High power laser hybrid welding – challenges and perspectives

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Abstract

High power industrial lasers at power levels up to 100 kW is now available on the market. Therefore, welding of thicker materials has become of interest for the heavy metal industry e.g. shipyards and wind mill producers. Further, the power plant industry, producers of steel pipes, heavy machinery and steel producers are following this new technology with great interest.

At Lindø Welding Technology (LWT), which is a subsidiary to FORCE Technology, a 32-kwatt disc laser is installed. At this laser facility, welding procedures related to thick section steel applications are developed. Material thicknesses between 40 and 100 mm are currently of interest. This paper describes some of the challenges that are related to the development of the high power hybrid laser welding process as well as to the perspectives for the technology as a production tool for the heavy metal industry.

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1. Introduction

This paper describes some of the preliminary work and first experiences within laser hybrid welding carried out at Lindø Welding Technology (LWT) in Denmark based on a 32-kW disc laser installation.

For more than a decade high power laser hybrid welding has been widely utilized within the European shipbuilding industry and has become a kind of state of the art joining technology in this field. The European Ship Classification Societies issued their first unified guidelines for the approval of CO₂ laser welding in 1996 and the 2005 edition now contains reference to hybrid welding (Lloyds, 2005).

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Due to the ongoing technical development and the increasing power levels available on the market for industrial lasers, other heavy section steel industries are now looking for new opportunities for joining heavy metal components as an alternative to traditional welding processes.

Especially, within production of offshore windmills the industry are looking for more cost efficient joining technologies. Welding is normally carried out manually or semi-automatic, typically GMAW or submerged arc welding. Offshore windmill steel foundations include a considerably large amount of manually GMAW welded joints which constitutes for a considerably amount of the costs. The costs of an offshore windmill foundation constitutes about 30% of the entire windmill installation. It is the aim before 2020 for this industry to reduce the overall production cost by 40% in order to maintain competitiveness with competitors outside Europe. The aimed reduction of manufacturing costs will be related to the development of more efficient joining technologies as well as optimizing designs.

Now three government supported development projects in Denmark are dealing with high power laser hybrid welding within the frame of above-mentioned topic. The projects are:

- Fabrication and surveillance of green offshore structures (2013-2015)
- Cost effective mass production of Universal foundations for large offshore wind parks (2014-2016)
- Offshore wind foundation on an industrial scale (2015-2016)

The 'Green offshore’ project involves laser hybrid welding related to the production of windmill towers. The 'Universal foundation’ project is focusing on the production of bucket foundations. The last mentioned project deals with the fabrication of node structures related to the offshore jacket foundations.

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![Fig.1 Offshore foundation jacket structure and windmill tower fabrication, (Mabey Bridge).](image)

2. Laser Hybrid Welding - principles

Laser hybrid welding combines the benefits from a laser beam with the benefits from a traditional arc welding process and to a certain degree eliminates the drawbacks from the individual technologies. The hybrid welding technology still produces welds, which are characterized by low distortion, high reproducibility and higher productivity. The laser hybrid welding process permits greater fit-up tolerance, elimination of defects due to the addition of filler material and the ability to weld thicker materials. In general, laser hybrid welding offers higher productivity, stable and high weld quality and the possibility of implementing an automated cost reducing welding process.

The characteristic deep laser hybrid weld profile is created by combining the focused laser beam and the arc in a common melt pool. This melt pool is moving along the weld pass, see Fig.2.

A number of standards are the basis for the evaluation of the laser hybrid weld quality. The most important ones are;
• The classification society’s requirements for the approval of CO₂ laser welding procedures, 1996.
• Classification guidelines for the approval of autogenous laser welding and hybrid laser welding, 2004.

3. 32 kW disc laser system at LWT

Recently, a 32-kW disc laser system was installed at the Lindø Welding Technology (LWT) in Denmark. The installation consists of two 16 kW disc laser units delivered by TRUMPF, couplet together via two 200 my fibers into the weld head. The weld head generates two focal spots super positioned nearly on top of each other. In this way, a laser power level of 32 kW into the melt pool can be established. The weld head is attached to a robot to carry out the movement along the weld pass, see Fig.3.

