KNOWLEDGE PLATFORM APPROACH FOR FIBERLASER WELDING OF HIGH STRENGTH STEEL

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Abstract

The goal of this paper is an attempt to generate a broad knowledge platform for lightweight design for a fiber-laser welding case of a high strength steel corner joint. Two different high strength steel grades are joined together as a fillet joint in a corner arrangement of the plates of 6 mm and 15 mm thickness. The sensitivity of the weld to the beam inclination angle, beam positioning and focal plane position where studied. Defects like lack of penetration, undercuts and pores had to be suppressed. In order to generate a broad knowledge of the process, several investigative methods were used, including high speed imaging with and without spectral illumination, photodiode monitoring of defects at three wavelength ranges, measurement of the weld surface topography, mechanical testing as well as FE-analysis of the stress concentration under load. One goal of the knowledge platform is the transferability of the information to other applications. Thus a general theoretical description is derived as a Bifurcation Flow Chart; a standardised new method for documentation to explain the impact of the tested parameters.

Keywords: laser, welding, lightweight design, high strength steel

1. Introduction

1.1 Background

The present paper addresses knowledge management from experimental but also theoretical findings in laser materials processing. A large need and high potential has been identified of improved access, use and combination of knowledge. The demonstrator case studied here is fibre laser welding of high strength steel for which different analysis methods are applied and discussed.

The project behind this research and evaluation is called LOST (Lightweight Optimization of conStRuctions) and is focussed on weight reduction in different construction applications. By reducing weight, savings can follow in economy, construction and in reduction of fuel...
consumption. Amongst all the ways in which weight can be reduced, improving the weld quality has, in some cases, a key role. While improving the welds with laser welding, beside other advantages the volume of the material can be optimised (e.g. by avoiding large flanges), and reduced even further if the material is changed to high strength steel. Traditional arc and spot welding methods soften the high strength steel severely in the heat affected zone (HAZ), thus the advantages get lost. Using laser welding it has been demonstrated that the softening remains limited to a very narrow zone which hardly affects the mechanical properties of the weld and product under load. Thus laser welding is an enabler for utilising high strength steel. With ultra-high strength steel the material thickness and weight can be further reduce up to 25% for laser welded railway or truck platforms.

The demonstrator cases studied in the project aims at weight reduction by laser welding high strength steels for certain applications. At the same time the project aims at a knowledge platform for lightweight structures, including, beside other issues, welding technology.

1.2 State-of-the-Art

The research presented here addresses both the technical demonstrator case studied (namely defect free fibre laser welding of high strength steel) as well as the manifold research methods applied, including human cognition as a key criterion for improved knowledge management.

Laser welding is characterised by many superior features but suffers from high investment costs and often from the difficulty to control the process quality, as the process is complex and not fully understood. The various welding defects occurring have to be suppressed to achieve a quality that sustains the loading conditions of the welded product in service.

Due to its excellent beam properties the fibre laser enables improved welding performance. However, this improved performance is accompanied by new or more pronounced defect phenomena such as violent evaporation and spatter, which have to be eliminated [1]. Monitoring of laser welding defects is a promising method [2], either by photodiodes or by cameras. Two comprehensive reviews provide a survey [3, 4].

Beside many established but limited methods of analysing welding results, a few research groups apply advanced methods like high speed imaging [1, 5, 6] or Finite Element Analysis (FEA) [7]. Recently, combinations of different methods turned out to be powerful, e.g. FEA and imaging [7], X-ray imaging of pore formation followed by modelling [6] or photodiode monitoring and high speed imaging combined with modelling [5].

The approach studied here tries to systematically combine the data and knowledge from different methods in order to provide a more comprehensive picture on the process and the resulting welded product [8]. One method developed for improved, generalised and standardised documentation of findings is the Bifurcation Flow Chart (BFC) [8].

For welding it is important to note that the process of loading the welded product in service is of same importance as the welding process itself. The weld is the interface between both. Standards [13] try to define the threshold properties of geometry and defects for prevailing load in service. The various kinds of welding defects are standardised, however not in a completely satisfactory manner. A survey on the fatigue analysis of welded joints is given in [14]. The mechanical properties of the weld are of particular importance for the here studied welding of high strength steel, e.g. fatigue testing [15, 16]. Laser welding and hybrid laser-MAG welding has shown highly promising results even for ultra high strength steel, as the laser keeps the heat affected zone (HAZ) narrow in contrast to arc welding that strongly softens the material. Although laser welding can also lead to softening, its limitation to a
narrow zone has much less impact during the compound behaviour of the material (weld, HAZ, base metal) under load.

