Classification and generalization of data from a fibre-laser hybrid welding case

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Abstract

Compared to autonomous laser welding, the amount of parameters is higher for laser hybrid welding. Consequently, empirical optimisation of these parameters is a challenge. Handling and evaluation at a higher systematic level is desired in order to enhance the ability to build research on previous knowledge. Such new approach is studied on a case with 10 mm high strength steel sheets, fibre-laser hybrid welded. Aim of the paper is to provide a method of documenting and handling data, transferable to other disciplines, to continuously build knowledge, to simplify repetition of experiments and to facilitate the start-up phase of new trials. Starting from 30 experimental results depending on 23 parameters, by the Matrix Flow Chart a guideline has been developed that filters the information through combination, priorities and quality categorization. A chart resulted where five categories of poor quality are graphically related to a high quality category which can be achieved when following the guidelines for eight main arc- or laser-parameters. The chart is a guideline suitable for extension and for exploring the limits of its validity.

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1. Introduction

From research we produce vast amounts of data from each test performed. However, the data do not necessarily support future experiments. The here presented paper aims at introducing tools to use as support in handling large quantities of data, not only restricted to the area of laser materials processing, but useable for a larger group. The research team has already successfully used the methods, both in combination and exclusively [1-4] to describe and facilitate interpretation of the manifold of data. The methods of data handling are the Bifurcation Flow Chart (BFC), used by the author [1], to describe in a sequential manner the phenomena affecting whether the weld seam is satisfactory or not, including the key criterion for a defect. The other method is Matrix Flow Chart (MFC) developed from the first Experimental Laser Database [2] by Karlsson [3-4]. The MFC:s matrix table, acting parallel instead of sequential, facilitates understanding of how parameters affect the result of a weld seam. It compresses the dimension

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of the database to get a more general view of the data and it also generalizes the results into classes. There are many ways of presenting multidimensional data [5] as reviewed by Gaede et al. To develop these methods in the correct direction it is important to have knowledge how the human mind interprets data [6]. This is important as there are two types of data [7], the explicit and the tacit. The explicit knowledge can be shown in numbers or in text and therefore it is the type that is shared as data, manuals or in other ways and it can therefore be transferred between persons, it is the opposite to tacit knowledge. A well known metaphor[8], Fig. 1, tries to describe the amount of knowledge hidden in the tacit part.

![Image of Iceberg metaphor](image)

Fig. 1 Iceberg metaphor describing weighting between knowledge types

Tacit knowledge is intuitive and it is therefore often very difficult to formulate and describe but it contains a lot of important information. Although the present paper does not in any way claim to show the perfect knowledge transfer method it tries to facilitate the use of large databases and how the data inside is visualized in an effective manner, better suitable for the graphical perception capabilities of humans. The bioscience area is where the database visualization techniques has been most explored [9] but also research within other areas has taken place[10]. We have now developed a method to simplify the interpretation of information, both explicit and tacit for fibrelaser hybrid welding.
2. Method

The fibrelaser hybrid welding method is described and also the method of saving and using data from the trials.

2.1. Fibrelaser hybrid welding method

To be able to reproduce results from fibrelaser hybrid welding the amount of parameters that needs to be saved is vast. It is not only the MAG- and laser-parameters that have to be saved but also the geometrical parameters such as the distance between the electric arc torch and the laser beam axis, Fig 2. A 15 kW Yb:fibre laser (IPG) was used, with an output fibre diameter of 200 µm and a Beam Parameter Product of 11.4 mm·mrad. The collimator length was 150 mm, different focusing lengths were applied.

Fig. 2 Geometrical parameters for the setup of fibrelaser hybrid welding [11].

With the setup in Fig. 2 it is also possible to choose whether the laser should be leading or trailing and also if the laser should be sticking or dragging, Fig 3. The changes of these two parameters are thought to affect the melt pool flow and also the penetration depth of the fibrelaser hybrid welding.

Fig. 3  (a) Sticking laser setup, (b) Dragging laser setup

2.2. Method of saving parameters and results

In Tab. 1, the parameters for setting up a laser hybrid test are shown and categorized. The amount of parameters that needs to be controlled is large and therefore the general view of the data is difficult. Some of the parameters in the table is not as important as others so the final table contains approximately 23 parameters to be handled.

Table 1 Parameter for fibrelaser hybrid welding

| Laser Parameters | Material properties | Geometrical Parameters, Fig. 2 | MAG Parameters |
|------------------|---------------------|-------------------------------|---------------|
| Power (P)        | Thickness (t)       | Contact to work piece distance (s) | Voltage (U)   |
From the resulting welds photographs of the top and root appearance were made. Microscopic photographs of the etched cross section provide the essential view on the shape and defects. The weld quality was then categorized, as will be shown below. The experiments were accompanied by high speed imaging for additional information.