As seen in Fig.4 the maximum bead-on-plate, BOP, depth of penetration is in the range 15-20 mm for a single laser at 16 kW. At 32 kW, running both lasers, the maximum BOP depth of penetration is in the range 20-25 mm.

The laser facility at LWT is among the largest in Europe. Recently, in 2014 a 100 kW fiber laser was installed in Japan at Osaka University, (Katayama et al., 2014). Preliminary welding results at this facility indicates that a BOP penetration depth in the range of 55 mm is possible at 100 kW in steel materials. Fig.5 illustrates the maximum BOP depth of penetration for the different high power lasers at FORCE Technology, LWT and Osaka University. It is seen
that in the 'lower' power end the penetration is approximately 1 mm per 1 kW up to approximately 20 kW. From 20 to 100 kW there is a 'loss' of penetration to approximately 0.5 mm per 1 kW.

Fig.4 BOP welding capability of the LWT laser installation, (LWT, 2015).

Fig.5 BOP welding capability of high power lasers FORCE Technology, LWT, Denmark and Osaka University, Japan, (FORCE).

4. Steel materials considerations

The laser welding process is characterized by producing a deep and narrow melt profile created by a low heat input. Both the narrowness and the low heat input are reasons for some restrictions related to the steel composition.

The deep and narrow melt profile, the nature of the solidification mechanism combined with the induced stresses often results in the formation of solidification cracks, see example in Fig.6.

Methods to evaluate the weldability for a certain steel composition is to produce a so-called weld-lobe and to calculate the 'steel index' which indicates the susceptibility for solidification cracking. These methods were developed within a project called 'HYBLAS', (Hyblas 2003).

Fig.7 illustrates a weld-lobe for a class 355 steel. A number of BOP welds are carried out at different welding speeds and power levels. The welds are evaluated visually as well as by X-ray. In the low welding speed range melt drop through is observed as the lower lobe boundary. In the high-speed end, solidification cracks are typically setting the upper lobe boundary. In between the lower and upper lobe boundary, the acceptable lobe area is located. The size of this acceptable lobe area is observed to be related to the steel composition.
In the HYBLAS project, weld lobes for approximately 50 steel compositions were produced. The acceptable lobe area for these steels were plotted as a function of different data adapted steel indexes of which one example is shown in Fig. 8. This plot suggest a steel index S=50C+5Mn+Si-7Cu-100S-200P+1 > 8. If the steel index for a specific steel composition full fill this condition, there is a good probability that the weldability of the steel is good.

The steel index evaluation is now a recommended part of the classification society’s guidelines. The steel index indicates that the amount of Sulphur and Phosphor has a strong influence on the susceptibility for solidification cracking as generally known from traditional welding technology. For this reason the unified classification guidelines suggests an upper limit for these chemical components as follows; P< 0.010 % and S< 0.005 % (Lloyd’s, 2005).

Due to the higher cooling rates involved with laser welding a suggested maximum Carbon level of 0.12% will assure that the hardness of the weld and HAZ will never exceed 380 Hv which is the upper limit accepted by the classification societies.
In the HYBLAS project, the lobe technique was investigated for laser hybrid welding as well. Fig. 9 shows two lobes related to the same steel created for two butt welds with a zero gap and a 0.5 mm gap. It is seen that in the latter case the acceptable lobe area is increased compared to the zero gap condition. This means that it is possible to affect the solidification of the weld metal by addition of filler materials. It is possible to affect the chemical composition of the melted material as well as the solidification mode.

