complete robot workspace, similar to seam-tracking systems known in other welding processes.

"Process Requirements for Robotic Friction Stir Welding in Automotive Applications": Project report which is planned to be further developed into a model for predictive control of the robot and weld quality, and subsequent publication:

This paper demonstrates the robustness of the process for parameter variations. The visual inspection of the weld is described in a quantitative way, by measuring surface roughness and waviness. Feedback from the SPS conference is used in this paper.

"Opportunities for lightweight vehicle design by using robotic friction stir welding": Will be presented at the Joining in Car Body Engineering Conference, Bad Nauheim, Germany- April 2012

The abstract was accepted and the paper is selected as program highlights. Instead of a 20 minute presentation, we are asked to give a one-hour workshop with presentation and interactive discussion about implementing FSW in vehicles and finding design solutions for robotic FSW that can make body parts light and production faster. All the big automotive manufacturers are represented at the conference, e.g. BMW, Audi, Mercedes.

"Three-dimensional Friction Stir Welding of Inconel 718 using the ESAB Rosio FSW-robot": Abstract accepted at the Trends in Welding Conference- June 2012.

Presentation of the first results from the tests in nickel-based alloys with the robot with pre-heating to decrease process forces and spindle torque. Furthermore a new backing bar material will be presented which improves the root of the weld significantly. It is, to our knowledge, the world's first attempt to perform FSW of steel on a 3D structure by using a robot.

"Influence of Roll Angle on Process Forces and Lap Joint Strength in Robotic Friction Stir Welding": Abstract accepted at the FSW Symposium 2012- May 2012.

The paper describes the effect of a new welding parameter in FSW. It is common to add a tilt angle to the FSW tool, in order to get more pressure on the material behind the tool tip. In an attempt to reduce the asymmetrical effects induced by the welding process, an extra welding parameter is introduced: the roll angle. This angle is not studied before as conventional machines do not have the required degrees of freedom to reach the angle. Initial results show a very limited influence of roll angle on the joint strength. This is however of great importance for 3D seams, where it is difficult to maintain a welding tool perpendicular to the surface along the 3D-path. The paper will be presented at the conference by Jeroen De Backer.

"Robotic Friction Stir Welding": Movie showing and summarizing results from the project, February 2012.

The movie describes results from the project work and can be viewed on YouTube at http://www.youtube.com/watch?v=euO-LIkew8o (3 minutes 38 sec, HD quality). In addition, several short clips are available as well at the following links (all in HD quality):

http://www.youtube.com/watch?v=zRuX7V6Heik (1:10),

http://www.youtube.com/watch?v=Z-DexeG8W70 (1:42),

http://www.youtube.com/watch?v=oS1JsBlbKbc (3:15)

6.4 Industrial Results

The participating companies have learnt the advantages of the process.

- ESAB has gained valuable experience from use of its robotised system and its limitations, and are interested in the proposed solutions.
- The end user Saab Automobile has experienced great interest in the use of robotised FSW for joining of car bodies, and especially the demonstrator with reinforcement details. A bachelor thesis work addressing the Saab-demonstrator problem has been supervised by Jeroen De Backer. Title "Förbättring av karosskonstruktion som möjliggörs av Friction Stir Welding", see Appendix 6.
- The end user Volvo Aero has gained experience from fixture demands for FSW of nickel based alloys, initially experiments were performed at the ESAB facility to tune parameters. A bachelor thesis work addressing fixture design and accessibility of the Volvo Aero demonstrator was supervised by Jeroen De Backer. Title: "Åtkomststudie för robotiserad svetsning av flygmotordetalj", see Appendix 7.

7 Conclusions and future research

The project has attracted much attention, not only from the project partners, but also from national and international scientific and industrial actors. The demonstrator cell at HV is of great importance for this.

The robotic solution has shown great potential, and a number of conclusions are drawn regarding path deviation and its dependence of the robot's work space. The robot is not performing the same way in all directions, which is necessary to cope with when large forces are applied. Understanding robotic kinematics and dynamics is therefore of great importance when planning the weld path, and new research questions are formulated. The process needs further research to fully understand the limitations regarding weld quality and path deviation associated with the large forces that the robot delivers. The possibility to tilt the tool angle is a natural feature using a robot, and the automotive industry is used to robotic solutions. Therefore the steps towards more industrial implementations are evident. The missing link is however the feedback to the designers. The project has addressed this issue to some extent and has found a number of new questions that need to be solved.

The tooling and how the material is affected by the process have been addressed only briefly in the project, but now that the demonstrator shows great potential, these matters need to be considered as well. Finally, it can be concluded that the StiRoLight project has significantly increased the knowledge of FSW within the Swedish vehicle industry and has laid a sound basis for industrial implementation, and has established HV as an international player in the field. The demonstrators have shown to be most valuable.

8 Participating parties and contact persons

Partner	Logotype	Contact person
University West	HÖGSKOLAN VÄST	Ass Prof Anna-Karin Christiansson
Innovatum Technology Park	INNOVATUM	Prof Lars Pejryd
Saab Automobile until Dec 2011	SAAB	Tommy Christensen
ESAB Engineering AB	ESAB	Dr Mikael Soron
AB Volvo	VOLVO	Håkan Sundberg