In a database spreadsheet the parameters were put in relation to the photographs. While documentation often ends here, as a next step we propose to categorize the resulting quality. The parameters can be expressed in relative values, like High/Low. A graphical table, the recently developed Matrix flow Chart can now be applied to connect the weld photos with high/low parameters (or further steps introduced). The main parameters can be identified, in relation to a high quality weld and reduced table results, where the weld quality categories are related to the essential parameters, applicable as a guideline on how to change the parameters to achieve good quality. “OR”-logic is applied. The information can be tracked back to the detailed welding results. The table is initially merely valid for the cases studied but can be extended to explore the limits. It is recommended to try the guidelines for different operating windows, as now disconnected from the absolute parameter values.

3. Results

The result of this paper is the method itself and its application to the case study. The research has shown that 10mm hot rolled, high strength steel, DOMEX 420MC can be hybrid welded (butt joint with gap) with acceptable results, according to SS EN-ISO 5817. The main difficulty was that the parts to be welded with a butt joint differed in the joint gap setup between 0 and 1mm. The edges were also rough, see Fig 4(a), gas-jet cut, and the oxides were not removed from the edges. The edge oxides are shown in Fig. 4(b). Study of the impact of the edges on the weld is actually part of a comprehensive study.

![Fig. 4 Surface topography of the gas-jet cut edge: (a) profilometry, (b) SEM-image of the upper part](image-url)
To gain knowledge about the process and the how fibrelaser hybrid welding is affected by parameter changes a high-speed imaging system (HSI) has also been used. The results from these images that have been recorded at a rate of 2000fps, as shown in Fig. 5 for the pulsed arc, its drop transfer and the keyhole. HSI is a very powerful tool for laser hybrid welding as it is possible to see into the processing zone and as many parameters are of geometric nature. This is possible because of the correct combination of illumination and filtering that removes all the process light and only leaving the illumination wavelength, to be recorded via a narrow bandpass filter. Figure 5 shows the detached drop moving downwards to the right in the first two pictures and in the four following the plasma buildup and drop formation and the two last pictures the drop detaches and moves towards the melt pool.

Fig. 5 Sequence of images of the pulsed electric arc and the drop transfer from the MAG wire to melt pool; right: keyhole

Part of the actual database with 70 entries (welding results, including top surface and cross section photos, comments, etc.) depending on 23 welding parameters is shown in Fig. 6. The results in the spreadsheet, contain both tacit and the explicit knowledge that is easy to communicate as a picture. The resulting welds have been cut, polished, examined and classified to five defect classes (plus acceptable quality), see Fig. 7.

The different classes shown in Fig. 7 are: undercut with excess weld, undercut, undercut with excess penetration (root drop-out), sagging and sagging with excess penetration. These were extracted from the 30 weld trials that are already ready from microscopy to be evaluated. They were deemed as a class if the defect occurred at least 3 times.

The next step is to enhance the readability of the database by transforming the values to arrows and figures to get a better understanding if there are any trends in the data, see Fig 8.
Fig. 8 The evolution of the database (a) to intermediate step (b) and the final MFC (c) shown in Fig. 9.

70 experiments in total reduced to 6 categories,
From 23 parameters 8 showed favoured trends.
Fig. 9, shows an MFC of the most important parameters versus the defect classes. It is used as a guideline for avoiding these types of defects that might occur with this setup. The operator has the actual weld cross section at hand and can by comparing the defect classes follow the lines to see what parameter that has affected the defect and also how to change the parameters to avoid it. For the current setup the sagging is avoided by looking at the horizontal line next to the defect and following it to where it has a dot. At the intersection with the dot follow the vertical line to the parameter, and there it says what to do with the parameter to avoid the defect and achieve an OK weld. The OK weld is specified acceptable according to the Swedish standard SS EN-ISO 5817

Fig. 9. Altered MFC of the 30 fibrelaser hybrid welded samples with its corresponding parameters. Circles show selected defect

4. Discussion

The use of these methods facilitates the interpretation of vast amount of data. It also tries to standardize how data are saved and therefore also minimizing the tacit part of knowledge and converting it to explicit knowledge. By succeeding with this task it is easier to spread information as one of the drawbacks with the tacit knowledge is that it is hard to communicate it to others. The graphical arrangement provides to point at data or connections and to track connections and relations, moreover to compare visually. Although the goal is not to remove the vast amount of data contained in the databases it is important to avoid saving unnecessary data that not only will take space but also time to record. The database it self is important as a database but it cannot be used effectively as an evaluation tool and therefore these methods must be further developed.
5. Conclusions

- Fibrelaser hybrid welding results from 70 experiments of a case study were entered into a database, from 30 already evaluated samples a graphical guideline was accomplished, to facilitate knowledge transfer
- The method of structuring the parameters and results in a MFC gives a good overview
- The method reduces the amount of experiments as it is simpler to use earlier knowledge
- Tacit knowledge is tried to be transformed into explicit knowledge, by finding ways to express the expert knowledge for each individual.
- By different combinations of MFC:s it becomes a strong method of explaining the result-parameter influence
- By having intermediate steps from the database to the MFC the user is free to choose the amount of information needed
- It is possible to track back each result in the MFC to the database facilitating the withdrawal of information for interesting cases

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