It was found that laser hybrid welding is less sensitive to defects formation compared to pure laser welding. The filler wire addition and the heat introduced by the arc are important instruments for being able to control and enhance the weld quality even at more poor steels.
5. Joint design

Most research work within laser welding of thick section steel is so far limited to thicknesses in the range up to 35-40 mm, primarily based on CO₂ lasers up to approximately 20 kW. Within the last 5 years, disc-laser systems up to 32 kW and fiber laser systems up to 100 kW have entered the scene and is now basis for laser hybrid welding research related to even thicker section welding up to approximately 100 mm.

From an applications point of view thicker section welding in general needs following considerations, which influences on the joint design:

- Welding from one side only
- Welding from both sides
- Only laser hybrid welding
- Combination of laser hybrid welding and arc welding

Dependent on the specific application and a realistic production set up, geometrical or physical conditions often puts limitations / restrictions to the joint design and the welding procedure.

Fig.10 illustrates two of the joining concepts; a) combination of hybrid welding with arc welding and b) laser hybrid welding only. The two concepts calls for different joint designs and the later one may have limitations in thickness range.

In the case a) laser hybrid welding is carried out in a certain thickness range dependent on the available laser power. The rest of the joint is typical a V-joint where an arc welding process, typically GMAW or SAW, is used to finalise the welding operation. This means that the joint design is a combination of a two designs, one part for the laser hybrid weld and another part for the arc weld. In case b) the joint design is only related to the laser hybrid welding process allowing a minimum gap in the joint area.

In both cases a) and b) advantages may be present in terms of higher productivity, consumption of less filler material and reduced distortions compared to a fully arc welded joint.

Fig.10 Joining concepts. a) Laser hybrid welding in combination with arc welding. b) Laser hybrid welding only, (FORCE).

Fig.11 illustrates the gain in productivity increase for case a). Laser hybrid welding can be carried out solely in up to appr. 40 mm thickness. For more than 40 mm thickness the joint is considered welded with GMAW.

Following welding parameters are basis for calculations:

- LASER: Power, 32 kW. Welding speed, 500 mm/min.
- GMAW: Wire speed, 15 m/min. Wire diameter, 1.2 mm. Welding speed 500 mm/min.

It is observed that in 40 mm thickness the productivity for pure laser hybrid welding is a factor 9 better than for pure GMAW welding. In thicker materials, which becomes a combination of hybrid laser welding and GMAW
welding the productivity increase compared to pure GMAW welding decreases to a factor 3 at a thickness of 100 mm. At even larger thicknesses the productivity difference will become even less.

It is obvious that the most benefit of laser hybrid welding process is obtained in the region where the laser power level suits the material thickness for a pure laser hybrid welding process or for a limited combination with GMAW.

Fig.11  Productivity increase by factor comparing a combination of laser hybrid welding and GMAW welding compared to pure GMAW welding. (FORCE).

In order to reduce the amount of weld passes case b), based on laser hybrid welding only, is preferable. A low number of weld passes in general requires a narrow joint design, which is only possible in limited material thickness as the accessibility for both laser beam, wire and arc control is of paramount importance. Fig.12 shows some cross sections of 3-pass laser hybrid welds carried out in 35 mm structural steel, (Kristensen et al., 2009).

Fig.12  Cross sections of a 3-pass hybrid GMAW/laser weld in 35 mm AH36 structural steel (Kristensen et al., 2009, FORCE)

6. Defect control through joint design

There are typical three types of weld defects to consider when evaluating the weld quality in accordance to the relevant standards.

- Geometrical defects
- Porosity
- Solidification cracks
Geometrical defects are typical visible defects like e.g. undercut. These defects may affect the fatigue properties and thereby the component lifetime. Porosities are generally ‘gas bobbles’, which did not escape the melt pool during solidification. Porosities are in general harmless defects and are allowed to a certain degree according to the standards. However, solidification cracks or flaws are not allowed due to the risk for larger crack formations during fatigue loading.

