Final report Tapertech – a Synergi project financed by the Knowledge Foundation

The project started 2019 and ended 2022.

PROJECT AIM

Core question: How to tailor the performance (functionality and integrity) of high strength/resistance steel components through laser and arc additive manufacturing

OBJECTIVES AND INTERMEDIATE OBJECTIVES

Global: The project aimed at developing a knowledge platform (and not a specific application) needed for industrial application of the technologies embraced by DED-AM (Directed Energy Deposition Additive Manufacturing), specifically using LMDp (Laser Metal Deposition with Powder) and WAAM (Wire + Arc Additive Manufacturing) processes, fulfilling the core question

Specific:

<u>At the research level</u>: To serve as a model for joint interdisciplinary research and to contribute significantly to the AM activities in the research environment of PTW.

<u>At the co-production level:</u> Strengthen the university-industry joint efforts with their respective knowledge and experience in new manufacturing strategies through demonstrators, workshops, and increase the level of confidence in DED-AM among the partners as well as develop the Co-production model at University West. BAE Systems Hägglunds will exploit the knowledge within product development, production and spare part manufacturing

<u>At the educational level:</u> To engage engineering students at different levels in a new technology through internships, courses, projects and thesis works, by providing doctoral courses with up-to-date knowledge of DED-AM processes and broadening the possibility for undergraduate students to integrate and be involved in company's internal research and development processes (Work Integrated Learning).

<u>At the scientific and technology level:</u> To develop novel technologies, knowledge and strategies for DED-AM using standard heat source equipment and, potentially, dedicated feedstock material in the form of metal wire or powder, so that geometric features can be built with the desired material properties.

<u>Subproject AMMet-Tapertech (Additive Manufacturing Metallurgy of Steels)</u>: to find out how the process parameters of DED-AM and dedicated feedstocks, considering both LMDp and WAAM, influence the macro and microstructures of the steels in the project.

Subproject AMSim-Tapertech (Additive Manufacturing Modelling and Simulation): to find out if the simulation of the temperature field evolution with time in DED-AM can be used as a predictive tool, considering both LMDp and WAAM, to simplify parametrization towards manufacturing of the relevant functional components through AM.

Subproject AMProc-Tapertech (Additive Manufacturing Process Development and Control): to find out how the parameters and dedicated feedstocks of DED-AM, considering both LMDp and WAAM, affects the thermal history, economic feasibility and dimensional (near net shape precision) as well as finish aspects of functional components made of structural/tool steels.

Subproject AMPMech-Tapertech (Additive Manufacturing Mechanical Characterization): to find out how the macro and microstructures from dedicated feedstocks and the thermal history of DED-AM, from both LMDp and WAAM, affects properties such as mechanical properties of functional components made of high strength and tool steels.

FINAL REPORT

PROJECT PLAN

The timetable has been followed. However, in the table “Qualitative Risk Analysis” of the Tapertech synergy project, one of the potential risks was “Lack of HR”, Post-docs and PhD students not hired for the time slots planned or with low performance. The action taken was to reschedule the working plan. The process of selection and hiring the personnel started, as planned, well before the kick-off meeting, around June 2019. It happened that the process of selection and hiring the personnel took much longer than expected, in order to follow the administrative rules. In addition, the were no suitable candidates living in Sweden (Visa constraints).

However, the project followed the plan in the methodology used and the final deliverables (demonstrators made for several steel grades). Splitting the report about the project plan into two routes, namely LMDp and WAAM, let´s start with the first:

Concerning LMDp route, the final goals were only partly achieved because:

- The original assumption in the proposal was that low-carbon steels, or High Strength Low Alloy Steels (HSLA) will be used for the LMDp trials. Instead, high carbon, high vanadium tool steels were presented by the partners, steels considered “unweldable” by most criteria (cold- and hot cracking susceptibility, temper embrittlement, etc).
- Because of extensive cracking in initial LMDp deposits in the V8 composition, one entirely different type of steel grade was introduced to the experimental mix one year after the project started (Corrax is a martensitic precipitation hardned stainless steel), while Dievar is a low alloyed tool steel and V4 and V8 are high Carbon/Vanadium air hardenable tool steels.