Despite a vast amount of experiments, case studies and applications in welding and laser welding, the transfer of knowledge to other applications is difficult, as each parameter situation differs from each other. Occasionally welding databases are developed, but due to differences for each parameter set and missing generalisation their use is limited. The need for transfer of knowledge is strong but hardly addressed, which is the motivation of the here presented research. Inspiration from other disciplines is appreciated. For example in machining a management information system was developed [12]. While many solutions have been developed for geometrical problems like shape identification, the treatment of complex abstract data like here parameter combinations in a multidimensional space is difficult and rare and the strategies are not obvious. In genetics artificial networks are developed where stronger connections between entries or selected output properties can be weighted and highlighted [11]. Suitable treatment and visualisation of data depends also on the capabilities and limitations of human cognition [9], e.g. the effect of colour on the performance of cognition [10]. With respect to welding these disciplines like generalisation of knowledge, visualisation and cognition are hardly addressed but could be a key for transferring knowledge in a more efficient manner.

1.3  Purpose

The purpose from our part in this project is to create a broad knowledge platform for how welding information may be transferred and used in a larger perspective. One problem with most projects today is that the information presented in them is not directly transferable to different applications, although the same solutions for suppressing defects might be applicable. To generate this platform, we need to gather a lot of data, and use different techniques in an attempt to create a wide picture of the welding process and the resulting welded joint. An issue concerning usability concerns human limits, which is how a reader perceives and remembers information. Limitations of the human mind to comprehend information involve memory, perception, readability and cultural differences. By making a knowledge platform from a weld situation, even if not all is usable, other similar but different applications may use parts of it and increase the resulting quality. If the limitations of the mind are compensated for, the usability may rise even further.

2.  Methodology

2.1  Vision of a knowledge platform

Since most laser welding projects are not really the same, a creation of a more generalised and standardised set of rules is desirable. In order to create these rules and make welding project results to be of more use in different but related situations, a wide array of analysis of welds can be made. Merely looking at the resulting welds does not tell why a defect occurs, only that it has decreased or increased compared to previous experiments. The transferability of knowledge is also a concern. By creating much information about a weld the chance increases that it will be of any use for other projects. Merely presenting result after result may create an incomprehensible amount of data which will not be usable by anyone unless it is structured in a manner that considers the human mind. The goal of creating a knowledge platform is so that a weld result, or fragments of it, may be of use in more than the actual case.
The context between the process and the critical conditions for the product in service is illustrated in Fig. 2.1 along with possible methods for analysing the situation, resulting in corresponding data and knowledge. Both the horizontal and the vertical chains are often treated separately, i.e. most research studies just apply one method to a certain aspect. The present research aims at initiating a more comprehensive combination of methods and data of the whole picture shown here in order to achieve more powerful solutions and more valuable knowledge.

Fig. 2.1: Context between the welding process and the resulting welded product under load and suitable methods for analysis and resulting data, all to be combined here in a comprehensive knowledge platform.

When it comes to building this knowledge platform a wide spectrum of methods can be applied to analyse a weld and its result. Besides making all of these tests and thus having a great deal of information, conclusions may be made when linking them together. There are mainly two steps of analysis of a weld that can be made; intermittent and sample analysis. Intermittent imaging gives an opportunity to detect defects and while and how they form, while sample analysis reveals which defects are present. By comparing the two methods of analysis, understanding of how to reduce or erase certain defects may be achieved. However, if one wants other people to really understand or have any use of all the information presented, one crucial part involves a human readers mind. A human mind needs visual aid, and the field of cognitive psychology [9] (how humans perceive and take in information) may be of real use here. Rules like redundancy and gestalt laws, may be used from this subject in an attempt to show how both understanding, memory and usability when reading articles may be improved. One application that will be used in analysis is the statement of rules. Rules that will be applied through a recently developed Bifurcation Flow Chart (BFC) [8], which ultimately states what the outcome will be when a variable changes from a current situation.

When dealing with a large amount of information, see the welding parameter structure in Fig. 2.2, especially when it seems to be too much information, searching and comparing is a key in discovering new ways to improve weld quality or describe a theory.
Fig. 2.2 Initial database structure (ELD)
A making of international standards and generalisations regarding defect gradations would be one step to make numbers more comprehensible. One suggestion is a numbered scale of 1-10 where each number represents, for example, a field of pore density, where a greater scale number represents a denser field of pores.