The avoidance of solidification cracks or flaws are therefore one of the most important challenges related to laser hybrid welding. For laser hybrid welding it has been demonstrated that filler material addition combined with heat input control is the key tools for controlling the defect level, (Hyblas 2003). The efficiency of filler material mixing with the base material and the effect on the solidification mode is directly related to the joint design. In order to evaluate the mixing conditions for the filler material with the base material, experimental work on different joint geometries using a stainless wire was carried out, hence using the Chromium content of the wire as tracer material.

Fig.13 shows the results from the filler material mixing experiments related to a I-butt joint with a zero gap and a 0.7 mm gap as well as for a simple V-shaped joint design. It is observed that for both the I-butt joints, which are welded from two sides, that the mixing of the filler material is quit uniform measured along the centerline of the weld. The amount of filler material in the melted region is approximately 15%. For V-shaped joint design, just welded from one side the mixing of filler material is approximately 25%.

It is obvious that a more ‘open’ joint design allows more filler material to enter to the weld. Therefore, the optimum joint design depends on how much filler material is required for the specific materials involved in order to avoid defects like solidification cracks. A too ‘closed’ joint design may reduce the filler mixing too much and a too ‘open’ joint design will require more filler materials, hence more welding passes.

When considering the combination of laser hybrid welding with traditional welding, case a), Fig.10, it may be beneficial to adapt the traditional welding to joint locations where filler material addition is specially required in order to avoid defects. The combination of welding processes into the same joint calls for more strategic joint design.

A number of different joint design currently being investigated is shown in Fig.14. These designs are tailored for both single sided and two sided welding as well as for combination of welding processes.

Fig.13 Evaluation of the efficiency of filler material mixing with the base material related to the joint design. a) butt joint, zero gap b) butt joint 0.7 mm gap, c) V-joint. Material thickness, 40 mm, (FORCE, LWT, 2015).
Fig. 14 Example of proposed joint designs investigated for laser hybrid welding in 40 mm material thickness, (FORCE).

Fig. 15 and Fig. 16 compares two types of laser hybrid welds carried out in 40 mm structural steel.

Fig. 15 illustrates a 0.5 mm gap I-butt joint welded from two sides. The individual penetration of each the melt profile is approximately 25 mm, which means a weld profile overlap of approximately 5 mm. Materials data, processing data as well as hardness measurements data are included as well.

Fig. 16 illustrates an X-shaped joint, designed for two GMAW welds, root and top, with a single laser hybrid weld between. The root weld serves as a tack weld when positioning the component parts as well as for positioning filler material in the root of the laser weld profile to avoid defects at this location. Further, good visual quality of the two surfaces of the weld is assured.

Fig. 15 Two sided laser hybrid welded I-butt joint in 40 mm thickness, (FORCE, LWT, 2015).

Fig. 16 Single sided laser hybrid welded I-butt joint in 40 mm thickness, covered by two GMAW weld at top and bottom (FORCE, LWT, 2015).
7. Conclusion

High power industrial lasers are on their way to enter the production of heavy metal constructions as basis for the laser hybrid welding process.

Power levels up to 100 kW is now available on the market. At Lindø Welding Technology (LWT), which is a subsidiary to FORCE Technology, a 32-kW disc laser is installed. Welding of thicker materials has become of interest for the heavy metal industry e.g. shipyards, wind mill producers, the power plant industry, producers of steel pipes and heavy machinery and steel producers in general.

The European Ship Classification Societies issued their first unified guidelines for the approval of CO₂ laser welding in 1996 and the 2005 edition now contains reference to hybrid welding. This means that the basis for further utilisation in other branches are present.

The laser hybrid welding process permits greater fit-up tolerance, elimination of defects due to the addition of filler material and the ability to weld thicker materials. In general, laser hybrid welding offers higher productivity, stable and high weld quality and the possibility of implementing an automated cost reducing welding process.

The challenges for heavy material thicknesses are defect control, which means the elimination of cracks and reduction of porosities. This is done by the addition of relevant filler materials as well as by optimum joint geometries allowing the filler material to mix with the base material and to assure a proper solidification.

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