- Powders delivered for LMDp had large variations in particle size (50-150 microns), which did not allow for proper powder feeding during LMDp.

Some deviations from the original plan were also made to accommodate unexpected results found during the project, such as the cracking of the V8 LMDp initial trials and consequences of the installation of a new 12 kW disk laser power source:

- Stair-like multi-pass, multilayer stepped demonstrators were built instead of single-pass multiple layer thin 3-D printed walls in order to simulate claddings and localized repairs;
- Similar multi-pass, variable layer deposit samples were made for post-LMDp heat treatment simulations;
- Powder delivered for LMDp had to be sieved because of the wide variation in particle size and a new, multi-nozzle solution had to be implemented to accommodate the above variation;
- Extensive Design of Experiment (DOE) trials were needed to adjust the laser delivery head to the new laser beam diameter and transverse power distribution (also had to correct the lack of symmetry in the deposit shape)

Adjustments had to be made to the LMDp parameters to accommodate the base metal compositional effects on the deposit geometry (depth/width ratio), most likely caused by the weld pool surface tension-drive fluid flow effect of sulfur.

Concerning the route WAAM:

The deviation from the initial working plan was concentrated in:

A) A new design and production concepts, including the possibility of hybrid WAAM + LMDp, multi-graded materials (surface machinable and/or corrosion resistant), methods for prevention of epitaxial grains growth and, consequently, degradation and anisotropy of mechanical properties, application of HFMI (high frequency mechanical impact) treatment in HSS AM, and interpasses control methods was not carried out, because of lack of human resources in time and the limitations appointed concerning the pandemic time

B) documents to support customers with new technologies, wire, powder and production equipment and automation were not produced as planned. However, a comprehensive report was delivered to them, through 3 documents, as seen attached:
The global project Final Report 2022 (5 pages)
WAAM Route Final Report 2022 (35 pages)
LMDp Route Final Report 2022 (58 pages)

C) The demonstrators of typical system hardware manufactured with WAAM and HSLA structural steels were not accomplished for the same reason pointed out above.

CONTRIBUTION TO UNIVERSITY WEST AND PRIMUS

The interaction with the industrial sector was intensified by regular meetings between the academia during the years (4 status update meetings, 5 LMDp route Sectorial meetings and 5 GMAW route Sectorial meetings per year). All these meetings were scheduled in advance, and minutes were generated and distributed to all members, regardless of whether they attended or not. Tapertech paved the path for a continuation project (DEDICATE) enlarged to a higher number of industrial partners and combined a wider range of areas of expertise (e.g. NDT).

CONTRIBUTIONS TO THE LONG-TERM INDUSTRIAL OR SOCIETAL CHALLENGES DEFINED FOR PRIMUS

The main contribution of Tapertech was towards competence development and innovation. For instance, the innovation in a method for WAAM parametrization (working envelope approach) and methods for analysis, such as thermal cycles measurements and interlayer dilution, and the consequent learning on how microstructure are tailored during layer depositions (competencies), will open new possibilities for WAAM application in the industry.

Cooperation with Uddeholm and ESAB, mainly, was excellent throughout the project. They provided materials, consumables (wire and powders), material characterization (radiography, OM and hardness analyses, EBSD, etc) and advice in a timely manner. We communicated effectively via Sectorial Meetings in an open and candid atmosphere throughout the project.