Most knowledge concerning certain aspects of welding resides within small groups of people (sometimes even individuals). Knowledge is not a concrete subject and hard to really express or comprehend, and as knowledge is carried with an individual in some cases, the loss of them may be devastating. Laser welding has more parameters than one might see at first. As an example/suggestion on how knowledge may be distributed and stored in a wider circuit, an online Experimental Laser materials processing Database (ELD) is proposed as part of the solution for this problem. It would be able to solve availability, comparability and storage issues for experiments. An initial structure for an experimental database can be seen in Fig. 2.2, as an illustration of the complexity of variables that are fought with in laser materials processing. This is a proposal for the lower structure of how an online experimental laser materials processing database may look like. As can be seen, there are a lot of parameters that one is not always concerned about, and the database must also be constructed against all eventualities.

2.2 Platform of methods applied

Among the methods used and discussed in analyzing weld results, the following have already been applied in the here presented cases:

Visual analysis:
- Inspection of top and root weld geometry.
- Microscopy, metallurgy and inspection of the weld cross section geometry.

Non-visual analysis:
- Hardness test of the weld cross section geometry.

Numerical simulation
- Finite Element Analysis (FEA) of the stress field in the weld under load conditions

Intermittent imaging:
- High speed imaging of the welding zone with and without laser illumination
- Photodiode monitoring system with three simultaneous spectrally filtered sensors for
  - 1070 nm (beam reflection)
  - 400-600 nm (“plasma” sensor)
  - 1100-1200 nm (temperature sensor)

Data transfer, storage and generalization of rules:
- Bifurcation Flow Chart (BFC)
- Experimental Laser Database (ELD)

Note that so far some of the above methods presented here were applied for Case 1 of the LOST project, others only for Case 2, while until the end of the project (in 2009) all methods will be applied comprehensively for both cases.

2.3 Demonstrator case studied

In the LOST project two cases (beside other demonstrators) were chosen to be deeply studied with respect to fibre laser welding of high strength steel. Below we describe Case 1 in detail
as an example of how a broad knowledge platform may be built, but Case 2 will also be briefly mentioned, as some of the above methods were so far only applied for Case 2.

**Case 1:** For the first case, a clear structure of purpose, equipment, setup and parameters is presented below. Also the reason for certain parameters, as some may be elusive to the reader.

**Purpose:** The purpose of Case 1 is to demonstrate laser welding of high strength steel to reduce the thickness and weight of the product by 25% by maintaining the mechanical properties required, including defect-free welding.

**Joint:** Laser welding of a 6\,mm deep corner joint with two different high strength steels is aimed at, one harder (Domex 960) than the other (Weldox 700). Both have been laser cut for edge preparation and the resulting cuts are unprocessed with the oxide layers remaining. Under these circumstances, they will be welded while suppressing defects like pores, lack of penetration and undercuts.

**Equipment and setup:** The weld situation and dimensions can be seen in **Fig. 2.3.** The whole support beam is a full 2 meters long seen in **Fig. 2.3a,** but for the experiments, 100\,mm long welds have been performed. The beam consists of two plates of Domex 960 and two plates of Weldox 700, placed in a fashion seen in **Fig. 2.3b.** The joint is a corner joint seen in **Fig. 2.3c** where one plate of 15\,mm thick Domex 960 and 6\,mm thick Weldox 700 are placed to form a corner joint with a joint 6\,mm deep.

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**Fig. 2.3** Weld joint situation; a) shows how the final support beam will be loaded, b) is the cross cut of the beam with the four weld points indicated. The dimensions of the cross section of the joint area are magnified in c)

The weld setup and the joint fixture can be seen in **Fig. 2.4.** The fixture is made so that the joint is supported from within and highly pressured from the top and from the sides to avoid heat deformations, that otherwise may cause misalignment defects. The joint is supported from within and has high pressure both from the top and from the sides to avoid deformations of the plates due to heat, that otherwise may cause lack of fusion when the plates separate or alter the depth of the joint.
Fig. 2.4 Experimental setup

Case 2: Also a second case is demonstrated for the intermittent imaging part, which is a laser hybrid weld (combining a laser beam with a MIG-arc) 6 mm thick high strength steel with a gap separation of 0,5\text{mm}. However, the parameters and experimental setup will not be presented here, as the aim is to demonstrate how a knowledge platform may be built.