PROJECT RESULTS AND GOAL ACHIEVEMENT

3 – Achievements after the project period

a) A knowledge platform, described by:

1) overall synergy evaluation report describing the integrity of AM-built structures of high-strength steels with the two processes (LMDp - Laser Metal Deposition with Powder - and WAAM - Wire + Arc Additive Manufacturing) related to the industry requirements, including technical results (e.g. process parameters, temperature measurements, a number of metallurgical characteristics coupled with mechanical property data, simulation results for both calibration and validation); (DONE)

2) evaluation of potential breakthroughs with origin from the project, such as self-heat treatment and grain refinement of the previous layers by the subsequent layers by controlling heat concentration, composition of feedstocks (powder and wire) as a means of controlling pool viscosity and reduce wall waviness, application of corrosion resistance

anisotropy as a means of predicting mechanical properties anisotropy in metal AM; (DONE)

3) new design and production concepts, including the possibility of hybrid WAAM + LMDp, multi-graded materials (surface machinable and/or corrosion resistant), methods for prevention of epitaxial grains growth and, consequently, degradation and anisotropy of mechanical properties, application of HFMI (high frequency mechanical impact) treatment in HSS AM, and interpasses control methods; (NOT DONE)

4) simulation models and process strategies for WAAM and high strength low alloy structural (HSLA) steels; (DONE)

5) simulation models and process strategies for LMDp and toolsteels; (DONE)

6) documents to support customers with new technologies, wire, powder and production equipment and automation. (NOT DONE)

b) Education and other academic activities, described by:

1) doctoral and master courses with up-to-date knowledge on WAAM and LMDp; (PARTIALLY DONE)
2) several master students trained (DONE)
3) workshop organized with invitations to a broad range of industries, especially those in the newly formed national arena on metal AM.(NOT DONE)

However, we also proposed some tangible deliverables

c) Demonstrators (NOT DONE):

1) of a typical system hardware manufactured with WAAM and HSLA structural steels;
2) of a typical system hardware manufactured with LMDp and tool steels;

d) New proposals for:

1) continuation of basic research (DONE);
2) higher verification level projects, such as company prototype demonstrators with subsequent product design and production to market.

e) Scientific knowledge dissemination (DONE), described by:

1) scientific publications in the respective scientific fields;
2) scientific joint publications in more general manufacturing journals and conferences;

f) Project management reports (DONE), described by:

1) reports to the KK-foundation and the partners according to formal agreements and to be developed in joint meetings with all partners.

PROJECT'S SCIENTIFIC ACHIEVEMENTS

Bachelor Degree Project:

1)Felix Nandin for accomplishing this task in such passioned way with the work "Development of a method to measure multiple thermal cycles in subsequent layers in Wire Arc Additive Manufacturing (WAAM) of thin walls", by Felix Nandin, on March 15, 2021. Advisor Peigang Li, Examiner: Americo Scotti. This project was awarded as the best 2021 Degree Project in Mechanical Engineering.

2) Tobias Hermansson Daniel Lindh, Topologioptimering inom Svetsbaserad Additiv Tillverkning: Applicerat på Pendelarm för Bandsystem, BSc. Final Project, Maskinteknik, Institutionen för ingenjörsvetenskap, Högskolan Väst (2022); Supervisor: Kjell Hurtig

Degree project for Master of Science in manufacturing engineering:

1) Shubham Amar Dahat, A Methodology to Parametrize Wire + Arc Additive Manufacturing Applied to a High Strength Low Alloy Steel, University West (Suécia)– 31 de Outubro de 2019, Supervisor: Americo Scotti; Examiner: Joel Andersson
2) Shashank Rayabandi, Application of WAAM to build functional components: topology improvements and intersection construction, University West (Suécia)– 25 de Setembro de 2020, Soperviisor: Americo Scotti, Examiner: Paul Kah
3) Javier Hernández Justicia, From design to Wire Arc Additive Manufacturing (WAAM): Development of a protocol from G-Code to Rapid-Code, on 2021-03-06, Examiner: Américo Scotti; Advisor: Peigang Li and Xiaoxiao Zhang

Publication:

1) DAHAT, Shubham; HURTIG, Kjell; ANDERSSON, Joel; SCOTTI, Americo. A Methodology to Parameterize Wire + Arc Additive Manufacturing: A Case Study for Wall Quality Analysis, J. Manuf. Mater. Process. 2020, 4 (1): 14 p.; doi:10.3390/jmmp4010014
2) "Laser Metal Deposition with powder of a martensitic precipitation-hardened stainless steel" by Aidin, G., Hogstrom M, Valiente, A., Andersson, J., Presented at IIW Conference in Tokyo, Japan, July 2022 and accepted for publication in the IIW Welding in the World
3) VALIENTE BERMEJO, Maria Asuncion; EYNIAN, Mahdi; MALMSKOLD, Lennart; SCOTTI, Americo, University-industry collaboration in curriculum design and delivery: A model and its application in manufacturing engineering courses, Industry and Higher Education, Dec 2021: Doi.org/10.1177/09504222211064204

Under preparation to be submitted for publication;

1) Elaboration of MC-CCT (Multiple-cycle Continuous Cooling Transformation) diagrams for WAAM feedstocks and their potentiality in parametrisation: the case study of a HSLA GMAW wire
2) Use of numerical simulation to explain heat profile in WAAM of thin walls and consequences on interlayer temperature control
3) Tool Steel Repair by Laser Metal Deposition (LMDp) versus Arc Welding (TIG), a comparison of thermal cycles and microstructures

CO-PRODUCTION ACHIEVEMENTS

In terms of applied research, and from a technical point of view, this project can present the outcome from the perspective of two routes, namely WAAM and LMDp.

- Topic activities developed in the WAAM route

a) Demonstration of topological optimization potentialities in WAAM of functional components;

b) A numerical simulation study of heat transfer during WAAM aiming at understanding the effect of multiple cycles on the microstructure of thin walls

c) Proposal and assessment of a methodology to determine processing parameters for WAAM of thin walls and its parameter transferability potential;

d) An experimental heat distribution study (thermal cycle measurement and graphical analysis) aiming at understanding the effect of multiple cycles on the microstructure;

e) A study of the metallurgical architecture of HSLA thin walls built with WAAM aiming at predicting mechanical properties;

f) Mechanical property assessment of walls using solid and metal-cored wires

- Topic activities developed in the LMDp route

a) Powder characterization completed, coaxial single nozzle vs. multi-nozzle powder feeding problem resolved;

b) Laser parameter optimization completed using Design of Experiment (DOE) using the new 12 kW disk laser for Corrax and Dievar;

c) Heat Affected Zone thermal cycles acquired for 1, 3, 5 and 10-layer deposits on Corrax stair-like samples. Gleeble simulations were completed using these thermal cycles;

d) Crack-free LMDp deposits made using Corrax, while promising Dievar and V4 deposits were also made (some cracking, porosity and lack of fusion);

e) LMDp deposits were compared with TIG deposits and found to produce much lower heat inputs and finer microstructures;

OTHER RESULTS AND EFFECT OF THE PROJECT

Due to the pandemic time, it was difficult to collaborate with other researchers outside the University and industrial partners.

We can highlight that Uddehome helped train one PhD student from HV in special metallography techniques and ESAB with one Master student in Radiography.

OTHER LESSONS

Regarding competence development, the LMDp route forced all participants to reconsider prior knowledge on Additive Manufacturing, being an extension of traditional welding. The newest laser power source development (12 kW disk laser) used in the second part of the project uses the most state-of-the-art solid-state beam generation technology. Therefore, all participants had to learn about new Transverse Energy Modes (TEM), laser beam spot size, focusing, etc., as it applies to LMDp.

Use of multi-nozzle LMDp powder feeding (instead of the initially used coaxial feed with the laser beam) was found to be less sensitive to powder size variations and produce higher deposition rates. Therefore, this multi-nozzle design was deemed more appropriate for tool steel applications; the equipment was purchased and installed.

Another innovative portion of the project revealed the differences between deposits made by current arc weld repair and cladding technologies (TIG and MIG) and LMDp. Deposited bead- and heat-affected zones (HAZ) were significantly smaller in LMDp, their hardness and response to post-weld heat treatment were also different. Ultimately, significantly less deposit cracking susceptibility was observed in LMDp, reducing the need for extensive preheats and interlayer temperature controls. LMDp was found to be superior to current arc welding technologies in all areas, except for producing lower deposition rates.