2.4 Process parameters

The parameters used (for Case 1) can be seen below. Only a few parameters have been chosen to illustrate how the defects undercut and lack of fusion have been cornered by adjusting the welding speed, which is the only varied parameter presented here (other properties varied were e.g. the beam angle and lateral and vertical focus position).

Welding speed: 1,25 m/min; 2.0 m/min; 2.5 m/min

For completion, all parameters below are used in all the experiments:
- Laser model: Yb:fiberlaser YLR-15000, maximum power 15 kW (cw), 200\(\mu\mathrm{m}\) fiber, BPP 10.4 mm-mrad, Wavelength: 1070 ± 5\text{nm}
- Optics (collimator length / focal length): 150/500 mm from lens to focal point). (Chosen because it has a long focal depth.) thus magnification 3,3:1
- Spot diameter: 0,67\text{mm}.
- Rayleigh length: ± 8 mm from focal point.

Laser beam arrangement:
- Focal plane position: -1 mm
- Laser inclination angle: 5° leaning, 45° turned

Laser power chosen:
- Laser power: 5000 W, cw. (Chosen so that it is well matched to the productivity and provides sufficient power density)
- Power density: 1,42 \times 10^{4} W/cm^{2} (for 5000W, average, in the focus).

Shielding gas:
- Argon, gas flow 20 liters/min., through a nozzle near and aimed at the weld. (Argon offers the same protection as helium when using fibre lasers but at a lesser price.)
For Case 2, which is hybrid welded, we do not here present the parameters but just demonstrate the analysis methods applied.

### 3. Results and discussion

#### 3.1 Weld cross section geometry

From the resulting welds from parameters given in Ch. 2.4, the weld geometry and cross sections was derived, as seen in **Fig. 3.1**. From the visual analysis, it seems that sample number two has the best results, as it has only little undercut and root dropout, while sample number one has significant root dropout and undercut and sample three has partial lack of fusion.

**Fig. 3.1** Weld cross sections (upper) and top side (middle) and root side (lower) of the welds for the three different welding speeds: a) 1,25 m/min, b) 2,0 m/min, c) 2,5 m/min

#### 3.2 BFC

But just stating this does not add a real value to the analysis. By creating a standardised generalisation of defect scales mentioned in Ch. 2.1, a value might be added to the root dropout and undercut defects, allowing easier comparisons with other experiments to be made, and at the same time increase the usability of the set of parameters. With the aid of these results, a simple set of rules and a theory can be stated, visualized by the Bifurcation Flow Chart (BFC) shown in **Fig. 3.2**. According to the rules created, the defect lack of fusion can be suppressed by welding at a slower speed, while dropout and undercut can be suppressed by increasing the speed. The results, along with the results would advantageously be put into the online Experimental Laser materials processing Database (ELD), and automatically indexed and be searchable for future work. Some guidelines/rules might be obvious and some might be apparent only for experts, but complete awareness of all findings will be highly advantageous. The readability of BFCs needs still to be improved.
3.3 FEA of the stress field

The Finite Element Analysis of the stress field was not yet applied for Case 1 but for a similar joint geometry, shown in Fig. 3.3. Stress raisers can be seen in the corner points that are dependent on the curvature and critical for crack initiation. Thus sharp corners or undercut have to be avoided, while lack of fusion turned out to be less critical as long as under compressive load.

3.4 Hardness measurements

One way to continue further analysis can be made by doing hardness testing of the cross cut weld. A Vickers hardness test of sample number two can be seen in Fig. 3.4, with support lines to ease the visual survey of the location of the hardness tested spots. Regions of the weld have also been enhanced to ease the general visual view. The hardness test is made on a sample with a welding speed of 2.0 m/min. The weld is hardest at the point where the inner and outer HAZ meet on the Domex 960 side of the weld. It is also least hard at the point where the base material of Weldox 700 and outer HAZ meet. The different hardness of the two materials can be seen as well as the slight softening in the HAZ.
Fig. 3.4 Vickers hardness test for the weld sample for a speed of 2.0 m/min

3.5 High speed imaging

So far high speed imaging has only been applied to Case 2, hybrid welding. A sequence of images is shown in Fig. 3.5.

Fig. 3.5 High speed imaging of a shortcut during MIG + laser welding
In the figures, the MIG wire can be seen as well as the keyhole, the weld pool and spatter ejections. At a).i) the MIG wire is visible and the laser keyhole is visible at a).ii). In c) – e) a MIG pulse is ignited. There is not enough energy to burn enough of the wire as seen in e), which in f).i) comes close enough to touch the work piece and cause a short circuit, creating a burst of small spatter f).ii). In g) – h) the spatter flies away and in h) – j) a new MIG pulse goes off. A lump of spatter begins to form in k) but attaches to the weld pool in l), possibly filling a gap created by the short circuit. As can be seen, high speed imaging is a very powerful tool to deliver additional information on the welding process.

3.6 Photodiode monitoring

For Case 2 the photodiode monitoring sensors were applied. In Fig. 3.6 the three photodiode detector signals made at the same time as the high speed imaging can be seen with the correspondent location of the resulting weld. How to interpret the detector signals is a next research step. The detector signals made at the same time as the high speed imaging can be seen roughly with the correspondent location of the resulting weld. The weld is a MIG + laser hybrid weld with a gap separation of $5,0 \text{ mm}$. Some indication of the result of the weld can possibly be given by the signals.

![Detection signals](image)

**Fig. 3.6** Weld with failures and detector signals for Case 2: “reflection” (upper), “plasma” (middle), “temperature” (lower)

3.7 Applied Cognitive Psychology rules

The analysis and the here presented results have also been discussed with respect to cognitive psychology in order to eventually succeed with creating methods and results best suited for humans, thus becoming applicable. Due to the large number of methods and data handled the risk for inflation of information and difficulties in cognition of the essential knowledge is large, thus the information has to be carefully treated – a process that was just initiated and is in progress.
The rules applied from *Cognitive Psychology* [9] have been applied as stated below:

- The *gestalt laws* concerns grouping of images, where the whole is more important than the individual images combined. In **Fig. 3.5** a series of high speed snapshots is presented. The best order a series can be presented depend on culture and personal experience. In order to clarify visually which order the images is to be followed, support arrows have been added.

- The *gestalt laws* have also been applied along with *Data-driven processes* (pieces of information put into a whole) in **Fig. 3.4** where the graph and sample cross cut image has been grouped together with added visual support lines and information boxes. The whole figure (graph, image and support lines) tells a greater story than they would alone or beside each other.

- The *law of symmetry* is applied in **Fig 3.1** and **Fig 3.5** in order to avoid confusion of the mind. If the images where not the same size and spaced equally, the mind might put more energy in placing the images “correctly” than focusing on the information presented.

- *Redundancy* (overflow of information) is also used throughout this paper. The reader should be clear about what e.g. a figure shows, and thus even if something has been written in the text, it is also marked in the figure.

- *Interference* may disturb short term memory, and in order to subdue interference, the parameters in the parameter list in **Ch. 2.4** has been ordered in order and not mixed randomly.

- *Theory driven processes* can be applied by putting appropriate titles. The mind starts from the whole and tries to put the details into that whole. An inappropriate title can mislead the reader’s coherence, e.g. by putting the title “Schematic of experimental lasers manufacturing” for **Fig. 2.2**.

- The reason why the defects in **Fig. 3.1** have been marked with the colour red is because the author wishes the reader to pay attention to that area. The colour red triggers a warning/heat alert in the readers mind and makes him pay more attention to the details, as they are considered dangerous [10]. This is especially useful when marking defects, as those are unwanted. It is, on the contrary, advised not to mark positive things with the colour red.

How to merge all the analyses made from a weld into a comprehensible whole, rules like the above can be of great help.

### 4 Conclusion

A first step towards developing a comprehensive knowledge platform was presented for a certain application. Several methods were studied.

In building a broad knowledge platform, many methods can be combined. When presenting the information, the stand-alone figures can be enhanced by practising the laws and rules of Cognitive Psychology. The importance of applying the rules increases when the different analyze methods are put together. Even more methods to build even larger knowledge
platforms about a weld can be by e.g. fatigue tests, CFD-analysis, modelling, X-ray imaging, etc.

We can conclude:

- Simple, but clear guidelines/rules for suppressing welding defects are desirable
- A standardised documentation including theoretical hypotheses and generalisations can facilitate the transfer of knowledge
- As an example the rules were derived and documented that increasing welding speed can suppress root sagging and undercuts while decreasing welding speed can suppress lack of penetration
- Applying manifold high level analysis methods leads to more comprehensive background knowledge and to a larger picture
- Further progress and studies are needed as well as feedback from people

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