Good correlations were found between simulative weldability testing and LMDp characteristics. Varestraint testing showed the relative hot cracking susceptibility between alloys, while proper Gleeble simulation procedures were developed to optimize preheat and interpass temperatures without having to make actual LMDp deposits.

Finally, going back to basics – single pass bead deposits instead of multi-bead, multi-layer deposits – for V4 revealed the basic characteristics of such hard and brittle LMDp deposits, opening the door for innovation: reducing temperature gradients by new deposition patterns such as spiral paths, use of Ni-base soft buffer layers between passes, etc.

MEASURABLE INDICATORS

Bachelor Degree Project:

1)Felix Nandin for accomplishing this task in such passioned way with the work "Development of a method to measure multiple thermal cycles in subsequent layers in Wire Arc Additive Manufacturing (WAAM) of thin walls", by Felix Nandin, on March 15, 2021. Advisor Peigang Li, Examiner: Americo Scotti. This project was awarded as the best 2021 Degree Project in Mechanical Engineering.

2) Tobias Hermansson Daniel Lindh, Topologioptimering inom Svetsbaserad Additiv Tillverkning: Applicerat på Pendelarm för Bandsystem, BSc. Final Project, Maskinteknik, Institutionen för ingenjörsvetenskap, Högskolan Väst (2022); Supervisor: Kjell Hurtig

Degree project for Master of Science in manufacturing engineering:

4) Shubham Amar Dahat, A Methodology to Parametrize Wire + Arc Additive Manufacturing Applied to a High Strength Low Alloy Steel, University West (Suécia)– 31 de Outubro de 2019, Supervisor: Americo Scotti; Examiner: Joel Andersson
5) Shashank Rayabandi, Application of WAAM to build functional components: topology improvements and intersection construction, University West (Suécia)– 25 de Setembro de 2020, Soperviisor: Americo Scotti, Examiner: Paul Kah
6) Javier Hernández Justicia, From design to Wire Arc Additive Manufacturing (WAAM): Development of a protocol from G-Code to Rapid-Code, on 2021-03-06, Examiner: Américo Scotti; Advisor: Peigang Li and Xiaoxiao Zhang

Publication:

4) DAHAT, Shubham; HURTIG, Kjell; ANDERSSON, Joel; SCOTTI, Americo. A Methodology to Parameterize Wire + Arc Additive Manufacturing: A Case Study for Wall Quality Analysis, J. Manuf. Mater. Process. 2020, 4 (1): 14 p.; doi:10.3390/jmmp4010014

5) "Laser Metal Deposition with powder of a martensitic precipitation-hardened stainless steel" by Aidin, G., Hogstrom M, Valiente, A., Andersson, J., Presented at IIW Conference in Tokyo, Japan, July 2022 and accepted for publication in the IIW Welding in the World

VALIENTE BERMEJO, Maria Asuncion; EYNIAN, Mahdi; MALMSKOLD, Lennart; SCOTTI, Americo, University-industry collaboration in curriculum design and delivery: A model and its application in manufacturing engineering courses, Industry and Higher Education, Dec 2021: Doi.org/10.1177/09504222211064204

IMPLEMENTATIONS

Concerning education, the master courses in Manufacturing Engineering Program (1 and

2 years) contain courses related to welding and welding-related additive manufacturing technologies. The teaching-oriented knowledge and new lab facilities stemming from the Tapertech project were engaged in the master courses. In particular, team members of the project elaborated an industrial collaboration with industrial partners (on the scope of the AVANS project) to improve a curriculum design for the Topics of Welding Processes and Welding Metallurgy (see the reported action in a publication). In addition, a lecture on WAAM, one of the routes of this project, was developed by one of the team members and offered to the students of the newly created course on Additive Manufacturing course.

COMMUNICATION

The project has been continuously represented and presented at the international institute of welding (IIW) working commission group meetings at annual assembly every year during the duration of the project. The IIW annual assembly span across more than hundreds of countries within the domain of welding and additive manufacturing including both academia and industry, therefore, serves as an excellent platform for dissemination of project results. Also, the project has been disseminated at various national platforms such as the journal "Svetsen".

PROFESSIONAL DEVELOPMENT

Project results vs. initial goals: as in many other applied research projects, some results were different from the initial goals because of several reasons. While most specific WAAM and LMDp results were achieved in process optimization, thermal cycle acquisition and use for physical simulations, microstructure/property characterization, new challenges arose after cracking was detected in early trials and powder feeding difficulties were encountered. The resulting process optimizations made by careful Design of Experiment (DOEs) produced process operational windows and the new multi-nozzle modification eliminated the need for sieving the powder before LMDp.

New LMDp steel compositions were tested beyond the initially envisioned HSLA (high strength low alloy) steels. In fact, more difficult-to-weld tool steel deposits were successfully made using LMDp in a martensitic stainless steel (Corrax), a modified H-13 high carbon tool steel (Dievar) and a high carbon, high vanadium air hardenable steel V 4 for tool and die applications. Optimum preheat-, interpass- and post weld heat treatment temperatures were not yet established in the process, but this preliminary work opens the door for more investigations.

1. Unexpected results: extensive cracking in preliminary V8 LMDp deposits forced the team to reconsider candidate materials and a new additional metal candidate (Corrax a martensitic precipitation hardenable steel) was introduced to the project

at Uddeholm's request in 2020. The consequent crack-free deposits allowed the team to perfect the LMDp technique and unexpectedly good results followed in deposit integrity and properties.

- Another unexpected (also positive) result was the adjustment of LMDp parameters to the more consistent laser beam transverse energy distribution provided by the new 12 kW disk laser introduced by Trump to the project in 2021. This resulted in better deposition consistency and less porosity and lack of fusion.
- Direct comparison of LMDp with TIG welding (the current technology which would be replaced) showed better quality and less solidification- or interpass cracking tendencies in LMDp than in TIG welding. Additionally, lower preheats and higher interpass temperatures produced LMDp deposits than TIG welds, proving that LMDp could be more productive in industrial applications (less waiting times between passes).
- The substrate material sulfur content was found to greatly influence the shape of the LMDp deposits (surface tension-driven fluid flow pattern reversal) in Corrax (0.029%S), as opposed to low sulfur (0.003%) Dievar steels. Therefore, the substrate composition will have to be always considered in future LMDp deposits, especially where few layers will be needed (cladding)
- The high Carbon, Chromium and Vanadium content in the Dievar, V4 and V8 deposits indicated susceptibility for Reheat Cracking during post-weld heat treatment (assuming that crack-free deposits can be made). Therefore, stress relief below 500C was recommended. Work should continue based on the positive experiences at Uddeholm, where these heat treatment are reportedly performed daily.

2. How was the overall synergy question answered ("How to tailor performance of AM steel components through WAAM and LMDp?") For the group of steels chosen, the performance question had to be split into customer's applications, and it was found that "tailoring" microstructure, properties, and geometry should be divided into two categories: a. thin claddings of 1-2 layers where wear and corrosion dominate, b. local repair of worn components and thick buildups (3 layers and above), where toughness is an added requirement. Indeed, for each application LMDp was found adequate to tailor properties to the application, thus no "universal solution" seems to exist.

3. The Hybrid WAAM+LMDp proposed solution was also not achieved, although there is a good potential for making large and complex tool bodies using low-carbon

steel WAAM and coating them by LMDp. The fundamental selection criteria would be finding tool and die sizes and shapes where WAAM could be cost-effective relative to forgings or castings. For any such solution found, LMDp is deemed perfectly capable for local buildups or thin claddings of the entire work surfaces.

The Acronym TAPERTECH stands for TAiloring of high PERformance parts through laser and arc additive manufacturing TECHhnologies.